HITACHI

GE Hitachi Nuclear Energy

3901 Castle Hayne Road, Wilmington, NC 28401

NEDC-33441

Revision 2

DRF 0000-0086-3665

Class I

June 2009

Licensing Topical Report

GE Hitachi Nuclear Energy Methodology for the Development of ESBWR Reactor Pressure Vessel Pressure-Temperature Curves

Licensing Topical Report

GE Hitachi Nuclear Energy Methodology for Development of ESBWR Reactor Pressure Vessel Pressure-Temperature Curves

Approved by:

Andy Meyers, Manager
Mechanical Analysis CoE

Approved by:

Gerald Deaver, Manager
ESBWR Engineering

LIST OF CONTRIBUTORS

The contributions of the following people to this report are acknowledged (in alphabetical order):

Brian Frew

David Keck

Hardayal Mehta

Donald Sampson

Lori Tilly

Waylon Webbon

Richard Wu

Tao Wu

Sampath Ranganath (XGEN engineering)

REPORT REVISION STATUS

Revision	Purpose
0	Original Issue
1	Corrected revision status page; Deleted affidavit page
2	Deleted the "GEH PROPRIETARY INFORMATION" header in redacted version on page 48,51 and 52

NON-PROPRIETARY INFORMATION NOTICE

This is a non-proprietary version of the document NEDC-33441P, Revision 2, from which the proprietary information has been removed. Portions of the document that have been removed are identified by white space within double square brackets, as shown here [[ ]].

Copyright GE Hitachi Nuclear Energy 2009

IMPORTANT NOTICE REGARDING THE CONTENTS OF THIS REPORT

Please Read Carefully

The information contained in this document is furnished as reference to Dominion with the expectation that it will be provided to the NRC Staff for the purpose of obtaining NRC approval of the ESBWR COL Application(s). The only undertakings of GE Hitachi Nuclear Energy (GEH) with respect to information in this document are contained in contracts between GEH and participating utilities, and nothing contained in this document shall be construed as changing those contracts. The use of this information by anyone other that for which it is intended is not authorized; and with respect to any unauthorized use, GEH makes no representation or warranty, and assumes no liability as to the completeness, accuracy, or usefulness of the information contained in this document.

ABSTRACT

This report describes the development of the generic pressure-temperature (P-T) curves for the Economic Simplified Boiling Water Reactor (ESBWR). Appendix G to 10 CFR 50 specifies fracture toughness requirements for pressure retaining components, fabricated from ferritic materials, in the reactor coolant pressure boundary of water cooled reactors. Section XI, ASME Boiler and Pressure Vessel Code forms the basis of the 10 CFR 50 requirements. The objective is to determine the minimum vessel metal temperature as a function of the steam dome pressure as required by 10 CFR 50 Appendix G. This is accomplished by demonstrating that the structural factor requirements for non-ductile fracture as described in Appendix G of Section XI, ASME Code are satisfied. Both beltline components (which are affected by exposure to neutron fluence) and non-beltline components such as nozzles, vessel and top head flange and bottom head (where the cumulative end-of-design life fluence is less than 10^{17} n/cm^2) are evaluated.

The ASME Boiler and Pressure Vessel Code and 10 CFR 50 Appendix G are used in this evaluation. The evaluation considers the vessel beltline region and the other non-beltline components separately. For the vessel beltline the adjusted reference temperature (ART) for the beltline material is calculated using RG 1.99 Rev.2 and the predicted end-of-design-life fluence. P-T curves for the beltline region are governing towards the end of life. The non-beltline P-T curves are governing during the early part of the design life. Following Appendix G of 10 CFR 50, separate P-T curves are presented for the hydrostatic test, core not critical normal operation and core critical normal operation.

Because of the very low initial RT_{NDT} of the non-beltline components, the ASME limits are not governing for the P-T curves for most of the non-beltline components. Instead, the 10 CFR 50 Appendix G criteria which require additional temperature requirements (depending on the pressure) beyond the ASME limits govern for all non-beltline components.

TABLE OF CONTENTS

1.0 INTRODUCTION 1

2.0 SCOPE OF THE ANALYSIS 4

3.0 RT_{NDT} SHIFT CALCULATION 7

3.1 INITIAL REFERENCE TEMPERATURE 7

3.2 MATERIAL COMPOSITION 7

3.3 PREDICTED FLUENCE 8

3.4 RG 1.99, Rev. 2 METHODOLOGY 8

3.4.1 Effect of Irradiation Temperature 9

3.5 PREDICTED RT_{NDT} SHIFT 10

4.0 PRESSURE-TEMPERATURE CURVES FOR THE BELTLINE REGION 15

4.1 PRESSURE-TEMPERATURE CURVE METHODOLOGY 15

4.2 P-T CURVES FOR THE BELTLINE REGION 16

5.0 PRESSURE-TEMPERATURE CURVES FOR NON- BELTLINE COMPONENTS 22

5.1 GENERAL METHODOLOGY 22

5.2 MAIN STEAM NOZZLE 24

5.3 FEEDWATER NOZZLE 25

5.4 CLOSURE HEAD FLANGES 26

5.5 BOTTOM HEAD 27

5.6 STANDBY LIQUID CONTROL NOZZLE 28

5.7 CORE DP NOZZLE 29

6.0 SUMMARY AND CONCLUSIONS 57

7.0 REFERENCES 59

LIST OF FIGURES

FIGURE 2-1 SCHEMATIC ILLUSTRATING THE COMPONENTS ANALYZED 6
FIGURE 3-1 MAXIMUM VESSEL ID FLUENCE AT DIFFERENT VESSEL ELEVATIONS 14
FIGURE 4-1 P-T CURVES FOR THE BELTLINE REGION 20
FIGURE 4-2 COMPARISON OF CURVE C WITH THE STEAM SATURATION CURVE 21
FIGURE 5-1 NOZZLE CORNER FLAW 32
FIGURE 5-2 TEMPERATURE REGIONS IN THE VESSEL 33
FIGURE 5-3 ESBWR MAIN STEAM OUTLET NOZZLE 34
FIGURE 5-4 STEAM NOZZLE FINITE ELEMENT MODEL 35
FIGURE 5-5 MAIN STEAM NOZZLE P-T CURVES 36
FIGURE 5-6 FEEDWATER NOZZLE 37
FIGURE 5-7 FW NOZZLE FINITE ELEMENT MODEL 38
FIGURE 5-8 P-T CURVES FOR THE FW NOZZLE 39
FIGURE 5-9 CLOSURE HEAD FLANGE 40
FIGURE 5-10 OVERALL FE MODEL OF THE CLOSURE HEAD ASSEMBLY 41
FIGURE 5-11 CIRCUMFERENTIAL CRACK EMBEDDED IN THE TOP HEAD FLANGE 42
FIGURE 5-12 VESSEL FLANGE CIRCUMFERENTIAL AND AXIAL CRACKS 43
FIGURE 5-13 P-T CURVES FOR THE TOP HEAD FLANGE 44
FIGURE 5-14 ESBWR BOTTOM HEAD CONFIGURATION 45
FIGURE 5-15 OVERALL FINITE ELEMENT MODEL OF THE BOTTOM HEAD REGION 46
FIGURE 5-16 RADIAL ID CRACK AT THE CENTER OF THE VESSEL 47
FIGURE 5-17 CIRCUMFERENTIAL ID CRACK IN THE HILLSIDE REGION 48
FIGURE 5-18 OD SURFACE CRACK BETWEEN TWO CRD STUB TUBES 49
FIGURE 5-19 P-T CURVES FOR THE BOTTOM HEAD 50
FIGURE 5-20 STANDBY LIQUID CONTROL (SLC) NOZZLE CONFIGURATION 51
FIGURE 5-21 SLC NOZZLE FINITE ELEMENT MODEL 52
FIGURE 5-22 P-T CURVES FOR THE SLC NOZZLE 53
FIGURE 5-23 CORE DP NOZZLE CONFIGURATION 54
FIGURE 5-24 CORE DP NOZZLE FE MODEL 55
FIGURE 5-25 CORE DF NOZZLE P-T CURVES 56
FIGURE 6-1 P-T CURVES FOR THE BELTLINE AND NON-BELTLINE COMPONENTS 58

LIST OF TABLES

TABLE 3-1 INITIAL RT_{NDT} FOR VESSEL COMPONENTS 13
TABLE 4-1 SUMMARY OF THE 10 CFR 50 APPENDIX G REQUIREMENTS 19
TABLE 5-1 SHELL AND NOZZLE COMPONENT SELECTION 30
TABLE 5-2 CALCULATED K VALUES FOR THE CLOSURE FLANGE 31
TABLE 5-3 CALCULATED K VALUES FOR THE BOTTOM HEAD REGION 31

1.0 INTRODUCTION

This report describes the development of the pressure-temperature (P-T) curves for the ESBWR. The objective is to determine the minimum vessel metal temperature as a function of the steam dome pressure as required by 10CFR 50 Appendix G [1]. This is accomplished by demonstrating that the structural factor requirements for non-ductile fracture as described in Appendix G of Section XI [2] are satisfied. Both beltline components (which are affected by exposure to neutron fluence and are subject to irradiation embrittlement) and non-beltline components such as nozzles, vessel and top head flange and bottom head (where the cumulative end-of-design life fluence is less than 10^{17} n/cm^2) are evaluated.

This document describes the methodology for developing the P-T curves and provides specific P-T curves for both the shell beltline and other limiting non-beltline components. This report is not plant-specific and assumes material properties (e.g. material composition – copper and nickel content, initial RT_{NDT}, cumulative fluence) based on the generic design specifications. The generic methodology described here can be used for a plant specific utility submittal to the appropriate regulatory staff.

Section 2 describes the scope of the analysis and the vessel components included in the P-T curve analysis.

Section 3 describes the determination of the RT_{NDT} shift and the final adjusted reference temperature (ART) at the end of the 60-year design life. The RT_{NDT} shift is calculated based on Regulatory Guide 1.99 Revision 2 [3]. This includes consideration of the effect of irradiation temperature. The ART at the end of design life is determined for both the vessel shell material and the associated weldment. The limiting ART is used for the determination of the P-T curves for the vessel beltline region.

Section 4 describes the P-T curve evaluation for the beltline region. P-T curves are developed using the geometry of the pressure vessel including the beltline shell region and discontinuity regions (e.g. nozzles, top head and vessel flange), the initial RT_{NDT} of the RPV materials, and the adjusted reference temperature (ART) for the beltline materials. The ASME Boiler and Pressure Vessel Code is used throughout in this evaluation. The P-T curve methodology includes the following steps:

- The use of K_{Ic} from Figure A-4200-1 of Appendix A [2] to determine the required $T\text{-}RT_{NDT}$
- Description of the postulated defect per ASME Code paragraph G-2214.1 [2]
- Determination of the stress intensity factors for the shell belt line region based on the ASME Code Appendix G methodology [2]
- Determination of the minimum vessel temperature for a given pressure based on the (ART) for the beltline materials for the predicted end-of- design-life fluence.

P-T curves are determined in accordance with [1] and are presented for:

a. Hydrostatic pressure test (Curve A)
b. Normal operation (heatup and cooldown) including anticipated operational occurrences; core not critical (Curve B)
c. Normal operation (heatup and cooldown); core critical (Curve C)

Section 5 describes the P-T curve evaluation for non-beltline components. It applies for nozzles, bottom head and flange components. Unlike the vessel beltline region where the stresses and stress intensity factors are based on the shell analysis, the non-beltline discontinuity regions have more complex stress distributions and the simplified ASME Code methods are not applicable. [[

]] The stress analysis is performed using the ANSYS finite element analysis code [4]. ANSYS uses these elements to compute Stress Intensity Factors using the KCALC command. Stress Intensity Factors are computed at the different nodes [[

]] Evaluation is performed for the pressure test and for different operational transients. Fracture evaluation is performed for transient times at which the combined pressure and thermal stresses are highest and the coolant temperature is the highest.

Section 6 summarizes the results and conclusions of the P-T curve analysis.

2.0 SCOPE OF THE ANALYSIS

The methodology for the pressure-temperature (P-T) curves is developed to present steam dome pressure versus minimum vessel metal temperature incorporating appropriate non-beltline limits and irradiation embrittlement effects in the beltline.

Figure 2-1 shows the different components for which fracture analysis is performed to determine the P-T curves. [[

]] This region is referred to as the core beltline region and is shown in Figure 2-1. It is seen that there are no nozzles or attachments (which are generally high stress locations) in the beltline region. P-T curves for the beltline region are developed based on the consideration of irradiation effect on the shift in RT_{NDT} as a function of neutron fluence. As required in Appendix G of the ASME Boiler and Pressure Vessel Code, a semi-elliptic quarter thickness flaw with length equal to 6 times the depth is postulated for the analysis. The shift in RT_{NDT} for the 60-year fluence is determined based on RG 1.99, Rev. 2 [3]. K_{Ic} from Figure A-4200-1 of Appendix A is used for the fracture assessment. The minimum temperature for a given pressure is determined for normal operation and test conditions based on assuring the appropriate structural factors in [2]. In addition to this, the added requirements of 10 CFR 50 Appendix G are also included in the P-T curves.

P-T curves are also developed for the non-beltline components. Unlike the beltline region, there is no shift in RT_{NDT} for irradiation effects (fluence is less than 10^{17} n/cm^2). P-T curves are determined with postulated flaws equal to a quarter of the local thickness (e.g. a nozzle corner flaw with depth equal to one-quarter of the corner thickness). Fracture evaluation is performed for operating conditions including the hydrostatic test and the heatup/cooldown transient. For components such as nozzles (with more complex geometry than the vessel shell beltline region), the conventional Appendix G to ASME Section XI stress equations may not be directly applicable. For these special cases, finite element models [[

]] are used to determine the stress intensity factors. The calculated stress intensity factors are used to demonstrate compliance with the Appendix G structural factor requirements. In general, the hydrostatic test is governing from the fracture mechanics viewpoint for most BWR components. Since the BWR follows the steam saturation curve, the vessel temperature is high enough that sufficient fracture toughness is maintained so that the Appendix G structural factors are maintained.

The P-T curves for the non-beltline components are governing during the early operating life (since the cumulative fluence is low). The P-T curve for the beltline region is governing towards the end of the design life.

[[

]]

3.0 RT_{NDT} SHIFT CALCULATION

3.1 INITIAL REFERENCE TEMPERATURE

The initial RT_{NDT} values for the low alloy steel vessel components are needed to develop the vessel P-T limits. The ESBWR reactor pressure vessel specification [5] prescribes the limiting initial RT_{NDT} values for the ESBWR vessel components. Table 3-1 from [5] shows the initial RT_{NDT} values. The RT_{NDT} values are based on testing that meet the ASME Code Section III, Subsection NB-2300 requirements [6]. Drop weight testing and Charpy testing are also required. Specifically, the Charpy test specimens are required to be transversely oriented (normal to the rolling direction) CVN specimens. The RT_{NDT} is defined as the higher of the drop weight NDT or 33°C below the temperature at which Charpy V-Notch 68 J energy and 0.89 mm lateral expansion are met. The RT_{NDT} values of the weld materials are required to be equal to or lower than the highest RT_{NDT} values of the materials being welded.

3.2 MATERIAL COMPOSITION

The ESBWR purchase specification requires that special base material for the beltline and weld material adjacent to the core beltline region be purchased to meet the following requirements:

a. The minimum upper shelf energy level, as determined by transverse Charpy-V notch impact specimens, shall be [[ ]].

b. Base Material. The material shall have the following chemical restrictions in both ladle and check analysis:

[[

]]

c. Weld Material. The weld material shall have the following chemical restrictions, as deposited:

[[

]]

The RG 1.99, Rev. 2 prediction of the shift in RT_{NDT} is dependent on the Nickel and Copper content. The values above are used in determining the adjusted RT_{NDT} (ART).

3.3 PREDICTED FLUENCE

Figure 3-1 from [7] shows the 60-year fluence as a function of elevation. The fluence analysis was performed using an NRC-approved methodology consistent with Regulatory Guide 1.190 [8]. The values shown in Figure 3-1 correspond to the ID surface and represent the maximum fluence at a given elevation. The quarter-T fluence can be calculated using the relationship in RG 1.99 Rev.2. The maximum ID fluence is [[ ]]n/cm^2 in the base material.

3.4 RG 1.99, Rev. 2 METHODOLOGY

The value of ART is computed by adding the SHIFT term to the initial RT_{NDT}. The SHIFT term is determined for a given value of fluence. The SHIFT equation consists of two terms:

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

where,

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

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

f = ¼T fluence / 10^{19}

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

σ_I = standard deviation on initial RT_{NDT}, which is taken to be 0°F unless otherwise specified.

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

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

The margin term σ_Δ as described above, is defined in RG1.99.

3.4.1 Effect of Irradiation Temperature

RG 1.99 Rev.2 specifies that the procedure is valid for a nominal irradiation temperature of 550°F (288°C) but is applicable down to 525°F. The shift prediction equation in RG 1.99 Rev.2 can be used for irradiation temperatures not lower than 525°F. Irradiation below 525°F is considered to produce greater embrittlement (than that predicted by RG 1.99 Rev.2) and irradiation above 590°F is considered to produce less embrittlement. A correction factor can be used for irradiation temperatures below 520°F. The temperature in the beltline region of the ESBWR is [[ ]] which is slightly outside the applicability region.

The recently issued PTS rule [9] can be used to determine the correction factor for the irradiation temperature. The predictive model in [9] is different from that in RG 1.99 Rev. 2, but since the RG 1.99 equation does not explicitly include irradiation temperature, the PTS rule can be used to predict the percent change as a result of differences in irradiation temperature. The predicted shift in the PTS rule is:

TTS =MF+CRP where TTS = predicted irradiation-induced shift in Charpy 41 J (30 ft-lb) transition temperature (in °F), MF = component of shift attributed to matrix features and CRP = component of shift attributed to Copper. CRP is not dependent on irradiation temperature T_i (in°F), but MF is a function of T_i.

In Equation 3-1:

$$MF = A(1-0.001718T_i)(1+6.13\ PMn^{2.47})(\varphi t_e)^{0.5}$$

where A = constant depending on whether the component is a plate, forging or weld, P = bulk P (wt%), Mn = bulk Mn (wt%) and φt_e is the effective flux. The correction factor is the ratio of the term $(1-0.001718T_i)$ corresponding to the two irradiation temperatures. Although only one of the terms (MF) in the predicted shift is a function of T_i, the correction factor can be applied to both terms (MF and CRP) so that the increase in RT_{NDT} shift as a result of the lower T_i is conservative. [[

]]

3.5 PREDICTED RT_{NDT} SHIFT

This section describes the determination of the shift in RT_{NDT} for the limiting fluence location. The fluence is highest in the middle of the vessel belt line in the forged ring. There are no axial welds in the beltline region. The two circumferential welds - upper and lower are located well outside the peak fluence region. The shift prediction for the vessel forging and the weld are shown below.

Vessel Forging

The ID surface fluence is [[ ]]. The quarter-T fluence can be calculated using the following relationship from [4]:

$F = f_{surf}\ (e^{-0.24x})$ where f_{surf} is the surface fluence and x is the distance from the ID surface in inches. For the quarter-T flaw, x = 0.25×[[ ]] inches. Substituting, the calculated quarter-T fluence is: [[ ]].

The chemistry factor CF corresponding to the beltline vessel composition [[ ]]. The fluence factor is:

$FF = f^{(0.28 - 0.10 \log f)}$ where f is the quarter-T fluence/10^{19}.

Substituting, FF= [[ ]]

The predicted ΔRT_{NDT} = [[ ]]. Multiplying it by the correction factor for the irradiation temperature, the corrected [[ ]]. The predicted shift including the margin term ([[ ]]) is:

SHIFT = [[ ]]. The adjusted RT_{NDT} at the end of the 60-year design life is given by:

ART = Initial RT_{NDT} + SHIFT = [[ ]].

Weld Material

The immediate welds connecting the beltline shell course are at elevations [[ ]] respectively. The calculated 60-year ID surface fluence exceeds 10^{17} n/cm^2 (E> 1 MEV) from the elevation [[ ]]. The welds are just within the region where fluence effects must be considered. The bounding fluence is approximately [[ ]]. As before, the quarter-T fluence is [[ ]]. The chemistry factor CF corresponding to the upper and lower welds in the belt line region vessel composition [[ ]]. The fluence factor is:

$FF = f^{(0.28 - 0.10 \log f)}$ where f is the quarter-T fluence/10^{19}.

Substituting, FF= [[ ]]. Applying, as before the correction factor for irradiation temperature,

ΔRT_{NDT} = [[ ]]. σ_Δ for the weld material is 28°F for welds material except that σ_Δ need not exceed 0.50 times the ΔRT_{NDT} value. Since the latter limit applies, σ_Δ = [[ ]]. Therefore the margin term is $2\sigma_\Delta$ or [[ ]]. The shift is calculated as:

SHIFT = [[ ]].

The adjusted RT_{NDT} at the end of the 60-year design life is given by:

ART = Initial RT_{NDT} + SHIFT = [[ ]].

Comparing the ART for limiting weld and the corresponding value for the shell forging, it is clear that the governing case is the shell forging. Therefore, the shell forging ART ([[ ]] at the end of the 60-year design life) is used for the derivation of the P-T curves.

Table 3-1 Initial RT_{NDT} for Vessel Components

Number	Component	Initial RT_{NDT} °C
1	Core beltline shell course	[[ ]]
2	Upper shell courses	[[ ]]
3	Bottom head knuckle (i.e., transition) shell	[[ ]]
4	Main closure flange, vessel flange and support flange forging	[[ ]]
5	Nozzle forgings, except nozzles integral with shell forgings	[[ ]]
6	The carbon steel weld metal and low alloy weld metal	$\leq RT_{NDT}$ of materials being welded
7	Lifting Lugs	[[ ]]
8	Stabilizer Brackets	[[ ]]

[[

]]

4.0 PRESSURE-TEMPERATURE CURVES FOR THE BELTLINE REGION

This section describes the development of the P-T curves for the beltline region of the vessel which is exposed to fluence in excess of $1x10^{17}$ n/cm^2 and experiences irradiation embrittlement. The P-T curves developed here correspond to the end of the 60-year design life and use the ART values described in Section 3. The P-T curves for the non-beltline components are described in the next section.

4.1 PRESSURE-TEMPERATURE CURVE METHODOLOGY

Nuclear Regulatory Commission (NRC) 10 CFR 50 Appendix G [1] specifies fracture toughness requirements to provide adequate margins of safety during the operating conditions to which a pressure-retaining component may be subjected over its service lifetime. ASME Section XI, Appendix G [2] forms the basis for the requirements of 10 CFR 50 Appendix G. However, 10 CFR 50 Appendix G has additional requirements beyond those of Section XI, Appendix G. Table 4-1 describes the additional requirements imposed in [1]. 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 (core not critical), referred to as Curve B; and (c) core critical operation, referred to as Curve C. As shown in Table 4-1, additional temperature requirements apply depending on whether the pressure is less than or higher than 20% of the required pressure for the preservice hydrostatic test (1.25 times the design pressure as specified in NB-6220 of ASME Section III). Different temperature requirements also apply depending on whether the core is critical or not. [[

]]

For the core not critical and the core critical curves, the P-T curves are based on a coolant heatup and cooldown temperature rate of [[ ]]. For the hydrostatic test curve, a coolant heatup temperature rate of 20°F/hr is assumed. 10 CFR 50 Appendix G limits the heatup rate (due to the residual heat from fuel in the vessel) to 20°F/hr and this value is assumed for Curve A.

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 in the outer wall during heatup. However, as a conservative simplification, the thermal gradient stress at the 1/4T location is assumed to be tensile for both heatup and cooldown. This results in the approach of applying the maximum tensile stress at the 1/4T location. This approach is conservative because irradiation effects cause the allowable toughness, K_{Ic}, 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.

4.2 P-T CURVES FOR THE BELTLINE REGION

P-T curves are developed for the vessel forging which is the governing component based on the ART evaluation described in Section 2. There are no axial welds in the beltline region since the beltline shell course is a forged ring. The two circumferential welds are barely in the beltline region (meaning that the fluence is slightly in excess of $1x\ 10^{17} n/cm^2$). The ART for these welds is lower than that for the vessel forging. There are other vessel circumferential welds are outside the beltline region. The RT_{NDT} value for the upper shelf course welds is [[ ]]. Thus the RT_{NDT} values for all the welds outside of the beltline are lower than the ART for the

beltline shell forging ([[ ]]). Therefore the P-T curves developed for the vessel forging bound those for all other vessel shell courses or associated welds.

Section XI, Appendix G provides simple rules for the determination of stress intensity factors for pressure and heatup/cooldown for a postulated quarter-T flaw.

Stress Intensity factor for membrane tension (pressure)

The stress intensity factor K_I for an inside quarter-T axial semi-elliptic flaw is given by:

$$K_{Im} = M_m \times (pR_i/t) \quad (1)$$

where p is the pressure in ksi, R_i is the inside radius and t is the thickness in inches, the K value is in ksi√in units and M_m is given by:

$$M_m = 0.926 \sqrt{t} \text{ for } 4 < t < 12 \text{ in.} \quad (2)$$

The values in SI units (MPa√m) can be determined by multiplying the ksi√in value calculated above by 1.1.

The equations above apply for an inside axial surface flaw. Separate equations are provided for an outside surface flaw. However, as described earlier, the inside surface flaw is bounding since the fluence is higher for the ID flaw and we are assuming tensile stresses for both heatup and cooldown.

Stress Intensity factor for bending (radial thermal gradient)

The stress intensity factor for a radial thermal gradient is given by

$$K_{It} = 0.953 \times 10^{-3} \times CR \times t^{2.5} \quad (3)$$

where CR is the cooling rate in °F/hr, t is the thickness in inches, and K_{It} is in ksi√in.

Curve A (hydrostatic test), Curve B (normal operation, core not critical) and Curve C (normal operation, core critical) were determined using the ASME Code equations above and the criteria in Table 4-1. Since 10 CFR 50 Appendix G limits the cooling rate (or heating rate) to 20°F/hr for the hydrostatic test, the thermal gradient stress for 20°F/hr is included in the K calculation for the hydrostatic test.

Figure 4-1 shows the P-T curves for the beltline region. They were based on the ART value of [[ ]] and bound the entire shell course. They are consistent with both Appendix G of 10 CFR 50 and the ASME Code. Curve A applies for the hydrostatic test and Curves B and C are intended for heatup/cooldown. Since the BWR temperatures are close to the steam saturation curve, the temperatures are generally well in excess of the P-T curve requirements. Figure 4-2 shows a comparison of Curve C and the steam saturation curve. It is seen that there are large temperature margins.

Table 4-1 Summary of the 10 CFR 50 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 pre-service hydrotest pressure	Larger of ASME Limits or of highest closure flange region initial RT_{NDT} + [[ ]]*
2. At > 20% of pre-service 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 pre-service hydrotest pressure	Larger of ASME Limits or of highest closure flange region initial RT_{NDT} + [[ ]]*
2. At > 20% of pre-service 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 pre-service 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 pre-service 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

[[ ]]

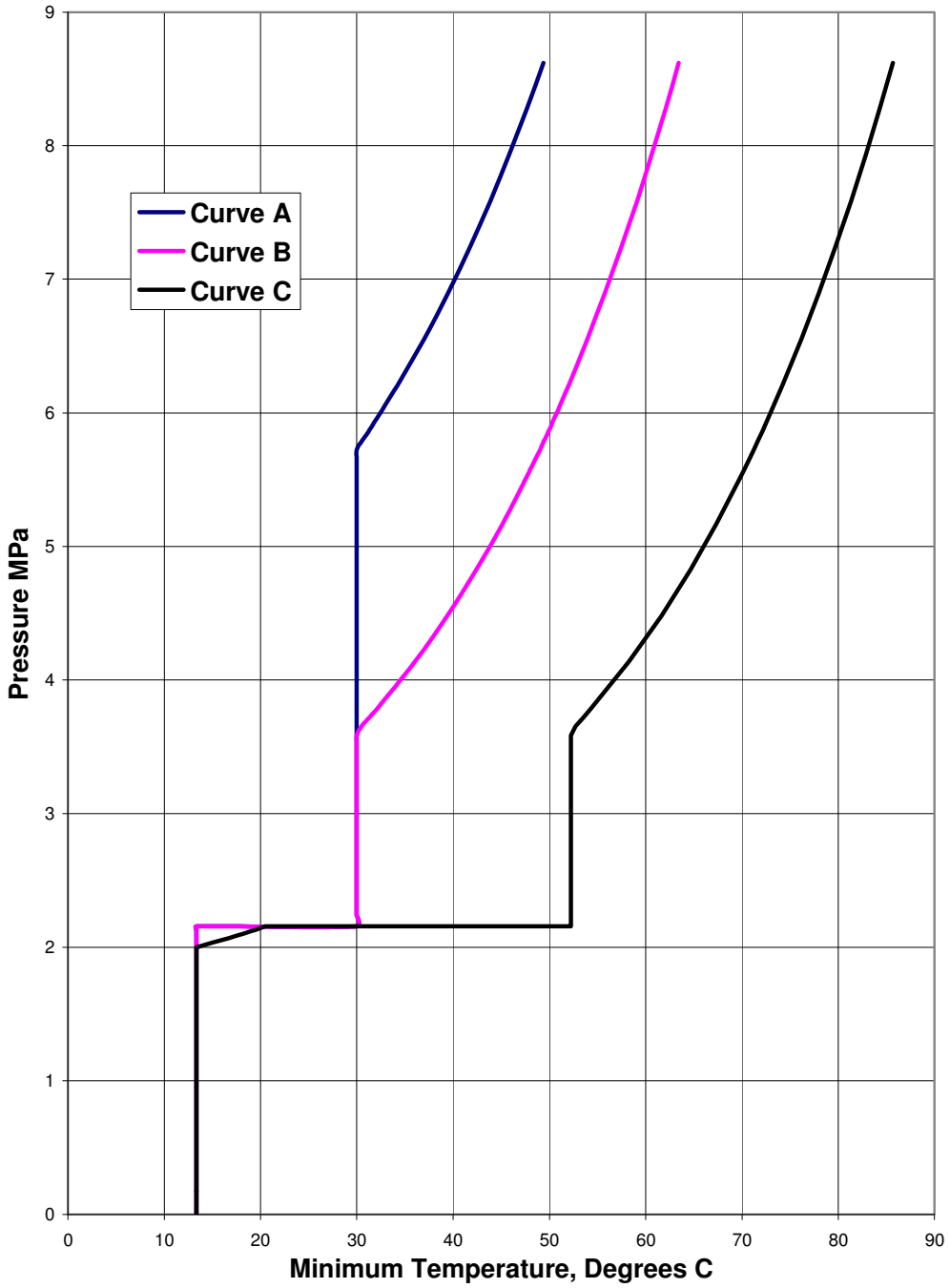


Figure 4-1 P-T Curves for the Beltline Region

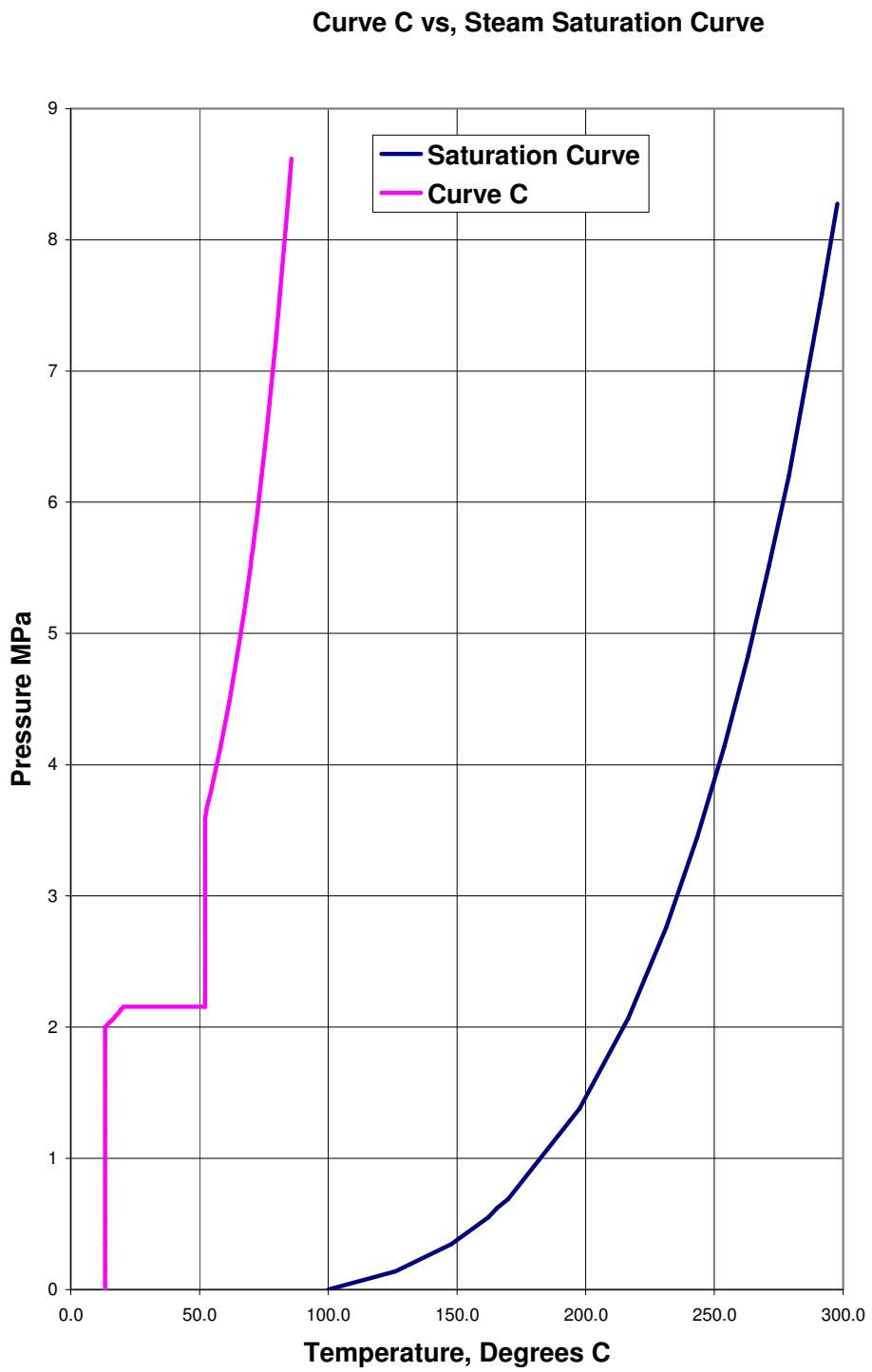


Figure 4-2 Comparison of Curve C with the Steam Saturation Curve

5.0 PRESSURE-TEMPERATURE CURVES FOR NON- BELTLINE COMPONENTS

The previous section described the P-T curves for the beltline shell regions that are exposed to neutron fluence in excess of $1x10^{17}$ n/cm^2 and experience shift in RT_{NDT}. The beltline P-T curves are limiting towards the end of the design life. However, during the early part of the design life, other discontinuity region components (e. g. nozzles, vessel and top head flanges which are subjected to higher stresses) are more limiting from the viewpoint of P-T curves. This section describes the development of P-T curves for the other non-beltline components. Table 5-1 shows a listing of the different discontinuity region components that could have an impact on the overall P-T curves. The thermal cycles and stresses in some components are such that P-T curves for these nozzles bound the P-T curves for the other nozzles. Detailed stress and fracture evaluations were performed for the items shown in bold in Table 5-1. As shown in this table, other components are bounded by these analyses.

5.1 GENERAL METHODOLOGY

The methodology for the evaluation of each non-beltline component in Table 5-1 is as follows:

- Develop a finite element model of the component for detailed thermal and stress analysis.
- Review the thermal cycle diagram to determine the critical time steps and transients for detailed stress analysis. Generally the combination of high pressure stress and tensile thermal stress (typically involving temperature drop) events are selected for more detailed stress analysis. Since the hydrostatic stress is almost always governing for BWR vessel from the fracture mechanics viewpoint, the combination of high stress (high applied stress intensity factor) and low temperature is governing for the P-T curves.

- Determine P-T curves for the hydrostatic test and heatup/cooldown events. For other critical operational transients, the requirement is to demonstrate that the Appendix G criterion of $2K_{IPrimary} + K_{ISecondary} < K_{Ic}$ is satisfied.
- There are two options for the determination of the stress intensity factor. The first option is to use available handbook solutions (e.g. Section XI Appendix G equations or polynomial curve fit solutions). The handbook approach uses the stress analysis based on the uncracked model. This works best for more simple configurations such as shells and in some cases for nozzles. The second approach uses the results from a finite element model with the crack modeled [[ ]] Except for the beltline region, all the analysis results in this report are based on the [[ ]] FEM. The stress intensity factor is determined at the deepest point of the postulated crack.
- For the heatup condition, the thermal stresses are generally compressive on the ID surface and when combined with the pressure stress they reduce the overall stress state. This is appropriate for a postulated ID flaw, but for an OD flaw, the pressure and thermal stresses can add up. A conservative approach is followed here; except in cases where separate analysis is performed with postulated ID and OD flaws, the thermal stresses during heatup/cooldown will be assumed to be tensile for all evaluations.
- Appendix G requires the postulation of a quarter-T semi-elliptic flaw. Depending on the location and the stress state, circumferential (hoop) direction flaws or meridional direction (axial) flaws (or in some cases, flaws in both directions) are postulated. This is appropriate for shell regions including vessel and top head flanges.
- For nozzles, a corner flaw in the blend radius region is postulated as shown in Figure 5-1. Stress Intensity Factors are determined along the 45° line as shown in Figure 5-1. This is the center of the crack and represents the deepest point.

- The vessel is divided into three temperature regions - Regions A, B and C as shown in Figure 5-2 and thermal cycles are specified for each region. Separate thermal cycles are specified for each vessel nozzle.

Details of the fracture analysis for the components in Table 5-1 are shown below. The transient selection, finite element model and fracture analysis results are described in the following sections.

5.2 MAIN STEAM NOZZLE

Figure 5-3 shows the details of the ESBWR main steam outlet nozzle [10]. The main steam nozzle is located in the upper plenum (Region A) of the vessel. The main thermal cycles of interest are the hydrostatic test (Event 2) and the heatup (Event 3) and cooldown (Event 15) events. In general, thermal cycling in Region A is minor and the steam outlet nozzle does not experience significant thermal stresses. In evaluating the hydrostatic test, in addition to pressure stress, thermal stress for 11°C/hr (20°F/hr) heatup is included. As described before, thermal stresses during heatup are assumed to be tensile (even though they are compressive for the ID flaw). Thermal stress for the heatup (55°C/hr) event is calculated for Event 3 and the value for the hydrostatic test (11°C/hr) is determined by linear interpolation.

Figure 5-4 shows the [[ ]] finite element model [[ ]] for the main steam nozzle. The thickness at the nozzle corner is [[ ]] and the postulated crack depth is [[ ]]. The calculated stress intensity factor for the hydrostatic test (pressure only) for the quarter-T nozzle is [[ ]] for the 8 MPa pressure. The stress intensity factor for the 55°C/hr cooldown is [[ ]]. Figure 5-5 shows the P-T curve for the steam nozzle. The thermal cycle diagram specifies the minimum temperature for the hydrostatic pressure test as [[ ]] which is conservative when compared with the Curve A limit in Figure 5-5.

5.3 FEEDWATER NOZZLE

Figure 5-6 shows the details of the ESBWR feedwater nozzle 110]. The feedwater nozzle is located in Region B of the vessel and is the one vessel component with the most significant thermal cycling. The main thermal cycles of interest are the hydrostatic test (Event 2) and the heatup (Event 3), cooldown (Event 15), [[

]].

Figure 5-7 shows the [[ ]] finite element model of the feedwater nozzle. It also shows the [[ ]]. The thickness at the nozzle corner is [[ ]] and the postulated crack depth is [[ ]]. The calculated stress intensity factor for the hydrostatic test (pressure only) for the quarter-T nozzle is [[ ]] for the 8 MPa pressure. The stress intensity factor for the 55°C/hr cooldown is [[ ]]. Figure 5-8 shows the P-T curve for the steam nozzle. As a result of the low RT_{NDT} value for the nozzle materials and the associated welds, the ASME temperature requirements are low. Because of the specific add-on terms in the 10CR50 Appendix G (e.g. Curve A: for pressure > 20% of pre-service hydro test pressure, the minimum temperature is the larger of ASME Limits or of highest closure flange region initial RT_{NDT} + 90°F, etc.) the ASME limits are not governing. As in the case of the steam nozzle, the 10 CFR 50 criteria are more limiting for the FW nozzle also.

The highest stress condition for the FW nozzle is the [[

]] The Appendix G requirement is:

$$2K_{IPrimary} + K_{ISecondary} < K_{Ic}$$

The available toughness K_{Ic} is [[ ]]. Substituting the calculated value in the above equation, [[ ]]which is less than K_{Ic} value of [[ ]]. Thus, even with the conservative assumptions the Appendix G requirement is met.

5.4 CLOSURE HEAD FLANGES

This includes both the top head and vessel flanges. Figure 5-9 shows the closure head flange configuration [11]. The top head and vessel flanges are located in Region A of the vessel. The main events of interest are bolt-up (Event 1), the hydrostatic test (Event 2) and the heatup (Event 3), and cooldown (Event 15). Figure 5-10 shows the overall finite element model that includes the bolting, the vessel and top head flange. The [[ ]] solid model considered a 1/8 pie slice of the closure flange. Since the bolt-up condition (which is the major source of loading on the flange) produces tensile stresses on the OD surface, the postulated flaw is on the [[ ]]. Figure 5-11 shows the finite element model with the [[ ]]. The thickness at the crack location is [[ ]] and the postulated crack depth is [[ ]]. The circumferential crack is selected since the predominant stress due to bolt-up is in the meridional direction. Figure 5-12 shows the finite element model of the vessel flange with [[ ]]. The axial crack case was added to address the hoop stress in the cylindrical shell region of the vessel flange/shell weld. The local thickness at the vessel flange region is [[ ]] and the postulated crack depth is [[ ]].

The hydrostatic test condition is limiting from a fracture mechanics viewpoint. As in typical bolted joint analysis, in addition to the bolt-up stress, a portion of the pressure load goes into the top head or vessel flange weld. Calculations were made for the hydrostatic test, bolt-up and the heatup (thermal only) transients. Table 5-2 shows the calculated stress intensity factor for the

postulated quarter-T flaw in the top head (circumferential) and vessel flange (circumferential and axial) regions. The heatup condition includes not only the stresses due to the temperature gradient, but also the discontinuity stress in the bolted joint. However, it does not include pressure stresses which are evaluated separately.

An important consideration for the closure head is that the stress intensity factor is high even at zero pressure because of the stresses due to bolt-up. Thus, the required temperature for core-critical operation (Curve C) at low pressure ($\leq$ 20% of pre-service hydrostatic test pressure) is somewhat higher for the closure head flanges than for the other non-beltline components.
The P-T curves for the top head flange is the most limiting (primarily because of the higher bolt-up stress) of the cases considered in Table 5-2. Still, because of the low RT_{NDT} value for the flange materials and the associated welds the ASME limits are not governing. Because of the specific add-on terms in the 10CR50 Appendix G (e.g. Curve A: for pressure > 20% of pre-service hydro test pressure, the minimum temperature is the larger of ASME Limits or of highest closure flange region initial RT_{NDT} + 90°F, etc.) the ASME limits are not governing. In all cases, the 10 CFR 50 criteria are more limiting. Figure 5-13 shows the P-T curve for the top head flange.

5.5 BOTTOM HEAD

The bottom head region includes the control rod drive (CRD) housing, in-core housing penetrations, support brackets and the bottom head. Temperatures in the bottom head correspond to Region C. Figure 5-14 shows the overall bottom head configuration. A [[ ]] finite element model of a 1/8 slice of the bottom head (Figure 5-15) was developed. The model includes the CRD and in-core penetrations and the support brackets. Three postulated flaws were selected for fracture analysis: [[

]] Figure 5-16 shows the [[ ]] model. Figure 5-17 shows the [[ ]] model. Figure 5-18 shows the [[ ]].

The events of interest for the bottom head are the hydrostatic test (Event 2) and the heatup (Event 3) and shutdown (Event 15) transients. There are other events where the cooldown rate is somewhat higher than the 55°C/hr for shutdown, but the overall stress state is not higher (either because the time duration of the temperature drop is smaller or the pressure drops rapidly). As described before, with the assumption of the heatup stress to be tensile in combination with the pressure, the analyses for the hydrostatic test and the heatup event bound all other cases.

Table 5-3 shows the calculated stress intensity factor for the postulated quarter-T flaw in the [[ ]]. The heatup condition includes only the stresses due to the temperature gradient and does not include pressure stresses which are evaluated separately.

Figure 5-19 shows the P-T curves for the bottom head. As in the case of the other vessel components such as the nozzles and the closure head, the ASME limits are not limiting. The P-T curve is entirely governed by the 10 CFR 50 Appendix G criteria.

5.6 STANDBY LIQUID CONTROL NOZZLE

Figure 5-20 shows the details of the standby liquid control (SLC) nozzle. The SLC nozzle is located in Region B of the vessel. The main thermal cycles of interest are the hydrostatic test (Event 2) and the heatup (Event 3), cooldown (Event 15) and the [[ ]]. Figure 5-21 shows the finite element model of the SLC nozzle. The thickness at the

nozzle corner is [[ ]] and the postulated crack depth is [[ ]]. The calculated stress intensity factor for the hydrostatic test (pressure only) for the quarter-T nozzle is [[ ]] for the 8 MPa pressure. The stress intensity factor for the 55°C/hr cooldown is [[ ]]. Figure 5-22 shows the P-T curve for the SLC nozzle. As in the previous cases, the ASME limits are not limiting. The P-T curve is entirely governed by the 10 CFR 50 Appendix G requirements.

5.7 CORE DP NOZZLE

Figure 5-23 shows the details of the core DP nozzle. The core DP nozzle is located in Region C of the vessel and is essentially a penetration in the bottom head. The thermal cycles for the bottom head apply to the core DP nozzles also. The main thermal cycles of interest are the hydrostatic test (Event 2) and the heatup (Event 3) and cooldown (Event 15). Figure 5-24 shows the finite element model of the core DP nozzle. The thickness at the nozzle penetration is [[ ]] and the postulated crack depth is [[ ]]. The calculated stress intensity factor for the hydrostatic test (pressure only) for the quarter-T nozzle is [[ ]] for the 8 MPa pressure. The stress intensity factor for the 55°C/hr cooldown is [[ ]]. Figure 5-25 shows the P-T curve for the core DP nozzle. As in the previous cases, the ASME limits are not limiting. The P-T curve is entirely governed by the 10 CFR 50 Appendix G requirements.

Table 5-1 Shell and Nozzle Component Selection

Item No.	Component	Comments including basis for Selection or other bounding cases
1	**Vessel Shell Beltline region**	[[ ]]
2	**Main Steam Outlet Nozzle (N3)**	[[ ]]
3	**Feedwater Nozzle(N4)**	[[ ]]
4	**Vessel and top head Flange**	[[ ]]
5	**Bottom head**	[[ ]]
6	**Standby Liquid Control Nozzle (N16)**	[[ ]]
7	**Core DP Penetration (N11)**	[[ ]]
8	DPV/IC Outlet Nozzle (N5)	[[ ]]
9	RWCU/SDC Outlet (N8)	[[ ]]
10	GDCS Nozzle (N6)	[[ ]]
11	GDCS Equalizing Line (N2)	[[ ]]
12	Water Level Instrumentation (N10)	[[ ]]
13	Water Level Instrumentation (N12)	
14	RPV Instrumentation (N13)	
15	Water Level Instrumentation (N14)	
16	CRD Penetrations	[[ ]]

Table 5-2 Calculated K values for the Closure Flange

Component	Flaw depth (mm)	Calculated K for a quarter-T postulated flaw (MPa√m)		
		Hydrostatic test	Bolt-up	Heatup
Vessel Flange (circumferential flaw)	[[			
Vessel Flange (Axial flaw)				
Top Head Flange (circumferential flaw)				]]

Table 5-3 Calculated K values for the Bottom Head Region

Component	Flaw depth (mm)	Calculated K for a quarter-T postulated flaw (MPa√m)	
		Hydrostatic test	Heatup
Bottom Head centerline region (ID surface radial flaw)	[[		
Bottom Head hillside region(ID surface circumferential flaw)			
Bottom Head (OD surface flaw between two stub tubes)			]]

* Compressive stresses conservatively assumed to be tensile

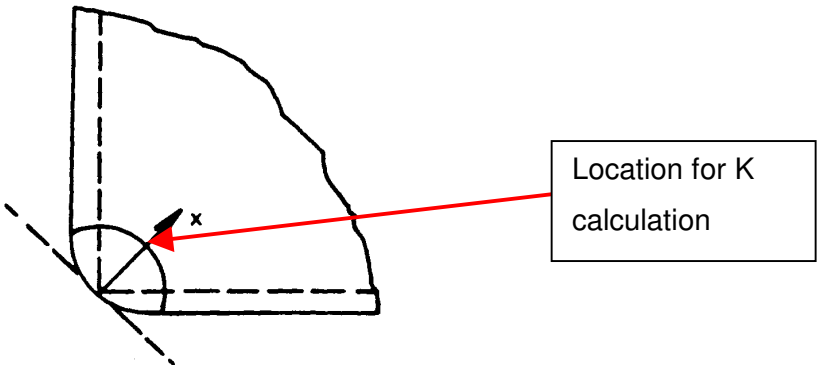


Figure 5-1 Nozzle Corner Flaw

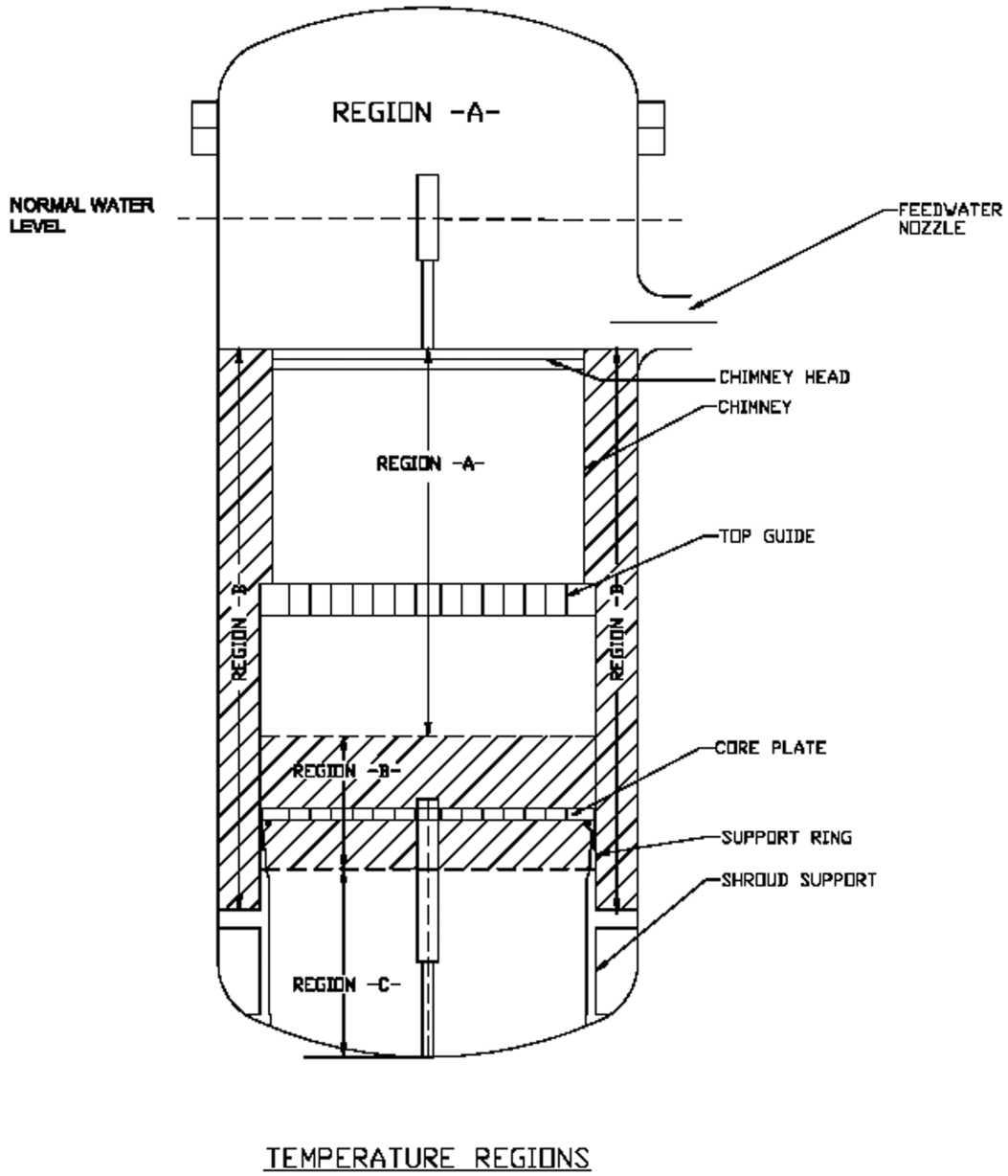


Figure 5-2 Temperature Regions in the Vessel

[[

]]

[[

]]

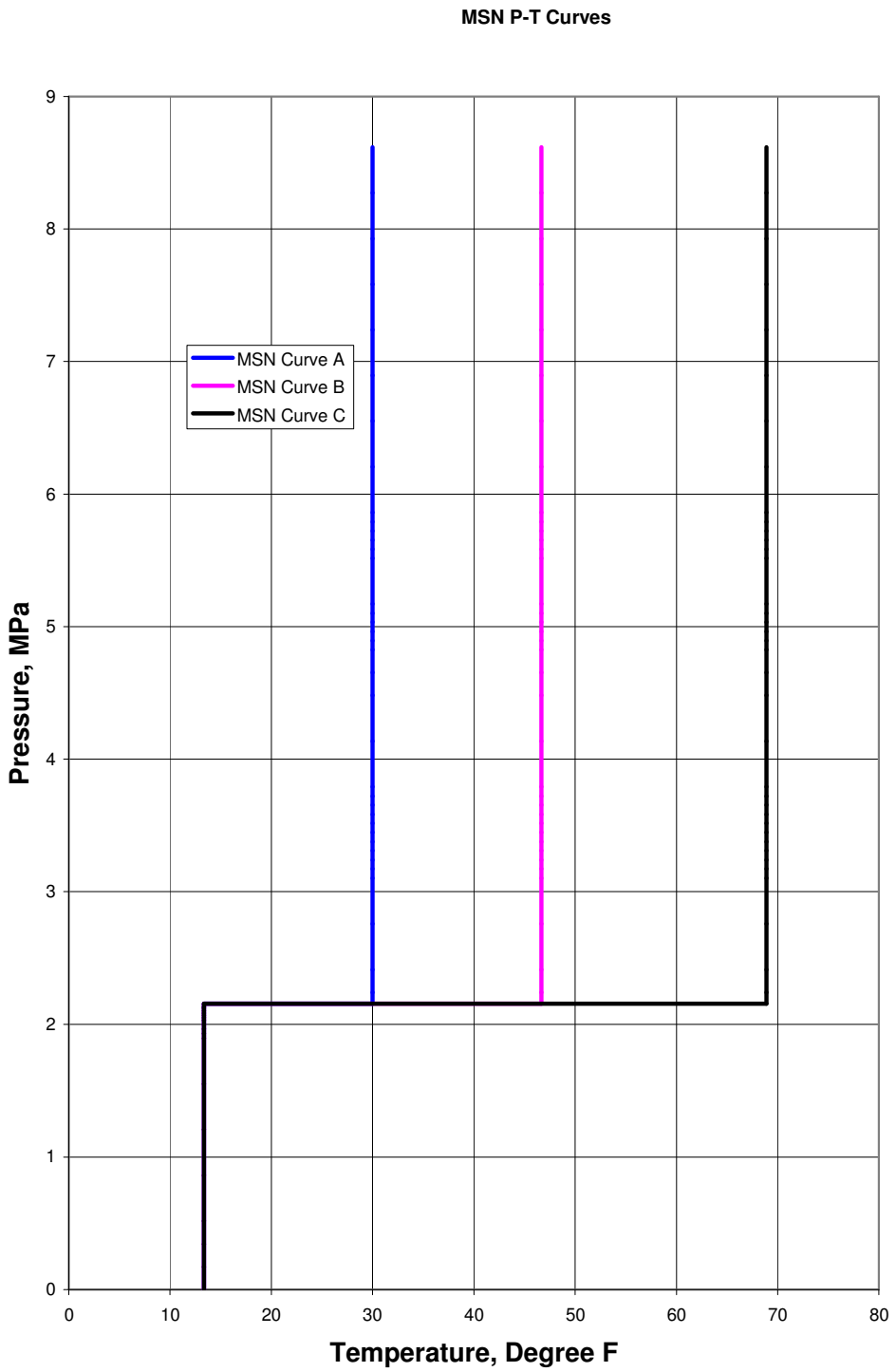


Figure 5-5 Main Steam Nozzle P-T Curves

[[

]]

[[

]]

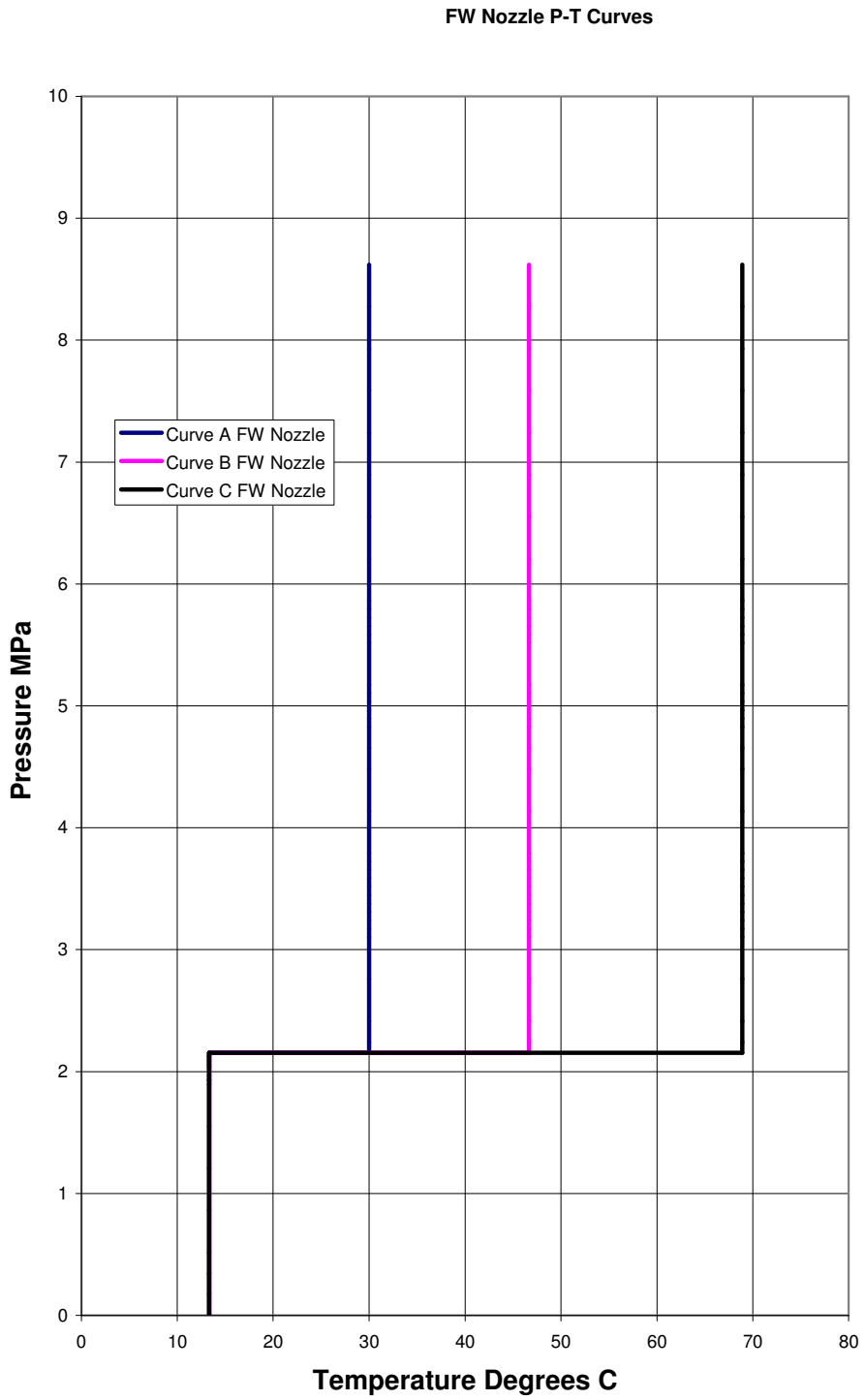


Figure 5-8 P-T Curves for the FW Nozzle

[[

]]

[[

]]

[[

]]

[[

]]

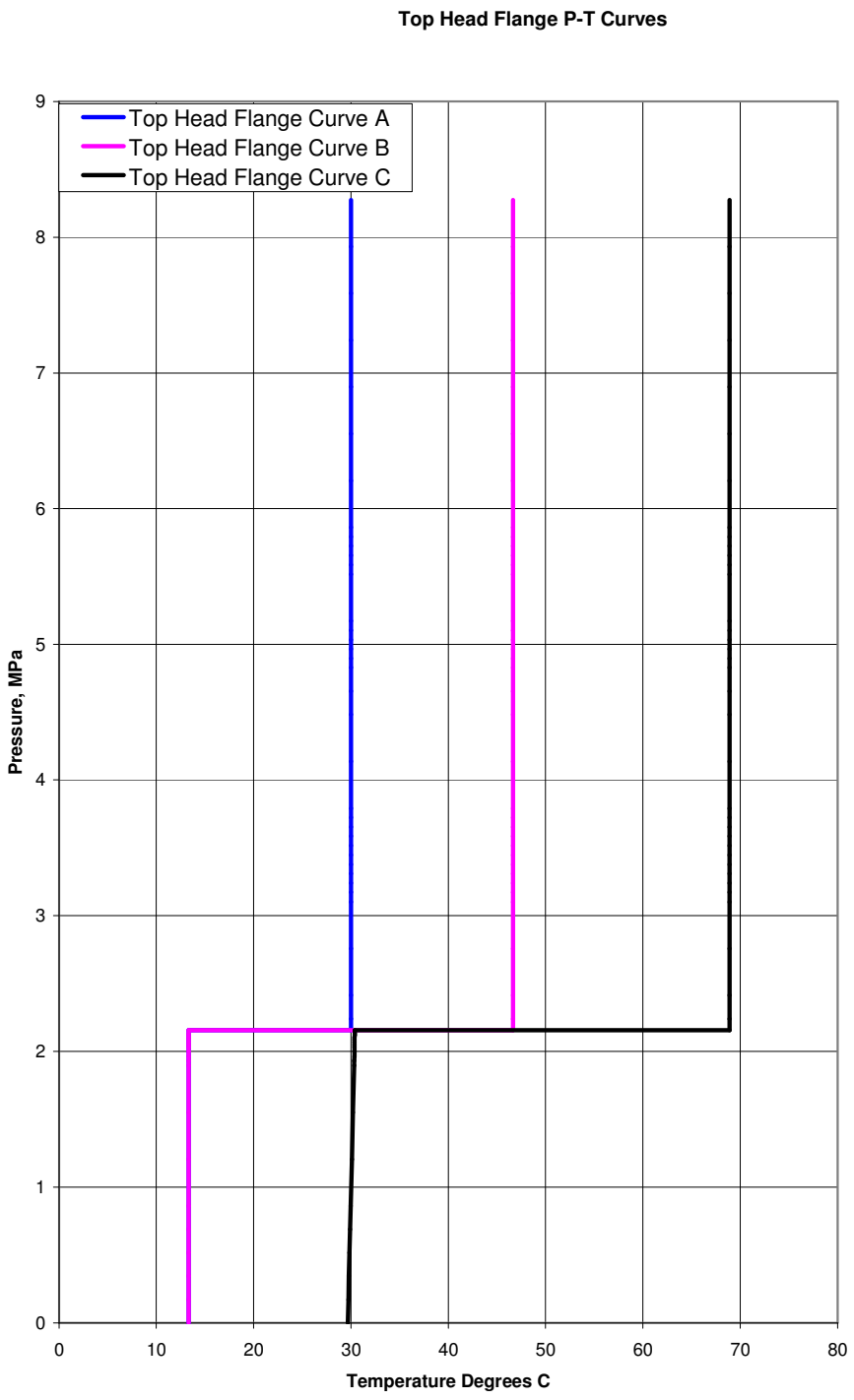


Figure 5-13 P-T Curves for the Top Head Flange

[[

]]

[[

]]

[[

]]

[[

]]

[[

]]

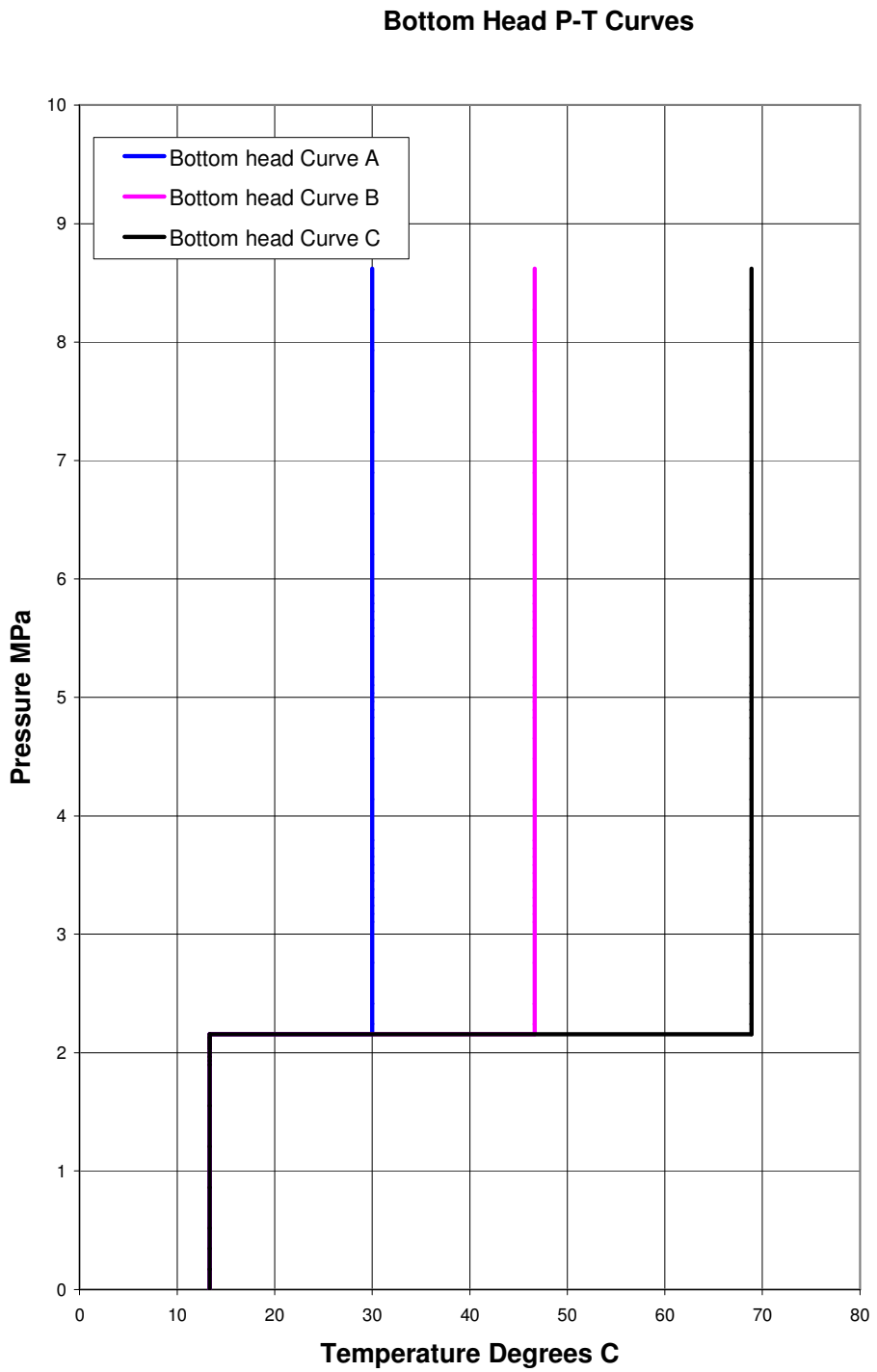


Figure 5-19 P-T Curves for the Bottom Head

[[

]]

[[

]]

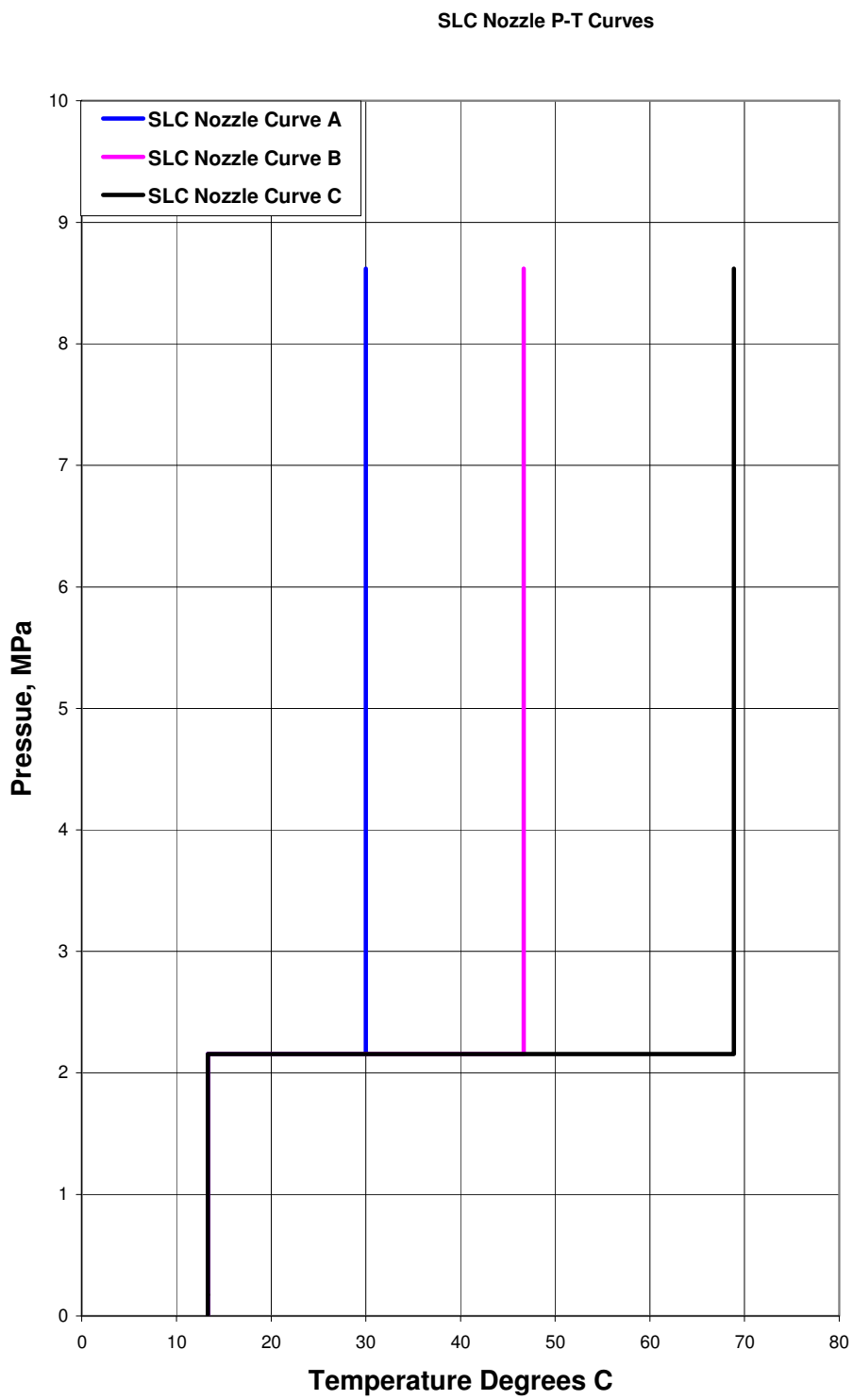


Figure 5-22 P-T Curves for the SLC Nozzle

[[

]]

[[

]]

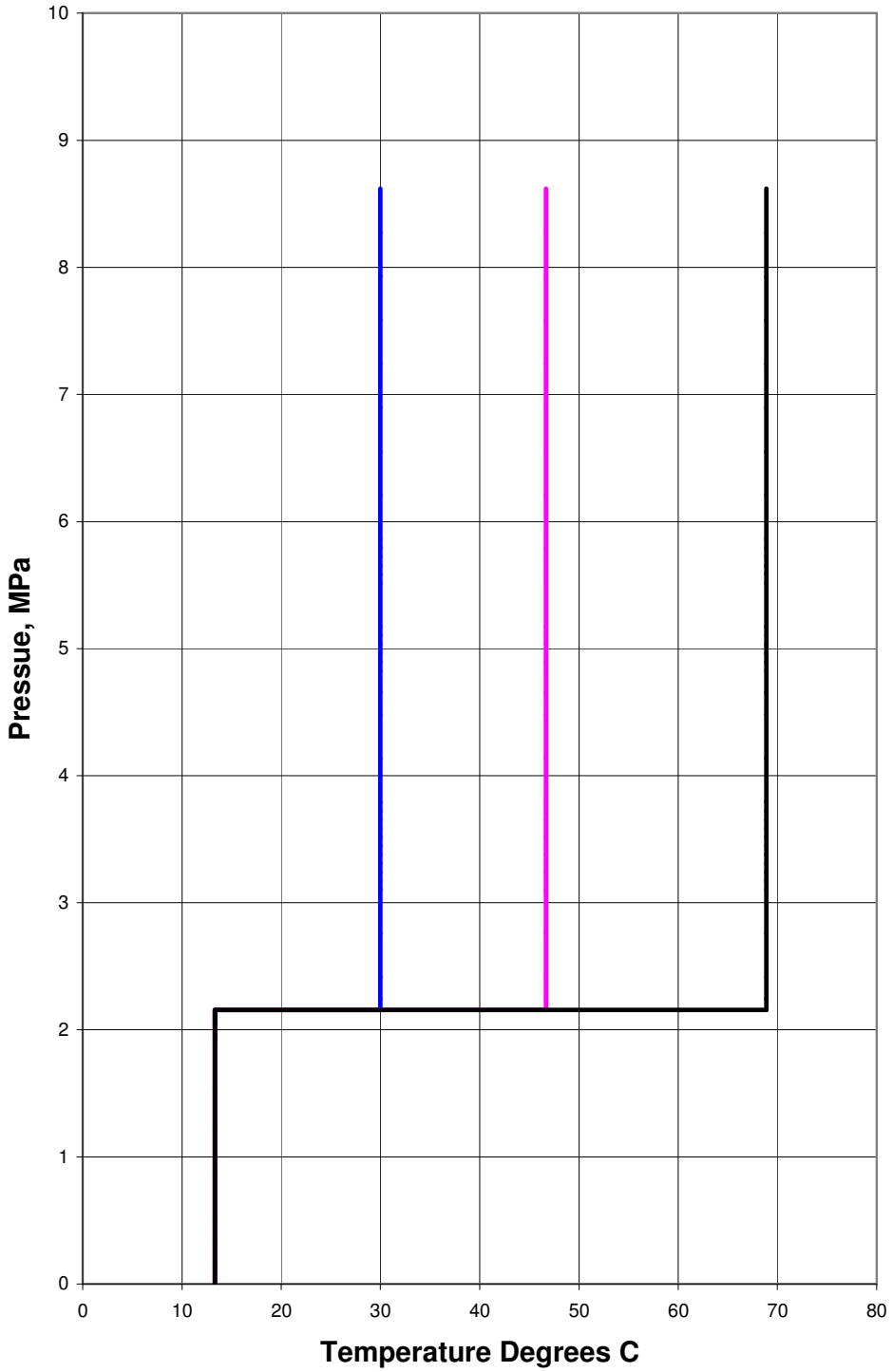


Figure 5-25 Core DF Nozzle P-T Curves

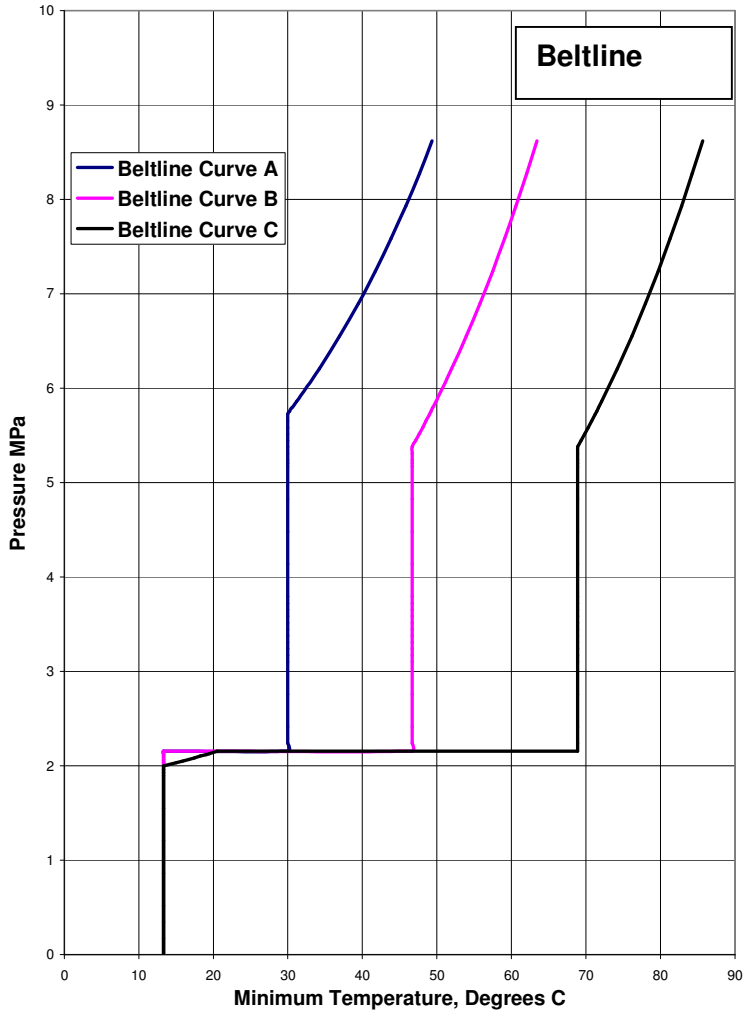
6.0 SUMMARY AND CONCLUSIONS

This report describes the development of the pressure-temperature (P-T) curves for the ESBWR. The minimum required vessel metal temperature is determined by the structural factor requirements for non-ductile fracture as described in Appendix G of Section XI. Both beltline components (which affected by exposure to neutron fluence and subject to irradiation embrittlement) and non-beltline components such as nozzles, vessel and top head flange and bottom head (where the cumulative end-of-design life fluence is less than 10^{17} n/cm^2) are evaluated.

Following Appendix G of 10 CFR 50, separate P-T curves are presented for:

a. Hydrostatic pressure test (Curve A)
b. Normal operation (heatup and cooldown) including anticipated operational occurrences; core not critical (Curve B)
c. Normal operation (heatup and cooldown); core critical (Curve C)

Figure 6-1 shows a comparison of the P-T curves for both the beltline and the non-beltline (limiting top head flange) components. Because of the very low initial RT_{NDT} of the non-beltline components, the ASME limits are not governing for the P-T curves for most of the non-beltline components. Instead, the 10 CFR 50 Appendix G criteria which require additional temperature requirements (depending on the pressure) beyond the ASME limits govern for the non-beltline components. This explains the straight lines in the non-beltline P-T curves. The non-beltline P-T curves are governing during the early part of the design life. P-T curves for the beltline region are governing towards the end of life.



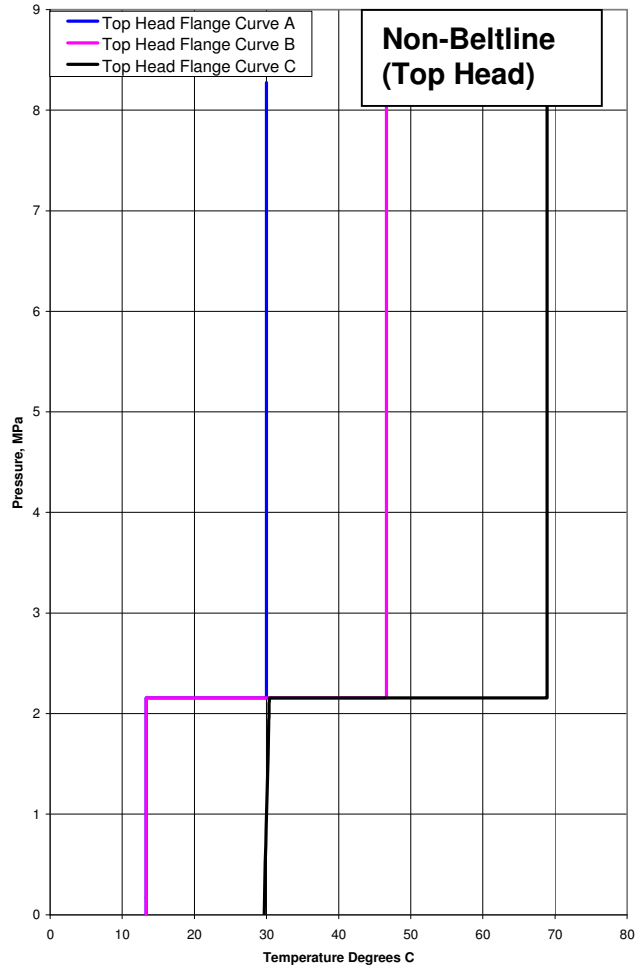


Figure 6-1 P-T Curves for the Beltline and Non-beltline Components

7.0 REFERENCES

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

2. "Fracture Toughness Criteria for Protection Against Non-ductile Failure", Appendix G to Section XI of the ASME Boiler and Pressure Vessel Code.

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

4. ANSYS 11.0SP1 (Level 2 certified installation), ANSYS Inc., Canonsburg, PA

5. [[ ]]

6. Section III, Subsection NB, ASME Boiler and Pressure Vessel Code.

7. [[ ]]

8. Regulatory Guide (RG) 1.190, ''Calculational and Dosimetry Methods for Determining Pressure Vessel Neutron Fluence,'' dated March 2001.

9. Alternate Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock Events', Proposed Rules, Federal Register, Vol 73, No. 1555, August 11, 2008

10. [[ ]]

11. [[ ]]