ENCLOSURE 1

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GE Hitachi Nuclear Energy Methodology for the Development of ESBWR Reactor Pressure Vessel Pressure-Temperature Curves, Revision 6

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GE Hitachi Nuclear Energy

NEDO-33441
Revision 6
GEH Public/Class I
DRF 0000-0086-3665
November 2013

Licensing Topical Report

GE HITACHI NUCLEAR ENERGY METHODOLOGY FOR THE DEVELOPMENT OF ESBWR REACTOR PRESSURE VESSEL PRESSURE-TEMPERATURE CURVES

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
3	Revised to address NRC Requests for Additional Information (RAIs).
4	Revised based on NRC comments. Key changes are: • Added new last sentence to Section 3.4.1, 2nd paragraph, and • Added new Section 7.0.
5	Changed Reference 17 from ASTM E185-02 to ASTM E185-82.
6	Changed the notice regarding the contents of the report to include Dominion and other Combined License Applicants as potential users of the report, added "2013" to the copyright, and changed the date of issuance of the report to November 2013.

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IMPORTANT NOTICE REGARDING THE CONTENTS OF THIS REPORT

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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 [6 x 10^{17} n/in^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.

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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 [6 x 10^{17} n/in^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 beltline shell region, 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 discusses temperature limits for bolt-up and hydrotest. Section 7 provides a brief description of the material surveillance program. Section 8 summarizes the results and conclusions of the P-T curve analysis. Section 9 provides a list of references.

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 [6 x 10^{17} n/in^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.

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Figure 2-1 Schematic Illustrating the Components Analyzed

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 (60°F) below the temperature at which Charpy V-Notch 68 J (50 ft-lbs) energy and 0.89 mm (0.035 in) 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 is documented in Reference 14 and is based on the methodology in Reference 15, which is 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 ([[ ]] n/in^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:

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

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}

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

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

σ_Δ = standard deviation on ΔRT_{NDT}, 16°C (28°F) for welds and 9°C (17°F) for base material, except that σ_Δ need not exceed 0.50 times the ΔRT_{NDT} value.

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

The margin term σ_Δ as described above, is defined in RG1.99, Revision 2.

3.4.1 Effect of Irradiation Temperature

RG 1.99 Rev.2 specifies that the procedure is valid for a nominal irradiation temperature of 288°C (550°F) but is applicable down to 274°C (525°F). The shift prediction equation in RG 1.99 Rev.2 can be used for irradiation temperatures not lower than 274°C (525°F). Irradiation below 274°C (525°F) is considered to produce greater embrittlement (than that predicted by RG 1.99 Rev.2) and irradiation above 310°C (590°F) is considered to produce less embrittlement. A correction factor can be used for irradiation temperatures below 271°C (520°F). The temperature in the beltline region of the ESBWR is [[ ]] which is slightly outside the applicability region.

There has been considerable work [9, 10] in the industry to include the effect of flux and irradiation temperature in the predictive model for the shift in RT_{NDT} with neutron fluence. The available industry models suggest that the effect of the slightly lower ESBWR irradiation temperature is not significant. The US NRC has not yet approved an update to RG 1.99, Revision 2, to include the effect of irradiation temperature. In the interim, the NRC staff has accepted the use of a conservative, but simple model to account for irradiation temperature effects [11]. Specifically, the NRC staff states in [11]: "Studies have shown that for temperatures near 550°F, a 1°F decrease in irradiation temperature will result in approximately a 1°F of increase in ΔRT_{NDT}". Since the use of this model has been approved by the NRC staff for use in licensee submittals, it will be used for the assessment of irradiation temperature effects for the ESBWR also. This method will be validated for the ESBWR in the future as more industry information becomes available and using results from the material surveillance program discussed in Section 7.0.

Since use of RG 1.99, Revision 2, is valid for irradiation temperatures down to 273.9°C (525°F), a case can be made that the increment in the predicted shift based on [11] should be (273.9 - 271.0) = 2.9°C (5.2°F). A more conservative approach based on the literal interpretation of [11] - for temperatures near 287.8°C (550°F), a 0.55°C (1°F) decrease in irradiation temperature will result in approximately a 0.55°C (1°F) increase in ΔRT_{NDT} – the increment in the predicted shift is assumed to be (287.8 - 271.0) = 16.8°C (30.2°F).

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.

<u>Vessel Forging</u>

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 or [[ ]] mm. 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} = [[ ]]. Adding the increment of 16.8°C (30.2°F) to account for the lower 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 (6 x 10^{17} n/in^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= [[ ]].

ΔRT_{NDT} = [[ ]]. Adding the increment of 16.8°C (30.2°F) to account for the lower irradiation temperature, the corrected [[ ]]. σ_Δ for the weld material is 16°C (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 (°F)
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	[[ ]]

[[

]]

Figure 3-1 Maximum Vessel ID Fluence at Different Vessel Elevations

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 (6 x 10^{17} n/in^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 11°C/hr (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 11°C/hr (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 [6 x 10^{17} n/in^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:

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

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:

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

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

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

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 11°C/hr (20°F/hr) for the hydrostatic test, the thermal gradient stress for 11°C (20°F/hr) is included in the K calculation for the hydrostatic test.

Figure 4-1 and Table 4-2 show 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 for operating conditions, 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 relative to the P-T curve requirements.

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 hydro test pressure	Larger of ASME Limits or of highest closure flange region initial RT_{NDT} + [[ ]]*
2. At > 20% of pre-service hydro test pressure	Larger of ASME Limits or of highest closure flange region initial RT_{NDT} + 50°C (90°F)
II. Normal operation (heatup and cooldown), including anticipated operational occurrences	
a. Core Not Critical - Curve B	
1. At ≤ 20% of pre-service hydro test pressure	Larger of ASME Limits or of highest closure flange region initial RT_{NDT} + [[ ]]*
2. At > 20% of pre-service hydro test pressure	Larger of ASME Limits or of highest closure flange region initial RT_{NDT} + 67°C (120°F)
b. Core Critical - Curve C	
1. At ≤ 20% of pre-service hydro test pressure, with the water level within the normal range for power operation	Larger of ASME Limits + 22°C (40°F) or of a.1
2. At > 20% of pre-service hydro test pressure	Larger of ASME Limits + 22°C (40°F) or of a.2 + 22°C (40°F) or the minimum permissible temperature for the inservice system hydrostatic pressure test

*[[ ]]

Table 4-2 P-T Data for the Beltline Region

Pressure		Curve A Temperature		Curve B Temperature		Curve C Temperature	
MPaG	psig	°C	°F	°C	°F	°C	°F
0	0	13.3	55.9	13.3	55.9	13.3	55.9
0.2	29	13.3	55.9	13.3	55.9	13.3	55.9
0.4	58	13.3	55.9	13.3	55.9	13.3	55.9
0.6	87	13.3	55.9	13.3	55.9	13.3	55.9
0.8	116	13.3	55.9	13.3	55.9	13.3	55.9
1	145	13.3	55.9	13.3	55.9	13.3	55.9
1.2	174	13.3	55.9	13.3	55.9	13.3	55.9
1.4	203	13.3	55.9	13.3	55.9	13.3	55.9
1.6	232	13.3	55.9	13.3	55.9	13.3	55.9
1.8	261	13.3	55.9	13.3	55.9	15.2	59.4
2	290	13.3	55.9	13.3	55.9	28.5	83.3
2.155	313	13.3	55.9	13.4	56.1	35.6	96.1
2.156	313	30.0	86.0	46.7	116	68.9	156
2.2	319	30.0	86.0	46.7	116	68.9	156
2.4	348	30.0	86.0	46.7	116	68.9	156
2.6	377	30.0	86.0	46.7	116	68.9	156
2.8	406	30.0	86.0	46.7	116	68.9	156
3	435	30.0	86.0	46.7	116	68.9	156
3.2	464	30.0	86.0	46.7	116	68.9	156
3.4	493	30.0	86.0	46.7	116	68.9	156
3.6	522	30.0	86.0	46.7	116	68.9	156
3.8	551	30.0	86.0	47.4	117	69.6	157
4	580	30.0	86.0	49.7	121	71.9	161
4.2	609	30.0	86.0	51.8	125	74.0	165
4.4	638	30.0	86.0	53.8	129	76.0	169
4.6	667	31.1	88.0	55.6	132	77.8	172
4.8	696	34.1	93.4	57.3	135	79.6	175
5	725	36.9	98.4	59.0	138	81.2	178
5.2	754	39.4	103	60.5	141	82.7	181
5.4	783	41.7	107	61.9	143	84.2	184
5.6	812	43.8	111	63.3	146	85.5	186
5.8	841	45.8	114	64.6	148	86.9	188
6	870	47.6	118	65.9	151	88.1	191
6.2	899	49.3	121	67.1	153	89.3	193
6.4	928	50.9	124	68.2	155	90.5	195
6.6	957	52.5	127	69.3	157	91.6	197
6.8	986	53.9	129	70.4	159	92.6	199
7	1015	55.3	132	71.4	161	93.7	201
7.2	1044	56.6	134	72.4	162	94.6	202
7.4	1073	57.9	136	73.4	164	95.6	204
7.6	1102	59.1	138	74.3	166	96.5	206
7.8	1131	60.2	140	75.2	167	97.4	207
8	1160	61.3	142	76.1	169	98.3	209

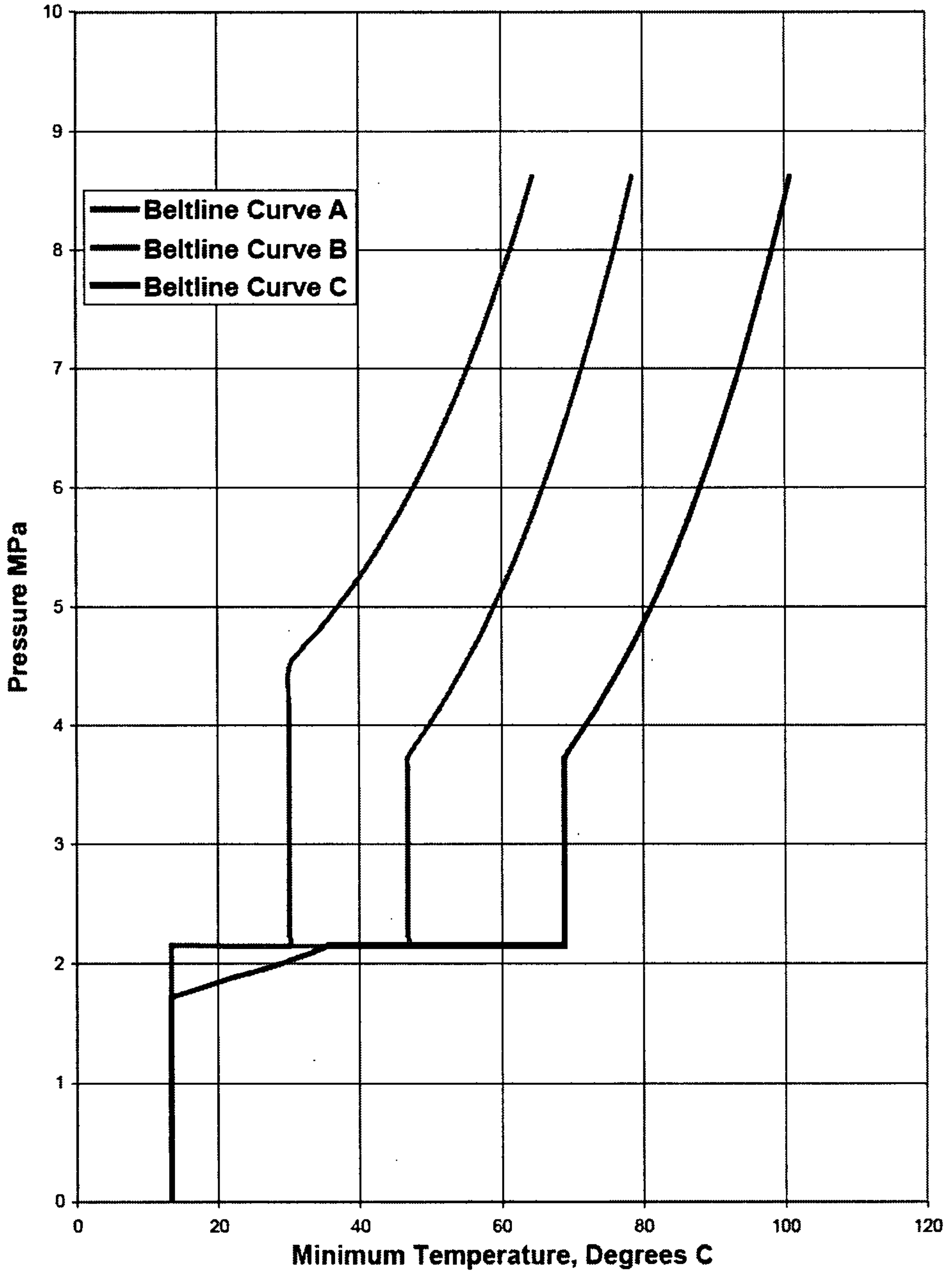

Figure 4-1 P-T Curves for the Beltline Region

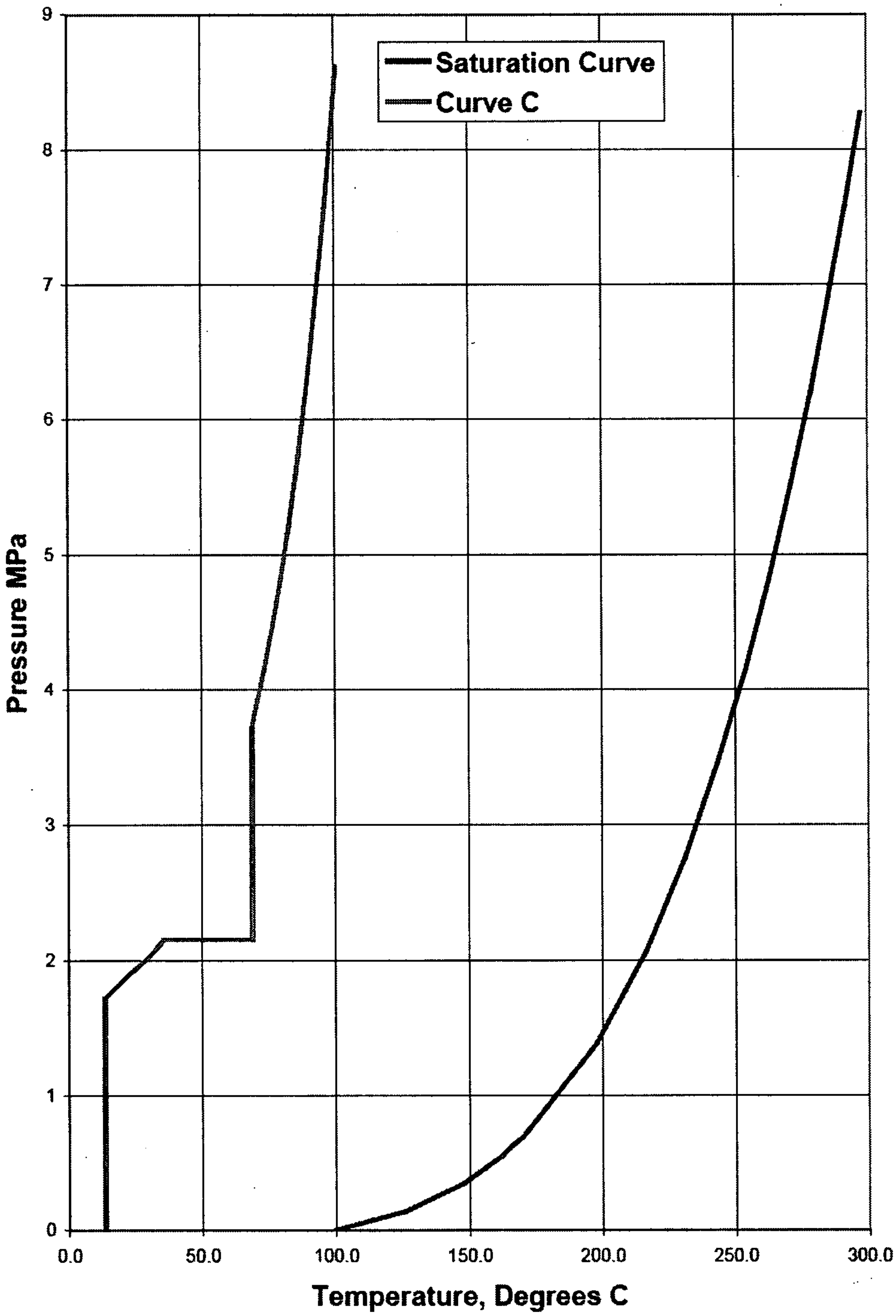

Figure 4-2 Comparison of Curve C with the Steam Saturation Curve

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 (6 x 10^{17} n/in^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 [12]. 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 [100°F/hr]) event is calculated for Event 3 and the value for the hydrostatic test (11°C/hr [20°F/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 (1160 psi) pressure. The stress intensity factor for the 55°C/hr (100°F/hr) cooldown is [[ ]]. Figure 5-5 and Table 5-4 show 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 [12]. 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 (1160 psi) pressure. The stress intensity factor for the 55°C/hr (100°F/hr) cooldown is [[ ]]. Figure 5-8 and Table 5-4 show the P-T curve for the FW 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} + 50°C (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 [13]. 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} + 50°C (90°F), etc.) the ASME limits are not governing. In all cases, the 10 CFR 50 criteria are more limiting. Figure 5-13 and Table 5-5 show 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 (100°F/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 and Table 5-4 show 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 (1160 psi) pressure. The stress intensity factor for the 55°C/hr (100°F/hr) cooldown is [[ ]]. Figure 5-22 and Table 5-4 show 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 (1160 psi) pressure. The stress intensity factor for the 55°C/hr (100°F/hr) cooldown is [[ ]]. Figure 5-25 and Table 5-4 show 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 (in)	Calculated K for a quarter-T postulated flaw MPa√m (ksi√in)		
		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 (ksi√in)	
		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

Table 5-4 P-T Data for the Main Steam, FW, SLC and Core DP Nozzles and Bottom Head

Pressure		Curve A Temperature		Curve B Temperature		Curve C Temperature	
MPaG	psig	°C	°F	°C	°F	°C	°F
0	0	13.3	56.0	13.3	56.0	13.3	56.0
0.2	29	13.3	56.0	13.3	56.0	13.3	56.0
0.4	58	13.3	56.0	13.3	56.0	13.3	56.0
0.6	87	13.3	56.0	13.3	56.0	13.3	56.0
0.8	116	13.3	56.0	13.3	56.0	13.3	56.0
1	145	13.3	56.0	13.3	56.0	13.3	56.0
1.2	174	13.3	56.0	13.3	56.0	13.3	56.0
1.4	203	13.3	56.0	13.3	56.0	13.3	56.0
1.6	232	13.3	56.0	13.3	56.0	13.3	56.0
1.8	261	13.3	56.0	13.3	56.0	13.3	56.0
2	290	13.3	56.0	13.3	56.0	13.3	56.0
2.155	313	13.3	56.0	13.3	56.0	13.3	56.0
2.156	313	30.0	86.0	46.7	116	68.9	156
2.2	319	30.0	86.0	46.7	116	68.9	156
2.4	348	30.0	86.0	46.7	116	68.9	156
2.6	377	30.0	86.0	46.7	116	68.9	156
2.8	406	30.0	86.0	46.7	116	68.9	156
3	435	30.0	86.0	46.7	116	68.9	156
3.2	464	30.0	86.0	46.7	116	68.9	156
3.4	493	30.0	86.0	46.7	116	68.9	156
3.6	522	30.0	86.0	46.7	116	68.9	156
3.8	551	30.0	86.0	46.7	116	68.9	156
4	580	30.0	86.0	46.7	116	68.9	156
4.2	609	30.0	86.0	46.7	116	68.9	156
4.4	638	30.0	86.0	46.7	116	68.9	156
4.6	667	30.0	86.0	46.7	116	68.9	156
4.8	696	30.0	86.0	46.7	116	68.9	156
5	725	30.0	86.0	46.7	116	68.9	156
5.2	754	30.0	86.0	46.7	116	68.9	156
5.4	783	30.0	86.0	46.7	116	68.9	156
5.6	812	30.0	86.0	46.7	116	68.9	156
5.8	841	30.0	86.0	46.7	116	68.9	156
6	870	30.0	86.0	46.7	116	68.9	156
6.2	899	30.0	86.0	46.7	116	68.9	156
6.4	928	30.0	86.0	46.7	116	68.9	156
6.6	957	30.0	86.0	46.7	116	68.9	156
6.8	986	30.0	86.0	46.7	116	68.9	156
7	1015	30.0	86.0	46.7	116	68.9	156
7.2	1044	30.0	86.0	46.7	116	68.9	156
7.4	1073	30.0	86.0	46.7	116	68.9	156
7.6	1102	30.0	86.0	46.7	116	68.9	156
7.8	1131	30.0	86.0	46.7	116	68.9	156
8	1160	30.0	86.0	46.7	116	68.9	156

Table 5-5 P-T Data for the Top Head Flange

Pressure		Curve A Temperature		Curve B Temperature		Curve C Temperature	
MPaG	psig	°C	°F	°C	°F	°C	°F
0	0	13.3	56.0	13.3	56.0	29.7	85.4
0.2	29	13.3	56.0	13.3	56.0	29.7	85.5
0.4	58	13.3	56.0	13.3	56.0	29.8	85.7
0.6	87	13.3	56.0	13.3	56.0	29.9	85.8
0.8	116	13.3	56.0	13.3	56.0	30.0	85.9
1	145	13.3	56.0	13.3	56.0	30.0	86.0
1.2	174	13.3	56.0	13.3	56.0	30.1	86.1
1.4	203	13.3	56.0	13.3	56.0	30.2	86.3
1.6	232	13.3	56.0	13.3	56.0	30.2	86.4
1.8	261	13.3	56.0	13.3	56.0	30.3	86.5
2	290	13.3	56.0	13.3	56.0	30.4	86.6
2.155	313	13.3	56.0	13.3	56.0	30.4	86.7
2.156	313	30.0	86.0	46.7	116	68.9	156
2.2	319	30.0	86.0	46.7	116	68.9	156
2.4	348	30.0	86.0	46.7	116	68.9	156
2.6	377	30.0	86.0	46.7	116	68.9	156
2.8	406	30.0	86.0	46.7	116	68.9	156
3	435	30.0	86.0	46.7	116	68.9	156
3.2	464	30.0	86.0	46.7	116	68.9	156
3.4	493	30.0	86.0	46.7	116	68.9	156
3.6	522	30.0	86.0	46.7	116	68.9	156
3.8	551	30.0	86.0	46.7	116	68.9	156
4	580	30.0	86.0	46.7	116	68.9	156
4.2	609	30.0	86.0	46.7	116	68.9	156
4.4	638	30.0	86.0	46.7	116	68.9	156
4.6	667	30.0	86.0	46.7	116	68.9	156
4.8	696	30.0	86.0	46.7	116	68.9	156
5	725	30.0	86.0	46.7	116	68.9	156
5.2	754	30.0	86.0	46.7	116	68.9	156
5.4	783	30.0	86.0	46.7	116	68.9	156
5.6	812	30.0	86.0	46.7	116	68.9	156
5.8	841	30.0	86.0	46.7	116	68.9	156
6	870	30.0	86.0	46.7	116	68.9	156
6.2	899	30.0	86.0	46.7	116	68.9	156
6.4	928	30.0	86.0	46.7	116	68.9	156
6.6	957	30.0	86.0	46.7	116	68.9	156
6.8	986	30.0	86.0	46.7	116	68.9	156
7	1015	30.0	86.0	46.7	116	68.9	156
7.2	1044	30.0	86.0	46.7	116	68.9	156
7.4	1073	30.0	86.0	46.7	116	68.9	156
7.6	1102	30.0	86.0	46.7	116	68.9	156
7.8	1131	30.0	86.0	46.7	116	68.9	156
8	1160	30.0	86.0	46.7	116	68.9	156

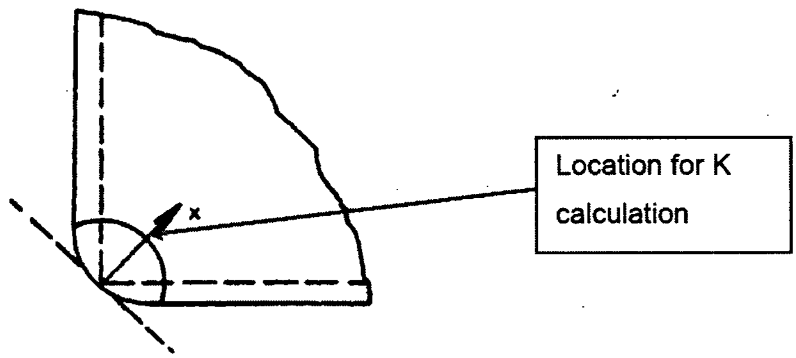

Figure 5-1 Nozzle Corner Flaw

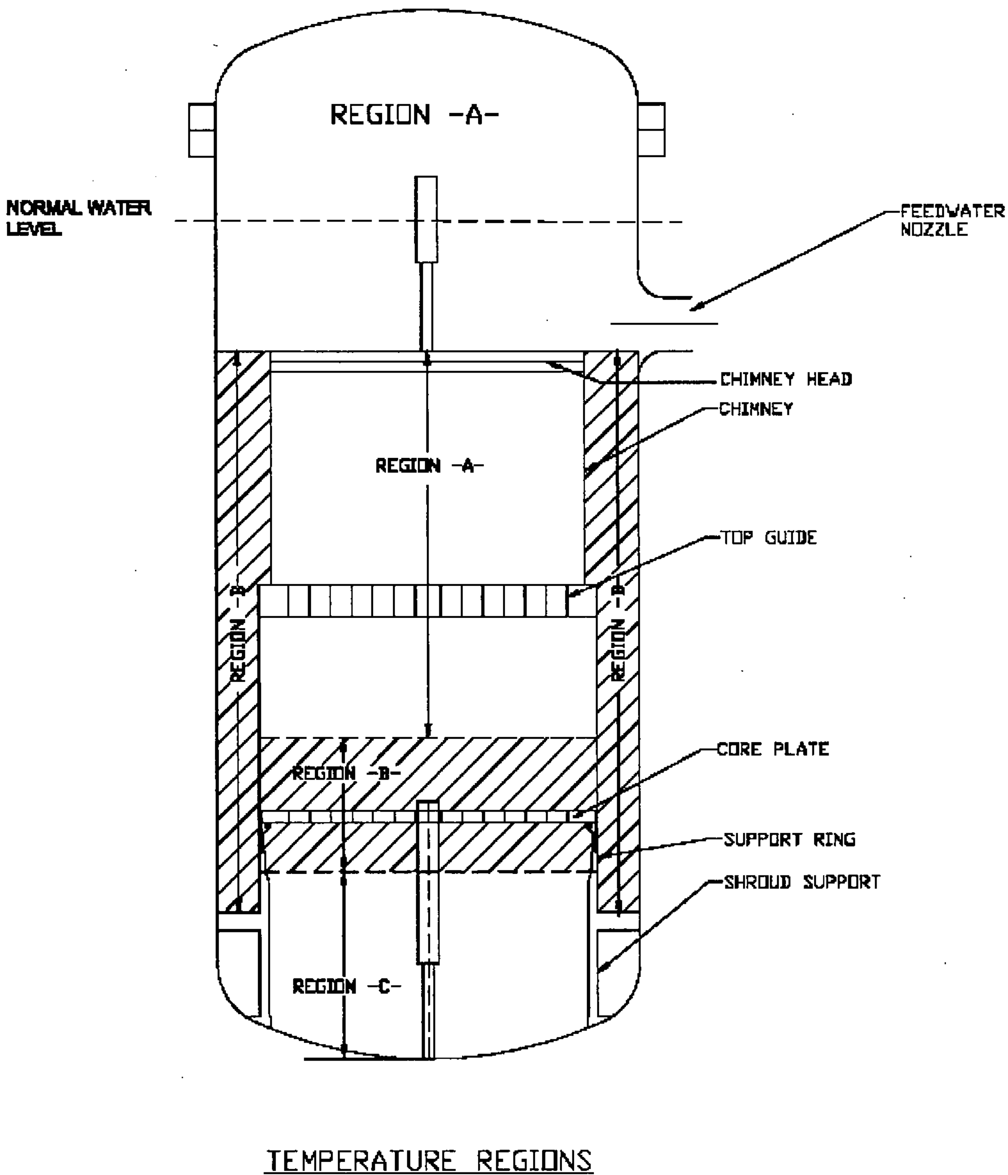

Figure 5-2 Temperature Regions in the Vessel

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Figure 5-3 ESBWR Main Steam Outlet Nozzle

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]]

Figure 5-4 Steam Nozzle Finite Element Model

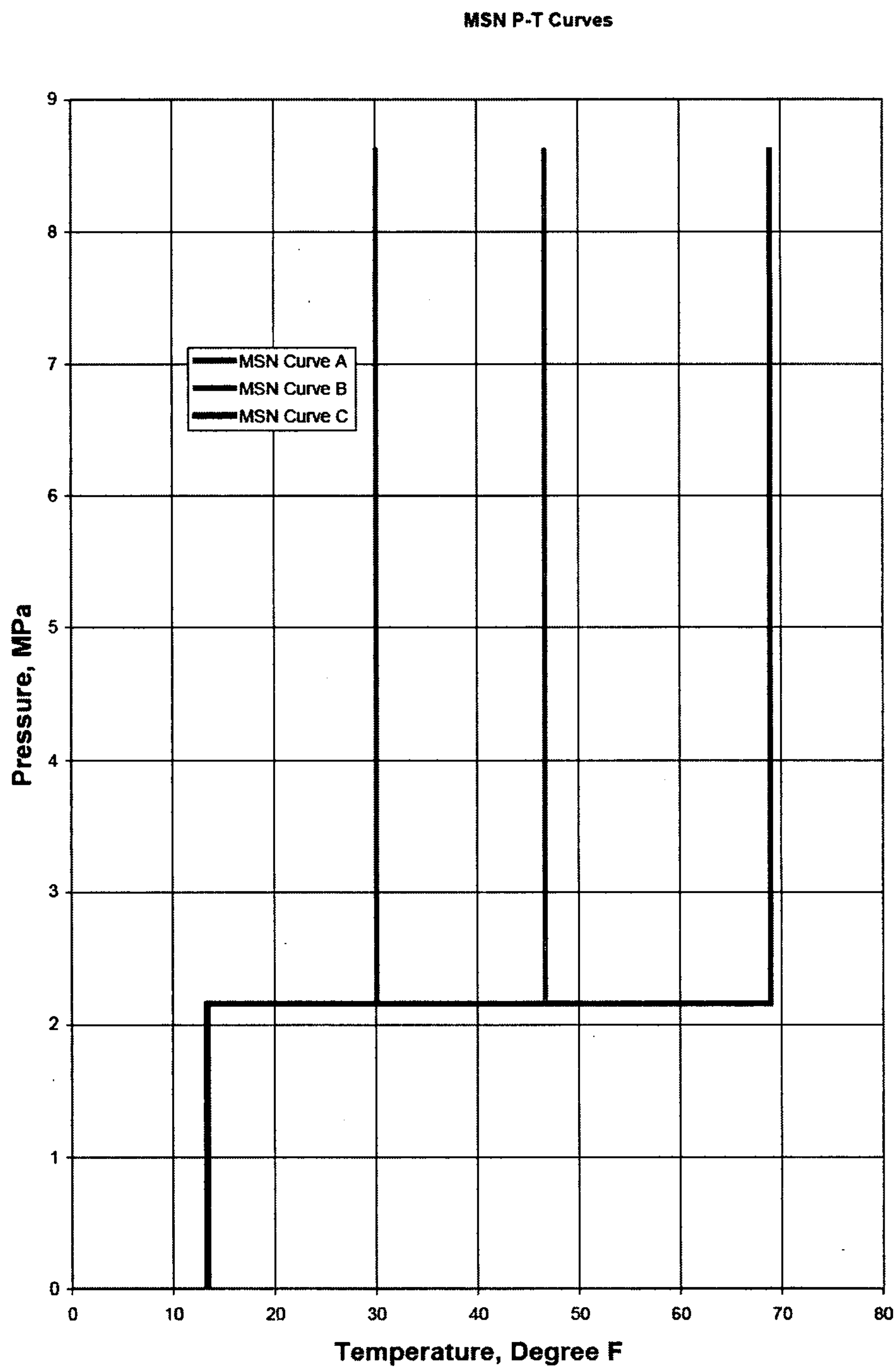

Figure 5-5 Main Steam Nozzle P-T Curves

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Figure 5-6 Feedwater Nozzle

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Figure 5-7 FW Nozzle Finite Element Model

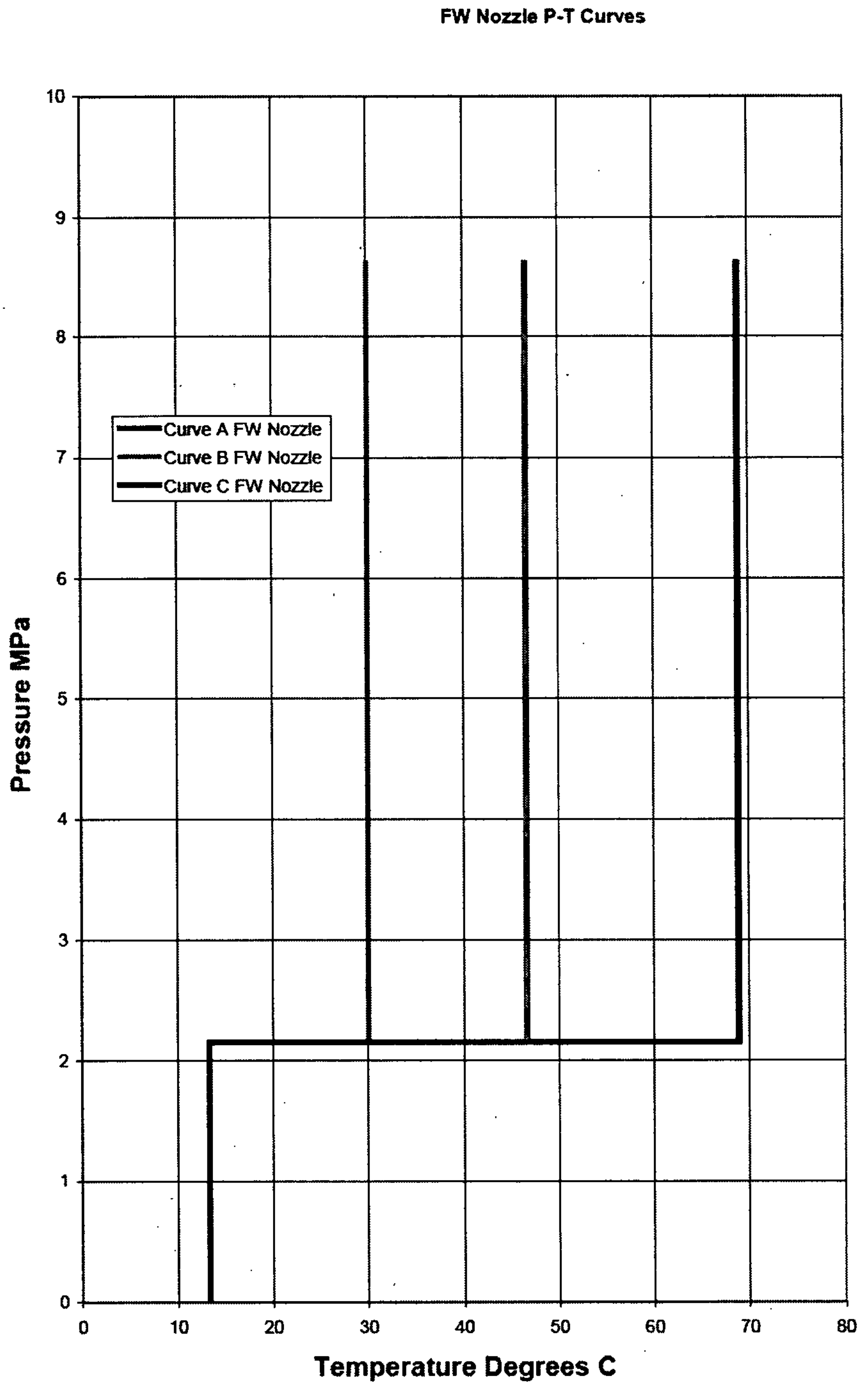

Figure 5-8 P-T Curves for the FW Nozzle

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Figure 5-9 Closure Head Flange

[[

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Figure 5-10 Overall FE Model of the Closure Head Assembly

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]]

Figure 5-11 Circumferential Crack Embedded in the Top Head Flange

[[

]]

Figure 5-12 Vessel Flange Circumferential and Axial Cracks

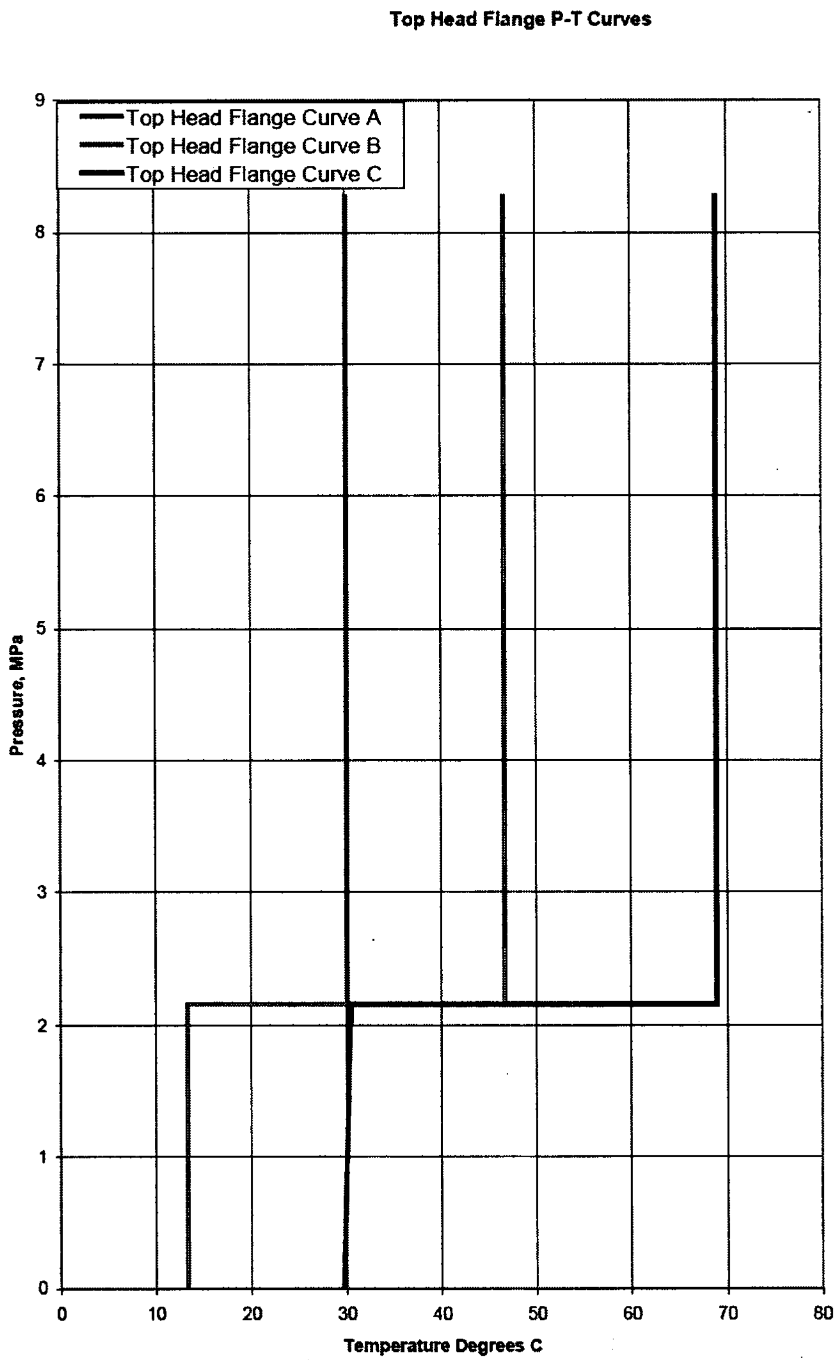

Figure 5-13 P-T Curves for the Top Head Flange

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]]

Figure 5-14 ESBWR Bottom Head Configuration

[[

]]

Figure 5-15 Overall Finite Element Model of the Bottom Head Region

[[

]]

Figure 5-16 Radial ID Crack at the Center of the Vessel

[[

]]

Figure 5-17 Circumferential ID Crack in the Hillside Region

[[

]]

Figure 5-18 OD Surface Crack between two CRD Stub Tubes

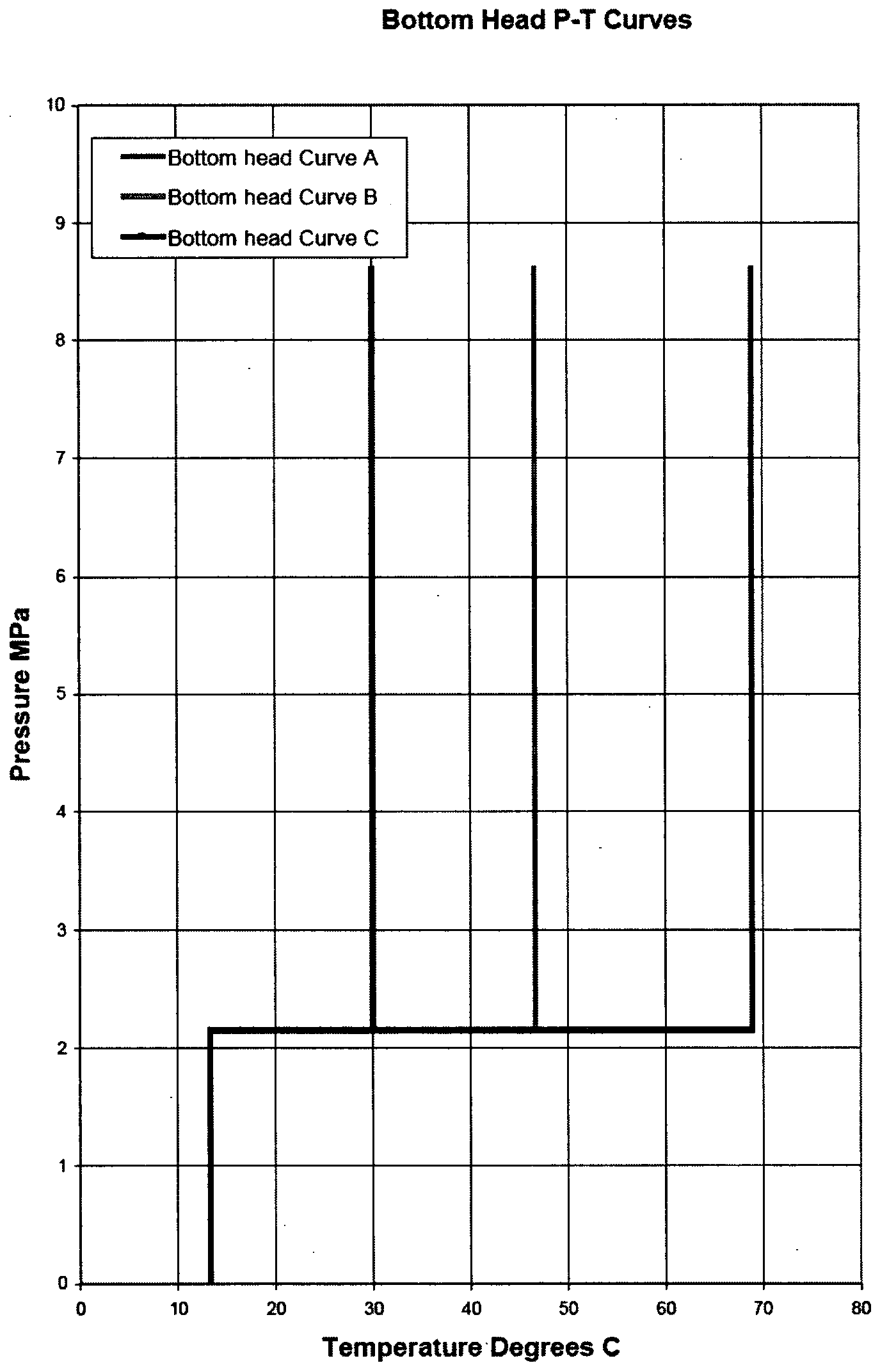

Figure 5-19 P-T Curves for the Bottom Head

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Figure 5-20 Standby Liquid Control (SLC) Nozzle Configuration

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Figure 5-21 SLC Nozzle Finite Element Model

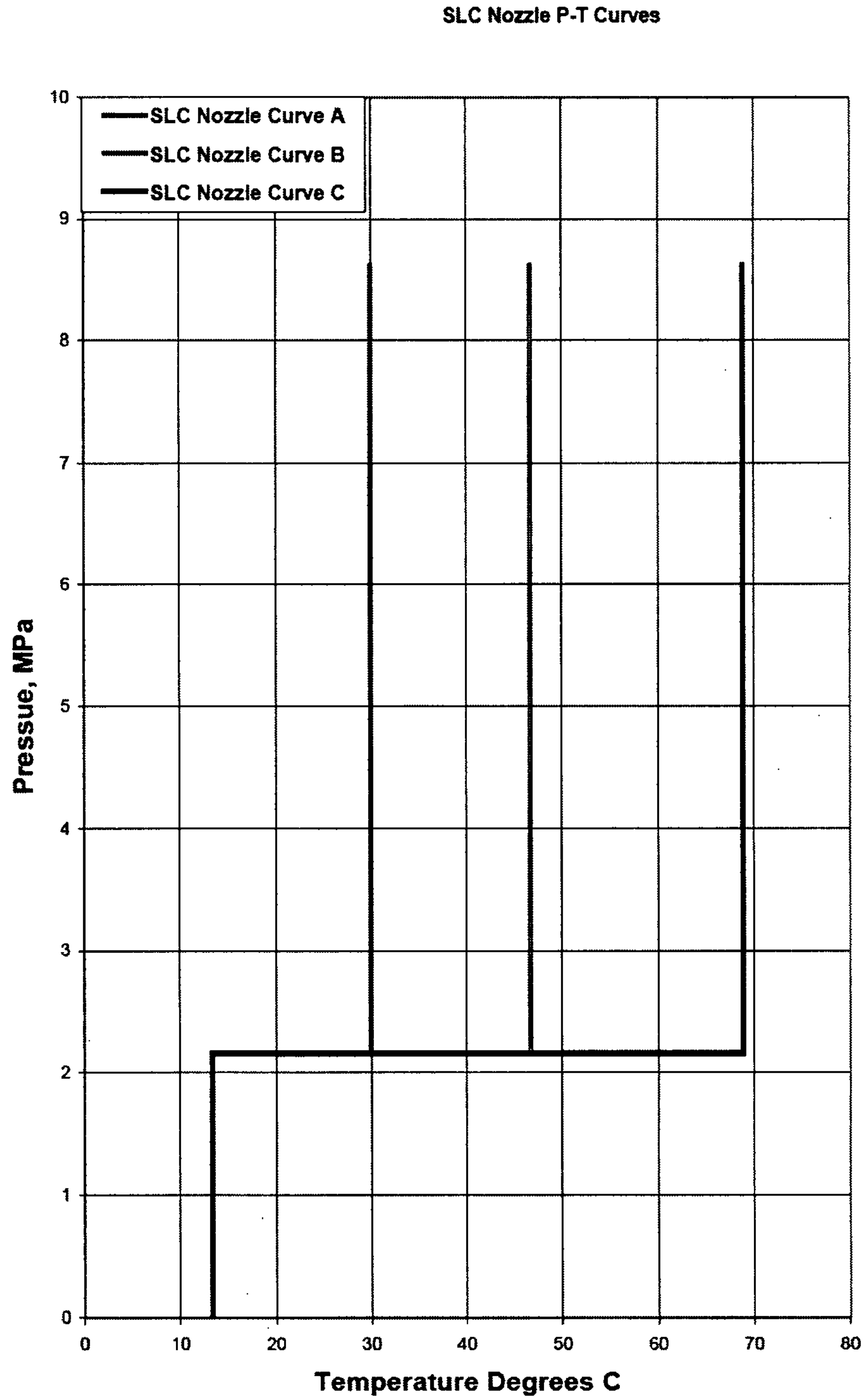

Figure 5-22 P-T Curves for the SLC Nozzle

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Figure 5-23 Core DP Nozzle Configuration

[[

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Figure 5-24 Core DP Nozzle FE Model

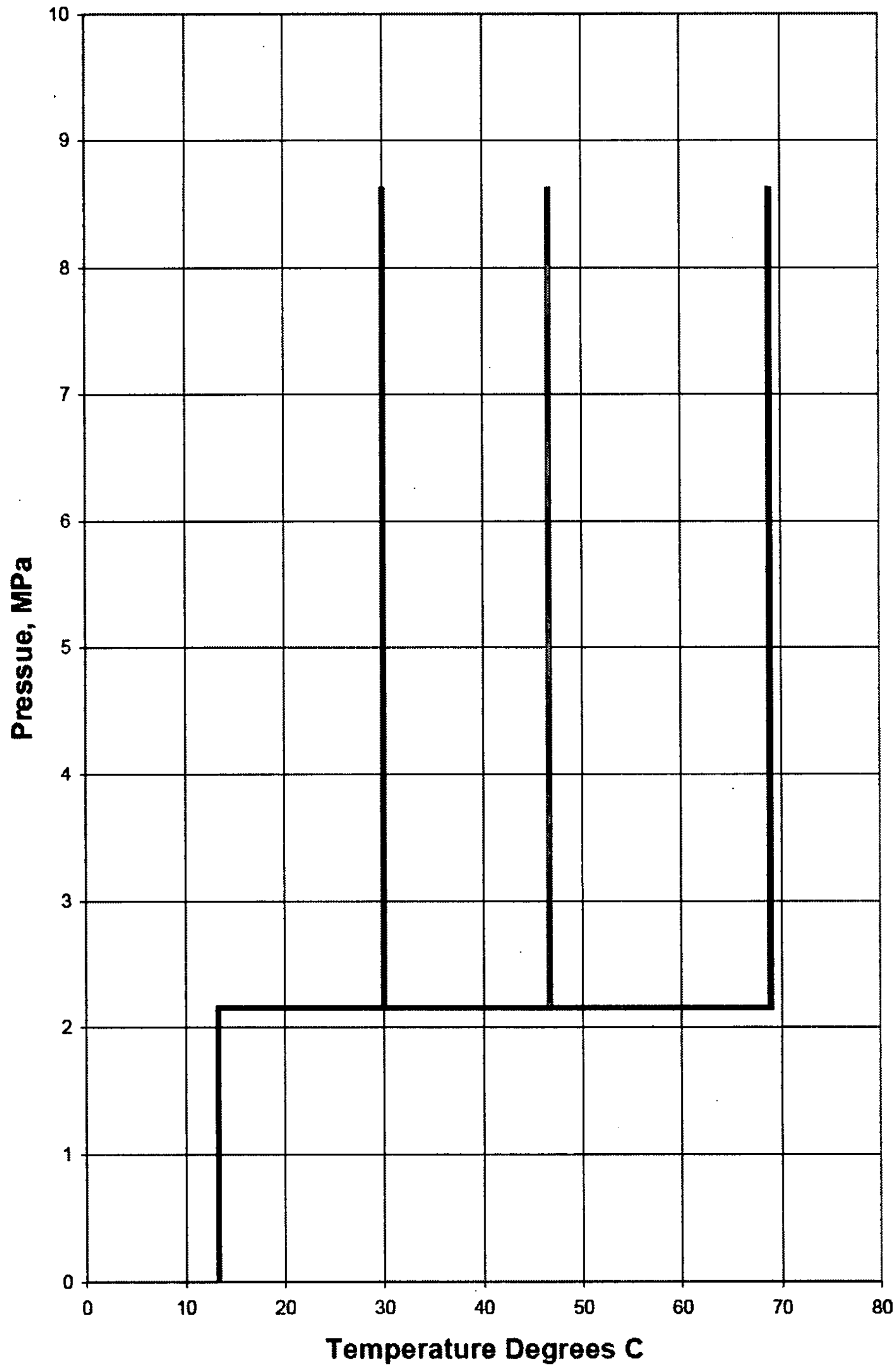

Figure 5-25 Core DP Nozzle P-T Curves

6.0 Temperature Limits for Bolt-up and Hydrotest

Minimum flange and fastener temperatures of reference temperature plus 33°C (60°F), or -20°C (-4°F) + 33°C (60°F) = 13°C (56°F), are required for tensioning at preload condition and during detensioning.

Pressure versus temperature limits for hydrostatic tests are represented by Curve A on the P-T curves. The limiting case is the beltline region (Figure 4-1), and the minimum temperature corresponding to the ASME Code hydrostatic test pressure (1.25* 8.62 Mpa = 10.8 MPa, or 1.25*1250 psig = 1563 psig) is approximately 57.6°C (136 °F). For other test pressures, the minimum temperature would vary, as shown in Figure 4-1.

7.0 Material Surveillance Program

Reactor vessel materials surveillance specimens are provided in accordance with the requirements of References 17 and 18. Materials for the program are selected to represent materials used in the reactor beltline region. Specimens are manufactured from forgings actually used in the beltline region and a weld typical of those in the beltline region and thus represent base metal, weld material and the weld heat-affected zone (HAZ) material. The base metal and weld are heat treated in a manner that simulates the actual heat treatment performed on the beltline region of the completed vessel. Four in-reactor surveillance capsules are provided. Each in-reactor surveillance capsule contains Charpy V-notch and tensile specimens taken from the three base metal forgings that are located within the reactor beltline region, the weld material and the weld HAZ material, as required. A set of out-of-reactor beltline Charpy V-notch specimens, tensile specimens and archive material are provided with the surveillance test specimens. Neutron dosimeters and temperature monitors are located within the capsules as required by Reference 17.

Four capsules are provided to consider the 60-year design life of the vessel. This exceeds the three capsules specified in Reference 17, as required by Reference 18, since the predicted transition temperature shift is less than 55.6°C (100°F) at the inside of the vessel. The following proposed withdrawal schedule is modified from the Reference 17 schedule to consider the 60-year design life:

- First capsule: after 6 effective full power years;
- Second capsule: after 20 effective full power years;
- Third capsule: with an exposure not to exceed the peak end of life (EOL) fluence; and
- Fourth capsule: schedule determined based on results of first three capsules per Reference 17, Paragraph 7.6.2.

Fracture toughness testing of irradiated capsule specimens are in accordance with requirements of Reference 17 as required by Reference 18.

No surveillance capsule reports have been prepared to-date. In future revisions to this report, surveillance capsule reports will be referenced by title and number, as appropriate. The results from the material surveillance program will be used to verify the value of ΔRT_{NDT} used to develop the P-T curves in accordance with Reference 3. The P-T curves will be adjusted, as necessary, based on these results.

8.0 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 8-1 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.

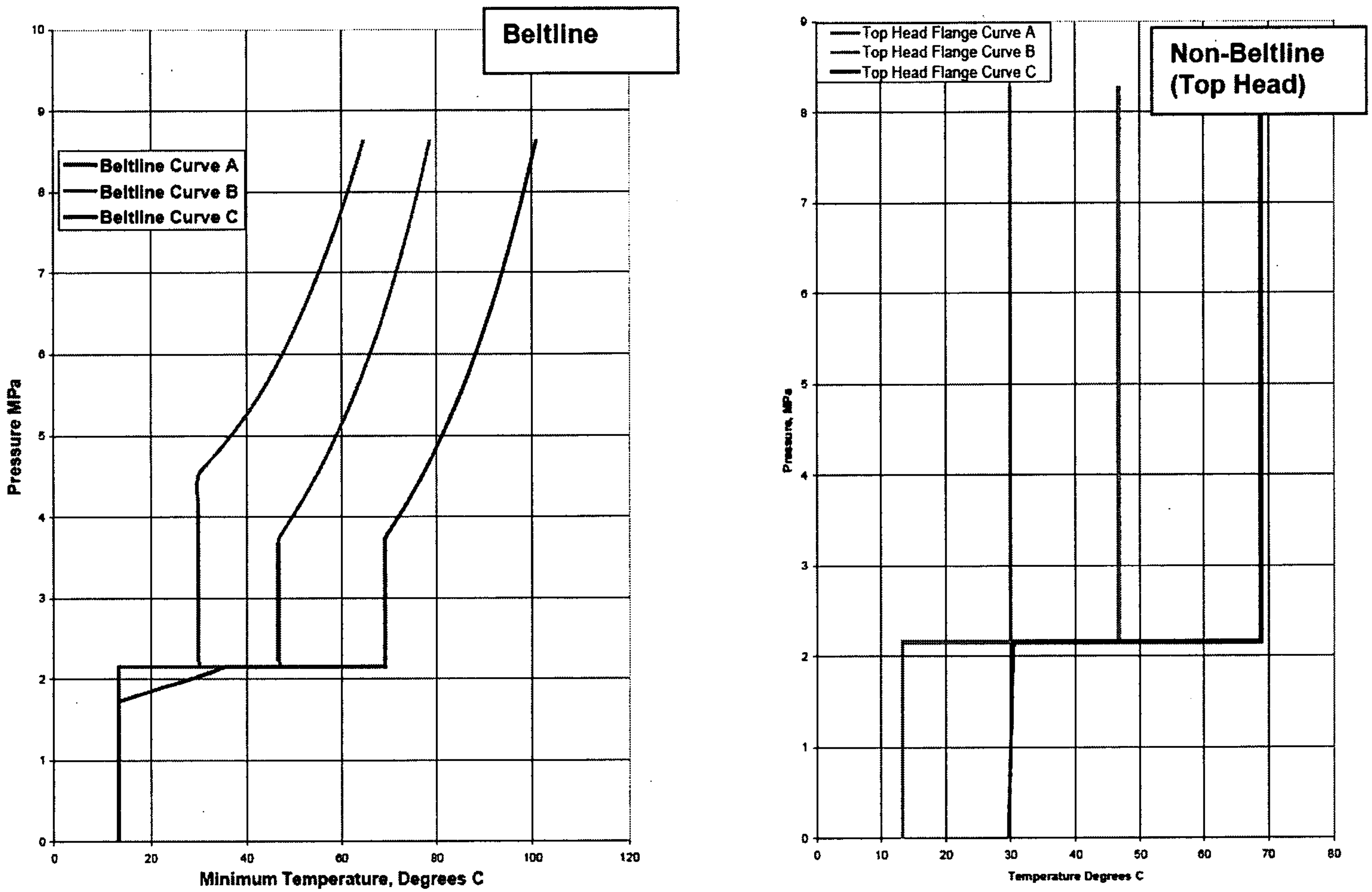

Figure 8-1 P-T Curves for the Beltline and Non-beltline Components

9.0 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. S. Asada, T. Hirano, N. Soneda, N. Yamashita, A. Yonehara, M. Tomimatsu, "*Incorporation of the new Irradiation Embrittlement Correlation Method into the Japanese Code of Surveillance Tests for Reactor Vessel Materials*," Paper PVP2008-61492, Proceedings of the 2008 ASME Pressure Vessels and Piping Division Conference, Chicago, Illinois, July 27-31, 2008

11. K. R. Wichman, M. A. Mitchell, A. L. Hiser, "*Generic Letter 92-01 and RPV Integrity Assessment,*" NRC / Industry Workshop on RPV Integrity Issues, February 12, 1998.

12. [[ ]]

13. [[ ]]

14. GE-NE-0000-0031-6244-R0, "ESBWR Neutron Fluence Evaluation," Revision 0, July 2005

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

16. North Anna 3 Combined License Application Part 2: Final Safety Analysis Report, Revision 2, May 2009

17. ASTM E185-82, Standard Practice for Design of Surveillance Programs for Light-Water Moderated Nuclear Power Reactor Vessels, 1982

18. Appendix H to Part 50 of Title 10 of the Code of Federal Regulations, Reactor Vessel Material Surveillance Program Requirements

ENCLOSURE 2

Affidavit for GEH Licensing Topical Report NEDC-33441P, Revision 6, "GE Hitachi Nuclear Energy Methodology for the Development of ESBWR Reactor Pressure Vessel Pressure-Temperature Curves"

GE-Hitachi Nuclear Energy Americas LLC

AFFIDAVIT

I, **Peter M. Yandow**, state as follows:

(1) I am Regulatory Affairs Manager – New Plants/Services, GE Hitachi Nuclear Energy ("GEH"), and have been delegated the function of reviewing the information described in paragraph (2) which is sought to be withheld, and have been authorized to apply for its withholding.

(2) The information sought to be withheld is contained in GEH Licensing Topical Report NEDC-33441P, "GE Hitachi Nuclear Energy Methodology for the Development of ESBWR Reactor Pressure Vessel Pressure-Temperature Curves" Revision 6, November 2013. The proprietary information is delineated by a [[dotted underline inside double square brackets [3]]]. Figures and large equation objects containing GEH proprietary information are identified with double square brackets before and after the object. In each case, the superscript notation [3] refers to Paragraph (3) of this affidavit, which provides the basis for the proprietary determination.

(3) In making this application for withholding of proprietary information of which it is the owner or licensee, GEH relies upon the exemption from disclosure set forth in the Freedom of Information Act ("FOIA"), 5 USC Sec. 552(b)(4), and the Trade Secrets Act, 18 USC Sec. 1905, and NRC regulations 10 CFR 9.17(a)(4), and 2.390(a)(4) for "trade secrets" (Exemption 4). The material for which exemption from disclosure is here sought also qualify under the narrower definition of "trade secret", within the meanings assigned to those terms for purposes of FOIA Exemption 4 in, respectively, Critical Mass Energy Project v. Nuclear Regulatory Commission, 975F2d871 (DC Cir. 1992), and Public Citizen Health Research Group v. FDA, 704F2d1280 (DC Cir. 1983).

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

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

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

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

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

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

(5) To address 10 CFR 2.390(b)(4), the information sought to be withheld is being submitted to NRC in confidence. The information is of a sort customarily held in confidence by GEH, and is in fact so held. The information sought to be withheld has, to the best of my knowledge and belief, consistently been held in confidence by GEH, no public disclosure has been made, and it is not available in public sources. All disclosures to third parties, including any required transmittals to NRC, have been made, or must be made, pursuant to regulatory provisions or proprietary agreements which provide for maintenance of the information in confidence. Its initial designation as proprietary information, and the subsequent steps taken to prevent its unauthorized disclosure, are as set forth in paragraphs (6) and (7) following.

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

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

(8) The information identified in paragraph (2) is classified as proprietary because it contains details of GEH's design and licensing methodology. The development of the methods used in these analyses, along with the testing, development and approval of the supporting methodology was achieved at a significant cost to GEH.

(9) Public disclosure of the information sought to be withheld is likely to cause substantial harm to GEH's competitive position and foreclose or reduce the availability of profit-making opportunities. The information is part of GEH's comprehensive BWR safety and technology base, and its commercial value extends beyond the original development cost. The value of the technology base goes beyond the extensive physical database and analytical methodology and includes development of the expertise to determine and apply the appropriate evaluation process. In addition, the technology base includes the value derived from providing analyses done with NRC-approved methods.

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

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

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

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

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

Executed on this 20th day of November 2013.

Peter M. Yandow
GE-Hitachi Nuclear Energy Americas LLC