Quality Assurance of Chapter 10: Requirements for Nozzles

This report documents the results of the quality assurance task for Chapter 10 of the draft technical basis NUREG for the risk-informed Appendix G project. Chapter 10 discusses fracture mechanics analyses of vessel nozzle locations. The quality assurance effort for this chapter involved review of an Oak Ridge National Laboratory report on finite element modeling of nozzles.

Review of 'Stress and Fracture Mechanics Analyses of Boiling Water Reactor and Pressurized Water Reactor Pressure Vessel Nozzles' ORNL/TM-2010/246

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ORNL/RM-2010/246 (ORNL report) provides Finite Element (FE) fracture mechanics evaluations of flaws in 5 BWR and PWR nozzles; ranging in size from BWR drill-hole style instrument to BWR/PWR outlet nozzles [1]. 2D axisymmetric and 3D FE modes were constructed for all nozzle geometries, allowing assessment of (1) differences between 2D/3D models, (2) Linear Elastic Fracture Mechanics (LEFM) closed form nozzle solutions, (3) significance of piping loads on LEFM evaluations, and (4) significance of crack face pressure on LEFM evaluations. The FE evaluations are used to support two explicit recommendations:

1. Simplified closed-form LEFM solutions presented in ORNL/RM-2010/246 for postulated nozzle corner crack are recommended to be incorporated into rived Paragraph G-2223, Appendix G of ASME Code Sections XI along with the use of a 1/4*t* postulated flaw size for establishing RPV P-T limits.

2. Peak stress correction factors ranged from 2.7 to 3.4 for the nozzle geometries modeled in ORNL/RM-2010/246. Based on these analyses, bounding stress correction factor of 3.1 is appropriate for nozzles with smooth inside corners and 3.5 is appropriate for nozzles with discontinuities or sharp inside corners.

This document reviews the LEFM methodology and support for the conclusions drawn in ORNL report.

LEFM Methodology

Closed-form LEFM solutions for the deepest point of a semicircular corner crack from reference [2] are described in the ORNL report. Closed-formed solutions for various nozzles containing circular corner cracks are provided. The form of the solutions is typical of influence function K-solutions, where a polynomial fit to the through-thickness stress profiles normal to the crack faces and the crack length describe the stress intensity factor, K_I, at the deepest point of the crack.

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FE Methodology

Cracks were embedded in 2D and 3D FE models following in accordance with procedures outlined in reference [3]. Specifically the elements along the crack face were collapsed, and mid-side nodes moved to *1/4t* position as is appropriate for cracked LEFM analyses. Contour integral evaluation for K_I was path independent indicating adequate mesh construction and refinement at the crack tip. Location of the cracks was chosen based on the location of maximum hoop stress from internal pressure, as well as thermal transients. Comparison of 2D to 3D FE models establish technical basis for the stress correction factors stated in recommendation 2. Piping loads and crack face pressures are established as a second order effect.

Technical Issue 1
As noted in the ORNL report, weight function K-solutions require that the through-wall stress state is well approximated by a polynomial fit. In the ORNL report the sensitivity of different fitting strategies is plotted in Figure 27. Polynomial fitting up to the crack tip (which is appropriate for weight function solutions) and the through-thickness polynomial fit yield similar K_I values, but the goodness of fit (as characterize by R^2) is quite different and the agreement in this case is coincidental. In the ORNL work thermal transients tend to produce some through-thickness stress distributions that are not well characterized by polynomial fits, as higher stresses are produced in the cladding relative to the base metal. In these cases the agreement between the closed form solutions and the FE is not favorable (Figure 42 of the ORNL report), though the agreement under combined loading (thermal + internal pressure) is favorable (Figure 45). One method of improving the goodness of fit not considered in the ORNL report is to force the fit to start at the ID stress, potential improving the fit when high stresses are observed in the cladding.

Care needs to be taken that the polynomial is a good approximation for the through-thickness stress distribution, if a good fit is not obtained polynomial weight function solutions should not be used. This issue could be resolved by expanding the discussion of polynomial fitting strategies on page 19 of the ORNL report.

Technical Issue 2
Scaling the LEFM solutions is appropriate in cases where the geometry remains constant and only aspect ratio of geometric features change. This is not the case for the 10% and 25% nozzle corner cracks, where the geometry of the crack with respect to the nozzle is different in each case. The assessment used is likely conservative, as a semi-circular crack is not an equilibrium crack and will have higher K_I at the surface than a semi-elliptical crack. These issues could be resolved by FE modeling of a 10% semi-circular crack (to verify the scaling used) and semi-elliptical flaw (to show the surface K_I reduction).

Technical Issue 3

The FE K_I results are scaled by the ratio of the weight function solutions K_I results for the 10% and 25% crack length. This is not appropriate as the FE results are scaled by the weight function solutions that they are being used to validate. The additional FE work suggested in Technical Issue 2 would resolve this concern.

References

[1] SY Yin, BR Bass, GL Stevens "Stress and Fracture Mechanics Analyses of Boiling Water Reactor and Pressurized Water Reactor Pressure Vessel Nozzles." ORNL/TM-2010/246

[2] SA Delvin, PC Ricardella "Fracture Mechanics Analysis of JAERI Model Pressure Vessel Test." ASME Paper No. 78-PVP-91, Proceedings of the 1978 ASME Pressure Vessels and Piping Conference, June 25-30, 1978, Montreal, Quebec, Canada.

[3] TL Anderson "Fracture Mechanics: Fundamentals and Applications, 3rd edition." Taylor and Francis Group, Boca Raton, 2005.