

Status report describing evaluation of embrittlement effects in a reactor pressure vessel nozzle

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1. BACKGROUND

Ensuring public safety and environmental protection is a prerequisite to all nuclear power plant operating and licensing decisions at all stages of reactor life. This includes the original license period of 40 years, the first license extension to 60 years, and certainly for any consideration of life beyond 60 years. For extended operating periods, it must be shown that adequate aging management programs are present or planned and that appropriate safety margins exist throughout the subsequent license renewal periods. Materials degradation can impact reactor reliability, availability, and potentially, safe operation. Extending reactor service to beyond 60 years will increase the demands on materials and components. The reactor pressure vessel (RPV) represents the first line of defense against radiation release in an accident at a light water reactor. Thus, regulations that govern the operation of commercial nuclear power plants require conservative margins of fracture toughness, both during normal operation and under accident scenarios. Prior to operation, the RPV has sufficient fracture toughness such that failure is implausible under any postulated condition, including pressurized thermal shock (PTS). However, during reactor operation, leakage of neutrons from the reactor core pass through the RPV resulting in irradiation embrittlement that can severely degrade the RPV fracture toughness, with the degree of toughness loss dependent on the radiation sensitivity of the materials. The available embrittlement predictive models, e.g. [1,2], and our present understanding of radiation damage are not fully quantitative, and do not treat all potentially significant variables and issues, particularly considering extension of operation to 80 years.

For reactor pressure vessels, a number of significant issues have been identified for recommended attention in future research activities. Sparse or nonexistent data at high fluences, for long times, and at high levels of embrittlement create large uncertainties for embrittlement predictions [3,4], as well as the influence of residual stresses that develop during the welding and fabrication process. As well, the use of test reactors at high fluxes to obtain high fluence data is problematic for representation of the low flux conditions in RPVs. Late-blooming phases, especially for high nickel welds, have been observed and additional experimental data are needed in the high fluence regime where they are expected. Other discussed issues include specific needs regarding application of the fracture toughness master curve, data on long term thermal aging, attenuation of embrittlement through the RPV wall, evaluation of three dimensional effects associated

with flaw placement and geometry at the location of material inhomogeneities associated with welds joining plate materials, and development of a embrittlement trend curve based on fracture toughness.

In this work, we have utilized the GRIZZLY tool [5] being developed within the Light Water Reactor Sustainability Program is to specifically evaluate the neutron embrittlement/aging and residual stress effects in the nozzles during a postulated pressurized thermal shock (PTS) transient. The next section briefly discusses the calculation of the embrittlement Eason, Odette, Nanstad, and Yamamoto (EONY) model of RPV embrittlement based on the fast neutron flux at the nozzle region due to neutron streaming. The following section summarizes the GRIZZLY analysis and explicitly considers the effect of different levels of residual stress on the resulting calculations of K_{Iapp} .

2. EMBRITTLEMENT ESTIMATE WITHIN THE NOZZLE REGION

Following the EONY model [1,2] and an estimate of the neutron flux level of 5×10^{15} n/cm² for the Zion reactor as a result of neutron streaming to the nozzle region following 16 effective full power years[6], we have assumed a similar flux rate to estimate a value of neutron fluence of 2×10^{16} n/cm² for an effective lifetime of 65 years (same flux of $\sim 1 \times 10^7$ ncm⁻²s⁻¹). We have also assumed that the nominal material conditions of the nozzle weldment are of a steel containing 0.243 wt% Cu, 0.65% Ni, 0.0015% P, and 1.2% Mn. Using the EONY correlation model, this combination results in a transition temperature shift, ΔT , of about 6°C. Therefore, it appears that the neutron embrittlement effects should be insufficient to cause any significant changes in the material properties, since a shift of less than 10°C is well within the scatter assumed for the unirradiated properties. There may still be a question of whether time at temperatures near 300°C with very low neutron flux are sufficient to induce significant copper precipitation and corresponding yield strength increases and ΔT shift. However, there is insufficient data available at this time to assess such an issue. Recovery of the nozzle materials, or a trepan through the nozzle of the Zion reactor would provide some experimental evaluation of this issue. Correspondingly, since the neutron embrittlement at the nozzle location is quite low and deemed insignificant, we have instead decided to evaluate another important aspect of the possibility for three-dimensional effects and nozzle failure by evaluating the influence of residual stress within the nozzle region. The following section describes the analysis and results.

3. METHODOLOGY TO ASSESS RESIDUAL STRESS IMPACT WITHIN RPV NOZZLE

To study flaws in the nozzle region of a RPV we used a full-scale 3D model of a four-loop RPV with a 4 mm stainless steel liner on the inner surface. The meshed model is shown in Fig. 1. The pressure vessel dimensions are based on the Pressure Vessel Research User Facility (PVRUF) vessel at ORNL. The model had 660,000 elements and

10 elements through the thickness of the wall in the belt line region. The innermost element represented the stainless steel liner.

Using the MOOSE-based code Grizzly [5], we performed stress analysis in the RPV model under a PTS transient. The PTS data is shown in Fig. 2 and was measured during a reactor turbine trip when a safety relief valve is stuck open and reclosed at 3,000 s. The closing of the relief valve lead to a sharp increase in pressure in the RPV, and the high pressure in combination with the low temperature of the coolant represents a worst-case scenario due to the simultaneous high stress on flaws and lowered fracture toughness at lower temperatures.

The pressure and temperature histories in Fig. 2 were prescribed as uniform boundary conditions on the inner surface of the vessel. To simulate the effect of residual stresses in the nozzle region, a section of the nozzle region was prescribed a higher stress free temperature and hence undergoes a larger thermal expansion than the rest of the wall. This difference in thermal expansion between the regions is a reasonable representation of the residual stresses that appear in welds during the cooling down of the weld.

The displacement and temperature distributions in the RPV model were used to drive submodels containing flaws embedded in the wall of the nozzle region. The flaws were penny shaped cracks with a diameter of 1 cm and a thickness of 2.5 μm . The crack tip was blunt and semicircular with a 1.25 μm radius. The side length of the submodel was 10 cm. Fig. 3 shows a cross section through the submodel and a close-up of the crack tip mesh. The normal to the crack plane was in the axial direction of the vessel and the submodel was placed in two locations at the inlet nozzle: in the vessel wall at the nozzle, and inside the nozzle (see Fig. 4). The inlet nozzle would normally see the coldest temperatures in the RPV, however, in this simplified model we prescribed a uniform pressure and temperature over the whole inner wall of the vessel and nozzles.

The stress intensity factors along the crack front were analyzed using the J-integral capability in Grizzly. The J-integral represents the total energy release rate from Modes I, II and III at the crack tip, but for simplicity we assumed that the load is primarily tensile (Mode I) and converted the J-integral to an equivalent stress intensity factor K_I to allow for comparison with literature values for the fracture toughness K_{Ic} .



Figure 1: RPV model used in the finite element simulations.

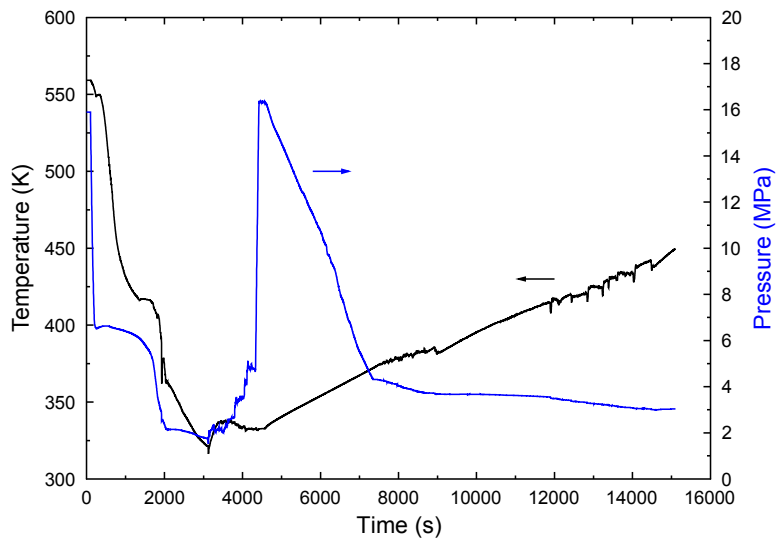


Figure 2: Temperature and pressure history in a RPV applied as boundary conditions at the inner surface of the RPV model.

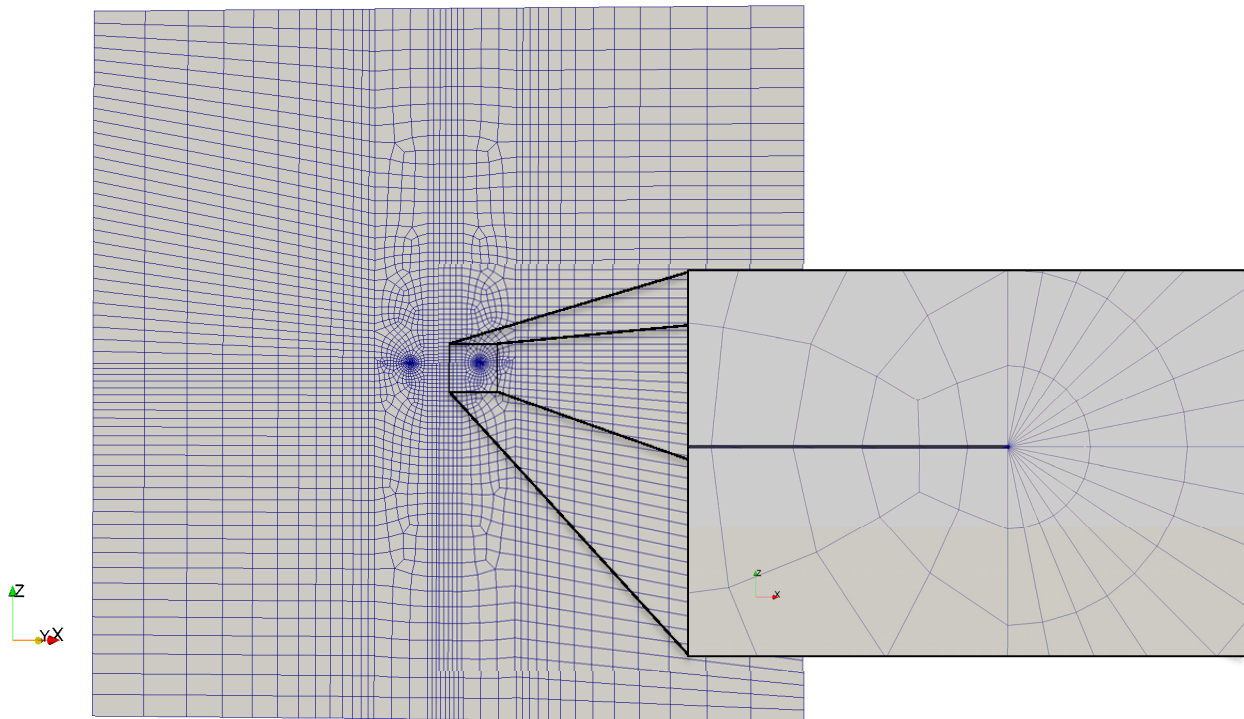


Figure 3: Cross section of the crack submodel mesh with a close-up of the blunt crack tip.

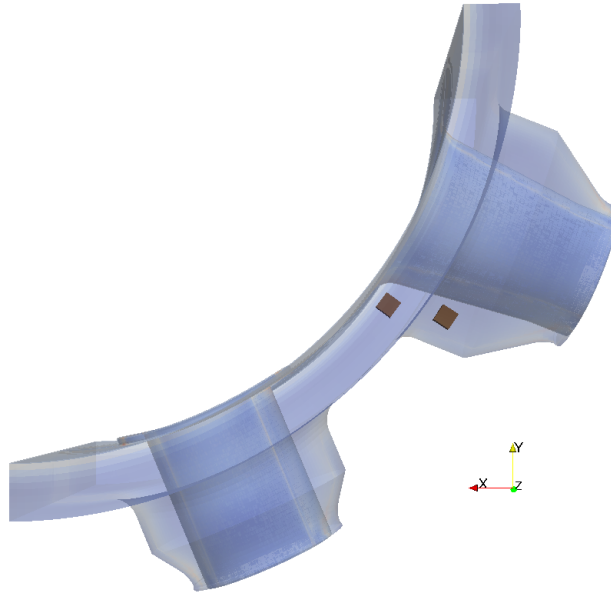


Figure 4: Locations of the two sub-models (brown cubes) in the RPV.

4. RESULTS AND DISCUSSION OF APPLIED K_I DURING PTS TRANSIENT

In Fig. 5 we plot the stress along an axially oriented line in the wall between the nozzles and through the residual stress region. The $z = 0$ level is at the upper head flange and the centers of the nozzles are at $z = 2170$ mm. The two levels of residual stress have an additional hydrostatic tensile stress of about 80 MPa and 160 MPa respectively compared to the base level at the location of the submodels.

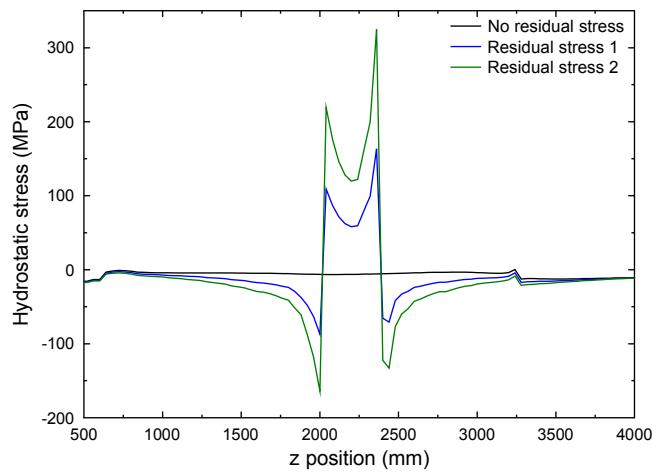


Figure 5: Hydrostatic stress along an axially oriented line through the residual stress region.

The stress intensity factors K_I along the crack fronts of the three different residual stress cases are plotted in Fig. 6 for the submodel in the wall and in Fig. 7 for the submodel in the nozzle. The angle 0° is at the position along the crack front farthest away from the inner wall. The presence of a residual stress clearly increases the K_I at the crack tip and more than doubles the values of the cracks with no residual stress.

In Fig. 8, data from the node at position 90° along the crack tip is plotted as a function of time. The peak in K_I coincides with the peak in coolant pressure (Fig. 2). The shape of the curve and height of the peaks is very similar for the two residual stresses and with no residual stress, but there is a shift to higher values due to the tensile residual stress. In Fig. 8(b) we see that the no residual stress curve has a similar but inverted shape compared to the other two cases between about 500 s and 4000 s. This is due to the stress on the crack being compressive during this time.

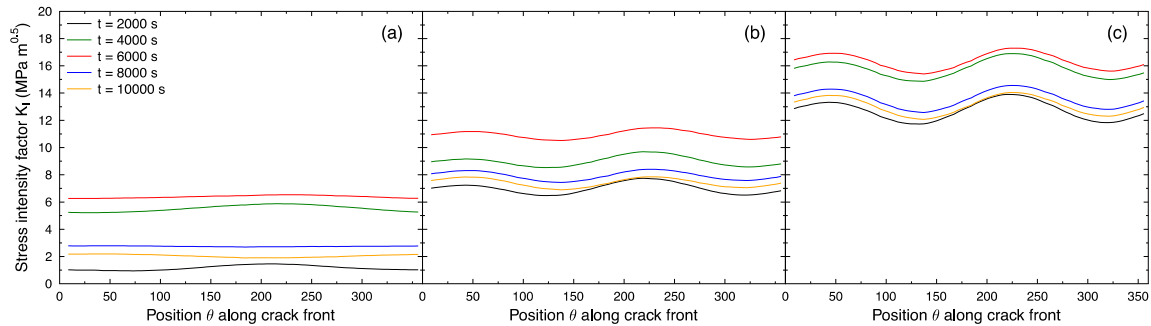


Figure 6: Stress intensity factors K_I along the crack front of the sub-model in the wall of the nozzle region with residual stress values of (a) 0 MPa, (b) 80 MPa, and (c) 160 MPa.

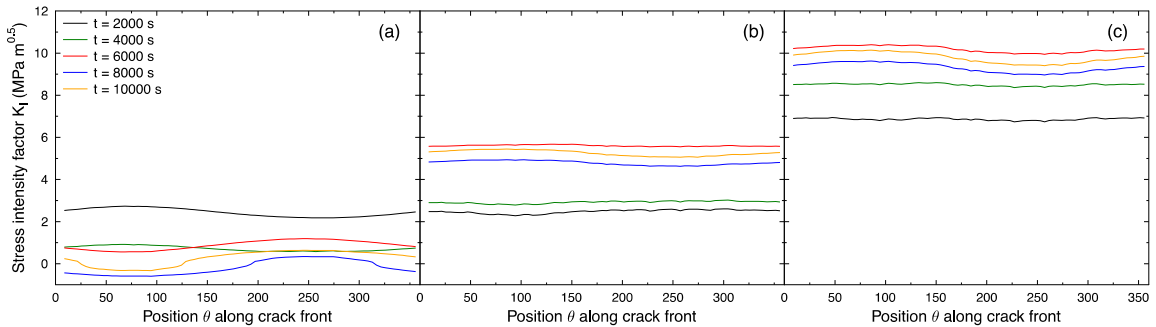


Figure 7: Stress intensity factors K_I along the crack front of the sub-model in the nozzle with residual stress values of (a) 0 MPa, (b) 80 MPa, and (c) 160 MPa.

All told, this analysis indicates that the level of the applied stress intensity factor during a PTS transient for flaws in the Nozzle region of the RPV should remain below $20 \text{ MPa}\sqrt{\text{m}}$, provided that the residual azimuthal tensile stress is less than 160 MPa. Further analysis will be performed to further evaluate more characteristic flaw distributions, as well as larger values of residual stress; however, the initial results do indicate that the applied stress intensity factors during the analyzed transient, as well as the very limited value of the transition temperature shift, are insufficient to cause any significant concern of crack initiation and through wall failure in the nozzle region.

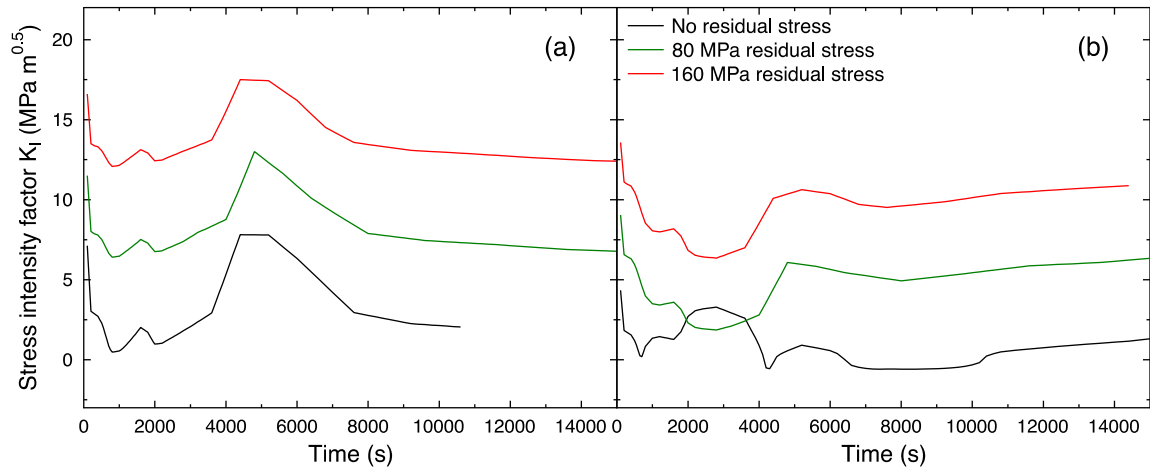


Figure 8: Stress intensity factor at position 90 as a function of time for (a) the sub-model in the nozzle wall and (b) the sub-model in the nozzle.

5. SUMMARY AND CONCLUSION

We studied the applied stress intensity factors along the crack front of embedded cracks in the nozzle region of an RPV during a simulated PTS transient using GRIZZLY. By prescribing a volume of higher thermal conductivity in the nozzle region and postulating flaws in that region, the effect of residual stresses in the RPV wall was simulated. Analysis of the stress distribution around the cracks enabled calculation of the applied stress intensity factor, K_I , and showed that the presence of a tensile residual stress increased K_I at the crack tip significantly with a nearly constant offset compared to the same crack without residual stress. However, for the level of residual stresses analyzed (maximum value of 160 MPa), the applied stress intensity factor was always below $20 \text{ MPa}\sqrt{\text{m}}$ for this PTS transient. Further analysis will be performed to further evaluate more characteristic flaw distributions, as well as larger values of residual stress; however, the initial results do indicate that the applied stress intensity factors, as well as the very limited value of the transition temperature shift, are insufficient to cause any significant concern of crack initiation and through wall failure in the RPV nozzle region.

5. REFERENCES

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