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Duane Arnold Energy Center
3313 DAEC Road
Palo, IA 52324-9646

Operated by Nuclear Management Company, LLC

January 19, 2001
NG-01-0071

Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Attn: Document Control Desk
Mail Station 0-P1-17
Washington, DC 20555-0001

Subject:	Duane Arnold Energy Center Docket No: 50-331 Op. License No: DPR-49 Technical Specification Change Request (TSCR-038): "Revised Pressure Temperature Curves"
Reference:	NG-00-1717, Letter dated October 16, 2000, from G. Van Middlesworth to NRC, TSCR-038 "Revised Pressure Temperature Curves"
File:	A-117

By the referenced letter, the Nuclear Management Company, LLC (NMC) requested a revision to the Duane Arnold Energy Center Technical Specifications. The proposed change revises the vessel pressure and temperature limit curves. The revised limits are based on methodology described in a technical report, General Electric Report GE-NE-A22-00100-08-01, "Pressure-Temperature Curves for Duane Arnold Energy Center," Revision 0, dated September 2000. A proprietary version of this report was included as an attachment to the letter. Subsequently, the Staff requested a redacted, non-proprietary version of that report. The redacted version, GE-NE-A22-00100-08-01a, is attached.

Should you have any questions regarding this matter, please contact this office.

Sincerely,

Kenneth E. Peveler
Manager, Regulatory Performance

Attachment
cc: G. Van Middlesworth (w/o)
M. Wadley (w/o)
B. Mozafari (NRC-NRR)
J. Dyer (Region III)
D. McGhee (State of Iowa)
NRC Resident Office
Docu

A001

GE Nuclear Energy

Engineering and Technology
General Electric Company
175 Curtner Avenue,
San Jose, CA 95125

GE-NE-A22-00100-08-01a
Revision 0
Class I
September 2000

Pressure-Temperature Curves

For

Duane Arnold Energy Center

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Engineering and Technology
General Electric Company
175 Curtner Avenue,
San Jose, CA 95125

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Revision 0
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September 2000

Pressure-Temperature Curves

For

Duane Arnold Energy Center

Prepared by: B D Frew

B. D. Frew, Senior Engineer
Structural Assessment and Mitigation

Prepared by: T A Caine for

A.Faal-Amiri, Senior Engineer
Structural Assessment and Mitigation

Approved by: B. J. Branlund

B. J. Branlund, Principal Engineer
Structural Assessment and Mitigation

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 1997 [1]. Several improvements were made to the P-T curve methodology; the improvements include, but are not limited to 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} rather than K_{Ia} to determine T-RT_{NDT}. Descriptions of other improvements are included in the P-T curve methodology section. This report also includes the effect of a change in irradiation on the embrittlement of the reactor pressure vessel (RPV) materials due to the increased flux associated with an increase in core thermal power for power uprate.

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 (including the N16 nozzle), 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 given in Section 5.0 and a tabulation of the curves is included in Appendix B.

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 1997 [1]. Several improvements were made to the P-T curve methodology; the improvements include, but are not limited to 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 [9] for a postulated defect normal to the direction of maximum stress. ASME Code Case N-640 allows the use of K_{IC} rather than K_{Ia} to determine T-RT_{NDT}. Descriptions of other improvements are included in the P-T curve methodology section. 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 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 were tabulated from the Certified Material Test Report (CMTR's). 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 fluence value of

3.90×10^{18} n/cm^2 used in this report was determined to be the maximum fluence value for Duane Arnold Extended Power Uprate. A discussion of fluence is included in Section 4.2.1.2 and Appendix E. The chemistry data was obtained from [1] for the beltline plates and welds. For the N16 nozzle, the chemistry was obtained from Certified Material Test Reports. Chemistry data is 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 to document 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.

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 1593 MW_{th} to 1912 MW_{th}, which is 120% of original rated thermal power, is included in Appendix E.

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 1997 [1]. A detailed description of the P-T curve bases is included in Section 4.3. Several improvements were made to the P-T curve methodology; the improvements include, but are not limited to 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 [9] for a postulated defect normal to the direction of maximum stress. ASME Code Case N-640 allows the use of K_{IC} rather than K_{Ia} to determine T-RT_{NDT}. Other improvements include, but are not limited to the following:

- 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 [6] to assure that adequate margin against brittle fracture of the reactor vessel exists. 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 [6].

Furthermore, curves are included to allow monitoring of the vessel bottom head and upper vessel regions separate from the beltline region. This refinement could lessen 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.

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 1593 MW_{th} to 1912 MW_{th}, which is 120% of original rated thermal power, is included in Appendix E.

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. ~20% of the year).

The N16 nozzle copper value was conservatively assumed to be 0.20% for purposes of calculating effects of irradiation.

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 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 is as follows:

a. Test specimens shall be transversely oriented (normal to the rolling direction) CVN specimens.
b. RT_{NDT} is defined as the higher of the dropweight NDT or 60°F below the temperature at which Charpy V-Notch 50 ft-lb. energy and 35 mils lateral expansion are met.
c. Bolt-up in preparation for a pressure test or normal operation shall be performed at or above the highest RT_{NDT} of the materials in the closure flange region or lowest service temperature (LST) of the bolting material, whichever is greater.

10CFR50 Appendix G [6] 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 [11] 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 [12], and approved by the NRC for generic use [13].

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, CMTR's). For Duane Arnold CMTR's, 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 plate heat C6794-2 in the upper shell course of Duane Arnold, 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:

$$T_{50L} = 10°F + [(50 - 33) \text{ ft-lb.} * 2°F/\text{ft-lb.}] - 60 = -16°F$$

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,

$$T_{50T} = -16°F + 30°F = 14°F$$

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 weld heat 432Z0471 in Shell #1 of Duane Arnold, the lowest Charpy energy and test temperature from the CMTR's is 100 ft-lb. at 10°F, which is greater than 50 ft-lbs. In addition, if there is no drop weight NDT available, the RT_{NDT} may not be less than -50°F. Since no drop weight was available, the RT_{NDT} for heat 432Z0471 is:

RT_{NDT} = 10°F –60 = -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, the NDT was 40°F and the lowest CVN data was 87 ft-lb. at 40°F. The corresponding value of (T_{50T} – 60°F) was:

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

Therefore, the initial RT_{NDT} was 40°F.

In the bottom head region of the vessel, the vessel plate method is applied for estimating RT_{NDT}. For the bottom head center of Duane Arnold (Heat B0390-3-1), the NDT was 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 + 30°F – 60°F = 10°F.

Therefore, the initial RT_{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 is the LST for the bolting materials. Charpy data for the Duane Arnold closure studs indicates the materials did 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. However, the highest RT_{NDT} in the closure flange region is 14°F, for shell ring #4. 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 materials are listed in Tables 4-1 and 4-2. This tabulation includes beltline, closure flange, feedwater nozzle, and bottom head materials that were considered in generating the P-T curves.

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	54	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 54-1	B0390-1	40	L	96	149	111	10	40	40
PC MK 54-2	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 and 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	50	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. An evaluation of ART for all beltline plates, the N16 nozzle, and several beltline welds were 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, $\Delta RT_{NDT} = [CF]*f^{(0.28 - 0.10 \log f)}$

$Margin = 2(\sigma_I^2 + \sigma_\Delta^2)^{1/2}$

$f = 1/4\ T\ fluence / 10^{19}$

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

Where:

CF = Chemistry Factor

f = ¼ T fluence (n/cm^2) divided by 10^{19}

σ_1 = Standard deviation on initial RT_{NDT}, which is taken to be 0°F.

σ_Δ = Standard deviation on RT_{NDT}. σ_Δ need not be greater than $0.5*\Delta RT_{NDT}$.

4.2.1.1 Chemistry

The vessel beltline copper and nickel values (except for the N16 nozzle) were obtained from [1]. For the N16 nozzle, a bounding value of 0.20 was assumed for copper, and the nickel value of 0.85 was obtained from a Certified Material Test Report. 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 [1]. 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*ΔRT_{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

The 32 EFPY peak fluence is 3.90 x 10^{18} n/cm^2 as discussed in Appendix E. This fluence includes the effect of uprated power from 1593 MW_{th} to 1912 MW_{th}.

4.2.2 Limiting Beltline Material

The limiting beltline material signifies the material that is estimated to have the smallest margin against fracture 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. Table 4-3 lists values of beltline ART for 25 EFPY and Table 4-4 lists the values for 32 EFPY.

BELTLINE ART VALUES FOR DUANE ARNOLD

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

Lower Shell Plate and Longitudinal welds and girth welds
Thickness = 4.469 inches
(Note: Actual number is 5.031, 4.469 was used for conservatism)
Attenuation factor= 1.18

N16 Nozzle
Thickness = 4.469 inches
Attenuation factor= 3.70

Lower-Intermediate Shell Plate and Longitudinal welds

32 EFPY Peak I.D. fluence =	3.90E+18	n/cm^2
32 EFPY Peak 1/4 T fluence =	2.98E+18	n/cm^2
25 EFPY Peak 1/4 T fluence =	2.33E+18	n/cm^2

Lower Shell Plate and Longitudinal welds and girth welds

32 EFPY Peak I.D. fluence =	3.32E+18	n/cm^2
32 EFPY Peak 1/4 T fluence =	2.54E+18	n/cm^2
25 EFPY Peak 1/4 T fluence =	1.98E+18	n/cm^2

N16 Nozzle

32 EFPY Peak I.D. fluence =	1.05E+18	n/cm^2
32 EFPY Peak 1/4 T fluence =	8.06E+17	n/cm^2
25 EFPY Peak 1/4 T fluence =	6.30E+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	σ_I	σ_Δ	Margin °F	25 EFPY Shift °F	25 EFPY ART °F
PLATES:														
Shell Ring #1														
1-18		C6439-2	0.09	0.51	58		40	1.98E+18	32.9	0.0	16.4	32.9	65.8	105.8
1-19		B0402-1	0.13	0.47	87		40	1.98E+18	49.3	0.0	17.0	34.0	83.3	123.3
Shell Ring #2														
1-20		B0436-2	0.15	0.64	111		10	2.33E+18	67.3	0.0	17.0	34.0	101.3	111.3
1-21		B0673-1	0.15	0.61	110	164	10	2.33E+18	99.4	0.0	8.5	17.0	116.4	126.4
1-21		B0673-1(a)	0.15	0.65	111	165	10	2.33E+18	100.3	0.0	8.5	17.0	117.3	127.3
WELDS:														
Lower														
D1,D2		432Z4521 Lot B020A27A	0.01	0.98	20		-50	1.98E+18	11.3	0.0	5.7	11.3	22.7	-27.3
D1,D2		432Z0471 Lot B003A27A	0.03	0.91	41		-50	1.98E+18	23.3	0.0	11.6	23.3	46.5	-3.5
Lower-Intmed														
E1,E2		432Z4521 Lot B020A27A	0.01	0.98	20		-50	2.33E+18	12.1	0.0	6.1	12.1	24.3	-25.7
E1,E2		432Z0471 Lot B003A27A	0.03	0.91	41		-50	2.33E+18	24.9	0.0	12.4	24.9	49.7	-0.3
Girth														
DE		09L853 Lot L017A27A	0.03	0.88	41		-50	1.98E+18	23.3	0.0	11.6	23.3	46.5	-3.5
DE		07L669 Lot K004A27A	0.03	1.02	41		-50	1.98E+18	23.3	0.0	11.6	23.3	46.5	-3.5
DE		CTY538 Lot A027A27A	0.03	0.83	41		-50	1.98E+18	23.3	0.0	11.6	23.3	46.5	-3.5
NOZZLES														
N16		Q2Q5VW (b)	0.2	0.85	160		40	6.30E+17	52.9	0.0	17.0	34.0	86.9	126.9

(a) Surveillance Plate (Best Estimate Chemistry)
(b) Estimated copper
(c) Material in the surveillance program has the CF adjusted by 1.49 in accordance with RG 1.99 Rev. 2

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

BELTLINE ART VALUES FOR DUANE ARNOLD

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

Lower-Intermediate Shell Plate and Longitudinal welds
32 EFPY Peak I.D. fluence = 3.90E+18 n/cm^2
32 EFPY Peak 1/4 T fluence = 2.98E+18 n/cm^2
32 EFPY Peak 1/4 T fluence = 2.98E+18 n/cm^2

Lower Shell Plate and Longitudinal welds and girth welds
Thickness = 4.469 inches Attenuation factor= 1.18
(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 = 3.32E+18 n/cm^2
32 EFPY Peak 1/4 T fluence = 2.54E+18 n/cm^2
32 EFPY Peak 1/4 T fluence = 2.54E+18 n/cm^2

N16 Nozzle
Thickness = 4.469 inches Attenuation factor= 3.70

N16 Nozzle
32 EFPY Peak I.D. fluence = 1.05E+18 n/cm^2
32 EFPY Peak 1/4 T fluence = 8.06E+17 n/cm^2
32 EFPY Peak 1/4 T fluence = 8.06E+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	σ_I	σ_Δ	Margin °F	32 EFPY Shift °F	32 EFPY ART °F
PLATES:														
Shell Ring #1														
1-18		C6439-2	0.09	0.51	58		40	2.54E+18	36.4	0.0	17.0	34.0	70.4	110.4
1-19		B0402-1	0.13	0.47	87		40	2.54E+18	54.6	0.0	17.0	34.0	88.6	128.6
Shell Ring #2														
1-20		B0436-2	0.15	0.64	111		10	2.98E+18	74.2	0.0	17.0	34.0	108.2	118.2
1-21		B0673-1	0.15	0.61	110	164	10	2.98E+18	109.6	0.0	8.5	17.0	126.6	136.6
1-21		**B0673-1(a)**	**0.15**	**0.65**	**111**	**165**	**10**	**2.98E+18**	**110.6**	**0.0**	**8.5**	**17.0**	**127.6**	**137.6**
WELDS:														
Lower														
D1,D2		432Z4521 Lot B020A27A	0.01	0.98	20		-50	2.54E+18	12.6	0.0	6.3	12.6	25.1	-24.9
D1,D2		432Z0471 Lot B003A27A	0.03	0.91	41		-50	2.54E+18	25.7	0.0	12.9	25.7	51.5	1.5
Lower-Intmed														
E1,E2		432Z4521 Lot B020A27A	0.01	0.98	20		-50	2.98E+18	13.4	0.0	6.7	13.4	26.8	-23.2
E1,E2		**432Z0471 Lot B003A27A**	**0.03**	**0.91**	**41**		**-50**	**2.98E+18**	**27.4**	**0.0**	**13.7**	**27.4**	**54.8**	**4.8**
Girth														
DE		09L853 Lot L017A27A	0.03	0.88	41		-50	2.54E+18	25.7	0.0	12.9	25.7	51.5	1.5
DE		07L669 Lot K004A27A	0.03	1.02	41		-50	2.54E+18	25.7	0.0	12.9	25.7	51.5	1.5
DE		CTY538 Lot A027A27A	0.03	0.83	41		-50	2.54E+18	25.7	0.0	12.9	25.7	51.5	1.5
NOZZLES														
N16		Q2Q5VW (b)	0.2	0.85	160		40	8.06E+17	60.0	0.0	17.0	34.0	94.0	134.0

(a) Surveillance Plate (Best Estimate Chemistry)
(b) Estimated copper
(c) Material in the surveillance program has the CF adjusted by 1.49 in accordance with RG 1.99 Rev. 2

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

4.3 PRESSURE-TEMPERATURE CURVE METHODOLOGY

4.3.1 Background

Nuclear Regulatory Commission (NRC) 10CFR50 Appendix G [6] 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 [9]) 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) include shells, components like the nozzles, the support skirt, and stabilizer brackets; these regions will also be called the non-beltline region.

For the core not critical and the core critical 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 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 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 and 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 4.4

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 [6] requirements. The non-beltline and beltline region operating limits are evaluated according to procedures in 10CFR50 Appendix G [6], ASME Code Appendix G [9], and Welding Research Council (WRC) Bulletin 175 [10]. The beltline region minimum temperature limits are adjusted to account for vessel irradiation.

[Redacted - Proprietary Information Deleted]

[Redacted]

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 to cause any significant shift of RT_{NDT}. Non-beltline components include most 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 [9] 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

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 in the upper vessel and bottom head, respectively, has made the analysis different from a shell analysis such as the beltline. This was the result of the stress concentrations and higher thermal stress for certain transient conditions experienced by the upper vessel and the bottom head.

[Redacted]

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

In a **[Redacted]** finite element analysis **[Redacted]**, the CRD penetration region was modeled to compute the local stresses for determination of the stress intensity factor, K_I. The **[Redacted]** evaluation was modified to consider the new requirement for M_m as discussed in ASME Paragraph G-2214.1 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.

[Redacted]

The limit for the coolant temperature change rate is 20°F/hr or less.

[Redacted]

The value of M_m for an inside axial postulated surface flaw from Paragraph G-2214.1 [9] was based on a thickness of 8.0 inches; hence, $t^{1/2} = 2.83$. The resulting value obtained was:

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

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

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

K_{Im} is calculated from the equation in Paragraph G-2214.1 [9] and K_{Ib} is calculated from the equation in Paragraph G-2214.2 [9]:

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

$K_{Ib} = (2/3)\, M_m \cdot \sigma_{pb}$ = **[Redacted]** 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} the equation of Paragraph A-4200 in ASME Appendix A [8]:

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

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

$$(T - RT_{NDT}) = 84°F$$

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.

[Redacted]

[Redacted]

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:

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

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

The Duane Arnold specific bottom head dimensions are R = 92.6875 inches and t =6.5 inches minimum [26], resulting in:

Duane Arnold specific: $$R / (t)^{1/2} = 92.6875 / (6.5)^{1/2} = 36 \text{ inch}^{1/2} \qquad (4\text{-}3)$$

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.

[Redacted]

The calculated value of K_I for pressure test is multiplied by a safety factor (SF) of 1.5, per ASME Appendix G [9] 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$^{1/2}$.

[Redacted]

Figure 4-1. CRD Penetration Fracture Toughness Limiting Transients

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 [8] 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. **[Redacted]**

As discussed in Section 4.3.2.1.1 an evaluation is performed to assure that the CRD discontinuity bounds the other discontinuities that are to be protected by the CRD curve with respect to pressure stresses (see Table 4-6, 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.

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 [10] 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. **[Redacted]**

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 σ $(\pi a)^{1/2}$ · F(a/r_n):

Nominal $K_I = 1.5 \quad 34.97 \cdot (\pi \cdot 2.36)^{1/2} \cdot 1.4 = 200$ 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 [8] for the pressure test condition:

$$(T - RT_{NDT}) = \ln [(K_I - 33.2) / 20.734] / 0.02$$
$$(T - RT_{NDT}) = \ln [(200 - 33.2) / 20.734] / 0.02$$
$$(T - RT_{NDT}) = 104.2°F$$

[Redacted]

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

[Redacted]

The highest RT_{NDT} for the 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.

[Redacted]

[Redacted]

Second, the P-T curve is dependent on the K_I value calculated. The Duane Arnold specific vessel shell and nozzle dimensions [22] applicable to the feedwater nozzle location 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: $\sigma = PR / t = 1563 \text{ psig} \cdot 92.69 \text{ inches} / (4.469 \text{ inches}) = 32{,}418$ psi. The Dead weight and thermal RFE stress of 2.967 ksi is conservatively added yielding $\sigma = 35.4$ ksi. The factor F (a/r_n) from Figure A5-1 of WRC-175 is 1.5 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	= $r_i + 0.29\, r_c$=6.0 inches
r_i =	actual inner radius of nozzle	= 5.375 inches
r_c =	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$^{1/2}$

[Redacted]

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 **[Redacted]** finite element analysis done specifically for the purpose of fracture toughness analysis **[Redacted]**. 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 4-2.

[Redacted]

Figure 4-2. Feedwater Nozzle Fracture Toughness Limiting Transient

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 [10].

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:

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

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

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 [10].

The stresses used in Equation 4-4 were taken from **[Redacted]** 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 [9] methods for secondary portion, K_{Is}:

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

In the case where the total stress exceeded yield stress, a plasticity correction factor was applied based on the recommendations of WRC Bulletin 175 Section 5.C.3 [10]. 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 [8]. The highest RT_{NDT} for the appropriate non-beltline components was then used to establish the P-T curves.

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

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

The non-beltline core not critical heatup/cooldown curve was based on the **[Redacted]** feedwater nozzle **[Redacted]** 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 **[Redacted]**. To produce conservative thermal stresses, a vessel and nozzle thickness of 7.5 inch was used in the evaluation. However, a thickness of 7.5 inch is not conservative for the pressure stress evaluation. Therefore, the pressure stress (σ_{pm}) was adjusted for the actual **[Redacted]** 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 = 7.08 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 [10]. (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.)

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

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

σ_{pm} = 24.84 ksi $\quad$ σ_{sm} = 9.44 ksi

σ_{pb} = 0.13 ksi $\quad$ σ_{sb} = 11.10 ksi

The value of M_m for an inside axial postulated surface flaw from Paragraph G-2214.1 [9] was based on the 4a thickness; hence, $t^{1/2}$ = 3.072. The resulting value obtained was:

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

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

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

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

$F(a/r_n) = 1.4$

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

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

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

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

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

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

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

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

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

$(T - RT_{NDT})$ = 115°F

The **[Redacted]** 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: 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 region component at Duane Arnold is 40°F as shown in Table 4-2. 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.

[Redacted]

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.

For the plates and welds in the beltline region, the stress intensity factors (K_I), calculated for the beltline region according to ASME Code Appendix G procedures [9], 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.

One nozzle (N16) is located in the beltline region. 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 N16 nozzle, the following dimensions were used to calculate the factor F (a/r_n) in accordance with WRC-175:

a =	$\frac{1}{4}(t_n^{\,2} + t_v^{\,2})^{1/2}$	=1.26 inches
t_n =	thickness of nozzle	= 2.30 inches
t_v =	thickness of vessel	= 4.469 inches
r_n =	apparent radius of nozzle	= r_i + 0.29 r_c= 1.8 inches
r_i =	actual inner radius of nozzle	= 1.16 inches
r_c =	nozzle radius (nozzle corner radius)	= 2.25 inches

Thus, a/r_n = 1.26 / 1.8 = 0.7. The value F(a/r_n), taken from Figure A5-1 of WRC Bulletin 175 for an a/r_n of 0.70, is 1.1. 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 [9] 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 [9]. The calculated value of K_{Im} for pressure test is multiplied by a safety factor (SF) of 1.5, per ASME Appendix G [9] 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 [8] for the pressure test condition:

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

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. The following inputs were used in the beltline limit calculation:

Adjusted RT_{NDT} = Initial RT_{NDT} + Shift	A = 10+ 131.5= 141.5°F (Based on ART values in Section 4.2)
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
Limiting Beltline Material Yield Strength	σ_y = 50.0 ksi

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:

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

The value of M_m for an inside axial postulated surface flaw from Paragraph G-2214.1 [9] 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 [8], 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+ 141.5 = 163.5°F for P = 1035 psig

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 [9]:

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

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-2214-2 of ASME Appendix G [9] by the through-wall temperature gradient ΔT_w, given that the temperature gradient has a through-wall shape similar to that shown in Figure G-2214-3 of ASME Appendix G [9]. The relationship used to compute the through-wall ΔT_w is based on one-dimensional heat conduction through an insulated flat plate:

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

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:

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

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-2214-3 of ASME Appendix G [9]. Therefore, ΔT_w calculated from Equation 4-15 is used with the appropriate M_t of Figure G-2214-2 of ASME Appendix G [9] to compute K_{It} for heatup and cooldown.

The M_t relationships were derived in the Welding Research Council (WRC) Bulletin 175 [10] 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.

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

This sample calculation is for a pressure of 1035 psi 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, C = 0.372 ft (4.469 inches)
Thermal diffusivity at 550°F (most conservative value), $\beta = 0.354\ ft^2/hr$ [28]

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

$$\Delta T = GC^2 / 2\beta \qquad (4\text{-}16)$$
$$= 100 \cdot (0.372)^2 / (2 \cdot 0.354) = 19.5°F$$

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 [9]. 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 $(T - RT_{NDT})$:

$$(T - RT_{NDT}) = \ln[((2 \cdot K_{Im} + K_{It}) - 33.2) / 20.734] / 0.2 \qquad (4\text{-}17)$$
$$= \ln[(2 \cdot 42.88 + 5.42 - 33.2) / 20.734] / 0.02$$
$$= 51.4\ °F$$

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

T = 51.4 + 141.5 = 192.9 °F   for P = 1035 psig

4.3.2.3 CLOSURE FLANGE REGION

10CFR50 Appendix G [6] 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 original ASME Code requirement for bolt-up was at qualification temperature (T_{30L}) plus 60°F. The ASME Code used for the currently licensed P-T curves is Appendix G to Section XI of the 1989 ASME Code. The ASME Code requirements state in Paragraph G-2222(c) that, for application of full bolt preload and reactor pressure up to 20% of hydrostatic test pressure, the RPV metal temperature must be at RT_{NDT} or greater. The approach used for Duane Arnold for the bolt-up temperature was based on a more 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 Table 4-2, the limiting initial RT_{NDT} for the closure flange region was 14°F, and the LST of the closure studs was 70°F; therefore, the bolt-up temperature value used was 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 [6] including Table 1, sets minimum temperature requirements for pressure above 20% hydrotest pressure based on the

RT_{NDT} of the closure region. Curve A temperature must be no less than (RT_{NDT} + 90°F) and Curve B temperature no less than (RT_{NDT} + 120°F).

For pressures below 20% of preservice hydrostatic test pressure (312 psig) and with full bolt preload, the closure flange region metal temperature is required to be at RT_{NDT} or greater as described above. At low pressure, the ASME Code [9] 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 applies when the head is on and tensioned and the 68°F limit for the bottom head curve 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 [6] 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 [6], Table 1. Table 1 of [6] 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 [6] 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 N16 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.

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

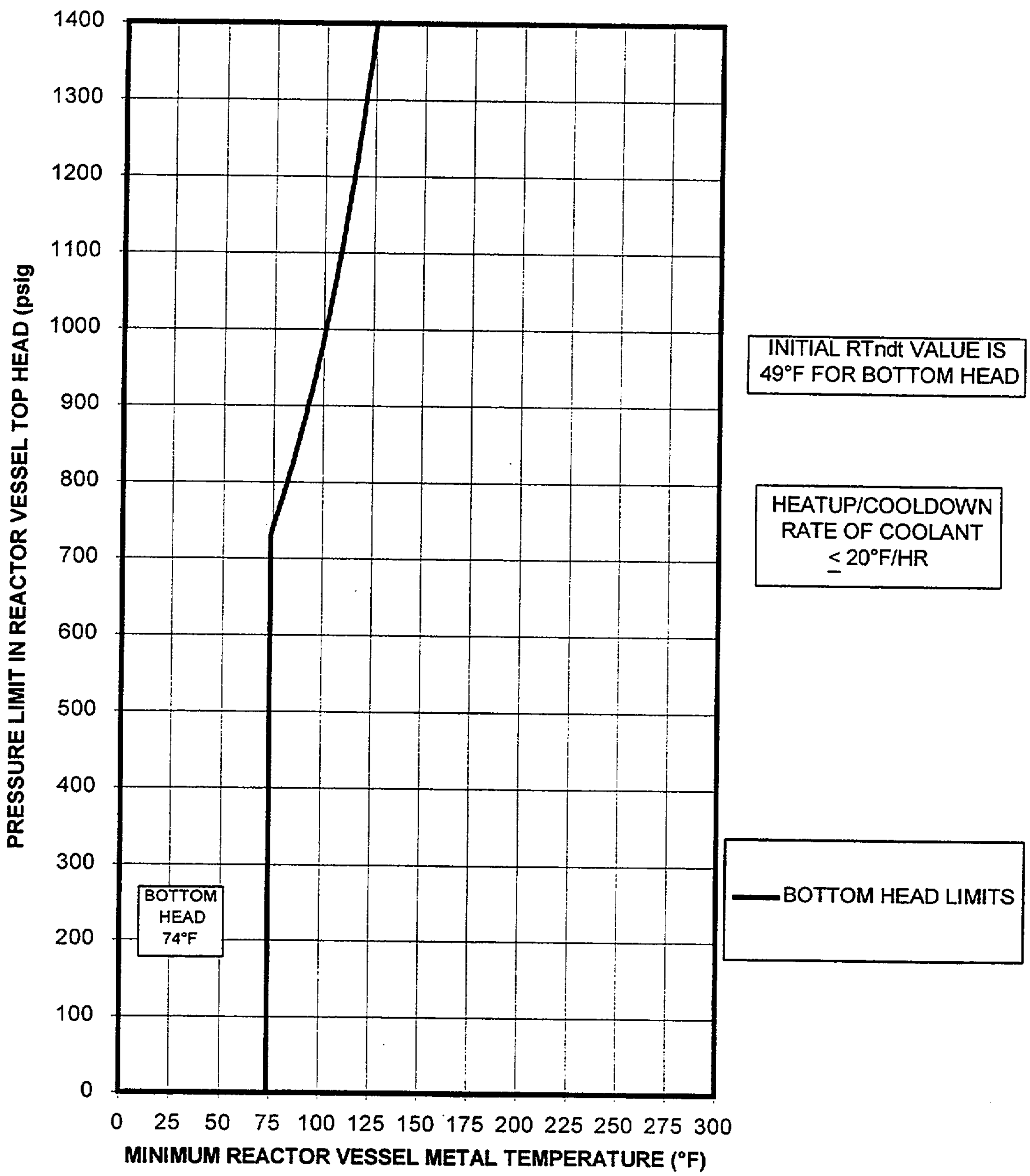

Figure 5-1: Bottom Head P-T Curve for Pressure Test [Curve A]
[20°F/hr or less coolant heatup/cooldown]

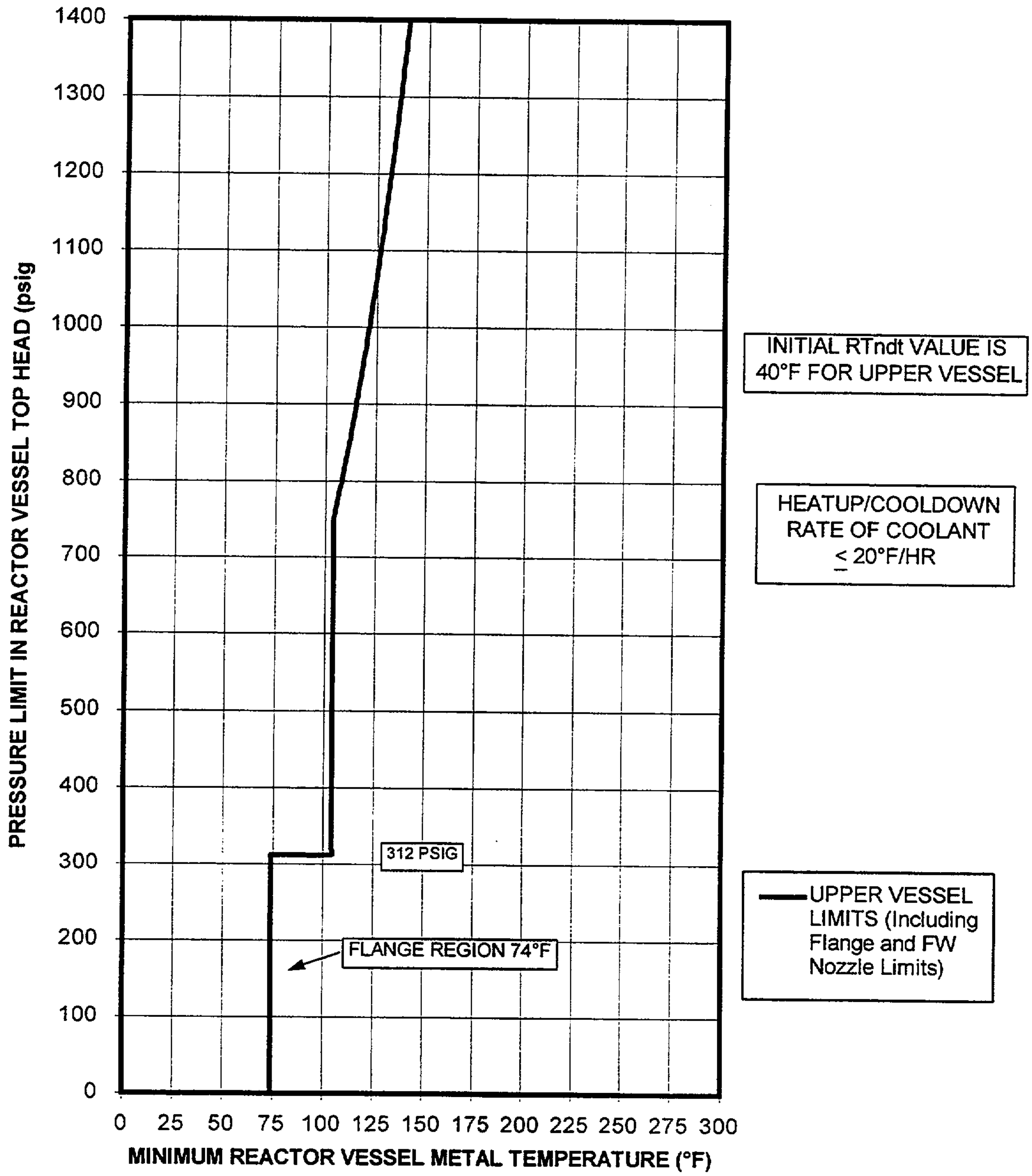

Figure 5-2: Upper Vessel P-T Curve for Pressure Test [Curve A]
[20°F/hr or less coolant heatup/cooldown]

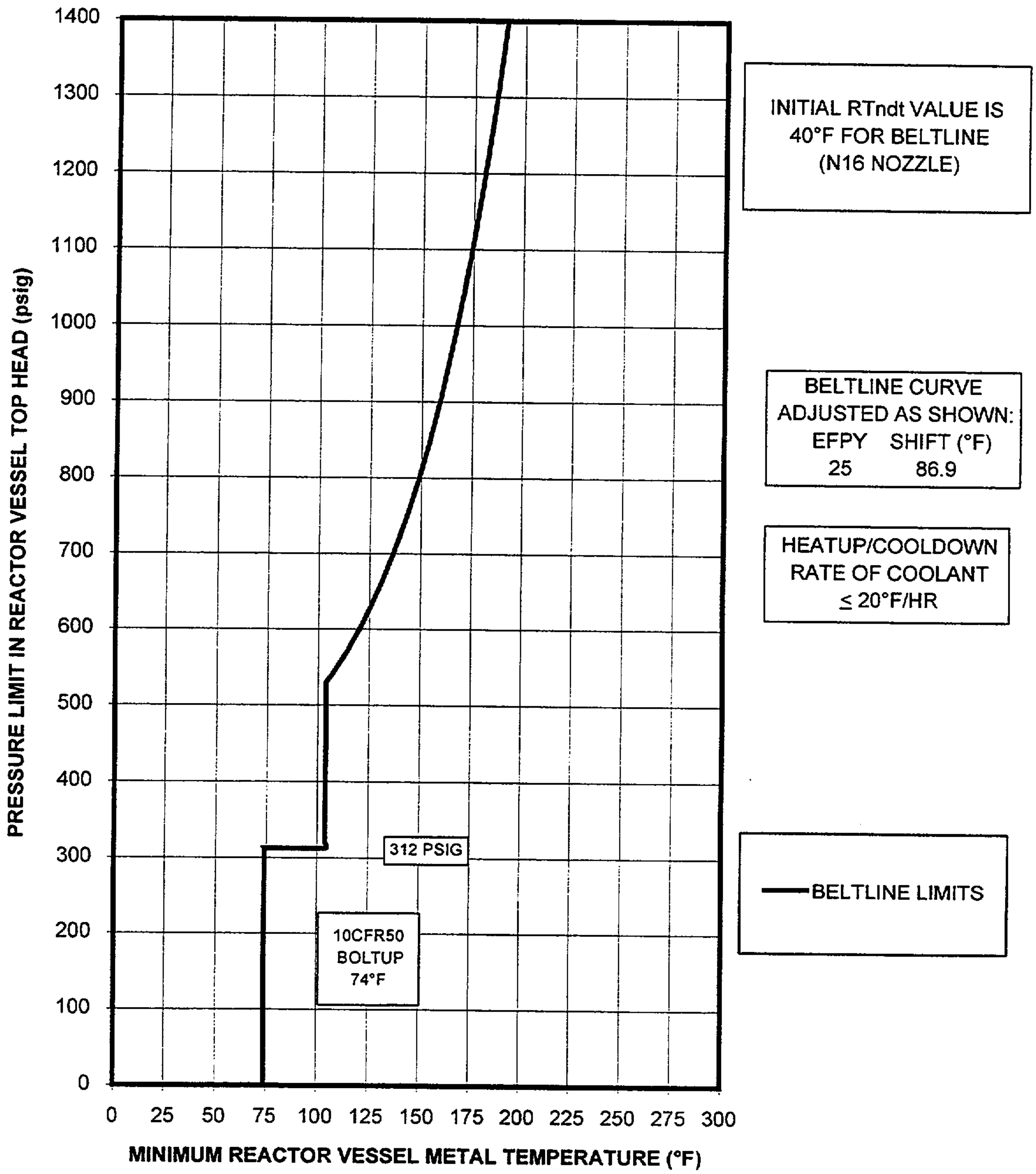

Figure 5-3: Beltline P-T Curve for Pressure Test [Curve A] up to 25 EFPY
[20°F/hr or less coolant heatup/cooldown]

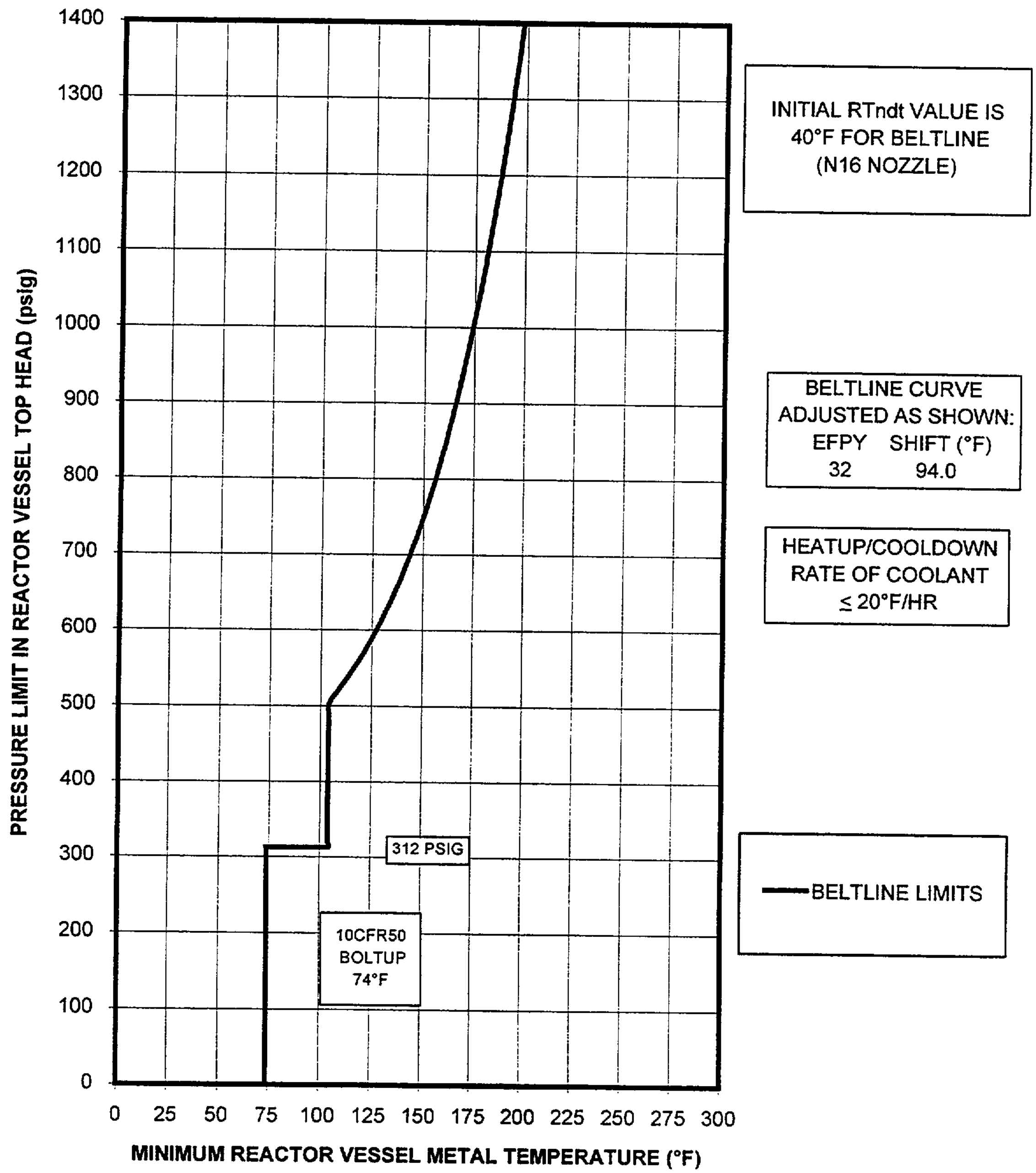

Figure 5-4: Beltline P-T Curve for Pressure Test [Curve A] up to 32 EFPY
[20°F/hr or less coolant heatup/cooldown]

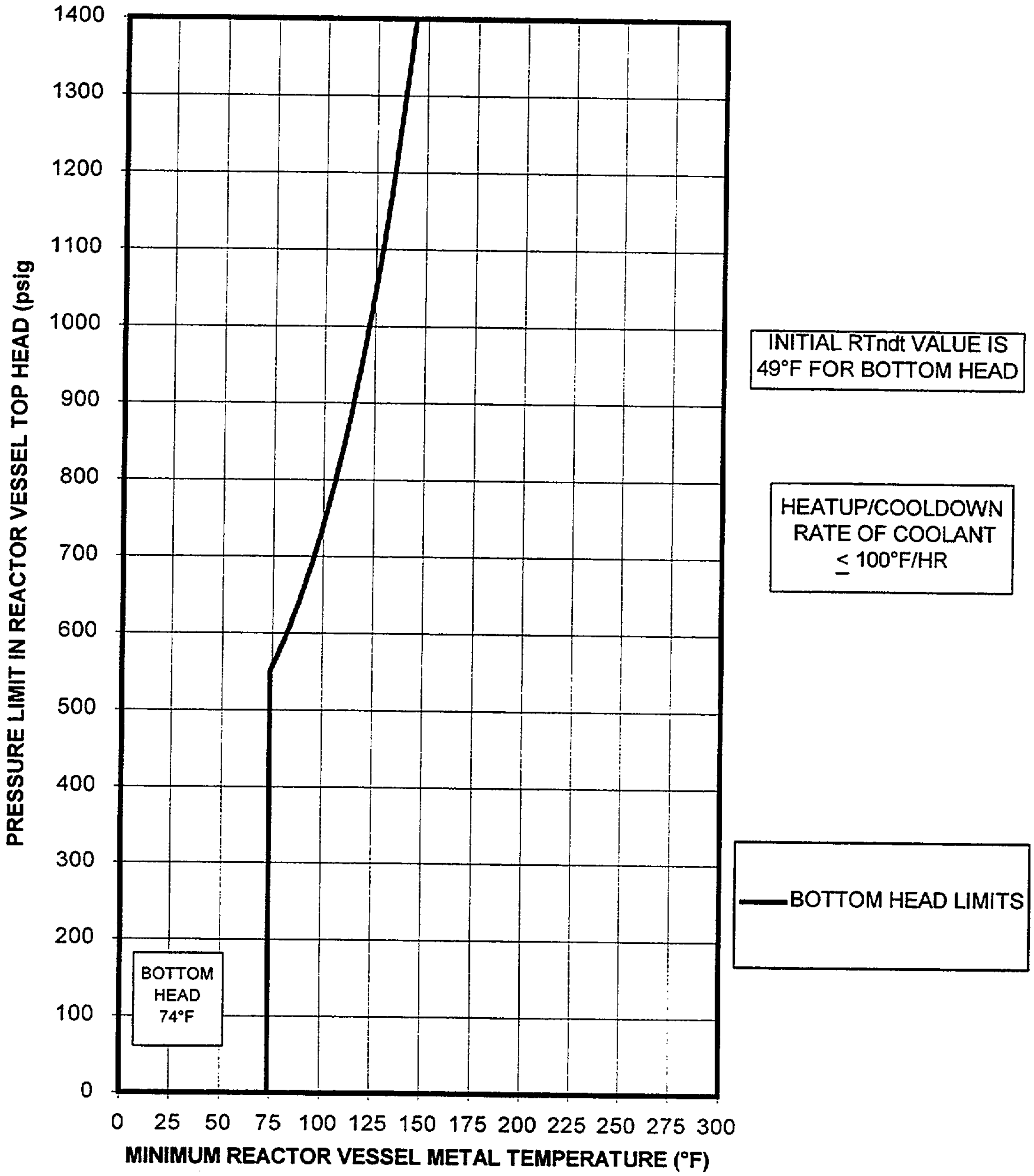

Figure 5-5: Bottom Head P-T Curve for Core Not Critical [Curve B]
[100°F/hr or less coolant heatup/cooldown]

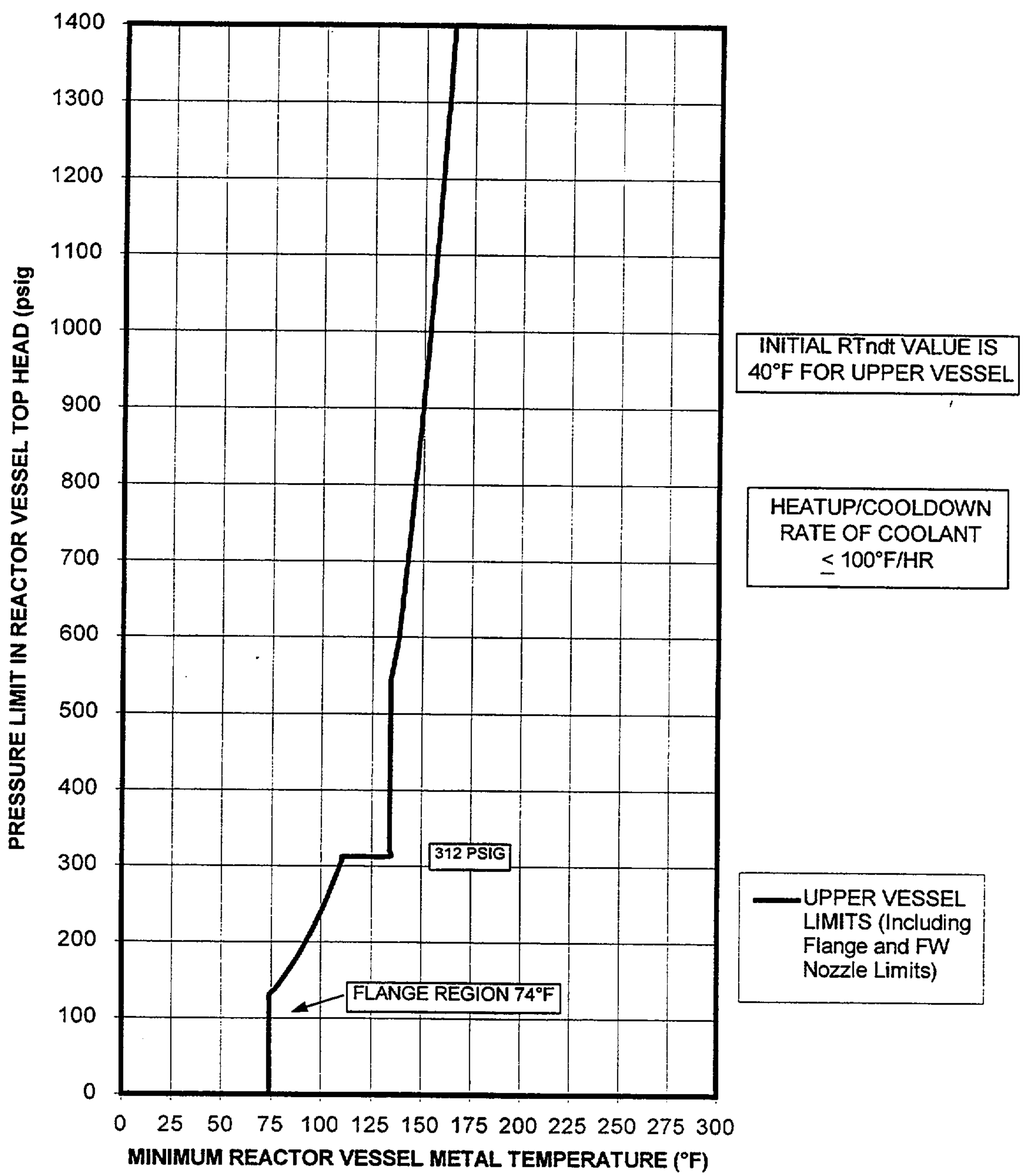

Figure 5-6: Upper Vessel P-T Curve for Core Not Critical [Curve B]
[100°F/hr or less coolant heatup/cooldown]

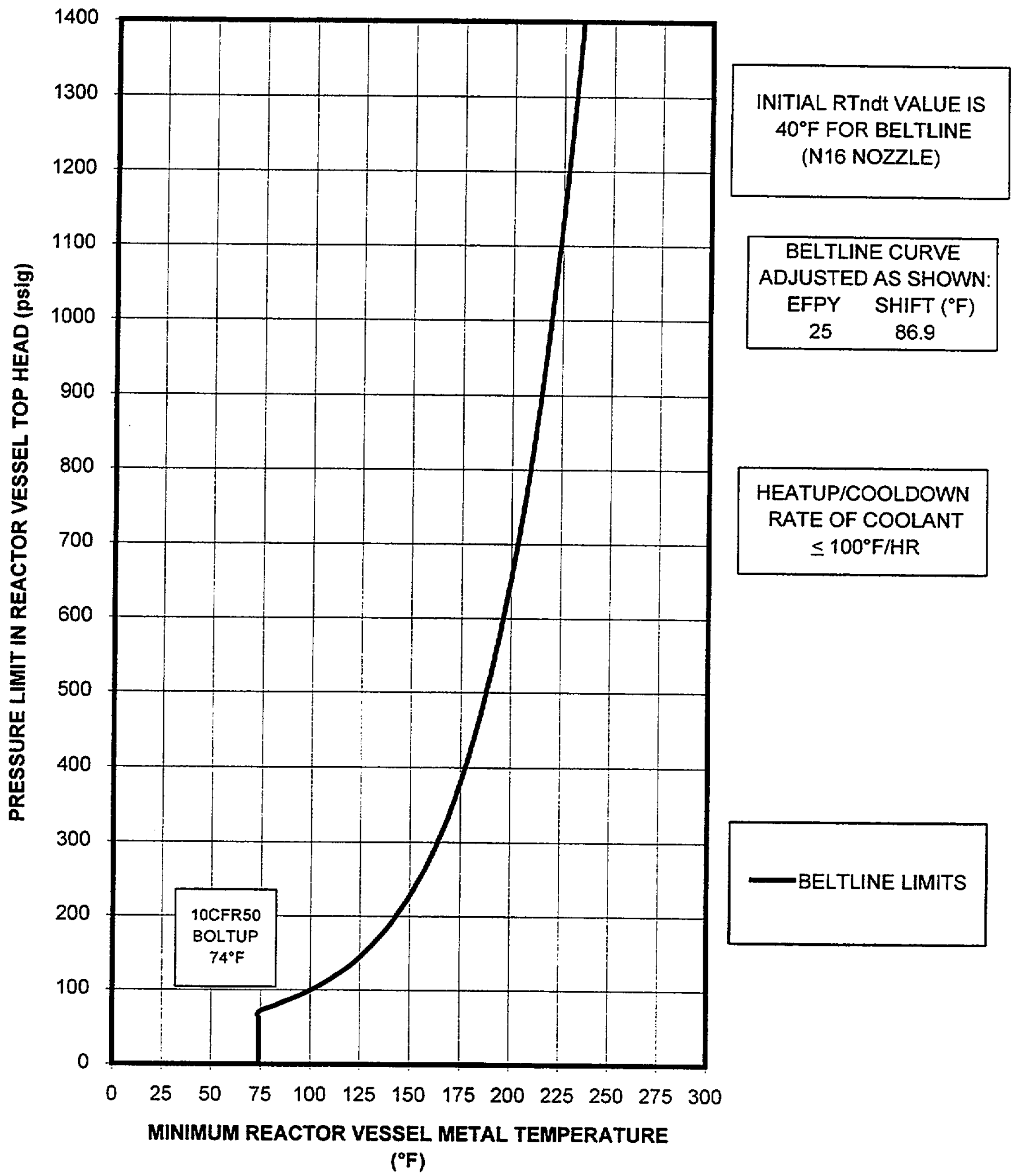

Figure 5-7: Beltline P-T Curve for Core Not Critical [Curve B] up to 25 EFPY [100°F/hr or less coolant heatup/cooldown]

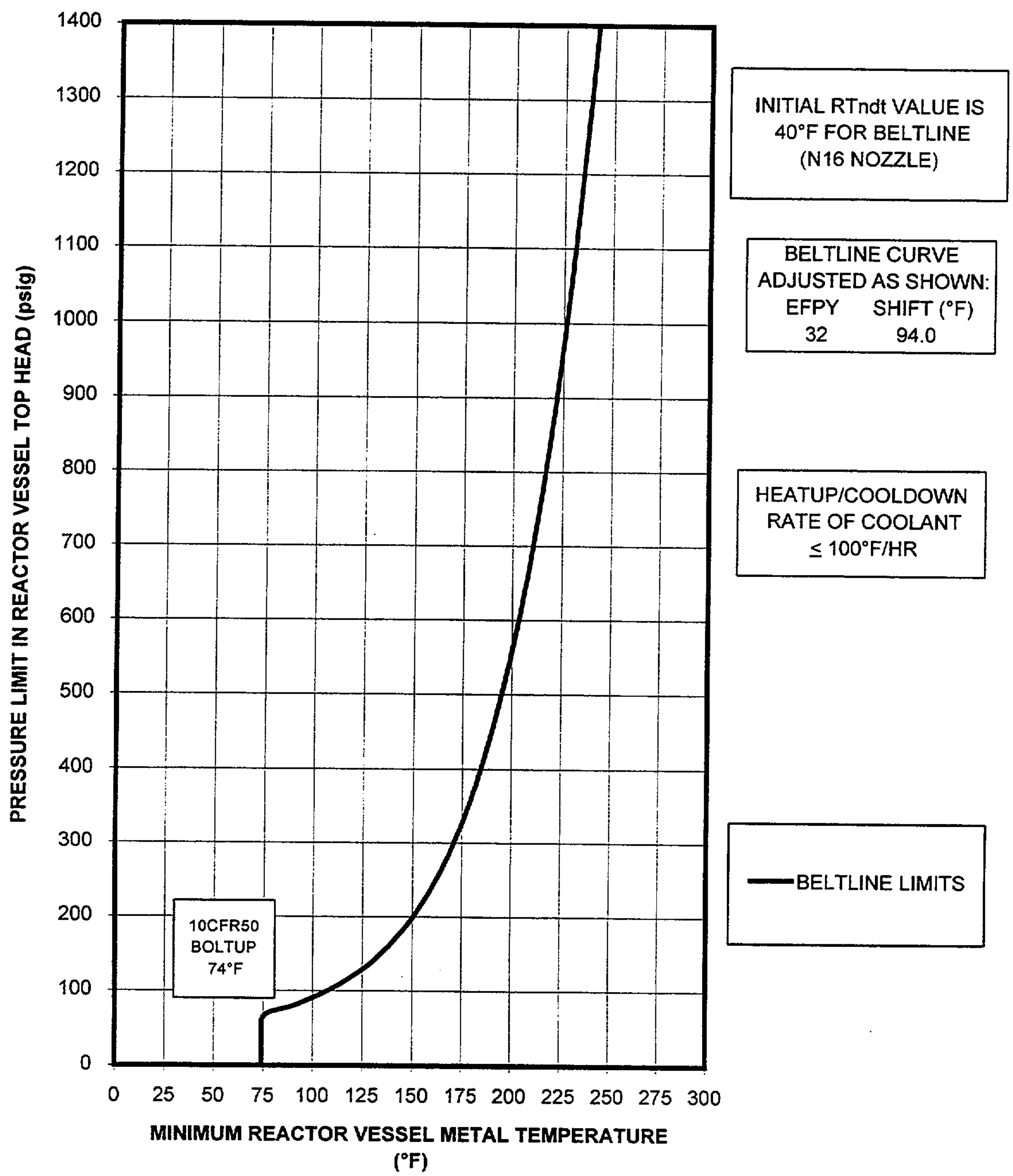

Figure 5-8: Beltline P-T Curves for Core Not Critical [Curve B] up to 32 EFPY
[100°F/hr or less coolant heatup/cooldown]

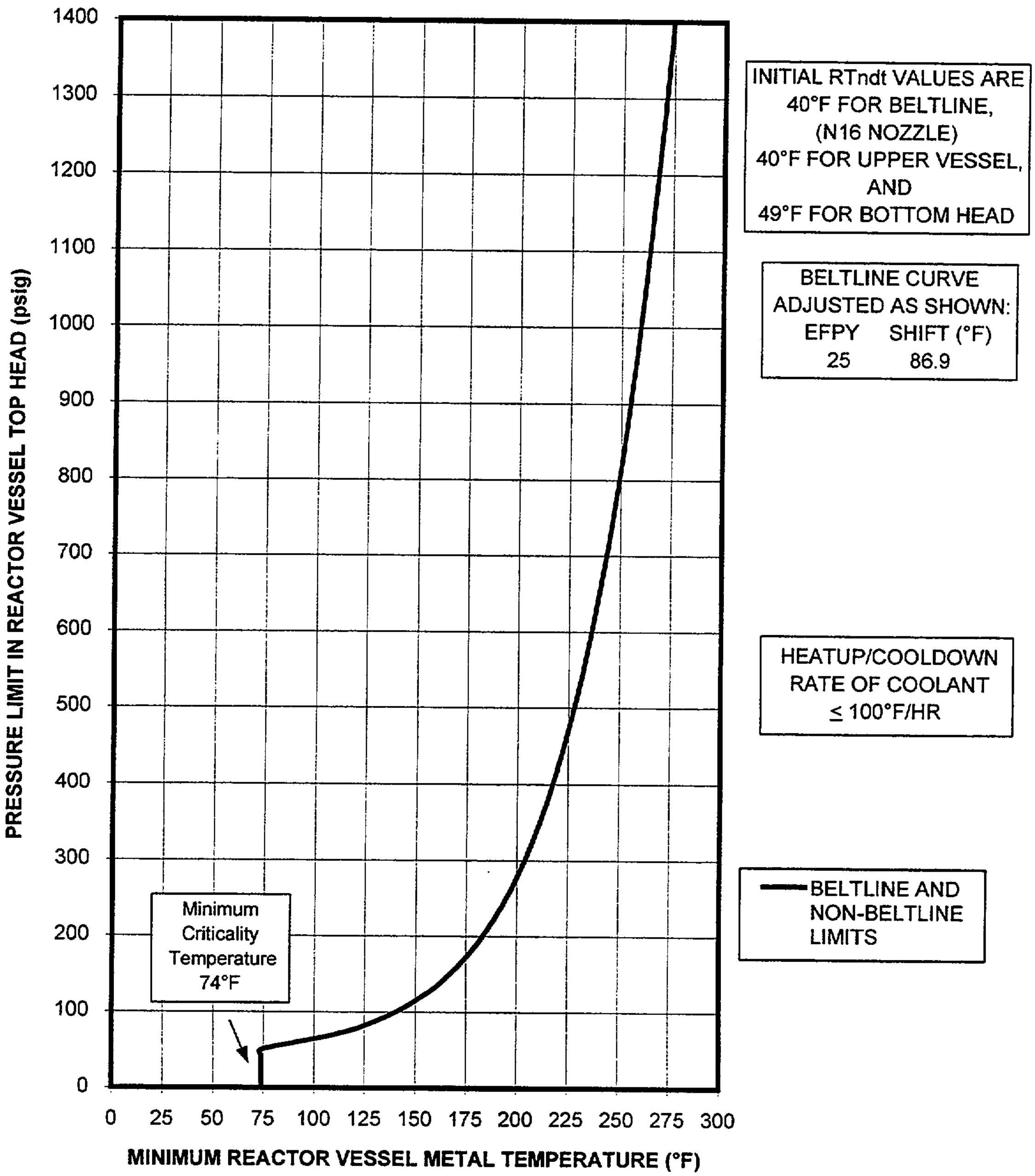

Figure 5-9: Core Critical P-T Curves [Curve C] up to 25 EFPY
[100°F/hr or less coolant heatup/cooldown]

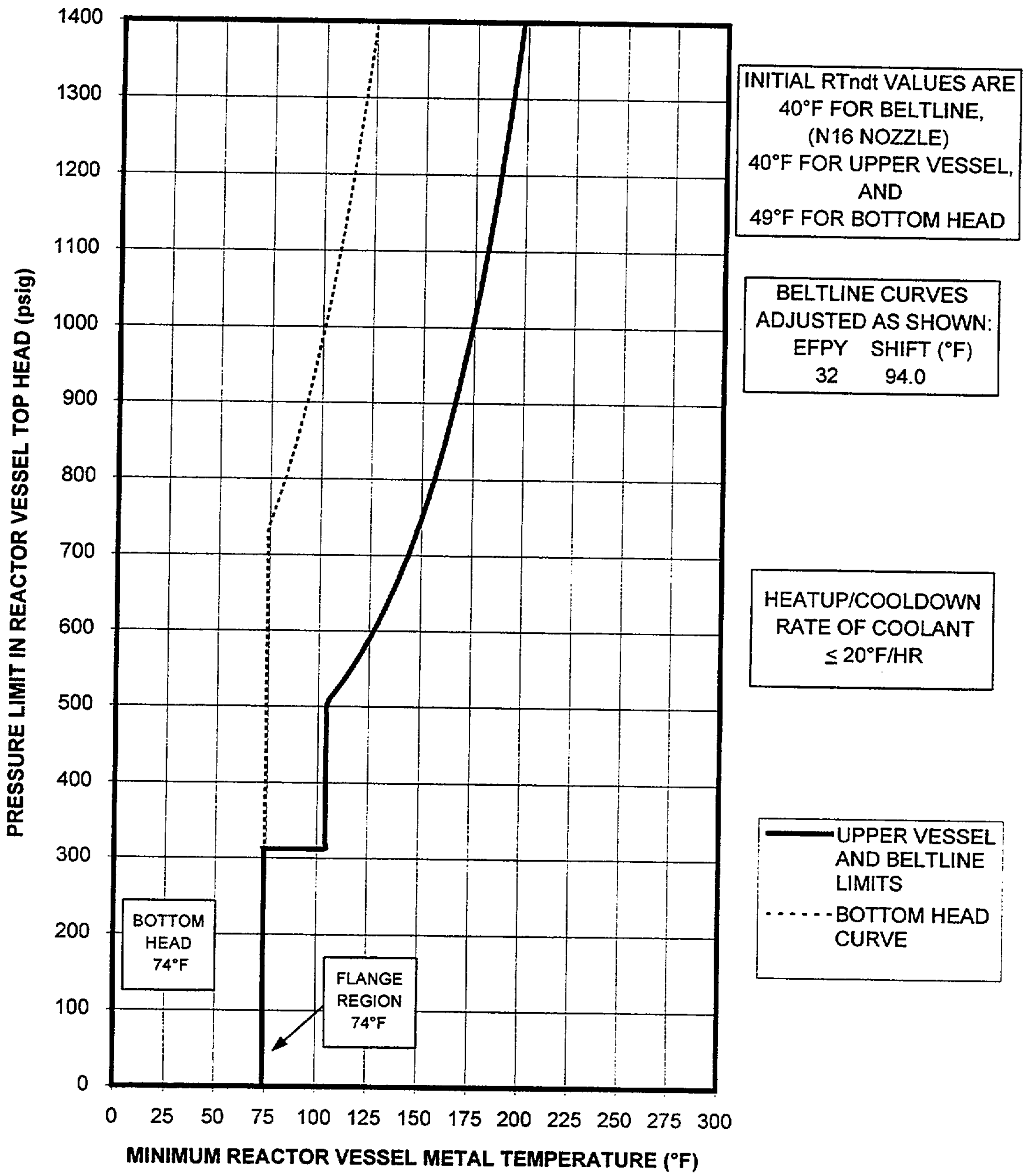

Figure 5-10: Pressure Test P-T Curves [Curve A] up to 32 EFPY
[20°F/hr or less coolant heatup/cooldown]

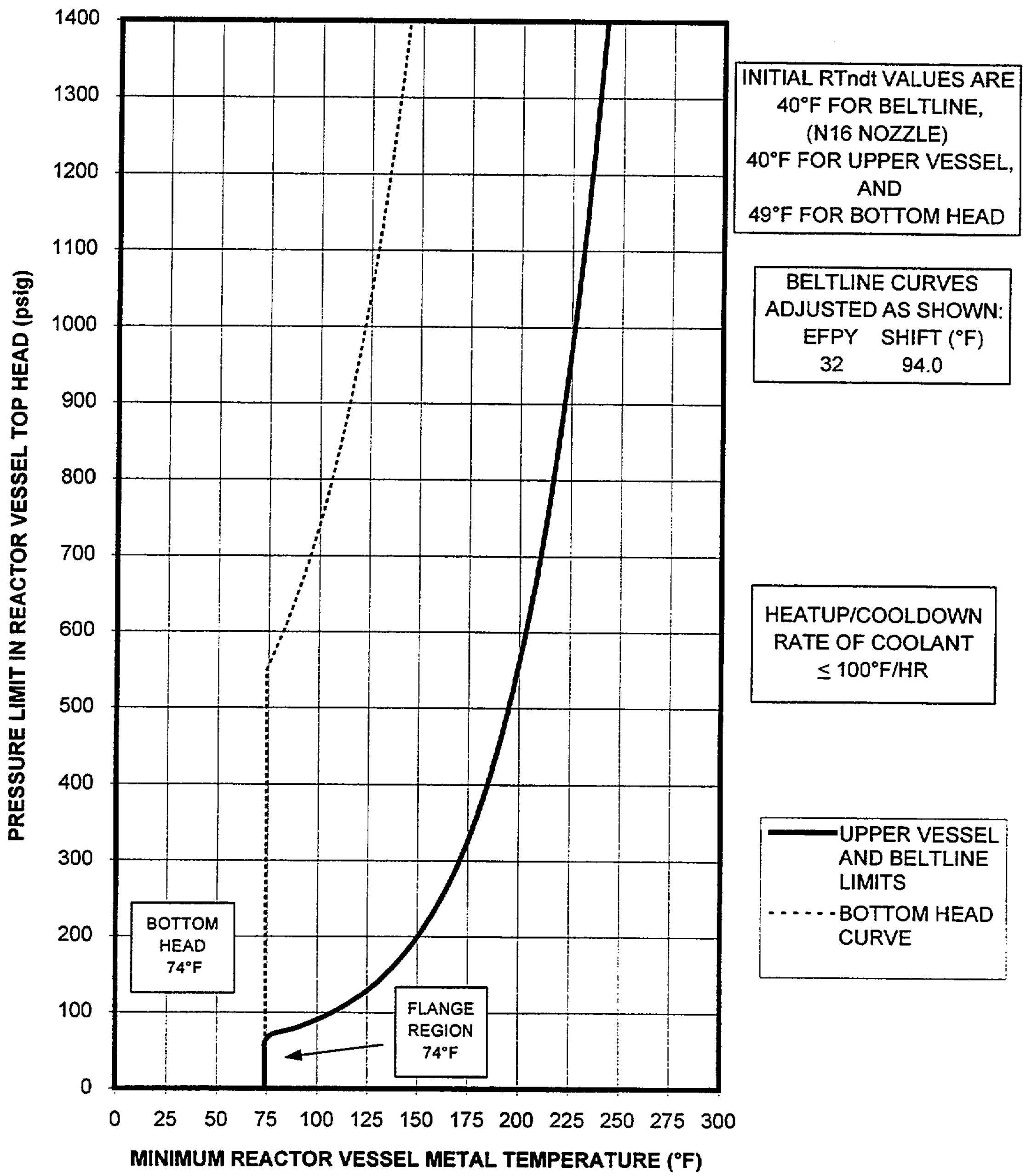

Figure 5-11: Core Not Critical P-T Curves [Curve B] up to 32 EFPY
[100°F/hr or less coolant heatup/cooldown]

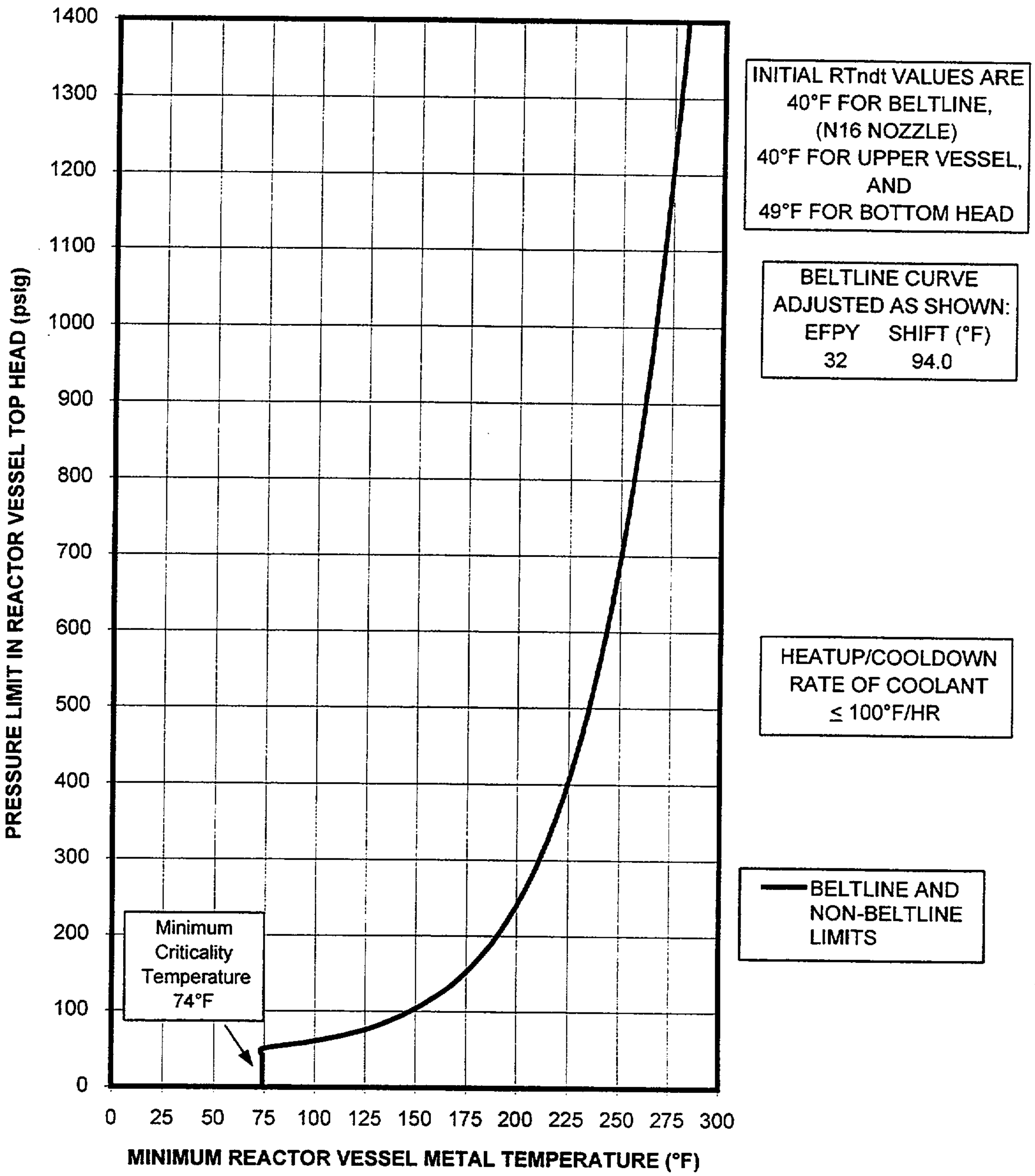

Figure 5-12: Core Critical P-T Curves [Curve C] up to 32 EFPY
[100°F/hr or less coolant heatup/cooldown]

6.0 REFERENCES

1. L. J. Tilly, "Duane Arnold RPV Surveillance Materials Testing and Analysis" GE-NE, San Jose, CA, July 1997, (GE-NE-B1100716-01R0.).

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 Rev. 0. (GE Proprietary Information)

3. GE Drawing Number 135B9990, "Nozzle Thermal Cycles – Reactor Vessel," GE-APED, San Jose, CA, sh1 Rev 1 sh 2-8 R0. Duane Arnold Nozzle Thermal Cycle Diagram. DAEC MDL document number APED-B11-003 <8> rev. 0. (GE Proprietary Information)

4. Alternative to Reference 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. Not Used.

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

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

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

9. "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.

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

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

12. 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).

13. 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.

14. Not Used.

15. Not Used.

16. Not Used.

17. Not Used.

18. Not Used.

19. Not Used.

20. Not Used.

21. Not Used.

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

23. Not Used.

24. **[Redacted]**

25. **[Redacted]**

26. "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 Rev. 10.

27. **[Redacted]**

28. "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

Table A-1 - Geometric Discontinuities for Duane Arnold

[Redacted]

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. Components not requiring 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.
N13,14	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> rev. 9 and APED-B11-084<2> rev.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 Rev. 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 Rev. 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 Rev. 5.

APPENDIX B

PRESSURE TEMPERATURE CURVE DATA TABULATION

TABLE B-1. Duane Arnold Power Uprate 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, AND 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	74.0	74.0	74.0	74.0	74.0	74.0
10	74.0	74.0	74.0	74.0	74.0	74.0
20	74.0	74.0	74.0	74.0	74.0	74.0
30	74.0	74.0	74.0	74.0	74.0	74.0
40	74.0	74.0	74.0	74.0	74.0	74.0
50	74.0	74.0	74.0	74.0	74.0	74.0
60	74.0	74.0	74.0	74.0	74.0	74.0
70	74.0	74.0	74.0	74.0	74.0	77.2
80	74.0	74.0	74.0	74.0	74.0	90.2
90	74.0	74.0	74.0	74.0	74.0	99.9
100	74.0	74.0	74.0	74.0	74.0	107.7
110	74.0	74.0	74.0	74.0	74.0	114.5
120	74.0	74.0	74.0	74.0	74.0	120.4
130	74.0	74.0	74.0	74.0	74.2	125.8
140	74.0	74.0	74.0	74.0	77.4	130.4
150	74.0	74.0	74.0	74.0	80.2	134.4
160	74.0	74.0	74.0	74.0	82.9	138.1
170	74.0	74.0	74.0	74.0	85.5	141.5
180	74.0	74.0	74.0	74.0	87.9	144.7
190	74.0	74.0	74.0	74.0	90.2	147.7
200	74.0	74.0	74.0	74.0	92.3	150.4
210	74.0	74.0	74.0	74.0	94.3	152.9
220	74.0	74.0	74.0	74.0	96.3	155.4
230	74.0	74.0	74.0	74.0	98.1	157.7
240	74.0	74.0	74.0	74.0	99.9	159.9
250	74.0	74.0	74.0	74.0	101.6	161.9
260	74.0	74.0	74.0	74.0	103.2	163.8
270	74.0	74.0	74.0	74.0	104.8	165.7
280	74.0	74.0	74.0	74.0	106.3	167.5
290	74.0	74.0	74.0	74.0	107.8	169.3
300	74.0	74.0	74.0	74.0	109.2	170.9
310	74.0	74.0	74.0	74.0	110.5	172.5
312.5	74.0	74.0	74.0	74.0	110.9	172.9
312.5	74.0	104.0	104.0	74.0	134.0	172.9
320	74.0	104.0	104.0	74.0	134.0	174.0

TABLE B-1. Duane Arnold Power Uprate 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, AND 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)
330	74.0	104.0	104.0	74.0	134.0	175.5
340	74.0	104.0	104.0	74.0	134.0	176.9
350	74.0	104.0	104.0	74.0	134.0	178.3
360	74.0	104.0	104.0	74.0	134.0	179.6
370	74.0	104.0	104.0	74.0	134.0	180.9
380	74.0	104.0	104.0	74.0	134.0	182.2
390	74.0	104.0	104.0	74.0	134.0	183.4
400	74.0	104.0	104.0	74.0	134.0	184.6
410	74.0	104.0	104.0	74.0	134.0	185.8
420	74.0	104.0	104.0	74.0	134.0	186.9
430	74.0	104.0	104.0	74.0	134.0	188.0
440	74.0	104.0	104.0	74.0	134.0	189.1
450	74.0	104.0	104.0	74.0	134.0	190.1
460	74.0	104.0	104.0	74.0	134.0	191.1
470	74.0	104.0	104.0	74.0	134.0	192.1
480	74.0	104.0	104.0	74.0	134.0	193.1
490	74.0	104.0	104.0	74.0	134.0	194.1
500	74.0	104.0	104.0	74.0	134.0	195.0
510	74.0	104.0	105.5	74.0	134.0	195.9
520	74.0	104.0	108.4	74.0	134.0	196.8
530	74.0	104.0	111.2	74.0	134.0	197.7
540	74.0	104.0	113.8	74.0	134.0	198.5
550	74.0	104.0	116.3	74.0	134.6	199.4
560	74.0	104.0	118.7	75.7	135.4	200.2
570	74.0	104.0	121.0	77.4	136.1	201.0
580	74.0	104.0	123.1	79.0	136.9	201.8
590	74.0	104.0	125.2	80.6	137.6	202.6
600	74.0	104.0	127.2	82.2	138.1	203.3
610	74.0	104.0	129.1	83.7	138.6	204.1
620	74.0	104.0	131.0	85.1	139.0	204.8
630	74.0	104.0	132.8	86.5	139.4	205.6
640	74.0	104.0	134.5	87.9	139.8	206.3
650	74.0	104.0	136.2	89.2	140.2	207.0
660	74.0	104.0	137.8	90.5	140.7	207.7
670	74.0	104.0	139.3	91.8	141.1	208.4
680	74.0	104.0	140.8	93.1	141.5	209.1
690	74.0	104.0	142.3	94.3	141.9	209.7

TABLE B-1. Duane Arnold Power Uprate 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, AND 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)
700	74.0	104.0	143.7	95.4	142.3	210.4
710	74.0	104.0	145.1	96.6	142.7	211.0
720	74.0	104.0	146.5	97.7	143.1	211.6
730	74.0	104.0	147.8	98.8	143.5	212.3
740	74.8	104.0	149.1	99.9	143.9	212.9
750	76.1	104.0	150.3	101.0	144.2	213.5
760	77.4	104.8	151.5	102.0	144.6	214.1
770	78.6	105.6	152.7	103.0	145.0	214.7
780	79.8	106.3	153.9	104.0	145.4	215.3
790	81.0	107.1	155.0	105.0	145.8	215.9
800	82.2	107.9	156.1	105.9	146.1	216.4
810	83.3	108.6	157.2	106.9	146.5	217.0
820	84.4	109.4	158.3	107.8	146.9	217.6
830	85.5	110.1	159.3	108.7	147.2	218.1
840	86.5	110.8	160.3	109.6	147.6	218.7
850	87.6	111.5	161.3	110.4	147.9	219.2
860	88.6	112.2	162.3	111.3	148.3	219.7
870	89.6	112.9	163.3	112.1	148.6	220.3
880	90.5	113.6	164.2	113.0	149.0	220.8
890	91.5	114.3	165.1	113.8	149.3	221.3
900	92.4	114.9	166.1	114.6	149.7	221.8
910	93.4	115.6	166.9	115.4	150.0	222.3
920	94.3	116.2	167.8	116.1	150.4	222.8
930	95.1	116.9	168.7	116.9	150.7	223.3
940	96.0	117.5	169.5	117.7	151.0	223.8
950	96.9	118.1	170.4	118.4	151.4	224.2
960	97.7	118.7	171.2	119.1	151.7	224.7
970	98.6	119.3	172.0	119.9	152.0	225.2
980	99.4	119.9	172.8	120.6	152.4	225.7
990	100.2	120.5	173.6	121.3	152.7	226.1
1000	101.0	121.1	174.3	122.0	153.0	226.6
1010	101.7	121.7	175.1	122.6	153.3	227.0
1020	102.5	122.2	175.8	123.3	153.6	227.4
1030	103.3	122.8	176.6	124.0	154.0	227.9
1040	104.0	123.4	177.3	124.6	154.3	228.3
1050	104.7	123.9	178.0	125.3	154.6	228.7
1060	105.4	124.5	178.7	125.9	154.9	229.2

TABLE B-1. Duane Arnold Power Uprate 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, AND 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)
1070	106.2	125.0	179.4	126.5	155.2	229.6
1080	106.9	125.5	180.1	127.2	155.5	230.0
1090	107.6	126.1	180.8	127.8	155.8	230.4
1100	108.2	126.6	181.4	128.4	156.1	230.8
1110	108.9	127.1	182.1	129.0	156.4	231.2
1120	109.6	127.6	182.7	129.6	156.7	231.7
1130	110.2	128.1	183.4	130.2	157.0	232.1
1140	110.9	128.6	184.0	130.7	157.3	232.5
1150	111.5	129.1	184.6	131.3	157.6	232.8
1160	112.1	129.6	185.2	131.9	157.9	233.2
1170	112.8	130.1	185.9	132.4	158.2	233.6
1180	113.4	130.6	186.5	133.0	158.5	234.0
1190	114.0	131.1	187.1	133.5	158.7	234.4
1200	114.6	131.5	187.6	134.1	159.0	234.8
1210	115.2	132.0	188.2	134.6	159.3	235.2
1220	115.8	132.5	188.8	135.2	159.6	235.5
1230	116.3	132.9	189.4	135.7	159.9	235.9
1240	116.9	133.4	189.9	136.2	160.2	236.3
1250	117.5	133.8	190.5	136.7	160.4	236.6
1260	118.0	134.3	191.0	137.2	160.7	237.0
1270	118.6	134.7	191.6	137.7	161.0	237.4
1280	119.1	135.2	192.1	138.2	161.2	237.7
1290	119.7	135.6	192.6	138.7	161.5	238.1
1300	120.2	136.0	193.2	139.2	161.8	238.4
1310	120.7	136.5	193.7	139.7	162.1	238.8
1320	121.3	136.9	194.2	140.2	162.3	239.1
1330	121.8	137.3	194.7	140.6	162.6	239.5
1340	122.3	137.7	195.2	141.1	162.8	239.8
1350	122.8	138.1	195.7	141.6	163.1	240.2
1360	123.3	138.6	196.2	142.0	163.4	240.5
1370	123.8	139.0	196.7	142.5	163.6	240.8
1380	124.3	139.4	197.2	142.9	163.9	241.2
1390	124.8	139.8	197.7	143.4	164.1	241.5
1400	125.3	140.2	198.1	143.8	164.4	241.7

TABLE B-2. Duane Arnold Power Uprate 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 AND BELTLINE AT 32 EFPY CURVE C (°F)
0	74.0	74.0	74.0	74.0	74.0
10	74.0	74.0	74.0	74.0	74.0
20	74.0	74.0	74.0	74.0	74.0
30	74.0	74.0	74.0	74.0	74.0
40	74.0	74.0	74.0	74.0	74.0
50	74.0	74.0	74.0	74.0	74.0
60	74.0	74.0	74.0	74.0	98.6
70	74.0	74.0	74.0	77.2	117.2
80	74.0	74.0	74.0	90.2	130.2
90	74.0	74.0	74.0	99.9	139.9
100	74.0	74.0	74.0	107.7	147.7
110	74.0	74.0	74.0	114.5	154.5
120	74.0	74.0	74.0	120.4	160.4
130	74.0	74.0	74.0	125.8	165.8
140	74.0	74.0	74.0	130.4	170.4
150	74.0	74.0	74.0	134.4	174.4
160	74.0	74.0	74.0	138.1	178.1
170	74.0	74.0	74.0	141.5	181.5
180	74.0	74.0	74.0	144.7	184.7
190	74.0	74.0	74.0	147.7	187.7
200	74.0	74.0	74.0	150.4	190.4
210	74.0	74.0	74.0	152.9	192.9
220	74.0	74.0	74.0	155.4	195.4
230	74.0	74.0	74.0	157.7	197.7
240	74.0	74.0	74.0	159.9	199.9
250	74.0	74.0	74.0	161.9	201.9
260	74.0	74.0	74.0	163.8	203.8
270	74.0	74.0	74.0	165.7	205.7
280	74.0	74.0	74.0	167.5	207.5
290	74.0	74.0	74.0	169.3	209.3
300	74.0	74.0	74.0	170.9	210.9
310	74.0	74.0	74.0	172.5	212.5
312.5	74.0	74.0	74.0	172.9	212.9
312.5	74.0	104.0	74.0	172.9	212.9
320	74.0	104.0	74.0	174.0	214.0
330	74.0	104.0	74.0	175.5	215.5
340	74.0	104.0	74.0	176.9	216.9

TABLE B-2. Duane Arnold Power Uprate 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 AND BELTLINE AT 32 EFPY CURVE C (°F)
350	74.0	104.0	74.0	178.3	218.3
360	74.0	104.0	74.0	179.6	219.6
370	74.0	104.0	74.0	180.9	220.9
380	74.0	104.0	74.0	182.2	222.2
390	74.0	104.0	74.0	183.4	223.4
400	74.0	104.0	74.0	184.6	224.6
410	74.0	104.0	74.0	185.8	225.8
420	74.0	104.0	74.0	186.9	226.9
430	74.0	104.0	74.0	188.0	228.0
440	74.0	104.0	74.0	189.1	229.1
450	74.0	104.0	74.0	190.1	230.1
460	74.0	104.0	74.0	191.1	231.1
470	74.0	104.0	74.0	192.1	232.1
480	74.0	104.0	74.0	193.1	233.1
490	74.0	104.0	74.0	194.1	234.1
500	74.0	104.0	74.0	195.0	235.0
510	74.0	105.5	74.0	195.9	235.9
520	74.0	108.4	74.0	196.8	236.8
530	74.0	111.2	74.0	197.7	237.7
540	74.0	113.8	74.0	198.5	238.5
550	74.0	116.3	74.0	199.4	239.4
560	74.0	118.7	75.7	200.2	240.2
570	74.0	121.0	77.4	201.0	241.0
580	74.0	123.1	79.0	201.8	241.8
590	74.0	125.2	80.6	202.6	242.6
600	74.0	127.2	82.2	203.3	243.3
610	74.0	129.1	83.7	204.1	244.1
620	74.0	131.0	85.1	204.8	244.8
630	74.0	132.8	86.5	205.6	245.6
640	74.0	134.5	87.9	206.3	246.3
650	74.0	136.2	89.2	207.0	247.0
660	74.0	137.8	90.5	207.7	247.7
670	74.0	139.3	91.8	208.4	248.4
680	74.0	140.8	93.1	209.1	249.1
690	74.0	142.3	94.3	209.7	249.7
700	74.0	143.7	95.4	210.4	250.4
710	74.0	145.1	96.6	211.0	251.0
720	74.0	146.5	97.7	211.6	251.6
730	74.0	147.8	98.8	212.3	252.3

TABLE B-2. Duane Arnold Power Uprate 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 AND BELTLINE AT 32 EFPY CURVE C (°F)
740	74.8	149.1	99.9	212.9	252.9
750	76.1	150.3	101.0	213.5	253.5
760	77.4	151.5	102.0	214.1	254.1
770	78.6	152.7	103.0	214.7	254.7
780	79.8	153.9	104.0	215.3	255.3
790	81.0	155.0	105.0	215.9	255.9
800	82.2	156.1	105.9	216.4	256.4
810	83.3	157.2	106.9	217.0	257.0
820	84.4	158.3	107.8	217.6	257.6
830	85.5	159.3	108.7	218.1	258.1
840	86.5	160.3	109.6	218.7	258.7
850	87.6	161.3	110.4	219.2	259.2
860	88.6	162.3	111.3	219.7	259.7
870	89.6	163.3	112.1	220.3	260.3
880	90.5	164.2	113.0	220.8	260.8
890	91.5	165.1	113.8	221.3	261.3
900	92.4	166.1	114.6	221.8	261.8
910	93.4	166.9	115.4	222.3	262.3
920	94.3	167.8	116.1	222.8	262.8
930	95.1	168.7	116.9	223.3	263.3
940	96.0	169.5	117.7	223.8	263.8
950	96.9	170.4	118.4	224.2	264.2
960	97.7	171.2	119.1	224.7	264.7
970	98.6	172.0	119.9	225.2	265.2
980	99.4	172.8	120.6	225.7	265.7
990	100.2	173.6	121.3	226.1	266.1
1000	101.0	174.3	122.0	226.6	266.6
1010	101.7	175.1	122.6	227.0	267.0
1020	102.5	175.8	123.3	227.4	267.4
1030	103.3	176.6	124.0	227.9	267.9
1040	104.0	177.3	124.6	228.3	268.3
1050	104.7	178.0	125.3	228.7	268.7
1060	105.4	178.7	125.9	229.2	269.2
1070	106.2	179.4	126.5	229.6	269.6
1080	106.9	180.1	127.2	230.0	270.0
1090	107.6	180.8	127.8	230.4	270.4
1100	108.2	181.4	128.4	230.8	270.8
1110	108.9	182.1	129.0	231.2	271.2
1120	109.6	182.7	129.6	231.7	271.7

TABLE B-2. Duane Arnold Power Uprate 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 AND BELTLINE AT 32 EFPY CURVE C (°F)
1130	110.2	183.4	130.2	232.1	272.1
1140	110.9	184.0	130.7	232.5	272.5
1150	111.5	184.6	131.3	232.8	272.8
1160	112.1	185.2	131.9	233.2	273.2
1170	112.8	185.9	132.4	233.6	273.6
1180	113.4	186.5	133.0	234.0	274.0
1190	114.0	187.1	133.5	234.4	274.4
1200	114.6	187.6	134.1	234.8	274.8
1210	115.2	188.2	134.6	235.2	275.2
1220	115.8	188.8	135.2	235.5	275.5
1230	116.3	189.4	135.7	235.9	275.9
1240	116.9	189.9	136.2	236.3	276.3
1250	117.5	190.5	136.7	236.6	276.6
1260	118.0	191.0	137.2	237.0	277.0
1270	118.6	191.6	137.7	237.4	277.4
1280	119.1	192.1	138.2	237.7	277.7
1290	119.7	192.6	138.7	238.1	278.1
1300	120.2	193.2	139.2	238.4	278.4
1310	120.7	193.7	139.7	238.8	278.8
1320	121.3	194.2	140.2	239.1	279.1
1330	121.8	194.7	140.6	239.5	279.5
1340	122.3	195.2	141.1	239.8	279.8
1350	122.8	195.7	141.6	240.2	280.2
1360	123.3	196.2	142.0	240.5	280.5
1370	123.8	196.7	142.5	240.8	280.8
1380	124.3	197.2	142.9	241.2	281.2
1390	124.8	197.7	143.4	241.5	281.5
1400	125.3	198.1	143.8	241.7	281.7

TABLE B-3. Duane Arnold Power Uprate 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, AND 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	74.0	74.0	74.0	74.0	74.0	74.0
10	74.0	74.0	74.0	74.0	74.0	74.0
20	74.0	74.0	74.0	74.0	74.0	74.0
30	74.0	74.0	74.0	74.0	74.0	74.0
40	74.0	74.0	74.0	74.0	74.0	74.0
50	74.0	74.0	74.0	74.0	74.0	74.0
60	74.0	74.0	74.0	74.0	74.0	74.0
70	74.0	74.0	74.0	74.0	74.0	74.0
80	74.0	74.0	74.0	74.0	74.0	83.1
90	74.0	74.0	74.0	74.0	74.0	92.8
100	74.0	74.0	74.0	74.0	74.0	100.6
110	74.0	74.0	74.0	74.0	74.0	107.4
120	74.0	74.0	74.0	74.0	74.0	113.3
130	74.0	74.0	74.0	74.0	74.2	118.7
140	74.0	74.0	74.0	74.0	77.4	123.3
150	74.0	74.0	74.0	74.0	80.2	127.3
160	74.0	74.0	74.0	74.0	82.9	131.0
170	74.0	74.0	74.0	74.0	85.5	134.4
180	74.0	74.0	74.0	74.0	87.9	137.6
190	74.0	74.0	74.0	74.0	90.2	140.6
200	74.0	74.0	74.0	74.0	92.3	143.3
210	74.0	74.0	74.0	74.0	94.3	145.8
220	74.0	74.0	74.0	74.0	96.3	148.3
230	74.0	74.0	74.0	74.0	98.1	150.6
240	74.0	74.0	74.0	74.0	99.9	152.8
250	74.0	74.0	74.0	74.0	101.6	154.8
260	74.0	74.0	74.0	74.0	103.2	156.7
270	74.0	74.0	74.0	74.0	104.8	158.6
280	74.0	74.0	74.0	74.0	106.3	160.4
290	74.0	74.0	74.0	74.0	107.8	162.2
300	74.0	74.0	74.0	74.0	109.2	163.8
310	74.0	74.0	74.0	74.0	110.5	165.4
312.5	74.0	74.0	74.0	74.0	110.9	165.8
312.5	74.0	104.0	104.0	74.0	134.0	165.8
320	74.0	104.0	104.0	74.0	134.0	166.9
330	74.0	104.0	104.0	74.0	134.0	168.4
340	74.0	104.0	104.0	74.0	134.0	169.8

TABLE B-3. Duane Arnold Power Uprate 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, AND 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)
350	74.0	104.0	104.0	74.0	134.0	171.2
360	74.0	104.0	104.0	74.0	134.0	172.5
370	74.0	104.0	104.0	74.0	134.0	173.8
380	74.0	104.0	104.0	74.0	134.0	175.1
390	74.0	104.0	104.0	74.0	134.0	176.3
400	74.0	104.0	104.0	74.0	134.0	177.5
410	74.0	104.0	104.0	74.0	134.0	178.7
420	74.0	104.0	104.0	74.0	134.0	179.8
430	74.0	104.0	104.0	74.0	134.0	180.9
440	74.0	104.0	104.0	74.0	134.0	182.0
450	74.0	104.0	104.0	74.0	134.0	183.0
460	74.0	104.0	104.0	74.0	134.0	184.0
470	74.0	104.0	104.0	74.0	134.0	185.0
480	74.0	104.0	104.0	74.0	134.0	186.0
490	74.0	104.0	104.0	74.0	134.0	187.0
500	74.0	104.0	104.0	74.0	134.0	187.9
510	74.0	104.0	104.0	74.0	134.0	188.8
520	74.0	104.0	104.0	74.0	134.0	189.7
530	74.0	104.0	104.1	74.0	134.0	190.6
540	74.0	104.0	106.7	74.0	134.0	191.4
550	74.0	104.0	109.2	74.0	134.6	192.3
560	74.0	104.0	111.6	75.7	135.4	193.1
570	74.0	104.0	113.9	77.4	136.1	193.9
580	74.0	104.0	116.0	79.0	136.9	194.7
590	74.0	104.0	118.1	80.6	137.6	195.5
600	74.0	104.0	120.1	82.2	138.1	196.2
610	74.0	104.0	122.0	83.7	138.6	197.0
620	74.0	104.0	123.9	85.1	139.0	197.7
630	74.0	104.0	125.7	86.5	139.4	198.5
640	74.0	104.0	127.4	87.9	139.8	199.2
650	74.0	104.0	129.1	89.2	140.2	199.9
660	74.0	104.0	130.7	90.5	140.7	200.6
670	74.0	104.0	132.2	91.8	141.1	201.3
680	74.0	104.0	133.7	93.1	141.5	202.0
690	74.0	104.0	135.2	94.3	141.9	202.6
700	74.0	104.0	136.6	95.4	142.3	203.3
710	74.0	104.0	138.0	96.6	142.7	203.9
720	74.0	104.0	139.4	97.7	143.1	204.5
730	74.0	104.0	140.7	98.8	143.5	205.2

TABLE B-3. Duane Arnold Power Uprate 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, AND 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)
740	74.8	104.0	142.0	99.9	143.9	205.8
750	76.1	104.0	143.2	101.0	144.2	206.4
760	77.4	104.8	144.4	102.0	144.6	207.0
770	78.6	105.6	145.6	103.0	145.0	207.6
780	79.8	106.3	146.8	104.0	145.4	208.2
790	81.0	107.1	147.9	105.0	145.8	208.8
800	82.2	107.9	149.0	105.9	146.1	209.3
810	83.3	108.6	150.1	106.9	146.5	209.9
820	84.4	109.4	151.2	107.8	146.9	210.5
830	85.5	110.1	152.2	108.7	147.2	211.0
840	86.5	110.8	153.2	109.6	147.6	211.6
850	87.6	111.5	154.2	110.4	147.9	212.1
860	88.6	112.2	155.2	111.3	148.3	212.6
870	89.6	112.9	156.2	112.1	148.6	213.2
880	90.5	113.6	157.1	113.0	149.0	213.7
890	91.5	114.3	158.0	113.8	149.3	214.2
900	92.4	114.9	159.0	114.6	149.7	214.7
910	93.4	115.6	159.8	115.4	150.0	215.2
920	94.3	116.2	160.7	116.1	150.4	215.7
930	95.1	116.9	161.6	116.9	150.7	216.2
940	96.0	117.5	162.4	117.7	151.0	216.7
950	96.9	118.1	163.3	118.4	151.4	217.1
960	97.7	118.7	164.1	119.1	151.7	217.6
970	98.6	119.3	164.9	119.9	152.0	218.1
980	99.4	119.9	165.7	120.6	152.4	218.6
990	100.2	120.5	166.5	121.3	152.7	219.0
1000	101.0	121.1	167.2	122.0	153.0	219.5
1010	101.7	121.7	168.0	122.6	153.3	219.9
1020	102.5	122.2	168.7	123.3	153.6	220.3
1030	103.3	122.8	169.5	124.0	154.0	220.8
1040	104.0	123.4	170.2	124.6	154.3	221.2
1050	104.7	123.9	170.9	125.3	154.6	221.6
1060	105.4	124.5	171.6	125.9	154.9	222.1
1070	106.2	125.0	172.3	126.5	155.2	222.5
1080	106.9	125.5	173.0	127.2	155.5	222.9
1090	107.6	126.1	173.7	127.8	155.8	223.3
1100	108.2	126.6	174.3	128.4	156.1	223.7
1110	108.9	127.1	175.0	129.0	156.4	224.1
1120	109.6	127.6	175.6	129.6	156.7	224.6

TABLE B-3. Duane Arnold Power Uprate 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, AND 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)
1130	110.2	128.1	176.3	130.2	157.0	225.0
1140	110.9	128.6	176.9	130.7	157.3	225.4
1150	111.5	129.1	177.5	131.3	157.6	225.7
1160	112.1	129.6	178.1	131.9	157.9	226.1
1170	112.8	130.1	178.8	132.4	158.2	226.5
1180	113.4	130.6	179.4	133.0	158.5	226.9
1190	114.0	131.1	180.0	133.5	158.7	227.3
1200	114.6	131.5	180.5	134.1	159.0	227.7
1210	115.2	132.0	181.1	134.6	159.3	228.1
1220	115.8	132.5	181.7	135.2	159.6	228.4
1230	116.3	132.9	182.3	135.7	159.9	228.8
1240	116.9	133.4	182.8	136.2	160.2	229.2
1250	117.5	133.8	183.4	136.7	160.4	229.5
1260	118.0	134.3	183.9	137.2	160.7	229.9
1270	118.6	134.7	184.5	137.7	161.0	230.3
1280	119.1	135.2	185.0	138.2	161.2	230.6
1290	119.7	135.6	185.5	138.7	161.5	231.0
1300	120.2	136.0	186.1	139.2	161.8	231.3
1310	120.7	136.5	186.6	139.7	162.1	231.7
1320	121.3	136.9	187.1	140.2	162.3	232.0
1330	121.8	137.3	187.6	140.6	162.6	232.4
1340	122.3	137.7	188.1	141.1	162.8	232.7
1350	122.8	138.1	188.6	141.6	163.1	233.1
1360	123.3	138.6	189.1	142.0	163.4	233.4
1370	123.8	139.0	189.6	142.5	163.6	233.7
1380	124.3	139.4	190.1	142.9	163.9	234.1
1390	124.8	139.8	190.6	143.4	164.1	234.4
1400	125.3	140.2	191.0	143.8	164.4	234.6

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)
0	74.0	74.0	74.0	74.0	74.0
10	74.0	74.0	74.0	74.0	74.0
20	74.0	74.0	74.0	74.0	74.0
30	74.0	74.0	74.0	74.0	74.0
40	74.0	74.0	74.0	74.0	74.0
50	74.0	74.0	74.0	74.0	74.0
60	74.0	74.0	74.0	74.0	91.5
70	74.0	74.0	74.0	74.0	110.1
80	74.0	74.0	74.0	83.1	123.1
90	74.0	74.0	74.0	92.8	132.8
100	74.0	74.0	74.0	100.6	140.6
110	74.0	74.0	74.0	107.4	147.4
120	74.0	74.0	74.0	113.3	153.3
130	74.0	74.0	74.0	118.7	158.7
140	74.0	74.0	74.0	123.3	163.3
150	74.0	74.0	74.0	127.3	167.3
160	74.0	74.0	74.0	131.0	171.0
170	74.0	74.0	74.0	134.4	174.4
180	74.0	74.0	74.0	137.6	177.6
190	74.0	74.0	74.0	140.6	180.6
200	74.0	74.0	74.0	143.3	183.3
210	74.0	74.0	74.0	145.8	185.8
220	74.0	74.0	74.0	148.3	188.3
230	74.0	74.0	74.0	150.6	190.6
240	74.0	74.0	74.0	152.8	192.8
250	74.0	74.0	74.0	154.8	194.8
260	74.0	74.0	74.0	156.7	196.7
270	74.0	74.0	74.0	158.6	198.6
280	74.0	74.0	74.0	160.4	200.4
290	74.0	74.0	74.0	162.2	202.2
300	74.0	74.0	74.0	163.8	203.8
310	74.0	74.0	74.0	165.4	205.4
312.5	74.0	74.0	74.0	165.8	205.8
312.5	74.0	104.0	74.0	165.8	205.8
320	74.0	104.0	74.0	166.9	206.9
330	74.0	104.0	74.0	168.4	208.4

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)
340	74.0	104.0	74.0	169.8	209.8
350	74.0	104.0	74.0	171.2	211.2
360	74.0	104.0	74.0	172.5	212.5
370	74.0	104.0	74.0	173.8	213.8
380	74.0	104.0	74.0	175.1	215.1
390	74.0	104.0	74.0	176.3	216.3
400	74.0	104.0	74.0	177.5	217.5
410	74.0	104.0	74.0	178.7	218.7
420	74.0	104.0	74.0	179.8	219.8
430	74.0	104.0	74.0	180.9	220.9
440	74.0	104.0	74.0	182.0	222.0
450	74.0	104.0	74.0	183.0	223.0
460	74.0	104.0	74.0	184.0	224.0
470	74.0	104.0	74.0	185.0	225.0
480	74.0	104.0	74.0	186.0	226.0
490	74.0	104.0	74.0	187.0	227.0
500	74.0	104.0	74.0	187.9	227.9
510	74.0	104.0	74.0	188.8	228.8
520	74.0	104.0	74.0	189.7	229.7
530	74.0	104.1	74.0	190.6	230.6
540	74.0	106.7	74.0	191.4	231.4
550	74.0	109.2	74.0	192.3	232.3
560	74.0	111.6	75.7	193.1	233.1
570	74.0	113.9	77.4	193.9	233.9
580	74.0	116.0	79.0	194.7	234.7
590	74.0	118.1	80.6	195.5	235.5
600	74.0	120.1	82.2	196.2	236.2
610	74.0	122.0	83.7	197.0	237.0
620	74.0	123.9	85.1	197.7	237.7
630	74.0	125.7	86.5	198.5	238.5
640	74.0	127.4	87.9	199.2	239.2
650	74.0	129.1	89.2	199.9	239.9
660	74.0	130.7	90.5	200.6	240.6
670	74.0	132.2	91.8	201.3	241.3
680	74.0	133.7	93.1	202.0	242.0
690	74.0	135.2	94.3	202.6	242.6
700	74.0	136.6	95.4	203.3	243.3
710	74.0	138.0	96.6	203.9	243.9

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)
720	74.0	139.4	97.7	204.5	244.5
730	74.0	140.7	98.8	205.2	245.2
740	74.8	142.0	99.9	205.8	245.8
750	76.1	143.2	101.0	206.4	246.4
760	77.4	144.4	102.0	207.0	247.0
770	78.6	145.6	103.0	207.6	247.6
780	79.8	146.8	104.0	208.2	248.2
790	81.0	147.9	105.0	208.8	248.8
800	82.2	149.0	105.9	209.3	249.3
810	83.3	150.1	106.9	209.9	249.9
820	84.4	151.2	107.8	210.5	250.5
830	85.5	152.2	108.7	211.0	251.0
840	86.5	153.2	109.6	211.6	251.6
850	87.6	154.2	110.4	212.1	252.1
860	88.6	155.2	111.3	212.6	252.6
870	89.6	156.2	112.1	213.2	253.2
880	90.5	157.1	113.0	213.7	253.7
890	91.5	158.0	113.8	214.2	254.2
900	92.4	159.0	114.6	214.7	254.7
910	93.4	159.8	115.4	215.2	255.2
920	94.3	160.7	116.1	215.7	255.7
930	95.1	161.6	116.9	216.2	256.2
940	96.0	162.4	117.7	216.7	256.7
950	96.9	163.3	118.4	217.1	257.1
960	97.7	164.1	119.1	217.6	257.6
970	98.6	164.9	119.9	218.1	258.1
980	99.4	165.7	120.6	218.6	258.6
990	100.2	166.5	121.3	219.0	259.0
1000	101.0	167.2	122.0	219.5	259.5
1010	101.7	168.0	122.6	219.9	259.9
1020	102.5	168.7	123.3	220.3	260.3
1030	103.3	169.5	124.0	220.8	260.8
1040	104.0	170.2	124.6	221.2	261.2
1050	104.7	170.9	125.3	221.6	261.6
1060	105.4	171.6	125.9	222.1	262.1
1070	106.2	172.3	126.5	222.5	262.5
1080	106.9	173.0	127.2	222.9	262.9
1090	107.6	173.7	127.8	223.3	263.3

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)
1100	108.2	174.3	128.4	223.7	263.7
1110	108.9	175.0	129.0	224.1	264.1
1120	109.6	175.6	129.6	224.6	264.6
1130	110.2	176.3	130.2	225.0	265.0
1140	110.9	176.9	130.7	225.4	265.4
1150	111.5	177.5	131.3	225.7	265.7
1160	112.1	178.1	131.9	226.1	266.1
1170	112.8	178.8	132.4	226.5	266.5
1180	113.4	179.4	133.0	226.9	266.9
1190	114.0	180.0	133.5	227.3	267.3
1200	114.6	180.5	134.1	227.7	267.7
1210	115.2	181.1	134.6	228.1	268.1
1220	115.8	181.7	135.2	228.4	268.4
1230	116.3	182.3	135.7	228.8	268.8
1240	116.9	182.8	136.2	229.2	269.2
1250	117.5	183.4	136.7	229.5	269.5
1260	118.0	183.9	137.2	229.9	269.9
1270	118.6	184.5	137.7	230.3	270.3
1280	119.1	185.0	138.2	230.6	270.6
1290	119.7	185.5	138.7	231.0	271.0
1300	120.2	186.1	139.2	231.3	271.3
1310	120.7	186.6	139.7	231.7	271.7
1320	121.3	187.1	140.2	232.0	272.0
1330	121.8	187.6	140.6	232.4	272.4
1340	122.3	188.1	141.1	232.7	272.7
1350	122.8	188.6	141.6	233.1	273.1
1360	123.3	189.1	142.0	233.4	273.4
1370	123.8	189.6	142.5	233.7	273.7
1380	124.3	190.1	142.9	234.1	274.1
1390	124.8	190.6	143.4	234.4	274.4
1400	125.3	191.0	143.8	234.6	274.6

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 which 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

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APPENDIX E
FLUENCE EVALUATION

E.1 Overview and Objective

[Redacted]

E.2.1 Scope

[Redacted]

E.2.2 Method of Evaluation

[Redacted]

[Redacted]

E.2.2.1 (r, θ) Model

[Redacted]

[Redacted]

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

[Redacted]

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

[Redacted]

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

[Redacted]

E.3 Evaluation Results

E.3.1 AEP Flux and Fluence at RPV ID

[Redacted]

E.3.2 AEP Flux and Fluence at Surveillance Capsule Location

[Redacted]

E.4 REFERENCES

[Redacted]