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Evaluation of Pressure-Temperature Limit Curve for Pressurized Water Reactor Vessel Nozzles

HyunChul Lee [a*], YoungJae Maeng [a], KyungSik Kim [a], SungHoon Yoo [a],
[a] *Korea Reactor Integrity Surveillance Technology, 324-8, Techno 2-ro, Yuseong-gu, Daejeon, Korea 34036*
[*] *Corresponding author: hclee@krist.co.kr*

1. Introduction

The purpose of the Pressure – Temperature (P-T) limit curve is to prevent a failure of reactor pressure vessel during operation of reactor coolant system. In Korea, P-T limit curves shall be met 10CFR50 Appendix G[1] according to Nuclear Safety and Security Commission Notification 2017-20. 10CFR50, Appendix G requires plant specific P-T limit curve for the beltline region of the reactor vessel. And the beltline region is defined as the region of the reactor vessel that directly surrounds the effective height of the active core and adjacent regions of the reactor vessel expected to sufficient neutron radiation damage. Therefore the P-T limit curves have been traditionally evaluated based on the beltline region which is the most affected by neutron irradiation embrittlement. However due to the geometric discontinuity, the inside corner regions of the vessel nozzles are the most highly stressed regions of reactor vessel. The most highly stressed nozzle region may result in more limiting P-T limit curve than beltline P-T limit curve. Thus, the evaluation of nozzle P-T limit curve should be evaluated and compared to the beltline P-T curve.

In 2014, the NRC issued Regulatory Issue Summary (RIS) 2014-11[2], which required the consideration of reactor vessel nozzles in P-T limits curve generation. Reactor vessel nozzle and other discontinuities have complex geometries that can exhibit significantly higher stresses than the reactor vessel beltline shell region. These higher stresses can potentially result in more restrictive P-T limits, even if the reference nil ductility transition temperatures (RT_{NDT}) for these components are not as high as those of the reactor vessel beltline shell materials that have simpler geometries.

The objective of this paper is to evaluate the reactor vessel nozzle corner region P-T limit curves and to compare with the P-T limit curves for the reactor vessel traditional beltline region in order to determine if the nozzles P-T limit curves are more conservative than the beltline P-T limit curves.

2. Nozzle P-T limit Curves Evaluation Methodology

In this section, nozzle P-T limit curve evaluation methodology is discussed in detail. Before ASME Code Section XI Appendix G 2013 edition[3] was issued, reactor vessel nozzle region were evaluated according to WRC Bulletin-175[4]. WRC Bulletin-175 approach is similar to the methodology of ASME Code Section XI Appendix G 2013 edition which has been developed on the basis of research results of ORNL/TM-2010/246[5]. Therefore ASME code Section XI Appendix G 2013 edition provides detailed evaluation procedures for nozzle P-T limit curves. In this study, nozzle P-T limit curves were evaluated according to ASME code Section XI Appendix G 2013 edition.

2.1 Determination of Adjusted Reference Temperature

In order to determine the nozzle P-T limits, the adjusted reference temperatures (ARTs) are calculated based on the nozzle material the chemistry factors (CFs) values, the nozzle fluence values, and the initial reference nil-ductility transition temperatures. However, because the objective of this study is to determine if the nozzles P-T limit curves are more limiting than the beltline P-T limit curves under the same condition, nozzle and beltline ARTs are set to the same values as 0°F.

2.2 Allowable Pressure Calculation

According to the ASME Code Section XI Appendix G 2013 edition, the stress sources which have to be considered in nozzle P-T limit evaluation are both internal pressure loading and thermal loading. For level A&B service condition, the following requirement shall be satisfied.

$$2K_{Ip} + K_{It} < K_{Ia} \quad (1)$$

K_{Ip} is stress intensity factor due to internal pressure loading. K_{It} is stress intensity factor due to thermal loading. In this study, K_{Ia} fracture toughness is considered in the generation of the nozzles corner P-T limits. Thus, for the nozzle P-T limit curves, the K_{Ia} fracture toughness is calculated based on the following equation.

$$K_{Ia} = 26.78 + 1.233 * e^{(0.0145(T - RT_{NDT} + 160))} ksi\sqrt{in} \quad (2)$$

Allowable pressure can be obtained by defining the K_{Ip} of equation (1) as function of internal pressure.

2.2.1. Stress Intensity Factors Determination

The applicable pressure and thermal transient stresses used to calculate pressure and thermal stress intensity factor, K_{Ip} and K_{It}, at the nozzle corner cut are determined based on a finite element analysis. Only cool-down transient stresses are considered since the inside surface of the nozzle corner would be in a tensile stress state during the cool-down transient. On the other hand the heat-up transient stresses makes compressive stress on the inside surface. Therefore, the cool-down transient is more limiting than the heat-up transient for nozzle P-T limit curves. The stress intensity factor calculation for the nozzle corner regions is based on a 1/4T circular corner flaw, as per ASME code Section XI Appendix G 2013 edition postulated flaw guidelines.

The stress intensity factor calculation method includes postulating an inside surface 1/4t nozzle corner flaw and calculating through-wall nozzle corner stresses for a cool-down rate of 100°F/hour. The through-wall stresses at the nozzle corner location were fitted based on a third-order polynomial of the form.

$$\sigma = A_0 + A_1 X + A_2 X^2 + A_3 X^3 \quad (3)$$

where σ is through-wall stress distribution, x is through-wall distance from inside surface. A_0, A_1, A_2, A_3 are coefficients of polynomial fit for the third-order polynomial, used in the stress intensity factor. Substituting the coefficients A_0, A_1, A_2, A_3 into the equation below, the stress intensity factor is calculated.

$$K_I = \sqrt{\pi a}\left[0.706A_0 + 0.537\left(\frac{2a}{\pi}\right)A_1 + 0.448\left(\frac{a^2}{2}\right)A_2 + 0.393\left(\frac{4a^3}{3\pi}\right)A_3\right] (4)$$

2.3 Finite Element Analysis

Stress intensity factors produced by pressure and thermal load are analyzed using a 3D finite element model. The nozzle finite element model for the stress analysis in this study is established based on the Korean standard nuclear reactor. Material of the nozzle model is SA-508 CL.3 and material properties are shown in Table.1. Due to the symmetry, only 1/4 of the nozzle was modeled and Fig.1 shows the outlet nozzle finite element model. SOLID70 element was used for heat transfer analysis and SOLID185 element was used for stress analysis.

Finite element analysis was carried out for heat transfer and thermal stress analysis using ANSYS V.16 and stress analysis by internal pressure was also performed.

Table I: Material properties for Nozzle FEM

Material		**SA-508 Class 3**			
Property		Elastic modulus ($\times10^3$ ksi)	Thermal Expansion ($\times10^{-6}$ in/in/°F)	Thermal Conductivity (Btu/hr-in-°F)	ρCp (Btu/in^3-°F)
Temp. (°F)	70	27.8	6.4	1.9750	0.0299
	100	27.6	6.5	1.9667	0.0303
	200	27.1	6.7	1.9583	0.0321
	300	26.7	6.9	1.9500	0.0338
	400	26.2	7.1	1.9250	0.0353
	500	25.7	7.3	1.8917	0.0368
	600	25.1	7.4	1.8500	0.0382

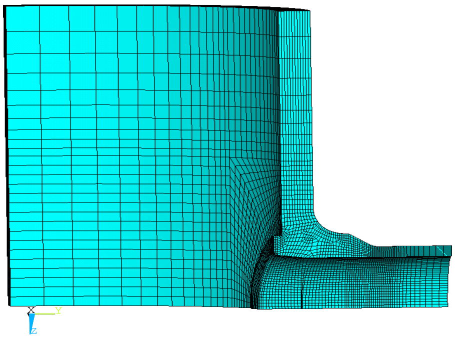

Fig. 1. Outlet Nozzle Finite element model

3. Result

In this section, results of nozzle FEM analysis are discussed. Also results of nozzle and beltline P-T limit curves are discussed.

3.1 Result of Stress Analysis of Nozzle Model

Fig. 2 shows stress intensity distribution when internal pressure of 2250 psig is applied. The maximum stress is shown at the nozzle corner. This is due to the influence of geometric discontinuity. Fig. 3 shows hoop stress extraction path for outlet nozzle model. The stress intensity factor is determined using stress values on the path.

Fig. 4 shows stress intensity distribution when thermal load is applied. High stresses are distributed at the corner of nozzle model.

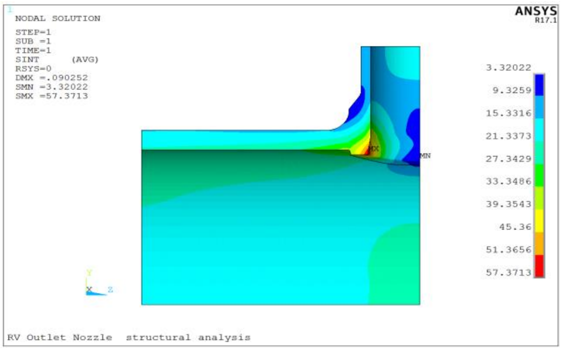

Fig. 2. Stress intensity distribution due to internal pressure

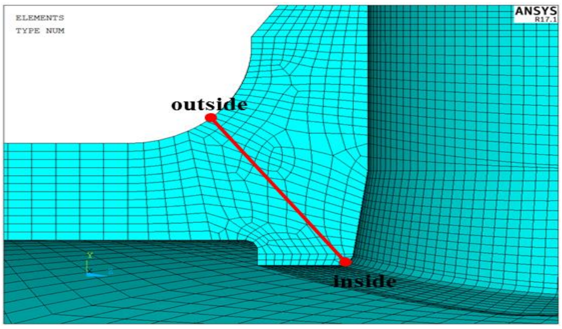

Fig. 3. Hoop stress Extraction path for nozzle model

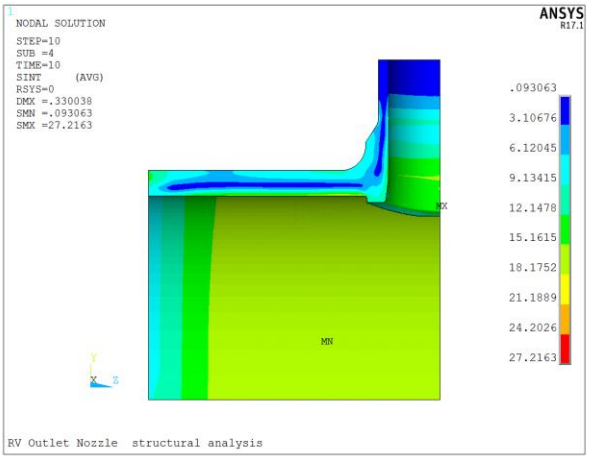

Fig. 4. Stress intensity distribution due to thermal load

3.2 Result of Nozzle and Beltline P-T Limit Curves

The nozzle P-T limit curves are determined for a cool-down rate of 100°F/hour, along with a steady-state condition. Fig.5 shows inlet nozzle and beltline P-T limit curves. Comparing the inlet nozzle P-T limit curves and the beltline curves, inlet nozzle P-T limit curves are more limiting than beltline curves in cool-down rate of 100°F/hour and steady–state.

As shown in Fig. 6, outlet nozzle P-T limit curves are more limiting than beltline curves in cool-down rate of 100°F/hour and steady–state.

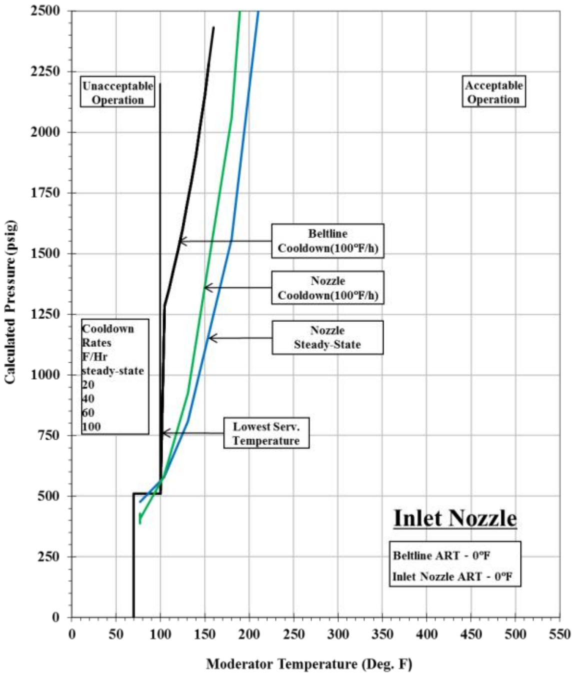

Fig. 5. Inlet nozzle and beltline P-T limit curves

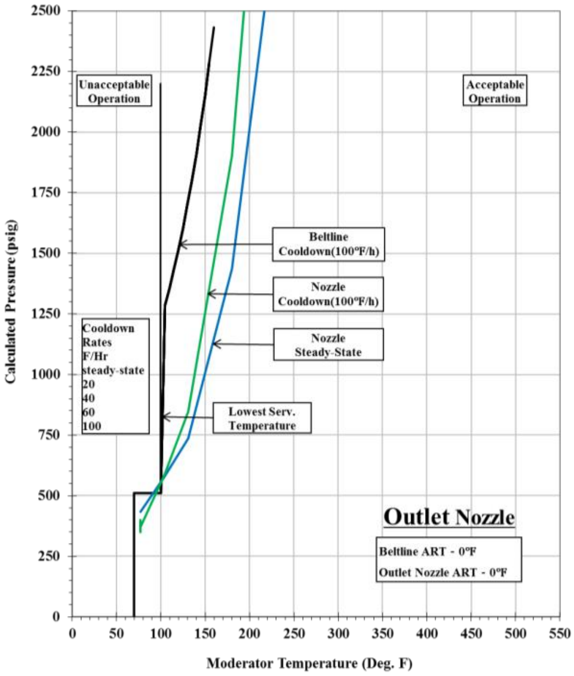

Fig. 6. Outlet nozzle and beltline P-T limit curves

3. Conclusions

The reactor vessel nozzle P-T limit curves were calculated based on the methodology described in ASME Section XI Appendix G 2013 edition. Due to the geometric discontinuity, nozzle P-T limit curves are more limiting than the beltline when the reference nil ductility transition temperatures (RT_{NDT}) for nozzle and beltline are the same. As a conclusion, the nozzle P-T limit curve evaluation should be continuously performed in order to confirm if nozzle P-T limit curves are bounded by beltline curves during the plant life.

REFERENCES

[1] Code of Federal Regulations, 10 CFR Part 50, Appendix G, "Fracture Toughness Requirements," U.S. Nuclear Regulatory Commission, Federal Register, Volume 60, No. 243, dated December 19,1995.

[2] NRC Regulatory Issue Summary (RIS) 2014-11, "Information on Licensing Applications for Fracture Toughness Requirements for Ferritic Reactor Coolant Pressure Boundary Components," U.S. NuclearRegulatory Commission, October 2014. [Agencywide Documents Access and Management System (ADAMS) Accession Number ML14149A165]

[3] ASME Boiler and Pressure Vessel (B&PV) Code, Section XI, Appendix G, 2013 edition.

[4] WRC BULLETIN 175, "PVRC Recommendation on Toughness Requirements for Ferritic Materials," Welding Research Council, August 1972.

[5] Oak Ridge National Laboratory Report, ORNL/TM-2010/246, "Stress and Fracture Mechanics Analyses of Boiling Water Reactor and Pressurized Water Reactor Pressure Vessel Nozzles – Revision 1," June 2012.