ENCLOSURE

SAFETY EVALUATIONS BY THE OFFICE OF NUCLEAR REACTOR REGULATION

1983/84 STEAM GENERATOR EVALUATION AND REPAIR REPORT

PALISADES NUCLEAR PLANT

DOCKET NUMBER 50-255

1.0 INTRODUCTION

By letter dated April 19, 1984, Consumers Power Company (CPC) submitted for our review, a report entitled, "1983/1984 Steam Generator Evaluation and Repair Program Summary", and on April 25, 1984, they provided responses to our request for additional information. Information meetings were held in Bethesda on October 25, 1983, February 21, 1984, and April 10, 1984. Members of the Headquarters and Region III staff, along with a consultant from the Oak Ridge National Laboratory, met with CPC on December 7, 1983 at the Corporate Research Center in Jackson, Michigan in order to examine Eddy Current Test (ECT) data records and to observe a demonstration of the eddy current system equipment.

The 1983-1984 inspection was performed on 100% of the tubes with a 4 x 4 pancake probe. The results of the final evaluation of the 1983-84 ECT data show a total of 181 tubes with cracks and 29 tubes with intergranular attack (IGA) greater than 50%. With preventive plugging, a total of 277 tubes were plugged in both steam generators.

2.0 BACKGROUND

Palisades is a pressurized water reactor having two Combustion Engineering designed U-tube steam generators. Each steam generator contains 8519 Inconel-600 tubes with a 0.750 inch outside diameter and a 0.048 inch minimum wall thickness.

On January 15, 1973 after approximately one year of intermittent operation at less than full power, the Palisades plant experienced its first steam generator tube leak. ECT examinations of the tubing detected general wastage attack in the U-bend area of tubes in the first eleven rows from the divider plate. The attack was attributed to the use of a coordinated phosphate secondary water chemistry. All tubes in these first eleven rows were plugged, and the plant returned to service in March, 1973.

The plant operated at essentially full power until August 11, 1973, when it was shut down because of excess steam generator tube leakage. ECT examinations in September, 1973 showed measurable wastage on nearly half of the steam-generator tubes. Evaluation of required tube strength showed that tubes with wastage less than 60% through-wall could remain in service. All tubes with greater than 60% wastage defects were plugged.

In May 1974, preoperational hydrotests identified two leaking tubes. ECT showed that wastage had increased and that IGA accompanied by shallow pitting was present between the support plates in the upper hot leg. All tubes with indications of IGA and those with greater than 50% wastage were plugged. The IGA was attributed to a mixture of reduced forms of sulfur and sodium phosphates.

Because the IGA appeared to be growing rapidly while the plant was in cold shutdown, the plant was permitted to return to power at levels up to 60% in order to flush or volatize any sulfur or soluble phosphorous compounds from the steam generators.

Upon return to service in October 1974, the secondary water chemistry treatment was changed to an all-volatile treatment as recommended by the steam generator vendor in order to arrest wastage-type corrosion. Subsequent ECT examinations in 1975 through 1981 showed that wastage corrosion of the steam generator tubing had essentially ceased although minor tube denting was occurring as a result of the switchover to all-volatile treatment.

In March, 1982, a primary-to-secondary leak in excess of the Technical Specification limit of 0.3 gpm occurred in steam generator "A". Initial ECT examination (with the standard "bobbin" probe) of about 35 tubes which had been identified as possible leakers by observation of moisture on the tubesheet, showed no indications of tube degradation other than those seen during previous inspections. Pressurization of the secondary side of the steam generator identified two leaking tubes.

Subsequent ECT examinations of the faulted tubes with the "bobbin" probe and an advanced "pancake"-style 4 x 4 ECT probe, which has better flaw detection capability for circumferential cracks and IGA, showed the defects to be through-wall with a circumferential orientation. The defect in one tube was found to be high in the straight, vertical hot-leg section of the tube at tube support plate No. 9, while the defect in the other tube was located in the horizontal section of a "Batwing." Additional ECT examinations were performed with both the "bobbin" and "4 x 4" probes to provide assurance that similar, pluggable defects did not exist in the remaining steam-generator tubes. Also, in recognition of the fact that one of the defects was found near the 90-degree bend plus the fact that the 4 x 4 ECT probe was incapable of transversing bends, CPC committed to develop a probe similar to the 4 x 4 probe but capable of transversing the full length of the tube for the 1983 steam generator inspection.

In 1983-84, CPC performed a 100% inspection of the steam generators with the new flexible "4 x 4 F" pancake probe. Initial ECT data, reported in October and November of 1983, indicated approximately 40,000 "non-quantifiable" indications and a large number of probable cracklike indications.

3.0 DISCUSSION

An extensive effort was conducted by the Licensee to identify the extent and nature of the apparent indications and to identify remedial actions. Portions of 56 steam generator tubes and approximately 70 tube-to-tube support plate intersections were removed from both steam generators for detailed metallurgical examination, chemical analysis and materials properties testing in order to correlate ECT indications with any observed degradation.

In addition, the licensee conducted a program based on 81 laboratory IGA samples in order to qualify the adequacy of the ECT technique to quantify the depth of IGA, to determine its sensitivity, and to establish its calibration. They confirmed that the IGA generated in the laboratory is metallurgically similar to that found in the actual steam generator and that ECT measurements on laboratory samples correlated with IGA samples removed from the steam generator.

As a result of this program, they have shown that the technique could correlate the volumetric loss of tube wall material due to IGA and express it as an equivalent average depth of intergranular attack within a statistical error of $\pm$ 6% of wall penetration and to a threshold of detectability of 30% of wall.

Conclusions reached by the licensee from the ECT results and the metallurgical examination are summarized as follows:

(1) Three types of OD initiated degradation are present on the tubes, these were general IGA, pits - shallow and deep, and IGA spikes. The deepest pit and the deepest IGA spike had 14% and 19% wall penetrations, respectively, A deep pit on one tube had 16% wall penetration.

(2) The incipient IGA and pits were distributed over all the tube sections, irrespective of their position in relation to the antivibration bars (AVBs). The IGA spikes appear to be limited to only the AVB intersections, where ECT indications were obtained.

(3) The class of ECT indications which the ECT interpreters had originally classed as "non-quantifiable" were shown not to be related to actual observable defects. Twelve tube-to-tube support plate intersections with indications that were called either "non-quantifiable" or "no-detectable-defect" were metallurgically examined and no degradation greater than 25% through wall were found. The eddy current signal associated with the "non-quantifiable" indications was apparently caused by surface deposits or dents. One intersection with a "no-detectable indication" was found to contain a 25% degradation.

(4) Three intersections from the B steam generator cold leg which had been identified by ECT as containing deep quantifiable defects were metallurgically examined and found to contain no degradation. The ECT signal was apparently caused by dents or tube deformation.

(5) Five intersections containing actual degradation (three cracklike defects and two IGA) were metallurgically examined. In all cases, ECT correctly called the degradation. In the case of the two IGA defects, ECT provided an accurate determination of the maximum average depth.

(6) The actual crack and IGA degradation was found to be less than 75 mils axial and 130° circumferential extent.

(7) The actual degradation was found to contain relatively large amounts of sulfur and the tubing was found to be highly sensitized. It is believed that the corrosion was caused by a reduced form of sulfur acting on sensitized Inconel-600 tubing and that it occurred prior to 1974, since similar pits and IGA spikes were observed in the tubes from the same steam generator in the 1974 examination.

(8) Most defects reside adjacent to dents at the upper or lower edge of the tube support plate.

(9) Since sulfur in the form of sulfide is noncorrosive, the licensee chooses not to remove the remaining sulfur from the secondary side of the steam generators.

In summary, the results show a total of 181 tubes with cracks and 29 tubes with IGA defects greater than 50%. The numbers for the "B" steam generator show 160 tubes with cracks and 22 tubes with IGA defects of greater than 50% depth. Similar numbers for the "A" steam generator are 21 tubes with cracks and 7 tubes with IGA defects greater than 50%. The licensee concluded that the steam generator tube IGA and pitting degradation were caused by reduced form of sulfur introduced in 1974.

4.0 EVALUATION

4.1 Determination of Causative Agent(s)

The licensee and its consultants conducted extensive microstructural and fractographic examinations on Inconel-600 tubing specimens taken from the Palisades steam generators. Degradation in the observed specimens exhibited a morphology characteristic of intergranular attack. In some instances, in addition to IGA, cracking was also observed.

Austenitic stainless steels and certain nickel-base alloys, such as Inconel-600, under certain conditions, are known to be susceptible to IGA and intergranular stress corrosion cracking (IGSCC). The occurrence of IGA requires the alloy to be in a sensitized condition or with a susceptible metallurgical condition and the presence of an aggressive environment. However, for IGSCC to occur, three conditions must be present simultaneously: (1) a high tensile stress, (2) a susceptible alloy microstructure, and (3) an aggressive environment.

Microstructural characterization of specimens taken from pulled tubes from the Palisades steam generator confirmed that the tubing alloy is typical for Inconel-600. In addition, the grain size (ASTM 5 and 7) is representative of mill annealed Alloy-600 microstructure with heavy carbide precipitation along grain boundaries. Modified Huey testing and electrochemical potentiokinetic reactivation (EPR) testing conducted by the licensee on removed tube sections confirmed that the alloy microstructure has been heavily sensitized. Based on this information, the staff agrees with the licensee's conclusion that the tubing in the Palisades S/Gs has been sensitized and is susceptible to IGA and IGSCC if containments are present in the S/G water.

Because the presence of IGA-causing corrosive species is a necessary condition for the observed tube degradation and cracking, the licensee and its consultants conducted numerous x-ray diffraction (XRD), scanning electron microscopy (SEM), and energy dispersive x-ray analysis (EDAX) on specimen taken from the defective tubes pulled from steam generators. The analytical results showed that high concentrations of sulfur existed. Although the presence of chloride, phosphorus, silicon, and calcium was also confirmed, sulfur, in the reduced form, is the only identified element that has been associated with IGA or IGSCC of Inconel-600[1, 2, 3].

Sulfur-induced IGA and IGSCC of sensitized stainless steels is a familiar phenomenon[1]. IGSCC of sensitized stainless steel by polythionic acid in defulfurizer hydrocrackers, and many other systems of the petrochemical industry has been well documented[2,3]. Furthermore, the sulfur-induced IGA and IGSCC have been previously observed in the nuclear industry and reproduced in laboratory tests by the licensee.

Based on the above analysis, the staff agrees with the licensee's conclusion that the type of corrosion observed at Palisades steam generator tube was primarily sulfur-induced IGA and, in some cases, accompanied by IGSCC.

4.2 Postulated Damage Scenario

Two types of corrosion related tube degradation were observed in the metallography. Intergrannular attack (IGA), and stress-assisted IGA or IGSCC. The licensee stated that the reduced sulfur and acidic pH, which occurred in the 1974 dry layup following sodium sulfite (Na_2SO_3) chemistry additions for oxygen control in secondary water, which is no longer used were responsible for the corrosion observed in 1974 and the currently detected steam generator tube degradation.

Given the referenced chemistry of reduced sulfur aqueous solutions, the postulated corrosion mechanism is supported directly by the following facts and observations:

(1) Removed tube degradation type, microstructure and sensitization, and reduced sulfur environment.

(2) Other similar commercial US PWR corrosion experience.

(3) CPC laboratory experience with generating IGA in sensitized Alloy-600.

(4) A definable plant event when sulfur corrosion is known to have occurred (1974 dry layup following Na_2SO_3 chemistry (oxygen control).

This scenerio is considered sufficient to account for local areas of IGA resulting from the dry layup event in 1973-1974. However, some tubes were found, in certain instances, to contain cracks within the

IGA. We attribute these cracks to the stresses imposed (operational-heatup/cooldown axial stresses, bending/dent related local stresses) in service(3).

Based upon the chemical analysis, and the correlation between the defects and sensitization, we conclude that the observed corrosion can be attributed to reduced sulfur, acidic pH, and the resulting stress-assisted IGA. The proposed damage scenario is consistent with known facts pertinent to the observed corrosion.

4.3 Determination of Intergrannular Attack Growth Rate

To define an operating allowance, the licensee developed repair criteria for the IGA detected during the 1983 steam generator inspection. This allowance consists of a minimum of two factors - eddy current accuracy and flaw growth rate. By comparing eddy current signals of pulled tube samples and laboratory IGA samples, and to a lessor degree on numerous historical data comparisons of in-generator suspected IGA indications, the licensee established a period in which IGA is believed to have occurred. Detail analysis and determination on IGA growth rate are described in Section 3.3 of the licensee's April 16, 1984 submittal.

The licensee attempted to establish a zero growth rate through the comparison of historical ECT data on IGA detected in 1983 with the sensitive 4 x 4 F probe and bobbin probe data collected prior to 1982. The licensee conceded that the ability of the bobbin probe to quantify IGA is poor. Therefore, their evaluation was qualitative and their argument to establish a zero growth rate was not convincing.

In addition, the staff felt that the occurrence of tube leaks in 1982 and the metallographic examination finding of cracks and IGA depths of up to 100% throughwall in samples removed in 1983-84 was not consistent with the licensee's contention of no defect growth since 1974. The staff was unconvinced by the licensee's argument that since plant chemistry records show a small level of leakage that fluctuated between 0.01/gal/min and zero from June 1975, that the tube leak event that occurred in 1982 was due to the opening up of a pre-existing (since 1974) throughwall crack caused by tube lockup loads imposed by denting which held the tube rigid against the support plates.

For the above stated reason we could not accept the licensee's argument and rule out the possibility of the development of a throughwall defect during the next operational period. We have therefore requested, and the licensee has agreed to implement a more stringent primary to secondary leakage rate limit than the 0.3gpm limit imposed by the Technical Specifiction. By letter dated May 15, 1984, the licensee agreed to reduce the allowable primary to secondary leakage limit to 0.1 gallon per minute. These restrictions will be imposed either by a "Standing Order" or a change to plant operating procedures. The leakage limit for periods of startup and major load changes will remain as currently specified in the Technical Specification. We find this acceptable.

4.4 Actions to Prevent Recurrence

Considering the nature of the observed steam generator tube degradation, the probable cause, and the rate of progression, the licensee has controlled the exposure of the tube to air or oxygen as the main measure to prevent recurrence of the observed corrosion. As such no specific changes in current operating practice are necessary. Continued emphasis on reducing periods of air exposure of tubing and controlling dissolved oxygen contents of the operating or layup fluids should be sufficient, since these measures have been effectively employed prior to 1978, when the degradation was stiffled.

Techniques for removal of the stable non-corrosive sulfur (presently as sulfide) has not been commercially demonstrated. Oxidation of the sulfur to sulfate during desulfurization process would risk additional tube corrosion due to the formation of the polythionate anions which are most likely responsible for the observed corrosion.

Based on the above analysis, the staff agrees with the licensee's decision not to desulfurize the secondary side, and concludes that reducing the exposure of the tubes to air or oxygen provides reasonable assurance that the observed tube degradation will not recur.

4.5 Conclusions

We conclude that the licensee has (1) identified the agent which caused the S/G tube degradation; (2) postulated a damage scenario which is consistent with the known facts pertinent to the observed corrosion; and (3) taken necessary actions to prevent recurrence of the observed S/G tube degradation.

The criteria of Regulatory Guide 1.121 provides for an operational allowance over the minimum steam generator tube wall required to preclude tube burst, consisting of two factors, an eddy current uncertainty and an allowance for possible flaw growth during the operational period. The licensee has adopted a plugging criteria of 51% through wall with the stipulation that all cracklike defects are plugged regardless of depth.

As discussed in Section 5.2 of this safety evaluation, the staff finds that a defect which is limited to 0.380 inches axial, 360° circumferential and 82 percent through-wall is acceptable. This provides an operational allowance of 31%. We conclude that this combined operational allowance for eddy current uncertainty and degradation growth rate along with the more stringent primary to secondary leakage rate allowance of 0.1gpm, provides reasonable assurance that the Palisades Nuclear Plant can be operated without undue risk to the public health and safety.

5.0 STEAM GENERATOR TUBE INTEGRITY EVALUATION

The requirements for steam generator tube plugging have been calculated in accordance with the guidelines set forth in Regulatory Guide 1.121 entitled "Basis for Plugging Degraded PWR Steam Generator Tubes", Reference 5. The basic requirements are summarized below.

1. For normal plant operation, primary tube stresses are limited such that a margin of 3 is provided against exceeding the ultimate tensile strength of the tube material, and the yield strength of the tube material is not exceeded.

2. For accident conditions, the requirements of paragraph NB-3225 of Section III of the ASME Code are to be met.

   In addition, it must be demonstrated that applied loads are less than the burst strength of the tubes at operating temperature as determined by testing.

3. For all design transients, the cumulative fatigue usage factor must be less than unity.

In addition, leak before break must be demonstrated i.e., through wall cracks with a specified leakage limit during normal operation do not propagate and result in tube rupture during postulated accident conditions.

For the evaluation of the plugging limit for the Palisades tubes the following information was used:

Tubing Geometry:	0.750" Diameter
	0.048" Thick
Material Properties:	S_Y = 27.9 Ksi at 600°F
	S_U = 80.8 Ksi at 600°F
Operating Conditions:	Normal: P_i = 2150 psi
	P_o = 770 psi
	Δ_p = 1380 psi
	Steam Line Break (SLB)
	Δ_p = 2150 psi
	Loss of Coolant Accident (LOCA)
	Maximum external pressure, zero internal pressure

The demonstration of tube integrity for uniform thinning of up to 64 percent is contained in Reference 6. For the purpose of establishing the tube integrity in bending for other than uniform thinning, a comparison of the structural capabilities relative to uniform thinning, was used as the basis.

Since Regulatory Guide 1.121 constitutes an operating rather than a design requirement, the allowable stress limits are based on expected lower bound actual material properties (as opposed to the Code specified minimum values). Expected strength properties were obtained from analyses of tensile test data of actual production tubing. These calculations were performed to support the uniform thinning plugging margin evaluation reported by Reference 6.

The degradation experienced in the Palisades steam generators is limited in both axial and azimuthal extent. The size of actual defects removed from the generator exhibits axial lengths of approximately 0.050" and azimuthal lengths of about 90 to 100 degrees. This range of defects can be conservatively bounded by considering the axial extent to be 0.075" and the azimuthal extent to be 135° (which conservatively envelopes the Eddy current testing (ET) limits of detectability of 130° for azimuthal tube degradation) for evaluation purposes. Defects limited to the extent specified could be analyzed as cracks since Inconel 600 is a ductile material and the crack tip plastic zone could be on the order of the axial extent dimension. For a tight circumferential crack, crack tip blunting to the axial extent of Palisades defects would occur before crack extension. For defects longer than the 0.075" considered to be bounding, the burst behavior of the tubes may or may not be adequately described by treating the defects as crack-like. In addition, since ET techniques are currently inadequate to accurately describe defect axial lengths below about 0.200", it is considered necessary to evaluate the Palisades degradation without relying on specifically characterizing the defects as having crack-like behavior.

The usual evaluation procedure employed to assess the effects of tube degradation assumes that the degradation extent is around the full circumference of the tube and is unlimited in the axial direction ($>$ 2.0 in.). Thus, the analysis is based on evaluating a uniform tube with a thickness equal to the minimum remaining thickness of the degraded tube. This has, in the past, been the usual approach based on the expediency of performing the analysis and the lack of a significant data base which could be used to quantify the beneficial effect of the degradation being of limited extent.

Limiting the extent of degradation has the effect of also limiting the stresses in the material in the degraded area. For degradation of limited axial extent, the magnitude of the hoop stress in the degraded area is restricted by the adjacent thicker material. For degradation of limited azimuthal extent, the adjacent material restricts the magnitude of the axial stress. The reinforcing effects of adjacent undegraded tube material can be quantified using available testing information on tubes with limited extent degradation, coupled with lower bound type collapse evaluations.

Effects of depth of thinning along with axial and circumferential extents of thinning on the burst strength of Inconel 600 tubing have been represented on a plot of axial extent of thinning versus depth of thinning by a family of curves which present the loci of all geometries having a given burst pressure. For tubes thinned completely around the circumference (360°) over a certain axial length, an empirical equation from Reference 4 was used to calculate burst pressure.

Results from limited axial extent, uniform circumferential thinning burst tests are also reported in Reference 7. In addition, an empirical equation was developed for relating the ratio of the burst pressure for the degraded tube to the burst pressure for the undegraded tube, the remaining strength fraction (RSF), to the remaining wall fraction (RWF) of the tube. A comparison of this empirical equation with test data indicates that for a RWF less than a specified value the burst pressure is overpredicted.

For normal tubes, and those in which the thinning is relatively long, the mode of burst failure is characterized by the opening of an axially oriented split due to the hoop stress being the maximum primary stress in the tube. For degradation of limited extent, the hoop stress in the degraded area is restricted by the amount of hoop deformation taking place in the undegraded region of the tube. The axial stress is however, mainly dependent on the remaining thickness. For small axial extent some notch strengthening will take place, but this will be of minor significance. For large depths and small axial extent the axial stress will become larger than the hoop stress and the mode of failure will be a circumferential separation rather than axial. This, in effect, limits the amount of strengthening which can be realized to a factor of 2, the ratio of the magnitude of hoop to axial stress in a tube of uniform thickness. The licensee has developed relations to predict the strengthening due this reinforcement that can be achieved by the undegraded material. In order to validate the use of these relations for application to Palisades, the data base in Reference 7 was expanded to include Westinghouse data for a variety of tube sizes and data specific to the heats of material used for the Palisades tubes. It was determined that the Reference 7 results are in general conservative with respect to the added Westinghouse and Palisades data. On this basis it was judged that these relations are applicable to Palisades and could be used to quantify the effect of limited axial extent on the burst pressure.

In order to evaluate actual tube burst performance during SLB, a tolerance line with a 95 percent probability of forming a lower bound for 95 percent of the population underlying the Reference 7 data was developed.

The final form of a plugging limit relation for tubes with limited axial extent was developed to satisfy the structural requirements of Regulatory Guide 1.121. The requirement for demonstrating adequacy using a factor of safety of 3 relative to the ultimate tensile strength is more restrictive than the primary stress requirements relative to yield strength and accident condition loads.

For the yield strength requirement of Regulatory Guide 1.121 it is noted that:

$$\frac{S_U}{S_Y} = 2.87$$

so $$S_Y = S_U/2.87 > S_U/3.0$$

Thus, limiting primary membrane stress, P_m, based on a factor of 3 relative to ultimate is conservative as compared to limiting P_m to less than the yield stress.

Similarly, the pressure differential during steam lein break (SLB) is related to the normal operating pressure as:

$$P_{SLB} = \frac{2150}{1380} \Delta P_o = 1.56 \Delta P_o$$

The stress limit during SLB is the lesser of 2.4 S_m or 0.7 S_U where S_m is found as the lesser of 2 $S_Y/3$ or $S_U/3$ at temperature. Using the Palisades tube properties, P_m is limited as given by the following equation:

$$P_m \leqslant 44.6 \text{ ksi} = 1.67\ (S_U/3)$$

Since the allowable stress is 67 percent larger than that during normal operation and the loading is only 56 percent larger, the requirement against the ultimate tensile strength is more restrictive.

For unlimited thinning, it is shown in Reference 6 that the amount of uniform degradation which can be accommodated is 64 percent. For limited axial extent thinning the wall thickness required to provide the same margin against circumferential burst is 0.0085", for an allowable degradation maximum of 82 percent. In order to account for the reinforcing effect for flaws of limited azimuthal extent, information was provided considering the effect on burst pressure of circumferential cracks (representing zero axial extent), the effect of burst pressure of axial part through wall and through wall cracks (representing zero azimuthal extent), and 90° and 180° upper bound limit solutions for rectangular patch type degradation (finite but limited axial and aximuthal dimensions). The evaluation for limited circumferential cracking relative to burst pressure is presented in the leak before break evaluation section of Reference 4. Considering the pressure differential of 4140 psi, burst would be expected for a circumferential crack with an included angle of 145°. Therefore, for cracks with less than an included angle of 145°, a margin of 3 against burst at normal operaing pressures exists relative to actual test data. The plugging limit developed for 360° thinning can be considered equally applicable for thinning limited in azimuthal extent to 145°.

Analytical models have been developed to compute the burst strength of Inconel 600 tubes with thinned areas of limited axial and circumferential extent. Effects of geometry on burst strength have been presented in terms of plots of axial extent of thinning and depth of thinning resulting in a given burst pressure. Effects of the extent of circumferential thinning on burst strength have been represented by a number of strength locus curves corresponding to different arc lengths of circumferential thinning. On the basis of these evaluations it has been demonstrated that a tube with through wall degradation up to 0.075 inches in axial extent and up to 145° in azimuthal extent is sufficient to withstand normal operating pressure with a factor of safety of 3.

An additional requirement from Regulatory Guide 1.121 relative to burst at steamline break, i.e., beyond the evaluation of primary membrane stress, is that margin be provided against the ultimate burst pressure as determined by burst tests performed at operating temperature. For this evaluation the lower tolerance limit line from the Reference 4 data was used to determine axial burst values expected for steamline break conditions. Since the lower tolerance limit is adequately below all of the additional data plotted and the original data, it provides a sufficient basis for evaluating axial burst pressures. In addition, a lower tolerance value for the undegraded burst pressure was used based on results reported in References 8 and 9. This evaluation demonstrates that axial burst pressures for the limited axial extent plugging criteria for steamline break are above the criteria established using a safety factor of 3 based on ultimate tensile strength.

Beyond the evaluation requirements on primary membrane stresses and the steamline break ultimate test pressures, Regulatory Guide 1.121 also requires that degraded tubes be evaluated in accordance with the requirements of the ASME Code Section III, Paragraph NB-3225. This paragraph of the ASME Code invokes the rules of Appendix F of the Code for the evaluation of faulted condition limits. In general, there are no primary bending stresses at degraded tube locations. This is either due to: (1) the ability to withstand bending moments is not necessary to satisfy requirements for equilibrium, or (2) deformations under accident conditions are limited by either the anti-vibration devices or the general deformation of the overall tube bundle, thus deformation of the degraded tube is displacement controlled. However, a comparison was made for the limited axial extent plugging margin criteria with the uniform thinning plugging margin criteria. In this case the ultimate limit moments were calculated for each degradation condition. As a limiting condition for the limited axial extent degradation, a 135° through wall crack was considered. This crack represents the maximum expected azimuthal extent in the Palisades steam generators. For this condition the ultimate bending moment for the limited axial extent plugging criteria is 12 percent higher than the limiting ultimate moment for a uniform thinning criteria of 64 percent. In addition, a comparison of the section properties was made for degradation extending to 135°

and 82 percent throughwall. In this case both the moment of inertia and the section modulus for the limited axial and azimuthal extent plugging margin criteria is greater than that for a tube degraded uniformly to 64 percent through wall.

Consideration of external collapse per the Code requirements can be made based on collapse data presented in Reference 7 The reference document demonstrates that for 0.875 inch diameter by 0.050 inch thick tubes, which have a collapse strength less than 84 percent of that for the Palisades 0.750 inch diameter by 0.048 inch thick tubes, that the collapse pressure is relatively unaffected for uniform thinning 3/8 ~~of~~ an inch long by 360° azimuthally for degradation up to 60 percent through wall. For degradation at 80 percent through wall, the collapse pressure was demonstrated to be ½ to 1 times ~~the~~ undefected tube collapse pressure. For all collapse tests performed, which included degradation up to 80 percent of the wall and 1.5 inches in axial length, the collapse pressures found were well in excess of the external secondary pressure during LOCA. In addition the limited degraded tube is judged to have more resistance to collapse than a tube which has been uniformly degraded with unlimited aximuthal and axial extent up to 64 percent through wall.

In order to examine the fatigue resistance for the limited extent plugging margin criteria, the evaluation was made of the tolerable stress concentration factor for a tube with no degradation, but including the effects of denting (to consider the bounding effect of a tube locked-in at the tube support plates), vibration and thermal stresses. It was found that a maximum allowable stress concentration factor (SCF) of 5.9 could be tolerated to result in a 40 year design life usage factor of 1.0. For degradation of limited axial extent, excluding cracks, the maximum stress concentration factor required by the ASME Code is 5.0.

For the case of through wall cracking, it is noted that there are very few cycles of significant stress levels. This results in low alternating fracture stress intensity values. The alternating fracture stress intensity is directly related to the alternative stress perpendicular to the flanks of the crack multiplied by the square root of pi times ½ the crack length, times a function of the crack length to thickness ratio. For the case of the Palisades tubes, the alternating stress is judged to be of the order of 7 ksi. For crack lengths which were on the order of twice the wall thickness, which would be the case for degradation with stress corrosion cracks, the alternating stress intensity factor would be less than the threshold required for crack growth. In addition, very deep cracks would be needed to plastically yield the remaining ligament of the tube. Crack growth would be on the order of the cyclic crack tip displacement, in which case several mils of growth would represent a generous fatigue crack growth allowance.

In summary the Regulatory Guide 1.121 structural requirement for normal operating conditions (maintenance or a factor of safety of 3 against burst) and accident conditions (compliance with pararaph NB-3225 of Section III of the ASME Code) have been met by the tube with 360° thinning of 82 percent with axial extent limited to 0.380 inches. Such a defect also satisfies the fatigue usage requirements for all applicable design transients.

5.1 Leak Before Break Evaluations

Two separate approaches were considered applicable to the Palisades defects to demonstrate leak before break. The first of these is based on the observed morphology that indicates that the defects could be evaluated as cracks. The second is based on considerations of finite axial extent in accordance with the range of the structural criteria discussed earlier.

These evaluations demonstrate that through wall cracking would develop prior to the crack reaching the critical circumferential length for a postulated SLB event. The growth of part through wall cracks in tubes at Palisades have been observed to exhibit a limited aspect ratio which results in extension through the wall prior to reaching the critical SLB bursting length. Furthermore, based on geometrical considerations, circumferential crack extension beyond 60° will lead to the axial bending stresses being a maximum at the crack front thus encouraging preferential growth through the wall. Evaluation of leak before break for degradation with finite axial extent was performed considering the limited extent upper bound of 82 percent to be uniform thinning extending 360° circumferentially and of unlimited axial extent. Final information is provided in the form of a pair of curves, one for cracks leaking at the technical specification limit and the other for burst a SLB. THe leak before break margin can be read as the distance between the curves as a function of crack extent and degradation depth. Based on these analytical evaluations the licensee has demonstrated that through wall cracking would develop prior to the crack reaching the length for a postulated SLB event.

5.2 Conclusions

Based on a review of the analyses and test data provided by the licensee in Section 4 of Reference 4 the staff concludes: (1) The structural limit of 82 percent for defects which are limited in axial extent to 0.075 and up to 135° in azimuthal extent is sufficient to meet the normal operating conditions, accident conditions and fatigue usage requirements outlined in Regulatory Guide 1.121. This includes the maintenance of a safety factor of 3 relative to ultimate strength which is the most restrictive primary membrane stress limit. (2) Leak before break has been demonstrated for degradation of extent limited such that it can be considered to behave as a crack. (3) A tube with 360° thinning of 82 percent with axial extent limited to 0.380 inches, has a safety factor against burst comparable to the margin afforded pressure vessels designed in accordance with Section III, of the ASME B and PV Code. (4) Leak before break of circumferential cracks has been demonstrated for uniform thinning degradation, extending 360° circumferentially and of unlimited axial extent, to a depth of 69 percent of the tube thickness. (5) The structural limit for uniformly thinned tubes with unlimited axial and circumferential extents is 64 percent thinning.

In accordance with these conclusions, a defect which is limited to 0.380 inches axial, 360° circumferential and 82 percent through-wall is acceptable. Therefore, as discussed in Section 4.5 of this report, the threshold for corrective action was determined by reducing the 82 percent through-wall by (1) an allowance for eddy current uncertainty, and (2) an allowance for possible flow growth during the operational period.

The staff finds the repair criterion of 51% through-wall acceptable for Palisades steam generators.

6.0 SUPPORT PLATE DEGRADATION CONSIDERATIONS

Evidence of denting related tube-to-tube support plate (TSP) interaction was observed during tube pulling and support plate removal operations at Palisades during the present outage. In certain instances large forces were required to remove tube specimens. Steam generator tube denting results in tubes being locked into tube support plates. The configuration of the TSP/tube bundle and corrosion mechanism leading to denting results in the development of compressive forces on the tubes and expansion of the tube support plate. This interaction can eventually lead to significant distortion of the TSP and cracking at areas of high stress concentration (e.g., TSP flow holes and slots).

Secondary side visual inspection of TSPs 14, 13, 12 and portions of 11 at the accessible periphery and in locations where TSP sections have been removed in the Palisades steam generators revealed no significant tube support plate degradation as a result of tube denting. In addition, ET data indicates denting growth rate has decreased in recent years. However, for conservatism, the structural analyses were performed to provide the basis for the determination that Palisades steam generator tube bundle integrity is maintained even if a single support plate is postulated to be missing, i.e. to lose its load carrying capability or fail to provide support for a tube.

A primary load capability evaluation of the Palisades steam generator tube bundle under an assumed general degradation was conducted using postulated SLB, LOCA and SSE loading. Tubing collapse potential and the resulting loss of tube flow area during a postulated LOCA and SSE event were analyzed. A detailed evaluation of the Palisades steam generator tubes in terms of responses to such forcing functions as turbulence and vortex shedding mechanisms and fluid elastic stability criteria was completed (i.e., a normal operation fluid-structure interaction evaluation). Fatigue effects resulting from the flow induced motions were also evaluated. Worst case vertical and horizontal tube spans were analyzed with a single tube support plate missing. Finally, tube wear estimates were calculated assuming a postulated TSP fragment and partial TSP support.

6.1 CONCLUSIONS

Based on review of the analyses presented by the license relative to the postulated loss of a single support plate, the potential tube flow area loss due to tube collapse during a LOCA and concurrent SSE, tube vibration and postulated loose plate pieces the staff concludes:

* The postulated loss of a single support plate does not adversely affect the tube bundle integrity during LOCA, SSE or SLB accident condition loadings.

* The potential tube flow area loss due to tube collapse during LOCA and concurrent SSE is equivalent to less than 260 tubes (of which 63 are currently plugged) with the postulated loss of load carrying capability of a single support plate.

* Tube vibration during normal operation should not be significant from flow-induced vibration mechanisms considering the postulated loss of a single support plate.

* Neither tube vibration nor postulated loose plate pieces lead to premature wear-through of a tube.

7.0 ACKNOWLEDGEMENT

H. Conrad, P. Wu, and J. Rajan prepared this report.

Dated: June 11, 1984

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