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NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, D. C. 20555

March 7, 1988

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MEMORANDUM FOR: David Ward

FROM: FOR Ivan Catton

SUBJECT: NORTH ANNA SG TUBE VIBRATION ANALYSIS

REFERENCES:

1. H. J. Connors, Jr., "Fluidelastic Vibration of Tube Arrays Excited by Cross Flow," Flow Induced Vibration in Heat Exchangers," ASME, New York, 1970

2. M. J. Pettigrew, J. H. Tromp, and M. Mastorakos, "Vibration of Tube Bundles Subjected to Two-Phase Cross-Flow," Symposium on Flow-Induced Vibrations, Vol. 2, Vibration of Arrays of Cylinders in Cross-Flow, M. P. Paidoussis, ed., ASME, New York, pp 251-268, December 1984

3. F. Axisa, B. Villard, R. J. Gibert, and M.A. Boheas, "Vibration of Tube Bundles Subject to Steam-Water Cross Flow: A Comparative Study of Square and Triangular Pitch Arrays," Proceedings of the Eighth SMIRT Conference, Brussels, August 1985

GENERAL COMMENTS

Westinghouse believes that the North Anna steam generator tube rupture was the result of high cycle fatigue failure. In that the usual thermal hydraulic calculations do not yield cyclic stresses of sufficient amplitude to cause fatigue failure, they argue that fluidelastic instabilities occur as well as the usual vortex shedding and turbulent pressure oscillations. It is clear from the papers cited and reviewed below that if fluidelastic instabilities occur, the vibration amplitudes will be of sufficient amplitude to cause fatigue failure. The question is whether or not their arguments that such an instability occurred are valid. Following the review of the papers cited by Westinghouse, I will address the question.

DOCUMENT REVIEW

In response to our request for information, Westinghouse sent the above three papers to Paul Boehnert. The three papers deal with mechanisms for inducing tube vibration in tubes where cross flow exists. The three papers deal only with flow normal to the tube axis. A summary of what the three papers contain is given below. In my view, the North Anna problem is not one of fluidelastic instability as claimed, because such an instability leads to very large amplitude vibrations straight away and they should have become apparent much earlier in the life of the steam generator. Further, as noted by the authors of the three papers, our present understanding is limited to flows being normal to the tubes. Little is known about steam generator geometries where the flow may take on almost any angle relative to the flow from normal to parallel.

Connors (Ref. 1), studied the tube vibration excitation mechanisms driven by cross flow. He developed a stability criterion for predicting the onset of large amplitude vibrations in single and multiple arrays that takes into account the interaction between the moving tube and the fluid flow. His stability criterion was then verified by dynamic stability tests on flexibly mounted tubes. The experiments were carried out in a 30 HP open circuit wind tunnel with an 8x8 inch test section. The tubes used were designed to have resonant frequencies in the 10-40 Hz or 200 Hz ranges. The tubes were 8 inches long and one inch in diameter. The experiment was conducted with both single and multiple row tube configurations. Connors notes that there are three primary mechanisms causing flow-induced vibration of tube arrays: vortex shedding, turbulence, and fluid elastic excitation. Vortex shedding results in an alternating force as the vortices are shed first from one side of the tube then the other and is only a problem when the departure frequency is approximately equal to the tube natural frequency. For a single tube, the phenomena is well understood. Unfortunately, this is not the case for multiple tubes where the vortex shedding frequency (sometimes called the Strouhal frequency) is a strong function of the tube spacing and array configuration. Turbulent pressure fluctuations occurring in the wake of a cylinder or carried to a cylinder from an upstream disturbance can be a potent mechanism for tube excitation. Turbulence will induce vibration in tubes at all flow speeds - although the amplitude will be small at low velocities. Again, the single tube is well understood, with closely packed tube arrays being an area for research.

Fluid elastic excitation occurs as a result of variations in the lift and drag coefficients as the angle of attack changes. The angle of attack changes as a direct result of the vibrational movement of the tube. As a result, one can see that the vibrations are clearly self excited. In an array of circular tubes, the momentary displacement of one tube effects its neighbors. It is this mechanism that is characterized by a threshold velocity. Connors argues that tubes in single and multi-row arrays experience large amplitude whirling vibrations when the flow velocity exceeds some critical value. These vibrations occur at the tube's natural frequency causing failure in service. They can only be explained in terms of fluid elastic excitation. The complexities described by Connors needs to be kept in mind when one tries to use this work in an assessment of steam generator tube vibration. Connors' experiment used air as the working fluid which could give results very different from the case of steam and water mixtures. The tube geometries were also different.

Pettigrew, et. al. (Ref 2), presented the results of their experiments on two-phase flow across normal triangular and normal square tube arrays with a pitch to diameter ratio of 1.47. The two-phase flow working fluid was air-water, based on the argument that steam-water would be "softer" and thus conservative in establishing vibration potential. This conjecture seems to be contradicted by the French work with steam and water as described below. Their results include measurements of damping, hydrodynamic mass, fluid-elastic instability, and random turbulence excitation.

The experimental apparatus by Pettigrew et al was capable of mass fluxes from 0 to 1000 Kg/s/m**2, steam quality from 0 to 40%, and void fractions from 0 to 97%. The work reported is apparently a small part of their complete program where different tubes, different pitch to diameter, and other geometric variations will be investigated. Their objectives are to understand and formulate flow-induced vibration excitation mechanisms in two-phase flow. As is usually done, they considered three excitation mechanisms: (1) fluidelastic instability, (2) periodic wake or vortex shedding, and (3) vibration response to random turbulent pressure fluctuations. It was found that periodic wake shedding, or, as defined above, vortex shedding, is only significant at very low void fractions.

They found that vibration response is generally greater in the flow direction (drag) than in the normal direction (lift) except near the fluidelastic instability threshold when the opposite is usually true. They conjecture that fluid-elastic coupling may be greater in two-phase flow when the tubes vibrate in the cross flow direction (lift direction). Coupling between fluid forces and tube motion is required for fluid elastic instabilities.

The fluidelastic instability was found to be very similar to that found in single phase fluids. The critical gap velocity correlated with the expression given by Connors. For random turbulence excitation, the vibration amplitude was found to be an almost linear function of the mass flux below the fluidelastic instability onset. Large damping ratios up to 8% were measured at intermediate void fractions between 20% and 80%. The vibration behavior of the tube bundles was affected by the flow regime in two-phase cross flow.

Axisa, et. al. (Ref. 3), studied tube bundles subjected to steam water cross flows. They found that the dominant mechanism causing tube vibration was fluidelastic instability. Vortex shedding was found to be far less efficient in two-phase flows than in single phase flows such as were investigated by Connors. Turbulent pressure fluctuations at the tube walls were noted to lead to small amplitude vibration which results in long term fretting wear and fatigue. This work began as a result of the observation by C.E.N. Saclay and FRAMATOME that data concerning fluid induced vibration in two-phase flows were rather limited.

Axis, et. al., present results on flow induced vibration in square and triangular straight tube bundles with a pitch to diameter ratio of 1.44. Their data show that the tube vibration amplitude slowly increases with flow velocity up to some critical velocity that is a function of void fraction. The increase in amplitude seen upon reaching the critical velocity is precipitous. The critical velocity at which the steep increase in amplitude occurs is easily discerned from the data even though the graphs in the paper are on a very small scale. Above the threshold, the tube response is clearly due to fluidelastic instability. Motion of tubes in a region are clearly correlated indicating that the fluid is an active participant in the process. Below the critical velocity, the amplitude is a slowly increasing function of the cross flow. Here the driving force is the turbulent pressure fluctuations.

When one tries to discern the effect of void fraction, the process becomes more complicated. The experiments were conducted with mass qualities ranging from 0.06 up to 0.34. At the higher qualities, tube response increases less regularly with flow velocities. At the highest values Alexis, et. al., found some indication that vortex shedding was contributing to the tube motion. The onset of fluidelastic instabilities was, however, still dramatic and overwhelmed all other mechanisms that might drive tube vibration. After looking at the data, I find it hard to accept the explanations we were given at the Meeting regarding the North Anna steam generator tube problem. Fluid elastic instabilities seem to drive a catastrophic instability, whereas the turbulent pressure fluctuations seem to drive a more ordered process. The data in the paper is admittedly partial and, as a result, my observations are tentative.

Tube damping factors were also measured by Alexis, et. al. The damping measurements produced scattered results. The values were seen to depend on steam-water quality, flow velocity, direction of tube motion, and on the tube under consideration. It was not clear to the authors whether or not the scattered results were real, and a function of parameter variation that was not understood, or due to experimental uncertainty. The measured values ranged from 0.5%, in a normal triangular array at a quality of 0.34, to 3.4%, in a parallel triangular array at a quality of 0.059. Even so, the measured values were consistently less than those of Pettigrew, et. al. (Ref. 2).

CONCLUDING REMARKS

To determine whether or not fluidelastic instabilities occur in the upper regions of a U-tube steam generator, one must first establish the magnitude of the threshold velocity for the given geometry and flow characteristics. This was not done at the Subcommittee meeting nor is it done in the cited papers. The papers certainly point one in the right direction. The next step should be to do some experiments with prototypical geometries and flow conditions. In the interim, one could make the argument that it is only the cross flow that matters-making the cited papers useful for an analysis. There are reasons, however, to believe that this would be highly approximate.

Given that we are willing to accept that only the flow normal to the tubes is important, one must still calculate the void fraction and liquid and steam velocities through the tubes. This was done by Westinghouse using potential flow theory. Potential flow theory will yield velocities, but their values have no meaning for the problem at hand. More complicated calculations need to be done that treat two-phase flow through rod bundles with phase change. Part of the complexity is a result of the water wanting to flow laterally while the steam rises. This is a troublesome calculation for the best of our codes. As a result, it is my opinion that Westinghouse has not demonstrated that they know what caused the steam generator tube rupture.

In my view, a more likely cause of the problem is turbulent pressure fluctuations. These lead to fatigue of the tubes in a slow but sure manner. That past thermal hydraulic calculations do not yield forces that will drive the tubes hard enough, may be a result of not knowing how to do the calculations in the bend region of the tubes. Given the complex geometry and difficulties in calculating the flow magnitude, one could easily be off by a great deal in estimating the cycle fatigue. As shown by the disagreement in estimates of the damping between the second and third papers, knowing the damping characteristics of a given tube is doubtful. This is compounded by uncertainties in the effectiveness of the antivibration bars.

The Westinghouse cure for the problem is to reduce the recirculation rates in the steam generators. If one knew the threshold value for fluidelastic instabilities, and the cause was such instabilities, then the Westinghouse cure would be effective-providing the velocity through the tubes is below the threshold value. On the other hand, if the cause is turbulent pressure fluctuations, then the amplitude will, at most, be reduced linearly with recirculation reduction. To be helpful, a significant change in the recirculation ratio may be required.

I don't believe Westinghouse has convincingly explained the North Anna incident. On the other hand, their arguments about why one should not expect simultaneous rupture of many tubes seems reasonable. I do, however, expect that we will see more and more steam generator tube ruptures as more and more tubes reach their fatigue limits. An increasing frequency of steam generator tube ruptures is also a concern of the industry. The original calculations of potential flow vibrations were based on inadequate knowledge of the thermal hydraulics. It is not clear that we have the knowledge now. The sensitivity to vibration is a strong function of tube-to-tube and tube-to-shell clearances. In many cases, internal modifications have been made and their implications are unknown. Our ability to calculate the flow is very limited, due to the complex steam separation process taking place in the upper part of the tube bundle. The tube curvature and placement of antivibration bars only complicates the problem. Our knowledge of the tube damping coefficients is very poor. It is the view of some that we cannot calculate it and, as you know, it has not been measured. It seems to me that this is an area where RES could very effectively contribute to the safety of nuclear power stations by implementing a program to address some of the areas where we are in ignorance.