Attachment 2 to
NG-03-0608
August 18, 2003

Revised Non-Proprietary

GE Report -

GE-NE-A22-00100-08-01a-R2

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Engineering and Technology
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175 Curtner Avenue
San Jose, CA 95125

GE-NE-A22-00100-08-01a-R2
Revision 2
DRF 0000-0018-2033
Class I
August 2003

Non-Proprietary Version

Pressure-Temperature Curves For Duane Arnold Energy Center

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REPORT REVISION STATUS

Revision	Purpose
1	The report was revised to incorporate a Regulatory Guide 1.190 compliant fluence.
2	The report was revised to correct proprietary markings and to clarify fluence information, N2 nozzle beltline calculations, and Figure 4-2 and the associated discussion.

**IMPORTANT NOTICE REGARDING
CONTENTS OF THIS REPORT
PLEASE READ CAREFULLY**

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 2000 [1]. The P-T curve methodology includes the following: 1) The incorporation of ASME Code Case N-640. 2) The use of the M_m calculation in the 1995 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 $T\text{-}RT_{NDT}$. This report incorporates a fluence calculated in accordance with the GE Licensing Topical Report NEDC-32983P, which has been approved by the NRC in SER [14], and is in compliance with Regulatory Guide 1.190.

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 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]. 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 20°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.

Composite P-T curves were generated for each of the Pressure Test, Core Not Critical and Core Critical conditions at 32 effective full power years (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 25 and 32 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 25 EFPY.

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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 25 and 32 effective full power years (EFPY). The P-T curves are provided in Section 5.0 and a tabulation of the curves is included in Appendix B. The P-T curves incorporate a fluence calculated in accordance with the GE Licensing Topical Report NEDC-32983P, which has been approved by the NRC in SER [14], and is in compliance with Regulatory Guide 1.190. This fluence is discussed in Section 4.2.1.2 and Appendix G.

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 2000 [1]. The P-T curve methodology includes the following: 1) The incorporation of ASME Code Case N-640 [4]. 2) The use of the M_m calculation in the 1995 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} of Figure A-4200-1 of Appendix A in lieu of Figure G-2210-1 in Appendix G to determine T-RT_{NDT}. 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} is 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 25 and 32 EFPY are included in Section 4.2. The 32 EFPY peak ID fluence value of

4.17×10^{18} n/cm^2 used in this report is discussed in Section 4.2.1.2 (also, see Appendix G). 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 the discontinuities.

Guidelines and requirements for operating and temperature monitoring are included in Appendix C. GE SIL 430, a GE service information letter regarding Reactor Pressure Vessel Temperature Monitoring is included in Appendix D. Appendix E demonstrates that all reactor vessel nozzles (other than the N16 Instrumentation and N2 Recirculation Inlet nozzles) are outside the beltline region. Appendix F provides the calculation for equivalent margin analysis (EMA) for upper shelf energy (USE).

A discussion of the effect of a change in irradiation on the embrittlement of the RPV materials due to the increased flux associated with an increase in core thermal power from 1658 MW_{th} to 1912 MW_{th}, which is 115% of current rated thermal power, is included in Appendix G. [[

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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 2000 [1]. The P-T curves in this report incorporate a fluence calculated in accordance with the GE Licensing Topical Report NEDC-32983P, which has been approved by the NRC in SER [14], and is in compliance with Regulatory Guide 1.190. This fluence is discussed in Section 4.2.1.2 and Appendix G. A detailed description of the P-T curve bases is included in Section 4.3. The P-T curve methodology includes the following: 1) The incorporation of ASME Code Case N-640. 2) The use of the M_m calculation in the 1995 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}. 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 Duane Arnold 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 (other than the N16 Instrumentation and N2 Recirculation Inlet nozzles) are outside the beltline region. Appendix F provides the calculation for equivalent margin analysis (EMA) for upper shelf energy (USE).

A discussion of the effect of a change in irradiation on the embrittlement of the RPV materials due to the increased flux associated with an increase in core thermal power from 1658 MW_{th} to 1912 MW_{th}, which is 115% of current rated thermal power, is included in Appendix G. [[

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3.0 ANALYSIS ASSUMPTIONS

The following assumptions are made for this analysis:

For end-of-license (32 EFPY) fluence an 80% capacity factor is used to determine the EFPY for a 40-year plant life. The 80% capacity factor is based on the objective to have BWR's available for full power production 80% of the year (refueling outages, etc. account for ~20% of the year).

The shutdown margin is calculated for a water temperature of 68°F, as defined in the Duane Arnold Technical Specification, Section 1.1.

For the N2 Recirculation Inlet and N16 Instrumentation nozzles, the chemistry value used in the analysis was assumed to be 0.18% copper; this is explained in Tables 4-3 and 4-4.

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 is 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 Duane Arnold 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, weld, HAZ, and forging, and bolting material LST are summarized in the remainder of this section.

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 Duane Arnold 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 Duane Arnold beltline plate heat C6794-2 in the upper shell course, the lowest Charpy energy and test temperature from the CMTRs is 33.0 ft-lb. at 10°F. The estimated 50 ft-lb longitudinal test temperature is:

$$T_{50L} = 10°F + [(50 - 33) \text{ ft-lb.} * 2°F/\text{ft-lb.}] = 44°F$$

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,

$$T_{50T} = 44°F + 30°F = 74°F$$

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 was listed in the CMTR; the NDT for the case above was 10°F. Thus, the initial RT_{NDT} for plate heat C6794-2 was 14°F.

For the Duane Arnold beltline weld heat 432Z0471 (contained in the lower shell course), the CVN results are used to calculate the initial RT_{NDT}. The 50 ft-lb test temperature is applicable to the weld material, but the 30°F adjustment to convert longitudinal data to transverse data is not applicable to weld material. Heat 432Z0471 has a lowest Charpy energy of 100 ft-lb at 10°F as recorded in weld qualification records. Therefore,

$$T_{50T} = 10°F - 60°F = -50°F.$$

The initial RT_{NDT} is the greater of nil-ductility transition temperature (NDT) or (T_{50T} - 60°F). For Duane Arnold, the dropweight testing to establish NDT was not recorded for most weld materials. GE procedure requires that, when no NDT is available for the weld, the resulting RT_{NDT} should be –50°F or higher. The value of (T_{50T} – 60°F) in this example is -50°F; therefore, the initial RT_{NDT} was -50°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 feedwater nozzle at Duane Arnold (Heat Q2Q6VW), the NDT is 40°F and the lowest CVN data is 87 ft-lb at 40°F. The corresponding value of (T_{50T} – 60°F) is:

$$(T_{50T} - 60°F) = 40°F + 30°F - 60°F = 10°F.$$

Therefore, the initial RT_{NDT} is the greater of nil-ductility transition temperature (NDT) or (T_{50T} - 60°F), which is 40°F.

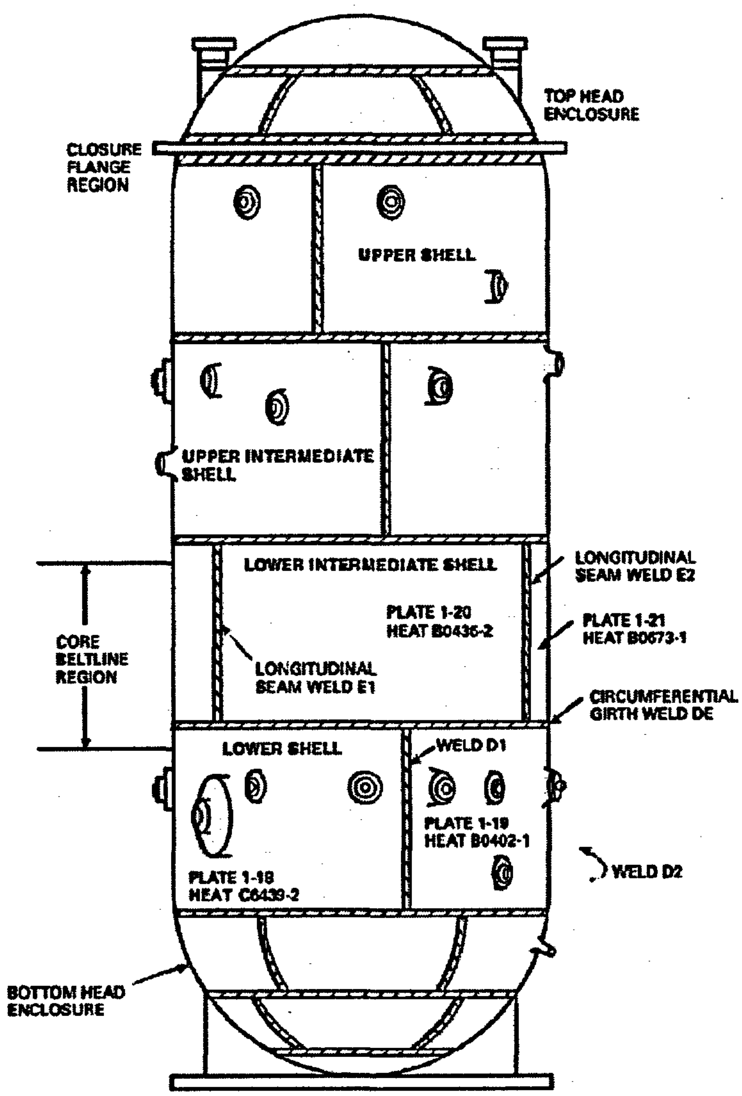
In the bottom head region of the vessel, the vessel plate method is applied for estimating RT_{NDT}. For the center plate of Duane Arnold (Heat B0390-3), the NDT is 40°F and the lowest CVN data was 71 ft-lb at 40°F. The corresponding value of (T_{50T} - 60°F) was:

$$(T_{50T} - 60°F) = 40°F + 30°F - 60°F = 10°F.$$

Therefore, the initial RT_{NDT}, being the greater of (T_{50T} - 60°F) or the NDT, was 40°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 (as discussed in Section 4.3.2.3) is the LST for the bolting materials. Charpy data for the Duane Arnold closure studs do not meet the 45 ft-lb, 25 MLE requirement at 10°F, but the CVN energy was greater than 30 ft-lb. Therefore, the LST for the bolting material is 70°F. The highest RT_{NDT} in the closure flange region is 14°F, for the vessel upper shell (Shell Ring #4) materials. Thus, the higher of the LST and the RT_{NDT} +60°F is 74°F, the boltup limit in the closure flange region.

The initial RT_{NDT} values for the Duane Arnold reactor vessel (refer to Figure 4-1 for the Duane Arnold schematic) materials are listed in Tables 4-1 and 4-2. 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 and 4-2 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 Duane Arnold RPV Showing Arrangement of Vessel Plates and Welds

Table 4-1: RT_{NDT} Values for Duane Arnold Vessel Materials

COMPONENT	HEAT	TEST TEMP. (°F)	Trans or Long	CHARPY ENERGY (FT-LB)			$(T_{50T}-60)$ (°F)	DROP WEIGHT NDT	RT_{NDT} (°F)
PLATES & FORGINGS:									
Top Head & Flange									
Shell Flange (Vessel) Piece 1-26	BYA242	10	L	114	96	87	-20	10	10
Head Flange Piece 1-27	BDD244	10	L	69	99	90	-20	10	10
Top Head Dome Piece 1-34	B0390-1	40	L	96	149	111	10	40	40
Top Head Side Plates									
Pieces 1-28 thru 1-30	C6491-3A	10	L	77	84	107	-20	10	10
Pieces 1-31 thru 1-33	C6491-3B	10	L	131	145	132	-20	10	10
Shell Courses									
Upper Shell									
Ring #4 Piece 1-24	C6794-2	10	L	37	44	33	14	10	14
Ring #4 Piece 1-25	C7090-1	10	L	61	67	79	-20	10	10
Upper Int. Shell									
Ring #3 Piece 1-22	B0402-2	40	L	78	88	65	10	40	40
Ring #3 Piece 1-23	C6491-1	40	L	103	101	115	10	40	40
Low-Int. Shell									
Ring #2 Piece 1-20	B0436-2	40	L	57	64	62	10	-30	10
Ring #2 Piece 1-21	B0673-1	40	L	99	104	121	10	-30	10
Lower Shell									
Ring #1 Piece 1-18	C6439-2	40	L	36	48	43	38	40	40
Ring #1 Piece 1-19	B0402-1	40	L	83	85	72	10	40	40
Bottom Head									
Center Plate									
Piece 1-1	B0390-3	40	L	90	77	71	10	40	40
Piece 1-2A and 1-2B	B0400-3	40	L	92	98	88	10	40	40
Piece 1-3	C6491-2A	40	L	63	68	74	10	40	40
Side Plate									
Pieces 1-4 thru 1-6	B0400-1	40	L	33	40	41	44	40	44
Pieces 1-7 thru 1-9	B0400-2	40	L	91	87	72	10	40	40
SUPPORT SKIRT									
PC MK 1-10 TO 17	B0390-1	40	L	96	149	111	10	40	40
STABILIZER BRACKETS									
PC MK 84-1	B0390-1	40	L	96	149	111	10	40	40
PC MK 84-2	C4629-2	10	L	79	68	49	-18	10	10
SHROUD SUPPORT									
PC MK 48-1-1,2,4	L51590-2							40	40
PC MK 48-1-3	L51589-1A							40	40
PC MK 48-2	L51589							40	40
PC MK 9-1	L51377							40	40

Table 4-2: RT_{NDT} Values for Duane Arnold Nozzle, Weld, & Bolting Materials

COMPONENT	HEAT	TEST TEMP. (°F)	Trans or Long	CHARPY ENERGY (FT-LB)			(T_{50T}-60) (°F)	DROP WEIGHT NDT	RT_{NDT} (°F)
NOZZLES:									
N1 Recirc. Outlet Nozzle	Q2Q17W	40	L	85	80	83	10	40	40
N2 Recirc Inlet Nozzle	Q2Q6VW	40	L	105	54	133	10	40	40
N3 Steam Outlet Nozzle	Q2Q11VW	40	L	92	89	99	10	40	40
N4 Feedwater Nozzle	Q2Q6VW	40	L	87	102	110	10	40	40
N5 Core Spray Nozzle	Q2Q6VW	40	L	86	104	103	10	40	40
N6 Head Spray & Instrumentation Nozzle	Q2Q1VW	40	L	132	99	73	10	40	40
N7 Vent Nozzle Piece 39-1	Q2Q3VW	40	L	86	74	75	10	40	40
N8 Jet Pump Instrumentation Nozzle	Q2Q1VW	40	L	109	48	60	14	40	40
N9 CRD Hyd Sys Rtn Nozzle	Q2Q1VW	40	L	109	48	60	14	40	40
N10 Core Diff Pressure Nozzle	E20VW	40	L	38	60	26	58	40	58
N11 Instrumentation Nozzle	Q2Q5VW	40	L	44	42	36	38	40	40
N12 Instrumentation Nozzle	E20VW	40	L	38	60	26	58	40	58
N13 Seal Leak Detection Nozzle	Q1Q9W	40	L	33	40	20	70	40	70
N14 Seal Leak Detection Nozzle	Q1Q9W	40	L	33	40	20	70	40	70
N15 Drain Nozzle	Q1Q2W	40	L	27	19	18	74	40	74
N16 Instrumentation Nozzle	Q2Q5VW	40	L	44	42	36	38	40	40
WELDS:									
Vertical Welds									
Shell Ring #1	432Z4521	10	n/a	83	94	96	-50		-50
Shell Ring #2	432Z4521	10	n/a	83	94	96	-50		-50
Girth Welds									
Ring #1 to Ring #2	07L669	10	n/a	50	50	54	-50		-50
STUDS:	15045 (a)	10	n/a	48	49	48	70	OK	
Piece 23-1	15966	10	n/a	56	56	58	10	OK	
NUTS and WASHERS:									
Piece 70-1 and 70-2	88230 (a)	10	n/a	40	37	38	70	OK	
BUSHINGS:	88230 (a)	10	n/a	40	37	38	70	OK	
Piece 24-1	88077	10	n/a	60	47	50	10	OK	

(a) These materials have the LST increased from 10 to 70 F because they do not meet the requirement for 45 ft-lbs. and 25 MLE.

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 (Rev 2) provides the methods for determining the ART. The Rev 2 methods for determining the limiting material and adjusting the P-T curves using ART are discussed in this section. As discussed in Appendix E, the beltline contains the N2 Recirculation Inlet nozzle and the N16 Instrumentation nozzle, which represents a slight extension beyond the core region. This is determined by the location on the vessel where the fluence exceeds $1x10^{17}$ n/cm^2. An evaluation of ART for all beltline plates, the N2 and N16 nozzles, and several beltline welds was made and summarized in Table 4-3 for 25 EFPY and Table 4-4 for 32 EFPY.

4.2.1 Regulatory Guide 1.99, Revision 2 (Rev 2) Methods

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

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

where,

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

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

CF = chemistry factor from Tables 1 or 2 of Rev. 2

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.

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 in Rev 2 of 17°F for plate and 28°F for weld. 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 weld materials.

4.2.1.1 Chemistry

The vessel beltline copper and nickel values (except for the N2 and N16 nozzles) were obtained from [5]. For the N2 and N16 nozzles, a bounding value of 0.18% was assumed for copper (see Tables 4-3 and 4-4), and the nickel values for N16 and N2 of 0.85% and 0.84%, respectively, were obtained from a Certified Material Test Report [12]. The copper (Cu) and nickel (Ni) values were used with Tables 1 and 2 of Rev 2, to determine a chemistry factor (CF) per Paragraph 1.1 of Rev 2 for welds and plates, respectively. For Plate Heat B0673-1, the CF was adjusted using Section 2.1 of Rev. 2; a detailed description of the adjustment is included in [5]. The margin term, σ_Δ, has constant values in Rev 2 of 17°F for plate and 28°F for weld. For Plate Heat B0673-1, the margin term was halved, consistent with the guidance in Section 2.1 of Rev. 2. However, σ_Δ need not be greater than $0.5{*}\Delta RT_{NDT}$. 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 materials and girth weld.

4.2.1.2 Fluence

A Duane Arnold flux for the vessel ID wall was calculated in accordance with the method described in GE Licensing Topical Report NEDC-32983P, which has been approved by the NRC [14], and is in compliance with Regulatory Guide 1.190. Peak fluxes have been determined for both the current rated power 1658 MW_t and EPU power of 1912 MW_t.

The peak RPV ID fluence used in the P-T curve evaluation is 4.17e18 n/cm^2, as discussed in detail in Appendix G, [[ ]] for the entire plant life. This fluence applies to the lower-intermediate plates and longitudinal welds. The fluence is adjusted for the lower plates and longitudinal welds and the girth

weld based upon an attenuation factor of 1.18; hence, the peak ID surface fluence for these components is 3.55e18 n/cm^2. Similarly, the fluence is adjusted for the N2 nozzle based upon an attenuation factor of 5.46; hence the peak ID surface fluence used for this component is 7.64e17 n/cm^2. The same method is applied to the N16 nozzle, which has an attenuation factor of 3.7, resulting in a peak ID surface fluence of 1.13e18 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, Rev 2 was applied to compute ART. For Duane Arnold, the N2 Recirculation Inlet nozzle is the limiting material for the beltline region as discussed in Section 4.3.2.2.2 and Appendix E. Table 4-3 lists values of beltline ART for 25 EFPY and Table 4-4 lists the values for 32 EFPY. Sections 4.3.2.2.2 and 4.3.2.2.3 provide a discussion of the limiting material.

Table 4-3: Duane Arnold Beltline ART Values (25 EFPY)

Lower-Intermediate Shell Plate and Longitudinal welds
Thickness = 4.469 inches

Lower-Intermediate Shell Plate and Longitudinal welds
32 EFPY Peak I.D. fluence = 4.17E+18 n/cm^2
32 EFPY Peak 1/4 T fluence = 3.19E+18 n/cm^2
25 EFPY Peak 1/4 T fluence = 2.49E+18 n/cm^2

Lower Shell Plate and Longitudinal welds and girth welds
Thickness = 4.469 inches Attenuation factor= 1.10
(Note: Actual number is 5.031, 4.469 was used for conservatism)

Lower Shell Plate and Longitudinal welds and girth welds
32 EFPY Peak I.D. fluence = 3.55E+18 n/cm^2
32 EFPY Peak 1/4 T fluence = 2.71E+18 n/cm^2
25 EFPY Peak 1/4 T fluence = 2.12E+18 n/cm^2

N16 Nozzle
Thickness = 4.469 inches Attenuation factor= 0.70

N16 Nozzle
32 EFPY Peak I.D. fluence = 1.43E+18 n/cm^2
32 EFPY Peak 1/4 T fluence = 8.63E+17 n/cm^2
25 EFPY Peak 1/4 T fluence = 6.74E+17 n/cm^2

N2 Nozzle
Thickness = 4.469 inches Attenuation factor 0.40

N2 Nozzle
32 EFPY Peak I.D. fluence = 7.44E+17 n/cm^2
32 EFPY Peak 1/4 T fluence = 5.33E+17 n/cm^2
25 EFPY Peak 1/4 T fluence = 4.97E+17 n/cm^2

COMPONENT	Weld Type	HEAT OR HEAT/LOT	%Cu	%Ni	CF	Adjusted CF (c)	Initial RTndt °F	1/4 T Fluence n/cm^2	25 EFPY Δ RTndt °F	σI	σΔ	Margin °F	25 EFPY Shift °F	25 EFPY ART °F
PLATES:														
Shell Ring #1														
1-18		C6409-2	0.09	0.51	58		40	2.12E+18	33.8	0.0	16.9	33.8	67.7	107.7
1-19		B0402-1	0.13	0.47	87		40	2.12E+18	50.8	0.0	17.0	34.0	84.8	124.8
Shell Ring #2														
1-20		B0436-2	0.15	0.64	111		10	2.49E+18	69.2	0.0	17.0	34.0	103.2	113.2
1-21		B0673-1	0.15	0.61	110	164	10	2.49E+18	102.2	0.0	8.5	17.0	119.2	129.2
1-21		B0673-1 (a)	0.16	0.63	111	166	10	2.49E+18	103.1	0.0	8.5	17.0	120.1	130.1
WELDS:														
Lower														
D1,D2		432Z4521 Lot B020A27A	0.01	0.93	20		-40	2.12E+18	11.7	0.0	5.8	11.7	23.3	-16.7
D1,D2		432Z0471 Lot B003A27A	0.03	0.91	41		-50	2.12E+18	23.9	0.0	12.0	23.9	47.8	-2.2
Lower Intmed														
F1,F2		432Z4521 Lot B020A27A	0.01	0.96	20		-40	2.49E+18	12.5	0.0	6.2	12.5	24.9	-15.1
E1,E2		432Z0471 Lot B003A27A	0.03	0.91	41		-50	2.49E+18	25.6	0.0	12.8	25.6	51.1	1.1
Girth														
DE		09L853 Lot L017A27A	0.03	0.85	41		-50	2.12E+18	23.9	0.0	12.0	23.9	47.8	-2.2
DE		07L669 Lot K004A27A	0.03	1.02	41		-50	2.12E+18	23.9	0.0	12.0	23.9	47.8	-2.2
DE		CTY336 Lot A027A27A	0.03	0.83	41		-50	2.12E+18	23.9	0.0	12.0	23.9	47.8	-2.2
NOZZLES														
N16		Q2Q5VW (b)	0.18	0.85	142		40	6.74E+17	48.6	0.0	17.0	34.0	82.6	122.6
N2		Q2Q6VW (b)	0.18	0.81	142		40	4.97E+17	39.6	0.0	17.0	34.0	73.6	113.6

(a) Surveillance Plate (Best Estimate Chemistry)
(c) Material in the surveillance program has the CF adjusted by 1.49 in accordance with RG 1.99 Rev. 2
(b) Estimated copper (In the absence of copper data, the content of 0.18% was based on heats of materials used for beltline nozzles at other plants. The mean from nine nozzles (0.119) plus one standard deviation (0.0617) was used to arrive at a value of 0.18

Table 4-4: Duane Arnold Beltline ART Values (32 EFPY)

Lower-Intermediate Shell Plate and Longitudinal welds
Thickness = 4.469 inches

Lower Shell Plate and Longitudinal welds and girth welds
Thickness = 4.469 inches Attenuation factor= 1.16
(Note: Actual number is 5.031, 4.469 was used for conservatism)

N16 Nozzle
Thickness = 4.469 inches Attenuation factor= 1.30

N2 Nozzle
Thickness = 4.469 inches Attenuation factor 1.16

Lower-Intermediate Shell Plate and Longitudinal welds
32 EFPY Peak I.D. fluence = 4.17E+18 n/cm^2
32 EFPY Peak 1/4 T fluence = 3.19E+18 n/cm^2
32 EFPY Peak 1/4 T fluence = 3.19E+18 n/cm^2

Lower Shell Plate and Longitudinal welds and girth welds
32 EFPY Peak I.D. fluence = 3.53E+18 n/cm^2
32 EFPY Peak 1/4 T fluence = 2.71E+18 n/cm^2
32 EFPY Peak 1/4 T fluence = 2.71E+18 n/cm^2

N16 Nozzle
32 EFPY Peak I.D. fluence = 1.13E+18 n/cm^2
32 EFPY Peak 1/4 T fluence = 8.63E+17 n/cm^2
32 EFPY Peak 1/4 T fluence = 8.63E+17 n/cm^2

N2 Nozzle
32 EFPY Peak I.D. fluence = 7.84E+17 n/cm^2
32 EFPY Peak 1/4 T fluence = 6.85E+17 n/cm^2
32 EFPY Peak 1/4 T fluence = 5.85E+17 n/cm^2

COMPONENT	Weld Type	HEAT OR HEAT/LOT	%Cu	%Ni	CF	Adjusted CF (c)	Initial RTndt °F	1/4 T Fluence n/cm^2	32 EFPY Δ RTndt °F	σI	σΔ	Margin °F	32 EFPY Shift °F	32 EFPY ART °F
PLATES:														
Shell Ring #1														
1-14		C4489-3	0.09	0.51	56		40	2.71E+18	37.4	0.0	17.0	34.0	71.4	111.4
1-15		B0402-1	0.13	0.47	87		40	2.71E+18	56.1	0.0	17.0	34.0	90.1	130.1
Shell Ring #2														
1-20		B0436-2	0.15	0.64	111		10	3.19E+18	76.2	0.0	17.0	34.0	110.2	120.2
1-21		B0673-1	0.12	0.61	114	164	10	3.19E+18	112.5	0.0	8.5	17.0	129.5	139.5
1-22		B0673-1(a)	0.15	0.65	111	165	10	3.19E+18	113.5	0.0	8.5	17.0	130.5	140.5
WELDS:														
Lower														
D4,D8		432Z4531 Lot 0030A27A	0.01	0.98	20		-50	2.71E+18	12.9	0.0	6.4	12.9	25.8	-24.2
D4,D8		432Z0471 Lot B003A27A	0.03	0.91	41		-50	2.71E+18	26.4	0.0	13.2	26.4	52.9	2.9
Lower-Intermed														
E1,E2		432Z4531 Lot 0030A27A	0.01	0.98	20		-50	3.19E+18	13.7	0.0	6.9	13.7	27.5	-22.5
E1,E2		432Z0471 Lot B003A27A	0.03	0.91	41		-50	3.19E+18	28.1	0.0	14.1	28.1	56.2	6.2
Girth														
DE		491S33 Lot L017A27A	0.00	0.88	41		-50	2.71E+18	26.4	0.0	13.2	26.4	52.9	2.9
DE		071A49 Lot K004A27A	0.03	1.02	41		-50	2.71E+18	26.4	0.0	13.2	26.4	52.9	2.9
DE		CTY318 Lot A027A27A	0.03	0.83	41		-50	2.71E+18	26.4	0.0	13.2	26.4	52.9	2.9
NOZZLES														
N16		Q2Q5VW (b)	0.18	0.85	143		40	8.63E+17	45.1	0.0	17.0	34.0	79.1	119.1
N2		Q2Q5VW (b)	0.18	0.85	143		40	6.85E+17	45.2	0.0	17.0	34.0	79.2	119.2

(a) Surveillance Plate (Best Estimate Chemistry) (c) Material is in the surveillance program has the CF adjusted by 1.49 in accordance with RG1.99 Rev. 2
(b) Estimated copper (In the absence of copper data, the content of 0.18% was based on heats of materials used for beltline nozzles at other plants. The mean from nine nozzles (0.118) plus one standard deviation (0.0617) was used to arrive at a value of 0.18

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 that a pressure-retaining component may be subjected to over its service lifetime. The ASME Code (Appendix G of Section XI of the ASME Code [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 portion of the vessel (i.e., upper vessel, lower vessel) includes 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 20°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 as follows in Table 4-5:

Table 4-5: 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} (see Appendix E). Non-beltline components include nozzles, 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 analyses took into account all mechanical loading and anticipated thermal transients. Transients considered include 100°F/hr start-up and shutdown, SCRAM, loss of feedwater heaters or flow, loss of recirculation pump flow, and all transients involving emergency core cooling injections. Primary membrane and bending stresses and secondary membrane and bending stresses due to the most severe of these transients were used according to 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 4-6 and 4-7.

Table 4-6: 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
Jet Pump Instrumentation Nozzle
Shell
CRD and Bottom Head (Curve B only)
Top Head Nozzles (Curve B only)
Recirculation Outlet Nozzle (Curve B only)

Table 4-7: Applicable BWR/4 Discontinuity Components for Use with CRD (Bottom Head) Curves A&B

Discontinuity Identification
CRD and Bottom Head
Top Head Nozzle
Recirculation Outlet Nozzle
Shell*
Support Skirt*
Shroud Support Attachment*
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, since 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 Duane Arnold 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 Duane Arnold by using plant specific RT_{NDT} values for the reactor pressure vessel (RPV). The presence of nozzles and CRD penetration holes of 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 [[ ]] 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 20°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:

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

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

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

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]:

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

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

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 44°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 Duane Arnold specific bottom head dimensions are R = 92.69 inches and t =6.5 inches minimum [19], resulting in:

Duane Arnold specific: $R / (t)^{1/2} = 92.69 / (6.5)^{1/2} = 36 \text{ inch}^{1/2}$ (4-3)

Since the generic value of $R/(t)^{1/2}$ is larger, the generic P-T curve is conservative when applied to the Duane Arnold 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 44°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 Tables 4-6, 4-7, 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 described below. The generic pressure test P-T curve is applied to the Duane Arnold feedwater nozzle curve by shifting the P vs. $(T - RT_{NDT})$ values above to reflect the RT_{NDT} value of 40°F.

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

Vessel Radius, R_v	92.69 inches
Vessel Thickness, t_v	4.469 inches
Vessel Pressure, P_v	1563 psig

Pressure stress: $\sigma = PR / t$ = 1563 psig · 92.69 inches / (4.469 inches) = 32,418 psi. The Dead weight and thermal RFE stress of 2.967 ksi is conservatively added yielding σ = 35.4 ksi. The factor F (a/r_n) from Figure A5-1 of WRC-175 is determined where:

a =	$\frac{1}{4} (t_n^{\,2} + t_v^{\,2})^{1/2}$	=1.78 inches
t_n =	thickness of nozzle	= 5.56 inches
t_v =	thickness of vessel	= 4.469 inches
r_n =	apparent radius of nozzle	= $r_i + 0.29\ r_o$=6.0 inches

r_i = actual inner radius of nozzle = 5.375 inches
r_o = nozzle radius (nozzle corner radius) = 2.25 inches

Thus, a/r_n = 1.78 / 6.0 = 0.3. The value $F(a/r_n)$, taken from Figure A5-1 of WRC Bulletin 175 for an a/r_n of 0.30, is 1.5. 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 $K_I = 1.5 \cdot 35.4 \cdot (\pi \cdot 1.78)^{1/2} \cdot 1.5 = 188$ 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 relatively cold feedwater flow in hotter 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, see 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}:

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

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.

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

Example of 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 temperature assumed for the crack root is the inside surface temperature.)

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

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:

$$K_{Is} = 2.845 \cdot (9.44 + 2/3 \cdot 11.10)$$
$$K_{Is} = 47.9 \text{ ksi-in}^{1/2}$$

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 Duane Arnold is 40°F as shown in Tables 4-1 and 4-2 and previously discussed. The generic curve is applied to the Duane Arnold upper vessel by shifting the P vs. (T - RT_{NDT}) values above to reflect the RT_{NDT} value of 40°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. 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.

The Recirculation Inlet (N2) nozzle is located in the extended beltline region, and is the most limiting material for the vessel. The stress intensity factors (K_I) for the Pressure Test and Core Not Critical Heatup/Cooldown conditions were calculated in the same manner as the feedwater nozzle (see Sections 4.3.2.1.3 and 4.3.2.1.4, respectively), except that the RT_{NDT} was adjusted to account for the effects of irradiation in accordance with Section 4.2. For the N2 nozzle, the following dimensions were used to calculate the factor F (a/r_n) in accordance with WRC-175:

a =	$\frac{1}{4}(t_n^{\,2} + t_v^{\,2})^{1/2}$	=1.89 inches
t_n =	thickness of nozzle	= 5.25 inches
t_v =	thickness of vessel	= 5.4375* inches
r_n =	apparent radius of nozzle	= r_i + 0.29 r_c= 6.4125 inches
r_i =	actual inner radius of nozzle	= 5.6875 inches
r_c =	nozzle radius (nozzle corner radius)	= 2.5 inches

*Includes cladding thickness

Thus, a/r_n = 1.89 / 6.4125 = 0.295. The value F(a/r_n), taken from Figure A5-1 of WRC Bulletin 175 for an a/r_n of 0.295, is 1.5. These values are used in the stress intensity factor equations described in Sections 4.3.2.1.3 and 4.3.2.1.4.

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:

$$\sigma_m = PR / t_{min} \tag{4-8}$$

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 of 20°F/hr 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 1035 psig at 32 EFPY for the limiting beltline plate material. The following inputs were used in the beltline limit calculation:

Adjusted RT_{NDT} = Initial RT_{NDT} + Shift	A = 10 + 130.5 = 140.5°F (Based on ART values in Table 4-4)
Vessel Height	H = 796.94 inches
Bottom of Active Fuel Height	B = 201 inches
Vessel Radius (to inside of clad)	R = 92.69 inches
Minimum Vessel Thickness (without clad)	t = 4.469 inches

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

$$P = 1035 \text{ psi} + (H - B)\ 0.0361 \text{ psi/inch} = P \text{ psig} \qquad (4\text{-}10)$$
$$= 1035 + (796.94 - 201)\ 0.0361 = 1057 \text{ psig}$$

Pressure stress:

$$\sigma = PR/t \qquad (4\text{-}11)$$
$$= 1.057 \cdot 92.69 / 4.469 = 21.9 \text{ ksi}$$

The value of M_m for an inside axial postulated surface flaw from Paragraph G-2214.1 [6] was based on a thickness of 4.469 inches (the minimum thickness without cladding); hence, $t^{1/2}$ = 2.114. The resulting value obtained was:

$$M_m = 1.85 \text{ for } \sqrt{t} \leq 2$$
$$M_m = 0.926\ \sqrt{t} \text{ for } 2 \leq \sqrt{t} \leq 3.464 = 1.958$$
$$M_m = 3.21 \text{ for } \sqrt{t} > 3.464$$

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 20°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} = 42.88, and K_{It} = 1.08 for a 20°F/hr coolant heatup/cooldown rate with a vessel thickness, t, that includes cladding:

$$(T - RT_{NDT}) = \ln[(1.5 \cdot K_{Im} + K_{It} - 33.2) / 20.734] / 0.02 \quad (4\text{-}12)$$
$$= \ln[(1.5 \cdot 42.88 + 1.08 - 33.2) / 20.734] / 0.02$$
$$= 22°F$$

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

T = 22 + 140.5 = 162.5°F for P = 1035 psig

For Duane Arnold, the N2 Recirculation Inlet nozzle is the limiting material for the beltline region for 32 EFPY. The beltline pressure test P-T curves provided in Section 5.0 of this report are calculated in the same manner as the Feedwater Nozzle pressure test P-T curves, using the N2-specific geometry, as described in Section 4.3.2.1.3. The initial RT_{NDT} for the N2 Recirculation Inlet nozzle materials is 40°F as shown in Table 4-2. The generic pressure test P-T curve is applied to the Duane Arnold N2 Nozzle curve by shifting the P vs. (T - RT_{NDT}) values in Section 4.3.2.1.3 to reflect the ART value of 119.2°F. Similarly, the generic pressure test P-T curve is applied to the Duane Arnold N2 Nozzle curve by shifting the P vs. (T-RT_{NDT}) values in Section 4.3.2.1.3 to reflect the 25 EFPY ART value of 113.6°F.

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 and 1/8T. For the flat plate geometry and radial thermal gradient, orientation of the crack is not important.

For Duane Arnold, the N2 Recirculation Inlet nozzle is the limiting material for the beltline region for 32 EFPY. The beltline core not critical P-T curves provided in Section 5.0 of this report are calculated in the same manner as the Feedwater Nozzle core not critical P-T curves, using the N2-specific geometry, as described in Section 4.3.2.1.4. The initial RT_{NDT} for the N2 Recirculation Inlet nozzle materials is 40°F as shown in Table 4-2. The generic core not critical P-T curve is applied to the Duane Arnold N2 Nozzle curve by shifting the P vs. $(T - RT_{NDT})$ values in Section 4.3.2.1.4 to reflect the ART value of 119.2°F. Similarly, the generic core not critical P-T curve is applied to the Duane Arnold N2 Nozzle curve by shifting the P vs. $(T-RT_{NDT})$ values in Section 4.3.2.1.4 to reflect the 25 EFPY ART value of 113.6°F.

Example of Core Not Critical Beltline Calculation Using N2 Recirculation Inlet Nozzle at 1050 psig and 32 EFPY

For the N2 Recirculation Inlet nozzle curve, the primary membrane stresses are scaled using the plant specific N2 nozzle geometry. The secondary thermal stresses for the FW nozzle are conservatively used for the N2 nozzle. These stresses are then adjusted for stresses above yield. From these stresses, K_I can be determined. The stresses are scaled for the various pressures and temperatures, similar to the scaling used for the FW nozzle core not critical curve in Section 4.3.2.1.4. The primary stresses are scaled by the nominal pressures, while the secondary stresses are scaled by the temperature difference of the cold FW nozzle (40°F) water injected into the hot reactor vessel nozzle. The base case is a pressure of 1050 psig and reactor vessel temperature is 551.4°F; this yields a K_I value of 305.6 ksi-in$^{1/2}$. Since the reactor vessel temperature follows the saturation temperature curve, the secondary stresses are scaled by ($T_{saturation}$ – 40°F) / (551.4°F – 40°F). From K_I, the associated T-RT_{NDT} can be calculated.

FW Nozzle t_v	=	6.1875 inches
N2 Nozzle tv	=	5.25 inches, however, t_v = 4.875 inches is conservatively used
$F(a/r_n)$	=	1.5

The FW nozzle stresses are used for the N2 nozzle; only the primary membrane stress is scaled for the plant specific vessel thickness, t_v. At a pressure of 1050 psig and a temperature of 551.4°F, the stresses are:

σ_{pm} = 24.84 ksi · (6.1875 inches / 4.875 inches) = 31.53 ksi

σ_{pb} = 0.22 ksi

σ_{sm} = 16.19 ksi

σ_{sb} = 19.04 ksi

K_I is calculated:

$t^{1/2} = (4a)^{1/2} = (4 \cdot 1.89)^{1/2}$ = 2.75

$M_m = 0.926 \cdot 2.75$ = 2.546

K_{IP} is calculated using Equation (4-4) as shown in Section 4.3.2.1.4:

$K_{IP} = 2.0 \cdot (31.53 + 0.22) \cdot (\pi \cdot 1.89)^{1/2} \cdot 1.5 = 232.1$ ksi-in$^{1/2}$

K_{Is} is calculated using Equation (4-5) as shown in Section 4.3.2.1.4:

$K_{Is} = 2.546 \cdot (16.19 + 2/3 \cdot 19.04) = 73.5$ ksi-in$^{1/2}$

$K_I = K_{IP} + K_{Is}$

KI = 232.1 ksi-in$^{1/2}$ + 73.5 ksi-in$^{1/2}$ = 305.6 ksi-in$^{1/2}$

T-RT_{NDT} is further calculated:

T-RT_{NDT} = ln[(305.6 – 33.2) / 20.734] / 0.02 = 128.8°F

T can be calculated by adding the N2 nozzle adjusted RT_{NDT} of 119.2°F from Table 4-4:

T = 128.8°F + 119.2°F = 248°F for P = 1050 psig

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

This sample calculation is for a pressure of 1035 psig for 32 EFPY. The core not critical heatup/cooldown curve at 1035 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 rather than test condition that necessitates 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 (the maximum vessel thickness is conservatively used)	C = 0.372 ft (4.469 inches)
Thermal diffusivity at 550°F (most conservative value)	β = 0.354 ft^2/ 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:

$$\Delta T = GC^2 / 2\beta \quad (4\text{-}16)$$

$= 100 \cdot (0.372)^2 / (2 \cdot 0.354) = 19.5°F$

The analyzed case for thermal stress is a 1/4T flaw depth with wall thickness of C. The corresponding value of M_t (=0.25) can be interpolated from ASME Appendix G, Figure G-2214-2 [6]. Thus the thermal stress intensity factor, $K_{It} = M_t \cdot \Delta T = 5.42$, can be calculated. 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 $(T - RT_{NDT})$:

$$(T - RT_{NDT}) = \ln[((2 \cdot K_{Im} + K_{It}) - 33.2) / 20.734] / 0.02 \quad (4\text{-}17)$$
$$= \ln[(2 \cdot 42.88 + 5.52 - 33.2) / 20.734] / 0.02$$
$$= 51.4 °F$$

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

$T = 51.4 + 140.5 = 191.9 °F$ for P = 1035 psig

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}. 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 Duane Arnold at low pressures.

The approach used for Duane Arnold for the bolt-up temperature was based on a 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 flaw size between 0.1 and 0.24 inches is acceptable. As shown in Tables 4-1 and 4-2, the upper vessel shell plate material at 14°F represent the limiting initial RT_{NDT} for the closure flange region, and the LST of the closure studs is 70°F; therefore, the bolt-up temperature value used is 74°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 pre-service 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 Duane Arnold Technical Specification, 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 74°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 74°F, based on an RT_{NDT} of 14°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 1035 psig). Due to the presence of the N2 nozzle discontinuity, the requirement of closure region RT_{NDT} + 160°F does not cause 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 20°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 Duane Arnold.

- Composite P-T curves were generated for each of the Pressure Test and Core Not Critical conditions at 32 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 25 and 32 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 25 and 32 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.

Using the fluence defined in Section 4.2.1.2 and Appendix G, the P-T curves are beltline (N2 Recirculation Inlet nozzle) limited above 240 and 230 psig for curve A for 25 and 32 EFPY, respectively, and above 30 psig for curve B for both 25 and 32 EFPY.

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
Curve A			
	Bottom Head Limits (CRD Nozzle)	Figure 5-1	B-1 & B-3
	Upper Vessel Limits (FW Nozzle)	Figure 5-2	B-1 & B-3
	Beltline Limits for 25 EFPY	Figure 5-3	B-3
	Beltline Limits for 32 EFPY	Figure 5-4	B-1
Curve B			
	Bottom Head Limits (CRD Nozzle)	Figure 5-5	B-1 & B-3
	Upper Vessel Limits (FW Nozzle)	Figure 5-6	B-1 & B-3
	Beltline Limits for 25 EFPY	Figure 5-7	B-3
	Beltline Limits for 32 EFPY	Figure 5-8	B-1
Curve C			
	Composite Curve for 25 EFPY**	Figure 5-9	B-4
A, B, & C	Composite Curves for 32 EFPY		
	Bottom Head and Composite Curve A for 32 EFPY*	Figure 5-10	B-2
	Bottom Head and Composite Curve B for 32 EFPY*	Figure 5-11	B-2
	Composite Curve C for 32 EFPY**	Figure 5-12	B-2

* 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.

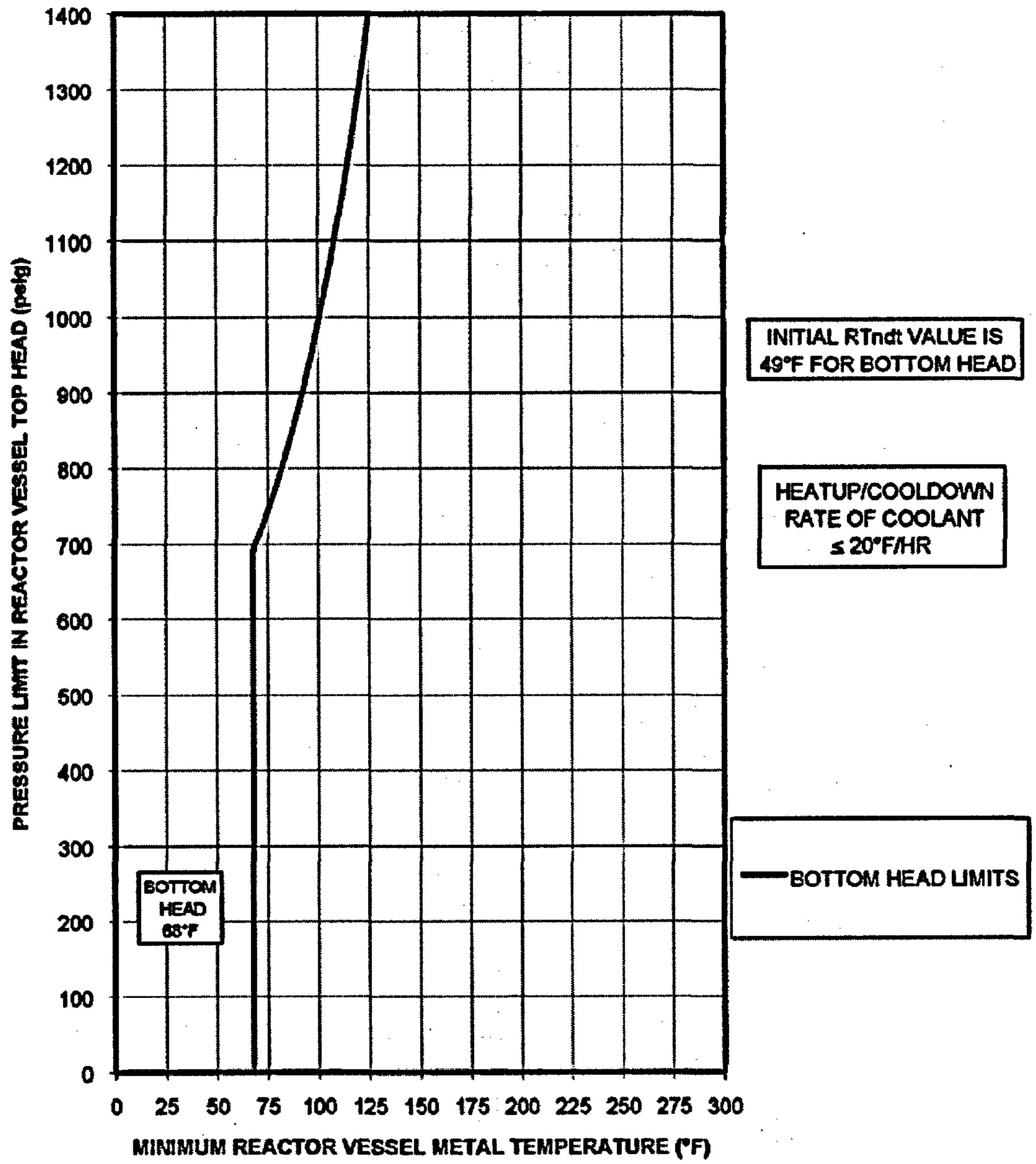

Figure 5-1: Bottom Head P-T Curve for Pressure Test [Curve A]
[20°F/hr or less coolant heatup/cooldown]

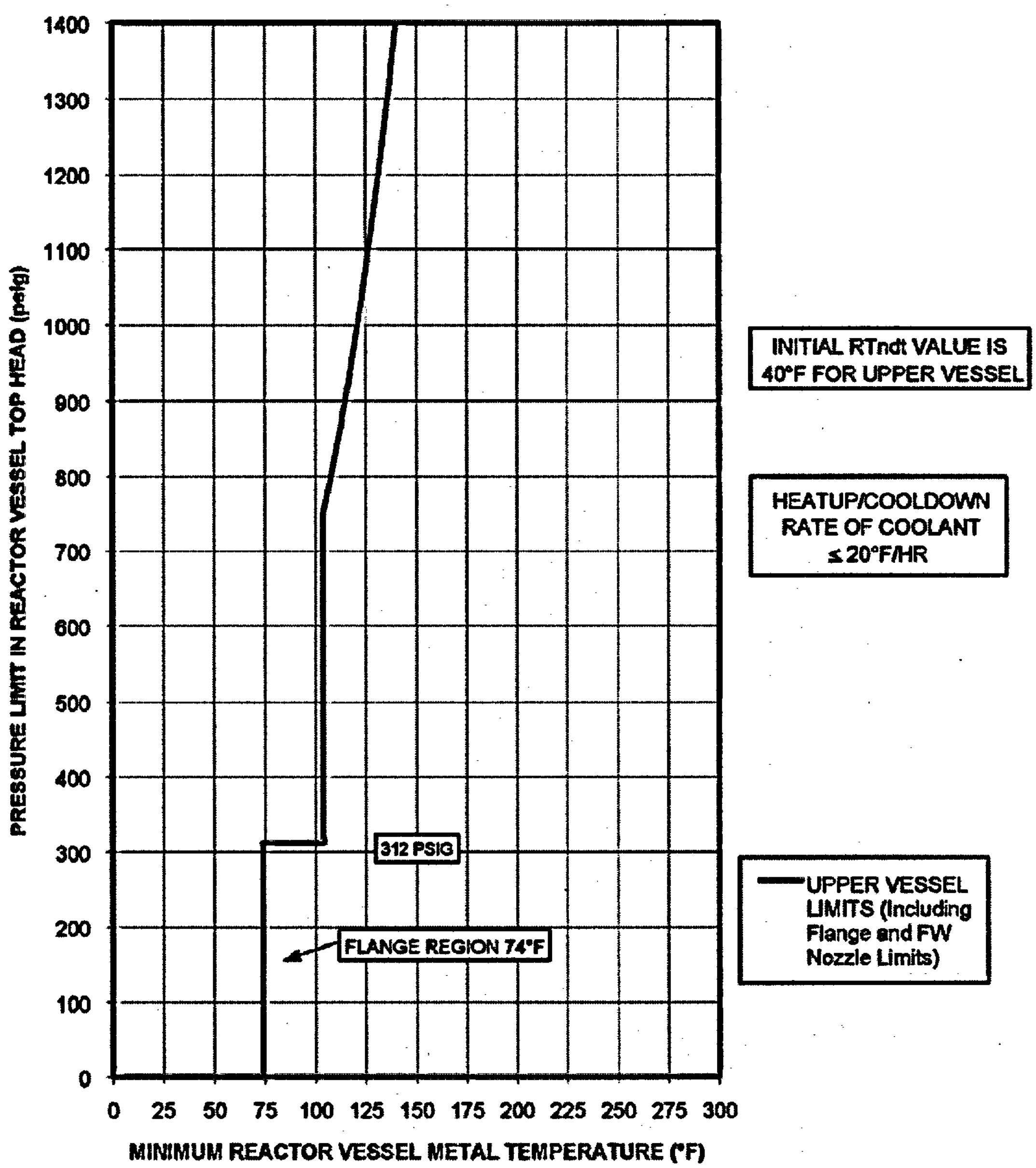

Figure 5-2: Upper Vessel P-T Curve for Pressure Test [Curve A]
[20°F/hr or less coolant heatup/cooldown]

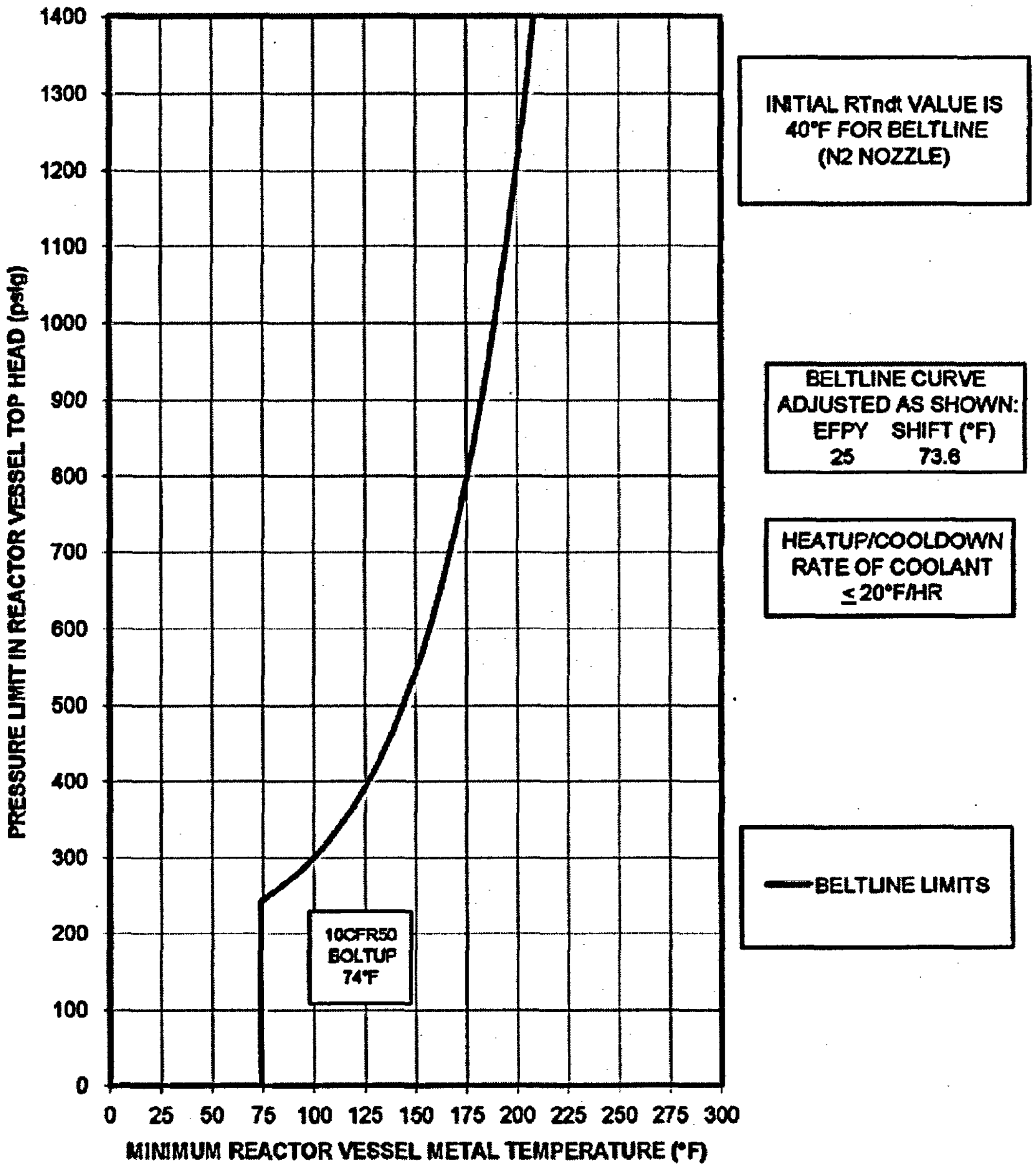

Figure 5-3: Beltline P-T Curve for Pressure Test [Curve A] up to 25 EFPY
[20°F/hr or less coolant heatup/cooldown]

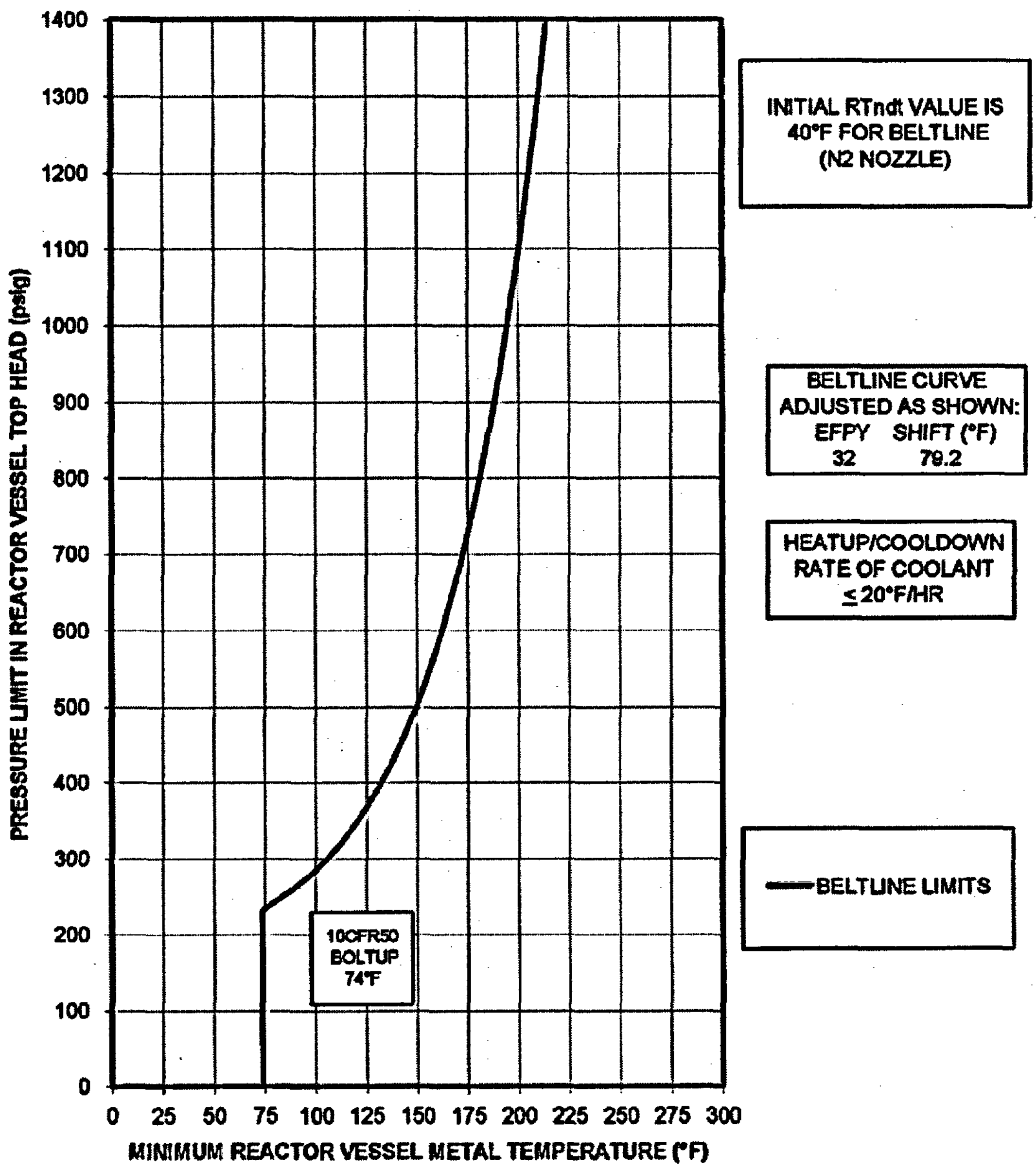

Figure 5-4: Beltline P-T Curve for Pressure Test [Curve A] up to 32 EFPY
[20°F/hr or less coolant heatup/cooldown]

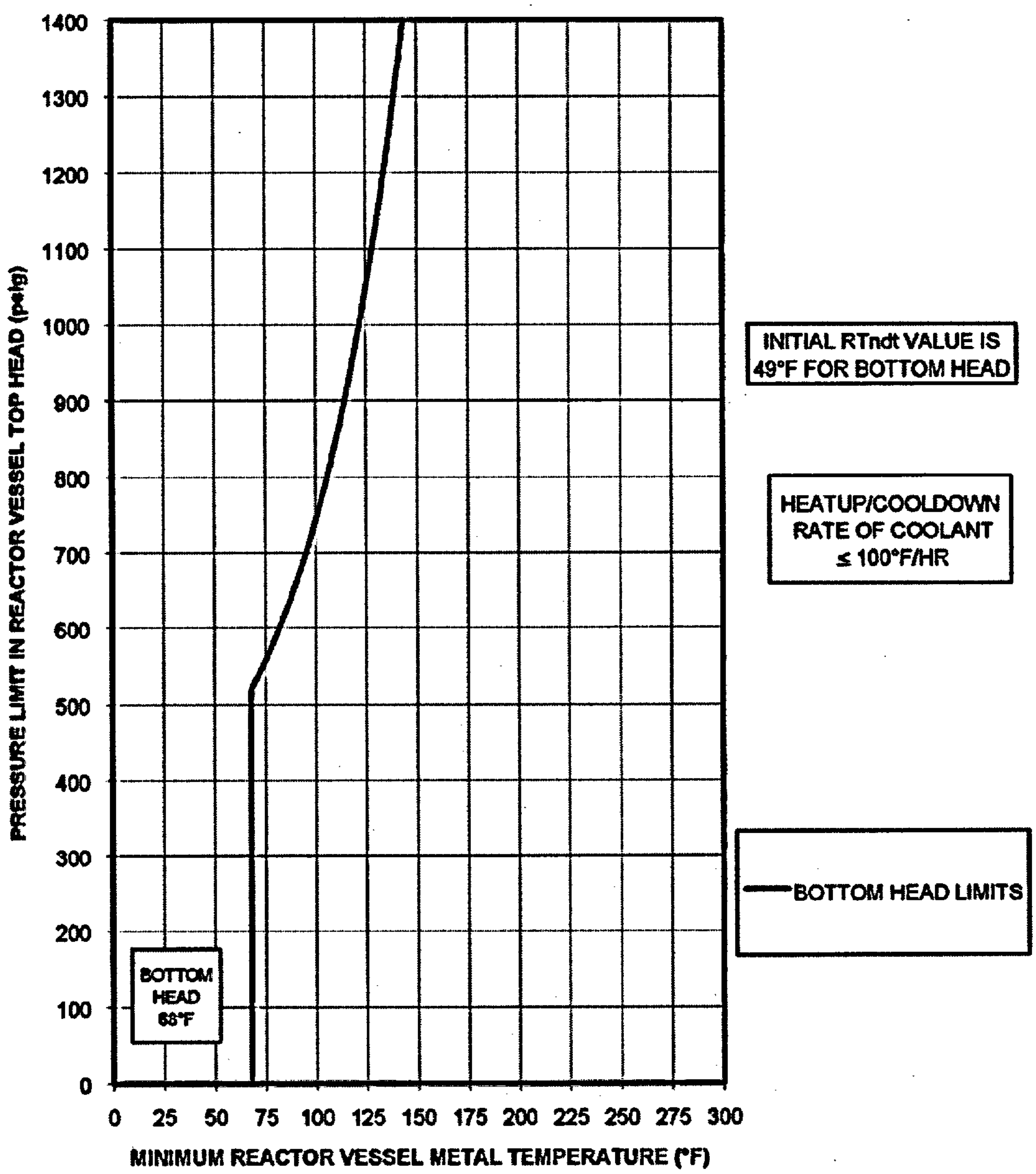

Figure 5-5: Bottom Head P-T Curve for Core Not Critical [Curve B]
[100°F/hr or less coolant heatup/cooldown]

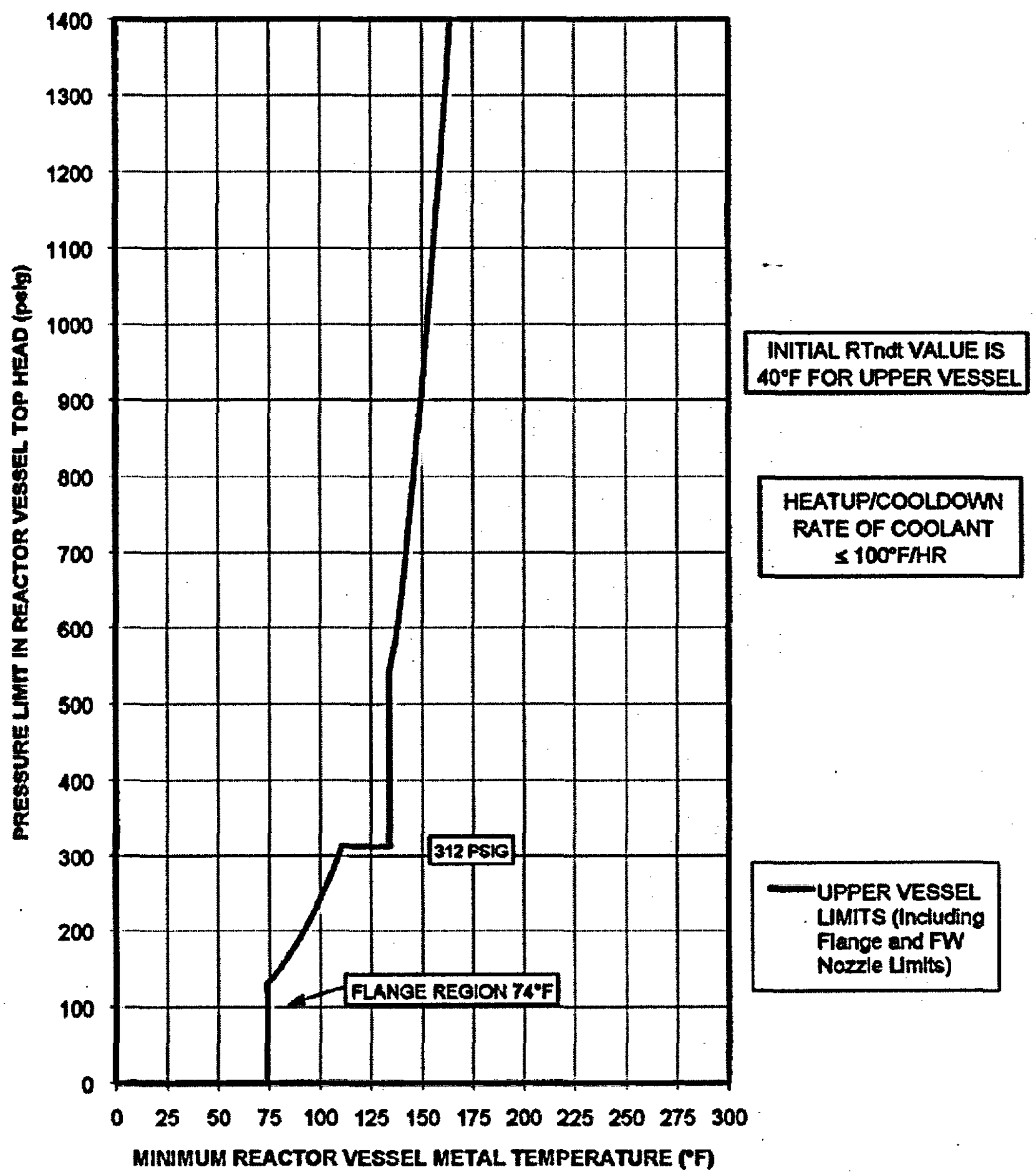

Figure 5-6: Upper Vessel P-T Curve for Core Not Critical [Curve B]
[100°F/hr or less coolant heatup/cooldown]

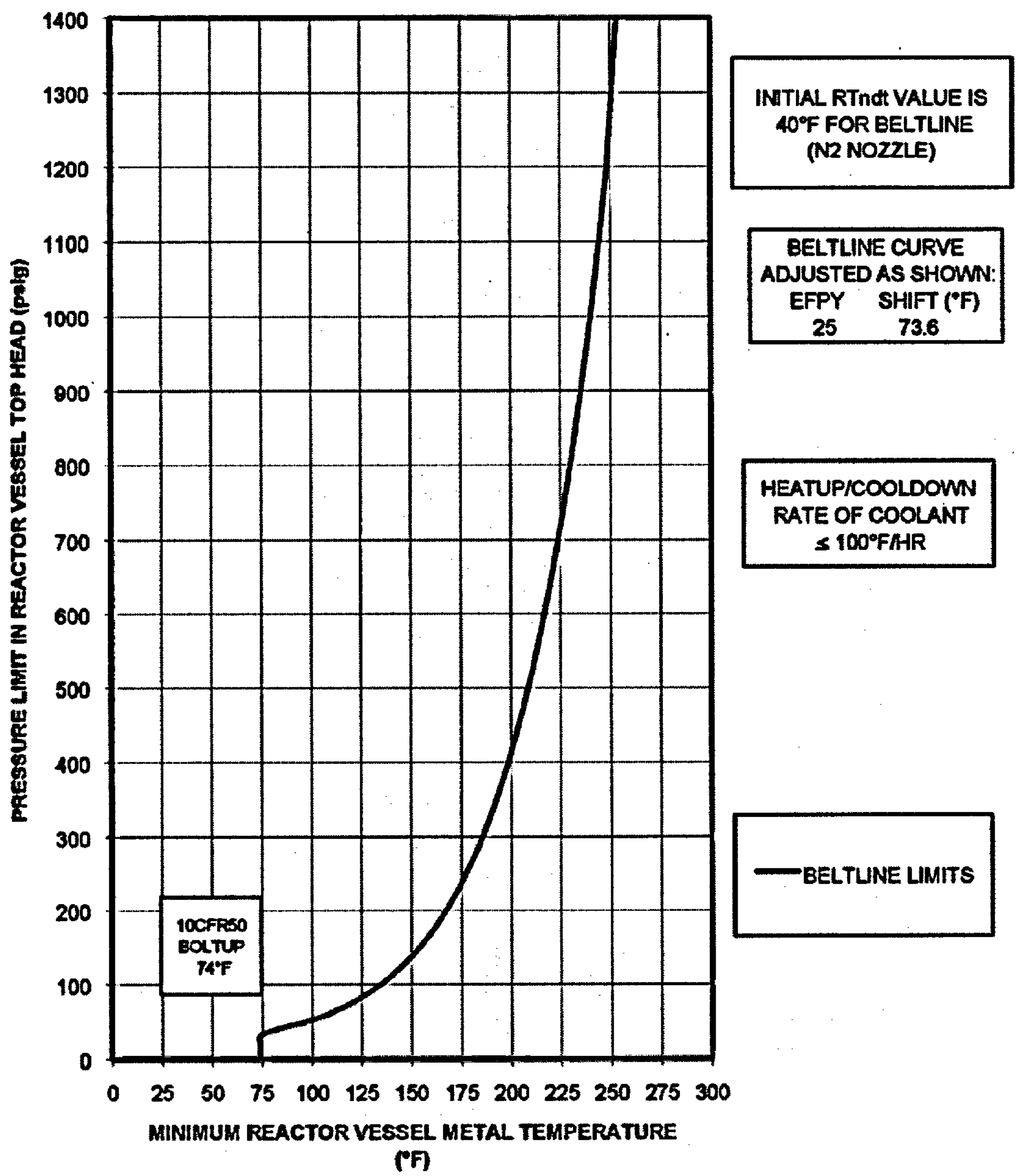

Figure 5-7: Beltline P-T Curve for Core Not Critical [Curve B] up to 25 EFPY
[100°F/hr or less coolant heatup/cooldown]

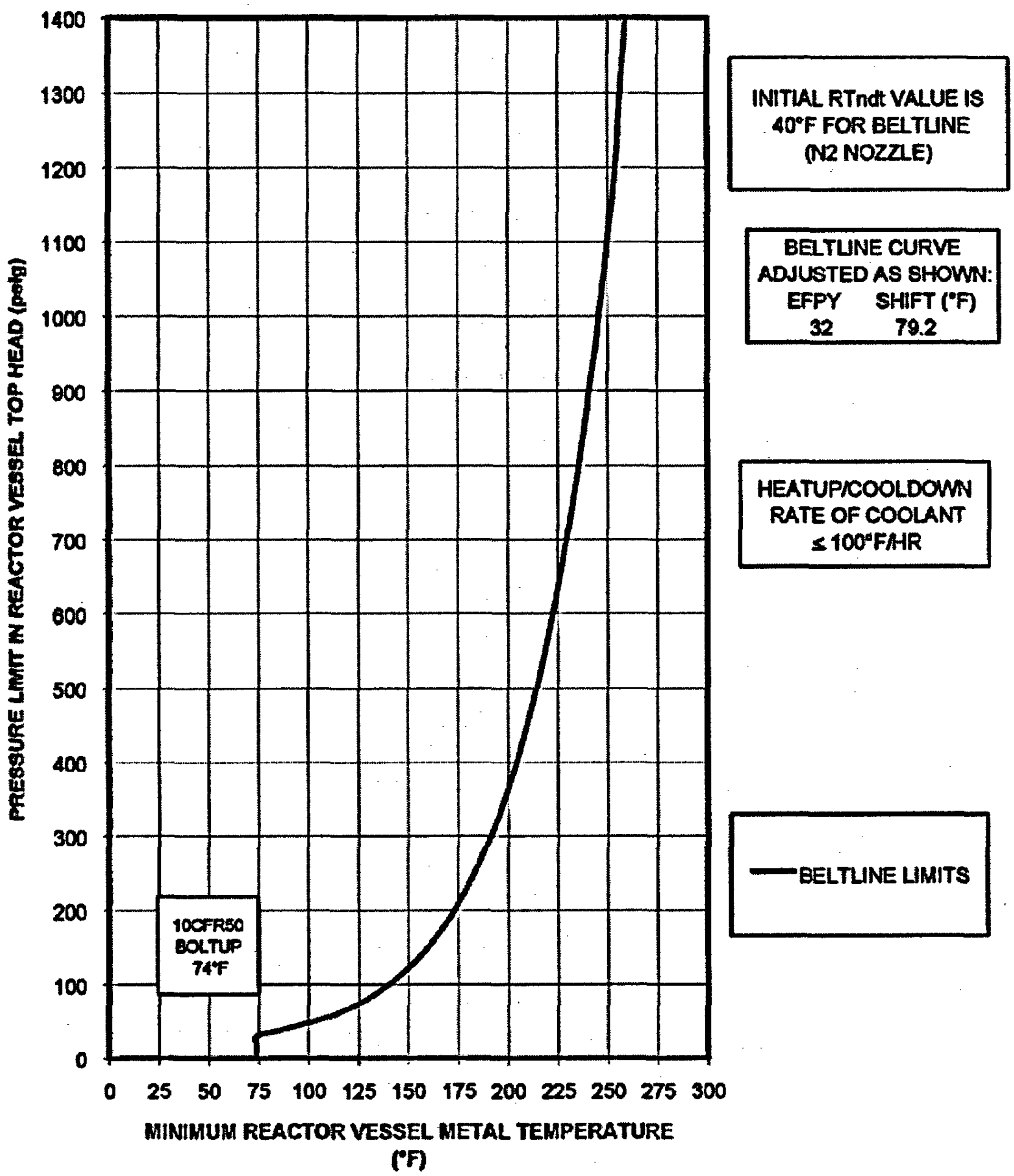

Figure 5-8: Beltline P-T Curves for Core Not Critical [Curve B] up to 32 EFPY [100°F/hr or less coolant heatup/cooldown]

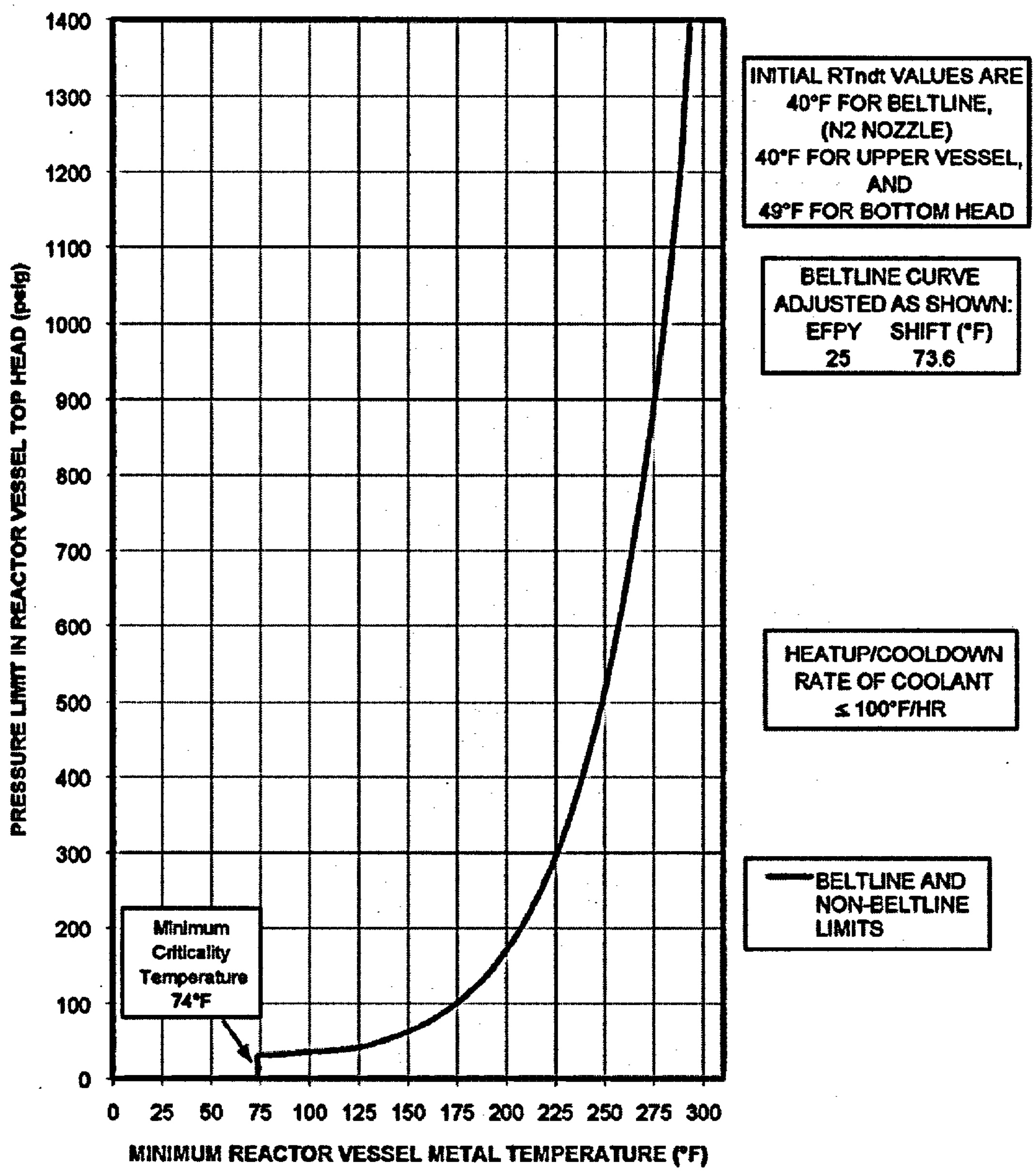

Figure 5-9: Composite Core Critical P-T Curves [Curve C] up to 25 EFPY
[100°F/hr or less coolant heatup/cooldown]

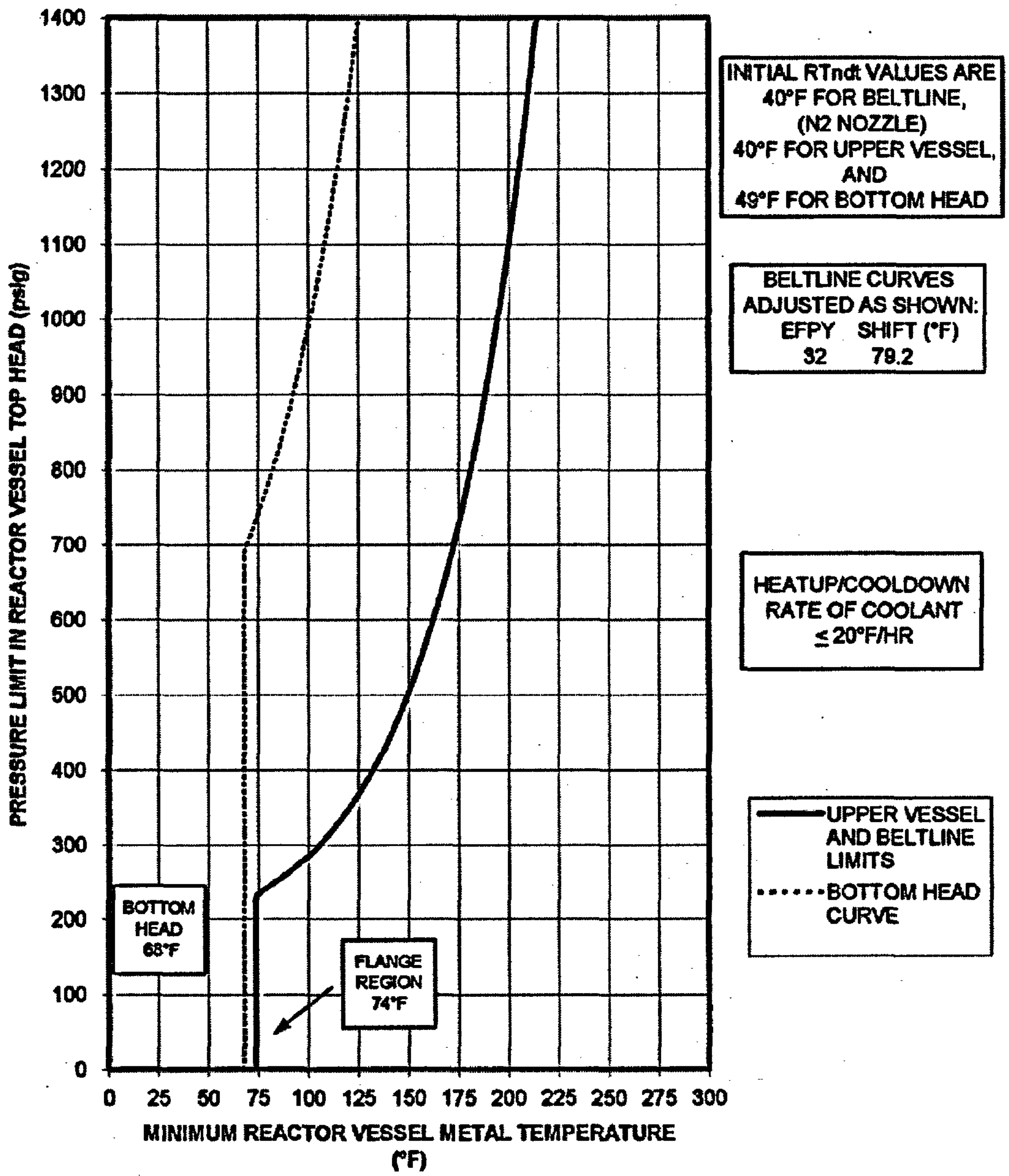

Figure 5-10: Composite Pressure Test P-T Curves [Curve A] up to 32 EFPY
[20°F/hr or less coolant heatup/cooldown]

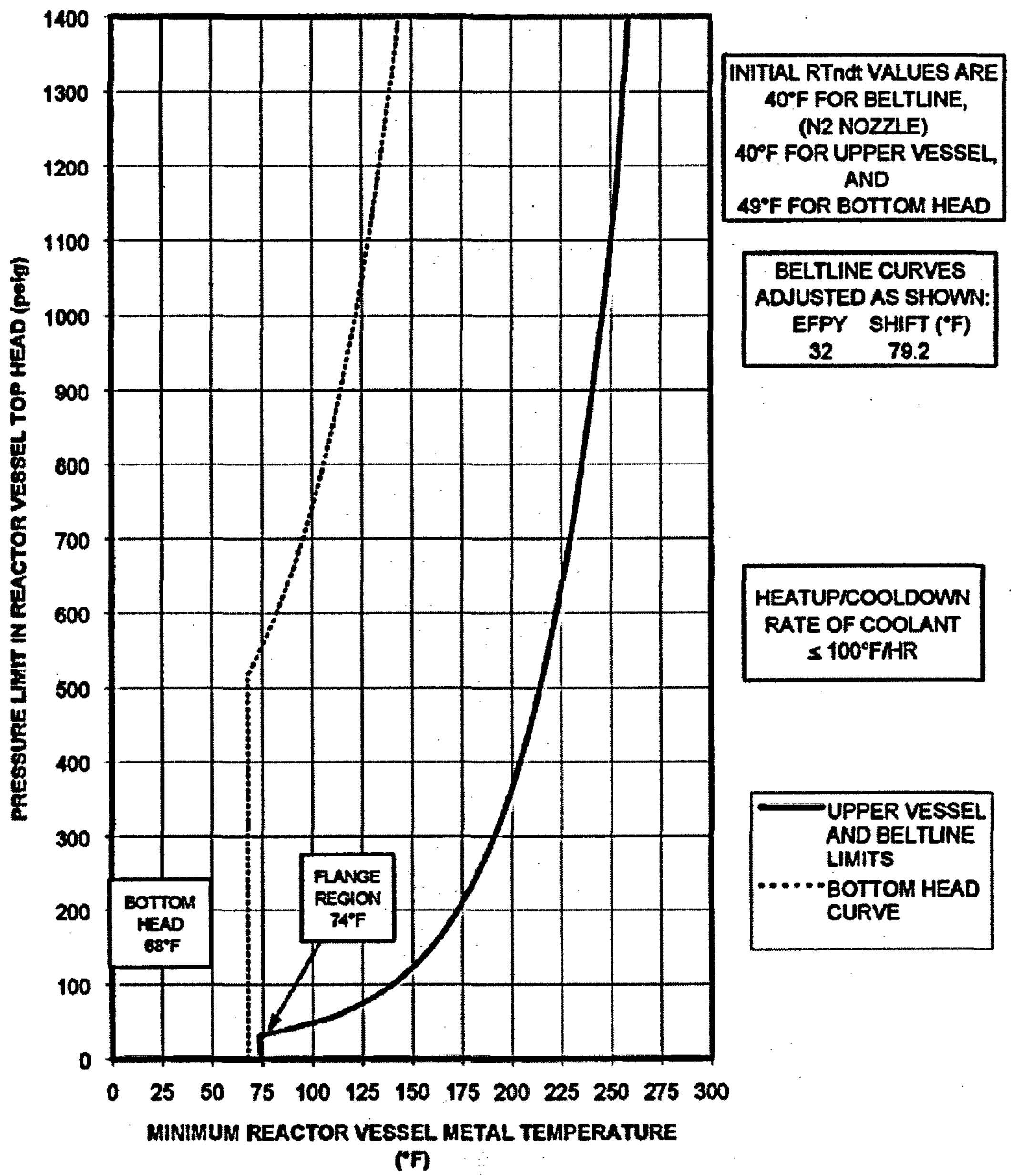

Figure 5-11: Composite Core Not Critical P-T Curves [Curve B] up to 32 EFPY
[100°F/hr or less coolant heatup/cooldown]

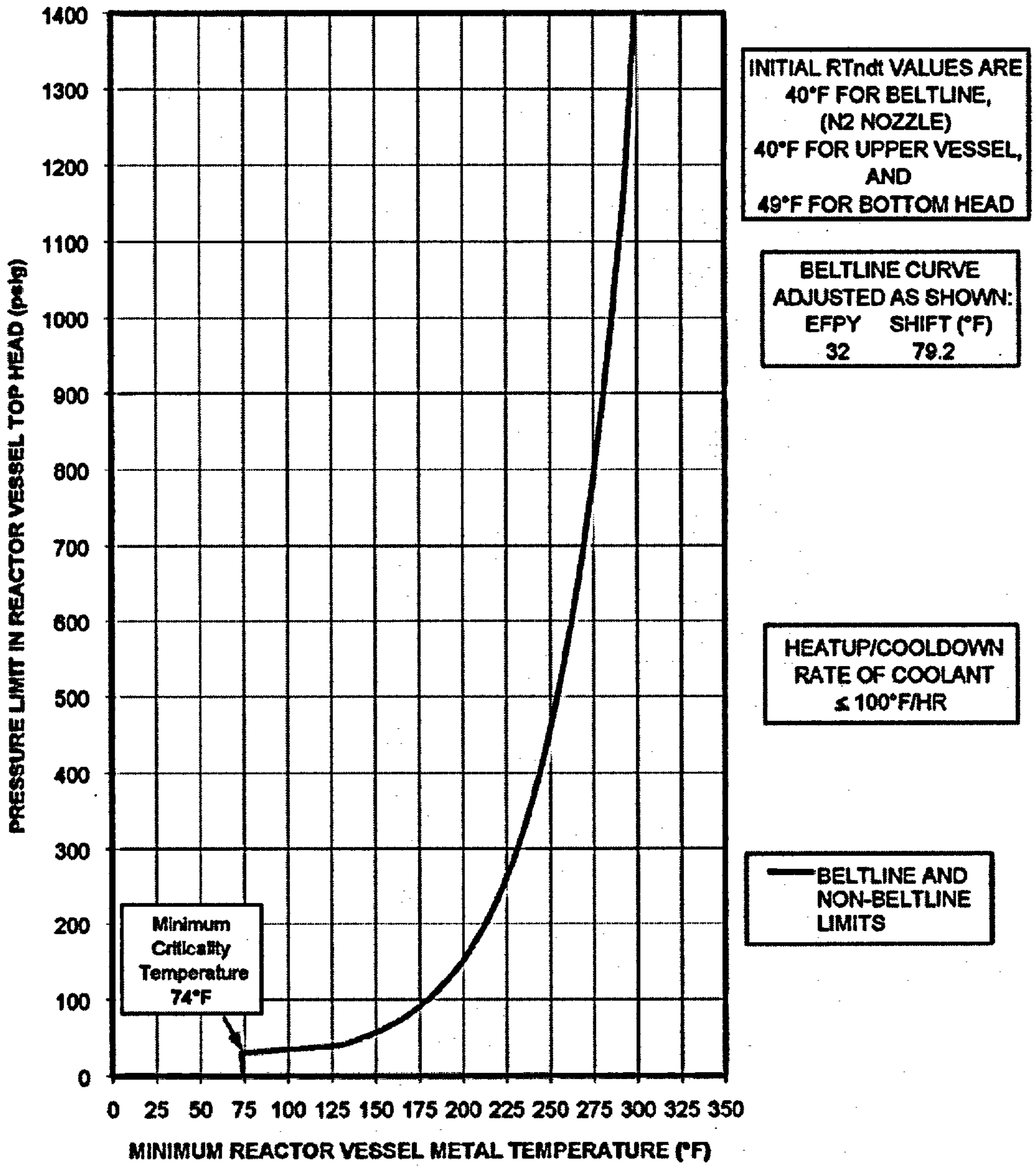

Figure 5-12: Composite Core Critical P-T Curves [Curve C] up to 32 EFPY
[100°F/hr or less coolant heatup/cooldown]

6.0 REFERENCES

1. B. D. Frew, "Pressure-Temperature Curves for Duane Arnold Energy Center," GE-NE, San Jose, CA, September 2000, (GE-NE-A22-00100-08-01 Revision 0) (GE Proprietary Information).

2. GE Drawing Number 729E762, "Reactor Thermal Cycles – Reactor Vessel," GE-NE, San Jose, CA, Revision 0. Duane Arnold RPV Thermal Cycle Diagram. DAEC MDL Document Number APED-A41-003 Revision 0 (GE Proprietary Information).

3. GE Drawing Number 135B9990, "Nozzle Thermal Cycles – Reactor Vessel," GE-APED, San Jose, CA, Sh1 Revision 1 Sh 2-8 Revision 0. Duane Arnold Nozzle Thermal Cycle Diagram. DAEC MDL Document Number APED-B11-003, <1> Revision 1 <2>-<8> Revision 0 (GE Proprietary Information).

4. "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.

5. L. J. Tilly, "Duane Arnold RPV Surveillance Materials Testing and Analysis" GE-NE, San Jose, CA, July 1997, (GE-NE-B1100716-01, Revision 0).

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 Information).

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 CMTR's: Duane Arnold - QA Records & RPV CMTR's Duane Amold GE PO# 205-H1289, Mfg by CBI)", General Electric Company Atomic Power Equipment Department (APED) Quality Control - Procured Equipment, RPV QC", Project: Duane Arnold, Purchase Order: 205-H1289, Vendor: Chicago Bridge & Iron Co, Location: Birmingham, Alabama.

13. Not Used

14. Letter, S.A. Richards, 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) "General Plan 183" BWR Nuclear Reactor Vessel for Iowa Electric Light and Power", CBI Nuclear Company (GE VPF 2655-18-10). DAEC MDL Document Number APED-B11-2655-018, Revision 10.

   b) "Feedwater Nozzle Mark N4 A/D," CBI Nuclear Company (GE VPF 2655-99-7). DAEC MDL Document Number APED-B11-2655-099, Revision 8.

20. [[

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

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. Nozzles and appurtenances made from Alloy 600 (Inconel) do not require fracture toughness analysis. Components that do not require a fracture toughness evaluation are listed below:

Nozzle or Appurtenance Identification	Nozzle or Appurtenance	Material	Reference	Remarks
MK 48-1-1,2,4 48-1-3 48-2 9-1	Shroud Support Attachment to RPV Bottom Head	Alloy 600 SB-168	1, 2, 3 & 5	Nozzles or appurtenances made from Alloy 600 (Inconel) require no fracture toughness evaluation.
MK 74, 75, 77-84	Insulation Brackets – Lower-Intermediate Shells and Bottom Head	SA-240 TP 304 L	1, 2, 3 & 5	Nozzles or appurtenances made from stainless steel require no fracture toughness evaluation.
MK 101-128	Control Rod Drive Stub Tubes – Bottom Head	Alloy 600 SB-167	2, 3 & 5	Nozzles or appurtenances made from Alloy 600 (Inconel) require no fracture toughness evaluation.
N13, N14	High and Low Pressure Seal Leak Detection * - Flange	. Alloy 600 SB-166	1, 3 & 5	Not a pressure boundary component; therefore, requires no fracture toughness evaluation.
MK 210	Top Head Lifting Lugs	SA-533 GR B CL I	1, 2, 3 & 5	Not a pressure boundary component and loads only occur on this component when the reactor is shutdown during an outage. Therefore, no fracture toughness evaluation is required.

* 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. GE Drawing # 197R608, Revision 9, "Reactor Assembly, Nuclear Boiler," GE-NE, San Jose, CA. DAEC MDL Document Number APED-B11-084<1> Revision 9 and APED-B11-084<2> Revision 8.

2. Certified Stress Report: "Stress Report, 183, BWR Vessel, Duane Arnold Energy Center, Iowa Electric Light and Power Co. VPF # 2655-330-1. DAEC MDL Document Number APED-B11-232 Revision 1.

3. QA Records & RPV CMTR's: Duane Arnold - QA Records & RPV CMTR's Duane Arnold GE PO# 205-H1289, Mfg by CBI)" General Electric Company Atomic Power Equipment Department (APED) Quality Control - Procured Equipment, RPV QC" Project: Duane Arnold, Purchase Order: 205-H1289, Vendor: Chicago Bridge & Iron Co, Location: Birmingham, Alabama.

4. "General Plan 183" BWR Nuclear Reactor Vessel for Iowa Electric Light and Power", CBI Nuclear Company (GE VPF 2655-18-10). DAEC MDL Document Number APED-B11-2655-018 Revision 10.

5. Chicago Bridge & Iron Co, "Vessel & Attachment Mat'l Identification", (GE-NE VPF# 2655-322(1)-1).

6. Chicago Bridge and Iron Co., "Instrumentation Nozzles Mark N11 A/B and N16 A/B," (GE-NE VPF 2655-109-6). DAEC MDL Document Number APED B11-2655-109, Revision 5.

7. Chicago Bridge & Iron Co, "Recirculation Inlet Nozzle MK N2 A/H", (GE-NE VPF# 2655-96-6).

APPENDIX B

Pressure-Temperature Curve Data Tabulation

TABLE B-1. Duane Arnold P-T Curve Values for 32 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figures 5-1, 5-2, 5-4, 5-5, 5-6, & 5-8

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER VESSEL CURVE A (°F)	32 EFPY BELTLINE CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	32 EFPY BELTLINE CURVE B (°F)
0	68.0	74.0	74.0	68.0	74.0	74.0
10	68.0	74.0	74.0	68.0	74.0	74.0
20	68.0	74.0	74.0	68.0	74.0	74.0
30	68.0	74.0	74.0	68.0	74.0	74.0
40	68.0	74.0	74.0	68.0	74.0	88.3
50	68.0	74.0	74.0	68.0	74.0	102.8
60	68.0	74.0	74.0	68.0	74.0	113.6
70	68.0	74.0	74.0	68.0	74.0	122.2
80	68.0	74.0	74.0	68.0	74.0	129.2
90	68.0	74.0	74.0	68.0	74.0	135.1
100	68.0	74.0	74.0	68.0	74.0	140.3
110	68.0	74.0	74.0	68.0	74.0	144.9
120	68.0	74.0	74.0	68.0	74.0	149.2
130	68.0	74.0	74.0	68.0	74.2	153.1
140	68.0	74.0	74.0	68.0	77.4	156.7
150	68.0	74.0	74.0	68.0	80.2	159.8
160	68.0	74.0	74.0	68.0	82.9	162.8
170	68.0	74.0	74.0	68.0	85.5	165.7
180	68.0	74.0	74.0	68.0	87.9	168.3
190	68.0	74.0	74.0	68.0	90.2	170.8
200	68.0	74.0	74.0	68.0	92.3	173.1
210	68.0	74.0	74.0	68.0	94.3	175.3
220	68.0	74.0	74.0	68.0	96.3	177.5
230	68.0	74.0	74.0	68.0	98.1	179.5

TABLE B-1. Duane Arnold P-T Curve Values for 32 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figures 5-1, 5-2, 5-4, 5-5, 5-6, & 5-8

PRESSURE	BOTTOM HEAD CURVE A	UPPER VESSEL CURVE A	32 EFPY BELTLINE CURVE A	BOTTOM HEAD CURVE B	UPPER VESSEL CURVE B	32 EFPY BELTLINE CURVE B
240	68.0	74.0	78.3	68.0	99.9	181.4
250	68.0	74.0	84.1	68.0	101.6	183.3
260	68.0	74.0	89.2	68.0	103.2	185.0
270	68.0	74.0	93.9	68.0	104.8	186.7
280	68.0	74.0	98.2	68.0	106.3	188.4
290	68.0	74.0	102.1	68.0	107.8	190.0
300	68.0	74.0	105.8	68.0	109.2	191.5
310	68.0	74.0	109.2	68.0	110.5	192.9
312.5	68.0	74.0	110.0	68.0	110.9	193.3
312.5	68.0	104.0	110.0	68.0	134.0	193.3
320	68.0	104.0	112.4	68.0	134.0	194.4
330	68.0	104.0	115.4	68.0	134.0	195.8
340	68.0	104.0	118.2	68.0	134.0	197.1
350	68.0	104.0	120.8	68.0	134.0	198.4
360	68.0	104.0	123.4	68.0	134.0	199.7
370	68.0	104.0	125.8	68.0	134.0	200.9
380	68.0	104.0	128.1	68.0	134.0	202.1
390	68.0	104.0	130.3	68.0	134.0	203.2
400	68.0	104.0	132.4	68.0	134.0	204.4
410	68.0	104.0	134.4	68.0	134.0	205.5
420	68.0	104.0	136.4	68.0	134.0	206.6
430	68.0	104.0	138.3	68.0	134.0	207.6
440	68.0	104.0	140.1	68.0	134.0	208.7
450	68.0	104.0	141.8	68.0	134.0	209.7
460	68.0	104.0	143.5	68.0	134.0	210.6
470	68.0	104.0	145.1	68.0	134.0	211.6

TABLE B-1. Duane Arnold P-T Curve Values for 32 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A

For Figures 5-1, 5-2, 5-4, 5-5, 5-6, & 5-8

PRESSURE	BOTTOM HEAD CURVE A	UPPER VESSEL CURVE A	32 EFPY BELTLINE CURVE A	BOTTOM HEAD CURVE B	UPPER VESSEL CURVE B	32 EFPY BELTLINE CURVE B
480	68.0	104.0	146.7	68.0	134.0	212.6
490	68.0	104.0	148.2	68.0	134.0	213.5
500	68.0	104.0	149.7	68.0	134.0	214.4
510	68.0	104.0	151.1	68.0	134.0	215.3
520	68.0	104.0	152.6	68.2	134.0	216.2
530	68.0	104.0	153.9	70.2	134.0	217.0
540	68.0	104.0	155.2	72.1	134.0	217.9
550	68.0	104.0	156.5	73.9	134.6	218.7
560	68.0	104.0	157.8	75.7	135.4	219.5
570	68.0	104.0	159.0	77.4	136.1	220.3
580	68.0	104.0	160.2	79.0	136.9	221.1
590	68.0	104.0	161.4	80.6	137.6	221.8
600	68.0	104.0	162.5	82.2	138.1	222.6
610	68.0	104.0	163.7	83.7	138.6	223.3
620	68.0	104.0	164.7	85.1	139.0	224.1
630	68.0	104.0	165.8	86.5	139.4	224.8
640	68.0	104.0	166.9	87.9	139.8	225.5
650	68.0	104.0	167.9	89.2	140.2	226.2
660	68.0	104.0	168.9	90.5	140.7	226.9
670	68.0	104.0	169.9	91.8	141.1	227.6
680	68.0	104.0	170.8	93.1	141.5	228.2
690	68.0	104.0	171.8	94.3	141.9	228.9
700	69.2	104.0	172.7	95.4	142.3	229.6
710	70.7	104.0	173.6	96.6	142.7	230.2
720	72.1	104.0	174.5	97.7	143.1	230.8
730	73.5	104.0	175.4	98.8	143.5	231.4

TABLE B-1. Duane Arnold P-T Curve Values for 32 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figures 5-1, 5-2, 5-4, 5-5, 5-6, & 5-8

PRESSURE	BOTTOM HEAD CURVE A	UPPER VESSEL CURVE A	32 EFPY BELTLINE CURVE A	BOTTOM HEAD CURVE B	UPPER VESSEL CURVE B	32 EFPY BELTLINE CURVE B
740	74.8	104.0	176.3	99.9	143.9	232.1
750	76.1	104.0	177.1	101.0	144.2	232.7
760	77.4	104.8	178.0	102.0	144.6	233.3
770	78.6	105.6	178.8	103.0	145.0	233.9
780	79.8	106.3	179.6	104.0	145.4	234.5
790	81.0	107.1	180.4	105.0	145.8	235.0
800	82.2	107.9	181.2	105.9	146.1	235.6
810	83.3	108.6	182.0	106.9	146.5	236.2
820	84.4	109.4	182.7	107.8	146.9	236.7
830	85.5	110.1	183.5	108.7	147.2	237.3
840	86.5	110.8	184.2	109.6	147.6	237.8
850	87.6	111.5	184.9	110.4	147.9	238.4
860	88.6	112.2	185.7	111.3	148.3	238.9
870	89.6	112.9	186.4	112.1	148.6	239.4
880	90.5	113.6	187.1	113.0	149.0	239.9
890	91.5	114.3	187.8	113.8	149.3	240.5
900	92.4	114.9	188.4	114.6	149.7	241.0
910	93.4	115.6	189.1	115.4	150.0	241.5
920	94.3	116.2	189.8	116.1	150.4	242.0
930	95.1	116.9	190.4	116.9	150.7	242.5
940	96.0	117.5	191.1	117.7	151.0	242.9
950	96.9	118.1	191.7	118.4	151.4	243.4
960	97.7	118.7	192.3	119.1	151.7	243.9
970	98.6	119.3	192.9	119.9	152.0	244.4
980	99.4	119.9	193.6	120.6	152.4	244.8
990	100.2	120.5	194.2	121.3	152.7	245.3

TABLE B-1. Duane Arnold P-T Curve Values for 32 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figures 5-1, 5-2, 5-4, 5-5, 5-6, & 5-8

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER VESSEL CURVE A (°F)	32 EFPY BELTLINE CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	32 EFPY BELTLINE
1000	101.0	121.1	194.8	122.0	153.0	245.8
1010	101.7	121.7	195.3	122.6	153.3	246.2
1020	102.5	122.2	195.9	123.3	153.6	246.7
1030	103.3	122.8	196.5	124.0	154.0	247.1
1040	104.0	123.4	197.1	124.6	154.3	247.5
1050	104.7	123.9	197.6	125.3	154.6	248.0
1060	105.4	124.5	198.2	125.9	154.9	248.4
1070	106.2	125.0	198.7	126.5	155.2	248.8
1080	106.9	125.5	199.3	127.2	155.5	249.3
1090	107.6	126.1	199.8	127.8	155.8	249.7
1100	108.2	126.6	200.4	128.4	156.1	250.1
1110	108.9	127.1	200.9	129.0	156.4	250.5
1120	109.6	127.6	201.4	129.6	156.7	250.9
1130	110.2	128.1	201.9	130.2	157.0	251.3
1140	110.9	128.6	202.4	130.7	157.3	251.7
1150	111.5	129.1	202.9	131.3	157.6	252.1
1160	112.1	129.6	203.5	131.9	157.9	252.5
1170	112.8	130.1	203.9	132.4	158.2	252.9
1180	113.4	130.6	204.4	133.0	158.5	253.3
1190	114.0	131.1	204.9	133.5	158.7	253.6
1200	114.6	131.5	205.4	134.1	159.0	253.9
1210	115.2	132.0	205.9	134.6	159.3	254.1
1220	115.8	132.5	206.4	135.2	159.6	254.4
1230	116.3	132.9	206.8	135.7	159.9	254.7
1240	116.9	133.4	207.3	136.2	160.2	254.9
1250	117.5	133.8	207.8	136.7	160.4	255.2

TABLE B-1. Duane Arnold P-T Curve Values for 32 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A

For Figures 5-1, 5-2, 5-4, 5-5, 5-6, & 5-8

PRESSURE	BOTTOM HEAD CURVE A	UPPER VESSEL CURVE A	32 EFPY BELTLINE CURVE A	BOTTOM HEAD CURVE B	UPPER VESSEL CURVE B	32 EFPY BELTLINE CURVE B
1260	118.0	134.3	208.2	137.2	160.7	255.4
1270	118.6	134.7	208.7	137.7	161.0	255.7
1280	119.1	135.2	209.1	138.2	161.2	255.9
1290	119.7	135.6	209.6	138.7	161.5	256.2
1300	120.2	136.0	210.0	139.2	161.8	256.4
1310	120.7	136.5	210.4	139.7	162.1	256.7
1320	121.3	136.9	210.9	140.2	162.3	256.9
1330	121.8	137.3	211.3	140.6	162.6	257.2
1340	122.3	137.7	211.7	141.1	162.8	257.4
1350	122.8	138.1	212.1	141.6	163.1	257.6
1360	123.3	138.6	212.6	142.0	163.4	257.9
1370	123.8	139.0	213.0	142.5	163.6	258.1
1380	124.3	139.4	213.4	142.9	163.9	258.4
1390	124.8	139.8	213.8	143.4	164.1	258.6
1400	125.3	140.2	214.2	143.8	164.4	258.8

TABLE B-2. Duane Arnold Composite P-T Curve Values for 32 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figures 5-10, 5-11 and 5-12

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 32 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 32 EFPY CURVE B (°F)	NON-BELTLINE & BELTLINE 32 EFPY CURVE C (°F)
0	68.0	74.0	68.0	74.0	74.0
10	68.0	74.0	68.0	74.0	74.0
20	68.0	74.0	68.0	74.0	74.0
30	68.0	74.0	68.0	74.0	105.9
40	68.0	74.0	68.0	88.3	128.3
50	68.0	74.0	68.0	102.8	142.8
60	68.0	74.0	68.0	113.6	153.6
70	68.0	74.0	68.0	122.2	162.2
80	68.0	74.0	68.0	129.2	169.2
90	68.0	74.0	68.0	135.1	175.1
100	68.0	74.0	68.0	140.3	180.3
110	68.0	74.0	68.0	144.9	184.9
120	68.0	74.0	68.0	149.2	189.2
130	68.0	74.0	68.0	153.1	193.1
140	68.0	74.0	68.0	156.7	196.7
150	68.0	74.0	68.0	159.8	199.8
160	68.0	74.0	68.0	162.8	202.8
170	68.0	74.0	68.0	165.7	205.7
180	68.0	74.0	68.0	168.3	208.3
190	68.0	74.0	68.0	170.8	210.8
200	68.0	74.0	68.0	173.1	213.1

TABLE B-2. Duane Arnold Composite P-T Curve Values for 32 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figures 5-10, 5-11 and 5-12

PRESSURE	BOTTOM HEAD CURVE A	UPPER RPV & BELTLINE AT 32 EFPY CURVE A	BOTTOM HEAD CURVE B	UPPER RPV & BELTLINE AT 32 EFPY CURVE B	NON-BELTLINE & BELTLINE 32 EFPY CURVE C
210	68.0	74.0	68.0	175.3	215.3
220	68.0	74.0	68.0	177.5	217.5
230	68.0	74.0	68.0	179.5	219.5
240	68.0	78.3	68.0	181.4	221.4
250	68.0	84.1	68.0	183.3	223.3
260	68.0	89.2	68.0	185.0	225.0
270	68.0	93.9	68.0	186.7	226.7
280	68.0	98.2	68.0	188.4	228.4
290	68.0	102.1	68.0	190.0	230.0
300	68.0	105.8	68.0	191.5	231.5
310	68.0	109.2	68.0	192.9	232.9
312.5	68.0	110.0	68.0	193.3	233.3
312.5	68.0	110.0	68.0	193.3	233.3
320	68.0	112.4	68.0	194.4	234.4
330	68.0	115.4	68.0	195.8	235.8
340	68.0	118.2	68.0	197.1	237.1
350	68.0	120.8	68.0	198.4	238.4
360	68.0	123.4	68.0	199.7	239.7
370	68.0	125.8	68.0	200.9	240.9
380	68.0	128.1	68.0	202.1	242.1
390	68.0	130.3	68.0	203.2	243.2
400	68.0	132.4	68.0	204.4	244.4

TABLE B-2. Duane Arnold Composite P-T Curve Values for 32 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figures 5-10, 5-11 and 5-12

PRESSURE	BOTTOM HEAD CURVE A	UPPER RPV & BELTLINE AT 32 EFPY CURVE A	BOTTOM HEAD CURVE B	UPPER RPV & BELTLINE AT 32 EFPY CURVE B	NON-BELTLINE & BELTLINE 32 EFPY CURVE C
410	68.0	134.4	68.0	205.5	245.5
420	68.0	136.4	68.0	206.6	246.6
430	68.0	138.3	68.0	207.6	247.6
440	68.0	140.1	68.0	208.7	248.7
450	68.0	141.8	68.0	209.7	249.7
460	68.0	143.5	68.0	210.6	250.6
470	68.0	145.1	68.0	211.6	251.6
480	68.0	146.7	68.0	212.6	252.6
490	68.0	148.2	68.0	213.5	253.5
500	68.0	149.7	68.0	214.4	254.4
510	68.0	151.1	68.0	215.3	255.3
520	68.0	152.6	68.2	216.2	256.2
530	68.0	153.9	70.2	217.0	257.0
540	68.0	155.2	72.1	217.9	257.9
550	68.0	156.5	73.9	218.7	258.7
560	68.0	157.8	75.7	219.5	259.5
570	68.0	159.0	77.4	220.3	260.3
580	68.0	160.2	79.0	221.1	261.1
590	68.0	161.4	80.6	221.8	261.8
600	68.0	162.5	82.2	222.6	262.6
610	68.0	163.7	83.7	223.3	263.3
620	68.0	164.7	85.1	224.1	264.1

TABLE B-2. Duane Arnold Composite P-T Curve Values for 32 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figures 5-10, 5-11 and 5-12

	BOTTOM HEAD	UPPER RPV & BELTLINE AT 32 EFPY	BOTTOM HEAD	UPPER RPV & BELTLINE AT 32 EFPY	NON-BELTLINE & BELTLINE 32 EFPY
PRESSURE	CURVE A	CURVE A	CURVE B	CURVE B	CURVE C
630	68.0	165.8	86.5	224.8	264.8
640	68.0	166.9	87.9	225.5	265.5
650	68.0	167.9	89.2	226.2	266.2
660	68.0	168.9	90.5	226.9	266.9
670	68.0	169.9	91.8	227.6	267.6
680	68.0	170.8	93.1	228.2	268.2
690	68.0	171.8	94.3	228.9	268.9
700	69.2	172.7	95.4	229.6	269.6
710	70.7	173.6	96.6	230.2	270.2
720	72.1	174.5	97.7	230.8	270.8
730	73.5	175.4	98.8	231.4	271.4
740	74.8	176.3	99.9	232.1	272.1
750	76.1	177.1	101.0	232.7	272.7
760	77.4	178.0	102.0	233.3	273.3
770	78.6	178.8	103.0	233.9	273.9
780	79.8	179.6	104.0	234.5	274.5
790	81.0	180.4	105.0	235.0	275.0
800	82.2	181.2	105.9	235.6	275.6
810	83.3	182.0	106.9	236.2	276.2
820	84.4	182.7	107.8	236.7	276.7
830	85.5	183.5	108.7	237.3	277.3
840	86.5	184.2	109.6	237.8	277.8

TABLE B-2. Duane Arnold Composite P-T Curve Values for 32 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figures 5-10, 5-11 and 5-12

PRESSURE	BOTTOM HEAD CURVE A	UPPER RPV & BELTLINE AT 32 EFPY CURVE A	BOTTOM HEAD CURVE B	UPPER RPV & BELTLINE AT 32 EFPY CURVE B	NON-BELTLINE & BELTLINE 32 EFPY CURVE C
850	87.6	184.9	110.4	238.4	278.4
860	88.6	185.7	111.3	238.9	278.9
870	89.6	186.4	112.1	239.4	279.4
880	90.5	187.1	113.0	239.9	279.9
890	91.5	187.8	113.8	240.5	280.5
900	92.4	188.4	114.6	241.0	281.0
910	93.4	189.1	115.4	241.5	281.5
920	94.3	189.8	116.1	242.0	282.0
930	95.1	190.4	116.9	242.5	282.5
940	96.0	191.1	117.7	242.9	282.9
950	96.9	191.7	118.4	243.4	283.4
960	97.7	192.3	119.1	243.9	283.9
970	98.6	192.9	119.9	244.4	284.4
980	99.4	193.6	120.6	244.8	284.8
990	100.2	194.2	121.3	245.3	285.3
1000	101.0	194.8	122.0	245.8	285.8
1010	101.7	195.3	122.6	246.2	286.2
1020	102.5	195.9	123.3	246.7	286.7
1030	103.3	196.5	124.0	247.1	287.1
1040	104.0	197.1	124.6	247.5	287.5
1050	104.7	197.6	125.3	248.0	288.0
1060	105.4	198.2	125.9	248.4	288.4

TABLE B-2. Duane Arnold Composite P-T Curve Values for 32 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figures 5-10, 5-11 and 5-12

PRESSURE	BOTTOM HEAD CURVE A	UPPER RPV & BELTLINE AT 32 EFPY CURVE A	BOTTOM HEAD CURVE B	UPPER RPV & BELTLINE AT 32 EFPY CURVE B	NON-BELTLINE & BELTLINE 32 EFPY CURVE C
1070	106.2	198.7	126.5	248.8	288.8
1080	106.9	199.3	127.2	249.3	289.3
1090	107.6	199.8	127.8	249.7	289.7
1100	108.2	200.4	128.4	250.1	290.1
1110	108.9	200.9	129.0	250.5	290.5
1120	109.6	201.4	129.6	250.9	290.9
1130	110.2	201.9	130.2	251.3	291.3
1140	110.9	202.4	130.7	251.7	291.7
1150	111.5	202.9	131.3	252.1	292.1
1160	112.1	203.5	131.9	252.5	292.5
1170	112.8	203.9	132.4	252.9	292.9
1180	113.4	204.4	133.0	253.3	293.3
1190	114.0	204.9	133.5	253.6	293.6
1200	114.6	205.4	134.1	253.9	293.9
1210	115.2	205.9	134.6	254.1	294.1
1220	115.8	206.4	135.2	254.4	294.4
1230	116.3	206.8	135.7	254.7	294.7
1240	116.9	207.3	136.2	254.9	294.9
1250	117.5	207.8	136.7	255.2	295.2
1260	118.0	208.2	137.2	255.4	295.4
1270	118.6	208.7	137.7	255.7	295.7
1280	119.1	209.1	138.2	255.9	295.9

TABLE B-2. Duane Arnold Composite P-T Curve Values for 32 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figures 5-10, 5-11 and 5-12

PRESSURE	BOTTOM HEAD CURVE A	UPPER RPV & BELTLINE AT 32 EFPY CURVE A	BOTTOM HEAD CURVE B	UPPER RPV & BELTLINE AT 32 EFPY CURVE B	NON-BELTLINE & BELTLINE 32 EFPY CURVE C
1290	119.7	209.6	138.7	256.2	296.2
1300	120.2	210.0	139.2	256.4	296.4
1310	120.7	210.4	139.7	256.7	296.7
1320	121.3	210.9	140.2	256.9	296.9
1330	121.8	211.3	140.6	257.2	297.2
1340	122.3	211.7	141.1	257.4	297.4
1350	122.8	212.1	141.6	257.6	297.6
1360	123.3	212.6	142.0	257.9	297.9
1370	123.8	213.0	142.5	258.1	298.1
1380	124.3	213.4	142.9	258.4	298.4
1390	124.8	213.8	143.4	258.6	298.6
1400	125.3	214.2	143.8	258.8	298.8

TABLE B-3. Duane Arnold P-T Curve Values for 25 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °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)	25 EFPY BELTLINE CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	25 EFPY BELTLINE CURVE B (°F)
0	68.0	74.0	74.0	68.0	74.0	74.0
10	68.0	74.0	74.0	68.0	74.0	74.0
20	68.0	74.0	74.0	68.0	74.0	74.0
30	68.0	74.0	74.0	68.0	74.0	74.0
40	68.0	74.0	74.0	68.0	74.0	82.7
50	68.0	74.0	74.0	68.0	74.0	97.2
60	68.0	74.0	74.0	68.0	74.0	108.0
70	68.0	74.0	74.0	68.0	74.0	116.6
80	68.0	74.0	74.0	68.0	74.0	123.6
90	68.0	74.0	74.0	68.0	74.0	129.5
100	68.0	74.0	74.0	68.0	74.0	134.7
110	68.0	74.0	74.0	68.0	74.0	139.3
120	68.0	74.0	74.0	68.0	74.0	143.6
130	68.0	74.0	74.0	68.0	74.2	147.5
140	68.0	74.0	74.0	68.0	77.4	151.1
150	68.0	74.0	74.0	68.0	80.2	154.2
160	68.0	74.0	74.0	68.0	82.9	157.2
170	68.0	74.0	74.0	68.0	85.5	160.1
180	68.0	74.0	74.0	68.0	87.9	162.7
190	68.0	74.0	74.0	68.0	90.2	165.2
200	68.0	74.0	74.0	68.0	92.3	167.5
210	68.0	74.0	74.0	68.0	94.3	169.7
220	68.0	74.0	74.0	68.0	96.3	171.9
230	68.0	74.0	74.0	68.0	98.1	173.9

TABLE B-3. Duane Arnold P-T Curve Values for 25 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figures 5-1, 5-2, 5-3, 5-5, 5-6, & 5-7

PRESSURE	BOTTOM HEAD CURVE A	UPPER VESSEL CURVE A	25 EFPY BELTLINE CURVE A	BOTTOM HEAD CURVE B	UPPER VESSEL CURVE B	25 EFPY BELTLINE CURVE B
240	68.0	74.0	74.0	68.0	99.9	175.8
250	68.0	74.0	78.5	68.0	101.6	177.7
260	68.0	74.0	83.6	68.0	103.2	179.4
270	68.0	74.0	88.3	68.0	104.8	181.1
280	68.0	74.0	92.6	68.0	106.3	182.8
290	68.0	74.0	96.5	68.0	107.8	184.4
300	68.0	74.0	100.2	68.0	109.2	185.9
310	68.0	74.0	103.6	68.0	110.5	187.3
312.5	68.0	74.0	104.4	68.0	110.9	187.7
312.5	68.0	104.0	104.4	68.0	134.0	187.7
320	68.0	104.0	106.8	68.0	134.0	188.8
330	68.0	104.0	109.8	68.0	134.0	190.2
340	68.0	104.0	112.6	68.0	134.0	191.5
350	68.0	104.0	115.2	68.0	134.0	192.8
360	68.0	104.0	117.8	68.0	134.0	194.1
370	68.0	104.0	120.2	68.0	134.0	195.3
380	68.0	104.0	122.5	68.0	134.0	196.5
390	68.0	104.0	124.7	68.0	134.0	197.6
400	68.0	104.0	126.8	68.0	134.0	198.8
410	68.0	104.0	128.8	68.0	134.0	199.9
420	68.0	104.0	130.8	68.0	134.0	201.0
430	68.0	104.0	132.7	68.0	134.0	202.0
440	68.0	104.0	134.5	68.0	134.0	203.1
450	68.0	104.0	136.2	68.0	134.0	204.1
460	68.0	104.0	137.9	68.0	134.0	205.0
470	68.0	104.0	139.5	68.0	134.0	206.0

TABLE B-3. Duane Arnold P-T Curve Values for 25 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figures 5-1, 5-2, 5-3, 5-5, 5-6, & 5-7

PRESSURE	BOTTOM HEAD CURVE A	UPPER VESSEL CURVE A	25 EFPY BELTLINE CURVE A	BOTTOM HEAD CURVE B	UPPER VESSEL CURVE B	25 EFPY BELTLINE CURVE B
480	68.0	104.0	141.1	68.0	134.0	207.0
490	68.0	104.0	142.6	68.0	134.0	207.9
500	68.0	104.0	144.1	68.0	134.0	208.8
510	68.0	104.0	145.5	68.0	134.0	209.7
520	68.0	104.0	147.0	68.2	134.0	210.6
530	68.0	104.0	148.3	70.2	134.0	211.4
540	68.0	104.0	149.6	72.1	134.0	212.3
550	68.0	104.0	150.9	73.9	134.6	213.1
560	68.0	104.0	152.2	75.7	135.4	213.9
570	68.0	104.0	153.4	77.4	136.1	214.7
580	68.0	104.0	154.6	79.0	136.9	215.5
590	68.0	104.0	155.8	80.6	137.6	216.2
600	68.0	104.0	156.9	82.2	138.1	217.0
610	68.0	104.0	158.1	83.7	138.6	217.7
620	68.0	104.0	159.1	85.1	139.0	218.5
630	68.0	104.0	160.2	86.5	139.4	219.2
640	68.0	104.0	161.3	87.9	139.8	219.9
650	68.0	104.0	162.3	89.2	140.2	220.6
660	68.0	104.0	163.3	90.5	140.7	221.3
670	68.0	104.0	164.3	91.8	141.1	222.0
680	68.0	104.0	165.2	93.1	141.5	222.6
690	68.0	104.0	166.2	94.3	141.9	223.3
700	69.2	104.0	167.1	95.4	142.3	224.0
710	70.7	104.0	168.0	96.6	142.7	224.6
720	72.1	104.0	168.9	97.7	143.1	225.2
730	73.5	104.0	169.8	98.8	143.5	225.8

TABLE B-3. Duane Arnold P-T Curve Values for 25 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figures 5-1, 5-2, 5-3, 5-5, 5-6, & 5-7

PRESSURE	BOTTOM HEAD CURVE A	UPPER VESSEL CURVE A	25 EFPY BELTLINE CURVE A	BOTTOM HEAD CURVE B	UPPER VESSEL CURVE B	25 EFPY BELTLINE CURVE B
740	74.8	104.0	170.7	99.9	143.9	226.5
750	76.1	104.0	171.5	101.0	144.2	227.1
760	77.4	104.8	172.4	102.0	144.6	227.7
770	78.6	105.6	173.2	103.0	145.0	228.3
780	79.8	106.3	174.0	104.0	145.4	228.9
790	81.0	107.1	174.8	105.0	145.8	229.4
800	82.2	107.9	175.6	105.9	146.1	230.0
810	83.3	108.6	176.4	106.9	146.5	230.6
820	84.4	109.4	177.1	107.8	146.9	231.1
830	85.5	110.1	177.9	108.7	147.2	231.7
840	86.5	110.8	178.6	109.6	147.6	232.2
850	87.6	111.5	179.3	110.4	147.9	232.8
860	88.6	112.2	180.1	111.3	148.3	233.3
870	89.6	112.9	180.8	112.1	148.6	233.8
880	90.5	113.6	181.5	113.0	149.0	234.3
890	91.5	114.3	182.2	113.8	149.3	234.9
900	92.4	114.9	182.8	114.6	149.7	235.4
910	93.4	115.6	183.5	115.4	150.0	235.9
920	94.3	116.2	184.2	116.1	150.4	236.4
930	95.1	116.9	184.8	116.9	150.7	236.9
940	96.0	117.5	185.5	117.7	151.0	237.3
950	96.9	118.1	186.1	118.4	151.4	237.8
960	97.7	118.7	186.7	119.1	151.7	238.3
970	98.6	119.3	187.3	119.9	152.0	238.8
980	99.4	119.9	188.0	120.6	152.4	239.2
990	100.2	120.5	188.6	121.3	152.7	239.7

TABLE B-3. Duane Arnold P-T Curve Values for 25 EFPY

Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A

For Figures 5-1, 5-2, 5-3, 5-5, 5-6, & 5-7

PRESSURE	BOTTOM HEAD CURVE A	UPPER VESSEL CURVE A	25 EFPY BELTLINE CURVE A	BOTTOM HEAD CURVE B	UPPER VESSEL CURVE B	25 EFPY BELTLINE CURVE B
1000	101.0	121.1	189.2	122.0	153.0	240.2
1010	101.7	121.7	189.7	122.6	153.3	240.6
1020	102.5	122.2	190.3	123.3	153.6	241.1
1030	103.3	122.8	190.9	124.0	154.0	241.5
1040	104.0	123.4	191.5	124.6	154.3	241.9
1050	104.7	123.9	192.0	125.3	154.6	242.4
1060	105.4	124.5	192.6	125.9	154.9	242.8
1070	106.2	125.0	193.1	126.5	155.2	243.2
1080	106.9	125.5	193.7	127.2	155.5	243.7
1090	107.6	126.1	194.2	127.8	155.8	244.1
1100	108.2	126.6	194.8	128.4	156.1	244.5
1110	108.9	127.1	195.3	129.0	156.4	244.9
1120	109.6	127.6	195.8	129.6	156.7	245.3
1130	110.2	128.1	196.3	130.2	157.0	245.7
1140	110.9	128.6	196.8	130.7	157.3	246.1
1150	111.5	129.1	197.3	131.3	157.6	246.5
1160	112.1	129.6	197.9	131.9	157.9	246.9
1170	112.8	130.1	198.3	132.4	158.2	247.3
1180	113.4	130.6	198.8	133.0	158.5	247.7
1190	114.0	131.1	199.3	133.5	158.7	248.0
1200	114.6	131.5	199.8	134.1	159.0	248.3
1210	115.2	132.0	200.3	134.6	159.3	248.5
1220	115.8	132.5	200.8	135.2	159.6	248.8
1230	116.3	132.9	201.2	135.7	159.9	249.1
1240	116.9	133.4	201.7	136.2	160.2	249.3
1250	117.5	133.8	202.2	136.7	160.4	249.6

TABLE B-3. Duane Arnold P-T Curve Values for 25 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °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	BELTLINE (°F)	BOTTOM HEAD CURVE B (°F)	UPPER VESSEL CURVE B (°F)	25 EFPY BELTLINE
1260	118.0	134.3	202.6	137.2	160.7	249.8
1270	118.6	134.7	203.1	137.7	161.0	250.1
1280	119.1	135.2	203.5	138.2	161.2	250.3
1290	119.7	135.6	204.0	138.7	161.5	250.6
1300	120.2	136.0	204.4	139.2	161.8	250.8
1310	120.7	136.5	204.8	139.7	162.1	251.1
1320	121.3	136.9	205.3	140.2	162.3	251.3
1330	121.8	137.3	205.7	140.6	162.6	251.6
1340	122.3	137.7	206.1	141.1	162.8	251.8
1350	122.8	138.1	206.5	141.6	163.1	252.0
1360	123.3	138.6	207.0	142.0	163.4	252.3
1370	123.8	139.0	207.4	142.5	163.6	252.5
1380	124.3	139.4	207.8	142.9	163.9	252.8
1390	124.8	139.8	208.2	143.4	164.1	253.0
1400	125.3	140.2	208.6	143.8	164.4	253.2

TABLE B-4. Duane Arnold Power Uprate Composite P-T Curve Values for 25 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figure 5-9

	BOTTOM HEAD	UPPER RPV & BELTLINE AT 25 EFPY	BOTTOM HEAD	UPPER RPV & BELTLINE AT 25 EFPY	NON-BELTLINE AND BELTLINE AT 25 EFPY
PRESSURE	CURVE A	CURVE A	CURVE B	CURVE B	CURVE C
(PSIG)	(°F)	(°F)	(°F)	(°F)	(°F)
0	68.0	74.0	68.0	74.0	74.0
10	68.0	74.0	68.0	74.0	74.0
20	68.0	74.0	68.0	74.0	74.0
30	68.0	74.0	68.0	74.0	100.3
40	68.0	74.0	68.0	82.7	122.7
50	68.0	74.0	68.0	97.2	137.2
60	68.0	74.0	68.0	108.0	148.0
70	68.0	74.0	68.0	116.6	156.6
80	68.0	74.0	68.0	123.6	163.6
90	68.0	74.0	68.0	129.5	169.5
100	68.0	74.0	68.0	134.7	174.7
110	68.0	74.0	68.0	139.3	179.3
120	68.0	74.0	68.0	143.6	183.6
130	68.0	74.0	68.0	147.5	187.5
140	68.0	74.0	68.0	151.1	191.1
150	68.0	74.0	68.0	154.2	194.2
160	68.0	74.0	68.0	157.2	197.2
170	68.0	74.0	68.0	160.1	200.1
180	68.0	74.0	68.0	162.7	202.7
190	68.0	74.0	68.0	165.2	205.2
200	68.0	74.0	68.0	167.5	207.5
210	68.0	74.0	68.0	169.7	209.7

TABLE B-4. Duane Arnold Power Uprate Composite P-T Curve Values for 25 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figure 5-9

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 25 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 25 EFPY CURVE B (°F)	NON-BELTLINE AND BELTLINE AT 25 EFPY CURVE C (°F)
220	68.0	74.0	68.0	171.9	211.9
230	68.0	74.0	68.0	173.9	213.9
240	68.0	74.0	68.0	175.8	215.8
250	68.0	78.5	68.0	177.7	217.7
260	68.0	83.6	68.0	179.4	219.4
270	68.0	88.3	68.0	181.1	221.1
280	68.0	92.6	68.0	182.8	222.8
290	68.0	96.5	68.0	184.4	224.4
300	68.0	100.2	68.0	185.9	225.9
310	68.0	103.6	68.0	187.3	227.3
312.5	68.0	104.4	68.0	187.7	227.7
312.5	68.0	104.4	68.0	187.7	227.7
320	68.0	106.8	68.0	188.8	228.8
330	68.0	109.8	68.0	190.2	230.2
340	68.0	112.6	68.0	191.5	231.5
350	68.0	115.2	68.0	192.8	232.8
360	68.0	117.8	68.0	194.1	234.1
370	68.0	120.2	68.0	195.3	235.3
380	68.0	122.5	68.0	196.5	236.5
390	68.0	124.7	68.0	197.6	237.6
400	68.0	126.8	68.0	198.8	238.8
410	68.0	128.8	68.0	199.9	239.9
420	68.0	130.8	68.0	201.0	241.0
430	68.0	132.7	68.0	202.0	242.0

TABLE B-4. Duane Arnold Power Uprate Composite P-T Curve Values for 25 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figure 5-9

	BOTTOM HEAD	UPPER RPV & BELTLINE AT 25 EFPY	BOTTOM HEAD	UPPER RPV & BELTLINE AT 25 EFPY	NON-BELTLINE AND BELTLINE AT 25 EFPY
PRESSURE (PSIG)	CURVE A (°F)	CURVE A (°F)	CURVE B (°F)	CURVE B (°F)	CURVE C (°F)
440	68.0	134.5	68.0	203.1	243.1
450	68.0	136.2	68.0	204.1	244.1
460	68.0	137.9	68.0	205.0	245.0
470	68.0	139.5	68.0	206.0	246.0
480	68.0	141.1	68.0	207.0	247.0
490	68.0	142.6	68.0	207.9	247.9
500	68.0	144.1	68.0	208.8	248.8
510	68.0	145.5	68.0	209.7	249.7
520	68.0	147.0	68.2	210.6	250.6
530	68.0	148.3	70.2	211.4	251.4
540	68.0	149.6	72.1	212.3	252.3
550	68.0	150.9	73.9	213.1	253.1
560	68.0	152.2	75.7	213.9	253.9
570	68.0	153.4	77.4	214.7	254.7
580	68.0	154.6	79.0	215.5	255.5
590	68.0	155.8	80.6	216.2	256.2
600	68.0	156.9	82.2	217.0	257.0
610	68.0	158.1	83.7	217.7	257.7
620	68.0	159.1	85.1	218.5	258.5
630	68.0	160.2	86.5	219.2	259.2
640	68.0	161.3	87.9	219.9	259.9
650	68.0	162.3	89.2	220.6	260.6
660	68.0	163.3	90.5	221.3	261.3
670	68.0	164.3	91.8	222.0	262.0

TABLE B-4. Duane Arnold Power Uprate Composite P-T Curve Values for 25 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figure 5-9

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 25 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 25 EFPY CURVE B (°F)	NON-BELTLINE AND BELTLINE AT 25 EFPY CURVE C (°F)
680	68.0	165.2	93.1	222.6	262.6
690	68.0	166.2	94.3	223.3	263.3
700	69.2	167.1	95.4	224.0	264.0
710	70.7	168.0	96.6	224.6	264.6
720	72.1	168.9	97.7	225.2	265.2
730	73.5	169.8	98.8	225.8	265.8
740	74.8	170.7	99.9	226.5	266.5
750	76.1	171.5	101.0	227.1	267.1
760	77.4	172.4	102.0	227.7	267.7
770	78.6	173.2	103.0	228.3	268.3
780	79.8	174.0	104.0	228.9	268.9
790	81.0	174.8	105.0	229.4	269.4
800	82.2	175.6	105.9	230.0	270.0
810	83.3	176.4	106.9	230.6	270.6
820	84.4	177.1	107.8	231.1	271.1
830	85.5	177.9	108.7	231.7	271.7
840	86.5	178.6	109.6	232.2	272.2
850	87.6	179.3	110.4	232.8	272.8
860	88.6	180.1	111.3	233.3	273.3
870	89.6	180.8	112.1	233.8	273.8
880	90.5	181.5	113.0	234.3	274.3
890	91.5	182.2	113.8	234.9	274.9
900	92.4	182.8	114.6	235.4	275.4
910	93.4	183.5	115.4	235.9	275.9

TABLE B-4. Duane Arnold Power Uprate Composite P-T Curve Values for 25 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figure 5-9

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 25 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 25 EFPY CURVE B (°F)	NON-BELTLINE AND BELTLINE AT 25 EFPY CURVE C (°F)
920	94.3	184.2	116.1	236.4	276.4
930	95.1	184.8	116.9	236.9	276.9
940	96.0	185.5	117.7	237.3	277.3
950	96.9	186.1	118.4	237.8	277.8
960	97.7	186.7	119.1	238.3	278.3
970	98.6	187.3	119.9	238.8	278.8
980	99.4	188.0	120.6	239.2	279.2
990	100.2	188.6	121.3	239.7	279.7
1000	101.0	189.2	122.0	240.2	280.2
1010	101.7	189.7	122.6	240.6	280.6
1020	102.5	190.3	123.3	241.1	281.1
1030	103.3	190.9	124.0	241.5	281.5
1040	104.0	191.5	124.6	241.9	281.9
1050	104.7	192.0	125.3	242.4	282.4
1060	105.4	192.6	125.9	242.8	282.8
1070	106.2	193.1	126.5	243.2	283.2
1080	106.9	193.7	127.2	243.7	283.7
1090	107.6	194.2	127.8	244.1	284.1
1100	108.2	194.8	128.4	244.5	284.5
1110	108.9	195.3	129.0	244.9	284.9
1120	109.6	195.8	129.6	245.3	285.3
1130	110.2	196.3	130.2	245.7	285.7
1140	110.9	196.8	130.7	246.1	286.1
1150	111.5	197.3	131.3	246.5	286.5

TABLE B-4. Duane Arnold Power Uprate Composite P-T Curve Values for 25 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figure 5-9

	BOTTOM HEAD	UPPER RPV & BELTLINE AT 25 EFPY	BOTTOM HEAD	UPPER RPV & BELTLINE AT 25 EFPY	NON-BELTLINE AND BELTLINE AT 25 EFPY
PRESSURE (PSIG)	CURVE A (°F)	CURVE A (°F)	CURVE B (°F)	CURVE B (°F)	CURVE C (°F)
1160	112.1	197.9	131.9	246.9	286.9
1170	112.8	198.3	132.4	247.3	287.3
1180	113.4	198.8	133.0	247.7	287.7
1190	114.0	199.3	133.5	248.0	288.0
1200	114.6	199.8	134.1	248.3	288.3
1210	115.2	200.3	134.6	248.5	288.5
1220	115.8	200.8	135.2	248.8	288.8
1230	116.3	201.2	135.7	249.1	289.1
1240	116.9	201.7	136.2	249.3	289.3
1250	117.5	202.2	136.7	249.6	289.6
1260	118.0	202.6	137.2	249.8	289.8
1270	118.6	203.1	137.7	250.1	290.1
1280	119.1	203.5	138.2	250.3	290.3
1290	119.7	204.0	138.7	250.6	290.6
1300	120.2	204.4	139.2	250.8	290.8
1310	120.7	204.8	139.7	251.1	291.1
1320	121.3	205.3	140.2	251.3	291.3
1330	121.8	205.7	140.6	251.6	291.6
1340	122.3	206.1	141.1	251.8	291.8
1350	122.8	206.5	141.6	252.0	292.0
1360	123.3	207.0	142.0	252.3	292.3
1370	123.8	207.4	142.5	252.5	292.5
1380	124.3	207.8	142.9	252.8	292.8
1390	124.8	208.2	143.4	253.0	293.0

TABLE B-4. Duane Arnold Power Uprate Composite P-T Curve Values for 25 EFPY
Required Coolant Temperatures at 100 °F/hr for Curves B & C and 20 °F/hr for Curve A
For Figure 5-9

PRESSURE (PSIG)	BOTTOM HEAD CURVE A (°F)	UPPER RPV & BELTLINE AT 25 EFPY CURVE A (°F)	BOTTOM HEAD CURVE B (°F)	UPPER RPV & BELTLINE AT 25 EFPY CURVE B (°F)	NON-BELTLINE AND BELTLINE AT 25 EFPY CURVE C (°F)
1400	125.3	208.6	143.8	253.2	293.2

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.

C.2.1 Curve A: Pressure Test

Curve A should be used during pressure tests at times when the coolant temperature is changing by ≤20°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 20°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 boltup, 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 boltup
- 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 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 boltup.	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 boltup.	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

Notice:

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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 nozzles are located where the peak neutron fluence is expected to exceed or equal 1.0e17 n/cm^2, then fracture toughness evaluation must be conducted and demonstrated on those nozzles which experience a fluence at or exceeding 1.0e17 n/cm^2.

The following dimensions are obtained from the referenced drawings:

Shell # 2 - Top of Active Fuel (TAF): 351" (from vessel 0)
Shell # 1 - Bottom of Active Fuel (BAF): 201" (from vessel 0)
Top of Active Fuel – Extended Beltline: 370" (from vessel 0)
Bottom of Active Fuel – Extended Beltline: 183" (from vessel 0)
Elevation of Top of N2 Nozzle in Shell # 1: 195.8125" (from vessel 0)
Elevation of Centerline of N2 Nozzle in Shell # 1: 182" (from vessel 0)
Elevation of Centerline of Nozzle N16 in Shell #2: 348" (from vessel 0)
Elevation of Centerline of Nozzle N1 in Shell #1: 131" (from vessel 0)
Elevation of Top of N1 Nozzle in Shell #1: 156.5" (from vessel 0)

Based on the axial flux profile, the RPV flux level at ~18" below the BAF dropped to less than 0.024 of the peak flux level at the same radius. Likewise, the RPV flux level at ~19" above the TAF dropped to less than 0.024 of the peak flux at the same radius. Therefore, since the best estimate peak RPV fluence is 4.17E18 n/cm^2 as defined in Section 4.2.1.2 and Appendix G, fluence at ~18" below BAF and ~19" above TAF is

expected to be less than 1.0E17 n/cm^2 at 32 EFPY. The beltline region considered in the development of the P-T curves is adjusted to include the additional area above and below the active fuel region. The adjusted beltline region extends from ~183" to ~370" above reactor vessel "0".

As shown above, the N2 Recirculation Inlet and N16 Instrumentation nozzles are within the core beltline region, and are bounded by the beltline curve as stated in Appendix A. The recirculation inlet nozzle is closest to the beltline region (the top of the Recirculation Inlet nozzle is ~13" above BAF – Extended Beltline), and the instrumentation nozzle is within the BAF-TAF region of the reactor vessel. Therefore, since it can be shown that no other 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 remaining reactor vessel nozzles are outside the beltline region of the reactor vessel.

Based on the above, it is concluded that none of the Duane Arnold reactor vessel nozzles, other than the Recirculation Inlet Nozzle and the Instrumentation Nozzle, which are considered in the P-T curve evaluation, are in the beltline region.

Appendix E References:

None

APPENDIX F

Evaluation For Upper Shelf Energy

Equivalent Margin Analysis (EMA)

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 up to 32 EFPY. Calculations of 32 EFPY USE, using Regulatory Guide 1.99, Rev. 2 [2] methods and BWROG Equivalent Margin Analyses (EMA) [3, 4] methods, are summarized in Tables F-1 through F-4.

Unirradiated upper shelf data was not available for all of the material heats in the Duane Arnold beltline region. Due to this lack of specific pre-operational USE data, Duane Arnold is evaluated to verify that the BWROG EMA is applicable. The USE decrease prediction values from Reg. Guide 1.99, Rev. 2 were used for the beltline components as shown in Tables F-1 through F-4. These calculations are based upon the 32 EFPY peak 1/4T fluence for each component as provided in Table 4-4.

Based on the results presented in Tables F-1 through F-4, the USE EMA values for the reactor vessel beltline materials remain within the limits of Reg. Guide 1.99, Rev. 2 and 10CFR50 Appendix G for 32 EFPY of operation.

Table F-1
Plate Equivalent Margin Analysis

PLANT APPLICABILITY VERIFICATION FORM
FOR Duane Arnold - BWR 4/MK I - Including Uprated Power Condition

BWR/3-6 PLATE

Surveillance Plate (Heat B0673-1) USE:

%Cu = 0.15

1st Capsule Fluence = 4.9×10^{17} n/cm^2
2nd Capsule Fluence = 1.1×10^{18} n/cm^2

Unirradiated to 1st Capsule Measured % Decrease = 2.5 (Charpy Curves)
Unirradiated to 2nd Capsule Measured % Decrease = 13 (Charpy Curves)

1st Capsule Rev 2 Predicted % Decrease = 12 (Rev 2, Figure 2)
2nd Capsule Rev 2 Predicted % Decrease = 14 (Rev 2, Figure 2)

Limiting Beltline Plate (Heat B0673-1) USE:

%Cu = 0.15

32 EFPY 1/4 T Fluence = 3.19×10^{18} n/cm^2

Rev 2 Predicted % Decrease = 19 (Rev 2, Figure 2)

Adjusted % Decrease = N/A (Rev 2, Position 2.2)

19 % ≤ 21%, so vessel plates are bounded by equivalent margin analysis

Table F-2
Weld Equivalent Margin Analysis

PLANT APPLICABILITY VERIFICATION FORM

FOR Duane Arnold - BWR 4/MK I - Including Uprated Power Condition

BWR/2-6 WELD

Surveillance Weld (Heat Unknown) USE:

%Cu = 0.02

1st Capsule Fluence = 4.9×10^{17} n/cm^2
2nd Capsule Fluence = 1.1×10^{18} n/cm^2

Unirradiated to 1st Capsule Measured % Decrease = 0 (Charpy Curves)
Unirradiated to 2nd Capsule Measured % Decrease = 3 (Charpy Curves)

1st Capsule Rev 2 Predicted % Decrease = 7 (Rev 2, Figure 2)
2nd Capsule Rev 2 Predicted % Decrease = 8 (Rev 2, Figure 2)

Limiting Beltline Weld (Heat 432Z0471 Lot B003A27A) USE:

%Cu = 0.03

32 EFPY 1/4 T Fluence = 3.19×10^{18} n/cm^2

Rev 2 Predicted % Decrease = 12.5 (Rev 2, Figure 2)

Adjusted % Decrease = N/A (Rev 2, Position 2.2)

12.5 % ≤ 34%, so vessel welds are bounded by equivalent margin analysis

Table F-3
Nozzle Equivalent Margin Analysis

PLANT APPLICABILITY VERIFICATION FORM
FOR Duane Arnold - BWR 4/MK I - Including Uprated Power Condition

BWR/3-6 PLATE

Surveillance Plate (Heat B0673-1) USE:

%Cu = 0.15

1st Capsule Fluence = 4.9×10^{17} n/cm^2
2nd Capsule Fluence = 1.1×10^{18} n/cm^2

Unirradiated to 1st Capsule Measured % Decrease = 2.5 (Charpy Curves)
Unirradiated to 2nd Capsule Measured % Decrease = 13 (Charpy Curves)

1st Capsule Rev 2 Predicted % Decrease = 12 (Rev 2, Figure 2)
2nd Capsule Rev 2 Predicted % Decrease = 14 (Rev 2, Figure 2)

Beltline Nozzle (N16 - Heat Q2Q5VW) USE:

%Cu = 0.18

32 EFPY 1/4 T Fluence = 8.63×10^{17} n/cm^2

Rev 2 Predicted % Decrease = 15.5 (Rev 2, Figure 2)

Adjusted % Decrease = N/A (Rev 2, Position 2.2)

15.5 % $\leq$ 21%, so vessel nozzles are bounded by equivalent margin analysis

Table F-4

Nozzle Equivalent Margin Analysis

PLANT APPLICABILITY VERIFICATION FORM
FOR Duane Arnold - BWR 4/MK I - Including Uprated Power Condition

BWR/3-6 PLATE

Surveillance Plate (Heat B0673-1) USE:

%Cu = 0.15

1st Capsule Fluence = 4.9×10^{17} n/cm^2
2nd Capsule Fluence = 1.1×10^{18} n/cm^2

Unirradiated to 1st Capsule Measured % Decrease = 2.5 (Charpy Curves)
Unirradiated to 2nd Capsule Measured % Decrease = 13 (Charpy Curves)

1st Capsule Rev 2 Predicted % Decrease = 12 (Rev 2, Figure 2)
2nd Capsule Rev 2 Predicted % Decrease = 14 (Rev 2, Figure 2)

Limiting Beltline Nozzle (N2 - Heat O2O6VW) USE:

%Cu = 0.18

32 EFPY 1/4 T Fluence = 5.85×10^{17} n/cm^2

Rev 2 Predicted % Decrease = 14.5 (Rev 2, Figure 2)

Adjusted % Decrease = N/A (Rev 2, Position 2.2)

14.5 % $\leq$ 21%, so vessel nozzles 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. H.S. Mehta, T.A. Caine, and S.E. Plaxton, "10CFR50 Appendix G Equivalent Margin Analysis for Low Upper Shelf Energy in BWR/2 through BWR/6 Vessels", GENE, San Jose, CA, February 1994 (NEDO-32205-A, Revision 1).
4. L.A. England (BWR Owners' Group) to Daniel G. McDonald (US NRC), "BWR Owners' Group Topical Report on Upper Shelf Energy Equivalent Margin Analysis – Approved Version", BWROG-94037, March 21, 1994.

APPENDIX G

Fluence Evaluation

G.1 Overview and Objective

Neutron irradiation of reactor pressure vessel (RPV) causes reduction in material ductility and creates structural embrittlement at higher operating temperatures. The effect is particularly significant when impurities such as nickel, copper, or phosphorus are imbedded in noticeable levels, as commonly true for the RPV steel. Therefore determination of neutron fluence level is one of the first steps toward RPV fracture toughness evaluations. Neutron fluence is accumulated neutron flux during irradiation time.

G.2.1 Scope

Fast neutron flux densities in the beltline region extending from the core through the RPV are calculated in this task. The operating condition assumed for this analysis corresponds to 120% of the ORTP.

The methodology used for the neutron flux calculation is documented in a Licensing Topical Report (LTR) NEDC-32983P-A [1], which was approved by the NRC for licensing applications in the Safety Evaluation Report (SER) [2]. In general, GE's methodology described in the LTR follows the intent of Regulatory Guide 1.190 [4] for neutron flux evaluation. This methodology is briefly discussed below.

G.2.2 Method of Evaluation

The three-dimensional spatial distribution of flux density in the vicinity of the reactor vessel is simulated by combining the results of two separate two-dimensional neutron transport analyses. The first of these is performed in (r,θ) geometry and provides the radial and azimuthal variation of flux in the core to the vessel at an elevation near the core midplane. The second analysis, which is performed in (r,z) geometry, establishes the relative variation of flux density with elevation. The (r,z) analysis is the basis for determining an axial "adjustment" factor to be applied to the core midplane (r, θ) analysis results.

The neutron flux calculations are performed with the two-dimensional discrete ordinates neutral particle transport code DORT [3]. DORT is distributed as part of the TORT code package by the Radiation Shielding Information Center at Oak Ridge National Laboratory and is the updated version of the DOT series of codes.

The DAEC core configuration is illustrated in Figure G-2-1. [[

]]

The cross-section data used in the DORT calculation are processed with the nuclear cross-section processing package in the GENE Engineering Computation Program (ECP) library. [[

]]

G.2.2.1 (r, θ) Model

[[

]]

G2.2.2 (r,z) Model

[[

]]

G2.3 Inputs and Assumptions

The AEP rated power was assumed to be 1912 MW_{th}. [[

]] The reactor vessel and shroud dimensions, together with the configuration and placement of surveillance capsule holders, are provided in [6].

Figure G-2-1: A Quadrant of DAEC Core

[[

]]

Figure G-2-2: Schematic View of (r, θ) Model

[[

]]

Figure G-2-3: Schematic View of (r,z) Model

[[

]]

G.3 Evaluation Results

G.3.1 AEP Flux and Fluence at RPV ID

Prior to implementation of extended power uprate, the calculated peak flux density (E>1 MeV) at the RPV ID is [[ ]], corresponding to current rated power of 1658 MW_t. The EPU peak full power (1912 MW_t) flux density is [[ ]]. Reference 6 indicated that EPU is expected to occur at 18.18 EFPY, or 5.74e8 EFPS. Assuming an 80% operation capacity factor during a 40 year plant life, or an equivalent 1.01e9 seconds of operation at full licensed power, then the 40 year plant life fluence is calculated as [[ ]]. This value has been reported in Revision 0 of this report.

The flux densities reported above do not include any bias adjustment, since they were calculated prior to NRC approval of NEDC-32983P, which recommends a [[ ]] bias adjustment. If a [[ ]] bias is applied, then the 40 year plant life fluence with 80% capacity factor becomes [[ ]] = 4.17e18 n/cm^2. This fluence value is used for P-T curve evaluation in this report.

G.3.2 AEP Flux and Fluence at Surveillance Capsule Location

The calculated EPU flux density (E>1 MeV) at the 36° surveillance capsule location is [[ ]] without bias adjustment, or [[ ]] with bias adjustment. The lead factor is therefore [[ ]] = 0.77.

G.4 REFERENCES

1. NEDC-32983P-A, Revision 1, "Licensing Topical Report, General Electric Methodology for Reactor Pressure Vessel Fast Neutron Flux Evaluations", December 2001.

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

3. CCC-543, "TORT-DORT Two-and Three-Dimensional Discrete Ordinates Transport Version 2.8.14", Radiation Shielding Information Center (RSIC), January 1994.

4. Regulatory Guide 1.190, "Calculational and Dosimetry Methods for Determining Pressure Vessel Neutron Fluence", USNRC March 2001.

5. Letter, S. A. Richards (USNRC) to G. A. Watford, "Amendment 26 to GE Licensing Topical Report NEDE-24011-P-A, GESTAR II – Implementing Improved GE Steady-State Methods (TAC No. MA6481)", November 10, 1999.

6. Alliant Energy Transmittal NG-00-1026, R. McGee (DAEC) to W. Farrell (GE) "Transmittal of DIR T0313 AEP Flux Analysis", 6-8-2000.

General Electric Co. Affidavit of Proprietary Information

and

Request for Withholding from Public Disclosure

General Electric Company

AFFIDAVIT

I, George B. Stramback, state as follows:

(1) I am Manager, Regulatory Services, General Electric Company ("GE") and have been delegated the function of reviewing the information described in paragraph (2) which is sought to be withheld, and have been authorized to apply for its withholding.

(2) The information sought to be withheld is contained in the GE proprietary report GE-NE-A22-00100-08-01-R2, *Pressure-Temperature Curves for Duane Arnold Energy Center,* Revision 2, Class III (GE Proprietary Information), dated August 2003. The proprietary information is delineated by a double underline inside double square brackets. Figures and large equation objects are identified with double square brackets before and after the object. In each case, the superscript notation{3} refers to Paragraph (3) of this affidavit, which provides the basis for the proprietary determination.

(3) In making this application for withholding of proprietary information of which it is the owner, GE relies upon the exemption from disclosure set forth in the Freedom of Information Act ("FOIA"), 5 USC Sec. 552(b)(4), and the Trade Secrets Act, 18 USC Sec. 1905, and NRC regulations 10 CFR 9.17(a)(4), and 2.790(a)(4) for "trade secrets" (Exemption 4). The material for which exemption from disclosure is here sought also qualify under the narrower definition of "trade secret", within the meanings assigned to those terms for purposes of FOIA Exemption 4 in, respectively, Critical Mass Energy Project v. Nuclear Regulatory Commission, 975F2d871 (DC Cir. 1992), and Public Citizen Health Research Group v. FDA, 704F2d1280 (DC Cir. 1983).

(4) Some examples of categories of information which fit into the definition of proprietary information are:

a. Information that discloses a process, method, or apparatus, including supporting data and analyses, where prevention of its use by General Electric's competitors without license from General Electric constitutes a competitive economic advantage over other companies;

b. Information which, if used by a competitor, would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing of a similar product;

c. Information which reveals aspects of past, present, or future General Electric customer-funded development plans and programs, resulting in potential products to General Electric;

d. Information which discloses patentable subject matter for which it may be desirable to obtain patent protection.

The information sought to be withheld is considered to be proprietary for the reasons set forth in paragraphs (4)a., and (4)b, above.

(5) To address 10 CFR 2.790 (b) (4), the information sought to be withheld is being submitted to NRC in confidence. The information is of a sort customarily held in confidence by GE, and is in fact so held. The information sought to be withheld has, to the best of my knowledge and belief, consistently been held in confidence by GE, no public disclosure has been made, and it is not available in public sources. All disclosures to third parties including any required transmittals to NRC, have been made, or must be made, pursuant to regulatory provisions or proprietary agreements which provide for maintenance of the information in confidence. Its initial designation as proprietary information, and the subsequent steps taken to prevent its unauthorized disclosure, are as set forth in paragraphs (6) and (7) following.

(6) Initial approval of proprietary treatment of a document is made by the manager of the originating component, the person most likely to be acquainted with the value and sensitivity of the information in relation to industry knowledge. Access to such documents within GE is limited on a "need to know" basis.

(7) The procedure for approval of external release of such a document typically requires review by the staff manager, project manager, principal scientist or other equivalent authority, by the manager of the cognizant marketing function (or his delegate), and by the Legal Operation, for technical content, competitive effect, and determination of the accuracy of the proprietary designation. Disclosures outside GE are limited to regulatory bodies, customers, and potential customers, and their agents, suppliers, and licensees, and others with a legitimate need for the information, and then only in accordance with appropriate regulatory provisions or proprietary agreements.

(8) The information identified in paragraph (2), above, is classified as proprietary because it contains detailed methods and processes, which GE has developed and applied to pressure-temperature curves for the BWR over a number of years. The development of the BWR pressure-temperature curves was achieved at a significant cost, on the order of ¾ million dollars, to GE.

The development of the evaluation process along with the interpretation and application of the analytical results is derived from the extensive experience database that constitutes a major GE asset.

(9) Public disclosure of the information sought to be withheld is likely to cause substantial harm to GE's competitive position and foreclose or reduce the availability of profit-making opportunities. The information is part of GE's comprehensive BWR safety and technology base, and its commercial value extends

beyond the original development cost. The value of the technology base goes beyond the extensive physical database and analytical methodology and includes development of the expertise to determine and apply the appropriate evaluation process. In addition, the technology base includes the value derived from providing analyses done with NRC-approved methods.

The research, development, engineering, analytical and NRC review costs comprise a substantial investment of time and money by GE.

The precise value of the expertise to devise an evaluation process and apply the correct analytical methodology is difficult to quantify, but it clearly is substantial.

GE's competitive advantage will be lost if its competitors are able to use the results of the GE experience to normalize or verify their own process or if they are able to claim an equivalent understanding by demonstrating that they can arrive at the same or similar conclusions.

The value of this information to GE would be lost if the information were disclosed to the public. Making such information available to competitors without their having been required to undertake a similar expenditure of resources would unfairly provide competitors with a windfall, and deprive GE of the opportunity to exercise its competitive advantage to seek an adequate return on its large investment in developing these very valuable analytical tools.

I declare under penalty of perjury that the foregoing affidavit and the matters stated therein are true and correct to the best of my knowledge, information, and belief.

Executed on this 14th day of August 2003.

George B. Stramback
General Electric Company