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April 20, 1983
5211-83-123

Office of Nuclear Reactor Regulations
Attn: John F. Stolz, Chief
Operating Reactors Branch No. 4
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555

Dear Sir:

Three Mile Island Nuclear Station, Unit 1 (TMI-1)
Operating License No. DPR-50
Docket No. 50-289
TMI-1 OTSG Repair

This letter is in response to your request for a nonproprietary version of our March 31. 1983 submittal of Topical Report 008, Rev. 2 on the return of TMI-1 to service following repair of the steam generators. The attached pages have the proprietary paragraphs masked. These pages are listed by number of the attachement, and should be used to replace the proprietary pages in Topical Report 008 when releasing the document to the public.

The masked paragraphs are currently undergoing review to determine if further portions can be designated nonproprietary. If further declassifications are made, we will inform you of the changes.

Sincerely,

H. D. Hukill
Director, TMI-1

A001

HDH:MJG:vjf
Enclosure
cc: J. Van Vliet
R. Conte

Pages for Substitution   Attachment

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FIGURE 1-4

sodium sulfate indicates that a threshold level of available reduced sulfur is necessary and that sulfur in the surface film of itself is not sufficient to produce intergranular cracking.

D. Repaired Tubing Corrosion Tests

This corrosion data base, supported the conclusion that an effective repair could be made. The choice of explosive expansion appeared to be the most technically feasible solution, however, with the expansion process came a new geometry which would have a transition from the expanded portion to the unexpanded portion of the tube which was not stress relieved. An accelerated short term test was conducted to assess the impact of this transition on the tube susceptibility to corrosion (Reference 29).

Even though all short term tests were done under accelerated conditions, it was still felt that a certain time dependency may be required for corrosion to initiate. Long term tests were developed to address this time dependent parameter (Reference 8). These tests have been scheduled to lead the actual performance of the generator and thus provide additional insight as to the expected performance of the tubes. The long term corrosion testing program was developed to assess performance of the tubing both in the unsupported regions of the generator and tubing at the new expanded transition region. The test is designed to run for approximately 13 months of operating time and to lead actual operation of the generator by a minimum of one month. As presently scheduled, lead testing will probably preceed operation of the generator by a minimum of 4 months.

These tests will be conducted under simulated operational parameters which will include load cycling as well as thermal cycling. Chemistry will simulate that expected under normal reactor operations. This will include decreasing boron levels as well as decreasing lithium levels throughout the test period. Test samples will be made from actual TMI steam generator tubes. Samples will be utilized both with known eddy current defects as well as without known eddy current defects. A minimum of 4 different heats of material will be utilized with samples from various elevations within the generator.

Samples in the lead test loops include both defective and nondefective tubing in order to assess both the initiation and propagation phases of intergranular stress assisted cracking. Tubes will be eddy current tested utilizing the .540" standard differential probe as well as a single coil absolute probe. The size and eddy current signature of the currently known defective tubes will be monitored and any changes in crack shape or eddy current signal will be closely watched. During the lead test, the tubes will be examined at the end of each test cycle (approximately every other month) and assessments will be made as to crack initiation or growth at each phase. In addition, at the end of each test cycle C-rings will be removed and destructively evaluated by metallography to assess the initiation of any intergranular attack. Through this lead test program, an assessment can be made regarding plant operation in the unlikely event that crack initiation or propagation is observed.

A third lead test loop will simulate the hydrogen peroxide cleaning process, then continue through the hot functional tests and operating cycle simulations. Sulfur in solution will be sulfate. All tube specimens used in this loop will be six-inch sections of actual TMI tubing which have been Immunol coated and subjected to expansion process debris. Additional specimens which are representative of reactor coolant system materials will be included in this loop.

The long term corrosion test program will provide a means for making a comprehensive assessment of tube performance in actual generator operation over long periods of time.

E. Conclusions

V. KINETIC EXPANSION REPAIR DESCRIPTION SUMMARY

A. Description of Process and Geometry

1. Introduction

TMI-1 OTSG tube examinations have revealed a large number of tubes with defects within the upper tubesheet. A defect is defined as any eddy current indication interpreted as greater than 40% through wall. The limits of eddy current detectability are defined in Section IX. The repair approach is to establish a new primary system pressure boundary below these defects. A kinetic expansion of the tube within the tubesheet will be the approach used to effect this repair. All tubes which are not currently plugged will be kinetically expanded irrespective of whether or not they have a defect, and irrespective of whether they will be plugged in the future. This repair will provide a load carrying and essentially leak-tight joint below known defects. The following sections summarize the repair program. Details can be found in Reference 1 and Reference 23.

2. Kinetic Tube Expansion

The process steps which are involved with this repair have the objective of providing a new pressure boundary below known defects through kinetic (explosive) expansion of the tube within the tubesheet.

Preliminary testing has determined that a 6" long expansion below the lowest defect will provide the desired load carrying margins. The expansion serving as the new pressure boundary is the bottom six-inches of a 17 inch expansion extending through the cracked area to the top of the upper tube sheet. Thus all tubes for which the lowest defect is at 11" or above have been provided with a new six-inch joint. Tubes with defects lower than 11" will be considered individually. Those with the lowest defect between 11" and 16" will be expanded using a 22" expansion. Those with defects lower than 16" below the top of the upper tubesheet will be taken out of service.

The TMI-1 OTSG repair process is as follows.

Step	Description
1	Flush the secondary side tube to upper tubesheet crevice.
2	Heat crevice to drive out moisture (vaporize water).
3	
4	Kinetically expand tubes
5	Clean debris from kinetic expansion
6	Mill tube ends
7	Flush OTSG
8	Plug necessary tubes
9	Clean OTSG with felt plugs.

B. Design Bases of Kinetic Joint

The new joint comprises a kinetic expansion of either 17 or 22 inches which begins just below the upper tubesheet top surface in the area of the original shop roll expansion. The kinetic expansion will be the pressure boundary and structural attachment of the tube to the tubesheet.

The original OTSG design basis is summarized in Reference 1. The following is a summary of design basis for the new kinetically expanded joint.

1. The repaired tube shall sustain the maximum design basis axial tensile load of 3140 lb. from the generic 177 FA MSLB accident analysis. Since this is a thermally induced load, satisfying this criteria requires no relative movement (slippage) between the expanded area and the tubesheet at the axial strain corresponding to this load (about .0016 in/in).

2. Thermal/Pressure Cycles

   The initial design life objective for the tube kinetic expansion is 5 years.

   Sufficient cyclic testing and/or analysis will be performed during the qualification program to satisfy this objective.

leak paths in all tubes to be repaired. Tubes with unacceptable leakage as indicated by the precritical drip and nitrogen bubble tests (see Appendix A) may be roll expanded above the lower 6" to attempt to seal the leakage. If this is unsuccessful the tube will be plugged and/or stabilized if necessary.

For plant operation, primary-to-secondary steam generator leakage limits will continue to be set by the Technical Specification limit of 1 gpm. However, in order to control the amount of waste that requires processing, a design goal of 1 lb/hr projected total leakage from both generators has been set for the qualification program. Bubble testing can distinguish a leak that is of the magnitude of 0.1 gallons per day. An engineering evaluation of bubble test results as they relate to expected leakage will be conducted in order to determine what tubes require plugging. Statistical analysis will be applied to the verification test results.

C. Qualification Program

A series of mechanical tests and chemical and corrosion tests were performed to qualify the kinetic expansion, and the kinetic expansion process to meet the design goals of producing a joint capable of carrying required loads, providing a leak tight seal, minimizing residual stress, and tube preload changes. A series of preliminary tests was conducted to establish the optimum parameters for a kinetic expansion process that will yield acceptable joints with low residual stresses. Additional tests were conducted on a full size steam generator at B&W's Mt. Vernon Works. A more detailed description of the tests and results can be found in Reference 23.

1. Mechanical Tests

a. Preliminary Leak and Axial Load Tests

Kinetic expansions were tested to determine the maximum axial load which could cause the expansion to slip. After a set of expansion parameters were postulated, leak rate and axial load tests were performed to determine whether the expansion would still appear adequate for a corroded tubesheet, after thermal and pressure cycling, and after adjacent tubes have been expanded.

The following acceptance goals were applied.

(1) Water leak at a pressure differential of 1275 psig (Primary to Secondary) 3.3×10^{-5} lb/hr per tube.

(2) Pullout load consistently above 3140 lb per tube.

(3) Margin in pullout loads and leak rate to account for possible deterioration of joint integrity from thermal cycling and for statistical analysis.

(4) Minimize expansion length.

(5) Minimize longitudinal strain induced in the tube by the expansion process.

(6) Minimize in-plane deformation of the expanded tube block hole and adjacent holes.

The effects of thermal and pressure cycling on pullout load were minimal.

b. Leak and Axial Load Qualification Tests

These tests predicted the leak tightness and confirmed the axial load carrying capability of the chosen expansion technique, and showed what effect kinetic expansion will have on adjacent repaired tubes and determined the effect of re-expanding previously expanded tubes.

Acceptance criteria required that a statistical evaluation of the results show a 99% confidence level that 99% of all tubes expanded would have a pullout load greater than 3140 lbs. A mean leakage rate goal of less than 3.2×10^{-5} lbs/hr/tube was desired.

Results indicate that thermal cycling tends to decrease pullout load, however thermally cycled blocks pulled at 70°F gave a 99% confidence level that 99% of the tube expanded will have pullout loads in excess of 4170 lb. One block which was pull tested at 330°F gave 99/99 statistical confidence that pullout load would be in excess of 3590 lbs. The goal of 99% confidence that 99% of the tubes have pullout above 3140 lb is easily met. In addition, an expansion pull test performed on a full scale generator at Mt. Vernon showed a load carrying capability of at least 3600 pounds.

Leak rate results after thermal cycling vary from 1.18×10^{-6} to 187.4×10^{-6} lbm/hr/tube. The average tube leakage was considered to be one-tenth of the total test block leakage in each case. Statistics indicate a 99% confidence that 99% of the normally expanded tubes will have leakage rates no greater then 132.4×10^{-6} lbm/hr/tube. While this rate exceeds the design objective of 3.2×10^{-5} lbm/hr/tube, it is still a very low leak rate. Results of leak rates after axial loading are found in Reference 23. If every tube in both OTSGs leaked at this maximum rate the cumulative leak rate would still be less than one-hundredth of the Technical Specifications limit of 1.0 gpm. The leak rate of the one block showed an increase between 10°F and 400°F (6% of the total range of leak rates) leading to the conclusion that the leak rate for a tube at operating temperatures would differ only slightly from what it would be at room temperature.

c. Residual Stress Testing

(1) Preliminary Transition Geometric Limitations

This test determined the expansion parameters which would lead to a transition that would minimize the transition residual stress and stress concentration factor. It was concluded that a transition length between .125 and .25 inch would be a goal, with a minimum acceptable transition length of .1 inch. A number of insert shapes were evaluated to determine which provided a smooth transition.

(2) Residual Stress Measurements

The actual residual stress was measured in special test blocks using X-ray diffraction and strain gage techniques to determine post-kinetic expansion tube stresses in the transition area at the bottom of the expansion and at a second point near the middle of the expansion. Both hard rolled and kinetically expanded tubes were examined using high and low yield strength materials.

The goal for this test was that the additional residual stress in the tube resulting from kinetic expansion would not exceed 45% of yield strength.

Results are reported in Reference 23.

(3) Comparison of Kinetic and Roller Expansion

Sample Inconel 600 tubes were expanded by rolling and kinetic processes in order to compare the resulting hardness and microstructure.

(4) Corrosion Testing of Transitions

d. Induced Strain Tests

Tests were performed to determine the effects of the expansion on the tube-to-tubesheet welds, and the tube length, and to determine the strain stored in the expansion. A design goal of changing the preload by less than ± 30 lbs due to elongation was applied.

e. Ligament Distortion

The effects of explosive expansion on the tubesheet ligament were determined. The dimensions of adjacent holes in the tubesheet were measured before and after the expansion and compared.

Based on the mechanical qualification tests it can be concluded that the kinetic expansion joint will meet the five year design life objective. The repaired tube will sustain the maximum design basis axial load of 3140 lbs., residual stresses will be minimized, tube preload will not change more than ± 30 lbf, and leakage will be much less than technical specification limits.

2. Chemical and Corrosion Testing

a. Residue Test

The amount and type of explosive residue that should be expected to remain in the steam generator after all tube repairs are completed was determined. A satisfactory cleaning method to reduce contaminants to acceptable primary system water chemistry levels was identified.

b. Crack Change Tests

The effect of kinetic expansion on existing cracks was determined.

c. Effects on Residual Sulfur

Testing was performed to assess what happens to the sulfur on the surface of steam generator tubes (i.e. driven into the base metal) after kinetic expansion.

D. Repair Testing

The in-process inspection and monitoring program was designed to verify that the in-generator expansions are similar to those obtained in the qualification program. Actual OTSG expansion profilometry and ECT results were compared to test program data to verify that the expansions are similar. Data obtained from TMI-1 was also compared statistically to test program data. The program consisted of video surveillance, profilometry measurements, and eddy current (ECT) examinations.

Video surveillance of operations during the expansion process were conducted where practical to verify that proper procedures were followed and that the correct tubes were expanded or examined. Random out-of-generator expansions were also conducted to verify that expansion inserts had not changed since the qualification program.

Verification sampling was performed on the tubes expanded by the initial charge strength in the first three lots in each OTSG and consisted of ECT and profilometry. ECT using an 8x1 probe was performed on almost 100% of the tubes expanded in the first lot in both OTSG's. Profilometry was performed on expanded tubes selected at random from the first three lots.

In addition to verification sampling, random diameter and depth checks sampling were done following initial expansion. The sampling plan can be found in Reference 19.

Results are presented below of both the expansion length inspection program and the program to verify that each tube was expanded as required.

3. If some of these ECT indications are from small cracks which were previously below the .540 ECT sensitivity within the upper tubesheet (UTS), their geometry is so small that the reliability of the new joint is not affected.

4. The most probable reason for these new indications is that the 8x1 probe is more sensitive than the .540 probe within the UTS. The 8x1 probe appears to be so sensitive enough to respond to pits which are so small they are of no consequence.

Section IX documents extensive work done to evaluate the maximum size crack which can be left in service for the life of the plant and not cause tube failure under normal or accident tube loadings. Acceptable circumferential extent vs. throughwall depth curves for various loading and analysis conditions in the free span are shown in Figure IX.2. The pit indications found in the area of the joint are smaller than the crack size leading to failure by any mechanical means in the free span. These curves are conservative for indications in the joint since loads imposed on the tubes are transmitted to the tubesheet in the area of the expansion. Loads on tubing in the area of the defects will be equal to or less than those analyzed for the free-span. Leakage through any small defects which are 100% throughwall is also expected to be less than or equal to similar cracks in the freespan. Unacceptable leakage will be identified during precritical testing and the tube will be either plugged or repaired. For these reasons, it is concluded that small pits or undetected cracks in the qualified area do not affect the reliability of the new joint.

It is expected that additional indications will be identified during the baseline 8x1 eddy current examination of the expanded region to be conducted following the kinetic expansion. These indications will be evaluated to confirm that they are acceptable, and will be left in service and reexamined during the 90 day ECT program.

2. <u>Identification and Expansion of Misfires</u>

The concern for a tube is that, potentially, being unable to carry sufficient axial load, the tube would fail, slip downward and lock. Therefore, an evaluation was performed to determine the likelihood of slippage during operation, and the potential consequences if the tube were plugged, stabilized or left in service.

. Leakage data for tubes is available from the preliminary qualification program for a defect free length of 8". For this length, leakage is expected to be sufficient to be identified during precritical testing. Similarly, leakage will be greater the shorter the defect free length. In addition, the tight annulus between the tube and tubesheet will provide a substantial restriction to any leakage.

. Assuming a minimum 6" leak length and a worst case 0.001" radial annulus, the leak rate past the expansion would be about 0.25 gpm or one quarter of the Technical Specification limit. This annulus size is considered to be conservative because any actual leak path past the expansion is expected to be a discrete path such as a scratch. A leaking tube would be located by conventional means and would be plugged and, if necessary, stabilized.

Of the approximately 7000 tubes

only about 100 were to be plugged. Slippage of a plugged tube could not be identified due to leakage. Thus if the tube slipped and locked, it could bow or be dynamically unstable in cross flow areas and cause wear damage to adjacent tubes. Approximately half of the plugged tubes will be stabilized, which should prevent wear damage. The remainder are in areas of minimal cross flow, so dynamic instability should not be a problem.

a relatively small point load against the neighboring tubes or tubesheet could force a node at the point of contact and prevent wearing.

E. Post Repair Testing

Following repair, testing will be performed to verify the acceptability of the joints. Post Repair tests include:

1. 150 psig bubble test. Upper tubesheet plugs, tubing and expansions leak test.

2. 150 psig drip test. Lower tubesheet plugs, tubing and expansions leak test.

3. Hot OTSG Testing

   Hot OTSG testing will include transients that will place operating loads on the new joint. These transients will include:

at any one time was acceptable. This was done by exploding 132 charges in the longest row in the generator. A maximum stress intensity of 95,000 psi at 800HZ was obtained at the strain gage closest to the expanded row. This compares to a static yield strength of 70,000 psi for the tubesheet material. Since the yield strength of steel increases markedly at high strain rates (up to twice static yield) and that no residual strain was measured on the strain gauges following expansion it is concluded that no plastic deformation occurred. The maximum stress intensity recorded for the weld between the tubesheet and shell was less than 10,000 psi. The strain gauge on the tube recorded very low values indicating that no significant excitation of the tube bundle occurred. A fatigue analysis has been performed and the tubesheet at the periphery was found to be limiting. The analysis was conservative in that it assumes that the principal stresses occur simultaneously and that all blasts yielded the same peak value. The other strain guage locations clearly show that the stress diminishes as the distance from the expansion increases. The results was a maximum fatigue usage of .12. From this data it was concluded that the use of up to 137 charges is acceptable and the total number of separate blasts will not present a fatigue problem.

In addition, Foster Wheeler has kinetically expanded over 2000 feedwater heaters and expanded as many as 5000 tubes in a heater in one detonation. They report that they have never experienced any tubesheet overstressing problems and do not believe this is of concern since the plan is to expand only 132 tubes simultaneously plus any misfires from the previous row up to a total of 137 total tubes ror the TMI-1 Steam Generator repair.

The combination of Foster-Wheeler experience and the strain gage data show the explosive expansion process to have no adverse effect on the steam generator.

C. Corrosion

Several concerns have been addressed relative to the susceptibility of the repair to corrosion. In tubes with through wall cracks, a leak path for primary system water may still exist even after kinetic expansion over the full 17 inches. The breech exposes the carbon steel tubesheet wall to the corrosive effects of a buffered solution of boric acid, i.e., clean reactor coolant.

As described earlier in this report, ID tube cracking due to the corrosive effect of sulfur and/or sulfur containing ions has been identified as a probable contributing cause of the TMI-1 steam generator problems. The first concern is therefore residual sulfur deposits in crevices above and below the repair seal area, particularly in pockets that may have resulted from corrosion of the tubesheet wall. Such deposit could cause an attack on the Inconel tubing. Sulfur attack would be preferential to the Inconel rather than the carbon steel tubesheet. It is presumed that the source of sulfur contamination no longer exists and the RCS is essentially sulfur free. As in the original design, a crevice will exist below the seal between the OD of the Inconel tube and the carbon steel tubesheet wall. The crevice has been flushed to reduce soluble deposits, particularly in the crevice area below the repair seal.