RES Addendum to Argonne National Laboratory (ANL) 13/08

Background:

All Ni-based alloys that utilize grain refinement as the predominant strengthening mechanism are expected to fail by plastic collapse when exposed to increasing pressure. No other failure mechanism has been observed during extensive laboratory testing and field experience. The ductile fracture mode is controlled by the tensile properties of the material.

UNR NRR-2012-0010 “User Need Request on Steam Generator Tube Inspection and Integrity Issues,” (ML12208A126) included a task to assess the application of ANL models for the structural / leakage integrity of steam generator (SG) tubes manufactured from mill-annealed Alloy 600 (600MA) to tubes manufactured from thermally-treated Alloy 690 (690TT). Based on best-available information, as of 2013, ANL considered the existing models are adequate to predict the performance of 690TT tubes. This has been documented in the ANL 13/08 lab report with recommendations for further testing. NRC RES has reassessed the current state of knowledge in 2021 to decide how best to proceed.

This staff Addendum is written with the intent to update the ANL 13/08 report assessment of structural integrity models for pressurized loading conditions, and is compared with the available test results. Measured test results from NUREG/CR-6789 [A-1] is used as the baseline to show how well the ANL models predict the leak/burst pressure for tubes manufactured from 600MA. Two recently published reports [A-2,A-3] where 690TT tubes were tested are used for comparison.

Assessment:

There is no need for an update to the majority of the ANL lab report to summarize the difference between 600MA and 690TT tubes. The manufacturing process is nearly identical for the two materials except for the final heat treatment, and those effects of heat treatment are reflected in the tensile properties. Table 1 in ANL 13/08 shows that the yield strength (YS) and ultimate tensile strength (UTS) of 690TT is essentially the same as that of 600MA, both at room temperature and at 650°F.

The only notable exception is related to Section 4.1.1 in ANL 13/08 that describes the ligament rupture and burst pressures during normal operation and accident conditions. In 2013, there were no available test results from 690TT that could be applied to the ANL structural integrity model. At this time, there are two notable references that allow direct comparisons to similar test results from the two materials. Ref. [A-1] represents a baseline for 600MA. Ref. [A-2] includes data for 690TT tubes for axial flaws with different lengths and depths. Ref. [A-3] proposed revised burst pressure estimation equations for SG tubes with single or multiple axial surface cracks and demonstrates the improved capability to predict the structural integrity by comparison to measured test results from flawed 690TT tubes.

The comparison between measured and predicted burst pressure for partial through-wall axial flaws is shown in Figure A-1 below. The agreement between prediction and measurement for 600MA is quite good. For 690TT, the comparison demonstrates a consistent, conservative bias where the measured values are slightly higher than predicted.

The slight differences found between measured and predicted failure pressures for 690TT tubes should not represent a problem for the application of the ANL models. The predicted results are conservative with respect to the measured values. Additional testing is not expected to fundamentally change the relationship.

A modified local plastic collapse model was proposed in Ref. [A-3] that did reduce the margin between predicted and measured test results for some flaw sizes. However, the improved predictions from the modified model were not consistent across the range of flaws tested. Another simple alternative to improve the accuracy of the predictions could be to adjust the definition of flow stress; a value of k (average of the YS and UTS) = 0.55 is used by the ANL models, which is a generally accepted as a conservative value. In the latest version of the Electric Power Research Institute (EPRI) handbook [A-4] for pop-thru of an axial flaw, k is assumed to be 0.6. The higher k value was justified based on comparison to a large database of testing that included laboratory and service-induced flaws.

In conclusion, the relationship uncertainty associated with the ANL models of the structural integrity should not be affected by the grade of material used to manufacture the tubing. Any material-specific uncertainties would be reflected by the uncertainties associated with the tensile properties for a specific grade.

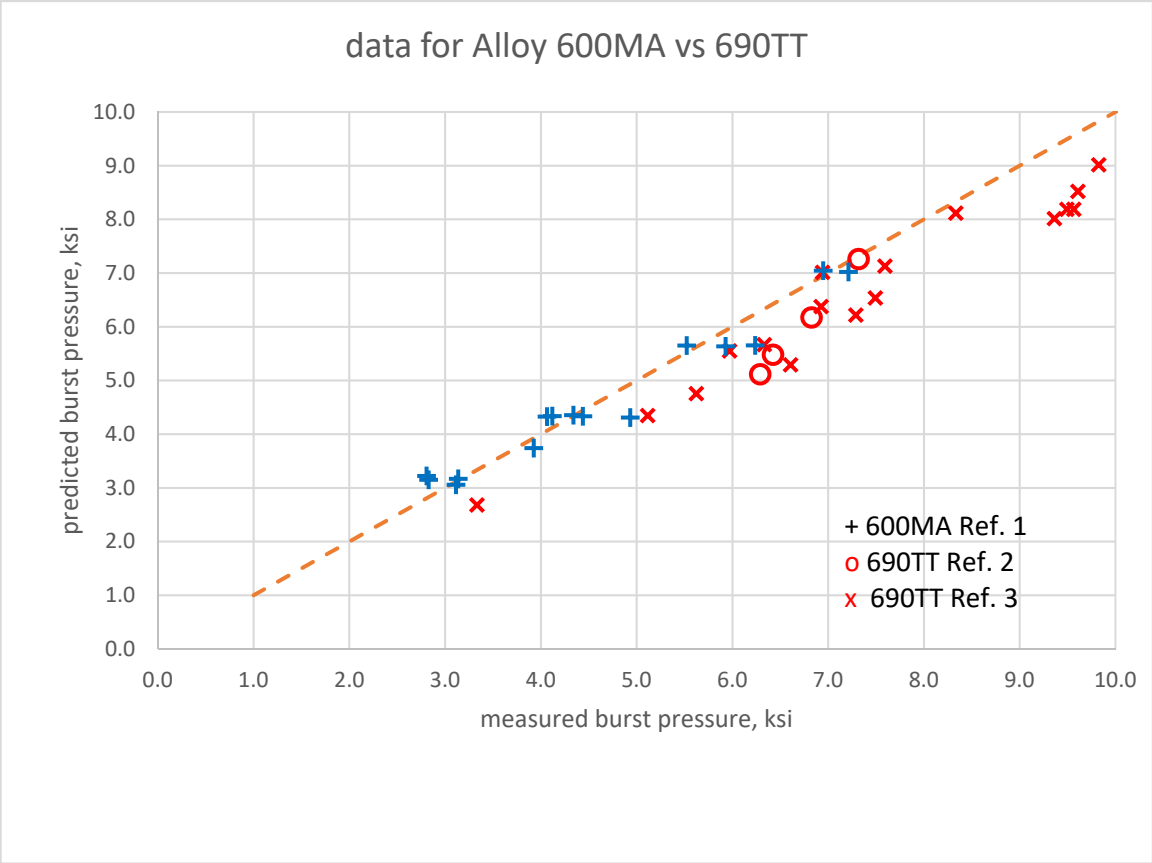

Figure A-1. Comparison of measured vs predicted burst pressures.

References

A-1. K. Kasza, S. Majumdar, **I.** Park, J. Franklin, NUREG/CR-6789, “Results from pressure and leak-rate testing of laboratory-degraded steam generator tubes”, November 2002.

A-2. K.H. Eom, J.W. Kim, Y.J. Kim, J.S. Kim, “Failure behavior of multiple-axial part-through-wall flaws in alloy 690TT steam generator tubes”, J Pressure Vessel Technology, vol. 138 (2) (2015) 021406.

A-3. M.W. Lee, J.S. Kim, Y.J. Kim, J.W. Kim, “Burst pressure estimation equations for steam generator tubes with multiple axial surface cracks”, Int. J. Pressure Vessel and Piping, vol. 158 (2017), pp 59-68.

A-4. Steam Generator Management Program: Steam Generator Degradation Specific Management Flaw Handbook, Revision 2. EPRI, Palo Alto, CA: 2015. 3002005426.