July 09, 2002

MEMORANDUM TO: Jack R. Strosnider, Jr., Deputy Director
Office of Nuclear Regulatory Research

FROM: Michael E. Mayfield, Director **/RA/**
Division of Engineering Technology
Office of Nuclear Regulation Research

SUBJECT: CLOSURE OF STEAM GENERATOR ACTION PLAN ITEMS 3.2 AND 3.6.

The purpose of this memorandum is to record the completion of two task milestones in the Steam Generator Action Plan that are associated with the Steam Generator (SG) Differing Professional Opinion (DPO). The first task is item 3.2, entitled, “Confirm that damage progression via jet cutting of adjacent tubes is of low enough probability that it can be neglected in accident analysis,” which was completed December 31, 2001. This task includes the following specific subtasks: a) Complete tests of jet impingement under MSLB conditions; b) Conduct long duration tests of jet impingement under severe accident conditions; and c) Document results from tasks 3.2a and 3.2b.

Task 3.2 included an analytical evaluation of crack-opening areas and leak rates of superheated steam through flaws in steam generator tubes and erosion of neighboring tubes due to jet impingement of superheated steam with entrained particles from core debris created during severe accidents. An analytical model for calculating crack-opening area as a function of time and temperature was validated with tests on tubes with machined flaws. A three-dimensional computational fluid dynamics (CDF) code was used to calculate the jet velocity impinging on neighboring tubes as a function of tube spacing and crack-opening area. Erosion tests were conducted in a high-temperature, high velocity erosion rig at the University of Cincinnati, using micron-sized nickel and aluminum oxide particles mixed in with high-temperature gas from a burner. The erosion results, together with analytical models, were used to estimate the erosive effects of superheated steam with entrained aerosols from the core during severe accidents.

In summary, the erosion data must be coupled with the results of the CFD analyses of the jet behavior to determine the effect of thinning of the tubes. The CFD analyses show that only the largest aerosol particles would be expected to strike the tube and that the impact velocity would be $\approx$2 m/s. Even with the more conservative assumption that the impact velocity is $\approx$ 200 m/s, the erosion data for Alloy 600 taken under conservative conditions related to the size and hardness of particles in the aerosol, together with a conservative estimate of the mass flux, suggests that the maximum wall thinning rate will be <2 mil/h.

Even after a crack had opened by creep at high temperatures, failure of an adjacent tube by jet impingement would take >10 h. However, once the system has reached these high temperatures, failure of some primary system component, including unflawed steam generator tubes, by creep would be expected to occur in <1 h. Thus, jet impingement is very unlikely to play a significant role. In a memorandum dated October 18, 2001, from George E. Apostolakis, Chairman, ACRS, to the Honorable Richard A. Meserve, Chairman, U.S. Nuclear Regulatory Commission, Subject: NRC Action Plan to Address the Differing Professional Opinion Issues on Steam Generator Tube Integrity, the Advisory Committee on Reactor Safeguards (ACRS) concluded that, “Results of the research on the effects of jet impingement on adjacent tubes have shown that the probability of damage progression is low enough that it can be neglected in the accident analyses.”

The detailed results of this task are documented in NUREG/CR-6756, “Analysis of Potential for Jet-Impingement Erosion from Leaking Steam Generator Tubes during Severe Accidents,” completed in December 2001, and printed in May 2002, which is attached to this memorandum.

Fluid jets from flawed SG tubes could produce damage in adjacent tubes through two basic erosion damage mechanisms, droplet impact and cavitation. In the case of jets comprised of water droplets, the impacts of the droplets give rise to fluctuating stresses in the target, which produce fatigue damage. In the case of cavitation, bubbles form in the liquid stream and then collapse on impact, again producing fluctuating stresses and fatigue in the target. Tests that provide a conservative simulation of a steam line break have been conducted to determine the susceptibility of steam generator tubes to erosive damage from impacting jets of superheated steam leaking from adjacent tubes.

The tests show that impact erosion depth varies with water temperature. The peak erosion rates occur for subcooling in the cold leg side of the steam generator, where cracking is much less likely to occur. Failure propagation by jet erosion is most likely in areas where the erosion rates are high combined with the presence of cracks. Erosion rates are much lower for conditions more typical of the hot leg side of the steam generator. However, even in the case of the cold leg where the erosion rates are the highest, the likelihood of failure propagation by jet erosion appears to be very low.

The detailed results of this study are documented in NUREG/CR-6774, “Validation of Failure and Leak-Rate Correlations for Stress Corrosion Cracks in Steam Generator Tubes,” completed in December 2001 and published in May 2002, which is attached to this memorandum.

The second task was Item 3.6, “To address an ACRS report conclusion that improvements can be made over the current use of a constant probability of detection (POD) for flaws in SG tubes, RES has recently completed an eddy current round robin inspection exercise on a SG mock-up as part of NRC's research to independently evaluate and quantify the inservice inspection reliability for SG tubes. This research has produced results that relate the POD to crack size, voltage, and other flaw severity parameters for stress corrosion cracks at different tube locations using industry qualified teams and procedures. Complete analysis of research results and preparation of a topical report to document the results,” has been completed.

This report presents an independent assessment of SG inspection reliability that was developed through a nondestructive evaluation round-robin on a steam generator mock-up at Argonne National Laboratory (ANL). The purpose of the round-robin was to assess the current state of

SG in-service inspection reliability and determine the POD as a function of flaw size or severity. Eleven teams participated in analyzing bobbin and rotating coil mock-up data collected by qualified industry personnel. The mock-up contains hundreds of cracks and simulations of artifacts such as corrosion deposits and tube support plates that make detection and characterization of cracks more difficult in operating SGs than in most laboratory situations. An expert Task Group from industry, ANL, and the NRC have reviewed the signals from the laboratory grown cracks used in the mock-up to ensure that they provide reasonable simulations of those obtained in the field. The number of tubes inspected and the number of teams participating in the round-robin are intended to provide better statistical data on POD than is currently available in EPRI qualification programs.

The conclusion from the analysis of the round-robin results is that good POD can be achieved for deep flaws when commercial techniques are used in a similar manner to that of the round-robin exercise. The level of success in detection of stress corrosion cracks did vary with flaw location. Estimates of maximum depth from eddy current crack profiles and false call rates were used to establish POD as a function of crack depth and m_p for cracks at different locations. POD was also evaluated as a function of voltage for ODSCC at the TSP. The term m_p is a stress multiplier that relates the stress in the ligament ahead of the crack to the stress in an unflawed tube under the same loading. Therefore, data is now available where POD varies as a function of flaw severity parameters.

No useful correlation was found between signal amplitude or phase and the maximum depth of the mock-up flaws. When PODs are considered as a function of m_p, it is found that in the TSP and free span regions the POD for cracks that would fail or leak under $3\Delta p$ internal pressure (corresponding to $m_p \approx 2.3$) is >95% even when accounting for uncertainties.

The results are documented in NUREG/CR-xxxx, “Evaluation of Eddy Current Reliability from Steam Generator Mock-Up Round-Robin,” completed November 2001. This report is currently in the process of being published.

Attachment: As stated

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