



UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION
RELATED TO AMENDMENT NO. 59 TO FACILITY OPERATING LICENSE NPF-9
AND AMENDMENT NO. 40 TO FACILITY OPERATING LICENSE NPF-17

DUKE POWER COMPANY

DOCKET NOS. 50-369 AND 50-370

McGUIRE NUCLEAR STATION, UNITS 1 AND 2

INTRODUCTION

By letters dated June 24, 1986, July 1 and 23, 1986, August 5, 13, and 18, 1986, Duke Power Company (the licensee for McGuire Nuclear Station, Units 1 and 2) requested a revision to the Technical Specifications (TS), Section 3/4.4.5., "Steam Generators." This revision seeks to change the plugging limit definition in TS 4.4.5.4.a. and would exclude from plugging those tubes with indications approximately 2 inches or greater below the top of the tubesheet provided that the top 2 inches of the tube within the tubesheet is not degraded. Westinghouse Reports WCAP 11224 and WCAP 11225 "Tubesheet Region Plugging Criterion," which are part of the TS amendment request, address the issue of plugging full depth hardroll expanded steam generator tubes which may have experienced degradation within the tubesheet area and provide the technical justification for the licensee's TS change request. WCAP 11225 is a nonproprietary version of WCAP 11224.

Existing plant TS tube plugging criteria apply throughout the tube length and do not take into account the reinforcing effect of the tubesheet on the external surface of the tube. The presence of the tubesheet will constrain the tube and will complement its integrity in that region by precluding tube deformation beyond its expanded outside diameter. The resistance to both tube rupture and tube collapse is significantly strengthened by the tubesheet. In addition, the proximity of the tubesheet significantly affects the leak behavior of throughwall tube cracks in this region, i.e., no significant leakage relative to plant technical specification allowables is to be expected. For these reasons, consideration of the use of an alternate criterion for plugging is justified.

The purpose for the development of the proposed criterion is to obviate the need to remove a tube from service (by plugging) due to detection of indications generally by eddy current testing (ECT) in a region extending over most of the length of tubing within the tubesheet. This safety evaluation assesses the integrity of the tube bundle with ECT indications on tubes within the tubesheet under normal operating and postulated accident conditions.

The proposed criterion identifies a distance, designated F^* and referred to as the F^* criterion, below the top of the tubesheet below which tube degradation of any extent does not necessitate plugging. The F^* criterion, according to the licensee's evaluation, provides the same level of protection for tube degradation in the tubesheet region as that afforded by Regulatory Guide (RG) 1.121 for degradation located outside the tubesheet region. Limitations on the use of the F^* criterion have also been discussed by the licensee.

EVALUATION

1. Westinghouse Reports WCAP 11224 and WCAP 11225

a. Engagement Distance Determination

The purpose of this development was the identification of a distance, designated F^* (and identified as the F^* criterion), below the top of the tubesheet below which tube degradation of any extent does not necessitate plugging. This criterion would be used in determining whether or not plugging of full depth hardroll expanded steam generator tubes is necessary for degradation which has been detected in that portion of the tube which is within the tubesheet.

Tube rupture in the conventional sense, i.e., characterized by an axially oriented "fishmouth" opening in the side of the tube, is not possible within the tubesheet. The reason for this is that the tubesheet material prevents the wall of the tube from expanding outward in response to the internally acting pressure forces. The forces which would normally act to cause crack extension are transmitted into the walls of the tubesheet, the same as for a nondegraded tube, instead of acting on the tube material. Thus, axially oriented linear indications, e.g., cracks, cannot lead to tube failure within the tubesheet and may be considered on the basis of leakage effects only.

Likewise, a circumferentially oriented tube rupture is resisted because the tube is not free to deform in bending within the tubesheet. When degradation has occurred such that the remaining tube cross sectional area does not present a uniform resistance to axial loading, bending stresses are developed which may significantly accelerate failure. When bending forces are resisted by lateral support loads, provided by the tubesheet, the acceleration mechanism is mitigated and a tube separation mode similar to that which would occur in a simple tensile test results. Such a separation mode, however, requires the application of significantly higher loads than for the unsupported case.

The proposed criterion forms the basis for obviating the need to remove a tube from service (by plugging) due to detection of indications, e.g., by eddy current testing (ECT), in a region extending over most of the length of tubing within the tubesheet. This evaluation applies to the McGuire Units 1 and 2 Westinghouse Model D steam generators and assesses the integrity of the tube bundle for tube ECT indications occurring in the length of tubing within the tubesheet, relative to:

- 1) Maintenance of tube integrity for all loadings associated with normal plant conditions, including startup, operation in power range, hot standby and cooldown, as well as all anticipated transients.

- 2) Maintenance of tube integrity under postulated limiting conditions of primary-to-secondary and secondary to primary differential pressure, e.g., steamline break (SLB) or feedwater line break (FLB).
- 3) Limitation of primary-to-secondary leakage consistent with accident analysis assumptions.

The F^* criterion provides for sufficient engagement of the tube to tubesheet hardroll such that pullout forces that could be developed during normal or accident operating conditions would be successfully resisted by the elastic preload between the tube and tubesheet even in the event of a circumferential break in the tube below the F^* distance. The necessary engagement length applicable to the McGuire Units 1 and 2 steam generators was found by Westinghouse to be less than the two inch F^* distance proposed by the licensee for McGuire based on preload analysis performed by Westinghouse.

Verification that the Westinghouse value is conservative was demonstrated by both pullout and hydraulic proof testing of tubes in tubesheet simulating collars. Application of the F^* criterion provides a level of protection for tube degradation in the tubesheet region commensurate with that afforded by RG 1.121 for degradation located outside the tubesheet region.

In order to evaluate the applicability of any developed criterion for indications within the tubesheet, some postulated type of degradation must necessarily be considered. For this evaluation it was postulated that a circumferential severance of a tube could occur, contrary to existing plant operating experience. However, implicit in assuming a circumferential severance to occur, is the consideration that degradation of any extent could be demonstrated to be tolerable below the location determined acceptable for the postulated condition.

When the tubes have been hardrolled into the tubesheet, any axial loads developed by pressure and/or mechanical forces acting on the tubes are resisted by frictional forces developed by the elastic preload that exists between the tube and the tubesheet. For some specific length of engagement of the hardroll, no significant axial forces will be transmitted further along the tube, and that length of tubing, i.e., F^* , will be sufficient to anchor the tube in the tubesheet. In order to determine the value of F^* for application in Model D steam generators, a testing program was conducted to measure the elastic preload of the tubes in the tubesheet.

The presence of the elastic preload also presents a significant resistance to flow of primary-to-secondary or secondary-to-primary water for degradation which has progressed fully through the thickness of the tube wall. In effect, no leakage would be expected if a sufficient length of hardroll is present. This has been demonstrated in high pressure fossil boilers where hardrolling of tube to the tubesheet joints is the only mechanism resisting flow, and in steam generator sleeve-to-tube joints made by the Westinghouse hybrid expansion joint process.

Tubes are installed in the steam generator tubesheet by a hardrolling process which expands the tube to bring the outside surface into intimate contact with the tubesheet hole. The roll process and roll torque are specified to result in a metal-to-metal interference fit between the tube and the tubesheet.

A test program was conducted by Westinghouse to quantify the degree of interference fit between the tube and the tubesheet provided by the full depth mechanical hardrolling operation. The data generated in these tests has been analyzed to determine the length of hardroll required to preclude axial tube forces from being transmitted further along the tube, i.e., to establish the F* criterion. The amount of interference was determined by installing tube specimens in collars specifically designed to simulate the tubesheet radial stiffness. A hardroll process representative of that used during steam generator manufacture was used in order to obtain specimens which would exhibit installed preload characteristics like the tubes in the tubesheet.

Once the hardrolling was completed, the test collars were removed from the tube specimens and the springback of the tube was measured. The amount of springback was used in an analysis to determine the magnitude of the interference fit, which is, therefore, representative of the residual tube-to-tubesheet radial load in Westinghouse Model D steam generators.

The test program was designed to simulate the interface of a tube-to-tubesheet full depth hardroll for a model D steam generator. The test configuration consisted of six cylindrical collars. A mill annealed, Inconel 600 (ASME SB-163), tubing specimen was hard rolled into each collar using a process which simulated actual tube installation conditions.

Following the taking of all post roll measurements, the collars were saw cut to within a small distance from the tube wall. The collars were then split for removal from the tube, and tube ID and OD measurements repeated. In addition, the axial length of the tube within the collar was measured both before and after collar removal.

The data recorded was that necessary to determine the interfacial conditions of the tubes and collars. These consisted of the ID and OD of the tubes prior to and after rolling and removal from the collars as well as the inside and outside dimensions of each collar before and after tube rolling. Two orthogonal measurements were taken at each of six axial locations within the collars and tubes. In addition, gage marks were put on the tubes so that any axial deformation that occurred during collar removal might be monitored. The remainder of the data of particular interest was calculated from these specific dimensions. The calculated dimensions included wall thickness, change in wall thickness for both rolling and removal of the tubes from the collars, and percent of springback. Using the measured and calculated physical dimensions, an analysis of the tube deflections was performed to determine the amount of preload radial stress present following the hardrolling.

During plant operation the amount of preload will change depending on the pressure and temperature conditions experienced by the tube. The room temperature preload stresses, i.e., radial, circumferential and axial, are such that the material is nearly in the yield state if a comparison is made to ASME Code minimum material properties. Since the coefficient of thermal expansion of the tube is greater than that of the tubesheet, heatup of the plant will result in an increase in the preload and could result in some yielding of the tube. In addition, the yield strength of the tube material decreases with temperature. Both of these effects may result in the preload being reduced upon return to ambient temperature conditions, i.e., in the cold condition.

Based on the results obtained from the pullout tests, this is not expected to be the case as even with a very high thermal relaxation soak the results show the analysis to be conservative.

The plant operating pressure influences the preload directly based on the application of the pressure load to the ID of the tube, thus increasing the amount of interface loading. The pressure also acts indirectly to decrease the amount of interface loading by causing the tubesheet to bow upward. This bow results in a dilatation of the tubesheet holes, thus, reducing the amount of tube-to-tubesheet preload. Each of these effects was quantitatively treated.

The maximum amount of tubesheet bow loss of preload will occur at the top of the tubesheet. Since F^* is measured from the bottom of the hardroll transition (BRT) or the top of the tubesheet, and leakage is to be restricted by the portion of the tube above F^* , the potential for the tube section above F^* to experience a net loosening during operation was considered for evaluation. The effects of the three identified mechanisms affecting the preload are considered as follows:

- 1) Thermal Expansion Tightening - The mean coefficient of thermal expansion for the Inconel tubing between ambient conditions and 600°F is 7.80×10^{-6} in/in/ $^{\circ}\text{F}$. That for the steam generator tubesheet is 7.28×10^{-6} in/in/ $^{\circ}\text{F}$. Thus, there is a net difference of 0.52×10^{-6} in/in/ $^{\circ}\text{F}$ in the expansion property of the two materials. Considering a temperature difference of 550°F between ambient and operating conditions the increase in preload between the tube and the tubesheet was calculated.

The results indicate that the increase in preload radial stress due to thermal expansion is positive during both normal operating and faulted conditions.

- 2) Internal Pressuring Tightening - The maximum normal operating differential pressure from the primary-to-secondary side of the steam generator is during a loss of load transient. The internal pressure acting on the wall of the tube will result in an increase of the radial preload in proportion to the increase in primary side pressure during the transient.

In actuality, the increase in preload will be dependent on the internal pressure of the tube since water at secondary side pressure would not be expected between the tube and the tubesheet.

For both normal and faulted conditions the results indicate that the preload radial stress is increased.

- 3) Tubesheet Bow Loosening - An analysis of the Model D3 steam generator tubesheet was performed to evaluate the loss of preload stress that would occur as a result of tubesheet bow. Basically, the deflection of the tubesheet was used to find the stresses active on the top surface and then the presence of the holes was accounted for. For the location where the loss of preload is a maximum, the radial preload stress would be reduced during normal operation and faulted SLB operating conditions. During LOCA the differential operating pressure is from secondary to primary. Thus, the radial preload will increase as the tubesheet bows downward.

Combining the room temperature hardroll preload with the thermal and pressure effects results in a net positive operating preload during normal and faulted operation. In addition to restraining the tube in the tubesheet, this preload should effectively retard leakage from indications in the tubesheet region of the tubes.

The applied loads to the tubes which could result in pullout from the tubesheet during all normal and postulated accident conditions are predominantly axial and due to the internal-to-external pressure differences. For a tube which has not been degraded, the axial pressure load is given by the product of the pressure with the internal cross-sectional area. However, for a tube with internal degradation, e.g., cracks oriented at an angle to the axis of the tube, the internal pressure may also act on the flanks of the degradation. Thus, for a tube which is conservatively postulated to be severed at some location within the tubesheet, the total force acting to remove the tube from the tubesheet is given by the product of the pressure and the cross-sectional area of the tubesheet hole. The force resulting from the pressure and internal area acts to pull the tube from the tubesheet and the force acting on the end of the tube tends to push the tube from the tubesheet. Any other forces such as fluid drag forces in the U-bends and vertical seismic forces are negligible by comparison.

The calculation of the required engagement distance is based on determining the length for preload frictional forces to equilibrate the applied operating loads. The axial friction force was found as the product of the radial preload force and the coefficient of friction between the tube and the tubesheet. The value assumed for the coefficient of friction was for sliding of nickel on mild steel under "greasy" conditions.

For the maximum normal pressure applied load with a safety factor of 3, the length of hardroll required is exceeded by the McGuire conservative value for F^* of two inches.

Similarly, the required engagement length for faulted conditions using a safety factor corresponding to an ASME Code safety factor of 1.0/0.7 for allowable stress for faulted conditions is similarly exceeded by the McGuire F^* value.

The F^* value thus determined for the required length of hardroll engagement below the BRT or the top of the tubesheet, whichever is greater relative to the top of the tubesheet, is sufficient to resist tube pullout during both normal and postulated accident condition loadings. Furthermore, the uncertainty in position of the ECT indication must be added to the criterion for the final calculation of F^* . A conservative allowance for uncertainty in ECT position indication is available in the conservative F^* distance of 2 inches for the McGuire Units 1 and 2 TS 3/4.4.5.

b. Rolled Tube Pullout Tests

The engagement distance determination discussed above was calculated from a derived preload force and an assumed static coefficient of friction for tube to tubesheet contact. A direct measurement of this static coefficient of friction is difficult. However, a simple pull test on a rolled tube joint provided both

support for the derived preload force (less the effects of thermal expansion and internal pressure tightening) and an indirect measurement of the static coefficient of friction. The results of the testing verify the calculation as being conservative.

Pullout tests were conducted on several actual rolled joints with various amounts of wall thinning. As with the preload tests, the test configuration consisted of mill annealed, Inconel 600 (ASME SB-163) Model D3 tubing, hard rolled into carbon steel collars with an outside diameter to simulate tubesheet rigidity. Inside surface roughness values of the collars were measured and recorded. The specification of surface roughness for the fabrication of the collars was the same as that used for the fabrication of the model D tubesheets. After rolling, an inside circumferential cut was machined through the wall of the tube at a controlled distance from the bottom of the hardroll transition (opposite the tube weld). The machined cut simulated a severed tube condition. To simulate any possible effect of reduced preload force due to tube yielding during manufacturing heat treatment and during reactor operation, the samples were subjected to a heat soak.

Based on the observed pullout forces, the coefficient of friction assumed in the engagement distance determination was verified to be conservative.

c. Rolled Tube Hydraulic Proof Tests

Similar to the rolled tube pullout tests, pressure tests were conducted on rolled joints and with nominal degrees of wall thinning. As with the preload and pullout tests, the test configuration consisted of mill annealed, Inconel 600 (ASME SB-163) Model D3 tubing, hard rolled into carbon steel collars with an outside diameter to simulate tubesheet rigidity. As with the pullout test samples, a machined cut was used to simulate a severed tube condition. To simulate any possible effects of reduced preload force due to tube yielding during manufacturing heat treatment, these samples were also subjected to a heat soak. The pressure tests were performed at room temperature using water.

These proof tests showed that even for rolled joints considerably less than the F^* distance in length at less than nominal wall thinning, pressure induced axial forces of several thousands of pounds or greater are necessary to cause the tube to release from the tubesheet. Thus, the preload based calculation of required engagement distance is indicated to be conservative.

d. Primary-to-Secondary Leakage Considerations

As described above, to apply the F^* criterion the applicable tube must have a certain minimum length of hardroll engagement below the top of the tubesheet or the BRT, whichever is greater relative to the top of the tubesheet. For McGuire Units 1 and 2 the licensee has conservatively established an F^* distance of two inches. Because of the interference fit created by the hardrolling operation, no leakage is expected to occur between the tube and the tubesheet regardless of the condition of the tube below the F^* distance. This was confirmed by the hydraulic proof test specimens which were pressurized up to and in excess of the faulted operating conditions.

Because of the difficulties in accurately sizing stress corrosion crack indications, the technical specifications require that no indications of cracking can be present within the F* distance in tubes to which the F* criterion is applied. This requirement has the effect of preventing the start of a leak path.

e. Tube Integrity Under Postulated Limiting Conditions

The final aspect of the evaluation is to demonstrate tube integrity under the postulated loss of coolant accident (LOCA) condition of secondary-to-primary differential pressure. A review of tube collapse strength characteristics indicates that the constraint provided to the tube by the tubesheet gives a significant margin between tube collapse strength and the limiting secondary-to-primary differential pressure condition, even in the presence of circumferential or axial indications.

2. Technical Specification Changes

The licensee first proposed TS changes to implement the F* criterion in a letter dated August 5, 1986. Based upon discussions with the Commission the licensee revised these proposed TS changes by letters dated August 13 and 18, 1986. The following addresses the changes in the TS proposed in the August 18, 1986 letter implementing the F* criterion.

- a. The TS is changed to contain a definition of the F* distance (i.e., the distance into the tubesheet from the top face of the tubesheet or the top of the last hardroll, whichever is lower (further into the tubesheet) that has been conservatively chosen to be two inches) and a definition of a F* tube, (i.e., a tube with degradation equal to or greater than 40%, below the F* distance and not degraded (i.e., no indications of cracking) within the F* distance).
- b. The TS is changed to contain a specific provision for reinspection of F* tubes. This reinspection is in addition to the normal TS required sampling.
- c. Special reports containing the results of inspection or reinspection of F* tubes are to be submitted to the Commission prior to restart.
- d. The F* criterion or plugging limit is defined such that tubes need not be plugged because of ECT indications, equal to or greater than 40% through wall, that are below the F* distance provided the tube is not degraded (i.e., no indications of cracking) within the F* distance. The restriction on no degradation within the F* distance has been incorporated (1) because of limitations in accurately sizing stress corrosion cracking (i.e., stress corrosion cracking that appears by ECT to be shallow may in fact be considerably deeper), and (2) because the engagement distance analysis and the testing program were based upon tubes that did not contain imperfections.

- e. The application of the F* criterion is being approved for about two cycles of operation (i.e., until the end of the fifth fuel cycle) for each McGuire unit. This time provision is included in the proposed TS at the request of the Commission to give the Commission the opportunity to review and evaluate the results of subsequent inspections before extending or revising Commission approval for use of the F* criterion.
- f. The Bases are supplemented to reflect the addition of F* criterion to the TS.

The Commission has reviewed the TS changes as revised through the August 18, 1986, letter and finds them acceptable. These TS changes provide acceptable implementation of the F* criterion as analyzed in the Westinghouse Reports and evaluated in this Safety Evaluation Report.

Accordingly, the Commission concludes that tubes can safely be left in-service with eddy current indications of pluggable magnitude that are located below the F* distance provided the tube is not degraded within the F* distance. The F* distance is defined as two inches from the top of the tubesheet or from the top of the last hardroll whichever is lower. From the results of the testing and analysis, the Commission concludes that following the installation of a tube by the standard hardrolling process, a residual radial preload stress exists due to the plastic deformation of the tube and tubesheet interface. This residual stress is sufficient to restrain the tube in the tubesheet while providing a leak limiting seal condition even if the tube is completely severed circumferentially at the F* distance below the top of the tubesheet. Nevertheless, until behavior of F* tubes has been confirmed by actual operation, the Commission concludes that its approval of these amendments should be limited to about two cycles of operation for each McGuire unit.

ENVIRONMENTAL CONSIDERATION

Pursuant to 10 CFR 51.32, the Commission has determined that issuance of the amendments will have no significant impact on the environment (51 FR 29173).

CONCLUSION

Notice of opportunity for a prior hearing was published in the Federal Register on July 16, 1986 (51 FR 25777). No requests for a hearing were received.

We have concluded, based on the considerations discussed above, that: (1) there is reasonable assurance that the health and safety of the public will not be endangered by operation in the proposed manner, and (2) such activities will be conducted in compliance with the Commission's regulations, and the issuance of these amendments will not be inimical to the common defense and security or to the health and safety of the public.

Principal Contributors: Darl S. Hood, PWR #4 Licensing-A
 C. Sellers, PAEB, PWR Licensing-A

Dated: August 19, 1986