ADAMS Package No. ML003781033

December 22, 2000

MEMORANDUM TO: Nilesh C. Chokshi, Chief
Materials Engineering Branch
Division of Engineering Technology
Office of Nuclear Regulatory Research

FROM: John H. Flack, Acting Chief **/RA/Original signed by Richard Lee for:**
Safety Margins and Systems Analysis Branch
Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research

SUBJECT: STEAM GENERATOR JET IMPINGEMENT CALCULATIONS

By memorandum dated February 10, 2000 from Farouk Eltawila to Edwin Hackett, SMSAB provided to you our preliminary analysis of the velocity of a steam jet that would be expected on a neighboring steam generator tube from a cracked tube during station blackout (SBO) conditions. Steam generator tube rupture during a severe accident (i.e., SBO) has been shown to be a potentially important risk contributor, because it is an event which results in fission product releases bypassing the containment boundary. SCDAP/RELAP5 calculations have been performed to estimate the temperatures of RCS components under SBO conditions to estimate the probability of a temperature-induced tube rupture. The potential failure mechanism reviewed in this work involves a jet of superheated steam and aerosols flowing out of a through-wall crack in a tube which causes ablation of an adjacent tube by jet impingement. Accordingly, your staff has requested an estimate of the velocity of the steam jet from a cracked tube impinging on an adjacent tube to assess the importance of this potential failure mechanism.

As was pointed out in the February 10, 2000, memorandum the calculations were preformed for the accident scenarios of greatest interest, the primary side pressure is at the relief valve set point and the secondary side pressure is atmospheric. Under these conditions, the secondary side to primary side pressure ratio is well below the critical pressure ratio, and the flow through the crack is choked.

The velocity calculations that were done in this earlier work were based on incompressible flow and therefore, they assume that the jet would not be further expanded due to the density decrease between the critical pressure and the atmospheric pressure. Additionally, the effects of shock waves were not considered. As was pointed out in this work, earlier NRR analysis assumed that supersonic velocities were reached in the fluid after leaving the crack based on an assumption of flow through a fixed converging diverging nozzle and because of this assumption developed high estimates of the fluid velocities. Also, in the earlier work it was identified that more detailed numerical methods might produce more accurate estimates of the jet velocity.

Subsequently, your staff requested a more detailed analyses of this phenomenon be provided, as well as an estimate of the velocity of the entrained aerosols. To provide more information on this potential failure mode, SMSAB contracted for a two dimensional Computation Fluid Dynamic (CFD) analysis to be carried out. The contractor reports from this analysis are attached.

The assessment included several studies to assess the capability of the CFD code (NPARC, a NASA/Air Force funded code for supersonic fluid flow calculations) for this application. In these studies (report one sections 3.1 and report two sections 2.1, 2.2) the code performed as expected. The analysis investigated several different steam generator configurations, including: a steam generator with 7/8 inch diameter tubes with a 0.4 inch spacing in a rectangular grid, typical of type 51 Westinghouse steam generators, a steam generator with 3/4 inch diameter tubes with a .3 inch spacing in a rectangular grid typical of type D Westinghouse steam generators, and a steam generator with 7/8 inch diameter tubes with a .25 inch spacing in a triangular grid typical of CE steam generators.

In addition to the base case (type 51 geometry, temperature equal to 1175 K, tube pressure equal to16 MPa and a crack width of 0.5mm) calculation, several sensitivity studies were included looking at the effects of pressure (report one section 3.2), temperature and crack size (report 2 section 4).

Upon exiting the crack the jet expands and the velocity and Mach number increases. The adjacent tube (target) acts as a bluff body and turns the flow, while forming a detached standing shock-wave. The position and strength of the shock-wave depend on the primary side pressure and crack size. Although the fluid velocity before the shocks are very high, after passing through the shock-wave the fluid velocity is low. As can be seen in the attached reports as the fluid expands the pressure drops rapidly and the velocity increases. As the fluid approaches the adjacent tube and goes thought the standing shock-wave the velocity decreases and the pressure rises. At the adjacent tube the velocity has dropped to 200 m/s on the 15^{o} line, and nearly zero on the line of symmetry at a pressure of 0.5 MPa.

As a result of this standing shock-wave the fluid flow moves quickly to the space between the adjacent tube and its next neighbor tube. The space between will act as a nozzle, allowing the flow to expand further. The jet will entrain a significant amount of ambient fluid as it expands. The jet will them form an another standing shock-wave in-front the next tube. This will continue until the fluid has loss enough energy that a shock-wave will not be formed. As the fluid expands and entrains additional fluid the energy available to cause tube failure will fall off rapidly. (In this case the velocities can be much higher, up to the sonic speed of steam at this temperature, approximately 630 M/s, but the density of the steam and flow rate will be much lower. Additionally the density of any aerosols entrained in the steam will be much lower.)

As part of this work the contractor developed an analysis of the motion of the aerosol particles in the jet. It was assumed that the particles would accelerate to the fluid speed in the jet as they left the crack. Our analysis shows that particles of sizes that will be in the reactor coolant

system, will be fully entrained in the fluid and will also rapidly decelerate as they move through the standing shock-wave.

Although the velocity of the jet and particles carried by the jet do not appear to present a significant challenge to the integrity of the adjacent tube, there is the issue of the pressure front that forms near the adjacent tube. As the velocity of the expanding jet is reduced by its impingement on the adjacent tube, the kinetic energy of the fluid is converted to increased pressure. This pressure front is of some concern until one considers that the inside of all the tube also is at a highly elevated pressure. In the case of the highest pressure front in the contractor's second report, the pressure near the adjacent tube is 4.6 MPa, but the pressure inside that and all other tubes is 16 MPa. Of addition potential concern is the effect on the adjacent tube while the standing shock-wave is being first establish. This does not appear to be a problem in that the standing shock-wave will be formed very quickly, on the order of a few milliseconds.

Some additional possible sources of error for the work include:

1) The calculation used air as a working fluid instead of steam. The ratio of specific heats differs by about 5%, and the viscosity law is different, however these effects are expected to be small. The gas constant is much higher for steam than for air (60% higher). This will cause the velocities to be approximately 25% higher than stated in the attached reports.

2) Modeling and Numerical errors. The Baldwin-Lomax turbulence model used in this analysis is known to over predict the spreading rates of jets by perhaps 10-20%. This will have the effect of under predicting the velocities in the present calculation. Numerical dissipation, especially near the shock wave will tend to increase the spreading rates of the jet, resulting in under prediction of velocities.

3) Perfect gas assumption. Within the range of pressures and temperatures seen in this analysis the compressibility factor is between .95 and 1.0, therefore no significant errors are expected. Notice, however, that during the jet expansion temperatures can fall to below the 0^{o} C. However the steam will spend only a few microsecond in this region and it is believed that the steam will not condense but become supersaturated, in effect delaying the formation of droplets. This phenomenon is common in the diverging portions of supersonic nozzles.

Additional discussion of possible sources of error or uncertainties can be found in the attached contractor reports. The a detailed look at flow streamline (reference figure 10 of the second report) shows that close to the target tube the maximum velocity is approximately 200 m/s. Given the possible errors discussed above we recommend that you use a value of 300 m/s as the reference velocity for you experimental work.

Attachments: As stated

cc: w/o att.:
M. Mayfield, RES/DET
F. Eltawila, RES/DSARE

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