THREE MILE ISLAND UNIT 1 STEAM GENERATOR LEFM AND LOAD CHARACTERIZATION

TECHNICAL EVALUATION REPORT

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INTRODUCTION

In November 1981, primary to secondary side leaks were discovered in both of the once-through steam generators (OTSG) at Three Mile Island Unit 1 (TMI 1). Subsequent inspections and failure analysis performed by the utility and their consultants revealed widespread circumferential intergranular stress corrosion cracking (SCC) on the Inconel 600 tubes in the upper portions of both OTSG's.

Extensive utility investigations combined with laboratory investigations performed at Brookhaven National Laboratory (BNL) have confirmed that the integranular SCC resulted from the presence of both oxygen and metastable sulfur compounds in the TMI-1 coolant. Proper future control of coolant water chemistry should prevent the reoccurence of SCC.

Although the root cause of attack was established and can be corrected, the tubes in the OTSG experienced degradation. Thru wall cracks and part thru wall cracks exist in many of the tubes in the region of the upper tube sheet (UTS). To bring the OTSG to an operable condition extensive inspections to locate the defects and corrective actions to repair the system have been performed. The corrective actions consist of tube plugging and stabilization of tubes showing unacceptable defects and explosive forming of tubes showing defects in the UTS. The repaired and remaining tubes still exhibit detectable defects. To support the contention that these tubes were serviceable a detailed linear elastic fracture mechanics evaluation (LEFM) was performed to demonstrate that defects of permissible size are not susceptible to unstable failure.

The present technical evaluation report is based on the BNL review of GPUNC topical report 008, Rev. 3 (8/19/83), GPUNC technical design reports TDR-388, (5/11/83) and TDR-417 (9/19/83) and GPUNC consultant reports "Stress Intensity Factor and COD calculations" and "The Residual Crack Opening Displacements in Tubes and Pipes" by F. Erdogan (Lehigh). The purpose of the review was to determine if the proper loadings were considered in the LEFM studies and if these studies support the GPUNC contention that cracks of permissable size will not lead to unstable failure.

DISCUSSION

GPUNC topical report 008, Rev. 3 (8/19/83)"Assessment of TMI-1 Plant Safety for return to service after Steam Generator Repair", provides a summary description of the GPUNC studies and asserts that the unrepaired portions of the OTSG tubes will satisfy the design criteria for the life of the plant. The corrosion studies indicate that the cracking mechanism has been arrested and will not reactivate in low sulfur primary coolant water chemistry. The Analyses show that cracks below a minimum range of length and through wall thickness will not propagate to failure under the combined effects of flow induced vibration, thermal cycles, and mechanicl loads. In addition, any defects that are large enough to propagate thru wall and are not detected during the 100% ECT inspection will be detected by leakage monitoring programs during the test program.

The loads considered in the LEFM studies include those due to differential thermal expansion of the shell and tubes during cooldown, pressure, tube pretension and fluid induced vibration bending loads. Tube axial tensile load is greatest during cooldown but can vary from compression to tension during operation. In the LEFM analysis a load cycle with a peak tensile load of 1107 lbs. corresponding to a 100°F/hr cooldown, taken from the generic design basis document, was used to represent this low cycle load function. Detailed load determinations considering tube sheet flexibility, actual TMI-1 thermal cycles and measured tube preloads support the contention that the generic cooldown load cycle bounds the cooldown load cycle corresponding to the operating guideline limiting shell to tube temperature differential of 70°F maximum. The measured tube preload was obtained from TMI-1 tubes which had parted from the UTS and jumped down to a presumed tension free condition. The high cycle component of loading, simulating fluid induced vibrations, was taken to correspond identically with measured tube deflections at 97% full power in TMI-2.

The stability of the crack growth and the size of cracks after 40 years of plant operation were calculated using the EPRI developed computer code BIGIF. Since this code did not include in its element library a model to simulate the cracked steam generator tubes, the stress intensity (K) data necessary to characterize the cracks was provided as input. This data was developed by Prof. Erdogan of Lehigh University. Other parameters pertinant to the analysis include the crack growth rate (da/dn) and the threshold stress intensity factor (K_{th}). Conservative estimates for thse parameters were derived from compiled experimental data for Inconel 600. The BIGIF code was then used to predict the locus of initial crack sizes that would exhibit stable crack growth over a period of 40 years. The predicted locus was well within the range of detection by ECT inspection and was used to define the size of permissible cracks.

A pertinant contention established by Crack Opening Displacement (COD) considerations was that a thru wall crack would result in detectable leakage. NSAC-EPRI and FAA developed the values of tube leak rates as a function of crack arc length with tubes subjected to 1107 lbs. and 500 lbs. tensile loads. This was done considering the linear and non-linear change in COD to predict the leakrate versus crack arc length. GPUN applied the NSAC method for predicting leakrate to other loads using comparative assumptions. The predicted minimum leakrate at cooldown for a single TMI-1 specific core tube with zero preload and a pre-critical thru wall crack was double the administrative limit of 6 GPH.

EVALUATION

Several elements entered into the LEFM analysis. These were the development of the loading function, definition of the input parameters, selection of the analysis method and implementation of the analysis. Considering each:

Loading function - the critical loads, those producing the maximum tensile state, were a combination of a generic cooldown thermal cycle and actual pressure and fluid induced vibration loads. The generic cooldown load was shown by detailed calculation to bound the cooldown load corresponding to the administrative limit cooldown rate. The pressures conform to actual system pressure extremes while the vibration loads are based on measured extremes for TMI-2.

Input Parameters - The material parameters were conservatively selected from available and applicable experimental data for inconel 600. The crack specific data (stress intensities) were developed by a recognized authority in the field.

Analysis Method - The BIGIF computer code is a recognized state of the art LEFM analysis method. The COD evaluations are extensions of acceptable NSAC-EPRI and FAA analyses.

Analysis Implementation - A developer of the BIGIF analysis method was engaged to guide the LEFM analysis. A recognized authority participated in the COD evaluations.

In summary the LEFM and COD analyses were performed in a professional fashion using state of the art methods, experimental data and the services of recognized consultants.

One oversight in the LEFM evaluation was the failure to perform a separate analysis to consider the effect of the residual stress generated by the explosive forming process. The stress state, as developed by GPUNC, varies from tension on the ID tube surface to yield in compression as the wall neutral axis is approached from the ID, to yield in tension as the neutral axis is crossed, to compression at the OD surface. This stress state exists at the juncture of the undeformed and deformed tube regions, two or eight inches above the lower surface of the upper tube sheet. If added to the state of stress produced by the LEFM loads the resultant stresses could acccelerate initial crack growth, impede radial growth and encourage circumferential growth as the crack tip enters the compression zone and finally accelerate radial growth as the crack tip enters the tensile yield zone. The crack charactization in this region will clearly differ from that predicted for the nominal tube, possible exhibiting greater arc extent at thru wall penetration. If this is true these transition regions may be susceptible to parting failure.

Another oversight by GPUNC is the lack of an investigation of the tubes which have experienced jump down. These tubes are assumed to be free of tensile preload and consequentially are more susceptible to the compressive loads associated with heat up than the nominal tubes. In particular design calculations by B&W indicate that a tube with 100 lbs. preload will experience a compressive load of 775 lbs. during normal heatup. A tube with no preload would then experience a compressive load of 875 lbs. However, a calculation by the GPUNC consultants MPR Associates indicates that the critical buckling load for the tubes is 779 lbs. Apparently tubes which have exhibited jump down experience compressive loads in excess of the buckling load and should be assumed to buckle. Since the loading is displacement induced these tubes will not fail but rather will develop transverse displacements (bowing) to accomodate that fraction of the loading above the critical value. GPUNC should address this condition to determine the associated tube stresses, the impact, if any, on the LEFM studies and the vibrational characteristics of these tubes. If the bowing or lateral displacements are not large the tube stresses will remain compressive throughout the cross section although exhibiting moment distributions. The tubes will exhibit lower natural frequencies than the nominal tube. However, the magnitude and significance of this difference is not known but felt to be minor. Lastly, at heat up, when the tubes are bowed, flow is low and little excitation of the tubes would be expected.

CONCLUSIONS

1. The LEFM and COD analyses were performed in a professional fashion using state of the art technology and the services of recognized authorities. The analyses are acceptable and support the GPUNC contentions concerning crack progagation and growth.

2. The residual stress fields in the formed tubes were not considered in the LEFM analyses. Since these stresses could alter crack propagation the developed crack characterization may not apply to these zones (i.e., locus of crack size for 40 year life). However early thru wall cracking in these zones should be detected by the leakage monitoring program. Additionally, a tube parted in this zone should remain trapped in the upper tube sheet minimizing the consequences of failure.

3. Tubes which have experienced jump down may exhibit bowing deflections during heat up. These deflections will induce bending stresses in and alter the vibrational characteristics of these tubes. Owing to the high axial compression, it is anticipated that the stresses in the bowed tubes will remain compressive and therefore this loading should not accelerate crack propagation. Considering vibrations, the bowed tubes should exhibit lower natural frequencies than the nominal tubes. However, since the fluid flow and consequentially the excitation force are minimal during heat up, the fluid induced vibrations of these tubes should be below that exhibited by the nominal tubes at full power.