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Pressure-Temperature Curves
For
TVA
Browns Ferry Unit 1

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EXECUTIVE SUMMARY

This report provides the pressure-temperature curves (P-T curves) developed to present steam dome pressure versus minimum vessel metal temperature incorporating appropriate non-beltline limits and irradiation embrittlement effects in the beltline. The methodology used to generate the P-T curves in this report is similar to the methodology used to generate the P-T curves in 1994 [1]; the P-T curves in this report represent 12 and 16 effective full power years (EFPY), where 16 EFPY represents the end of the 40 year license, and 12 EFPY is provided as a midpoint between the current EFPY and 16 EFPY. The 1995 Edition of the ASME Boiler and Pressure Vessel Code including 1996 Addenda was used in this evaluation. The P-T curve methodology includes the following: 1) the incorporation of ASME Code Cases N-640 and N-588, and 2) the use of the M_m calculation in the ASME Code paragraph G-2214.1 for a postulated defect normal to the direction of maximum stress. ASME Code Case N-640 allows the use of K_{IC} of Figure A-4200-1 of Appendix A in lieu of Figure G-2210-1 in Appendix G to determine $T-RT_{NDT}$. ASME Code Case N-588 allows the use of an alternative procedure for calculating the applied stress intensity factors of Appendix G for axial and circumferential welds. This report incorporates a fluence calculated in accordance with the GE Licensing Topical Report NEDC-32983P, which has been approved by the NRC in a SER [14], and is in compliance with Regulatory Guide 1.190. This fluence represents an Extended Power Uprate (EPU) for the rated power of 3952 MW_t.

CONCLUSIONS

The 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 four vessel regions that should be monitored against the P-T curve operating limits; these regions are defined on the thermal cycle diagram [2]:

- Closure flange region (Region A)

- Core beltline region (Region B)
- Upper vessel (Regions A & B)
- Lower vessel (Regions B & C)

For the core not critical and the core critical curves, the P-T curves specify a coolant heatup and cooldown temperature rate of 100°F/hr or less for which the curves are applicable. However, the core not critical and the core critical curves were also developed to bound transients defined on the RPV thermal cycle diagram [2] and the nozzle thermal cycle diagrams [3]. The bounding transients used to develop the curves are described in this report. For the hydrostatic pressure and leak test curve, a coolant heatup and cooldown temperature rate of 15°F/hr or less must be maintained at all times.

The P-T curves apply for both heatup and cooldown and for both the 1/4T and 3/4T locations because the maximum tensile stress for either heatup or cooldown is applied at the 1/4T location. For beltline curves this approach has added conservatism because irradiation effects cause the allowable toughness, K_{Ir}, at 1/4T to be less than that at 3/4T for a given metal temperature.

Composite P-T curves were generated for each of the Pressure Test, Core Not Critical and Core Critical conditions at 12 and 16 EFPY. The composite curves were generated by enveloping the most restrictive P-T limits from the separate bottom head, beltline, upper vessel and closure assembly P-T limits. Separate P-T curves were developed for the upper vessel, beltline (at 12 and 16 EFPY), and bottom head for the Pressure Test and Core Not Critical conditions.

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1.0 INTRODUCTION

The pressure-temperature (P-T) curves included in this report have been developed to present steam dome pressure versus minimum vessel metal temperature incorporating appropriate non-beltline limits and irradiation embrittlement effects in the beltline. Complete P-T curves were developed for 12 and 16 effective full power years (EFPY), where 16 EFPY represents the end of the 40 year license, and 12 EFPY is provided as a midpoint between the current EFPY and 16 EFPY. The P-T curves are provided in Section 5.0 and a tabulation of the curves is included in Appendix B. This report incorporates a fluence calculated in accordance with the GE Licensing Topical Report NEDC-32983P, which has been approved by the NRC in a SER [14], and is in compliance with Regulatory Guide 1.190. This fluence represents an Extended Power Uprate (EPU) for the rated power of 3952 MW_t.

The methodology used to generate the P-T curves in this report is presented in Section 4.3 and is similar to the methodology used to generate the P-T curves in 1994 [1]. The 1995 Edition of the ASME Boiler and Pressure Vessel Code including 1996 Addenda was used in this evaluation. The P-T curve methodology includes the following: 1) the incorporation of ASME Code Cases N-640 and N-588 [4], and 2) the use of the M_m calculation in the ASME Code paragraph G-2214.1 [6] for a postulated defect normal to the direction of maximum stress. ASME Code Case N-640 allows the use of K_{IC} from Figure A-4200-1 of Appendix A [17] in lieu of Figure G-2210-1 in Appendix G to determine T-RT_{NDT}. ASME Code Case N-588 allows the use of an alternative procedure for calculating the applied stress intensity factors of Appendix G for axial and circumferential welds. P-T curves are developed using geometry of the RPV shells and discontinuities, the initial RT_{NDT} of the RPV materials, and the adjusted reference temperature (ART) for the beltline materials.

The initial RT_{NDT} is the reference temperature for the unirradiated material as defined in Paragraph NB-2331 of Section III of the ASME Boiler and Pressure Vessel Code. The Charpy energy data used to determine the initial RT_{NDT} values are tabulated from the Certified Material Test Report (CMTRs). The data and methodology used to determine initial RT_{NDT} are documented in Section 4.1.

Adjusted Reference Temperature (ART) is the reference temperature when including irradiation shift and a margin term. Regulatory Guide 1.99, Rev. 2 [7] provides the methods for calculating ART. The value of ART is a function of RPV 1/4T fluence and beltline material chemistry. The ART calculation, methodology, and ART tables for 12 and 16 EFPY are included in Section 4.2. The peak ID fluence values of 5.3×10^{17} n/cm^2 (12 EFPY) and 7.06×10^{17} n/cm^2 (16 EFPY) used in this report are discussed in Section 4.2.1.2. Beltline chemistry values are discussed in Section 4.2.1.1.

Comprehensive documentation of the RPV discontinuities that are considered in this report is included in Appendix A. This appendix also includes a table that documents which non-beltline discontinuity curves are used to protect each discontinuity.

Guidelines and requirements for operating and temperature monitoring are included in Appendix C. Temperature monitoring requirements and methods are available in GE Services Information Letter (SIL) 430 contained in Appendix D. Appendix E demonstrates that all reactor vessel nozzles requiring fracture toughness evaluation are outside the beltline region. Finally, Appendix F provides the calculation for equivalent margin analysis (EMA) for upper shelf energy (USE).

2.0 SCOPE OF THE ANALYSIS

The methodology used to generate the P-T curves in this report is similar to the methodology used to generate the P-T curves in 1994 [1]. A detailed description of the P-T curve bases is included in Section 4.3. The 1995 Edition of the ASME Boiler and Pressure Vessel Code including 1996 Addenda was used in this evaluation. The P-T curve methodology includes the following: 1) the incorporation of ASME Code Cases N-640 and N-588, and 2) the use of the M_m calculation in the ASME Code paragraph G-2214.1 for a postulated defect normal to the direction of maximum stress. ASME Code Case N-640 allows the use of K_{IC} from Figure A-4200-1 of Appendix A in lieu of Figure G-2210-1 in Appendix G to determine T-RT_{NDT}. ASME Code Case N-588 allows the use of an alternative procedure for calculating the applied stress intensity factors to consider attenuation to reference flaw orientation of Appendix G for circumferential welds. This Code Case also provides an alternative procedure for calculating the applied stress intensity factor for axial welds. Other features presented are:

- Generation of separate curves for the upper vessel in addition to those generated for the beltline, and bottom head.
- Comprehensive description of discontinuities used to develop the non-beltline curves (see Appendix A).

The pressure-temperature (P-T) curves are established to the requirements of 10CFR50, Appendix G [8] 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, Rev. 2 [7].

In addition to beltline considerations, there are non-beltline discontinuity limits such as nozzles, penetrations, and flanges that influence the construction of P-T curves. The non-beltline limits are based on generic analyses that are adjusted to the maximum reference temperature of nil ductility transition (RT_{NDT}) for the applicable Browns Ferry Unit 1 vessel components. The non-beltline limits are discussed in Section 4.3 and are also governed by requirements in [8].

Furthermore, curves are included to allow monitoring of the vessel bottom head and upper vessel regions separate from the beltline region. This refinement could minimize heating requirements prior to pressure testing. Operating and temperature monitoring requirements are found in Appendix C. Temperature monitoring requirements and methods are available in GE Services Information Letter (SIL) 430 contained in Appendix D. Appendix E demonstrates that all reactor vessel nozzles requiring fracture toughness evaluation are outside the beltline region. Finally, Appendix F provides the calculation for equivalent margin analysis (EMA) for upper shelf energy (USE).

3.0 ANALYSIS ASSUMPTIONS

The following assumptions are made for this analysis:

The hydrostatic pressure test will be conducted at or below 1064 psig; the evaluation conservatively uses this maximum pressure.

The shutdown margin, provided in the Definitions Section of the Browns Ferry Unit 1 Technical Specification [5], is calculated for a water temperature of 68°F.

The fluence is conservatively calculated using an EPU flux for the entire plant life. The flux is calculated in accordance with Regulatory Guide 1.190.

4.0 ANALYSIS

4.1 INITIAL REFERENCE TEMPERATURE

4.1.1 Background

The initial RT_{NDT} values for all low alloy steel vessel components are needed to develop the vessel P-T limits. The requirements for establishing the vessel component toughness prior to 1972 were per the ASME Code Section III, Subsection NB-2300 and are summarized as follows:

a. Test specimens shall be longitudinally oriented CVN specimens.

b. At the qualification test temperature (specified in the 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 used to establish an initial RT_{NDT} value are significantly different. For plants constructed according to the ASME Code after Summer 1972, the requirements per the ASME Code Section III, Subsection NB-2300 are as follows:

a. Test specimens shall be transversely oriented (normal to the rolling direction) CVN specimens.

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 highest RT_{NDT} of the materials in the closure flange region or lowest service temperature (LST) of the bolting material, whichever is greater.

10CFR50 Appendix G [8] 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 developed methods for analytically

converting fracture toughness data for vessels constructed before 1972 to comply with current requirements. These methods were developed from data in WRC Bulletin 217 [9] and from data collected to respond to NRC questions on FSAR submittals in the late 1970s. In 1994, these methods of estimating RT_{NDT} were submitted for generic approval by the BWR Owners' Group [10], and approved by the NRC for generic use [11].

4.1.2 Values of Initial RT_{NDT} and Lowest Service Temperature (LST)

To establish the initial RT_{NDT} temperatures for the Browns Ferry Unit 1 vessel per the current requirements, calculations were performed in accordance with the GE method for determining RT_{NDT}. Example RT_{NDT} calculations for vessel plate, forging, and for bolting material LST are summarized in the remainder of this section.

The RT_{NDT} values for the vessel weld materials were not calculated; these values were obtained from [13] (see Table 4-2).

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 (obtained from certified material test reports, CMTRs [12]). For Browns Ferry Unit 1 CMTRs, typically six energy values were listed at a given test temperature, corresponding to two sets of Charpy tests. The lowest energy Charpy value is adjusted by adding 2°F per ft-lb energy difference from 50 ft-lb.

For example, for the Browns Ferry Unit 1 beltline plate heat C2868-2 in the lower-intermediate shell course; the lowest Charpy energy and test temperature from the CMTRs is 25 ft-lb at 10°F. The estimated 50 ft-lb longitudinal test temperature is:

$$T_{50L} = 10°F + [\ (50 - 25)\ \text{ft-lb} \cdot 2°F/\text{ft-lb}\ ] = 60°F$$

The transition from longitudinal data to transverse data is made by adding 30°F to the 50 ft-lb longitudinal test temperature; thus, for this case above,

$$T_{50T} = 60°F + 30°F = 90°F.$$

The initial RT_{NDT} is the greater of nil-ductility transition temperature (NDT) or (T_{50T}- 60°F). Dropweight testing to establish NDT for plate material is listed in the CMTR; the NDT for the case above is 0°F. Thus, the initial RT_{NDT} for plate heat C2868-2 is 30°F.

For the vessel 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 recirculation inlet nozzle at Browns Ferry Unit 1, Heat ZT2869, the NDT is 30°F and the lowest CVN data is 31 ft-lb at 40°F. The corresponding value of (T_{50T}- 60°F) is:

$$(T_{50T} - 60°F) = \{ [40 + (50 - 31) \text{ ft-lb} \cdot 2°F/\text{ft-lb}] + 30 \} - 60°F = 48°F.$$

Therefore, the initial RT_{NDT} is the greater of nil-ductility transition temperature (NDT) or (T_{50T}- 60°F), which is 48°F.

In the bottom head region of the vessel, the vessel plate method is applied for estimating RT_{NDT}. For the bottom head lower torus plate heat of Browns Ferry Unit 1 (Heat C1412-3), the NDT is 40°F and the lowest CVN data was 27 ft-lb at 40°F. The corresponding value of (T_{50T} - 60°F) was:

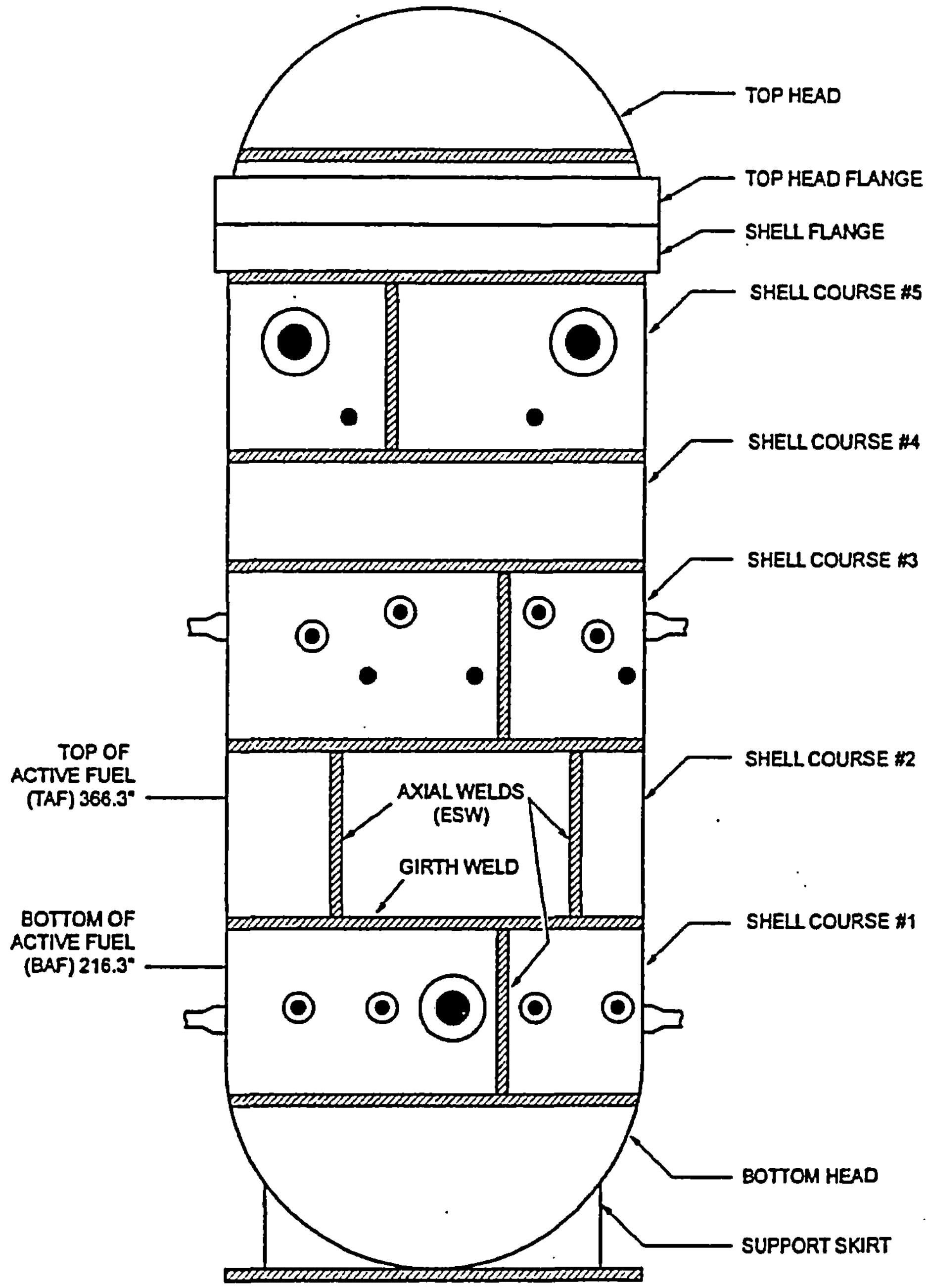
$$(T_{50T} - 60°F) = \{ [40 + (50 - 27) \text{ ft-lb} \cdot 2°F/\text{ft-lb}] + 30°F \} - 60°F = 56°F.$$

Therefore, the initial RT_{NDT} was 56°F.

For bolting material, the current ASME Code requirements define the lowest service temperature (LST) as the temperature at which transverse CVN energy of 45 ft-lb and 25 mils lateral expansion (MLE) were achieved. If the required Charpy results are not met, or are not reported, but the CVN energy reported is above 30 ft-lb, the requirements of the ASME Code Section III, Subsection NB-2300 at construction are applied, namely that the 30 ft-lb test temperature plus 60°F is the LST for the bolting materials. Some Charpy data for the Browns Ferry Unit 1 closure studs did not meet the 45 ft-lb, 25 MLE requirements at 10°F. Therefore, the LST for the bolting material is 70°F. The highest

RT_{NDT} in the closure flange region is 23.1°F, for the vertical electroslag weld material in the upper shell. Thus, the higher of the LST and the RT_{NDT} +60°F is 83.1°F, the bolt-up limit in the closure flange region.

The initial RT_{NDT} values for the Browns Ferry Unit 1 reactor vessel (refer to Figure 4-1 for the Browns Ferry Unit 1 Schematic) materials are listed in Tables 4-1, 4-2, and 4-3. This tabulation includes beltline, closure flange, feedwater nozzle, and bottom head materials that are considered in generating the P-T curves.



Notes: (1) Refer to Tables 4-1, 4-2, and 4-3 for reactor vessel components and their heat identifications.
(2) See Appendix E for the definition of the beltline region.

Figure 4-1: Schematic of the Browns Ferry Unit 1 RPV Showing Arrangement of Vessel Plates and Welds

Table 4-1: RT_{NDT} Values for Browns Ferry Unit 1 Vessel Materials

Component	Heat	Test Temp (°F)	Charpy Energy (ft-lb)			$(T_{50T}-60)$ (°F)	Drop Weight NDT (°F)	RT_{NDT} (°F)
PLATES & FORGINGS:								
Top Head & Flange								
Shell Flange (MK48)								
48-127-1	ALU 55	10	118	90	79	-20	10	10
Top Head Flange (MK209)								
209-127-1	AMW 56	10	120	109	126	-20	10	10
Top Head Dollar (MK201)								
201-122-2	C-1354-3	40	67	58	51	10	Not Available	40
Top Head Side Plates (MK202)								
202-122-1	A0057-2	10	45	41	55	-2	10	10
202-122-2	A0057-2	10	37	30	42	20	10	20
202-122-5	C1182-1	10	41	60	50	-2	10	10
202-122-6	C1182-1	10	57	45	62	-10	10	10
202-139-5	C2737-2	10	68	90	86	-20	10	10
202-139-6	C2737-2	10	84	78	86	-20	10	10
Shell Courses								
Upper Shell Plates (MK60)								
6-127-7	A0973-1	10	57	60	41	-2	10	10
6-127-12	C1942-2	10	46	52	52	-12	10	10
6-127-19	C2496-2	10	56	58	54	-20	10	10
Transition Shell Plates (MK16)								
15-127-2	C-2533-2	10	53	48	43	-6	10	10
15-127-5	A-0954-3	10	46	40	32	16	10	16
15-127-6	A-0954-3	10	41	52	45	-2	10	10
Upper Intermediate Shell Plates (MK59)								
6-127-3	B5842-1	10	63	62	61	-20	10	10
6-127-8	A0954-1	10	52	60	55	-20	10	10
6-127-10	B5853-2	10	70	65	66	-20	10	10
Lower Intermediate Shell Plates (MK58)								
6-139-19	C2884-2	10	33	55	34	14	0	14
6-139-20	C2868-2	10	46	55	25	30	0	30
6-139-21	C2753-1	10	39	58	57	2	-20	2
Lower Shell Segments (MK57)								
6-127-2	B5864-1	10	84	73	62	-20	-20	-20
6-127-4	A1009-1	10	62	84	77	-20	-10	-10
6-127-1	A0999-1	10	56	59	66	-20	-20	-20
Bottom Head								
Bottom Head Upper Torus (MK2)								
2-122-7	B5924-1	40	75	70	75	10	40	40
2-122-8	B5924-1	40	37	61	44	36	40	40
2-122-10	A0942-2	40	62	62	65	10	40	40
2-127-7	C2412-3	40	91	90	57	10	40	40
2-127-8	C2412-3	40	95	92	82	10	40	40
2-127-9	C2393-2	40	105	125	112	10	40	40
Bottom Head Lower Torus (MK4)								
4-122-5	A0927-2	40	71	50	59	10	40	40
4-122-6	A0927-2	40	75	66	64	10	40	40
4-122-7	C1412-3	40	30	41	40	50	40	50
4-122-8	C1412-3	40	27	35	49	56	40	56
Bottom Head Dollar (MK1)								
1-122-2	B5861-1	40	45	50	49	20	40	40

NOTE: *These are minimum Charpy values.*

Table 4-2: RT_{NDT} Values for Browns Ferry Unit 1 Nozzle and Weld Materials

Component	Heat or Heat/Flux/Lot	Test Temp (°F)	Charpy Energy (ft-lb)			(T_{50T}-60) (°F)	Drop Weight NDT (°F)	RT_{NDT} (°F)
Nozzles:								
N1 Recirc Outlet Nozzle (MK8)								
8-127-1	E31VW 431H-1	40	109	86	90	10	40	40
8-139-2	AV1696 7J-6327	40	34	46	44	42	40	42
N2 Recirc Inlet Nozzle (MK7)								
7-122-1	ZT2872 9709-1	40	65	54	58	10	30	30
7-122-7	ZT2869 9704-1	40	31	38	39	48	30	48
7-127-9	E25VW 433H-9	40	93	103	110	10	40	40
7-122-10	ZT2872 9709-2	40	65	54	58	10	30	30
7-122-11	ZT2885 9711-1	40	34	37	41	42	30	42
7-122-12	ZT2885 9711-2	40	34	37	41	42	30	42
7-122-13	ZT2885-3 9710-2	40	64	48	38	39	30	39
7-122-16	ZT-2885	40	38	38	48	35	30	35
7-122-18	ZT2885 9712-2	40	54	52	49	12	30	30
7-122-19	ZT2869 9705-1	40	69	53	42	27	30	30
N3 Steam Outlet Nozzle (MK14)								
14-127-1	E26VW 435H-1	40	97	77	94	10	40	40
14-127-2	E26VW 435H-2	40	86	84	76	10	40	40
14-127-3	E26VW 435H-3	40	102	92	105	10	40	40
14-127-4	E26VW 435H-4	40	119	94	94	10	40	40
N4 Feedwater Nozzle (MK10)								
10-127-1	E25VW 436H-1	40	98	97	92	10	40	40
10-127-2	E25VW 436H-2	40	124	98	105	10	40	40
10-127-3	E25VW 436H-3	40	99	84	92	10	40	40
10-127-4	E25VW 436H-4	40	111	98	101	10	40	40
10-127-5	E25VW 436H-5	40	114	114	110	10	40	40
10-127-6	E25VW 436H-6	40	117	111	112	10	40	40
N5 Core Spray Nozzle (MK11)								
11-111-1	BT2001-2 7098	40	48	32	42	46	40	46
11-111-2	BT2001-3 6945-1	40	54	36	49	38	40	40
N6 Top Head Instrumentation Nozzle (MK206) 206-139-1 & -4	BT2615-4	40	123	143	144	10	40	40
N7 Vent Nozzle (MK204) 204-127-1	ZT3043-3	40	102	130	117	10	40	40
N8 Jet Pump Instr. Nozzle (MK19) 19-127-1 & -2	ZT3043	40	107	112	113	10	40	40
N9 CRD HYD System Return Nozzle (MK13) 13-145-1	EV9793 7K-6233A	40	81	50	91	10	40	40
N10 Core DP & Liquid Control Nozzle (MK17) 17-127-1	ZT3043	40	106	136	111	-20	40	40
N11, N12, N16 Instrumentation Nozzle (MK12) 12-127-1 through 6	Inconel 8564							
N13, N14 High & Low Pressure Seal Leak (MK139) 139-127-1 & -2	Not Available						40	40*
N15 Drain Nozzle (MK22) 22-127-1	213099	40	42	44	39	32	40	40
WELDS: *Cylindrical Shell Axial Welds* Electroslag Welds	ESW							23.1**
Girth Welds Shell 1 to Shell 2 WF 154 (SAW)	406L44, Lot 8720							20**

* No NDT value available on CMTR; obtained from Purchase Specification 21A1111.

** Weld initial RT_{NDT} values obtained from [13].

NOTE: These are minimum Charpy values.

Table 4-3: RT_{NDT} Values for Browns Ferry Unit 1 Appurtenance and Bolting Materials

Component	Heat	Test Temp (°F)	Charpy Energy (ft-lb)			(T_{50T}-60) (°F)	Drop Weight NDT (°F)	RT_{NDT} (°F)
Miscellaneous Appurtenances: Support Skirt Segment (MK24) 24-139-1 through -4	C3888-5	10	38	40	41	4	40	40
Shroud Support (MK51, MK52, MK53)	Alloy 600							
Steam Dryer Support Bracket (MK131) 131-127-1 through -4	Stainless Steel 00431							
Core Spray Bracket (MK132) 132-127-1 through -8	Stainless Steel 3342230							
Dryer Hold Down Bracket (MK133) 133-127-1 through -4	EV-8446	40	38	42	37	36	40	40
Guide Rod Bracket (MK134) 134-127-1 & -2	Stainless Steel 139506							
Feedwater Sparger Brackets (MK135) 135-127-1 through -12	Stainless Steel 00431							
Stabilizer Bracket (MK196) 196-127-5 through -12	C6458-1	10	60	59	56	-20	40	40
Surveillance Brackets (MK199 & MK200) 199-127-1 through -3 200-127-1 through -3	Stainless Steel 342633-2 342633-2							
Lifting Lugs (MK210) 210-122-1, -2, -3, & -6	A1210-3B	10	83	98	95	-20	40	40
CRD penetrations (MK101 - MK128) 101 through 128	Alloy 600							
Refueling Containment Skirt (MK71) 71-127-1 through -4	B7478-4B							40*

Component	Heat	Test Temp (°F)	Charpy Energy (ft-lb)			Lateral Expansion (mils)	LST (°F)
STUDS: Closure (MK61)	6730502	10	34	52	68	n/a	70
NUTS: Closure (MK62)	6730502	10	34	52	68	n/a	70
	23514	10	49	53	63	29	10
	6780382	10	45	42	46	n/a	70
	6790156	n/a	n/a	n/a	n/a	n/a	70
BUSHINGS: Closure (MK63)	T3798	10	61	69	73	51	10
	M2513	10	64	65	67	40	10
	M2514	10	66	56	70	42	10
	EV9474	10	67	64	62	n/a	70
	AV3107	10	63	70	72	n/a	70
WASHERS: Closure (MK64 and MK65)	6730502	10	34	52	68	n/a	70
	6780278	n/a	n/a	n/a	n/a	n/a	70

* No Charpy or NDT values available on CMTR; obtained from Purchase Specification 21A1111.
NOTE: These are minimum Charpy values.

4.2 *ADJUSTED REFERENCE TEMPERATURE FOR BELTLINE*

The adjusted reference temperature (ART) of the limiting beltline material is used to adjust the beltline P-T curves to account for irradiation effects. Regulatory Guide 1.99, Revision 2 (RG1.99) provides the methods for determining the ART. The RG1.99 methods for determining the limiting material and adjusting the P-T curves using ART are discussed in this section. An evaluation of ART for all beltline plates and welds was performed and is summarized in Tables 4-4 and 4-5 for 12 and 16 EFPY, respectively.

4.2.1 Regulatory Guide 1.99, Revision 2 (RG1.99) 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 RG1.99, the SHIFT equation consists of two terms:

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

where,

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

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

CF = chemistry factor from Tables 1 or 2 of RG1.99

f = ¼T fluence / 10^{19}

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

σ_I = standard deviation on initial RT_{NDT}, which is taken to be 0°F (13°F for electroslag welds).

σ_Δ = standard deviation on ΔRT_{NDT}, 28°F for welds and 17°F for base material, except that σ_Δ need not exceed 0.50 times the ΔRT_{NDT} value.

$$ART = Initial\ RT_{NDT} + SHIFT$$

The margin term σ_Δ has constant values of 17°F for plate and 28°F for weld as defined in RG1.99. However, σ_Δ need not be greater than $0.5 \cdot \Delta RT_{NDT}$. Since the GE/BWROG method of estimating RT_{NDT} operates on the lowest Charpy energy value (as described in Section 4.1.2) 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 plate and most weld materials, except that σ_I is 13°F for the beltline electroslag weld materials and 10°F for the beltline SAW girth weld material [13].

4.2.1.1 Chemistry

The vessel beltline plate chemistries were obtained from [1] and the beltline weld material chemistries were obtained from [13].

The copper (Cu) and nickel (Ni) values were used with Tables 1 and 2 of RG1.99, to determine a chemistry factor (CF) per Paragraph 1.1 of RG1.99 for welds and plates, respectively. Best estimate results are used for the beltline electroslag [13] materials for the initial RT_{NDT}; therefore, the standard deviation (σ_I) is specified.

4.2.1.2 Fluence

An EPU (Extended Power Uprate) flux for the vessel ID wall was calculated using methods consistent with Regulatory Guide 1.190, and is determined for the EPU rated power of 3952 MW_t. The peak fast flux for the RPV inner surface, used for determination of the P-T curves, is 1.4e9 n/cm^2-s for EPU conditions.

For comparison, the calculated fast flux at the representative (Browns Ferry Unit 2 Cycle 7) capsule center is 8.85e8 n/cm^2-s with a corresponding lead factor of 0.98; Browns Ferry Unit 2 is used as a representative capsule because Browns Ferry Unit 1 has not yet removed a capsule. This calculation was performed prior to Regulatory Guide 1.190 (RG1.190), using methodology similar to RG1.190. [[

]], the calculated fast flux at this capsule is 9.5e8 n/cm^2-s. The flux wire measurement for the Browns Ferry Unit 2 Cycle 7 capsule removed during the Fall 1994 refueling outage at 8.2 EFPY is 5.9e8 n/cm^2-s [22] (with a lead factor of 0.98), resulting in a calculation-to-measurement ratio of 1.6. The currently licensed 12 EFPY Browns Ferry Unit 1 P-T curves are based upon a 32 EFPY fluence of 7.6e17 n/cm^2 [1].

16 EFPY Fluence

Browns Ferry Unit 1 will begin EPU operation at approximately 6 EFPY, thereby operating for 10 EFPY at EPU conditions for a total of 16 EFPY. As can be seen above, use of the EPU flux of 1.4e9 n/cm^2-s to determine the fluence for the entire 16 EFPY (representing the 40 year Browns Ferry Unit 1 license period) is conservative. The RPV peak ID fluence is calculated as follows:

$1.4e9\ n/cm^2\text{-s} \cdot 5.05e8\ s = 7.06e17\ n/cm^2$.

This fluence applies to the lower-intermediate plate and axial weld materials. The fluence is adjusted for the lower shell and axial welds, as well as for the lower to lower-intermediate girth weld based upon a peak / lower shell location ratio of 0.81 for EPU conditions (at an elevation of approximately 258" above vessel "0"); hence the peak ID fluence used for these components is 5.72e17 n/cm^2. It was determined that the fluence calculated using the EPU flux (1.4e9 n/cm^2-s) with the corresponding distribution factor of 0.81 bounds the fluence calculated using the pre-EPU flux (9.5e8 n/cm^2-s) with the corresponding factor of 0.86 calculated during the 1995 Browns Ferry Unit 2 capsule evaluation [22].

The fluence at 1/4T is calculated per Equation 3 of Regulatory Guide 1.99, Revision 2 [7] using the Browns Ferry Unit 1 plant specific fluence and vessel thickness of 6.13". The 16 EFPY 1/4T fluence for the lower-intermediate shell plate and axial welds is:

$7.06e17\ n/cm^2 \cdot \exp(-0.24 \cdot (6.13 / 4)) = 4.89e17\ n/cm^2$.

The 16 EFPY 1/4T fluence for the lower shell plate and axial welds and the lower to lower-intermediate girth weld is:

$5.72e17\ n/cm^2 \cdot \exp(-0.24 \cdot (6.13 / 4)) = 3.96e17\ n/cm^2$.

12 EFPY Fluence

The RPV peak ID fluence for 12 EFPY is scaled from the 16 EFPY calculation above:

$7.06e17\ n/cm^2 \cdot (12 / 16) = 5.3e17\ n/cm^2$.

Similarly, this fluence applies to the lower-intermediate plate and axial weld materials. The fluence is adjusted for the lower shell and axial welds, as well as for the lower to lower-

intermediate girth weld based upon a peak / lower shell location ratio of 0.81 for EPU conditions; hence the peak ID fluence used for these components is 4.29e17 n/cm^2.

The fluence at 1/4T is calculated per Equation 3 of Regulatory Guide 1.99, Revision 2 [7] using the Browns Ferry Unit 1 plant specific fluence and vessel thickness of 6.13". The 12 EFPY 1/4T fluence for the lower-intermediate shell plate and axial welds is:

5.3e17 n/cm^2 · exp(-0.24 · (6.13 / 4)) = 3.67e17 n/cm^2.

The 12 EFPY 1/4T fluence for the lower shell plate and axial welds and the lower to lower-intermediate girth weld is:

4.29e17 n/cm^2 · exp(-0.24 · (6.13 / 4)) = 2.97e17 n/cm^2.

4.2.2 Limiting Beltline Material

The limiting beltline material signifies the material that is estimated to receive the greatest embrittlement due to irradiation effects combined with initial RT_{NDT}. Using initial RT_{NDT}, chemistry, and fluence as inputs, RG1.99 was applied to compute ART. Tables 4-4 and 4-5 list values of beltline ART for 12 and 16 EFPY, respectively.

Table 4-4: Browns Ferry Unit 1 Beltline ART Values (12 EFPY)

Lower-Intermediate Plates and Axial Welds

Thickness in inches = 6.13 | Ratio Peak/ Location = 1.00

12 EFPY Peak I.D. fluence = 5.30E+17 n/cm^2
12 EFPY Peak 1/4 T fluence = 3.67E+17 n/cm^2
12 EFPY Peak 1/4 T fluence = 3.67E+17 n/cm^2

Lower Plates and Axial Welds & Lower to Lower-Intermediate Girth Weld

Thickness in inches= 6.13 | Ratio Peak/ Location = 0.81

12 EFPY Peak I.D. fluence = 4.29E+17 n/cm^2
12 EFPY Peak 1/4 T fluence = 2.97E+17 n/cm^2
12 EFPY Peak 1/4 T fluence = 2.97E+17 n/cm^2

COMPONENT	HEAT OR HEAT/LOT	%Cu*	%Ni*	CF	Initial RTndt °F	1/4 T Fluence n/cm^2	12 EFPY Δ RTndt °F	σ_I	σ_Δ	Margin °F	12 EFPY Shift °F	12 EFPY ART °F
PLATES:												
Lower Shell												
6-127-1	A0999-1	0.14	0.60	100	-20	2.97E+17	22	0	11	22	44	24
6-127-2	B5864-1	0.15	0.44	101	-20	2.97E+17	22	0	11	22	44	24
6-127-4	A1009-1	0.14	0.50	96	-10	2.97E+17	21	0	10	21	42	32
Lower-Intermediate Shell												
6-139-19	C2884-2	0.12	0.53	82	14	3.67E+17	20	0	10	20	40	54
6-139-20	C2868-2	0.09	0.48	58	30	3.67E+17	14	0	7	14	29	59
6-139-21	C2753-1	0.08	0.50	51	2	3.67E+17	13	0	6	13	25	27
WELDS:												
Axial Welds												
ESW	–	0.24	0.37	141	23.1	3.67E+17	35	13	17	43	78	101
Girth												
WF154	406L44	0.27	0.60	184	20	2.97E+17	40	10	20	45	85	105

* Chemistries obtained from [1] and [13].

Table 4-5: Browns Ferry Unit 1 Beltline ART Values (16 EFPY)

Lower-Intermediate Plates and Axial Welds

Thickness in inches = 6.13 Ratio Peak/ Location = 1.00

16 EFPY Peak I.D. fluence = 7.06E+17 n/cm^2
16 EFPY Peak 1/4 T fluence = 4.89E+17 n/cm^2
16 EFPY Peak 1/4 T fluence = 4.89E+17 n/cm^2

Lower Plates and Axial Welds & Lower to Lower-Intermediate Girth Weld

Thickness in inches= 6.13 Ratio Peak/ Location = 0.81

16 EFPY Peak I.D. fluence = 5.72E+17 n/cm^2
16 EFPY Peak 1/4 T fluence = 3.96E+17 n/cm^2
16 EFPY Peak 1/4 T fluence = 3.96E+17 n/cm^2

COMPONENT	HEAT OR HEAT/LOT	%Cu*	%Ni*	CF	Initial RTndt °F	1/4 T Fluence n/cm^2	16 EFPY Δ RTndt °F	σ_I	σ_Δ	Margin °F	16 EFPY Shift °F	16 EFPY ART °F
PLATES:												
Lower Shell												
6-127-1	A0999-1	0.14	0.60	100	-20	3.96E+17	26	0	13	26	51	31
6-127-2	B5864-1	0.15	0.44	101	-20	3.96E+17	26	0	13	26	52	32
6-127-4	A1009-1	0.14	0.50	96	-10	3.96E+17	25	0	12	25	49	39
Lower-Intermediate Shell												
6-139-19	C2884-2	0.12	0.53	82	14	4.89E+17	24	0	12	24	47	61
6-139-20	C2868-2	0.09	0.48	58	30	4.89E+17	17	0	8	17	34	64
6-139-21	C2753-1	0.08	0.50	51	2	4.89E+17	15	0	7	15	29	31
WELDS:												
Axial Welds												
ESW	-	0.24	0.37	141	23.1	4.89E+17	41	13	20	48	89	112
Girth												
WF154	406L44	0.27	0.60	184	20	3.96E+17	47	10	24	51	99	119

* Chemistries obtained from [1] and [13].

4.3 PRESSURE-TEMPERATURE CURVE METHODOLOGY

4.3.1 Background

Nuclear Regulatory Commission (NRC) 10CFR50 Appendix G [8] specifies fracture toughness requirements to provide adequate margins of safety during the operating conditions to which a pressure-retaining component may be subjected over its service lifetime. The ASME Code (Appendix G of Section XI [6]) forms the basis for the requirements of 10CFR50 Appendix G. The 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 four vessel regions that should be monitored against the P-T curve operating limits; these regions are defined on the thermal cycle diagram [2]:

- Closure flange region (Region A)
- Core beltline region (Region B)
- Upper vessel (Regions A & B)
- Lower vessel (Regions B & C)

The closure flange region includes the bolts, top head flange, and adjacent plates and welds. The core beltline is the vessel location adjacent to the active fuel, such that the neutron fluence is sufficient to cause a significant shift of RT_{NDT}. The remaining portions of the vessel (i.e., upper vessel, lower vessel) include shells, components like the nozzles, the support skirt, and stabilizer brackets; these regions will also be called the non-beltline region.

For the core not critical and the core critical curves, the P-T curves specify a coolant heatup and cooldown temperature rate of 100°F/hr or less for which the curves are applicable. However, the core not critical and the core critical curves were also developed to bound transients defined on the RPV thermal cycle diagram [2] and the nozzle thermal cycle diagrams [3]. The bounding transients used to develop the curves

are described in the sections below. For the hydrostatic pressure and leak test curve, a coolant heatup and cooldown temperature rate of 15°F/hr or less must be maintained at all times.

The P-T curves for the heatup and cooldown operating condition at a given EFPY apply for both the 1/4T and 3/4T locations. When combining pressure and thermal stresses, it is usually necessary to evaluate stresses at the 1/4T location (inside surface flaw) and the 3/4T 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 1/4T location is assumed to be tensile for both heatup and cooldown. This results in the approach of applying the maximum tensile stress at the 1/4T location. This approach is conservative because irradiation effects cause the allowable toughness, K_{Ir}, at 1/4T to be less than that at 3/4T for a given metal temperature. This approach causes no operational difficulties, since the BWR is at steam saturation conditions during normal operation, well above the heatup/cooldown curve limits.

The applicable temperature is the greater of the 10CFR50 Appendix G minimum temperature requirement or the ASME Appendix G limits. A summary of the requirements is provided in Table 4-6.

Table 4-6: Summary of the 10CFR50 Appendix G Requirements

Operating Condition and Pressure	Minimum Temperature Requirement
I. Hydrostatic Pressure Test & Leak Test (Core is Not Critical) - Curve A	
1. At ≤ 20% of preservice hydrotest pressure	Larger of ASME Limits or of highest closure flange region initial RT_{NDT} + 60°F*
2. At > 20% of preservice hydrotest pressure	Larger of ASME Limits or of highest closure flange region initial RT_{NDT} + 90°F
II. Normal operation (heatup and cooldown), including anticipated operational occurrences	
a. Core not critical - Curve B	
1. At ≤ 20% of preservice hydrotest pressure	Larger of ASME Limits or of highest closure flange region initial RT_{NDT} + 60°F*
2. At > 20% of preservice hydrotest pressure	Larger of ASME Limits or of highest closure flange region initial RT_{NDT} + 120°F
b. Core critical - Curve C	
1. At ≤ 20% of preservice hydrotest pressure, with the water level within the normal range for power operation	Larger of ASME Limits + 40°F or of a.1
2. At > 20% of preservice hydrotest pressure	Larger of ASME Limits + 40°F or of a.2 + 40°F or the minimum permissible temperature for the inservice system hydrostatic pressure test

* 60°F adder is included by GE as an additional conservatism as discussed in Section 4.3.2.3.

There are four vessel regions that affect the operating limits: the closure flange region, the core beltline region, and the two regions in the remainder of the vessel (i.e., the upper vessel and lower vessel non-beltline regions). The closure flange region limits are controlling at lower pressures primarily because of 10CFR50 Appendix G [8] requirements. The non-beltline and beltline region operating limits are evaluated according to procedures in 10CFR50 Appendix G [8], ASME Code Appendix G [6], and Welding Research Council (WRC) Bulletin 175 [15]. The beltline region minimum temperature limits are adjusted to account for vessel irradiation.

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4.3.2 P-T Curve Methodology

4.3.2.1 Non-Beltline Regions

Non-beltline regions are defined as the vessel locations that are remote from the active fuel and where the neutron fluence is not sufficient ($<1.0e17$ n/cm^2) to cause any significant shift of RT_{NDT}. Non-beltline components include nozzles (see Appendix E), the closure flanges, some shell plates, the top and bottom head plates and the control rod drive (CRD) penetrations.

Detailed stress analyses of the non-beltline components were performed for the BWR/6 specifically for the purpose of fracture toughness analysis. The BWR/6 stress analysis bounds for BWR/2 through BWR/5 designs, as will be demonstrated in the following evaluation. The analyses took into account mechanical loading and anticipated thermal transients. Transients considered include all normal and upset transients such as 100°F/hr start-up and shutdown, SCRAM, and loss of feedwater heaters. Primary membrane and bending stresses and secondary membrane and bending stresses due to the most severe of these transients were used according to the ASME Code [6] to develop plots of allowable pressure (P) versus temperature relative to the reference temperature ($T - RT_{NDT}$). Plots were developed for the limiting BWR/6 components: the feedwater nozzle (FW) and the CRD penetration (bottom head). All other components in the non-beltline regions are categorized under one of these two components as described in Tables 4-7 and 4-8.

Table 4-7: Applicable BWR/4 Discontinuity Components for Use With FW (Upper Vessel) Curves A & B

Discontinuity Identification
FW Nozzle
CRD HYD System Return
Core Spray Nozzle
Recirculation Inlet Nozzle
Steam Outlet Nozzle
Main Closure Flange
Support Skirt
Stabilizer Brackets
Shroud Support Attachments
Core ΔP and Liquid Control Nozzle
Steam Water Interface
Water Level Instrumentation Nozzle
Jet Pump Instrumentation Nozzle
Shell
CRD and Bottom Head
Top Head Nozzles
Recirculation Outlet Nozzle
Drain Nozzle

Table 4-8: Applicable BWR/4 Discontinuity Components for Use with CRD (Bottom Head) Curves A&B

Discontinuity Identification
CRD and Bottom Head
Top Head Nozzles
Recirculation Outlet Nozzle
Drain Nozzle
Shell**
Support Skirt**
Shroud Support Attachments**
Core ΔP and Liquid Control Nozzle**

** These discontinuities are added to the bottom head curve discontinuity list to assure that the entire bottom head is covered, because separate bottom head P-T curves are provided to monitor the bottom head.

The P-T curves for the non-beltline region were conservatively developed for a large BWR/6 (nominal inside diameter of 251 inches). The analysis is considered appropriate for Browns Ferry Unit 1 as the plant specific geometric values are bounded by the generic

analysis for a large BWR/6, as determined in Section 4.3.2.1.1 through Section 4.3.2.1.4. The generic value was adapted to the conditions at Browns Ferry Unit 1 by using plant specific RT_{NDT} values for the reactor pressure vessel (RPV). The presence of nozzles and CRD penetration holes in the upper vessel and bottom head, respectively, has made the analysis different from a shell analysis such as the beltline. This was the result of the stress concentrations and higher thermal stress for certain transient conditions experienced by the upper vessel and the bottom head.

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4.3.2.1.1 Pressure Test - Non-Beltline, Curve A (Using Bottom Head)

In a [[ ]] finite element analysis .[[ ]], the CRD penetration region was modeled to compute the local stresses for determination of the stress intensity factor, K_I. The [[ ]] generic evaluation was modified to consider the new requirement for M_m as discussed in ASME Code Section XI Appendix G [6] and shown below. The results of that computation were K_I = 143.6 ksi-in$^{1/2}$ for an applied pressure of 1593 psig (1563 psig preservice hydrotest pressure at the top of the vessel plus 30 psig hydrostatic pressure at the bottom of the vessel). The computed value of (T - RT_{NDT}) was 84°F. [[

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The limit for the coolant temperature change rate is 15°F/hr or less.

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The value of M_m for an inside axial postulated surface flaw from Paragraph G-2214.1 [6] was based on a thickness of 8.0 inches; hence, $t^{1/2} = 2.83$. The resulting value obtained was:

$$M_m = 1.85 \text{ for } \sqrt{t} \leq 2$$

$$\mathbf{M_m} = 0.926 \sqrt{t} \text{ for } 2 \leq \sqrt{t} \leq 3.464 = \mathbf{2.6206}$$

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

K_{Im} is calculated from the equation in Paragraph G-2214.1 [6] and K_{Ib} is calculated from the equation in Paragraph G-2214.2 [6]:

$K_{Im} = M_m \cdot \sigma_{pm}$ = [[ ]] ksi-in$^{1/2}$

$K_{Ib} = (2/3)\, M_m \cdot \sigma_{pb}$ = [[ ]] ksi-in$^{1/2}$

The total K_I is therefore:

$$K_I = 1.5\,(K_{Im} + K_{Ib}) + M_m \cdot (\sigma_{sm} + (2/3) \cdot \sigma_{sb}) = 143.6 \text{ ksi-in}^{1/2}$$

This equation includes a safety factor of 1.5 on primary stress. The method to solve for $(T - RT_{NDT})$ for a specific K_I is based on the K_{Ic} equation of Paragraph A-4200 in ASME Appendix A [17]:

$$(T - RT_{NDT}) = \ln\,[(K_I - 33.2) / 20.734] / 0.02$$

$(T - RT_{NDT}) =$ ln [(144 – 33.2) / 20.734] / 0.02

$(T - RT_{NDT}) =$ 84°F

The generic curve was generated by scaling 143.6 ksi-in$^{1/2}$ by the nominal pressures and calculating the associated $(T - RT_{NDT})$:

Pressure Test CRD Penetration K_I and $(T - RT_{NDT})$ as a Function Of Pressure

Nominal Pressure (psig)	K_I (ksi-in$^{1/2}$)	$T - RT_{NDT}$ (°F)
1563	144	84
1400	129	77
1200	111	66
1000	92	52
800	74	33
600	55	3
400	37	-88

The highest RT_{NDT} for the bottom head plates and welds is 56°F, as shown in Tables 4-1 and 4-2. [[

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Second, the P-T curve is dependent on the calculated K_I value, and the K_I value is proportional to the stress and the crack depth as shown below:

$$K_I \propto \sigma (\pi a)^{1/2} \quad (4\text{-}1)$$

The stress is proportional to R/t and, for the P-T curves, crack depth, *a*, is t/4. Thus, K_I is proportional to $R/(t)^{1/2}$. The generic curve value of $R/(t)^{1/2}$, based on the generic BWR/6 bottom head dimensions, is:

Generic: $R / (t)^{1/2} = 138 / (8)^{1/2} = 49 \text{ inch}^{1/2}$ (4-2)

The Browns Ferry Unit 1 specific bottom head dimensions are R = 125.7 inches and t =8 inches minimum [19], resulting in:

Browns Ferry Unit 1 specific: $R / (t)^{1/2} = 125.7 / (8)^{1/2} = 44 \text{ inch}^{1/2}$ (4-3)

Since the generic value of $R/(t)^{1/2}$ is larger, the generic P-T curve is conservative when applied to the Browns Ferry Unit 1 bottom head.

4.3.2.1.2 Core Not Critical Heatup/Cooldown - Non-Beltline Curve B (Using Bottom Head)

As discussed previously, the CRD penetration region limits were established primarily for consideration of bottom head discontinuity stresses during pressure testing. Heatup/cooldown limits were calculated by increasing the safety factor in the pressure testing stresses (Section 4.3.2.1.1) from 1.5 to 2.0. [[

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The calculated value of K_I for pressure test is multiplied by a safety factor (SF) of 1.5, per ASME Appendix G [6] for comparison with K_{IR}, the material fracture toughness. A safety factor of 2.0 is used for the core not critical. Therefore, the K_I value for the core not critical condition is $(143.6 / 1.5) \cdot 2.0 = 191.5$ ksi-in$^{1/2}$.

Therefore, the method to solve for $(T - RT_{NDT})$ for a specific K_I is based on the K_{Ic} equation of Paragraph A-4200 in ASME Appendix A [17] for the core not critical curve:

$$(T - RT_{NDT}) = \ln[(K_I - 33.2) / 20.734] / 0.02$$
$$(T - RT_{NDT}) = \ln[(191.5 - 33.2) / 20.734] / 0.02$$
$$(T - RT_{NDT}) = 102°F$$

The generic curve was generated by scaling 192 ksi-in$^{1/2}$ by the nominal pressures and calculating the associated (T - RT_{NDT}):

Core Not Critical CRD Penetration K_I and (T - RT_{NDT}) as a Function of Pressure

Nominal Pressure (psig)	K_I (ksi-in$^{1/2}$)	T - RT_{NDT} (°F)
1563	192	102
1400	172	95
1200	147	85
1000	123	73
800	98	57
600	74	33
400	49	-14

The highest RT_{NDT} for the bottom head plates and welds is 56°F, as shown in Tables 4-1 and 4-2. [[

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As discussed in Section 4.3.2.1.1 an evaluation is performed to assure that the CRD discontinuity bounds the other discontinuities that are to be protected by the CRD curve with respect to pressure stresses (see Table 4-8 and Appendix A). With respect to thermal stresses, the transients evaluated for the CRD are similar to or more severe than those of the other components being bounded. Therefore, for heatup/cooldown conditions, the CRD penetration provides bounding limits.

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4.3.2.1.3 Pressure Test - Non-Beltline Curve A (Using Feedwater Nozzle/Upper Vessel Region)

The stress intensity factor, K_I, for the feedwater nozzle was computed using the methods from WRC 175 [15] together with the nozzle dimension for a generic 251-inch BWR/6 feedwater nozzle. The result of that computation was $K_I = 200$ ksi-in$^{1/2}$ for an applied pressure of 1563 psig preservice hydrotest pressure. [[

]] The respective flaw depth and orientation used in this calculation is perpendicular to the maximum stress (hoop) at a depth of 1/4T through the corner thickness.

To evaluate the results, K_I is calculated for the upper vessel nominal stress, PR/t, according to the methods in ASME Code Appendix G (Section III or XI). The result is compared to that determined by CBIN in order to quantify the K magnification associated with the stress concentration created by the feedwater nozzles. A calculation of K_I is shown below using the BWR/6, 251-inch dimensions:

Vessel Radius, R_v	126.7 inches
Vessel Thickness, t_v	6.1875 inches
Vessel Pressure, P_v	1563 psig

Pressure stress: σ = PR / t = 1563 psig · 126.7 inches / (6.1875 inches) = 32,005 psi. The dead weight and thermal RFE stress of 2.967 ksi is conservatively added yielding σ = 34.97 ksi. The factor F (a/r_n) from Figure A5-1 of WRC-175 is 1.4 where:

a =	$\frac{1}{4}(t_n^{\,2} + t_v^{\,2})^{1/2}$	=2.36 inches
t_n =	thickness of nozzle	= 7.125 inches
t_v =	thickness of vessel	= 6.1875 inches
r_n =	apparent radius of nozzle	= r_i + 0.29 r_c=7.09 inches
r_i =	actual inner radius of nozzle	= 6.0 inches
r_c =	nozzle radius (nozzle corner radius)	= 3.75 inches

Thus, a/r_n = 2.36 / 7.09 = 0.33. The value $F(a/r_n)$, taken from Figure A5-1 of WRC Bulletin 175 for an a/r_n of 0.33, is 1.4. Including the safety factor of 1.5, the stress intensity factor, K_I, is $1.5\,\sigma\,(\pi a)^{1/2} \cdot F(a/r_n)$:

Nominal $K_I = 1.5 \cdot 34.97 \cdot (\pi \cdot 2.36)^{1/2} \cdot 1.4 = 200$ ksi-in$^{1/2}$

The method to solve for $(T - RT_{NDT})$ for a specific K_I is based on the K_{Ic} equation of Paragraph A-4200 in ASME Appendix A [17] for the pressure test condition:

$$(T - RT_{NDT}) = \ln[(K_I - 33.2) / 20.734] / 0.02$$

$$(T - RT_{NDT}) = \ln[(200 - 33.2) / 20.734] / 0.02$$

$$(T - RT_{NDT}) = 104.2°F$$

[[

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The generic pressure test P-T curve was generated by scaling 200 ksi-in$^{1/2}$ by the nominal pressures and calculating the associated $(T - RT_{NDT})$. [[

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The highest RT_{NDT} for the feedwater nozzle materials is 40°F as shown in Table 4-2. However, the RT_{NDT} was increased to 51°F to consider the stresses in the bottom head lower torus together with the initial RT_{NDT} as described below. The generic pressure test P-T curve is applied to the Browns Ferry Unit 1 feedwater nozzle curve by shifting the P vs. $(T - RT_{NDT})$ values above to reflect the RT_{NDT} value of 51°F.

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Second, the P-T curve is dependent on the K_I value calculated. The Browns Ferry Unit 1 specific vessel shell and nozzle dimensions applicable to the feedwater nozzle location [19] and K_I are shown below:

Vessel Radius, R_v	125.7 inches
Vessel Thickness, t_v	6.125 inches
Vessel Pressure, P_v	1563 psig

Pressure stress: σ = PR / t = 1563 psig · 125.7 inches / (6.125 inches) = 32,077 psi. The dead weight and thermal RFE stress of 2.967 ksi is conservatively added yielding σ = 35.04 ksi. The factor F (a/r_n) from Figure A5-1 of WRC-175 is determined where:

a =	$\frac{1}{4}(t_n^2 + t_v^2)^{1/2}$		=2.32 inches
t_n =	thickness of nozzle		= 6.96 inches
t_v =	thickness of vessel		= 6.125 inches
r_n =	apparent radius of nozzle		= r_i + 0.29 r_c=6.9 inches
r_i =	actual inner radius of nozzle		= 6.0 inches
r_c =	nozzle radius (nozzle corner radius)		= 3.0 inches

Thus, a/r_n = 2.32 / 6.96 = 0.33. The value F(a/r_n), taken from Figure A5-1 of WRC Bulletin 175 for an a/r_n of 0.33, is 1.4. Including the safety factor of 1.5, the stress intensity factor, K_I, is 1.5 σ $(\pi a)^{1/2}$ · F(a/r_n):

Nominal $K_I = 1.5 \cdot 35.04 \cdot (\pi \cdot 2.32)^{1/2} \cdot 1.4 = 198.7$ ksi-in$^{1/2}$

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4.3.2.1.4 *Core Not Critical Heatup/Cooldown - Non-Beltline Curve B (Using Feedwater Nozzle/Upper Vessel Region)*

The feedwater nozzle was selected to represent non-beltline components for fracture toughness analyses because the stress conditions are the most severe experienced in the vessel. In addition to the pressure and piping load stresses resulting from the nozzle discontinuity, the feedwater nozzle region experiences feedwater flow that is colder relative to the vessel coolant.

Stresses were taken from a [[ ]] finite element analysis done specifically for the purpose of fracture toughness analysis [[ ]]. Analyses were performed for all feedwater nozzle transients that involved rapid temperature changes. The most severe of

these was normal operation with cold 40°F feedwater injection, which is equivalent to hot standby, as seen in Figure 4-3.

The non-beltline curves based on feedwater nozzle limits were calculated according to the methods for nozzles in Appendix 5 of the Welding Research Council (WRC) Bulletin 175 [15].

The stress intensity factor for a nozzle flaw under primary stress conditions (K_{IP}) is given in WRC Bulletin 175 Appendix 5 by the expression for a flaw at a hole in a flat plate:

$$K_{IP} = SF \cdot \sigma (\pi a)^{1/2} \cdot F(a/r_n) \qquad (4\text{-}4)$$

where SF is the safety factor applied per WRC Bulletin 175 recommended ranges, and $F(a/r_n)$ is the shape correction factor.

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Finite element analysis of a nozzle corner flaw was performed to determine appropriate values of $F(a/r_n)$ for Equation 4-4. These values are shown in Figure A5-1 of WRC Bulletin 175 [15].

The stresses used in Equation 4-4 were taken from [[ ]] design stress reports for the feedwater nozzle. The stresses considered are primary membrane, σ_{pm}, and primary bending, σ_{pb}. Secondary membrane, σ_{sm}, and secondary bending, σ_{sb}, stresses are included in the total K_I by using ASME Appendix G [6] methods for secondary portion, K_{Is}:

$$K_{Is} = M_m (\sigma_{sm} + (2/3) \cdot \sigma_{sb}) \qquad (4\text{-}5)$$

In the case where the total stress exceeded yield stress, a plasticity correction factor was applied based on the recommendations of WRC Bulletin 175 Section 5.C.3 [15]. However, the correction was not applied to primary membrane stresses because primary stresses satisfy the laws of equilibrium and are not self-limiting. K_{IP} and K_{Is} are added to obtain the total value of stress intensity factor, K_I. A safety factor of 2.0 is applied to primary stresses for core not critical heatup/cooldown conditions.

Once K_I was calculated, the following relationship was used to determine $(T - RT_{NDT})$. The method to solve for $(T - RT_{NDT})$ for a specific K_I is based on the K_{Ic} equation of Paragraph A-4200 in ASME Appendix A [17]. The highest RT_{NDT} for the appropriate non-beltline components was then used to establish the P-T curves.

$$(T - RT_{NDT}) = \ln[(K_I - 33.2) / 20.734] / 0.02 \qquad (4\text{-}6)$$

Example Core Not Critical Heatup/Cooldown Calculation for Feedwater Nozzle/Upper Vessel Region

The non-beltline core not critical heatup/cooldown curve was based on the [[ ]] feedwater nozzle [[ ]] analysis, where feedwater injection of 40°F into the vessel while at operating conditions (551.4°F and 1050 psig) was the limiting normal or upset condition from a brittle fracture perspective. The feedwater nozzle corner stresses were obtained from finite element analysis [[ ]]. To produce conservative thermal stresses, a vessel and nozzle thickness of 7.5 inches was used in the evaluation. However, a thickness of 7.5 inches is not conservative for the pressure stress evaluation. Therefore, the pressure stress (σ_{pm}) was adjusted for the actual [[ ]] vessel thickness of 6.1875 inches (i.e., σ_{pm} = 20.49 ksi was revised to
20.49 ksi · 7.5 inches/6.1875 inches = 24.84 ksi). These stresses, and other inputs used in the generic calculations, are shown below:

σ_{pm} = 24.84 ksi	σ_{sm} = 16.19 ksi	σ_{ys} = 45.0 ksi	t_v = 6.1875 inches
σ_{pb} = 0.22 ksi	σ_{sb} = 19.04 ksi	a = 2.36 inches	r_n = 7.09 inches
t_n = 7.125 inches			

In this case the total stress, 60.29 ksi, exceeds the yield stress, σ_{ys}, so the correction factor, R, is calculated to consider the nonlinear effects in the plastic region according to the following equation based on the assumptions and recommendation of WRC Bulletin 175 [15]. (The value of specified yield stress is for the material at the temperature under consideration. For conservatism, the inside surface temperature is used.)

$$R = [\sigma_{ys} - \sigma_{pm} + ((\sigma_{total} - \sigma_{ys}) / 30)] / (\sigma_{total} - \sigma_{pm}) \quad (4\text{-}7)$$

For the stresses given, the ratio, R = 0.583. Therefore, all the stresses are adjusted by the factor 0.583, except for σ_{pm}. The resulting stresses are:

σ_{pm} = 24.84 ksi σ_{sm} = 9.44 ksi
σ_{pb} = 0.13 ksi σ_{sb} = 11.10 ksi

The value of M_m for an inside axial postulated surface flaw from Paragraph G-2214.1 [6] was based on the 4a thickness; hence, $t^{1/2} = 3.072$. The resulting value obtained was:

$$M_m = 1.85 \text{ for } \sqrt{t} \leq 2$$

$$M_m = 0.926 \sqrt{t} \text{ for } 2 \leq \sqrt{t} \leq 3.464 = 2.845$$

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

The value $F(a/r_n)$, taken from Figure A5-1 of WRC Bulletin 175 for an a/r_n of 0.33, is therefore,

$$F(a/r_n) = 1.4$$

K_{IP} is calculated from Equation 4-4:

$$K_{IP} = 2.0 \cdot (24.84 + 0.13) \cdot (\pi \cdot 2.36)^{1/2} \cdot 1.4$$

$$K_{IP} = 190.4 \text{ ksi-in}^{1/2}$$

K_{Is} is calculated from Equation 4-5:

$K_{Is} = 2.845 \cdot (9.44 + 2/3 \cdot 11.10)$

$K_{Is} = 47.9$ ksi-in$^{1/2}$

The total K_I is, therefore, 238.3 ksi-in$^{1/2}$.

The total K_I is substituted into Equation 4-6 to solve for $(T - RT_{NDT})$:

$(T - RT_{NDT}) = \ln [(238.3 - 33.2) / 20.734] / 0.02$

$(T - RT_{NDT}) = 115°F$

The [[ ]] curve was generated by scaling the stresses used to determine the K_I; this scaling was performed after the adjustment to stresses above yield. The primary stresses were scaled by the nominal pressures, while the secondary stresses were scaled by the temperature difference of the 40°F water injected into the hot reactor vessel nozzle. In the base case that yielded a K_I value of 238 ksi-in$^{1/2}$, the pressure is 1050 psig and the hot reactor vessel temperature is 551.4°F. Since the reactor vessel temperature follows the saturation temperature curve, the secondary stresses are scaled by $(T_{saturation} - 40) / (551.4 - 40)$. From K_I the associated $(T - RT_{NDT})$ can be calculated:

Core Not Critical Feedwater Nozzle K_I and $(T - RT_{NDT})$ as a Function of Pressure

Nominal Pressure (psig)	Saturation Temp. (°F)	R	K_I* (ksi-in$^{1/2}$)	$(T - RT_{NDT})$ (°F)
1563	604	0.23	303	128
1400	588	0.34	283	124
1200	557	0.48	257	119
1050	551	0.58	238	115
1000	546	0.62	232	113
800	520	0.79	206	106
600	489	1.0	181	98
400	448	1.0	138	81

*Note: For each change in stress for each pressure and saturation temperature condition, there is a corresponding change to R that influences the determination of K_I.

The highest non-beltline RT_{NDT} for the feedwater nozzle at Browns Ferry Unit 1 is 40°F as shown in Table 4-2. However, the RT_{NDT} was increased to 51°F to consider the stresses in the bottom head lower torus as previously discussed. The generic curve is applied to the Browns Ferry Unit 1 upper vessel by shifting the P vs. (T - RT_{NDT}) values above to reflect the RT_{NDT} value of 51°F as discussed in Section 4.3.2.1.3.

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4.3.2.2 CORE BELTLINE REGION

The pressure-temperature (P-T) operating limits for the beltline region are determined according to the ASME Code [6]. As the beltline fluence increases with the increase in operating life, the P-T curves shift to a higher temperature.

The stress intensity factors (K_I), calculated for the beltline region according to ASME Code Appendix G procedures [6], were based on a combination of pressure and thermal stresses for a 1/4T 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; values were calculated for 100°F/hr coolant thermal gradient. The shift value of the most limiting ART material was used to adjust the RT_{NDT} values for the P-T limits.

4.3.2.2.1 Beltline Region - Pressure Test

The methods of ASME Code Section XI, Appendix G [6] 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:

$$\sigma_m = PR / t_{min} \quad (4\text{-}8)$$

The stress intensity factor, K_{Im}, is calculated using Paragraph G-2214.1 of the ASME Code.

The calculated value of K_{Im} for pressure test is multiplied by a safety factor (SF) of 1.5, per ASME Appendix G [6] for comparison with K_{IC}, the material fracture toughness. A safety factor of 2.0 is used for the core not critical and core critical conditions.

The relationship between K_{IC} and temperature relative to reference temperature ($T - RT_{NDT}$) is based on the K_{IC} equation of Paragraph A-4200 in ASME Appendix A [17] for the pressure test condition:

$$K_{Im} \cdot SF = K_{IC} = 20.734 \exp[0.02\,(T - RT_{NDT})] + 33.2 \quad (4\text{-}9)$$

This relationship provides values of pressure versus temperature (from K_{IR} and ($T-RT_{NDT}$), respectively).

GE's current practice for the pressure test curve is to add a stress intensity factor, K_{It}, for a coolant heatup/cooldown rate, specified as 15°F/hr for Browns Ferry Unit 1, to provide operating flexibility. For the core not critical and core critical condition curves, a stress intensity factor is added for a coolant heatup/cooldown rate of 100°F/hr. The K_{It} calculation for a coolant heatup/cooldown rate of 100°F/hr is described in Section 4.3.2.2.3 below.

4.3.2.2.2 Calculations for the Beltline Region - Pressure Test

This sample calculation is for a pressure test pressure of 1064 psig at 16 EFPY. The following inputs were used in the beltline limit calculation:

Adjusted RT_{NDT} = Initial RT_{NDT} + Shift	A = 23 + 89 = 112°F (Based on ART values in Table 4-5)
Vessel Height	H = 875.13 inches
Bottom of Active Fuel Height	B = 216.3 inches
Vessel Radius (to inside of clad)	R = 125.7 inches
Minimum Vessel Thickness (without clad)	t = 6.13 inches

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

$$P = 1064 \text{ psi} + (H - B)\, 0.0361 \text{ psi/inch} = P \text{ psig} \quad (4\text{-}10)$$
$$= 1064 + (875.13 - 216.3)\, 0.0361 = 1088 \text{ psig}$$

Pressure stress:

$$\sigma = PR/t \quad (4\text{-}11)$$
$$= 1.088 \cdot 125.7 / 6.13 = 22.3 \text{ ksi}$$

The value of M_m for an inside axial postulated surface flaw from Paragraph G-2214.1 [6] was based on a thickness of 6.13 inches (the minimum thickness without cladding); hence, $t^{1/2} = 2.48$. The resulting value obtained was:

$$M_m = 1.85 \text{ for } \sqrt{t} \le 2$$
$$M_m = 0.926 \sqrt{t} \text{ for } 2 \le \sqrt{t} \le 3.464 = 2.29$$
$$M_m = 3.21 \text{ for } \sqrt{t} > 3.464$$

The stress intensity factor for the pressure stress is $K_{Im} = M_m \cdot \sigma$. The stress intensity factor for the thermal stress, K_{It}, is calculated as described in Section 4.3.2.2.4 except that the value of "G" is 15°F/hr instead of 100°F/hr.

Equation 4-9 can be rearranged, and 1.5 K_{Im} substituted for K_{IC}, to solve for (T - RT_{NDT}). Using the K_{IC} equation of Paragraph A-4200 in ASME Appendix A [17], K_{Im} = 51.1, and K_{It} = 1.71 for a 15°F/hr coolant heatup/cooldown rate with a vessel thickness, t, that includes cladding:

$$
\begin{aligned}
(T - RT_{NDT}) &= \ln[(1.5 \cdot K_{Im} + K_{It} - 33.2) / 20.734] / 0.02 \\
&= \ln[(1.5 \cdot 51.1 + 1.71 - 33.2) / 20.734] / 0.02 \\
&= 38.9°F
\end{aligned}
\qquad (4\text{-}12)
$$

T can be calculated by adding the adjusted RT_{NDT}:

T = 38.9 + 112 = 150.9°F for P = 1064 psig at 16 EFPY

For Browns Ferry Unit 1, the beltline girth weld is the limiting material for both 12 and 16 EFPY. However, because the calculated value of K_{Im} is reduced for a girth weld due to implementation of Code Case N-588 (circumferentially oriented defect for circumferential welds), the axial weld bounds the P-T curve beltline region requirements. To demonstrate that by using Code Case N-588, the axial weld has the most limiting temperature for the P-T curves in the beltline region, the stress intensity calculations for both the axial and girth welds at 16 EFPY are presented.

Axial Weld Calculation:

The value of M_m for an inside axial postulated surface flaw from Paragraph G-2214.1 [6] was based on a thickness of 6.13 inches (the minimum thickness without cladding); hence, $t^{1/2} = 2.48$. The resulting value obtained was:

$$M_m = 1.85 \text{ for } \sqrt{t} \leq 2$$

$$M_m = 0.926 \sqrt{t} \text{ for } 2 \leq \sqrt{t} \leq 3.464 = \mathbf{2.29}$$

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

The stress intensity factor for the pressure stress is $K_{Im} = M_m \cdot \sigma$. The stress intensity factor for the thermal stress, K_{It}, is calculated as described in Section 4.3.2.2.4 except that the value of "G" is 15°F/hr instead of 100°F/hr.

Equation 4-9 can be rearranged, and 1.5 K_{Im} substituted for K_{IC}, to solve for $(T - RT_{NDT})$. Using the K_{Ic} equation of Paragraph A-4200 in ASME Appendix A [17], $K_{Im} = 51.1$, and $K_{It} = 1.71$ for a 15°F/hr coolant heatup/cooldown rate with a vessel thickness, t, that includes cladding:

$$\begin{aligned}(T - RT_{NDT}) &= \ln[(1.5 \cdot K_{Im} + K_{It} - 33.2) / 20.734] / 0.02 \quad (4\text{-}12)\\ &= \ln[(1.5 \cdot 51.1 + 1.71 - 33.2) / 20.734] / 0.02\\ &= 38.9°F\end{aligned}$$

T can be calculated by adding the adjusted RT_{NDT}:

$T = 38.9 + 112 = 150.9°F$ for P = 1064 psig at 16 EFPY

Girth Weld Calculation:

The value of M_m for an inside circumferential postulated surface flaw from Paragraph G-2214.1 [6] was based on a thickness of 6.13 inches (the minimum thickness without cladding); hence, $t^{1/2}$ = 2.48. The resulting value obtained was:

$$M_m = 0.89 \text{ for } \sqrt{t} \leq 2$$

$$M_m = 0.443 \sqrt{t} \text{ for } 2 \leq \sqrt{t} \leq 3.464 = \mathbf{1.10}$$

$$M_m = 1.53 \text{ for } \sqrt{t} > 3.464$$

The stress intensity factor for the pressure stress is $K_{Im} = M_m \cdot \sigma$. The stress intensity factor for the thermal stress, K_{It}, is calculated as described in Section 4.3.2.2.4 except that the value of "G" is 15°F/hr instead of 100°F/hr.

Equation 4-9 can be rearranged, and 1.5 K_{Im} substituted for K_{IC}, to solve for $(T - RT_{NDT})$. Using the K_{Ic} equation of Paragraph A-4200 in ASME Appendix A [17], K_{Im} = 24.5, and K_{It} = 1.71 for a 15°F/hr coolant heatup/cooldown rate with a vessel thickness, t, that includes cladding:

$$\begin{aligned}(T - RT_{NDT}) &= \ln[(1.5 \cdot K_{Im} + K_{It} - 33.2) / 20.734] / 0.02 \qquad (4\text{-}12)\\ &= \ln[(1.5 \cdot 24.5 + 1.71 - 33.2) / 20.734] / 0.02\\ &= -68.6°F\end{aligned}$$

T can be calculated by adding the adjusted RT_{NDT}:

T = -68.6 + 119 = 50.4°F for P = 1064 psig at 16 EFPY

As stated above, based on the applied pressure and temperature stress intensity factors, the axial weld flaw bounds the P-T curve in the beltline region for 16 EFPY.

4.3.2.2.3 Beltline Region - Core Not Critical Heatup/Cooldown

The beltline curves for core not critical heatup/cooldown conditions are influenced by pressure stresses and thermal stresses, according to the relationship in ASME Section XI Appendix G [6]:

$$K_{IC} = 2.0 \cdot K_{Im} + K_{It} \qquad (4\text{-}13)$$

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 above, 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 that 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-2214-1 of ASME Appendix G [6] 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-2214-2 of ASME Appendix G [6]. The relationship used to compute the through-wall ΔT_w is based on one-dimensional heat conduction through an insulated flat plate:

$$\partial^2 T(x,t) / \partial x^2 = 1 / \beta \, (\partial T(x,t) / \partial t) \qquad (4\text{-}14)$$

where T(x,t) is temperature of the plate at depth x and time t, and β is the thermal diffusivity.

The maximum stress will occur when the radial thermal gradient reaches a quasi-steady state distribution, so that $\partial T(x,t) / \partial t = dT(t) / dt = G$, where G is the coolant heatup/cooldown rate, normally 100°F/hr. The differential equation is integrated over x for the following boundary conditions:

1. Vessel inside surface (x = 0) temperature is the same as coolant temperature, T_0.
2. Vessel outside surface (x = C) is perfectly insulated; the thermal gradient dT/dx = 0.

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

$$T = Gx^2 / 2\beta - GCx / \beta + T_0 \qquad (4\text{-}15)$$

This equation is normalized to plot $(T - T_0) / \Delta T_w$ versus x / C.

The resulting through-wall gradient compares very closely with Figure G-2214-2 of ASME Appendix G [6]. Therefore, ΔT_w calculated from Equation 4-15 is used with the appropriate M_t of Figure G-2214-1 of ASME Appendix G [6] to compute K_{It} for heatup and cooldown.

The M_t relationships were derived in the Welding Research Council (WRC) Bulletin 175 [15] for infinitely long cracks of 1/4T. For the flat plate geometry and radial thermal gradient, orientation of the crack is not important.

4.3.2.2.4 Calculations for the Beltline Region Core Not Critical Heatup/Cooldown

This Browns Ferry Unit 1 sample calculation is for a pressure of 1064 psig for 16 EFPY. The core not critical heatup/cooldown curve at 1064 psig uses the same K_{Im} as the pressure test curve, but with a safety factor of 2.0 instead of 1.5. The increased safety factor is used because the heatup/cooldown cycle represents an operational condition rather than test condition; the operational condition necessitates the use of a higher safety factor. In addition, there is a K_{It} term for the thermal stress. The additional inputs used to calculate K_{It} are:

Coolant heatup/cooldown rate, normally 100°F/hr	G = 100 °F/hr
Minimum vessel thickness, including clad thickness	C = 0.526 ft (6.125" + 0.188" = 6.313")
Thermal diffusivity at 550°F (most conservative value)	β = 0.354 ft²/ hr [21]

Equation 4-15 can be solved for the through-wall temperature (x = C), resulting in the absolute value of ΔT for heatup or cooldown of:

$$\Delta T = GC^2 / 2\beta \qquad (4\text{-}16)$$
$$= 100 \cdot (0.526)^2 / (2 \cdot 0.354) = 39°F$$

The analyzed case for thermal stress is a 1/4T flaw depth with wall thickness of C. The corresponding value of M_t (=0.2914) can be interpolated from ASME Appendix G, Figure G-2214-2 [6]. Thus the thermal stress intensity factor, $K_{It} = M_t \cdot \Delta T = 11.39$, can be calculated. The conservative value for thermal diffusivity at 550°F is used for all calculations; therefore, K_{It} is constant for all pressures. K_{Im} has the same value as that calculated in Section 4.3.2.2.2.

The pressure and thermal stress terms are substituted into Equation 4-9 to solve for $(T - RT_{NDT})$:

$$(T - RT_{NDT}) = \ln[((2 \cdot K_{Im} + K_{It}) - 33.2) / 20.734] / 0.02 \qquad (4\text{-}17)$$
$$= \ln[(2 \cdot 51.1 + 11.39 - 33.2) / 20.734] / 0.02$$
$$= 67.8\ °F$$

T can be calculated by adding the adjusted RT_{NDT}:

T = 67.8 + 112= 179.8 °F for P = 1064 psig at 16 EFPY

4.3.2.3 CLOSURE FLANGE REGION

10CFR50 Appendix G [8] 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}. Similar to the evaluations performed for the bottom head and upper vessel, a BWR/6 finite element analysis [18] was used to model the flange region. The local stresses were computed for determination of the stress intensity factor, K_I. Using a 1/4T flaw size and the K_{IC} formulation to determine T - RT_{NDT}, for pressures above 312 psig the P-T limits for all flange regions are bounded by the 10CFR50 Appendix G requirement of RT_{NDT} + 90°F (the largest T-RT_{NDT} for the flange at 1563 psig is 73°F). For pressures below 312 psig, the flange curve is bounded by RT_{NDT} + 60 (the largest T - RT_{NDT} for the flange at 312 psig is 54°F); therefore, instead of determining a T (temperature) versus pressure curve for the flange (i.e., T - RT_{NDT}) the value RT_{NDT} + 60 is used for the closure flange limits.

In some cases, the results of analysis for other regions exceed these requirements and closure flange limits do not affect the shape of the P-T curves. However, some closure flange requirements do impact the curves, as is true with Browns Ferry Unit 1 at low pressures.

The approach used for Browns Ferry Unit 1 for the bolt-up temperature was based on the conservative value of (RT_{NDT} + 60), or the LST of the bolting materials, whichever is greater. The 60°F adder is included by GE for two reasons: 1) the pre-1971 requirements of the ASME Code Section III, Subsection NA, Appendix G included the 60°F adder, and 2) inclusion of the additional 60°F requirement above the RT_{NDT} provides the additional assurance that a 1/4T flaw size is acceptable. As shown in Tables 4-1, 4-2, and 4-3, the limiting initial RT_{NDT} for the closure flange region is represented by the electroslag weld materials in the upper shell at 23.1°F, and the LST of the closure studs is 70°F; therefore, the bolt-up temperature value used is the more conservative value of 83°F. This conservatism is appropriate because bolt-up is one of the more limiting operating conditions (high stress and low temperature) for brittle fracture.

10CFR50 Appendix G, paragraph IV.A.2 [8] including Table 1, 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).

For pressures below 20% of preservice hydrostatic test pressure (312 psig) and with full bolt preload, the closure flange region metal temperature is required to be at RT_{NDT} or greater as described above. At low pressure, the ASME Code [6] allows the bottom head regions to experience even lower metal temperatures than the flange region RT_{NDT}. However, temperatures should not be permitted to be lower than 68°F for the reason discussed below.

The shutdown margin, provided in the Browns Ferry Unit 1 Technical Specification [5], is calculated for a water temperature of 68°F. Shutdown margin is the quantity of reactivity needed for a reactor core to reach criticality with the strongest-worth control rod fully withdrawn and all other control rods fully inserted. Although it may be possible to safely allow the water temperature to fall below this 68°F limit, further extensive calculations would be required to justify a lower temperature. The 83°F limit for the upper vessel and beltline region and the 68°F limit for the bottom head curve apply when the head is on and tensioned and when the head is off while fuel is in the vessel. When the head is not tensioned and fuel is not in the vessel, the requirements of 10CFR50 Appendix G [8] do not apply, and there are no limits on the vessel temperatures.

4.3.2.4 CORE CRITICAL OPERATION REQUIREMENTS OF 10CFR50, APPENDIX G

Curve C, the core critical operation curve, is generated from the requirements of 10CFR50 Appendix G [8], Table 1. Table 1 of [8] requires that core critical P-T limits be 40°F above any Curve A or B limits when pressure exceeds 20% of the pre-service system hydrotest pressure. Curve B is more limiting than Curve A, so limiting Curve C values are at least Curve B plus 40°F for pressures above 312 psig.

Table 1 of 10CFR50 Appendix G [8] indicates that for a BWR with water level within normal range for power operation, the allowed temperature for initial criticality at the closure flange region is (RT_{NDT} + 60°F) at pressures below 312 psig. This requirement makes the minimum criticality temperature 83°F, based on an RT_{NDT} of 23.1°F. In addition, above 312 psig the Curve C temperature must be at least the greater of RT_{NDT} of the closure region + 160°F or the temperature required for the hydrostatic pressure test (Curve A at 1064 psig). The requirement of closure region RT_{NDT} + 160°F causes a temperature shift in Curve C at 312 psig.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The 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 four vessel regions that should be monitored against the P-T curve operating limits; these regions are defined on the thermal cycle diagram [2]:

- Closure flange region (Region A)
- Core beltline region (Region B)
- Upper vessel (Regions A & B)
- Lower vessel (Regions B & C)

For the core not critical and the core critical curve, the P-T curves specify a coolant heatup and cooldown temperature rate of 100°F/hr or less for which the curves are applicable. However, the core not critical and the core critical curves were also developed to bound transients defined on the RPV thermal cycle diagram [2] and the nozzle thermal cycle diagrams [3]. For the hydrostatic pressure and leak test curve, a coolant heatup and cooldown temperature rate of 15°F/hr or less must be maintained at all times.

The P-T curves apply for both heatup/cooldown and for both the 1/4T and 3/4T locations because the maximum tensile stress for either heatup or cooldown is applied at the 1/4T location. For beltline curves this approach has added conservatism because irradiation effects cause the allowable toughness, K_{Ir}, at 1/4T to be less than that at 3/4T for a given metal temperature.

The following P-T curves were generated for Browns Ferry Unit 1:

- Composite P-T curves were generated for each of the Pressure Test and Core Not Critical conditions at 12 and 16 effective full power years (EFPY). The composite curves were generated by enveloping the most restrictive P-T limits from the separate beltline, upper vessel and closure assembly P-T limits. A separate Bottom Head Limits (CRD Nozzle) curve is also individually included with the composite curve for the Pressure Test and Core Not Critical condition.
- Separate P-T curves were developed for the upper vessel, beltline (at 12 and 16 EFPY), and bottom head for the Pressure Test and Core Not Critical conditions.
- A composite P-T curve was also generated for the Core Critical condition at 12 and 16 EFPY. The composite curves were generated by enveloping the most restrictive P-T limits from the separate beltline, upper vessel, bottom head, and closure assembly P-T limits.

While the Bottom Head (CRD Nozzle) and Upper Vessel (FW Nozzle) curves are valid for the entire plant license period (16 EFPY), for clarity and convenience of Browns Ferry Unit 1 personnel, two (2) sets of these curves are provided, each with a designation of EFPY (either 12 or 16) within the title. It should be understood that this designation of EFPY in non-beltline curves does not imply limitations with regard to EFPY.

The P-T curves are beltline limited above 720 psig for both Curve A and Curve B at 16 EFPY. At 12 EFPY, the P-T curves become beltline limited above 920 psig for Curve A and above 970 psig for Curve B.

Table 5-1 shows the figure numbers for each P-T curve. A tabulation of the curves is presented in Appendix B.

Table 5-1: Composite and Individual Curves Used To Construct Composite P-T Curves

Curve	Curve Description	Figure Numbers for Presentation of the P-T Curves	Table Numbers for Presentation of the P-T Curves
	12 EFPY Curves		
A	Bottom Head Limits (CRD Nozzle) – 12 EFPY	Figure 5-1	Table B-1
A	Upper Vessel Limits (FW Nozzle) – 12 EFPY	Figure 5-2	Table B-1
A	Beltline Limits - 12 EFPY	Figure 5-3	Table B-1
A	Bottom Head and Composite Curve A – 12 EFPY*	Figure 5-4	Table B-2
B	Bottom Head Limits (CRD Nozzle) – 12 EFPY	Figure 5-5	Table B-1
B	Upper Vessel Limits (FW Nozzle) – 12 EFPY	Figure 5-6	Table B-1
B	Beltline Limits - 12 EFPY	Figure 5-7	Table B-1
B	Bottom Head and Composite Curve B – 12 EFPY*	Figure 5-8	Table B-2
C	Composite Curve C – 12 EFPY**	Figure 5-9	Table B-2
B & C	Composite Curve C** and Curve B* with Bottom Head Curve - 12 EFPY	Figure 5-10	Tables B-1 & 2
	16 EFPY Curves		
A	Bottom Head Limits (CRD Nozzle) – 16 EFPY	Figure 5-11	Table B-3
A	Upper Vessel Limits (FW Nozzle) – 16 EFPY	Figure 5-12	Table B-3
A	Beltline Limits - 16 EFPY	Figure 5-13	Table B-3
A	Bottom Head and Composite Curve A – 16 EFPY*	Figure 5-14	Table B-4
B	Bottom Head Limits (CRD Nozzle) – 16 EFPY	Figure 5-15	Table B-3
B	Upper Vessel Limits (FW Nozzle) – 16 EFPY	Figure 5-16	Table B-3
B	Beltline Limits - 16 EFPY	Figure 5-17	Table B-3
B	Bottom Head and Composite Curve B – 16 EFPY*	Figure 5-18	Table B-4
C	Composite Curve C – 16 EFPY**	Figure 5-19	Table B-4
B & C	Composite Curve C** and Curve B* with Bottom Head Curve - 16 EFPY	Figure 5-20	Tables B-3 & 4

* The Composite Curve A & B curve is the more limiting of three limits: 10CFR50 Bolt-up Limits, Upper Vessel Limits (FW Nozzle), and Beltline Limits. A separate Bottom Head Limits (CRD Nozzle) curve is individually included on this figure.

** The Composite Curve C curve is the more limiting of four limits: 10CFR50 Bolt-up Limits, Bottom Head Limits (CRD Nozzle), Upper Vessel Limits (FW Nozzle), and Beltline Limits.

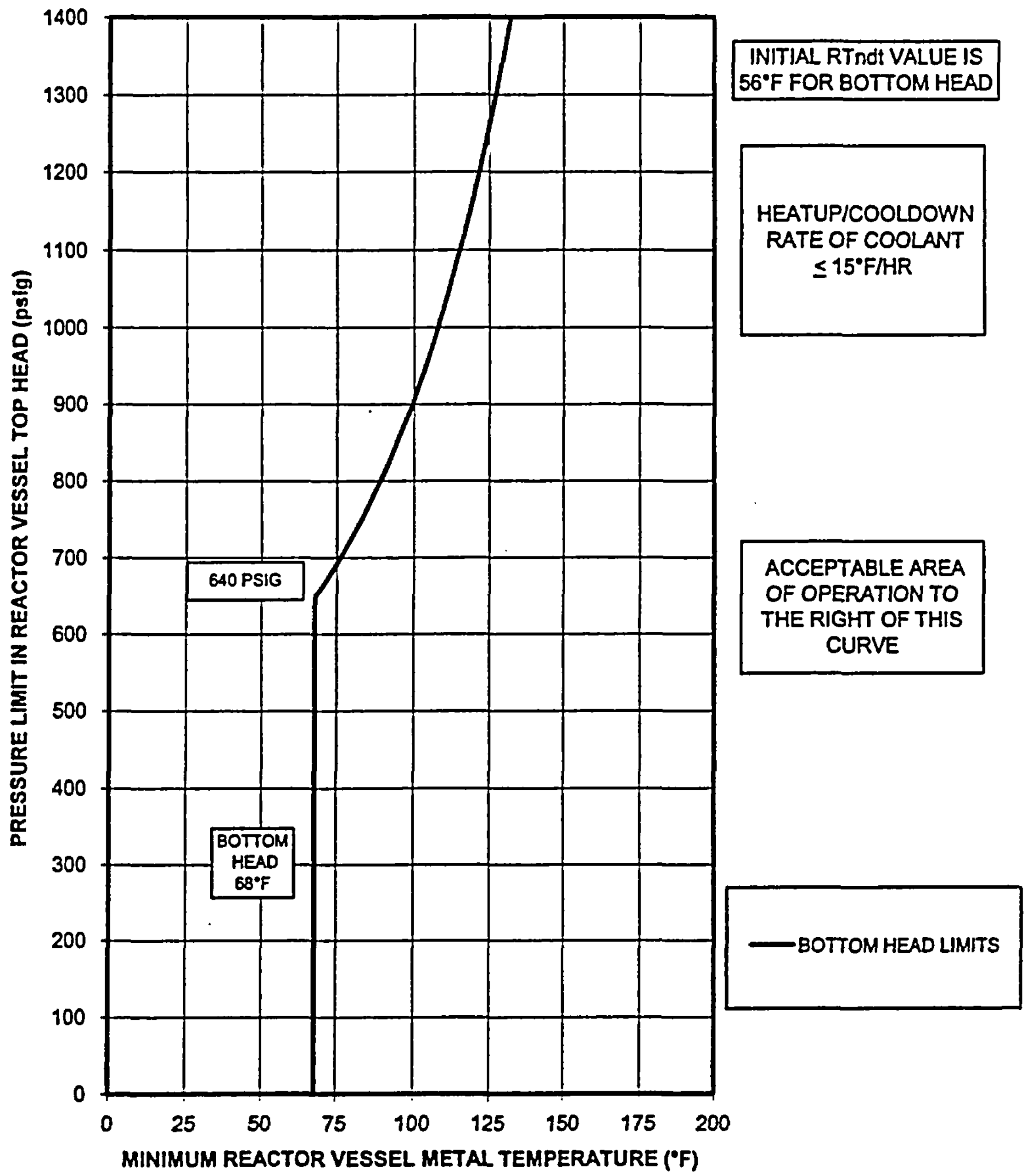

Figure 5-1: Bottom Head P-T Curve for Pressure Test [Curve A] – 12 EFPY
[15°F/hr or less coolant heatup/cooldown]

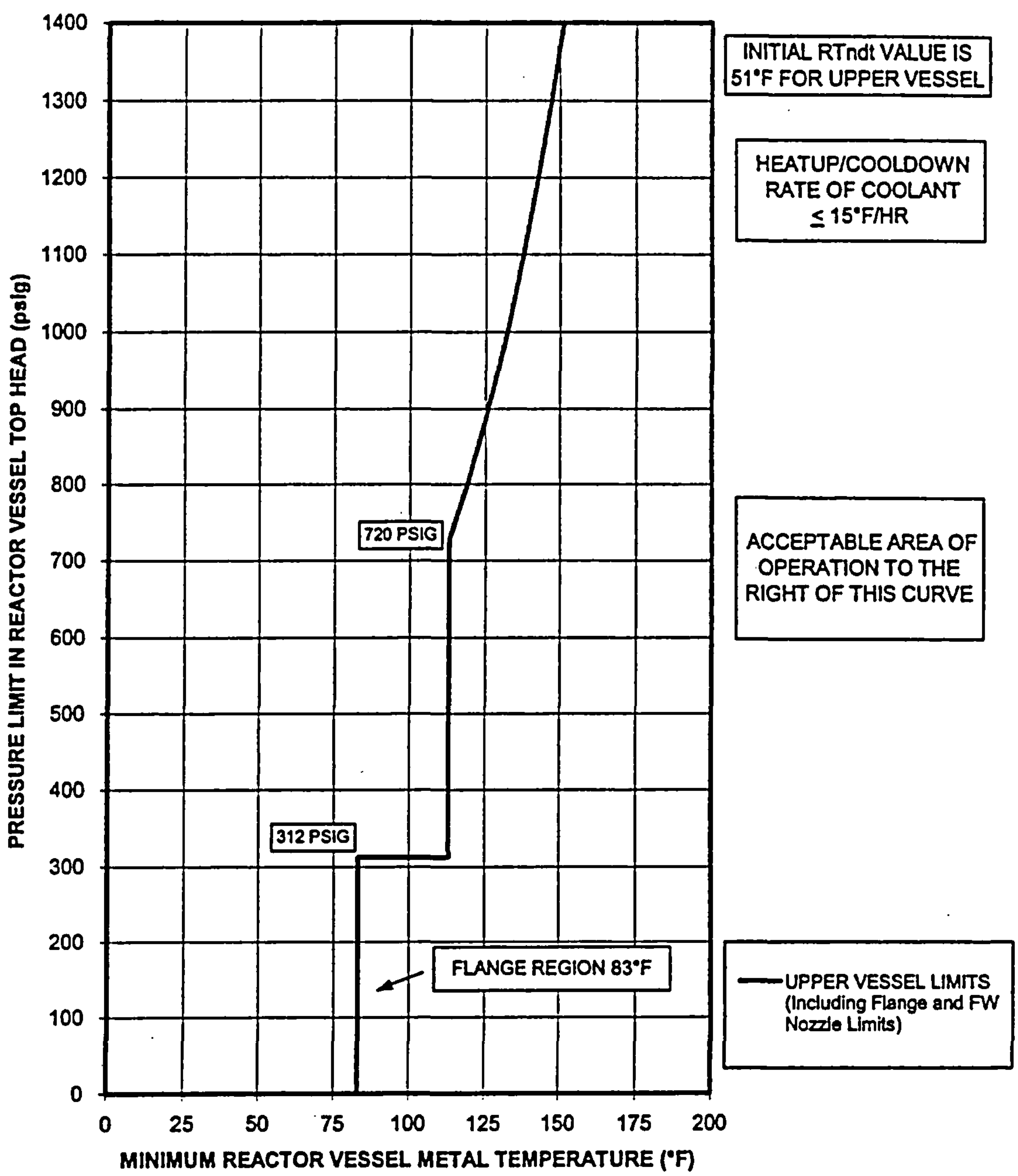

Figure 5-2: Upper Vessel P-T Curve for Pressure Test [Curve A] – 12 EFPY

[15°F/hr or less coolant heatup/cooldown]

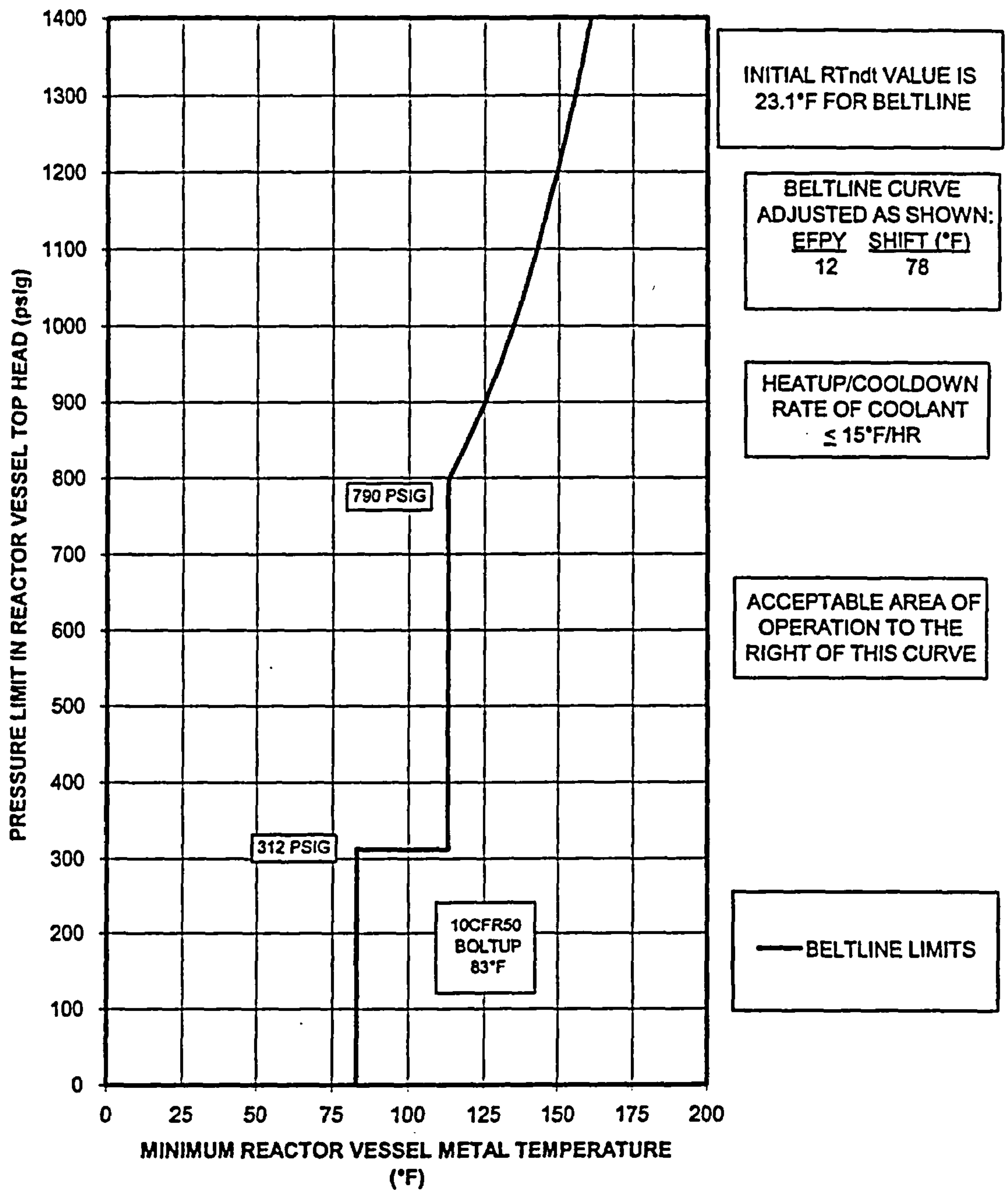

Figure 5-3: Beltline P-T Curve for Pressure Test [Curve A] up to 12 EFPY
[15°F/hr or less coolant heatup/cooldown]

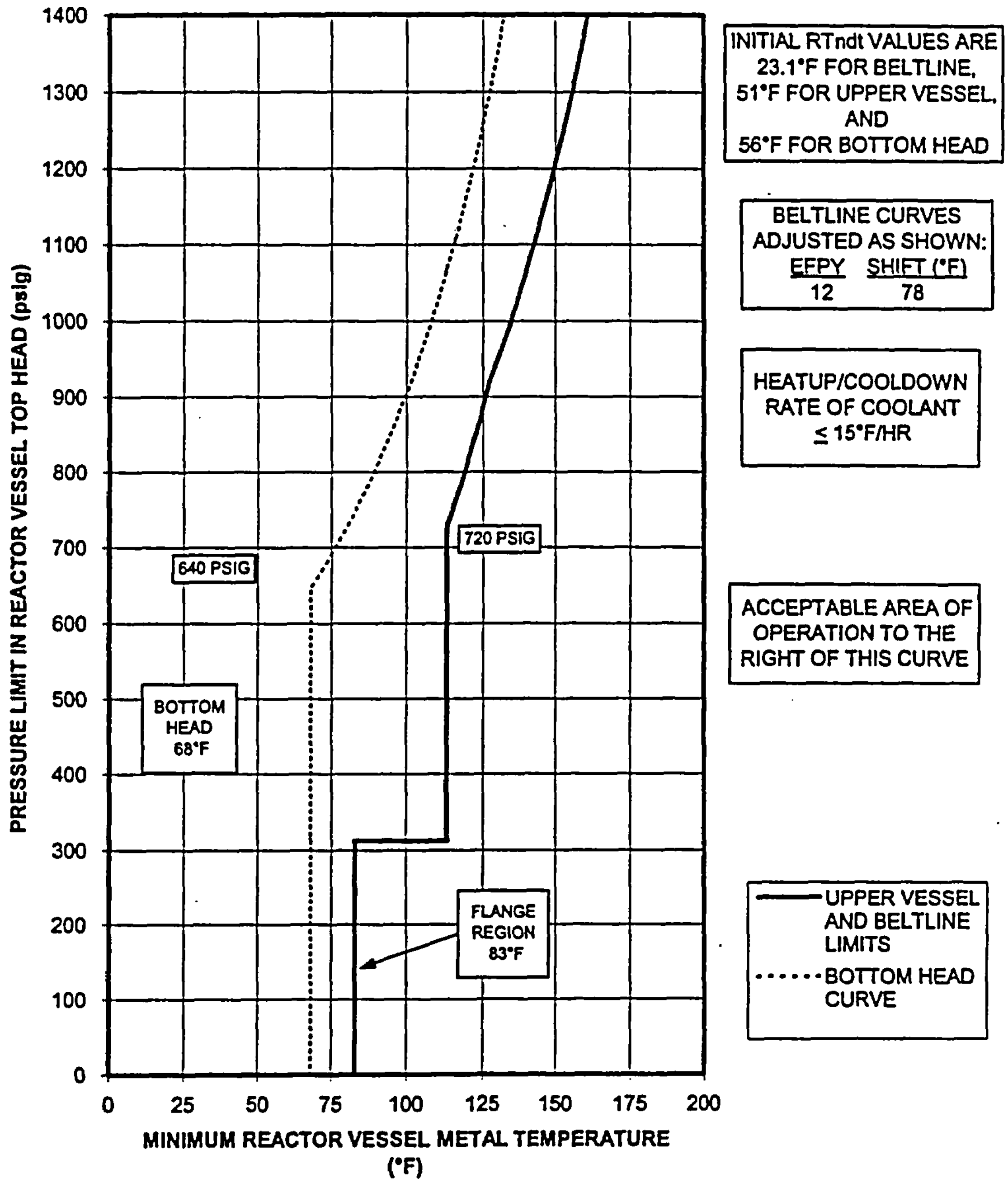

Figure 5-4: Composite Pressure Test P-T Curves [Curve A] up to 12 EFPY
[15°F/hr or less coolant heatup/cooldown]

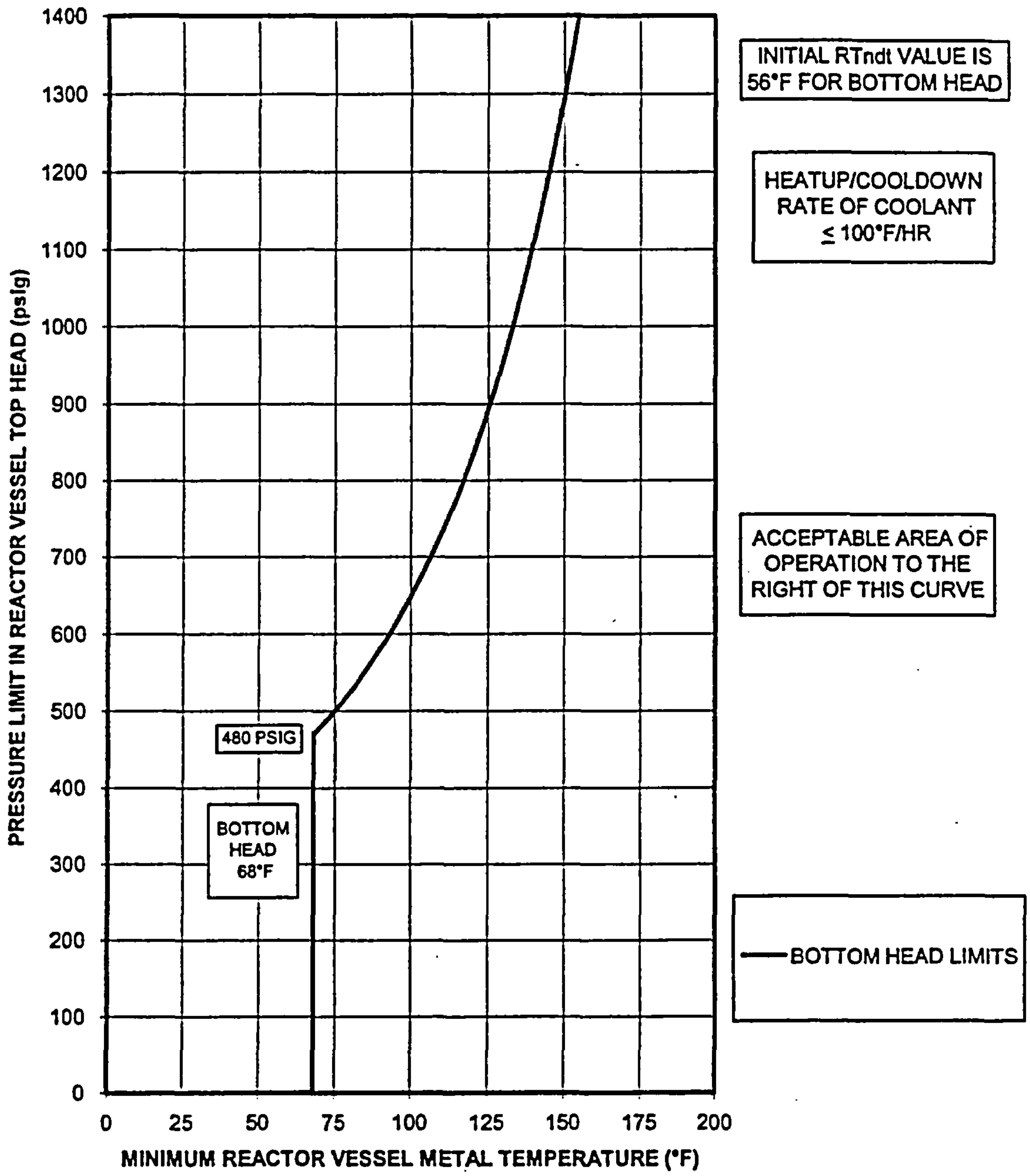

Figure 5-5: Bottom Head P-T Curve for Core Not Critical [Curve B] – 12 EFPY
[100°F/hr or less coolant heatup/cooldown]

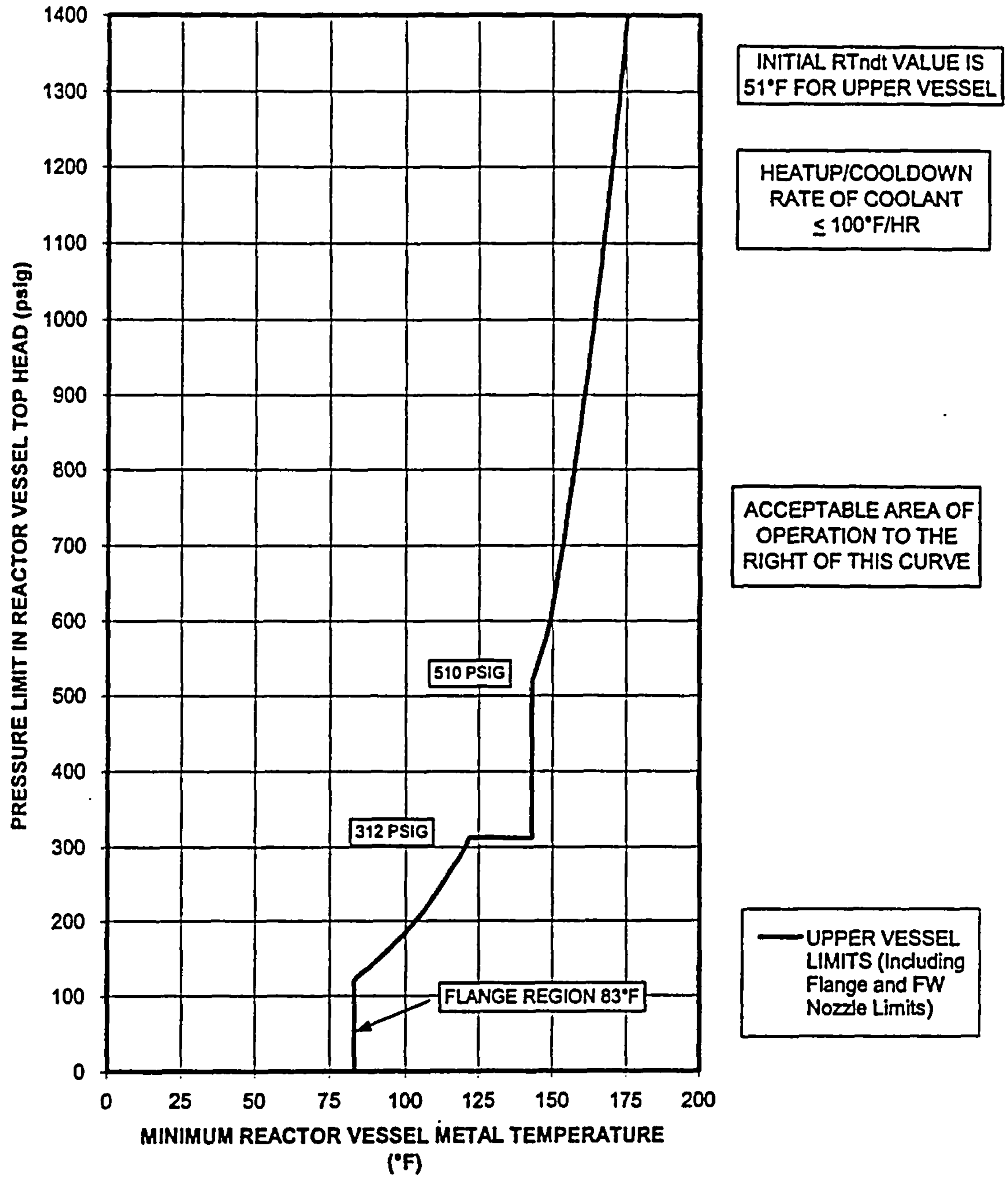

Figure 5-6: Upper Vessel P-T Curve for Core Not Critical [Curve B] – 12 EFPY
[100°F/hr or less coolant heatup/cooldown]

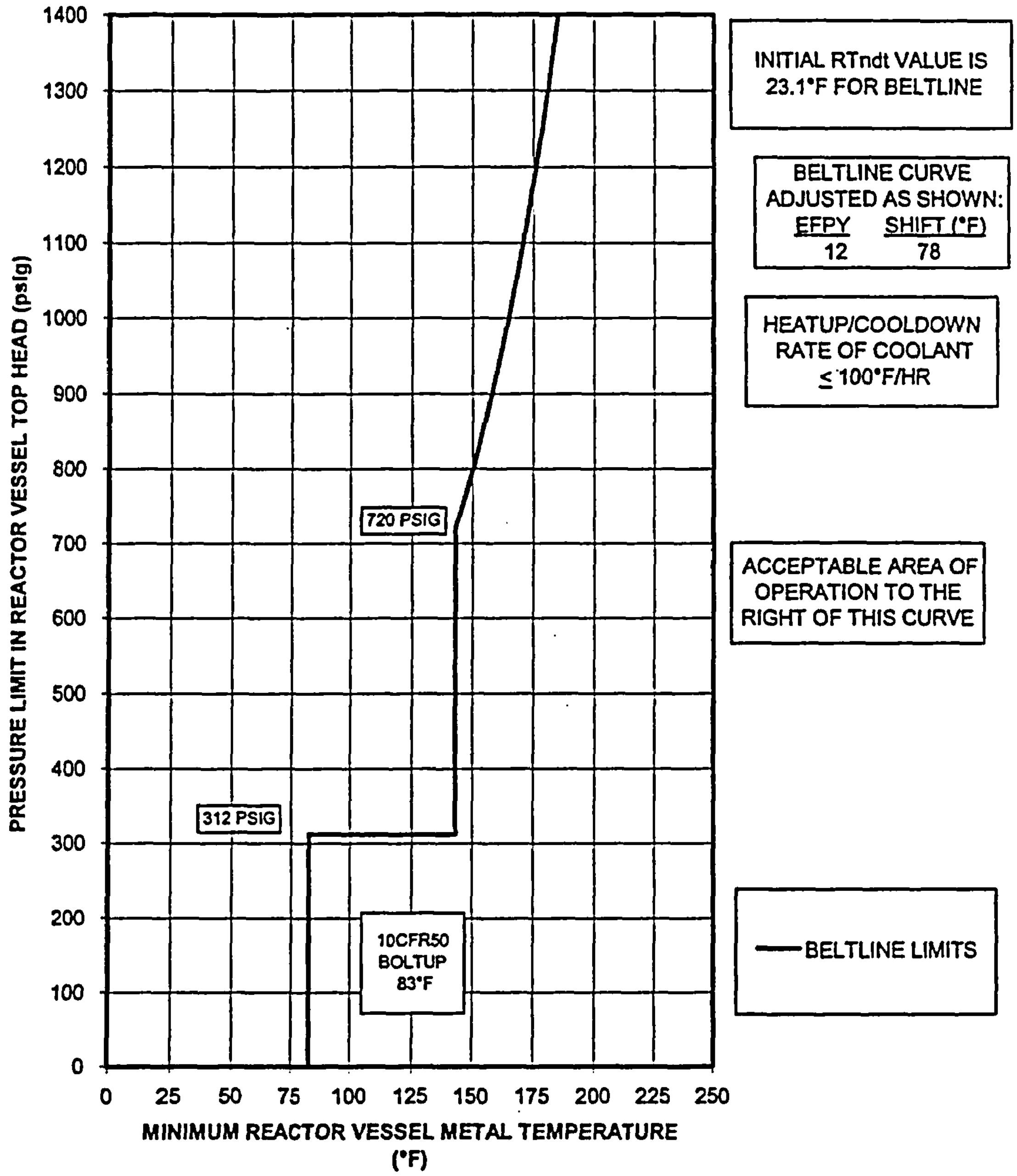

Figure 5-7: Beltline P-T Curve for Core Not Critical [Curve B] up to 12 EFPY
[100°F/hr or less coolant heatup/cooldown]

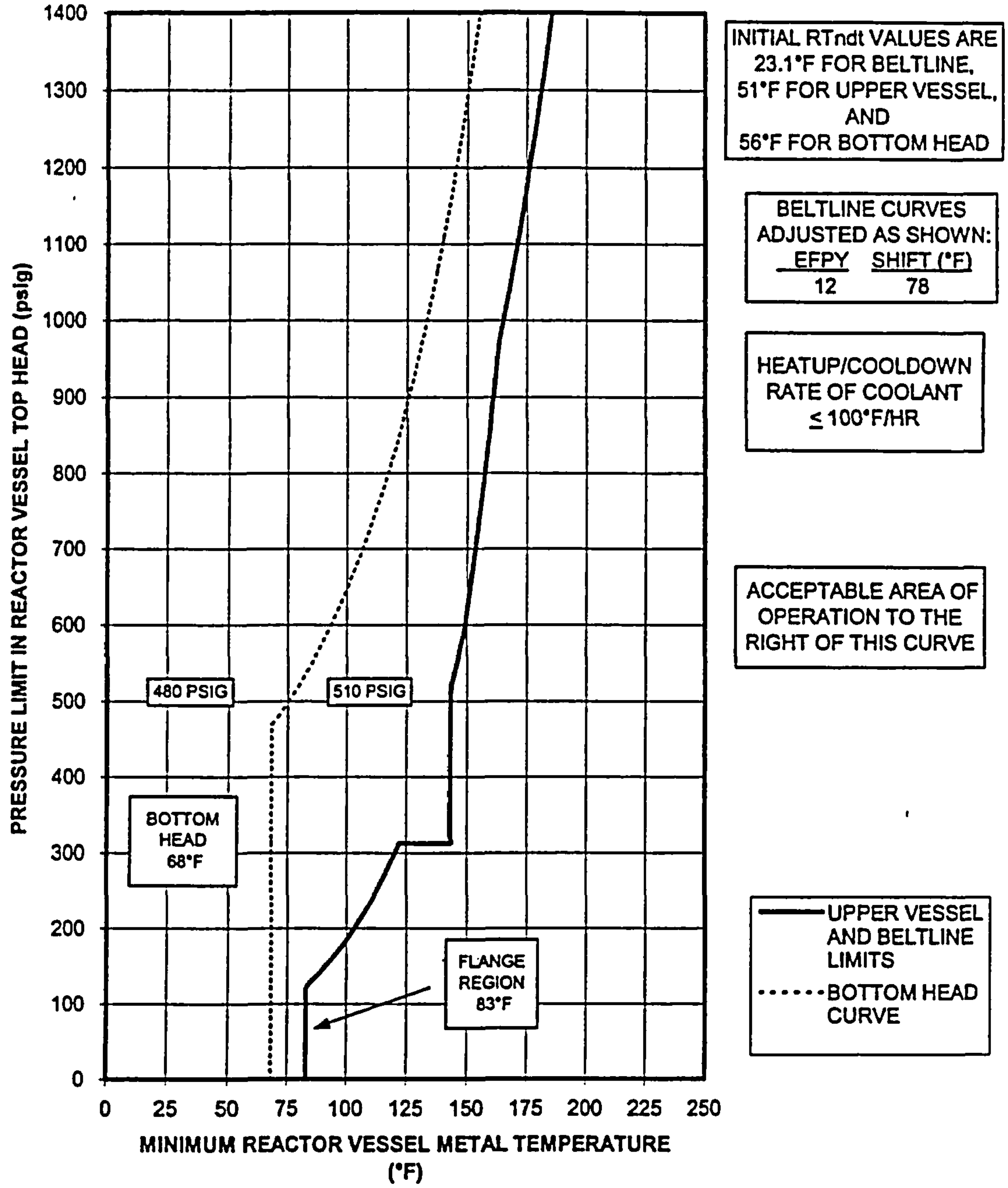

Figure 5-8: Composite Core Not Critical P-T Curves [Curve B] up to 12 EFPY
[100°F/hr or less coolant heatup/cooldown]

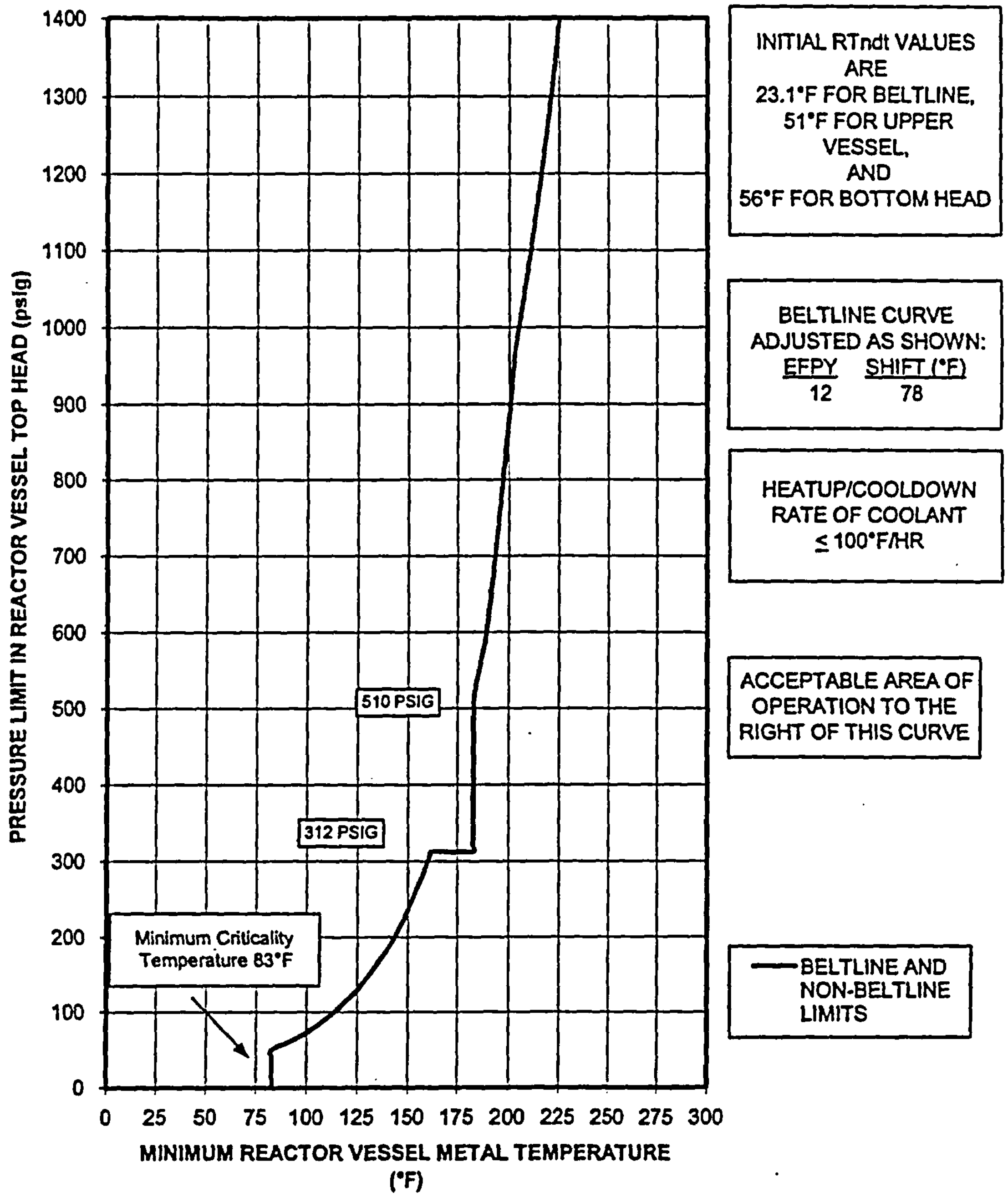

Figure 5-9: Composite Core Critical P-T Curves [Curve C] up to 12 EFPY
[100°F/hr or less coolant heatup/cooldown]

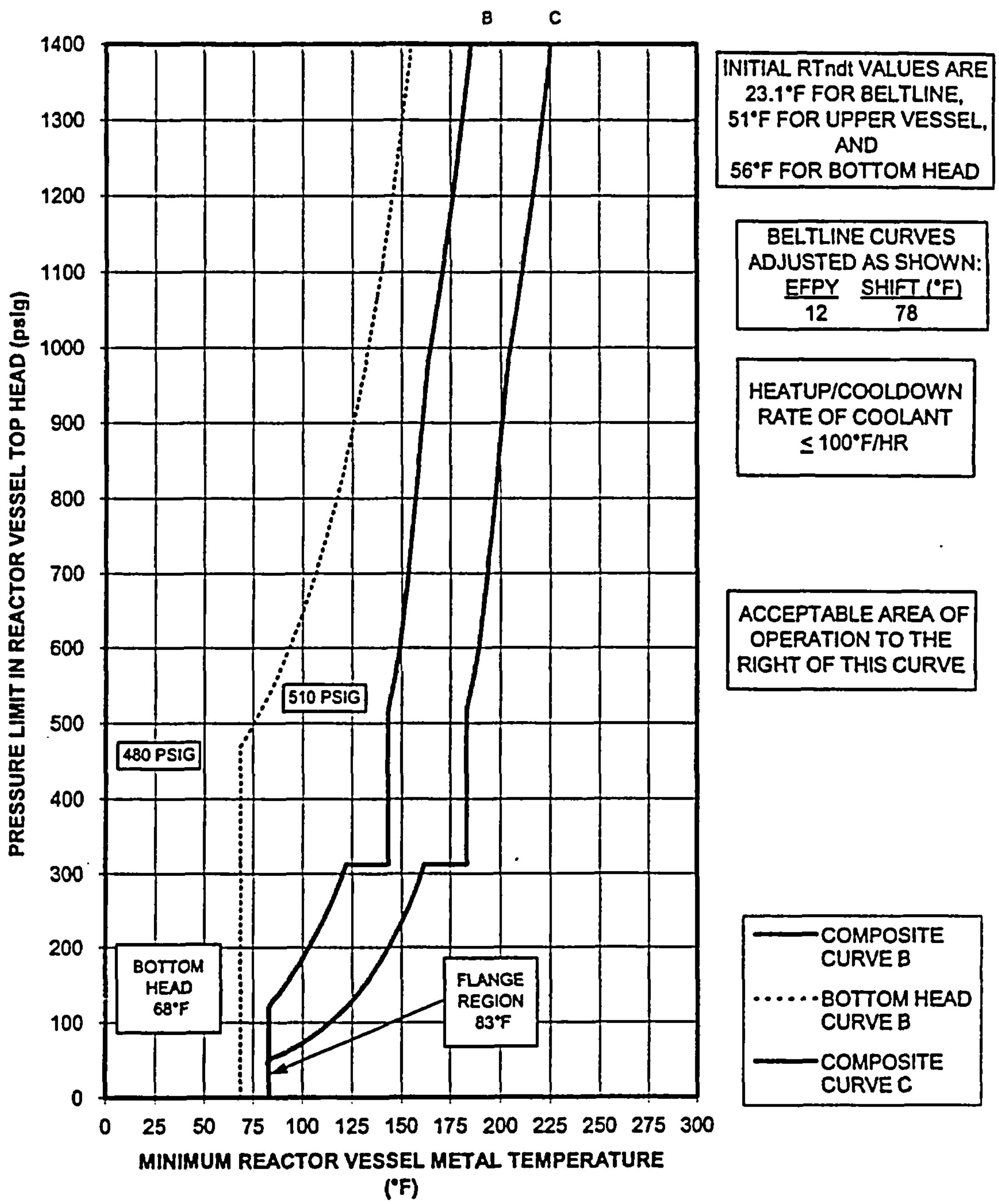

Figure 5-10: Composite Core Not Critical [Curve B] including Bottom Head and Core Critical P-T Curves [Curve C] up to 12 EFPY [100°F/hr or less coolant heatup/cooldown]

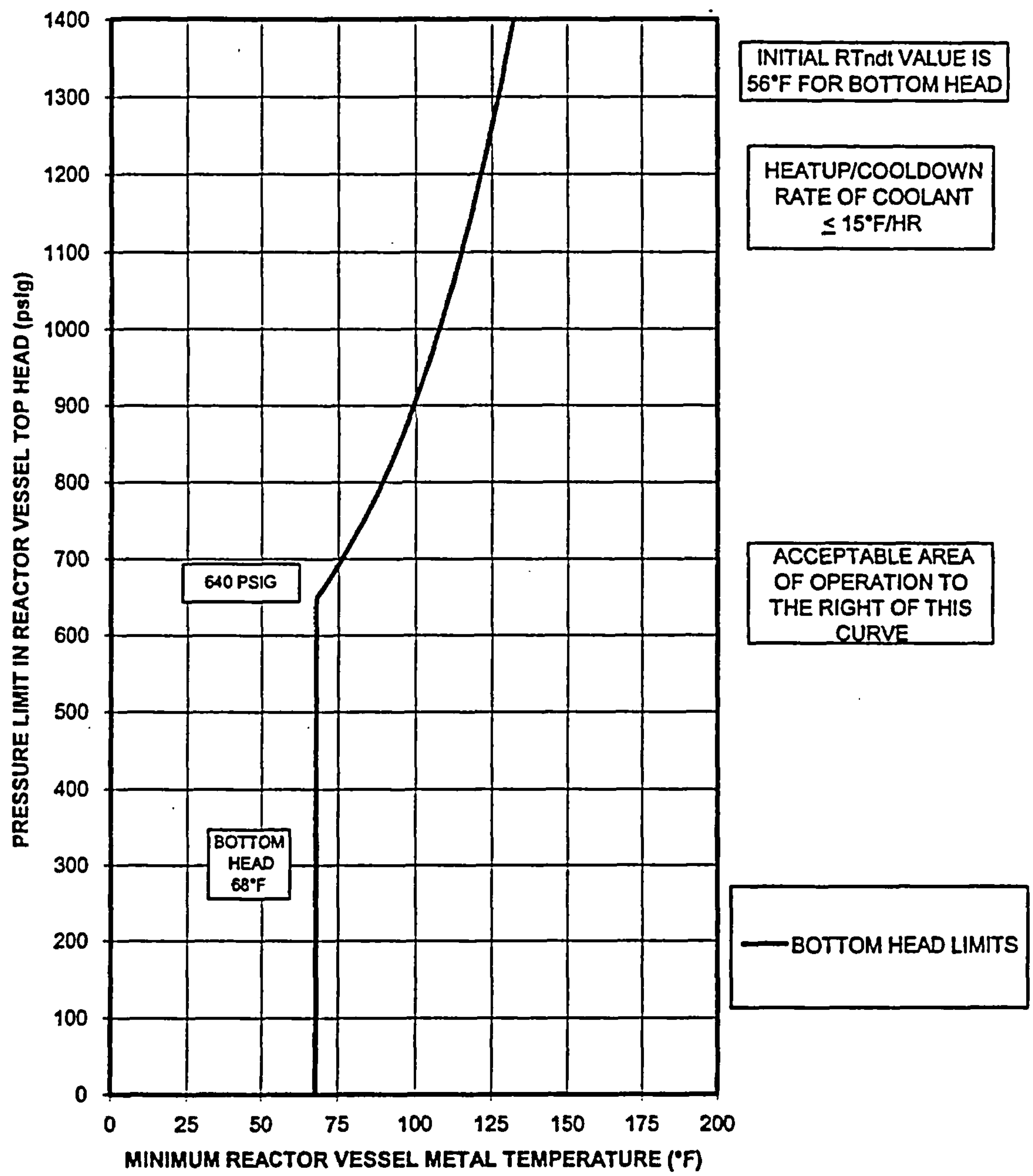

Figure 5-11: Bottom Head P-T Curve for Pressure Test [Curve A] – 16 EFPY

[15°F/hr or less coolant heatup/cooldown]

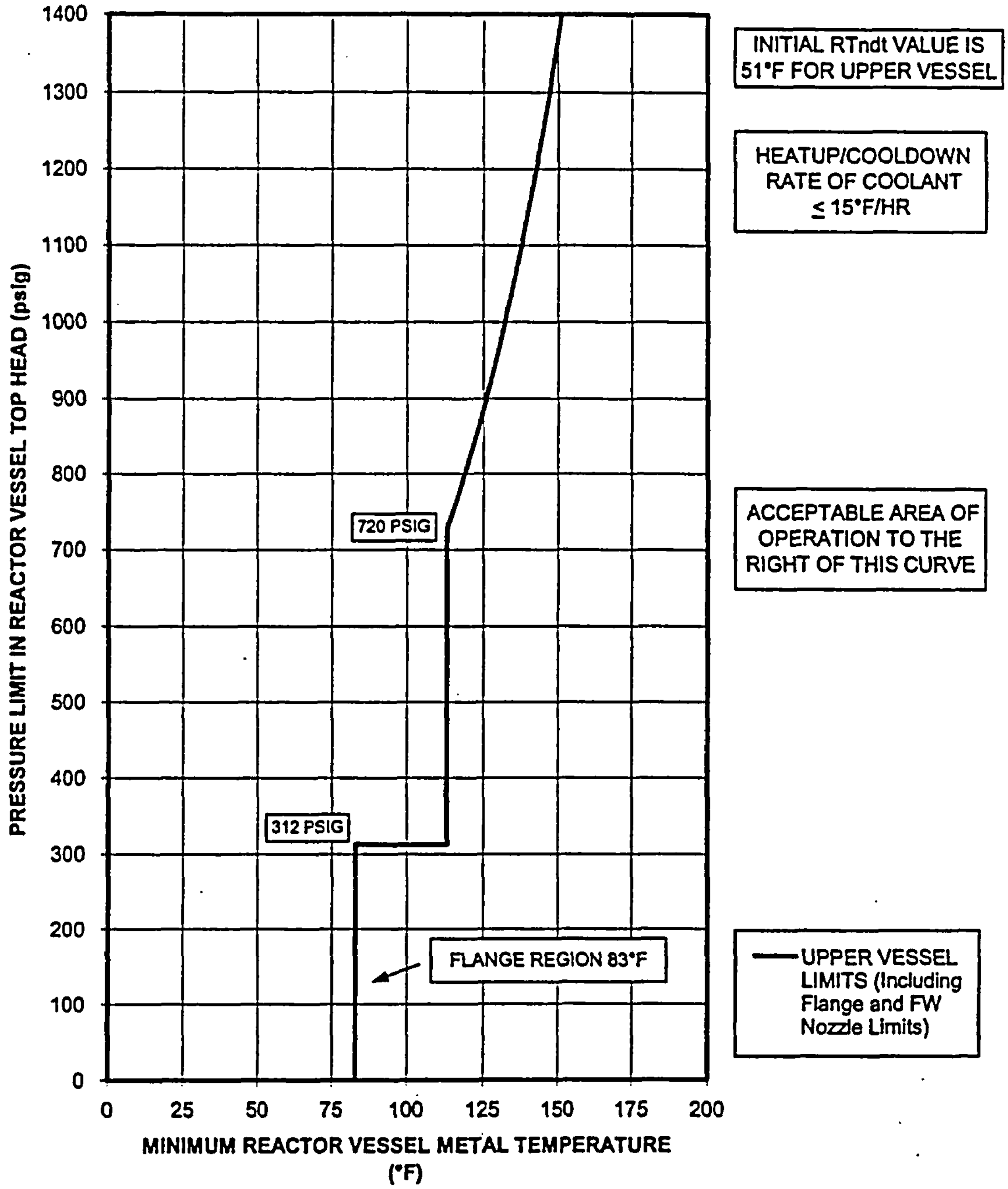

Figure 5-12: Upper Vessel P-T Curve for Pressure Test [Curve A] – 16 EFPY
[15°F/hr or less coolant heatup/cooldown]

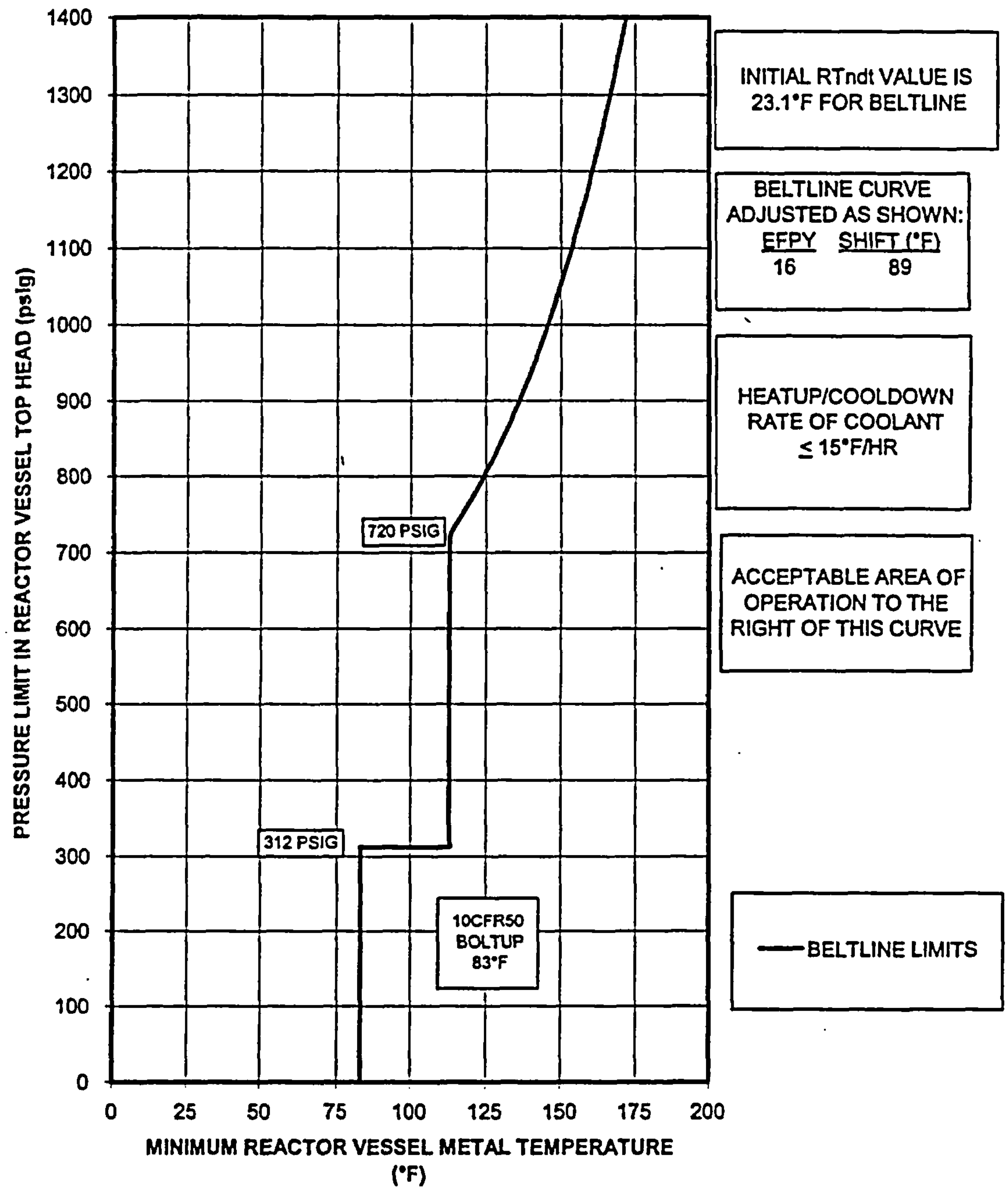

Figure 5-13: Beltline P-T Curve for Pressure Test [Curve A] up to 16 EFPY
[15°F/hr or less coolant heatup/cooldown]

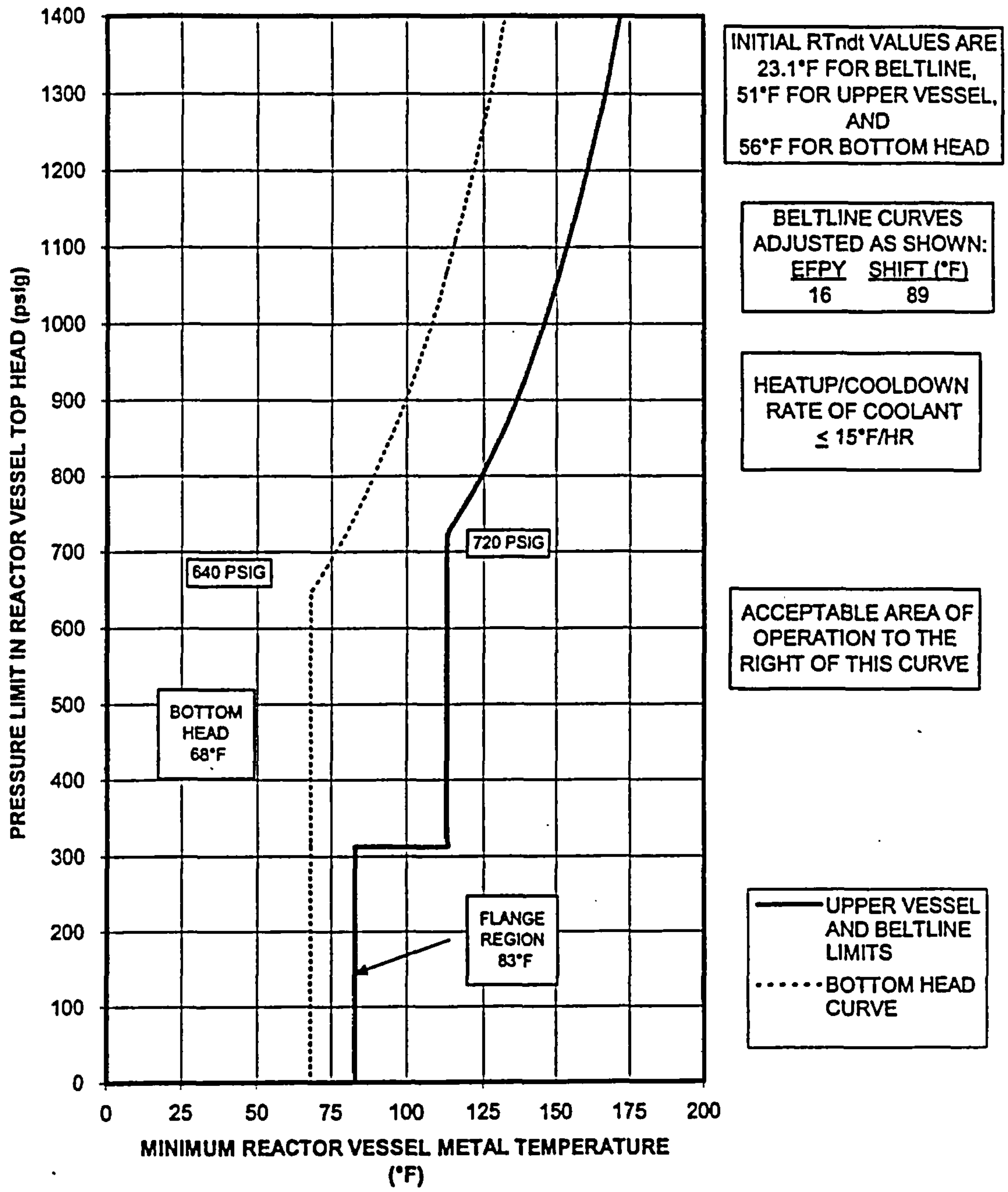

Figure 5-14: Composite Pressure Test P-T Curves [Curve A] up to 16 EFPY
[15°F/hr or less coolant heatup/cooldown]

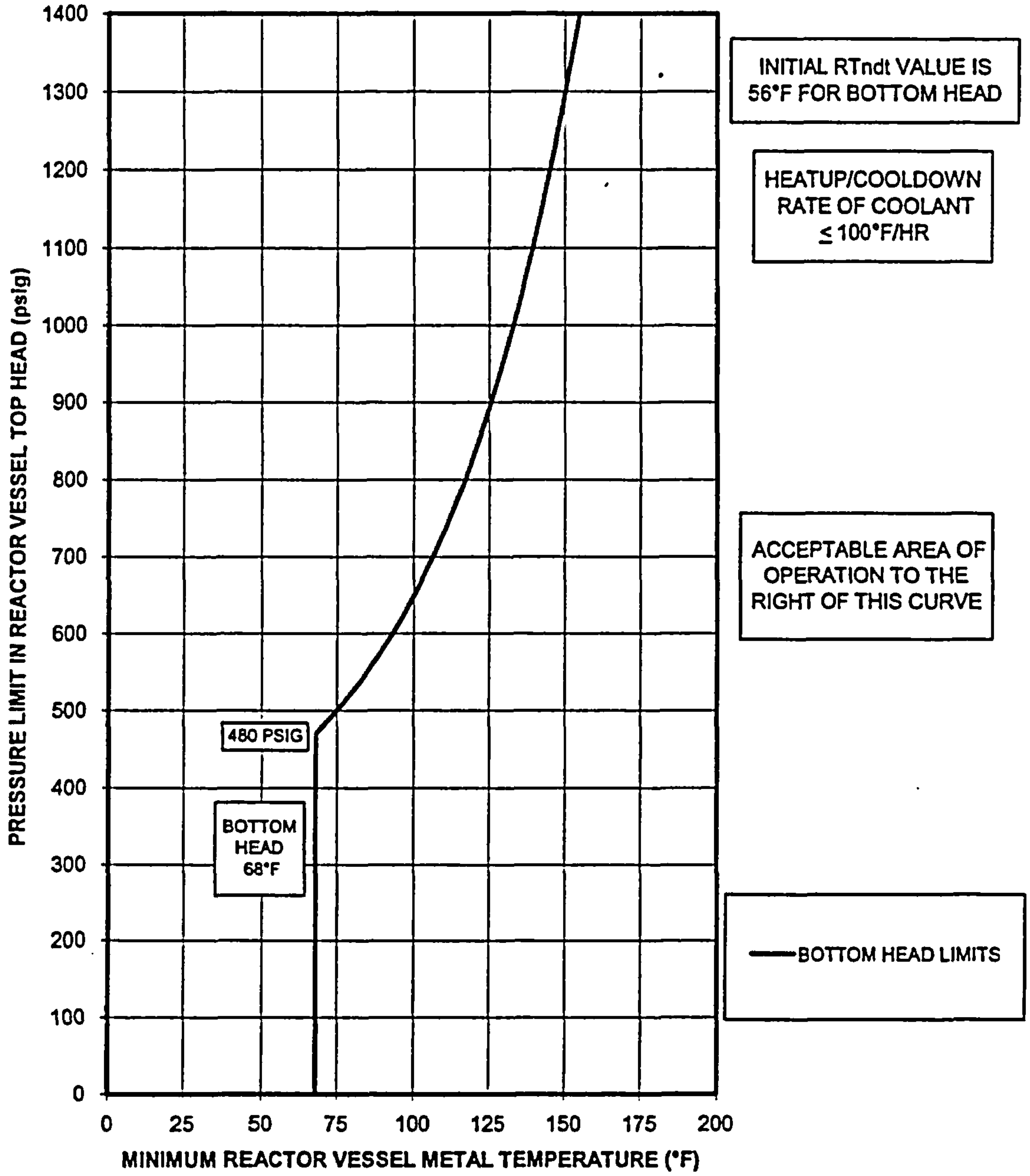

Figure 5-15: Bottom Head P-T Curve for Core Not Critical [Curve B] – 16 EFPY
[100°F/hr or less coolant heatup/cooldown]

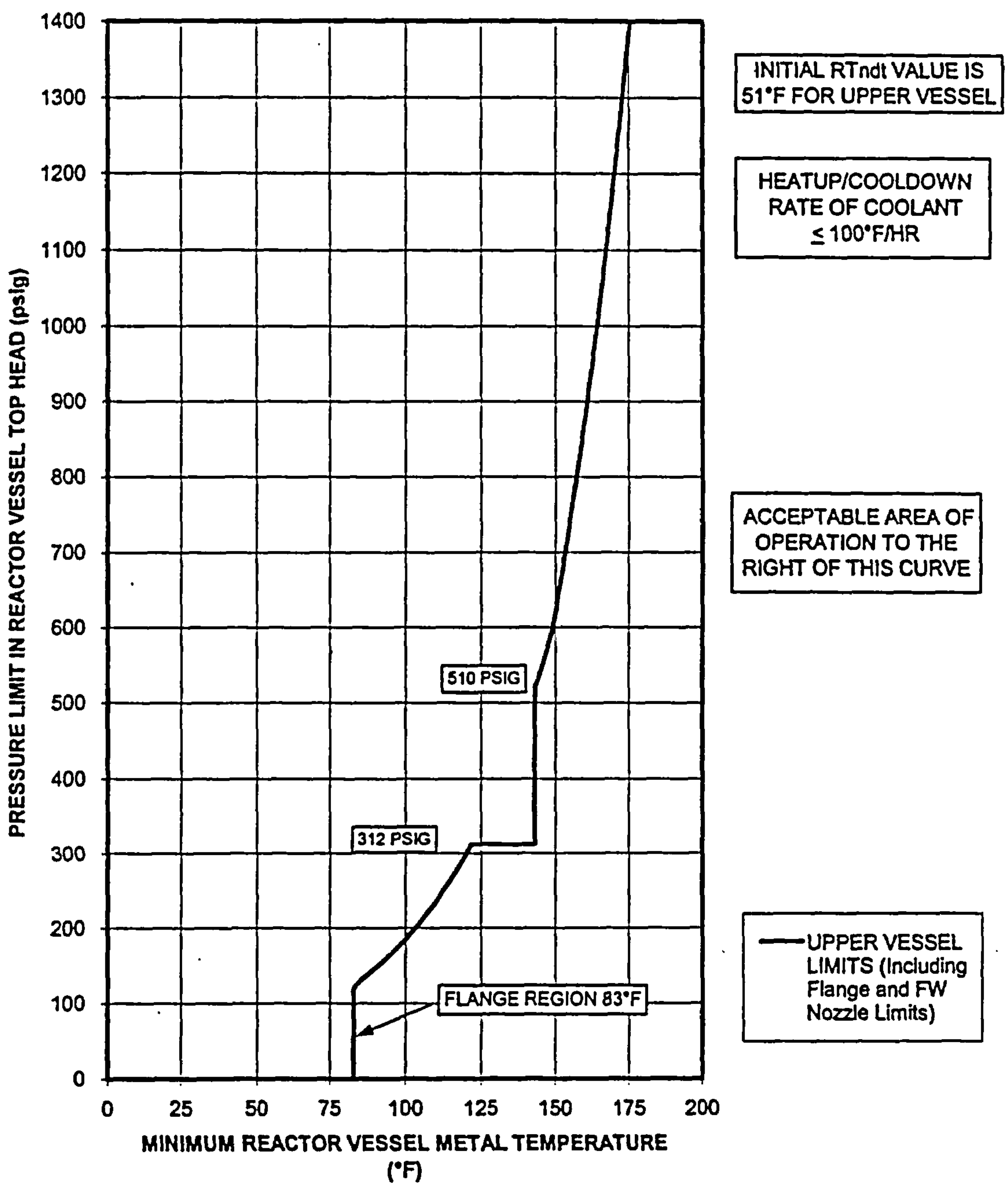

Figure 5-16: Upper Vessel P-T Curve for Core Not Critical [Curve B] – 16 EFPY

[100°F/hr or less coolant heatup/cooldown]

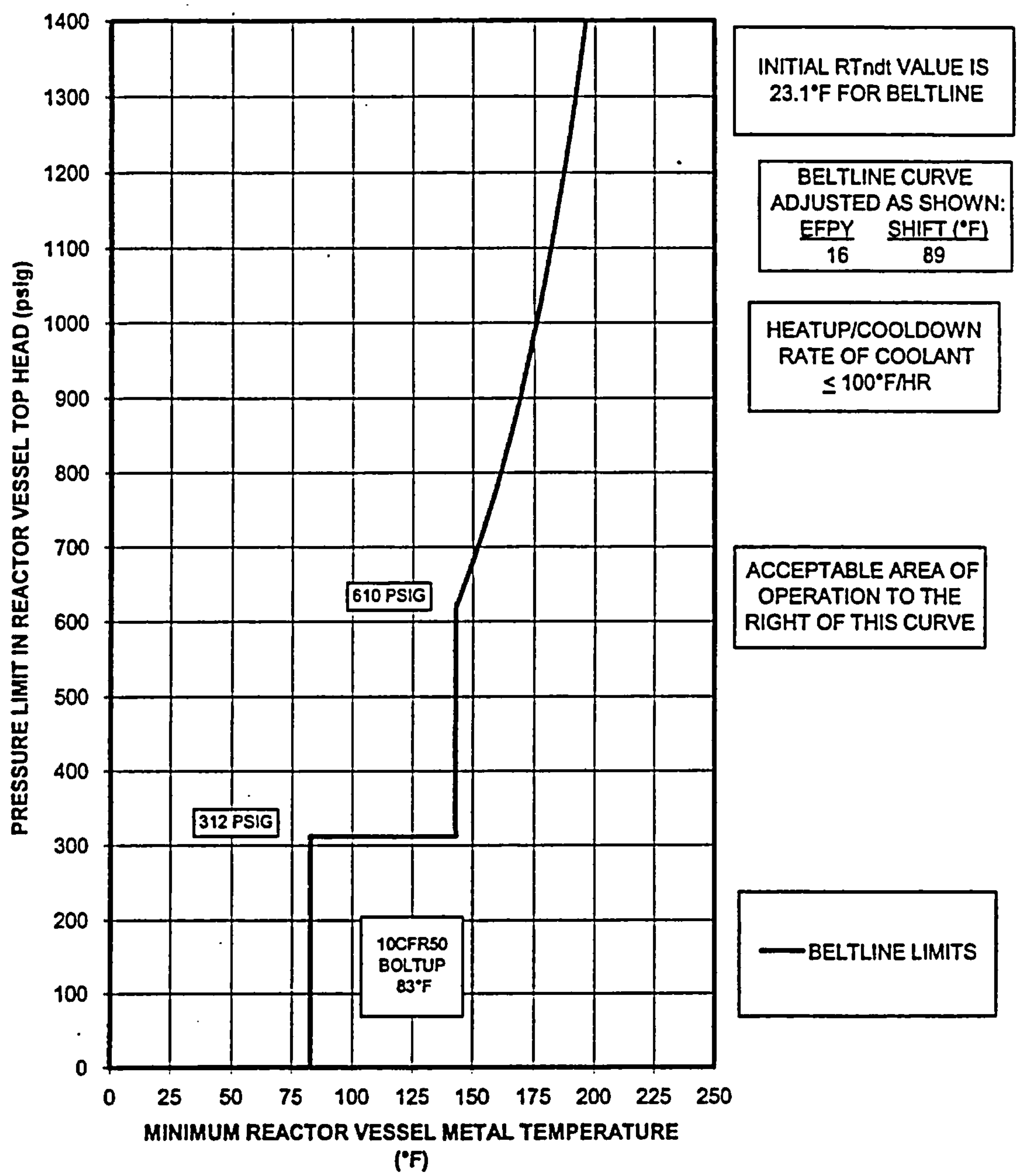

Figure 5-17: Beltline P-T Curve for Core Not Critical [Curve B] up to 16 EFPY [100°F/hr or less coolant heatup/cooldown]

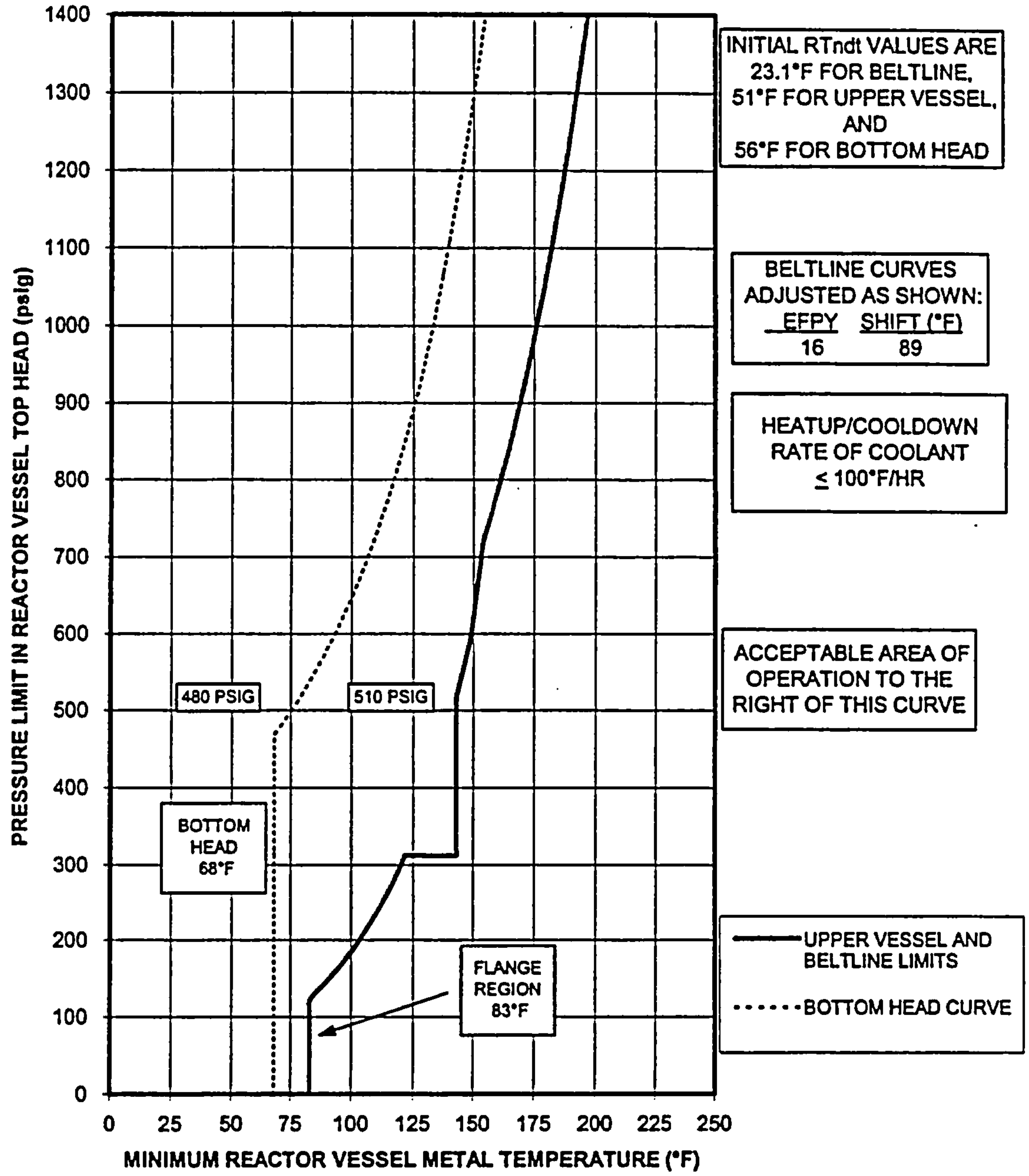

Figure 5-18: Composite Core Not Critical P-T Curves [Curve B] up to 16 EFPY
[100°F/hr or less coolant heatup/cooldown]

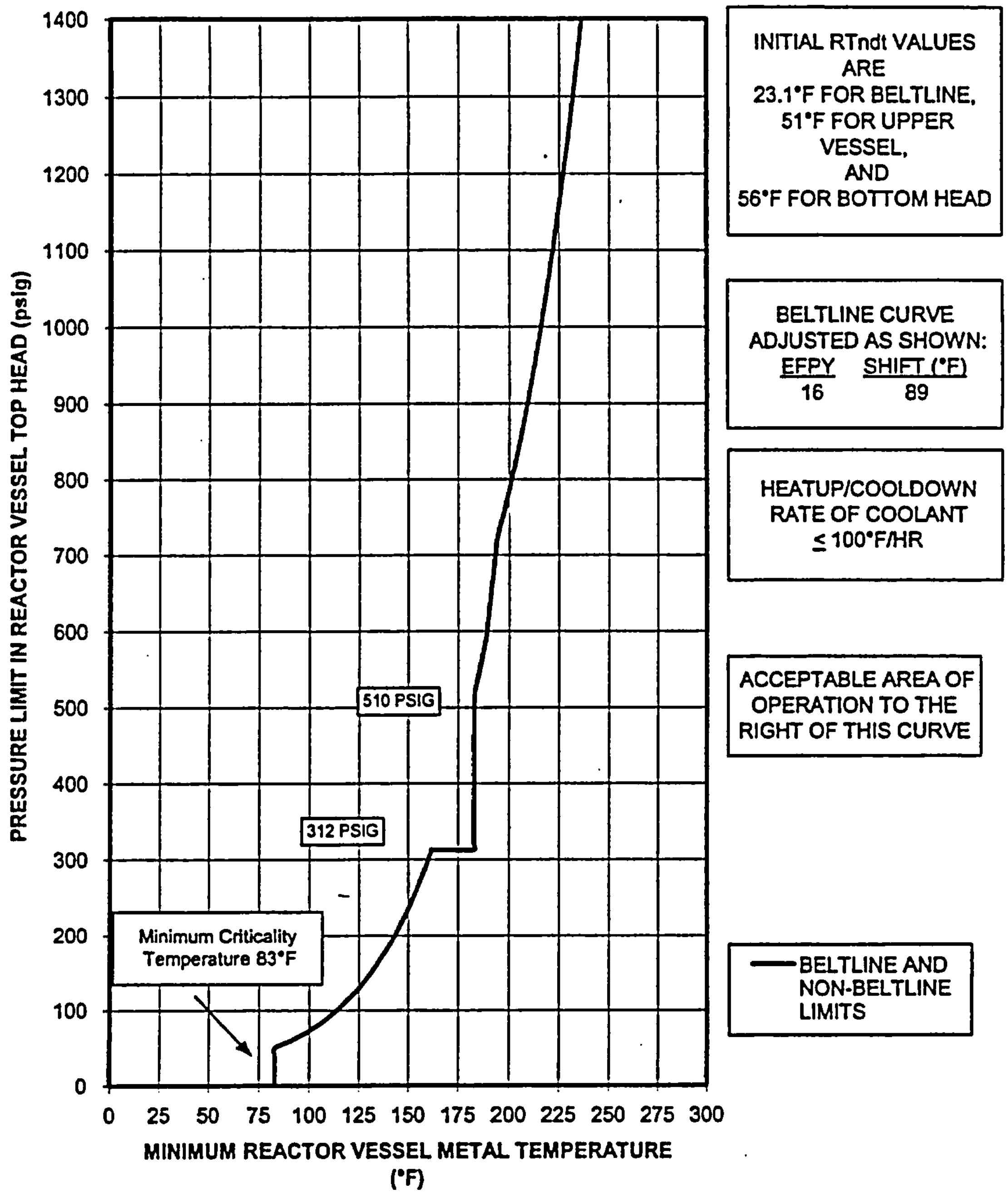

Figure 5-19: Composite Core Critical P-T Curves [Curve C] up to 16 EFPY
[100°F/hr or less coolant heatup/cooldown]

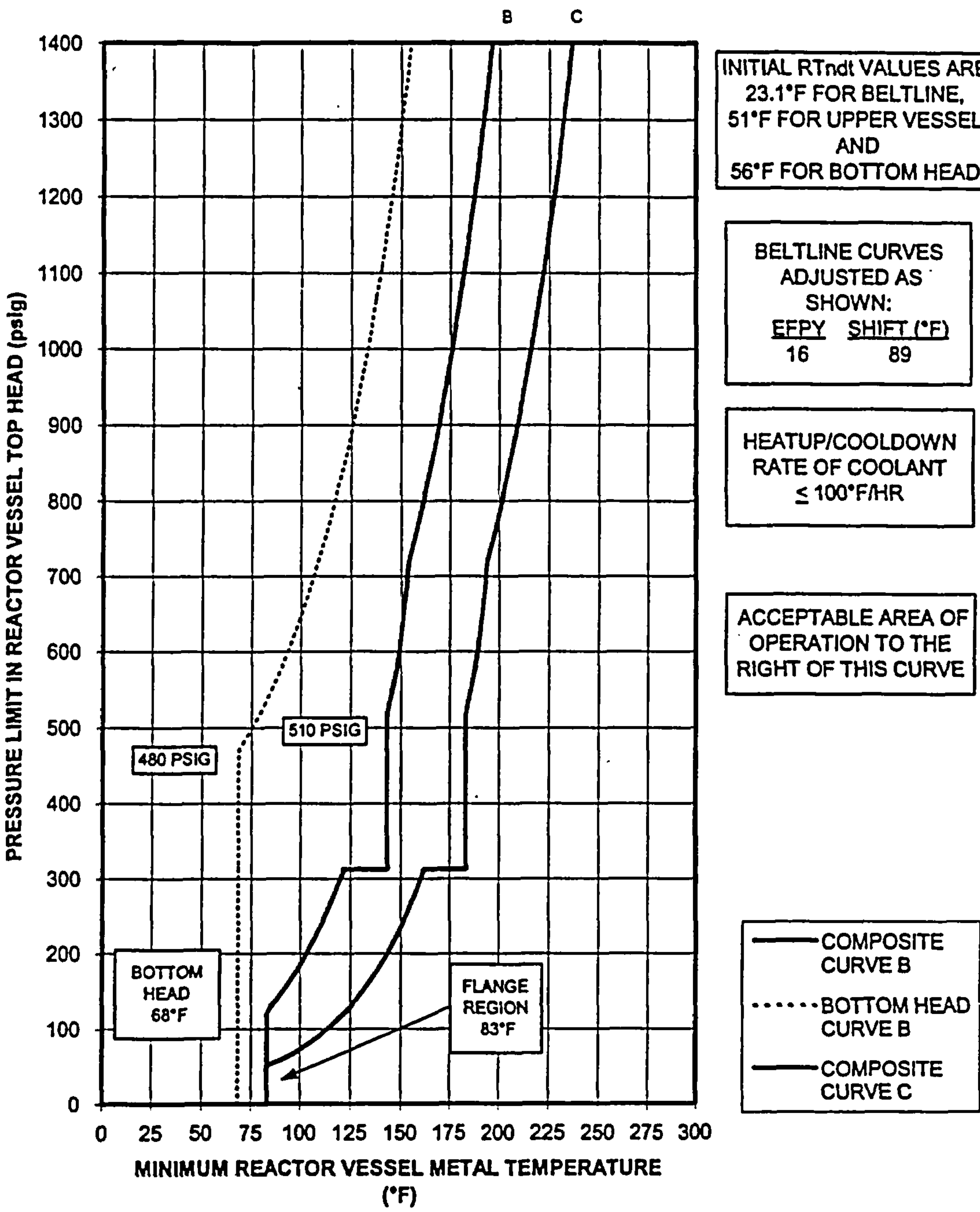

Figure 5-20: Composite Core Not Critical [Curve B] including Bottom Head and Core Critical P-T Curves [Curve C] up to 16 EFPY [100°F/hr or less coolant heatup/cooldown]

6.0 REFERENCES

1. GW Contreras, "Tennessee Valley Authority Browns Ferry Nuclear Plant Units 1, 2, and 3: Pressure Temperature Operating Limits", GENE, San Jose, CA, June 1994 (GE-NE-523-A65-0594, DRF 137-0010-7, Revision 1).

2. GE Drawing Number 729E7625, "Reactor Thermal Cycles – Reactor Vessel," GE-APED, San Jose, CA, Revision 0 (GE Proprietary).

3. GE Drawing Number 135B9990, "Nozzle Thermal Cycles - Reactor Vessel," GE-APED, San Jose, CA, Revision 1 (GE Proprietary).

4. a) "Alternative Reference Fracture Toughness for Development of P-T Limit Curves Section XI, Division 1," Code Case N-640 of the ASME Boiler & Pressure Vessel Code, Approval Date February 26, 1999.

   b) "Alternative to Reference Flaw Orientation of Appendix G for Circumferential Welds in Reactor Vessels Section XI, Division 1", Code Case N-588 of the ASME Boiler & Pressure Vessel Code, Approval Date December 12, 1997.

5. Technical Specifications For Browns Ferry Nuclear Plant, Unit 1.

6. "Fracture Toughness Criteria for Protection Against Failure", Appendix G to Section III or XI of the ASME Boiler & Pressure Vessel Code, 1995 Edition with Addenda through 1996.

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

8. "Fracture Toughness Requirements", Appendix G to Part 50 of Title 10 of the Code of Federal Regulations, December 1995.

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

10. GE Nuclear Energy, NEDC-32399-P, "Basis for GE RT_{NDT} Estimation Method", Report for BWR Owners' Group, San Jose, California, September 1994 (GE Proprietary).

11. Letter from B. Sheron to R.A. Pinelli, "Safety Assessment of Report NEDC-32399-P, Basis for GE RT_{NDT} Estimation Method, September 1994", USNRC, December 16, 1994.

12. QA Records & RPV CMTRs Browns Ferry Unit 1 GE PO# 205-55577, Manufactured by B&W, "General Electric Company Atomic Power Equipment Department (APED) Quality Control – Procured Equipment, RPV QC", Mt. Vernon, Indiana, and Madison, Indiana.

13. a) "Evaluation of RT_{NDT}, USE, and Chemical Composition of Core Region Electroslag Welds for Quad Cities Units 1 and 2", Framatome Technologies, Lynchburg, Virginia, January 1996 (BAW-2259).

    b) Letter, TE Abney (TVA) to US NRC, "Browns Ferry Nuclear Plant (BFN) – Units 1, 2, and 3 – Generic Letter (GL) 92-01, Revision 1, Supplement 1, Reactor Vessel Structural Integrity – Response to NRC Request for Additional Information (TAC Nos. MA1179, MA1180, and MA1181), September 8, 1998.

14. Letter, S.A. Richard, USNRC to J.F. Klapproth, GE-NE, "Safety Evaluation for NEDC-32983P, General Electric Methodology for Reactor Pressure Vessel Fast Neutron Flux Evaluation (TAC No. MA9891)", MFN 01-050, September 14, 2001.

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

16. [[

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17. "Analysis of Flaws", Appendix A to Section XI of the ASME Boiler & Pressure Vessel Code, 1995 Edition with Addenda through 1996.

18. [[

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19. Bottom Head and Feedwater Nozzle Dimensions:
    a. Babcock & Wilcox Company Drawing 122859E, Revision 10, "Lower Head Forming Details" (GE VPF 1805-003).
    b. Babcock & Wilcox Company Drawing 94975C, Revision 1, "MK-10 12" Feedwater Nozzle" (GE VPF 1805-035).

20. [[

]]

21. "Materials - Properties", Part D to Section II of the ASME Boiler & Pressure Vessel Code, 1995 Edition with Addenda through 1996.

22. C. Oza, "Browns Ferry Steam Electric Station Unit 2 Vessel Surveillance Materials Testing and Fracture Toughness Analysis", GE-NE, San Jose, CA, August 1995 (GENE-B1100639-01, Revision 1).

APPENDIX A

DESCRIPTION OF DISCONTINUITIES

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Table A-2 - Geometric Discontinuities Not Requiring Fracture Toughness Evaluations

Per ASME Code Appendix G, Section G2223 (c), fracture toughness analysis to demonstrate protection against non-ductile failure is not required for portions of nozzles and appurtenances having a thickness of 2.5" or less provided the lowest service temperature is not lower than RT_{NDT} plus 60°F. Also Inconel discontinuities require no fracture toughness evaluations.

Nozzle or Appurtenance	Material	Reference	Remarks
MK12 - 2" Instrumentation (attached to Shells 58, 59, 60) Shell 58 MK12 nozzle is within the beltline region (see Appendix E).	Alloy 600	1, 6, 9, 10, 23	Nozzles made from Alloy 600 and less than 2.5" require no fracture toughness evaluation.
MK 71 – Refueling Containment Skirt Attachment (to Shell Flange)	SA302 GR B	1, 24, 25	Not a pressure boundary component; therefore requires no fracture toughness evaluation.
MK 74, 75, 81, 82 - Insulation Brackets (Shells 57 and 59)	Carbon Steel	1, 26	Not a pressure boundary component; therefore requires no fracture toughness evaluation.
MK 85, 86 – Thermocouple Pads (all Shells, Shell Flange, Bottom Head, Feedwater Nozzle)	Carbon Steel	1, 27	Not a pressure boundary component; therefore requires no fracture toughness evaluation.
MK101 – 128 - Control Rod Drive Stub Tubes (in Bottom Head Dollar Plate)	Alloy 600	1, 12, 15, 16	Nozzles made from Alloy 600 require no fracture toughness evaluation.
MK131 – Steam Dryer Support Bracket (Shell 60)	SA182 F304	1, 21, 22	Appurtenances made from Stainless Steel require no fracture toughness evaluation.
MK132 – Core Spray Bracket (Shell 59)	SA276 T304	1, 21, 22	Appurtenances made from Stainless Steel require no fracture toughness evaluation.
MK133 – Dryer Hold Down Bracket (Top Head Flange)	SA508 CL2	1, 22	Not a pressure boundary component; therefore requires no fracture toughness evaluation.
MK134 – Guide Rod Bracket (Shell Flange)	SA182 F304	1, 21, 22	Appurtenances made from Stainless Steel require no fracture toughness evaluation.
MK135 – Feedwater Sparger Bracket (Shell 59)	SA182 F304	1, 21, 22	Appurtenances made from Stainless Steel require no fracture toughness evaluation.
MK 139* – N13 High and N14 Low Pressure Seal Leak Detection Penetration (Shell Flange)	Carbon Steel	1, 24	Not a pressure boundary component; therefore requires no fracture toughness evaluation.
MK199, 200 – Surveillance Specimen Brackets (Shells 58 and 59)	SA276 304	1, 21, 22	Appurtenances made from Stainless Steel require no fracture toughness evaluation.
MK 210 - Top Head Lifting Lugs	SA302 GR B	1, 17	Loading only occurs during outages. Not a pressure boundary component; therefore requires no fracture toughness evaluation.

* The high/low pressure leak detector, and the seal leak detector are the same nozzle; these nozzles are the closure flange leak detection nozzles.

APPENDIX A REFERENCES:

1. Vessel Drawings and Materials:
   - Drawing #24185F, Revision 11, "General Outline", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-042).
   - Drawing #24186F, Revision 14, "Outline Sections", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-018).
   - Drawing #24187F, Revision 11, "Vessel Sub-Assembly", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-059).
   - Drawing #122855E, Revision 14, "List of Materials", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-056).
   - Drawing 886D499, Revision 12, "Reactor Vessel", General Electric Company, GENE, San Jose, California.

2. J. Valente (TVA) to Dale Porter (GE), "Browns Ferry Nuclear Plant (BFN) - Pressure-Temperature Curves Design Input Request (DIR) – Transmittal of DIR Rev. 0", July 17, 2003 (TVA RIMS No. W83 030717 001).

3. Drawing #122859E, Revision 10, "Lower Head Forming Details", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-003).

4. Drawing #122860E, Revision 8, "Shell Segment Assembly Course #1 and #4", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-017).

5. Drawing #122864E, Revision 4, "Recirculation Nozzles", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-041).

6. Drawing #122861E, Revision 8, "Shell Segment Assembly Course #3", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-020).

7. Drawing #94975C, Revision 1, "MK-10 12" Feedwater Nozzle Forging", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-035).

8. Drawing #94976C, Revision 1, "MK-11 Core Spray Nozzle Forging", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-036).

9. Drawing #122868E, Revision 5, "2" Instrument and 4" CRD HYD System Return Nozzles", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-054).

10. Drawing #122862E, Revision 6, "Shell Segment Assembly Course #5", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-019).

11. Drawing #122865E, Revision 4, "26" Steam Outlet Nozzle", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-040).

12. Drawing #122856E, Revision 11, "Lower Head Assembly", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-013).

13. Drawing #122858E, Revision 11, "Lower Head Upper Segment Assembly", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-012).

14. Drawing #122869E, Revision 3, "4" Jet Pump Nozzle", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-051).

15. Drawing #122857E, Revision 11, "Lower Head Bottom Segment Assembly", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-011).

16. Control Rod Nozzles:

    - Drawing #122883E, Revision 5, "Control Rod Nozzles, Unit #1", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-065).
    - Drawing #149938E, Revision 2, "Control Rod Nozzles, Unit #2", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-144).

17. Drawing #122876E, Revision 7, "Closure Head Assembly", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-049).

18. Drawing #122877E, Revision 5, "Closure Head Nozzles", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-048).

19. Drawing #122872E, Revision 8, "Support Skirt Assembly and Detail", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-108).

20. Drawing #122870E, Revision 6, "Shroud Support", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-039).

21. Drawing #122881E, Revision 9, "Vessel Subassembly Details", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-058).

22. Drawing #122871E, Revision 6, "Vessel Attachment Details", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-057).

23. Drawing #142115E, Revision 3, "Shell Segment Assembly Course #2", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-104).

24. Drawing #122863E, Revision 6, "Shell Flange Details", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-107).

25. Drawing #122875E, Revision 2, "Refueling Containment Skirt", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-050).

26. Drawing #122873E, Revision 1, "Vessel Insulation Support", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-068).

27. Drawing #122874E, Revision 2, "Vessel Thermocouple Pads", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-069).

APPENDIX B

PRESSURE TEMPERATURE CURVE DATA TABULATION

TABLE B-1. Browns Ferry Unit 1 P-T Curve Values for 12 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-1, 5-2, 5-3, 5-5, 5-6, & 5-7

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER VESSEL CURVE A (°F)	12 EFPY BELTLINE CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	12 EFPY BELTLINE CURVE B (°F)
0	68.0	83.0	83.0	68.0	83.0	83.0
10	68.0	83.0	83.0	68.0	83.0	83.0
20	68.0	83.0	83.0	68.0	83.0	83.0
30	68.0	83.0	83.0	68.0	83.0	83.0
40	68.0	83.0	83.0	68.0	83.0	83.0
50	68.0	83.0	83.0	68.0	83.0	83.0
60	68.0	83.0	83.0	68.0	83.0	83.0
70	68.0	83.0	83.0	68.0	83.0	83.0
80	68.0	83.0	83.0	68.0	83.0	83.0
90	68.0	83.0	83.0	68.0	83.0	83.0
100	68.0	83.0	83.0	68.0	83.0	83.0
110	68.0	83.0	83.0	68.0	83.0	83.0
120	68.0	83.0	83.0	68.0	83.0	83.0
130	68.0	83.0	83.0	68.0	85.2	83.0
140	68.0	83.0	83.0	68.0	88.4	83.0
150	68.0	83.0	83.0	68.0	91.2	83.0
160	68.0	83.0	83.0	68.0	93.9	83.0
170	68.0	83.0	83.0	68.0	96.5	83.0
180	68.0	83.0	83.0	68.0	98.9	83.0
190	68.0	83.0	83.0	68.0	101.2	83.0
200	68.0	83.0	83.0	68.0	103.3	83.0
210	68.0	83.0	83.0	68.0	105.3	83.0
220	68.0	83.0	83.0	68.0	107.3	83.0

TABLE B-1. Browns Ferry Unit 1 P-T Curve Values for 12 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-1, 5-2, 5-3, 5-5, 5-6, & 5-7

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER VESSEL CURVE A (°F)	12 EFPY BELTLINE CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	12 EFPY BELTLINE CURVE B (°F)
230	68.0	83.0	83.0	68.0	109.1	83.0
240	68.0	83.0	83.0	68.0	110.9	83.0
250	68.0	83.0	83.0	68.0	112.6	83.0
260	68.0	83.0	83.0	68.0	114.2	83.0
270	68.0	83.0	83.0	68.0	115.8	83.0
280	68.0	83.0	83.0	68.0	117.3	83.0
290	68.0	83.0	83.0	68.0	118.8	83.0
300	68.0	83.0	83.0	68.0	120.2	83.0
310	68.0	83.0	83.0	68.0	121.5	83.0
312.5	68.0	83.0	83.0	68.0	121.9	83.0
312.5	68.0	113.0	113.0	68.0	143.0	143.0
320	68.0	113.0	113.0	68.0	143.0	143.0
330	68.0	113.0	113.0	68.0	143.0	143.0
340	68.0	113.0	113.0	68.0	143.0	143.0
350	68.0	113.0	113.0	68.0	143.0	143.0
360	68.0	113.0	113.0	68.0	143.0	143.0
370	68.0	113.0	113.0	68.0	143.0	143.0
380	68.0	113.0	113.0	68.0	143.0	143.0
390	68.0	113.0	113.0	68.0	143.0	143.0
400	68.0	113.0	113.0	68.0	143.0	143.0
410	68.0	113.0	113.0	68.0	143.0	143.0
420	68.0	113.0	113.0	68.0	143.0	143.0
430	68.0	113.0	113.0	68.0	143.0	143.0
440	68.0	113.0	113.0	68.0	143.0	143.0
450	68.0	113.0	113.0	68.0	143.0	143.0

TABLE B-1. Browns Ferry Unit 1 P-T Curve Values for 12 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-1, 5-2, 5-3, 5-5, 5-6, & 5-7

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER VESSEL CURVE A (°F)	12 EFPY BELTLINE CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	12 EFPY BELTLINE CURVE B (°F)
460	68.0	113.0	113.0	68.0	143.0	143.0
470	68.0	113.0	113.0	68.0	143.0	143.0
480	68.0	113.0	113.0	70.5	143.0	143.0
490	68.0	113.0	113.0	72.8	143.0	143.0
500	68.0	113.0	113.0	75.0	143.0	143.0
510	68.0	113.0	113.0	77.2	143.0	143.0
520	68.0	113.0	113.0	79.2	143.2	143.0
530	68.0	113.0	113.0	81.2	144.0	143.0
540	68.0	113.0	113.0	83.1	144.8	143.0
550	68.0	113.0	113.0	84.9	145.6	143.0
560	68.0	113.0	113.0	86.7	146.4	143.0
570	68.0	113.0	113.0	88.4	147.1	143.0
580	68.0	113.0	113.0	90.0	147.9	143.0
590	68.0	113.0	113.0	91.6	148.6	143.0
600	68.0	113.0	113.0	93.2	149.1	143.0
610	68.0	113.0	113.0	94.7	149.6	143.0
620	68.0	113.0	113.0	96.1	150.0	143.0
630	68.0	113.0	113.0	97.5	150.4	143.0
640	68.0	113.0	113.0	98.9	150.8	143.0
650	68.2	113.0	113.0	100.2	151.2	143.0
660	69.9	113.0	113.0	101.5	151.7	143.0
670	71.6	113.0	113.0	102.8	152.1	143.0
680	73.2	113.0	113.0	104.1	152.5	143.0
690	74.7	113.0	113.0	105.3	152.9	143.0
700	76.2	113.0	113.0	106.4	153.3	143.0

TABLE B-1. Browns Ferry Unit 1 P-T Curve Values for 12 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-1, 5-2, 5-3, 5-5, 5-6, & 5-7

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER VESSEL CURVE A (°F)	12 EFPY BELTLINE CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	12 EFPY BELTLINE CURVE B (°F)
710	77.7	113.0	113.0	107.6	153.7	143.0
720	79.1	113.0	113.0	108.7	154.1	143.0
730	80.5	113.3	113.0	109.8	154.5	144.0
740	81.8	114.1	113.0	110.9	154.9	144.9
750	83.1	115.0	113.0	112.0	155.2	145.9
760	84.4	115.8	113.0	113.0	155.6	146.8
770	85.6	116.6	113.0	114.0	156.0	147.7
780	86.8	117.3	113.0	115.0	156.4	148.6
790	88.0	118.1	113.0	116.0	156.8	149.4
800	89.2	118.9	113.3	116.9	157.1	150.3
810	90.3	119.6	114.6	117.9	157.5	151.1
820	91.4	120.4	115.9	118.8	157.9	151.9
830	92.5	121.1	117.2	119.7	158.2	152.8
840	93.5	121.8	118.4	120.6	158.6	153.6
850	94.6	122.5	119.6	121.4	158.9	154.3
860	95.6	123.2	120.7	122.3	159.3	155.1
870	96.6	123.9	121.9	123.1	159.6	155.9
880	97.5	124.6	123.0	124.0	160.0	156.6
890	98.5	125.3	124.0	124.8	160.3	157.4
900	99.4	125.9	125.1	125.6	160.7	158.1
910	100.4	126.6	126.1	126.4	161.0	158.8
920	101.3	127.2	127.2	127.1	161.4	159.5
930	102.1	127.9	128.2	127.9	161.7	160.2
940	103.0	128.5	129.1	128.7	162.0	160.9
950	103.9	129.1	130.1	129.4	162.4	161.6

TABLE B-1. Browns Ferry Unit 1 P-T Curve Values for 12 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-1, 5-2, 5-3, 5-5, 5-6, & 5-7

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER VESSEL CURVE A (°F)	12 EFPY BELTLINE CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	12 EFPY BELTLINE CURVE B (°F)
960	104.7	129.7	131.0	130.1	162.7	162.3
970	105.6	130.3	132.0	130.9	163.0	162.9
980	106.4	130.9	132.9	131.6	163.4	163.6
990	107.2	131.5	133.8	132.3	163.7	164.2
1000	108.0	132.1	134.6	133.0	164.0	164.8
1010	108.7	132.7	135.5	133.6	164.3	165.5
1020	109.5	133.2	136.3	134.3	164.6	166.1
1030	110.3	133.8	137.2	135.0	165.0	166.7
1040	111.0	134.4	138.0	135.6	165.3	167.3
1050	111.7	134.9	138.8	136.3	165.6	167.9
1060	112.4	135.5	139.6	136.9	165.9	168.5
1064	112.7	135.7	139.9	137.2	166.0	168.7
1070	113.2	136.0	140.4	137.5	166.2	169.1
1080	113.9	136.5	141.1	138.2	166.5	169.7
1090	114.6	137.1	141.9	138.8	166.8	170.2
1100	115.2	137.6	142.6	139.4	167.1	170.8
1105	115.6	137.8	143.0	139.7	167.3	171.1
1110	115.9	138.1	143.4	140.0	167.4	171.4
1120	116.6	138.6	144.1	140.6	167.7	171.9
1130	117.2	139.1	144.8	141.2	168.0	172.4
1140	117.9	139.6	145.5	141.7	168.3	173.0
1150	118.5	140.1	146.2	142.3	168.6	173.5
1160	119.1	140.6	146.9	142.9	168.9	174.0
1170	119.8	141.1	147.5	143.4	169.2	174.6
1180	120.4	141.6	148.2	144.0	169.5	175.1

TABLE B-1. Browns Ferry Unit 1 P-T Curve Values for 12 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-1, 5-2, 5-3, 5-5, 5-6, & 5-7

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER VESSEL CURVE A (°F)	12 EFPY BELTLINE CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	12 EFPY BELTLINE CURVE B (°F)
1190	121.0	142.1	148.9	144.5	169.7	175.6
1200	121.6	142.5	149.5	145.1	170.0	176.1
1210	122.2	143.0	150.2	145.6	170.3	176.6
1220	122.8	143.5	150.8	146.2	170.6	177.1
1230	123.3	143.9	151.4	146.7	170.9	177.6
1240	123.9	144.4	152.0	147.2	171.2	178.1
1250	124.5	144.8	152.6	147.7	171.4	178.6
1260	125.0	145.3	153.2	148.2	171.7	179.0
1270	125.6	145.7	153.8	148.7	172.0	179.5
1280	126.1	146.2	154.4	149.2	172.2	180.0
1290	126.7	146.6	155.0	149.7	172.5	180.5
1300	127.2	147.0	155.6	150.2	172.8	180.9
1310	127.7	147.5	156.1	150.7	173.1	181.4
1320	128.3	147.9	156.7	151.2	173.3	181.8
1330	128.8	148.3	157.2	151.6	173.6	182.3
1340	129.3	148.7	157.8	152.1	173.8	182.7
1350	129.8	149.1	158.3	152.6	174.1	183.2
1360	130.3	149.6	158.9	153.0	174.4	183.6
1370	130.8	150.0	159.4	153.5	174.6	184.0
1380	131.3	150.4	159.9	153.9	174.9	184.4
1390	131.8	150.8	160.5	154.4	175.1	184.9
1400	132.3	151.2	161.0	154.8	175.4	185.3

TABLE B-2. Browns Ferry Unit 1 Composite P-T Curve Values for 12 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-4, 5-8, 5-9 and 5-10

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE B (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE C (°F)
0	68.0	83.0	68.0	83.0	83.0
10	68.0	83.0	68.0	83.0	83.0
20	68.0	83.0	68.0	83.0	83.0
30	68.0	83.0	68.0	83.0	83.0
40	68.0	83.0	68.0	83.0	83.0
50	68.0	83.0	68.0	83.0	83.0
60	68.0	83.0	68.0	83.0	91.0
70	68.0	83.0	68.0	83.0	98.2
80	68.0	83.0	68.0	83.0	104.2
90	68.0	83.0	68.0	83.0	109.3
100	68.0	83.0	68.0	83.0	113.8
110	68.0	83.0	68.0	83.0	117.9
120	68.0	83.0	68.0	83.0	121.7
130	68.0	83.0	68.0	85.2	125.2
140	68.0	83.0	68.0	88.4	128.4
150	68.0	83.0	68.0	91.2	131.2
160	68.0	83.0	68.0	93.9	133.9
170	68.0	83.0	68.0	96.5	136.5
180	68.0	83.0	68.0	98.9	138.9
190	68.0	83.0	68.0	101.2	141.2
200	68.0	83.0	68.0	103.3	143.3
210	68.0	83.0	68.0	105.3	145.3
220	68.0	83.0	68.0	107.3	147.3

TABLE B-2. Browns Ferry Unit 1 Composite P-T Curve Values for 12 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-4, 5-8, 5-9 and 5-10

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE B (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE C (°F)
230	68.0	83.0	68.0	109.1	149.1
240	68.0	83.0	68.0	110.9	150.9
250	68.0	83.0	68.0	112.6	152.6
260	68.0	83.0	68.0	114.2	154.2
270	68.0	83.0	68.0	115.8	155.8
280	68.0	83.0	68.0	117.3	157.3
290	68.0	83.0	68.0	118.8	158.8
300	68.0	83.0	68.0	120.2	160.2
310	68.0	83.0	68.0	121.5	161.5
312.5	68.0	83.0	68.0	121.9	161.9
312.5	68.0	113.0	68.0	143.0	183.0
320	68.0	113.0	68.0	143.0	183.0
330	68.0	113.0	68.0	143.0	183.0
340	68.0	113.0	68.0	143.0	183.0
350	68.0	113.0	68.0	143.0	183.0
360	68.0	113.0	68.0	143.0	183.0
370	68.0	113.0	68.0	143.0	183.0
380	68.0	113.0	68.0	143.0	183.0
390	68.0	113.0	68.0	143.0	183.0
400	68.0	113.0	68.0	143.0	183.0
410	68.0	113.0	68.0	143.0	183.0
420	68.0	113.0	68.0	143.0	183.0
430	68.0	113.0	68.0	143.0	183.0
440	68.0	113.0	68.0	143.0	183.0
450	68.0	113.0	68.0	143.0	183.0

TABLE B-2. Browns Ferry Unit 1 Composite P-T Curve Values for 12 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-4, 5-8, 5-9 and 5-10

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE B (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE C (°F)
460	68.0	113.0	68.0	143.0	183.0
470	68.0	113.0	68.0	143.0	183.0
480	68.0	113.0	70.5	143.0	183.0
490	68.0	113.0	72.8	143.0	183.0
500	68.0	113.0	75.0	143.0	183.0
510	68.0	113.0	77.2	143.0	183.0
520	68.0	113.0	79.2	143.2	183.2
530	68.0	113.0	81.2	144.0	184.0
540	68.0	113.0	83.1	144.8	184.8
550	68.0	113.0	84.9	145.6	185.6
560	68.0	113.0	86.7	146.4	186.4
570	68.0	113.0	88.4	147.1	187.1
580	68.0	113.0	90.0	147.9	187.9
590	68.0	113.0	91.6	148.6	188.6
600	68.0	113.0	93.2	149.1	189.1
610	68.0	113.0	94.7	149.6	189.6
620	68.0	113.0	96.1	150.0	190.0
630	68.0	113.0	97.5	150.4	190.4
640	68.0	113.0	98.9	150.8	190.8
650	68.2	113.0	100.2	151.2	191.2
660	69.9	113.0	101.5	151.7	191.7
670	71.6	113.0	102.8	152.1	192.1
680	73.2	113.0	104.1	152.5	192.5
690	74.7	113.0	105.3	152.9	192.9
700	76.2	113.0	106.4	153.3	193.3

TABLE B-2. Browns Ferry Unit 1 Composite P-T Curve Values for 12 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-4, 5-8, 5-9 and 5-10

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE B (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE C (°F)
710	77.7	113.0	107.6	153.7	193.7
720	79.1	113.0	108.7	154.1	194.1
730	80.5	113.3	109.8	154.5	194.5
740	81.8	114.1	110.9	154.9	194.9
750	83.1	115.0	112.0	155.2	195.2
760	84.4	115.8	113.0	155.6	195.6
770	85.6	116.6	114.0	156.0	196.0
780	86.8	117.3	115.0	156.4	196.4
790	88.0	118.1	116.0	156.8	196.8
800	89.2	118.9	116.9	157.1	197.1
810	90.3	119.6	117.9	157.5	197.5
820	91.4	120.4	118.8	157.9	197.9
830	92.5	121.1	119.7	158.2	198.2
840	93.5	121.8	120.6	158.6	198.6
850	94.6	122.5	121.4	158.9	198.9
860	95.6	123.2	122.3	159.3	199.3
870	96.6	123.9	123.1	159.6	199.6
880	97.5	124.6	124.0	160.0	200.0
890	98.5	125.3	124.8	160.3	200.3
900	99.4	125.9	125.6	160.7	200.7
910	100.4	126.6	126.4	161.0	201.0
920	101.3	127.2	127.1	161.4	201.4
930	102.1	128.2	127.9	161.7	201.7
940	103.0	129.1	128.7	162.0	202.0
950	103.9	130.1	129.4	162.4	202.4

TABLE B-2. Browns Ferry Unit 1 Composite P-T Curve Values for 12 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-4, 5-8, 5-9 and 5-10

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE B (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE C (°F)
960	104.7	131.0	130.1	162.7	202.7
970	105.6	132.0	130.9	163.0	203.0
980	106.4	132.9	131.6	163.6	203.6
990	107.2	133.8	132.3	164.2	204.2
1000	108.0	134.6	133.0	164.8	204.8
1010	108.7	135.5	133.6	165.5	205.5
1020	109.5	136.3	134.3	166.1	206.1
1030	110.3	137.2	135.0	166.7	206.7
1040	111.0	138.0	135.6	167.3	207.3
1050	111.7	138.8	136.3	167.9	207.9
1060	112.4	139.6	136.9	168.5	208.5
1064	112.7	139.9	137.2	168.7	208.7
1070	113.2	140.4	137.5	169.1	209.1
1080	113.9	141.1	138.2	169.7	209.7
1090	114.6	141.9	138.8	170.2	210.2
1100	115.2	142.6	139.4	170.8	210.8
1105	115.6	143.0	139.7	171.1	211.1
1110	115.9	143.4	140.0	171.4	211.4
1120	116.6	144.1	140.6	171.9	211.9
1130	117.2	144.8	141.2	172.4	212.4
1140	117.9	145.5	141.7	173.0	213.0
1150	118.5	146.2	142.3	173.5	213.5
1160	119.1	146.9	142.9	174.0	214.0
1170	119.8	147.5	143.4	174.6	214.6
1180	120.4	148.2	144.0	175.1	215.1

TABLE B-2. Browns Ferry Unit 1 Composite P-T Curve Values for 12 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-4, 5-8, 5-9 and 5-10

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE B (°F)	UPPER RPV & BELTLINE AT 12 EFPY CURVE C (°F)
1190	121.0	148.9	144.5	175.6	215.6
1200	121.6	149.5	145.1	176.1	216.1
1210	122.2	150.2	145.6	176.6	216.6
1220	122.8	150.8	146.2	177.1	217.1
1230	123.3	151.4	146.7	177.6	217.6
1240	123.9	152.0	147.2	178.1	218.1
1250	124.5	152.6	147.7	178.6	218.6
1260	125.0	153.2	148.2	179.0	219.0
1270	125.6	153.8	148.7	179.5	219.5
1280	126.1	154.4	149.2	180.0	220.0
1290	126.7	155.0	149.7	180.5	220.5
1300	127.2	155.6	150.2	180.9	220.9
1310	127.7	156.1	150.7	181.4	221.4
1320	128.3	156.7	151.2	181.8	221.8
1330	128.8	157.2	151.6	182.3	222.3
1340	129.3	157.8	152.1	182.7	222.7
1350	129.8	158.3	152.6	183.2	223.2
1360	130.3	158.9	153.0	183.6	223.6
1370	130.8	159.4	153.5	184.0	224.0
1380	131.3	159.9	153.9	184.4	224.4
1390	131.8	160.5	154.4	184.9	224.9
1400	132.3	161.0	154.8	185.3	225.3

TABLE B-3. Browns Ferry Unit 1 P-T Curve Values for 16 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-11, 5-12, 5-13, 5-15, 5-16, 5-17 & 5-20

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER VESSEL CURVE A (°F)	16 EFPY BELTLINE CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	16 EFPY BELTLINE CURVE B (°F)
0	68.0	83.0	83.0	68.0	83.0	83.0
10	68.0	83.0	83.0	68.0	83.0	83.0
20	68.0	83.0	83.0	68.0	83.0	83.0
30	68.0	83.0	83.0	68.0	83.0	83.0
40	68.0	83.0	83.0	68.0	83.0	83.0
50	68.0	83.0	83.0	68.0	83.0	83.0
60	68.0	83.0	83.0	68.0	83.0	83.0
70	68.0	83.0	83.0	68.0	83.0	83.0
80	68.0	83.0	83.0	68.0	83.0	83.0
90	68.0	83.0	83.0	68.0	83.0	83.0
100	68.0	83.0	83.0	68.0	83.0	83.0
110	68.0	83.0	83.0	68.0	83.0	83.0
120	68.0	83.0	83.0	68.0	83.0	83.0
130	68.0	83.0	83.0	68.0	85.2	83.0
140	68.0	83.0	83.0	68.0	88.4	83.0
150	68.0	83.0	83.0	68.0	91.2	83.0
160	68.0	83.0	83.0	68.0	93.9	83.0
170	68.0	83.0	83.0	68.0	96.5	83.0
180	68.0	83.0	83.0	68.0	98.9	83.0
190	68.0	83.0	83.0	68.0	101.2	83.0
200	68.0	83.0	83.0	68.0	103.3	83.0
210	68.0	83.0	83.0	68.0	105.3	83.0
220	68.0	83.0	83.0	68.0	107.3	83.0
230	68.0	83.0	83.0	68.0	109.1	83.0

TABLE B-3. Browns Ferry Unit 1 P-T Curve Values for 16 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-11, 5-12, 5-13, 5-15, 5-16, 5-17 & 5-20

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER VESSEL CURVE A (°F)	16 EFPY BELTLINE CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	16 EFPY BELTLINE CURVE B (°F)
240	68.0	83.0	83.0	68.0	110.9	83.0
250	68.0	83.0	83.0	68.0	112.6	83.0
260	68.0	83.0	83.0	68.0	114.2	83.0
270	68.0	83.0	83.0	68.0	115.8	83.0
280	68.0	83.0	83.0	68.0	117.3	83.0
290	68.0	83.0	83.0	68.0	118.8	83.0
300	68.0	83.0	83.0	68.0	120.2	83.0
310	68.0	83.0	83.0	68.0	121.5	83.0
312.5	68.0	83.0	83.0	68.0	121.9	83.0
312.5	68.0	113.0	113.0	68.0	143.0	143.0
320	68.0	113.0	113.0	68.0	143.0	143.0
330	68.0	113.0	113.0	68.0	143.0	143.0
340	68.0	113.0	113.0	68.0	143.0	143.0
350	68.0	113.0	113.0	68.0	143.0	143.0
360	68.0	113.0	113.0	68.0	143.0	143.0
370	68.0	113.0	113.0	68.0	143.0	143.0
380	68.0	113.0	113.0	68.0	143.0	143.0
390	68.0	113.0	113.0	68.0	143.0	143.0
400	68.0	113.0	113.0	68.0	143.0	143.0
410	68.0	113.0	113.0	68.0	143.0	143.0
420	68.0	113.0	113.0	68.0	143.0	143.0
430	68.0	113.0	113.0	68.0	143.0	143.0
440	68.0	113.0	113.0	68.0	143.0	143.0
450	68.0	113.0	113.0	68.0	143.0	143.0
460	68.0	113.0	113.0	68.0	143.0	143.0
470	68.0	113.0	113.0	68.0	143.0	143.0

TABLE B-3. Browns Ferry Unit 1 P-T Curve Values for 16 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-11, 5-12, 5-13, 5-15, 5-16, 5-17 & 5-20

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER VESSEL CURVE A (°F)	16 EFPY BELTLINE CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	16 EFPY BELTLINE CURVE B (°F)
480	68.0	113.0	113.0	70.5	143.0	143.0
490	68.0	113.0	113.0	72.8	143.0	143.0
500	68.0	113.0	113.0	75.0	143.0	143.0
510	68.0	113.0	113.0	77.2	143.0	143.0
520	68.0	113.0	113.0	79.2	143.2	143.0
530	68.0	113.0	113.0	81.2	144.0	143.0
540	68.0	113.0	113.0	83.1	144.8	143.0
550	68.0	113.0	113.0	84.9	145.6	143.0
560	68.0	113.0	113.0	86.7	146.4	143.0
570	68.0	113.0	113.0	88.4	147.1	143.0
580	68.0	113.0	113.0	90.0	147.9	143.0
590	68.0	113.0	113.0	91.6	148.6	143.0
600	68.0	113.0	113.0	93.2	149.1	143.0
610	68.0	113.0	113.0	94.7	149.6	143.0
620	68.0	113.0	113.0	96.1	150.0	143.1
630	68.0	113.0	113.0	97.5	150.4	144.3
640	68.0	113.0	113.0	98.9	150.8	145.5
650	68.2	113.0	113.0	100.2	151.2	146.7
660	69.9	113.0	113.0	101.5	151.7	147.8
670	71.6	113.0	113.0	102.8	152.1	148.9
680	73.2	113.0	113.0	104.1	152.5	149.9
690	74.7	113.0	113.0	105.3	152.9	151.0
700	76.2	113.0	113.0	106.4	153.3	152.0
710	77.7	113.0	113.0	107.6	153.7	153.0
720	79.1	113.0	113.0	108.7	154.1	154.0
730	80.5	113.3	114.1	109.8	154.5	155.0

TABLE B-3. Browns Ferry Unit 1 P-T Curve Values for 16 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-11, 5-12, 5-13, 5-15, 5-16, 5-17 & 5-20

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER VESSEL CURVE A (°F)	16 EFPY BELTLINE CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	16 EFPY BELTLINE CURVE B (°F)
740	81.8	114.1	115.7	110.9	154.9	155.9
750	83.1	115.0	117.2	112.0	155.2	156.9
760	84.4	115.8	118.7	113.0	155.6	157.8
770	85.6	116.6	120.2	114.0	156.0	158.7
780	86.8	117.3	121.6	115.0	156.4	159.6
790	88.0	118.1	123.0	116.0	156.8	160.4
800	89.2	118.9	124.3	116.9	157.1	161.3
810	90.3	119.6	125.6	117.9	157.5	162.1
820	91.4	120.4	126.9	118.8	157.9	162.9
830	92.5	121.1	128.2	119.7	158.2	163.8
840	93.5	121.8	129.4	120.6	158.6	164.6
850	94.6	122.5	130.6	121.4	158.9	165.3
860	95.6	123.2	131.7	122.3	159.3	166.1
870	96.6	123.9	132.9	123.1	159.6	166.9
880	97.5	124.6	134.0	124.0	160.0	167.6
890	98.5	125.3	135.0	124.8	160.3	168.4
900	99.4	125.9	136.1	125.6	160.7	169.1
910	100.4	126.6	137.1	126.4	161.0	169.8
920	101.3	127.2	138.2	127.1	161.4	170.5
930	102.1	127.9	139.2	127.9	161.7	171.2
940	103.0	128.5	140.1	128.7	162.0	171.9
950	103.9	129.1	141.1	129.4	162.4	172.6
960	104.7	129.7	142.0	130.1	162.7	173.3
970	105.6	130.3	143.0	130.9	163.0	173.9
980	106.4	130.9	143.9	131.6	163.4	174.6
990	107.2	131.5	144.8	132.3	163.7	175.2

TABLE B-3. Browns Ferry Unit 1 P-T Curve Values for 16 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-11, 5-12, 5-13, 5-15, 5-16, 5-17 & 5-20

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER VESSEL CURVE A (°F)	16 EFPY BELTLINE CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	16 EFPY BELTLINE CURVE B (°F)
1000	108.0	132.1	145.6	133.0	164.0	175.8
1010	108.7	132.7	146.5	133.6	164.3	176.5
1020	109.5	133.2	147.3	134.3	164.6	177.1
1030	110.3	133.8	148.2	135.0	165.0	177.7
1040	111.0	134.4	149.0	135.6	165.3	178.3
1050	111.7	134.9	149.8	136.3	165.6	178.9
1060	112.4	135.5	150.6	136.9	165.9	179.5
1064	112.7	135.7	150.9	137.2	166.0	179.7
1070	113.2	136.0	151.4	137.5	166.2	180.1
1080	113.9	136.5	152.1	138.2	166.5	180.7
1090	114.6	137.1	152.9	138.8	166.8	181.2
1100	115.2	137.6	153.6	139.4	167.1	181.8
1105	115.6	137.8	154.0	139.7	167.3	182.1
1110	115.9	138.1	154.4	140.0	167.4	182.4
1120	116.6	138.6	155.1	140.6	167.7	182.9
1130	117.2	139.1	155.8	141.2	168.0	183.4
1140	117.9	139.6	156.5	141.7	168.3	184.0
1150	118.5	140.1	157.2	142.3	168.6	184.5
1160	119.1	140.6	157.9	142.9	168.9	185.0
1170	119.8	141.1	158.5	143.4	169.2	185.6
1180	120.4	141.6	159.2	144.0	169.5	186.1
1190	121.0	142.1	159.9	144.5	169.7	186.6
1200	121.6	142.5	160.5	145.1	170.0	187.1
1210	122.2	143.0	161.2	145.6	170.3	187.6
1220	122.8	143.5	161.8	146.2	170.6	188.1
1230	123.3	143.9	162.4	146.7	170.9	188.6

TABLE B-3. Browns Ferry Unit 1 P-T Curve Values for 16 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-11, 5-12, 5-13, 5-15, 5-16, 5-17 & 5-20

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER VESSEL CURVE A (°F)	16 EFPY BELTLINE CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	16 EFPY BELTLINE CURVE B (°F)
1240	123.9	144.4	163.0	147.2	171.2	189.1
1250	124.5	144.8	163.6	147.7	171.4	189.6
1260	125.0	145.3	164.2	148.2	171.7	190.0
1270	125.6	145.7	164.8	148.7	172.0	190.5
1280	126.1	146.2	165.4	149.2	172.2	191.0
1290	126.7	146.6	166.0	149.7	172.5	191.5
1300	127.2	147.0	166.6	150.2	172.8	191.9
1310	127.7	147.5	167.1	150.7	173.1	192.4
1320	128.3	147.9	167.7	151.2	173.3	192.8
1330	128.8	148.3	168.2	151.6	173.6	193.3
1340	129.3	148.7	168.8	152.1	173.8	193.7
1350	129.8	149.1	169.3	152.6	174.1	194.2
1360	130.3	149.6	169.9	153.0	174.4	194.6
1370	130.8	150.0	170.4	153.5	174.6	195.0
1380	131.3	150.4	170.9	153.9	174.9	195.4
1390	131.8	150.8	171.5	154.4	175.1	195.9
1400	132.3	151.2	172.0	154.8	175.4	196.3

TABLE B-4. Browns Ferry Unit 1 Composite P-T Curve Values for 16 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-14, 5-18, 5-19 & 5-20

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE B (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE C (°F)
0	68.0	83.0	68.0	83.0	83.0
10	68.0	83.0	68.0	83.0	83.0
20	68.0	83.0	68.0	83.0	83.0
30	68.0	83.0	68.0	83.0	83.0
40	68.0	83.0	68.0	83.0	83.0
50	68.0	83.0	68.0	83.0	83.0
60	68.0	83.0	68.0	83.0	91.0
70	68.0	83.0	68.0	83.0	98.2
80	68.0	83.0	68.0	83.0	104.2
90	68.0	83.0	68.0	83.0	109.3
100	68.0	83.0	68.0	83.0	113.8
110	68.0	83.0	68.0	83.0	117.9
120	68.0	83.0	68.0	83.0	121.7
130	68.0	83.0	68.0	85.2	125.2
140	68.0	83.0	68.0	88.4	128.4
150	68.0	83.0	68.0	91.2	131.2
160	68.0	83.0	68.0	93.9	133.9
170	68.0	83.0	68.0	96.5	136.5
180	68.0	83.0	68.0	98.9	138.9
190	68.0	83.0	68.0	101.2	141.2
200	68.0	83.0	68.0	103.3	143.3
210	68.0	83.0	68.0	105.3	145.3
220	68.0	83.0	68.0	107.3	147.3

TABLE B-4. Browns Ferry Unit 1 Composite P-T Curve Values for 16 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-14, 5-18, 5-19 & 5-20

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE B (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE C (°F)
230	68.0	83.0	68.0	109.1	149.1
240	68.0	83.0	68.0	110.9	150.9
250	68.0	83.0	68.0	112.6	152.6
260	68.0	83.0	68.0	114.2	154.2
270	68.0	83.0	68.0	115.8	155.8
280	68.0	83.0	68.0	117.3	157.3
290	68.0	83.0	68.0	118.8	158.8
300	68.0	83.0	68.0	120.2	160.2
310	68.0	83.0	68.0	121.5	161.5
312.5	68.0	83.0	68.0	121.9	161.9
312.5	68.0	113.0	68.0	143.0	183.0
320	68.0	113.0	68.0	143.0	183.0
330	68.0	113.0	68.0	143.0	183.0
340	68.0	113.0	68.0	143.0	183.0
350	68.0	113.0	68.0	143.0	183.0
360	68.0	113.0	68.0	143.0	183.0
370	68.0	113.0	68.0	143.0	183.0
380	68.0	113.0	68.0	143.0	183.0
390	68.0	113.0	68.0	143.0	183.0
400	68.0	113.0	68.0	143.0	183.0
410	68.0	113.0	68.0	143.0	183.0
420	68.0	113.0	68.0	143.0	183.0
430	68.0	113.0	68.0	143.0	183.0
440	68.0	113.0	68.0	143.0	183.0
450	68.0	113.0	68.0	143.0	183.0
460	68.0	113.0	68.0	143.0	183.0

TABLE B-4. Browns Ferry Unit 1 Composite P-T Curve Values for 16 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-14, 5-18, 5-19 & 5-20

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE B (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE C (°F)
470	68.0	113.0	68.0	143.0	183.0
480	68.0	113.0	70.5	143.0	183.0
490	68.0	113.0	72.8	143.0	183.0
500	68.0	113.0	75.0	143.0	183.0
510	68.0	113.0	77.2	143.0	183.0
520	68.0	113.0	79.2	143.2	183.2
530	68.0	113.0	81.2	144.0	184.0
540	68.0	113.0	83.1	144.8	184.8
550	68.0	113.0	84.9	145.6	185.6
560	68.0	113.0	86.7	146.4	186.4
570	68.0	113.0	88.4	147.1	187.1
580	68.0	113.0	90.0	147.9	187.9
590	68.0	113.0	91.6	148.6	188.6
600	68.0	113.0	93.2	149.1	189.1
610	68.0	113.0	94.7	149.6	189.6
620	68.0	113.0	96.1	150.0	190.0
630	68.0	113.0	97.5	150.4	190.4
640	68.0	113.0	98.9	150.8	190.8
650	68.2	113.0	100.2	151.2	191.2
660	69.9	113.0	101.5	151.7	191.7
670	71.6	113.0	102.8	152.1	192.1
680	73.2	113.0	104.1	152.5	192.5
690	74.7	113.0	105.3	152.9	192.9
700	76.2	113.0	106.4	153.3	193.3
710	77.7	113.0	107.6	153.7	193.7
720	79.1	113.0	108.7	154.1	194.1

TABLE B-4. Browns Ferry Unit 1 Composite P-T Curve Values for 16 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-14, 5-18, 5-19 & 5-20

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE B (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE C (°F)
730	80.5	114.1	109.8	155.0	195.0
740	81.8	115.7	110.9	155.9	195.9
750	83.1	117.2	112.0	156.9	196.9
760	84.4	118.7	113.0	157.8	197.8
770	85.6	120.2	114.0	158.7	198.7
780	86.8	121.6	115.0	159.6	199.6
790	88.0	123.0	116.0	160.4	200.4
800	89.2	124.3	116.9	161.3	201.3
810	90.3	125.6	117.9	162.1	202.1
820	91.4	126.9	118.8	162.9	202.9
830	92.5	128.2	119.7	163.8	203.8
840	93.5	129.4	120.6	164.6	204.6
850	94.6	130.6	121.4	165.3	205.3
860	95.6	131.7	122.3	166.1	206.1
870	96.6	132.9	123.1	166.9	206.9
880	97.5	134.0	124.0	167.6	207.6
890	98.5	135.0	124.8	168.4	208.4
900	99.4	136.1	125.6	169.1	209.1
910	100.4	137.1	126.4	169.8	209.8
920	101.3	138.2	127.1	170.5	210.5
930	102.1	139.2	127.9	171.2	211.2
940	103.0	140.1	128.7	171.9	211.9
950	103.9	141.1	129.4	172.6	212.6
960	104.7	142.0	130.1	173.3	213.3
970	105.6	143.0	130.9	173.9	213.9
980	106.4	143.9	131.6	174.6	214.6

TABLE B-4. Browns Ferry Unit 1 Composite P-T Curve Values for 16 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-14, 5-18, 5-19 & 5-20

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE B (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE C (°F)
990	107.2	144.8	132.3	175.2	215.2
1000	108.0	145.6	133.0	175.8	215.8
1010	108.7	146.5	133.6	176.5	216.5
1020	109.5	147.3	134.3	177.1	217.1
1030	110.3	148.2	135.0	177.7	217.7
1040	111.0	149.0	135.6	178.3	218.3
1050	111.7	149.8	136.3	178.9	218.9
1060	112.4	150.6	136.9	179.5	219.5
1064	112.7	150.9	137.2	179.7	219.7
1070	113.2	151.4	137.5	180.1	220.1
1080	113.9	152.1	138.2	180.7	220.7
1090	114.6	152.9	138.8	181.2	221.2
1100	115.2	153.6	139.4	181.8	221.8
1105	115.6	154.0	139.7	182.1	222.1
1110	115.9	154.4	140.0	182.4	222.4
1120	116.6	155.1	140.6	182.9	222.9
1130	117.2	155.8	141.2	183.4	223.4
1140	117.9	156.5	141.7	184.0	224.0
1150	118.5	157.2	142.3	184.5	224.5
1160	119.1	157.9	142.9	185.0	225.0
1170	119.8	158.5	143.4	185.6	225.6
1180	120.4	159.2	144.0	186.1	226.1
1190	121.0	159.9	144.5	186.6	226.6
1200	121.6	160.5	145.1	187.1	227.1
1210	122.2	161.2	145.6	187.6	227.6
1220	122.8	161.8	146.2	188.1	228.1

TABLE B-4. Browns Ferry Unit 1 Composite P-T Curve Values for 16 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 15 °F/hr for Curve A
For Figures 5-14, 5-18, 5-19 & 5-20

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE B (°F)	UPPER RPV & BELTLINE AT 16 EFPY CURVE C (°F)
1230	123.3	162.4	146.7	188.6	228.6
1240	123.9	163.0	147.2	189.1	229.1
1250	124.5	163.6	147.7	189.6	229.6
1260	125.0	164.2	148.2	190.0	230.0
1270	125.6	164.8	148.7	190.5	230.5
1280	126.1	165.4	149.2	191.0	231.0
1290	126.7	166.0	149.7	191.5	231.5
1300	127.2	166.6	150.2	191.9	231.9
1310	127.7	167.1	150.7	192.4	232.4
1320	128.3	167.7	151.2	192.8	232.8
1330	128.8	168.2	151.6	193.3	233.3
1340	129.3	168.8	152.1	193.7	233.7
1350	129.8	169.3	152.6	194.2	234.2
1360	130.3	169.9	153.0	194.6	234.6
1370	130.8	170.4	153.5	195.0	235.0
1380	131.3	170.9	153.9	195.4	235.4
1390	131.8	171.5	154.4	195.9	235.9
1400	132.3	172.0	154.8	196.3	236.3

APPENDIX C

OPERATING AND TEMPERATURE MONITORING REQUIREMENTS

C.1 NON-BELTLINE MONITORING DURING PRESSURE TESTS

It is likely that, during leak and hydrostatic pressure testing, the bottom 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. By using a bottom head curve, the required test temperature at the bottom head could be lower than the required test temperature at the beltline, avoiding the necessity of heating the bottom head to the same requirements of the vessel beltline.

One condition on monitoring the bottom 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 that 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. Thermocouples on the RPV flange to shell junction outside surface should be used to monitor compliance with upper vessel curve. Thermocouples on the bottom head outside surface should be used to monitor compliance with bottom head curves. A description of these measurements is given in GE SIL 430, attached in Appendix D. First, however, it should be determined whether there are significant temperature differences between the beltline region and the bottom head region.

C.2 DETERMINING WHICH CURVE TO FOLLOW

The following subsections outline the criteria needed for determining which curve is governing during different situations. The application of the P-T curves and some of the assumptions inherent in the curves to plant operation is dependent on the proper monitoring of vessel temperatures. A discussion of monitoring of vessel temperatures can be found in Section 4 of the pressure-temperature curve report prepared in 1989 [1].

C.2.1 Curve A: Pressure Test

Curve A should be used during pressure tests at times when the coolant temperature is changing by ≤15°F per hour. If the coolant is experiencing a higher heating or cooling rate in preparation for or following a pressure test, Curve B applies.

C.2.2 Curve B: Non-Nuclear Heatup/Cooldown

Curve B should be used whenever Curve A or Curve C do not apply. In other words, the operator must follow this curve during times when the coolant is heating or cooling faster than 15°F per hour during a hydrotest and when the core is not critical.

C.2.3 Curve C: Core Critical Operation

The operator must comply with this curve whenever the core is critical. An exception to this principle is for low-level physics tests; Curve B must be followed during these situations.

C.3 REACTOR OPERATION VERSUS OPERATING LIMITS

For most reactor operating conditions, coolant pressure and temperature are at saturation conditions, which are well into the acceptable operating area (to the right of the P-T curves). The operations where P-T curve compliance is typically monitored closely are planned events, such as vessel bolt-up, leakage testing and startup/shutdown operations, where operator actions can directly influence vessel pressures and temperatures.

The most severe unplanned transients relative to the P-T curves are those that result from SCRAMs, which sometimes include recirculation pump trips. Depending on operator responses following pump trip, there can be cases where stratification of colder water in the bottom head occurs while the vessel pressure is still relatively high. Experience with such events has shown that operator action is necessary to avoid P-T curve exceedance, but there is adequate time for operators to respond.

In summary, there are several operating conditions where careful monitoring of P-T conditions against the curves is needed:

- Head flange bolt-up
- Leakage test (Curve A compliance)
- Startup (coolant temperature change of less than or equal to 100°F in one hour period heatup)
- Shutdown (coolant temperature change of less than or equal to 100°F in one hour period cooldown)
- Recirculation pump trip, bottom head stratification (Curve B compliance)

APPENDIX C REFERENCES:

1. T.A. Caine, "Pressure-Temperature Curves Per Regulatory Guide 1.99, Revision 2 for the Dresden and Quad Cities Nuclear Power Stations", SASR 89-54, Revision 1, August 1989.

APPENDIX D

GE SIL 430

September 27, 1985 SIL No. 430

REACTOR PRESSURE VESSEL TEMPERATURE MONITORING

Recently, several BWR owners with plants in initial startup have had questions concerning primary and alternate reactor pressure vessel (RPV) temperature monitoring measurements for complying with RPV brittle fracture and thermal stress requirements. As such, the purpose of this Service Information Letter is to provide a summary of RPV temperature monitoring measurements, their primary and alternate uses and their limitations (See the attached table). Of basic concern is temperature monitoring to comply with brittle fracture temperature limits and for vessel thermal stresses during RPV heatup and cooldown. General Electric recommends that BWR owners/operators review this table against their current practices and evaluate any inconsistencies.

TABLE OF RPV TEMPERATURE MONITORING MEASUREMENTS (Typical)

Measurement	Use	Limitations
Steam dome saturation temperature as determined from main steam instrument line pressure	Primary measurement above 212°F for Tech Spec 100°F/hr heatup and cooldown rate.	Must convert saturated steam pressure to temperature.
Recirc suction line coolant temperature.	Primary measurement below 212°F for Tech Spec 100°F/hr heatup and cooldown rate.	Must have recirc flow. Must comply with SIL 251 to avoid vessel stratification.
	Alternate measurement above 212°F.	When above 212°F need to allow for temperature variations (up to 10-15°F lower than steam dome saturation temperature) caused primarily by FW flow variations.

TABLE OF RPV TEMPERATURE MONITORING MEASUREMENTS (CONTINUED)

(Typical)

Measurement	Use	Limitations
	Alternate measurement for RPV drain line temperature (can use to comply with delta T limit between steam dome saturation temperature and bottom head drain line temperature).	
RHR heat exchanger inlet coolant temperature	Alternate measurement for Tech Spec 100°F/hr cooldown rate when in shutdown cooling mode.	Must have previously correlated RHR inlet coolant temperature versus RPV coolant temperature.
RPV drain line coolant temperature	Primary measurement to comply with Tech Spec delta T limit between steam dome saturated temp and drain line coolant temperature.	Must have drain line flow. Otherwise, lower than actual temperature and higher delta T's will be indicated Delta T limit is 100°F for BWR/6s and 145°F for earlier BWRs.
	Primary measurement to comply with Tech Spec brittle fracture limits during cooldown.	Must have drain line flow. Use to verify compliance with Tech Spec minimum metal temperature/reactor pressure curves (using drain line temperature to represent bottom head metal temperature).
	Alternate information only measurement for bottom head inside/ outside metal surface temperatures.	Must compensate for outside metal temperature lag during heatup/cooldown. Should have drain line flow.

TABLE OF RPV TEMPERATURE MONITORING MEASUREMENTS (CONTINUED)

(Typical)

Measurement	Use	Limitations
Closure head flanges outside surface T/Cs	Primary measurement for BWR/6s to comply with Tech Spec brittle fracture metal temperature limit for head bolt-up.	Use for metal (not coolant) temperature. Install temporary T/Cs for alternate measurement, if required.
	One of two primary measurements for BWR/6s for hydro test.	
RPV flange-to-shell junction outside surface T/Cs	Primary measurement for BWRs earlier than 6s to comply with Tech Spec brittle fracture metal temperature limit for head bolt-up.	Use for metal (not coolant) temperature. Response faster than closure head flange T/Cs.
	One of two primary measurements for BWRs earlier than 6s for hydro test. Preferred in lieu of closure head flange T/Cs if available.	Use RPV closure head flange outside surface as alternate measurement.
RPV shell outside surface T/Cs	Information only.	Slow to respond to RPV coolant changes. Not available on BWR/6s.
Top head outside surface T/Cs	Information only.	Very slow to respond to RPV coolant changes. Not available on BWR/6s.

TABLE OF RPV TEMPERATURE MONITORING MEASUREMENTS (CONTINUED)

(Typical)

Measurement	Use	Limitations
Bottom head outside surface T/Cs	1 of 2 primary measurements to comply with Tech Spec brittle fracture metal temperature limit for hydro test.	Should verify that vessel stratification is not present for vessel hydro. (see SIL No. 251).
	Primary measurement to comply with Tech Spec brittle fracture metal temperature limits during heatup.	Use during heatup to verify compliance with Tech Spec metal temperature/reactor pressure curves.

Note: RPV vendor specified metal T limits for vessel heatup and cooldown should be checked during initial plant startup tests when initial RPV vessel heatup and cooldown tests are run.

Product Reference: B21 Nuclear Boiler

Prepared By: A.C. Tsang

Approved for Issue:
B.H. Eldridge, Mgr.
Service Information
and Analysis

Issued By:
D.L. Allred, Manager
Customer Service Information

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APPENDIX E

DETERMINATION OF BELTLINE REGION AND IMPACT ON FRACTURE TOUGHNESS

10CFR50, Appendix G defines the beltline region of the reactor vessel as follows:

"The region of the reactor vessel (shell material including welds, heat affected zones, and plates or forgings) that directly surrounds the effective height of the active core and adjacent regions of the reactor vessel that are predicted to experience sufficient neutron radiation damage."

To establish the value of peak fluence for identification of beltline materials (as discussed above), the 10CFR50 Appendix H fluence value used to determine the need for a surveillance program was used; the value specified is a peak fluence (E>1 MEV) of 1.0e17 n/cm^2. Therefore, if it can be shown that no nozzles are located where the peak neutron fluence is expected to exceed or equal 1.0e17 n/cm^2, then it can be concluded that all reactor vessel nozzles are outside the beltline region of the reactor vessel, and do not need to be considered in the P-T curve evaluation.

The following dimensions are obtained from the referenced drawings and are specified as the distance above vessel "0":

Shell # 2 - Top of Active Fuel (TAF)	366.3" [1]
Shell # 1 - Bottom of Active Fuel (BAF)	216.3" [1,2]
Centerline of Recirculation Outlet Nozzle N1 in Shell # 1	161.5" [2,3]
Top of Recirculation Outlet Nozzle N1 in Shell # 1	188.0" [4]
Centerline of Recirculation Inlet Nozzle N2 in Shell # 1	181.0" [2,3]
Top of Recirculation Inlet Nozzle N2 in Shell # 1	193.3" [4]
Centerline of Instrumentation Nozzle N16 in Shell #2	366.0" [2,3]
Girth Weld between Shell Ring #2 and Shell Ring #3	391.5" [1,5]

From [2], it is obvious that the recirculation inlet and outlet nozzles are closest to the beltline region (the top of the recirculation inlet nozzle is ~23" below BAF and the top of the recirculation outlet nozzle is ~28" below BAF). As shown in [2,3], the N16 Instrumentation Nozzle is contained within the core beltline region; however, this 2" nozzle is fabricated from Alloy 600 materials. As noted in Table A-2, components

made from Alloy 600 and/or having a diameter of less than 2.5" do not require fracture toughness evaluations. No other nozzles are within the BAF-TAF region of the reactor vessel. The girth weld between Shell Rings #2 and #3 is ~25" above TAF. Therefore, if it can be shown that the peak fluence at these locations is less than 1.0e17 n/cm^2, it can be safely concluded that all nozzles and welds, other than those included in Tables 4-4 and 4-5, are outside the beltline region of the reactor vessel.

Based on the axial flux profile for EPU, which bounds the pre-EPU axial flux profile, the RPV fluence drops to less than 1.0e17 n/cm^2 at ~5" below the BAF and at ~7" above TAF. The beltline region considered in the development of the P-T curves is adjusted to include the additional 7" above the active fuel region and the additional 5" below the active fuel region. This adjusted beltline region extends from 211.3" to 373.3" above reactor vessel "0" for 16 EFPY.

Based on the above, it is concluded that none of the Browns Ferry Unit 1 reactor vessel plates, nozzles, or welds, other than those included in Tables 4-4 and 4-5, are in the beltline region.

APPENDIX E REFERENCES:

1. J. Valente (TVA) to Dale Porter (GE), "Browns Ferry Nuclear Plant (BFN) - Pressure-Temperature Curves Design Input Request (DIR) – Transmittal of DIR Rev. 0", July 17, 2003 (TVA RIMS No. W83 030717 001).
2. Drawing 886D499, Revision 12, "Reactor Vessel", General Electric Company, GENE, San Jose, California.
3. Drawing #254185F, Revision 11, "General Outline", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-042).
4. Drawing #122864E, Revision 4, "Recirculation Nozzles", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-041).
5. Drawing #24187F, Revision 11, "Vessel Sub-Assembly", Babcock & Wilcox Company, Mt. Vernon, Indiana (GE VPF #1805-059).

APPENDIX F

EQUIVALENT MARGIN ANALYSIS (EMA) FOR UPPER SHELF ENERGY (USE)

Paragraph IV.B of 10CFR50 Appendix G [1] sets limits on the upper shelf energy of the beltline materials. The USE must remain above 50 ft-lb at all times during plant operation, assumed here to be 16 EFPY. Calculations of 16 EFPY USE, using Regulatory Guide 1.99, Revision 2 [2] methods and BWROG Equivalent Margin Analyses [3, 4] methods are summarized in Tables F-1 and F-2.

Unirradiated upper shelf data was not available for all of the material heats in the Browns Ferry Unit 1 beltline region. Therefore, Browns Ferry Unit 1 is evaluated to verify that the BWROG EMA is applicable. The USE decrease prediction values from Regulatory Guide 1.99, Revision 2 are used for the beltline components as shown in Tables F-1 and F-2. These calculations are based upon the 16 EFPY peak 1/4T fluence as provided in Tables 4-4 and 4-5. Surveillance capsule data is not available for Browns Ferry Unit 1.

Based on the results presented in Tables F-1 and F-2, the USE EMA values for the Browns Ferry Unit 1 reactor vessel beltline materials remain within the limits of Regulatory Guide 1.99, Revision 2 and 10CFR50 Appendix G for 16 EFPY of operation.

Table F-1

Equivalent Margin Analysis

Plant Applicability Verification Form for Browns Ferry Unit 1

For 16 EFPY (including Extended Power Uprate)

BWR/3-6 PLATE

Surveillance Plate USE:

%Cu = N/A

1st Capsule Fluence = N/A

1st Capsule Measured % Decrease = N/A (Charpy Curves)

1st Capsule R.G. 1.99 Predicted % Decrease = N/A (R.G. 1.99, Figure 2)

Limiting Beltline Plate (Heat B5864-1) USE:

%Cu = 0.15

16 EFPY 1/4T Fluence = 3.96×10^{17} n/cm^2

R.G. 1.99 Predicted % Decrease = 11.5 (R.G. 1.99, Figure 2)

Adjusted % Decrease = N/A (R.G. 1.99, Position 2.2)

11.5% ≤ 21%, so vessel plates are bounded by equivalent margin analysis

Table F-2

Equivalent Margin Analysis

Plant Applicability Verification Form for Browns Ferry Unit 1

For 16 EFPY (including Extended Power Uprate)

BWR/2-6 WELD

Surveillance Weld USE:

%Cu = N/A

1st Capsule Fluence = N/A

1st Capsule Measured % Decrease = N/A (Charpy Curves)

1st Capsule R.G. 1.99 Predicted % Decrease = N/A (R.G. 1.99, Figure 2)

Limiting Beltline Weld (Heat 406L44) USE:

%Cu = 0.27

16 EFPY 1/4T Fluence = 3.96×10^{17} n/cm^2

R.G. 1.99 Predicted % Decrease = 20 (R.G. 1.99, Figure 2)

Adjusted % Decrease = N/A (R.G. 1.99, Position 2.2)

20% ≤ 34%, so vessel welds are bounded by equivalent margin analysis

APPENDIX F REFERENCES:

1. "Fracture Toughness Requirements", Appendix G to Part 50 of Title 10 of the Code of Federal Regulations, December 1995.
2. "Radiation Embrittlement of Reactor Vessel Materials," USNRC Regulatory Guide 1.99, Revision 2, May 1988.
3. J.T. Wiggins (NRC) to L.A. England (Gulf States Utilities Co.), "Acceptance for Referencing of Topical Report NEDO-32205, Revision 1, '10CFR50 Appendix G Equivalent Margin Analysis for Low Upper Shelf Energy in BWR/2 Through BWR/6 Vessels'", December 8, 1993.
4. L.A. England (BWR Owners' Group) to Daniel G. McDonald (USNRC), "BWR Owners' Group Topical Report on Upper Shelf Energy Equivalent Margin Analysis – Approved Version", BWROG-94037, March 21, 1994.