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Assessments and Comparisons of PWR Reactor PT Limits per Deterministic and Risk Informed by ASME Code Rules

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Abstract

During the normal and anticipated operational occurrence of the nuclear power plants such as reactor start-ups and shut-downs, the RPV pressures and temperatures are required to be maintained within certain limits called Pressure-Temperature (P-T) limit curves to prevent the non-ductile fracture failure. The conventional deterministic procedure of P-T limits involves the use of Regulatory Guide (RG) 1.99, Revision 2. However, using available data from operating plants and improved understanding of embrittlement mechanism, a risk-informed procedure has been developed and added to the current ASME Code. This paper does a comparative study of P-T limit curves for PWR Pressurized Water Reactor based on the current 2017 ASME Code and the results from the utility owner. This involved collecting reactor material properties, developing heat-up and cooldown profiles, and applying ASME code of 1998 used currently in the plant and comparing with the 2017 ASME code. Korea's Optimized Power Reactor (OPR1000) which has been in operation since March 1995. The results obtained indicate a considerable decrease in conservativeness in P-T limit curves constructed using the current 2017 ASME code both in deterministic and risk-informed methods. Comparing the two methods of 2017 ASME code, the risk-informed method is slightly more conservative in high temperatures and less conservative in low temperatures. The major difference between the two methods is the Lowest Service Temperature which is 125 °F and 175 °F for the risk-informed and the deterministic method respectively. This paper proposes the adoption of the current fracture toughness requirements of the ASME code to increase operational flexibility and plant safety of Operating PWR.

Keywords - Non-ductile failure, Deterministic P-T limit curve, Risk-informed P-T limit curve

I. INTRODUCTION

It is a requirement from USNRC for utility owners to develop P-T limit curves and maintain the operating conditions to ensure a safe operation of Reactor Pressure Vessel (RPV) [1, 2]. Using linear fracture mechanics analysis, P-T limit curves are determined for heat up, cold down and hydrostatic test conditions [2]. The 10 CFR50 Appendix G [1] gives the fracture toughness requirements for the ferritic material used in the reactor coolant pressure boundary of light water nuclear power reactors to provide adequate margins of safety during Level A and B Service Conditions. In order to ensure an acceptable safety margin against the brittle failure of RPV, plant operators are required to adhere to P-T limit curves to maintain plant operation within an acceptable operational window. Any operation outside P-T limit curves will cause undesirable high tensile stresses due to thermal gradient on the inner surface during cooldown and the outer surface during heat-up of RPV. To avoid this phenomenon, the utility designers have installed an inadvertent relief actuation valve and established a Low- Temperature Overpressure Protection (LTOP) system which must be set to preclude excursions beyond the code allowable pressure for the reactor vessel [2, 3].

P-T limit curves are calculated and constructed based on a predicted or a calculated level of embrittlement at a specified Effective Full Power Years (EFPY). This implies that P-T limits should be adjusted periodically based on the measured shift in Reference Temperature for Nil-Ductility Transition (RT_{NDT}) by testing the reactor vessel surveillance material samples [2]. These updates are necessary for the continued operation of NPP, power uprate, life extension, or when the existing P-T limit curves expire. The revised fluence calculations are periodically performed using an approved fluence methodology given in NRC Regulation Guide 1.190 [4]. The P-T limit curve operating envelop reduces progressively because of periodic adjustment to accommodate the effects of irradiation embrittlement of the RPV material as shown in Fig 1 next page.

The conventional deterministic P-T limit curves involve the use of Reg. guide 199 Rev. 2. However, using the available data from operating plants and improved understanding of embrittlement mechanism, a risk-informed methodology has been developed and incorporated in the ASME code through Probabilistic Fracture Mechanics (PFM). Nevertheless, the application of this alternative method has been prohibited by USNRC because additional information such as plant-specific In-Service Inspection (ISI) data is required to ensure RPV flaw types and their distributions are consistent with flaw distributions assumed in PFM evaluations. In this paper, risk-informed factors adopted by the ASME code after gathering different data from different PWR have been used comparison purpose.

OPR1000 is South Korea's tenth Nuclear Power Plant owned by Korea Hydro and Nuclear Power (KHNP) constructed under the third phase of self-reliance in nuclear technology. The Plant attained full commercial operation since 1995. It is a 1000 MWe pressurized light water reactor with a design life of 40 years.

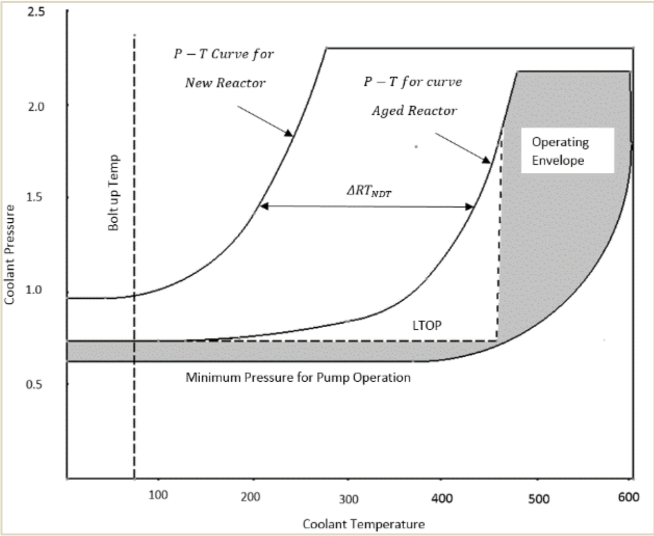

Figure 1. P-T operating envelop for RPV [5]

The purpose of this research is to construct P-T limit curves base on ASME BPVC 2017 for Hanbit unit 3 PWR Power Plant. Both deterministic and risk-informed P-T limit curves will be constructed and their results compared. Then pre-2006 ASME P-T limit curves based on K_{IR} curve, currently used in the plant, will be constructed and results compared with the 2017 ASME code. The material properties of OPR1000 reactor vessel, fabrication methods and fluence levels used for evaluation of the P-T limit curves were adopted from Final Safety Analysis Report (FSAR) of OPR1000 [6], and other relevant reports. The result of this paper is recommended for adoption in Korean NPPs.

II. 2. MATERIAL PARAMETERS OF NUCLEAR REACTOR VESSEL

The RPV consists of vessel flange, reactor closure head, forged rings of the upper, intermediate and lower sections, and a hemispherical bottom head. The vessel flange is first forged and then ledge machined on the inner surface to support core support barrel. The reactor closure head is fabricated and bolted to the RPV. The doom and the flange are welded together to form reactor closure head. The three forged ring, reactor closure head, and bottom hemispherical head are joined together by welding as shown in Figure 2 below.

The material for RPV is SA-508 Grade 3 Class 1 with material properties defined in the ASME code [7, 6]. In order to reduce the effects neutron irradiation, the amount Copper, Nickel, Phosphorous and Manganese in RPV fabrication are restricted. The percentages of Copper and Nickel for Hanbit unit 3 and the surveillance capsules are given in Table 1 below [6]. Other elements restricted include phosphorus (P) and Manganese (Mn) as shown in Table 2 below [8].

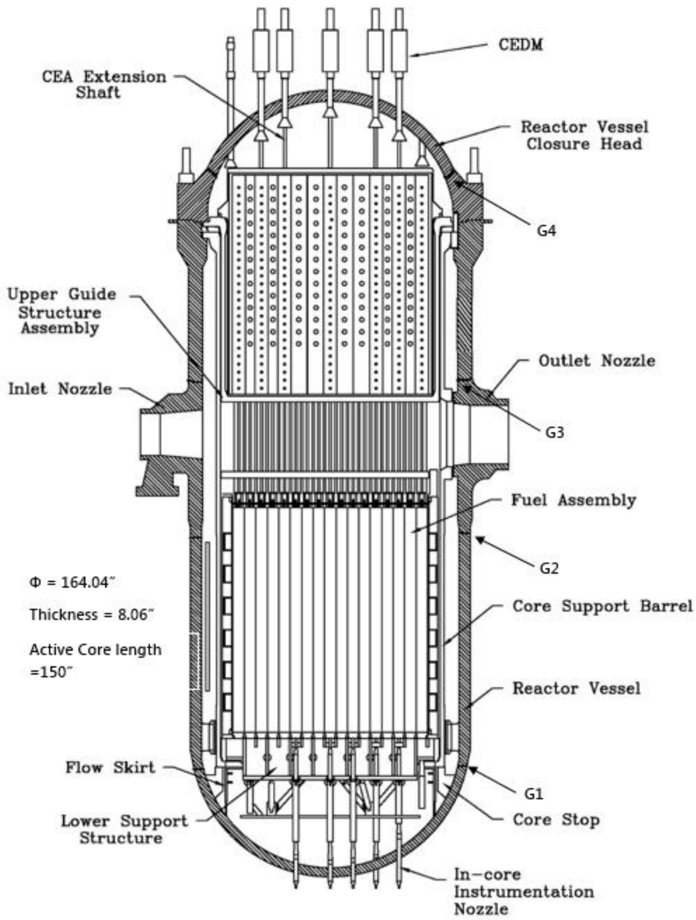

Figure 2: Nuclear Reactor Pressure Vessel Cross-section and Weld Regions Indicated by G-numbers [6]

Table 1: Average Cu and Ni weight percentage values for the beltline materials

	Percentage (wt. %)	
Material (Product)	Cu (wt. %)	Ni (wt. %)
Base metal (BM)	0.05	0.78
BM surveillance	0.047	0.76
Weld metal	0.02	0.056
weld surveillance	0.02	0.091

Table 2: Average Phosphorus and Manganese weight percentage for beltline materials

	OPR1000 RPV	
Elements	Base metal (wt. %)	Weld metal (wt. %)
Phosphorus	0.007	0.009
Manganese	1.4	1.69

III. MATERIAL PROPERTIES RELATED TO P-T LIMIT CURVES

III.I Fracture Toughness

Fracture toughness is the property of the material containing a crack or postulated crack to resist fracture. The General Design Criterion (GDC) 31 of the 10 CFR 50 Appendix A [9] requires the pressure boundary components to be designed with adequate margin to assure that when stressed under Service Level A, Level B or postulated accident conditions, the Pressure boundary shall behave in a non-brittle manner with low likelihood of a rapidly propagating crack. The design shall also be consistent with the change of material properties due to differences in service temperatures, effects of radiation embrittlement and distribution flaw sizes in RPV.

III.II Reference Temperature for Nil-Ductility Transition (RT_{NDT})

RT_{NDT} is defined as the temperature below which the impact resistance as measured by the standard Charpy impact test falls below 41J (30 ft-lb) [7]. RT_{NDT} is determined based on a nil-ductility transition temperature (T_{NDT}) obtained through a drop weight test and the results of Charpy V-notch tests which are carried out at temperatures not greater than T_{NDT} + 60 °F. RT_{NDT} is, therefore, T_{NDT} when the Charpy V-notch test results exhibit at least 0.89 mm (35mils) lateral expansion and not less than 68 J (50 ft-lb) absorbed energy at temperatures not greater than T_{NDT} + 60 °F. The test coupons, test specimens, testing procedures, testing requirements, and acceptance criteria for RT_{NDT} determination are fabricated, established, or applied in accordance with ASME Section III, NB-2300 [7]. The Initial RT_{NDT} of un-irradiated OPR1000 reactor vessel shell products and weld material are given in **Error! Reference source not found.** below [6].

Table 3: Initial RT_{NDT} for beltline material, weld region and surveillance specimen

Region	Initial RT_{NDT}
Vessel beltline material (base metal)	10°F
Vessel beltline surveillance	10°F
Vessel weld material	-50°F
Vessel weld surveillance	-50°F

III.III Upper Shelf Energy

The initial Charpy upper-shelf energy must not be less than 75 ft-lb and not less than 50 ft-lb throughout the life of the reactor vessel [2].

III.IV Fluence Levels

Neutron fluence is defined as the number of neutrons accumulated for a given irradiation period per unit area. It is believed that neutrons with threshold energy greater than 1MeV are responsible RPV embrittlement. The estimated peak fluence level for OPR1000 [6] are tabulated in **Error! Reference source not found.** below.

Table 4: Peak fluence levels for OPR1000

EFPY (Effective Full-Power Years)	Max. fluence levels (10^{19} n/cm^2, E>1MeV)
20	1.167
24	1.404
32	1.878

III.V Maximum Postulated Defect

The Maximum postulated defects is defined by ASME Code, Section XI, paragraph G-2120 as a sharp-edged surface crack defect oriented axially for plates, forgings and axial welds, and circumferentially for circumferential welds. The depth of crack is 1/4 of the vessel thickness exist at the inner and outer surface of the vessel with a length equal to 1.5 of the vessel thickness range thickness range between 4 inches to 12 inches [2, 3].

III.VI Reference Critical Stress Intensity Factors

Stress intensity factor is a parameter used in Linear Elastic Fracture Mechanics (LEFM) to predict the stress state near the tip of a crack as a result of remote loading or residual stress. The reference critical stress intensity factor applicable by ASME Code is based on the lower bound of static critical $\boldsymbol{K}_{IC}$ values for opening crack [2, 3, 10].

IV. REGULATORY APPROACH TO P-T LIMIT CURVES

P-T limit curves are developed in accordance with ASME Section XI, Appendix G which comply with the USA 10 CFR Part 50, Appendix G requirements. The constituents of the P-T Limit Curves include:

a. The minimum bolt-up temperature for RPV head (ASME Section III Division1-Subsection NB-2332)

$$T_{MIN}\_BOLTUP = \ Initial\ RT_{NDT} + effects\ due\ to\ radiation$$

The effect of irradiation embrittlement is negligible and T_{MIN} _BOLTUP = the refuelling water temperature) = 70°F

b. Low-Temperature Overpressure Protection (LTOP) set at the Lowest Service Temperature. It is defined as 20% of the preoperational hydrostatic test pressure.

$$= 20\%\ of\ 2500\,psi = 625\,psi$$

c. Lowest Service Temperature, LST (NB-2332)

It is defined to be not lower than RT_{NDT}+100°F

d. Normal operation - heat up and cooldown rate

e. Pump seal requirement- affected by narrow operation window of P-T Curves. The probability of pump seal getting damaged increases due to inadequate cooling [10].

IV-I Adjusted Reference Temperature (ART) - Deterministic Approach

As a result of fast neutron irradiation in the core beltline region, RT_{NDT} of the irradiated material increases with the operation of RPV. The effect of neutron irradiation is taken into account in accordance with NRC RG 1.99 Rev.2 [4]. Therefore, RT_{NDT} must be adjusted to account for the increase in reference temperature caused by neutron irradiation.

The Adjusted Reference Temperature (ART) is given as:

$$ART = IRT_{NDT} + \Delta RT_{NDT} + Margin \qquad (1)$$

IRT_{NDT} is a reference temperature for the un-irradiated material.

ΔRT_{NDT} is a function of Fluence Factors and Chemistry Factors.

$$\Delta RT_{NDT} = CF \times FF \qquad (2)$$

Where:

CF (°F): Chemistry Factor – a function of Cu and Ni, according to RG 1.99, Rev.2.

$$FF = f^{(0.28-0.1 log f)} \qquad (3)$$

Also;

$FF = fluence\ factor\ (in\ 10^{19}\ n/\mathrm{cm}^2,\ E = 1MeV)$

The neutron fluence, f at any depth in the vessel wall is calculated using a method that conforms to the guideline of RG 1.99 Rev. 2.

$$f = f_{surf}(e^{-0.24x}) \qquad (4)$$

When two or more credible surveillance data sets of the RPV are available, CF may be determined as below:

$$CF = \Sigma(Ai\ x\ FFi) \,/\, \Sigma(FFi)^2\ , °\mathrm{F} \qquad (5)$$

$Where:$

$i = 1 \sim n\ (n:\ number\ of\ surveillance\ data\ sets)$

Ai: $measured\ value\ of\ \Delta RT_{NDT}$

FFi: $Fluence\ Factor\ at\ corresponding\ data\ points.$

"Margin" According to RG 1.99 Rev 2, is the amount of temperature added to account for uncertainties in the evaluating the values of Initial RT_{NDT}, Cu and Ni contents, fluence, and calculation procedures [4, 2]. It is given by:

$$Margin = 2\sqrt{\sigma_1{}^2 + \sigma_\Delta{}^2} \qquad (6)$$

Where

σ_1 =Standard deviation for the initial RT_{NDT}

σ_Δ = Standard deviation of ΔRT_{NDT}

The standard deviation for ΔRT_{NDT} (σ_Δ) is 28°F for welds and 17 °F for base metal, and should not exceed 0.50 times the mean value of ΔRT_{NDT} [4].

The determination of the allowable pressure to prevent brittle fracture is given by ASME Section XI Appendix G, Paragraph G-2215 [2, 3].

$$K_{IC} > 2\ K_{IM} + K_{IT} \qquad (7)$$

Where

K_{IC}= Reference critical stress intensity factor

K_{IM} = Stress intensity factor for membrane stress due to pressure and is defined in G-2214.1 of ASME Sec. XI, Appendix G [2, 1].

$$K_{IM = M_m} * \frac{Pr}{t} \qquad (8)$$

Where:

M_m = Membrane correction factor defined in the ASME Section XI Appendix G, Paragraph G-2214.1

P = Internal RPV pressure

r = Internal radius of RPV

t = Reactor vessel wall thickness

K_{IT} = Thermal stress intensity factor defined in ASME Sec XI Appendix G, Paragraph G-2214.3

$$K_{IT} = 0.953 * 10^{-3} * CR * t^{2.5} \qquad (9a)$$

$$K_{IT} = 0.753 * 10^{-3} * HU * t^{2.5} \qquad (9b)$$

Where CR is cooldown rate in (°F/ hr.),

HU is the Heat-up rate in (°F / hr.)

t is the thickness of the vessel wall (inch.)

The K_{IT} defined by equations (9a) and (9b) corresponds to the maximum temperature difference between vessel inner-surface to outer-surface throughout heat-up and cooldown operation.

k_{IT} at any point is given by:

$$k_{IT} = \frac{Max\ K_{IT}}{\Delta T}$$

K_{IC} Reference critical stress intensity factor is defined in ASME Section XI App. G, paragraph 2210-1.

$$K_{IC} = 33.2 + 20.734e^{[0.02(T-RT_{NDT})]}\ (ksi/\sqrt{inch}) \quad (10)$$

From (6) to (9), the pressure at any time is a function of operating pressure and is given by:

$$P = (K_{IC} - K_{IT}) * {}^{t}/_{r} * {}^{1}/_{2} * 1/M_m \quad (11)$$

IV.II ART based on Risk-Informed Approach

The advancement of knowledge in Probabilistic Fracture Mechanic (PFM) and transient analysis, suggest that the original screening limits are overly conservative in their application as summarized below [5, 11].

a) Fracture toughness was characterized by RT_{NDT}, a parameter which was intentionally conservative

b) The assumed flaw distribution in the interior surface of the RPV and their sizes are much larger than those found during in-service inspections

c) RPV model assumed the RPV was constructed using brittle material constituents

d) Fluence model for assessing embrittlement assumed that all interior surfaces of the RPV experience peak fluence

The Appendix G of ASME Code Section XI paragraph G-2216 gives the formula for evaluating allowable pressure, applicable for heat up and cool-down rates not exceeding 100 $°F/hr$ [3].

$$P = (33.2 + 20.734e^{[0.02(T-RT_{NDT}-\beta)]} - K_{IT}) * {}^{t}/_{r} * {}^{1}/_{\alpha} * 1/M_m \quad (12)$$

Where β and α are the risk-informed factor with values of 110 °F and 1 for Heat-up and cooldown, and 60 °F and 1 for hydrostatic leak tests [5].

The Adjusted Reference Temperature RT_{NDT} is given:

$$RT_{NDT} = RT_{NDT(u)} + \Delta RT_{NDT} \quad (13)$$

The expression for RT_{NDT} is similar to the deterministic one without the margin term. This is because the ΔRT_{NDT} of the Risk-informed methodology results from a low acceptable probability of fracture based on operational experience using probabilistic fracture mechanics. The change in RT_{NDT} is determined from plant-specific surveillance data or the irradiated degradation model used to compute Risk-informed allowable pressure [3, 11]. The terms $RT_{NDT(u)}$ and ΔRT_{NDT} are equivalent to un-irradiated RT_{NDT} calculated in accordance with ASME Section III NB-2300 [7] and an adjustment for irradiation effects respectively.

The adjustments due to irradiation effects is given by:

$$\Delta RT_{NDT} = MF + CRP \quad (14)$$

Where:

MF = Matrix Feature, a function of irradiation temperature T_i, phosphorus content, manganese content and neutron fluence

$$MF = A(1 - 0.001718T_i)(1 + 6.13PMn^{2.471})(\Phi_e)^{0.5} \quad (15)$$

Where

A = 1.140×10^{-7} for forgings

= 1.561×10^{-7} for plates

= 1.417×10^{-7} for welds

Mn = Bulk Modulus manganese content, wt. %

P= Bulk Modulus phosphorus content, wt. %

T_i = Irradiation temperature, ^{0} F

$$\Phi_e = \begin{cases} \Phi & ,\ ø \geq 4.39 \times 10^{10} \\ \Phi = \left(\frac{4.39\times10^{10}}{ø}\right)^{0.2595} & ,\ ø < 4.39 \times 10^{10} \end{cases} \quad (16)$$

Where

$\Phi_e = effective\ neutron\ fluence, cm^2$,

$\Phi = neutron\ fluence, cm^2$ and

$ø\ neuton\ flux,\ cm^{-2}s^{-1}$

CRP = Copper Rich Precipitate, a function of Nickel content, copper content and neutron fluence.

$$CRP = B(1 + 3.77Ni^{1.191})f(Cu_e, P)g(Cu_e, Ni, \Phi_e) \quad (17)$$

Where

B = 102.3 for forgings

= 135.2 for plates in vessels manufactured by CE

= 102.5 for non-CE plates

= 155.0 for welds

$$Cu_e = \begin{cases} 0, & Cu < 0.072 \\ min[Cu, Cu_{Max}], & Cu > 0.072 \end{cases} \tag{18}$$

Cu = bulk material copper content, wt. %

$$f(Cu_e, P) =$$

Cu_{Max} = 0.243 -for Linde 80 welds with Ni > 0.5 = 0.301 for all other materials.

$$\left\{ \begin{matrix} 0, & Cu \leq 0.072 \\ [Cu_e - 0.072]^{0.668}, & u > 0.072 \; and \; P \leq 0.008 \\ [Cu - 0.072 + 1.359[P - 0.008]]^{0.668}, & u > 0.072 \; and \; P > 0.0 \end{matrix} \right\} \tag{19}$$

$$g(Cu_e, Ni, \Phi_e) = \frac{1}{2} + \frac{1}{2} tahn \left[\frac{log_{10}(\Phi_e) + 1.139Cu_e - 0.448Ni - 18.120}{0.629} \right] \tag{20}$$

V. PROCEDURE FOR CONSTRUCTING P-T LIMIT CURVES

The procedure for constructing P-T limit curves for both deterministic and Risk-informed is summarized in Fig 3 below.

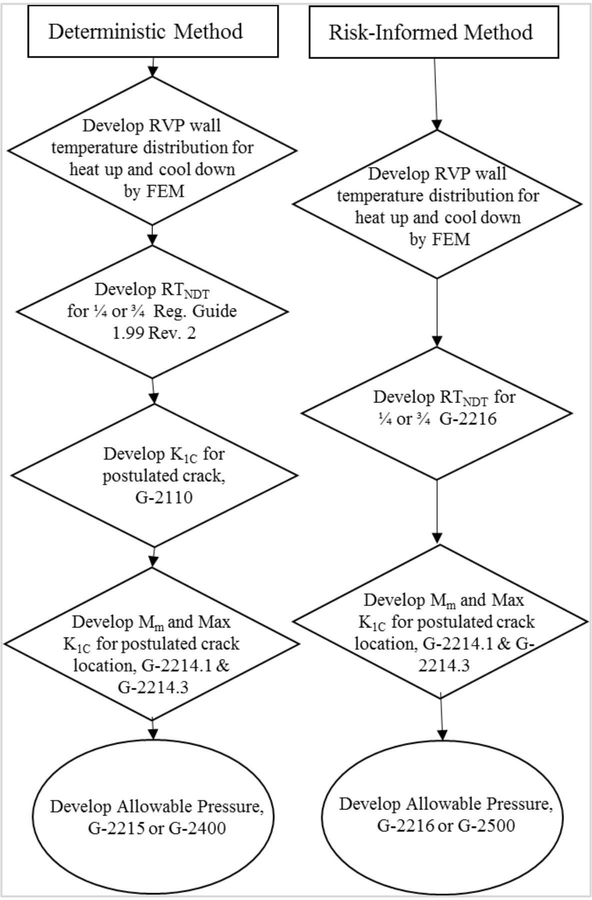

Figure 2: Procedure for constructing of P-T limit curves

V.I Setting up of RPV Model for Thermal Transient Analysis

To determine the RPV thermal gradient and maximum temperature gradient during heat-up and cooldown, a 2D axisymmetric model representing the active core region was created in ANSYS workbench 19.1 and material properties specified for transient thermal analysis. Using the reactor vessel wall thickness for OPR1000, 8.06 inches and the active core height of 150 inches, the model was set as shown in Fig 4 below.

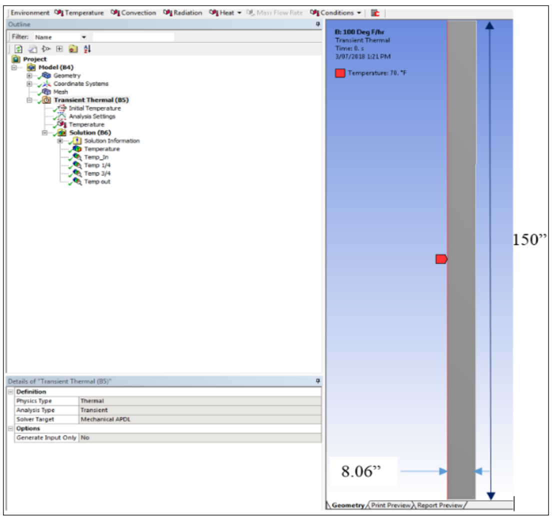

Figure 4. Thermal transient boundary conditions

The maximum heat-up or cooldown rate of 100°F/hour was then defined in the analysis set-up and RPV beltline temperature profiles at the inner Surface, ¼ thickness, ¾ thickness and outer surface noted by setting the probes as illustrated in Fig 5 below.

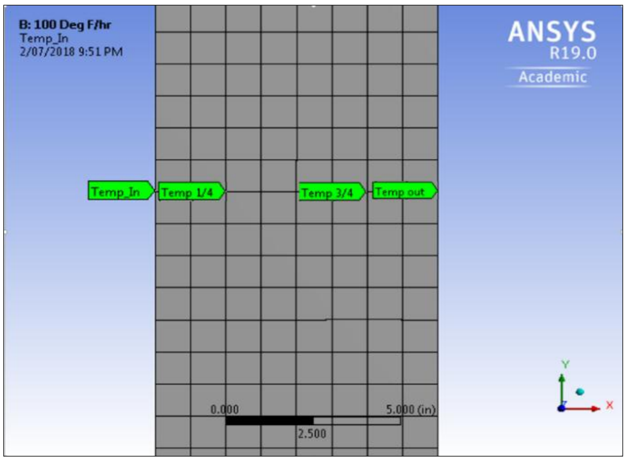

Figure 5: Temperature probes at various RPV regions

V.II Determination of ART for Deterministic Method

From the percentages of Copper and Nickel, chemistry factors were read directly from RG 1.99 Rev. 2 [4] and results used in the computation of ART. Using the peak fluence for neutrons E>1.0 MeV on the pressure vessel/base metal interface for OPR1000 at 32 EFPY, ART values were calculated for both ¼ and ¾ surfaces of the RPV using (1) to (6) above. The results obtained are summarized in Table 5 below.

Table 5: ART for the deterministic method

¼t Region	Base metal	Weld metal
Chemistry Factor, CF(^0F)	31.00	36.64
Surface Fluence, x10^{19} cm^2	1.88	1.88
Fluence, f(1/4) x10^{19} n/cm^2	1.16	1.16
IRT_{NDT}, ^0F	10.00	- 50.00
ΔRT_{NDT} at ¼ t, ^0F	32.27	38.14
Margin at ¼ t, ^0F	32.27	28.00
$ART = IRT_{NDT} + \Delta RT_{NDT} + Margin$, ^0F	74.54	16.14
¾t Region	Base metal	Weld metal
Chemistry Factor (CF), ^0F	31.00	36.64
Surface Fluence, x10^{19} cm^2	1.88	1.88
Fluence, f(3/4) x10^{19} n/cm^2	0.44	0.44
IRT_{NDT}, ^0F	10	- 50
ΔRT_{NDT} at ¾ t, ^0F	23.93	28.28
Margin at ¾ t , ^0F	23.93	28.28
$ART = IRT_{NDT} + \Delta RT_{NDT} + Margin$, ^0F	57.85	6.56

V.III Determination of ART for Risk Informed Method

$Give\ that$:

$A = 1.140 \times 10^{-7}\ for\ forgings,$

$Ti = 565\ °F,$

$P = 0.007,$

$Mn = 1.4,$

$B = 102.3\ for\ forgings$

$Design\ life\ of\ 40\ years\ with\ plant\ availability\ of$

$90\%\ and\ \ Cu = 0, for\ Cu < 0.072)$

By applying risk-informed (13) to (20) above, critical values of ART were obtained and results tabulated as shown in ***Error! Reference source not found.*** below.

Table 6: ART for risk-informed method

¼t Region	Base metal	Weld metal
Surface Fluence, x10^{19} cm^2	1.88	1.88
Fluence, f(1/4) x10^{19} n/cm^2	1.16	1.16
$RT_{NDT(U)}$	10	-50
Neutron flux (1/4) 10^{10}n/cm^2/s	1.02	1.02
Matrix Features (MF), ^0F	15.1	20.5
Copper Rich Precipitate (CRP), ^0F	0	0
$\Delta RT_{NDT} = MF + CRP$	15.1	20.53
$ART = RT_{NDT(u)} + \Delta RT_{NDT}$	25.1	-29.47
¾t Region	Base metal	Weld metal
Surface Fluence, x10^{19} cm^2	1.88	1.88
Fluence, f(3/4) x10^{19} n/cm^2	0.44	0.44
$RT_{NDT(U)}$	10	-50
Neutron flux (3/4), 10^{10}n/cm^2/s	0.39	0.39
Matrix Features (MF), ^0F	10.60	14.40
Copper Rich Precipitate (CRP), ^0F	0	0
$\Delta RT_{NDT} = MF + CRP$	10.56	14.35
$ART = RT_{NDT(u)} + \Delta RT_{NDT}$	20.56	-35.65

V.IV Comparison of P-T Limit Curves between Deterministic and Risk-Informed

Using the data from Table 5 and Table 6 above, and relevant equations, the P-T limit curves for 100 °F/hr. cooldown and heat-up are shown in Fig 5 and Fig 6 next page.

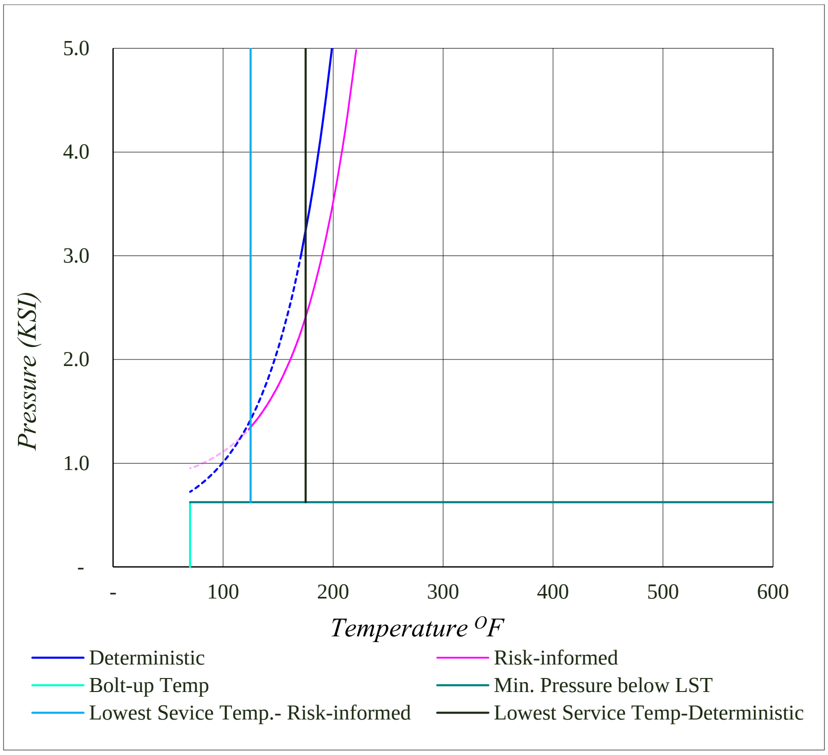

Figure 5. Comparison between deterministic and risk- informed – 100 °F / hr. cooldown

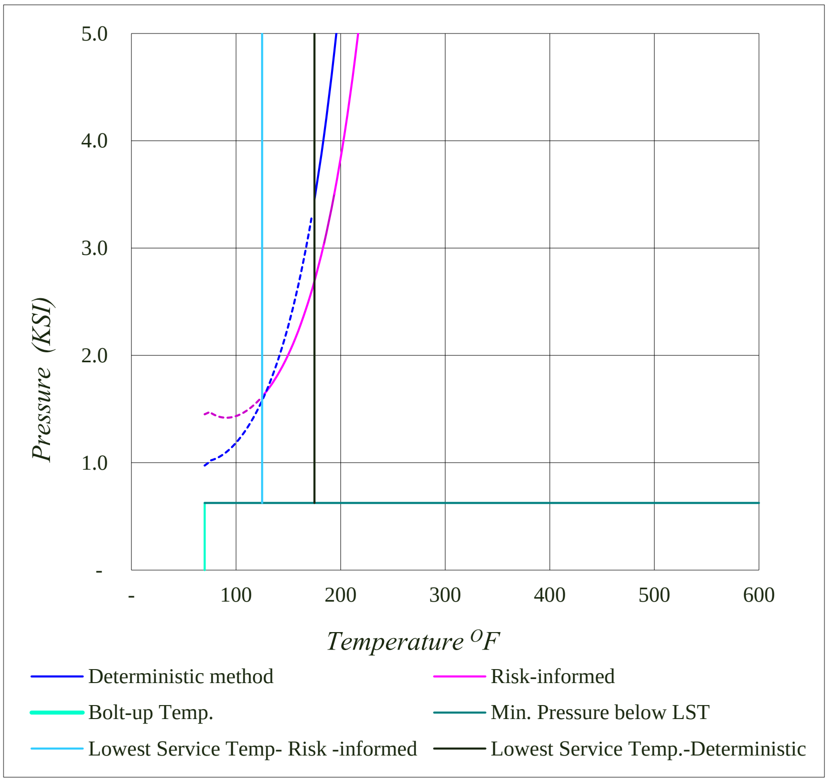

Figure 6. Comparison between deterministic and risk-informed – 100 °F / hr. Heat-up

From Fig 5 and Fig 6, the Risk-informed method is slightly more conservative in high temperatures and less conservative in low temperatures. However, the major difference between the two methods is results from the determination of ΔRTNDT which is 75°F for deterministic method and 25°F for risk informed method. These values imply that the Lowest Service

Temperature is 125 °F and 175 °F for the risk-informed and the deterministic method respectively

V.V P-T Limit Curve Prior to 2006

Subject to Code Case N-640 of 1999, and subsequent approval of its use by USNRC in 2004 for the development of P-T limit curves without exemptions, later editions of ASME code are based in K_{IC} curve. The Pre-2006 editions were based on K_{IR} curve which is the critical reference stress intensity factor based on the lower bound of static, dynamic and crack arrest as recommended in paragraph G-2210-1 of ASME Section XI 1998, Appendix G [12].

Since currently operating OPR NPPs were installed from the mid 90ties, ASME methodology prior to 2006 shall be applied and the governing equations are as follows:

$$K_{IR} > 2\, K_{IM} + K_{IT} \tag{21}$$

Where K_{IM} = stress intensity factor for membrane stress due to pressure, (ksi $\sqrt{in}$)

$$K_{IM} = M_m \times (\sigma_m) \tag{22}$$

Where K_{IR} = critical reference stress intensity factor based on the lower bound of static, dynamic and crack arrest.

$$K_{IR} = 26.78 + 1.223e^{[0.0145(T-RT_{NDT})+160]} \tag{23}$$

Where K_{IT} = Radial thermal stress intensity factor as give in paragraph G-2120

$K_{IT} = M_t \times \Delta T$ - From paragraph G-2214-2 of ASME Section XI 1998, Appendix G [12].

$$P = \frac{(K_{IR}-K_{IT})\times t}{2\times r\times M_m} \tag{24}$$

V.VI Comparison of P-T limit curves prior to 2006 Code with 2017 ed.

From the Fig 7 and Fig 8 below, the P-T limit curves based on ASME 2017 edition are less conservative for both deterministic and risk-informed. This is due to use of static K_{IC} which is higher than K_{IR} used in ASME 1998 edition.

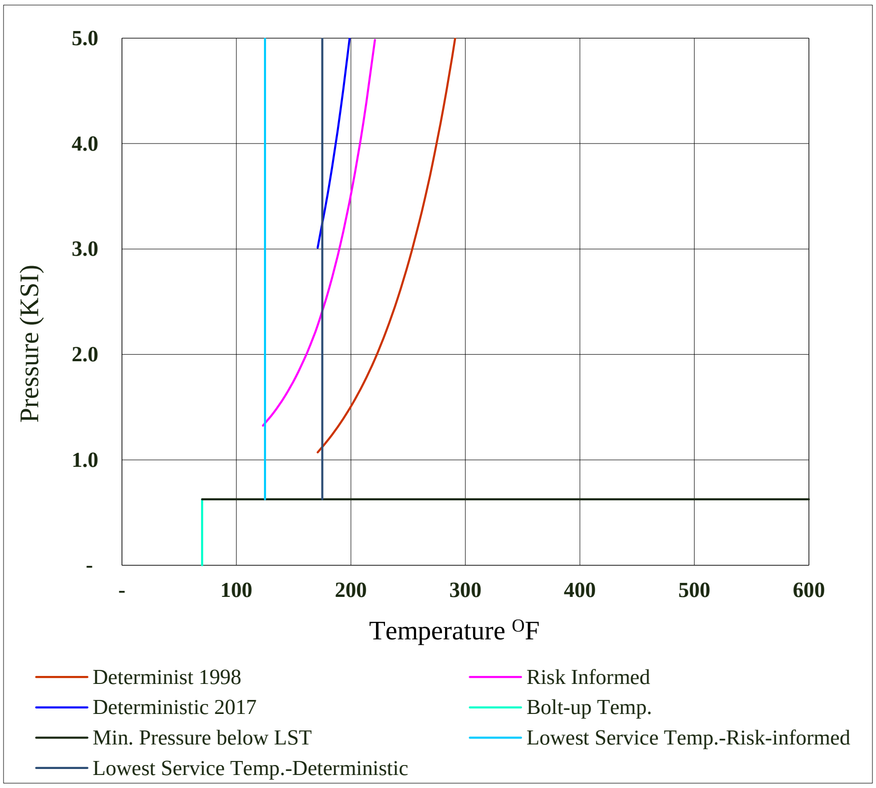

Figure 7. Comparison of P-T limit curves prior to 2006 Code with 2017 ed. – cooldown

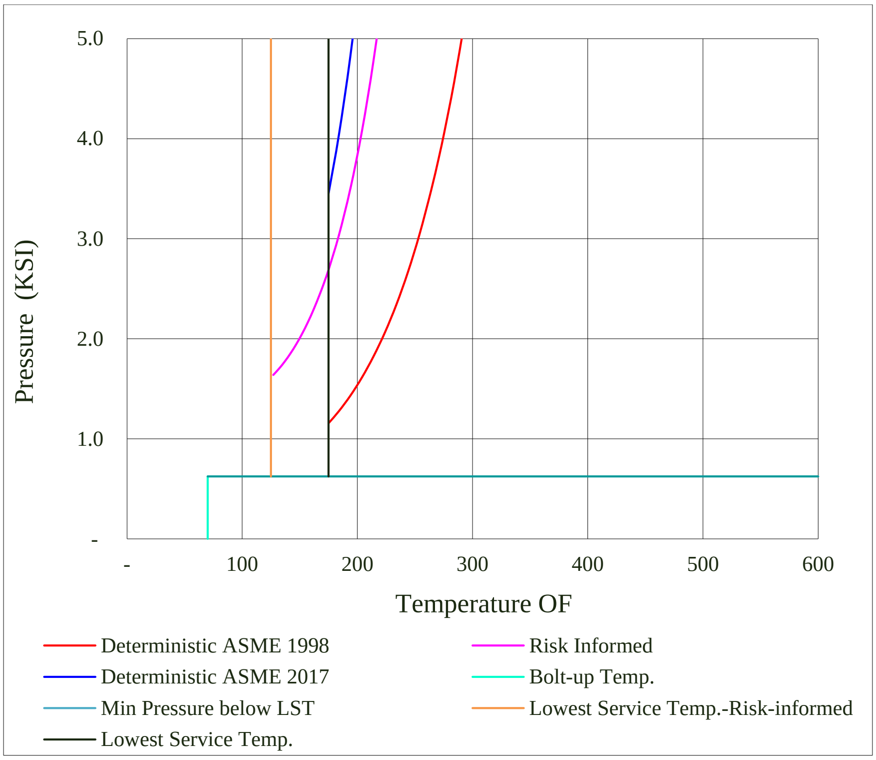

Figure 8. Comparison of P-T limit curves prior to 2006 Code with 2017 ed. – heat-up

VI. CONCLUSIONS

P-T limit curves are calculated and constructed based on a predicted or a calculated level of embrittlement at a specified Effective Full Power Years (EFPY) to prevent RPV from Non-ductile failure by providing a safe operational window. This implies that P-T limits should be adjusted periodically based on the measured shift in RTNDT by testing the reactor vessel surveillance material samples. These updates are necessary for the continued operation of NPP, life extension, or when the existing P-T curves expire.

To construct OPR1000 P-T limit curves, reactor material properties, fabrication methods and fluence levels were adopted from Final Safety Analysis Report (FSAR) of the plant, surveillance capsules test report and other relevant reports. Both heat up and cool-down temperature profiles at the inner surface, ¼ thickness, ¾ thickness and the outer surface of RPV were developed using transient thermal analysis module of ANSYS 19.1 software. To determine ΔRTNDT for the deterministic method, Copper content, Nickel content and neutron fluence levels were used and safety margin added. For the risk-informed method, ΔRTNDT was determined based on improved embrittlement mechanism based on the formation of Copper Rich Precipitates and Matrix Features resulting from dislocation motion caused by neutron flux. The P-T limit curves of RPV beltline region were then obtained using both ASME code of 1998 and 2017 editions for both 100°F/hr. heat-up and cooldown.

The results obtained indicate a considerable decrease in conservativeness in P-T limit curves constructed using the current 2017 ASME code both in deterministic and risk-informed methods. The adoption of the current fracture toughness requirements of the 2017 ASME code will increase operational flexibility and plant safety. This is because the less conservative P-T limit curves widen the operational window which in turn enhances the durability of pump seal due to adequate cooling. The pump seal failure is known for causing a Small Break Loss of Coolant Accident (SBLOCA) which is not desirable. For the two methods of 2017 ASME code, the risk-informed method is slightly more conservative in high temperatures and less conservative in low temperatures. The lower values of ΔRTNDT obtained in risk-informed are beneficial in increasing the fuel damage margin. It actually removes the need for flux suppression system associated with high values of ΔRTNDT to maintain an acceptable P-T envelope. In order to utilize the benefits of risk informed methodology, future work needs to involve plant-specific data to obtain actual risk-informed factors for adoption.

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