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Mr. Emmett Murphy
NRC-NRR
One White Flint
Rockville, MD

Dear Emmett:

Attached are my comments from the May 14, 2004 Steam Generator tube safety factor review meeting with industry. Call if you have any questions.

Regards,

Dr. Gery M. Wilkowski, P.E.
President
Engineering Mechanics Corporation of Columbus

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Review Comments on Industry Presentation on SG Tube Performance Evaluation Safety Factors

by

Dr. Gery M. Wilkowski, P.E.
Engineering Mechanics Corporation of Columbus
5/20/04

There were two technical points at the presentation where comments are provided. The first technical point was on recent results to evaluate the effect of bending moment on burst for a circumferential crack in a steam generator tube. The second technical point is on the safety factors for thermal stresses.

1. Safety Factor Evaluations on Bending Moment for Burst

The industry group presented some new experimental results that they developed in a very timely manner to address NRC comments. To ensure that I understood the presentations correctly, I would first like to summarize the results. Hence if I have any misunderstandings the industry group can correct them.

1.1. Summary of Recent Industry Experimental Efforts
In an effort to provide some additional information to the NRC, the industry group conducted a set of steam generator tube burst tests with an applied moment and then pressurized the tube with a circumferential crack to failure. The tests were done on 16.5" and 36" U-bends as well as on straight tube sections at room temperature. Through-wall cracks were used mostly with a 245-degree length and some supplemental tests with 180-degree through-wall cracks. The cracks were sealed using a past procedure (plastic tubing with a brass foil was inserted in the SG tube).

The strength of the SG tube was checked in a simple burst test, which agreed with the CMTR information. They stated the strength of Alloy 600 and 690 tubes was the same, but I could not find a viewgraph that said which tube material they actually tested. I'm guessing it was Alloy 690 tubing.

The service stresses were determined from several different vendor stress analysis reports to give an outer fiber bending stress of 50 ksi (elastically calculated). I'm guessing that this service stress is at a temperature somewhere between 600F and 550F. In the recent experiments, a dead-weight load at the apex of the U-bends was calculated to give a bending stresses of ~52 ksi at the start of the U-bend turn, where the circumferential crack was located[1]. For the straight tube

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[1] Strictly speaking the moment in the room temperature tests should have been scaled up to account for the higher strength of the Alloy 690 tubing at room temperature compared to the service transient temperature. Since failure is by the Net-Section Collapse (Hernalsteen) analysis, the test moment should have been increased by the ratio of the flow stresses at the two temperatures.

section tests, a weight was hung on the center of the span. The moment developed at the center of the span changes significantly depending if the ends are held fixed (or have some axial load) or are simply supported.

There were two different support conditions for the tube. One was a simple eyebolt connection, and the other was a tube sheet support plate. There was a difference in the burst pressures for different support conditions. The test results showed that the tube sheet support plate behaved like a pinned-joint connection.

The cracked-tube analysis presented was a limit-load analysis referred to as the Hernalsteen Equations and modification of the Hernalsteen equations. In actuality, these are just the Net-Section Collapse equations originally developed by Dave Broek in EPRI NP-192 (1976) for circumferential cracks in stainless steel BWR piping[2]. The original Net-Section Collapse equations were for combined pressure and bending, where the pressure load was considered an axial load-controlled force. Note, however, that the Net-Section-Collapse analysis accounts for an induced-bending effect from the pressure loads at the crack plane. The assumption is that the applied bending moments do not restrict these induced moments, i.e., the rotation from the pressure-induced bending at the crack plane is not restricted by the applied moments or rotations. Under dead-weight load like used in these SG tube tests, the pressure-induced moment should not be restricted. (In pipe tests with applied rotation at load points, this pressure-induced moment is affected.)

The logic in the evaluation of the experiments was that the Hernalsteen equations under predict the burst pressure since the moment applied near the cracked section is ~50% of the moment computed for an uncracked tube. For the U-bend tests, this moment reduction comes from the pinning behavior at the tube sheet.

1.2. Clarification Points Needed to Understand the Recent Results Better
The first aspect that needs clarification is how the boundary conditions in the actual steam generator stress analysis (the 50 ksi outer fiber bending stress) compares to the experimental boundary conditions. If the steam-generator stress-analysis boundary conditions are closer to the pinned condition, then perhaps the proposed correction on the moment from the experimental results should not be applied.

It is also important to understand the transient conditions that gave the 50-ksi stress in the steam generator analysis. There was no information about the actual steam generator transient event or stress analysis. For instance, if the transient loads were from a seismic loading, the oscillatory nature of the tubes moving back and forth in the tube-sheet holes may give substantially different boundary conditions than that from the static overload tests done. The gouging in the tube from the static pull of the dead-weight loads may not occur under seismic loading to give the pinned joint behavior.

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[2] Kanninen, M. F., Broek, D., Marschall, C. W., Rybicki, E. F., Sampath, S. G., Simonen, F. A., and Wilkowski, G. M., "Mechanical Fracture Predictions for Sensitized Stainless Steel Piping with Circumferential Cracks," EPRI Report NP-192, September 1976.

It was mentioned during the industry presentation that the rotation of the tube at the crack plane might affect the bending moments. The 245-degree circumferential crack certainly is a worst-case large crack, but it also is a case where the rotation at the crack plane is very large. As I mentioned at the meeting, it is possible to have a deep 360-degree surface crack that would fail at the same moment or axial force (from pressure) as the 245-degree through-wall crack. The 360-degree surface crack, however, would have a lot smaller amount of rotation at the crack plane. Hence a concern I have is whether the moment-reduction factor shown from the through-wall-cracked tube experiments is a properly bounding case.

Another point that needs clarification is how the moments were actually calculated in the experiments. In the experiments, a dead weight was attached to the apex of the U-bends. There are plots showing the applied loads versus vertical displacement. However, as shown in one of the photographs, as the apex of the tube displaces downward (vertically) it also moves horizontally toward the crack. Hence effectively the moment-arm length is changing. The change in the moment-arm length should be accounted for in reducing the experimental data. Therefore the moments in the experimental results may be lower with this moment-arm correction.

2. Safety Factor for Thermal Stresses

Thermal stresses for the steam generator tubes, especially once-through generators may become more important if there is a large circumferential crack. As noted in my earlier letter report, there are experimental results that show if the circumferential crack is large enough so that the failure would be below the yield strength of the uncracked tube, then the thermal expansion stresses will have enough elastic follow-up to behave as a primary stress. Hence, technically the thermal stress should have the same safety factor as the primary stress. Attachment A is a set of viewgraphs from a presentation I made at the 16th SMiRT conference (August 2001) on the importance of secondary stresses in pipe systems with circumferential cracks. I also presented these results at the May 2004 Section XI Working Group on Pipe Flaw Evaluations. I suggested to the committee that they make a similar re-evaluation of the importance of secondary stresses.

Also as noted in my earlier letter report, the original Code writers included a cautionary note in ASME B31.1 and Section III of the ASME B&PV Code for class 2 and 3 piping. This cautionary paragraph (i.e., NC-3672.6) is referred to as "Local Overstrain", and states that if a cross section of the pipe is weaker from geometric or strength considerations, then these locally higher stresses sections will experience a further strain concentration from elastic follow-up. If the compliance of the pipe system is large compared to the local compliance of the cracked section (as is typical of a surface-cracked pipe system), then this elastic follow-up doesn't allow for unloading the plastically strained weak section and essentially makes the secondary stress behave as a primary stress at that location.

Unfortunately, this "Local Overstrain" warning is not in Section III for Class 1 piping. Mr. Keith Wichman just brought that fact to the attention to the main Section III committee, and Mr. Don Landers has an action item to look into adding this same warning for Class I piping.

Hence, I recommend that for the steam generator tube performance-based criteria, that if the flaw of interest is large enough to failure below yield of the uncracked tubing, then the thermal stress should have the same safety factor as a primary stress for that crack. The difficult part is to determine when to transition the safety factor back from a primary stress to a secondary stress, or possibly to an even lower category. For instance, residual stresses in girth welds are important for subcritical crack growth, but effectively have no contribution to elastic-plastic or limit-load fracture. Hence for much smaller flaws, the thermal stresses could have a negligible effect on the SG tube fracture.

Given the simple geometry of the once through steam generator, it would be relatively easy to calculate the significance of the thermal stresses on fracture with a series of finite element analyses.