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REVIEW OF TUBE SUPPORT PLATE ANALYSIS FOR STEAM GENERATORS OF MILLSTONE UNIT II NUCLEAR POWER PLANT

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ABSTRACT

Magnetite growth in steam generator tube support plates was observed in the Millstone Unit II Nuclear Power Plant. If growth is allowed to continue, the tube may eventually fail resulting from plate shifting and the squeezing action of the growing magnetite. The corrective actions undertaken by the Northeast Nuclear Energy Company (NNECO) for this effect have been summarized in a report submitted to the U.S. Nuclear Regulatory Commission (NRC) entitled, "Millstone Unit No. II Steam Generator Repairs and Corrective Actions," Docket No. 50-336. The analytical study part of this report is reviewed here, and conclusions and recommendations for further research are given.

1. INTRODUCTION

The subject report[†] under review was prepared by the Northeast Nuclear Energy Company (NNECO) at the request of the U.S. Nuclear Regulatory Commission (NRC) describing corrective actions undertaken to repair denting-related damage that has occurred in the Millstone Unit II steam generator tubes and tube bundle support plates (Fig. 1). Also included are different analyses evaluating the safety impact of these repairs on continuing operations for the scheduled duration of Cycle 2.

Early tube denting was detected in May 1977. It appeared to be a direct result of magnetite (Fe_3O_4) growth in the annulus between a tube and a support plate and caused by secondary water chloride contamination from condenser leaks. Afterward, the condenser was retubed and the plant resumed operation in June 1977. The tube denting continued to grow but at a reduced rate. By November 1977, a continuous series of ligament cracks between tube holes and flow holes in support plate Nos. 10 and 11 was observed. Shifting of the perforated portion of the plate relative to the rim portion at the crack line produced a shearing action on the tubes that deformed the tube wall. Since the November 1977 shutdown, NNECO has:

- Removed the welded lugs on support plate Nos. 10 and 11 and the rim section from support plate No. 11 (see Fig. 1) to reduce the tendency for further support plate shifting along crack lines.
- Inspected all tubes passing through support plate Nos. 10 and 11 by Eddy Current Test (ECT) probes during the ECT program conducted in January 1978. Following this program, about 300 out of the 4400 tubes passing through support plate Nos. 10 and 11 in each steam generator were plugged (pp. 3-4 and 3-5, NNECO report). These plug tubes were
 - Adjacent to the solid rim.
 - Not accepting the ECT probe, i.e., the tube denting had reduced the inner hole of the tube so that the ECT probe (0.54-in. o.d.)

[†] Hereafter referred to as NNECO report, see Reference 1.

FIG. 1. Millstone Unit II steam generator tube bundle and support plates.

could not penetrate. Based on the 0.654-in. i.d. of the tube, the magnitude of denting in these tubes is at least $(0.654 \text{ in.} - 0.540 \text{ in.})/2 = 0.057 \text{ in.}$ (57 mils)[†] on the radius.

- Surrounded by the dented tubes in (2) above.
- Lying along an apparent continuous series of cracks.

For the unplugged tubes, the recorded maximum radial dents for both steam generators are 24 mils on the cold side and 15 mils on the hot side.

The effectiveness of the modified tube bundle support plates in reducing support plate/tube deformations at different stages of magnetite growth (including that expected during Cycle 2) was assessed by analytical studies presented in Sec. 4.3, pp. 4-10 to 4-30, of the NNECO report. These studies are reviewed herein, and a tentative plan for a modified and expanded analysis program is proposed and outlined in the Conclusions and Recommendations.

[†]One mil = one thousandth of an inch.

2. REVIEW OF NNECO SUPPORT PLATE/TUBE ANALYSIS

NNECO has performed the following tasks in order to provide an analytical evaluation of the modified support design:

- Collected support plate and tube geometry and material properties.
- Developed denting model relating magnetite growth, plate corrosion, and tube denting (see discussion on support plate corrosion and tube denting in section 3.2 of this report).
- Obtained support plate uniaxial stress-strain curves from experiments (Fig. 4.3-6, NNECO report).
- Obtained the load (axisymmetrical external loading) vs deformation (axisymmetrical denting) curves for a typical tube (Inconel 600 material) from experiments (Fig. 4.3-7, NNECO report).
- Used the nonlinear stress analysis program ANSYS (Engineering Analysis Systems) to obtain the internal pressure vs plate expansion curve for the unrestrained, perforated support plate No. 11 without lugs and rim section (Fig. 4.3-12, NNECO report).
- Determined the maximum local ligament membrane stress around the tube holes at radial denting values of 10 and 15 mils (projected denting levels in Cycle 2). The results indicated that the local ligament stress at these denting levels should not exceed the ultimate strength.
- Studied the effect of different constraints for perforated support plates. Three cases were examined: support plate with lugs and rim; plate without lugs, but with rim sections; and the unrestrained support plate. Only linear-elastic analyses were performed. The effect of lug and rim restraints on the perforated support plate was seen by comparing the results of the three analyses. In these analyses, a local-region finite element analysis was performed to generate the stiffness properties for the perforated support plate region. The possibility of further support plate shifting in support plate No. 10 was examined as a result of the elastic analysis. It was concluded that no further support plate shifting should occur in modified support plate Nos. 10 and 11 for the projected dent growth to 15 mils.

3. COMMENTS

3.1 DENTING MEASUREMENT

Many denting deformation modes are possible and not all are axisymmetric (refer to Table 1). An ECT probe presumably measures the gap between the inside surface of the tube and the outer diameter of the probe. In the case of nonaxisymmetric tube deformations, the gap width is not uniform around the circumferential direction, and the ECT measurement must represent an averaged value of denting. The expression for this averaged value should be given.

TABLE 1. Denting deformation modes.

Cause	Mode	Remarks
1. Direct squeezing action from magnetite expansion in the annulus		Axisymmetric deformation often occurs at early stage of denting
2. Same as 1 above, but the squeezed shape is nonaxisymmetric		This deformation pattern may occur at late stage of denting
3. Plate rigid body movement resulting from magnetite growth in tube holes		Tube is being pushed in the direction of support plate movement and squashed on contact
4. Continuing support plate expansion in the unstrained direction causing a shear crack to develop in the weak plane		Shifting movement across the crack causes the deformation of the intersected tube

During the November 1977 ECT inspection, a selected group of 104 of measurements were taken from steam generator Unit II. The average values of these measurements were reported to be as follows (p. 4-27, NNECO report):

<u>Plate[†]</u>	<u>Mar. 1977</u>	<u>Nov. 1977</u>
No. 11 hot leg	4.9 mils	6.0 mils
No. 10 hot leg	5.6 mils	6.4 mils
No. 10 cold leg	8.6 mils	9.7 mils
No. 11 cold leg	7.9 mils	---

During the following ECT inspection program in January 1978, all 8800 tubes passing support plate Nos. 10 and 11 were inspected for the two steam generators. NNECO reported only the maximum values of the results (24 mils on cold-leg side and 15 mils on hot-leg side), and no other test results (data) were mentioned. Because the January 1978 data are more complete than the data obtained from the November 1977 inspections, they should be used as the denting data for the analysis described in Sec. 4.3 of the NNECO report.

3.2 SUPPORT PLATE CORROSION AND TUBE DENTING

Two assumptions were made about the denting phenomenon:

- The rate of plate corrosion was equal to the rate of tube denting (measured radially).
- Two parts of magnetite will grow out of one part of corroded plate.^{††}

To illustrate the inconsistencies between these two assumptions, calculations were made and are shown below.

[†]See Fig. 1 for support plate locations.

^{††}The 2:1 ratio is probably realistic because magnetite (Fe_3O_4) is chemically formed out of steel plate material; its density is about one-half that of steel.

From considering the compatibility of radial displacements in the axisymmetric mode, the relationship of magnetite growth (δ_{mag}), plate corrosion (δ_{cor}), gap (δ_{gap}), tube deformation (δ_{dent}), and plate deformation (δ_{plate}) is given by

$$\delta_{\text{mag}} = \delta_{\text{cor}} + \delta_{\text{gap}} + \delta_{\text{dent}} + \delta_{\text{plate}} \quad (1)$$

By substituting $\delta_{\text{mag}} = 2\delta_{\text{cor}}$ (which is the second assumption), Eq. (1) becomes

$$\delta_{\text{cor}} = \delta_{\text{gap}} + \delta_{\text{dent}} + \delta_{\text{plate}} \quad (2)$$

In contrast, $\delta_{\text{cor}} = \delta_{\text{dent}}$ (the first assumption) was used in the NNECO report. It should be noted that before the annulus between the support plate and the tube is filled, there is no interference stress. During this period, both δ_{dent} and δ_{plate} are zero.

Support plate corrosion around the tube hole reduces the minimum ligament thickness between the flow hole and the tubehole by δ_{cor} . The reduced ligament thickness is

$$t = t_0 - \delta_{\text{cor}} \quad (3)$$

where

t_0 = ligament thickness without corrosion.

3.3 LIGAMENT STRESS CALCULATIONS

Using Eq. (2) for δ_{cor} in lieu of $\delta_{\text{cor}} = \delta_{\text{dent}}$ will reduce the ligament thickness (t). As a result, the local ligament stress (σ_m) obtained will be larger than that computed by NNECO using t_0 .

Examples are as follows:

- For a 10-mil dent ($\delta_{\text{dent}} = 10$ mils),

$$\sigma_m = \frac{PR}{t} = 85 \text{ ksi (vs 54.8 ksi on p. 4-28, NNECO report)}$$

where

$$\begin{aligned} P &= \text{internal pressure} = 7.6 \text{ ksi} \\ R &= \text{hole radius} = 0.375 \text{ in.} \\ t &= \text{reduced ligament thickness } (t_o - \delta_{\text{cor}}) = 0.062 - \delta_{\text{cor}} \\ &= 0.062 - (0.015 + 0.010 + (0.39) (0.09)^{\dagger})^{\dagger\dagger} = 0.0335 \text{ in.} \end{aligned}$$

- For a 15-mil dent ($\delta_{\text{dent}} = 15 \text{ mils}$),

$$\sigma_m = \frac{PR}{t} = 110 \text{ ksi (vs 65.4 ksi on p. 4-29, NNECO report)}$$

where

$$\begin{aligned} P &= 8.2 \text{ ksi} \\ R &= 0.375 \text{ in.} \\ t &= 0.062 - (0.015 + 0.015 + (0.39) (0.011)^{\dagger})^{\dagger\dagger} = 0.0277 \text{ in.} \end{aligned}$$

Since the ultimate strength of the support plate was reported to be 79.9 ksi to 89.9 ksi (Table 4.3.1, NNECO report), these results indicate that the ligament around the dented holes was close to fracture at 10-mil denting, and should have fractured at 15-mil denting.

3.4 DENTING-RELATED STRESSES IN ASME III CODE EVALUATION

The tube and support plate stresses developed at different stages of magnetite growth have been evaluated in the NNECO report from the standpoint of whether or not the stress will exceed the ultimate strength of the component. Because denting is expected to grow throughout the plant operation and the denting-related stresses are by nature self-limiting or deformation-controlled, they may have to be included in the usual ASME III code service level A or B stress checks along with other expected stresses during normal operations. Additionally, when checking for tube failure using the ultimate strength criteria, stresses due to other causes (i.e., internal pressure, gravity, and earthquake effects) should also be included.

[†]Support plate hole radius times support plate expansion, in % strain (obtained by entering the dent value (δ_{dent}) into Fig. 4.3-12, NNECO report).

^{††} $\delta_{\text{cor}} = \delta_{\text{gap}} + \delta_{\text{dent}} + \delta_{\text{plate}}$ in Eq. (2).

3.5 UNRESTRAINED SUPPORT PLATE ANALYSIS

Comment 1: An explanation is required as to why the "true" stress-strain curve in Fig. 4.3.6 of the NNECO report instead of a "nominal" one was used in ANSYS analysis. Is this because ANSYS analysis was performed considering geometric nonlinearity?

Comment 2: The local-region model used for predicting support plate free expansion is given in Fig. 4.3-10 of the NNECO report. This model can be used only if it is assumed that there is no interaction between the model and the neighboring pieces, or that no boundary forces can develop around the model during support plate expansion. Justification for this assumption is needed.

Comment 3: The report did not mention which curve (mechanical test or pressure tests in Fig. 4.3.7 of the NNECO report) was used in the later analysis to relate denting pressure with the amount of denting.

3.6 SECONDARY CONDITION ANALYSIS (SUPPORT PLATE RESTRAINT EFFECTS)

Comment 1: The equivalent elastic modulus and Poisson's ratio obtained from the NNECO finite element analysis for the perforated region do not compare well with the results values obtained from Fig. A-8131-1, Appendix A, ASME III code.[†] It should be pointed out that in the ASME perforated plate geometry there are no 1/4-in. flow holes. To correct for this effect, the minimum thickness (h) was taken as that across two tube holes which cut through the flow hole, as illustrated below:

[†]See Fig. 2. The curves were obtained from a theoretical closed-form analysis.

FIG. 2 Equivalent perforated plate properties, E^* and ν^* , as a function of ligament efficiency.

The ligament efficiency factor, h/p (ligament thickness divided by the hole pitch), is then equal to $0.14/1.0 = 0.14$. From Fig. 2, for $h/P = 0.14$, $E^*/E = 0.075$, and $\nu^* = 0.56$, then $E^* = 0.075E$ (modulus of elasticity in ksi) $= 0.075 (26.15 \times 10^3) = 1.96 \times 10^3$ ksi. In comparison, the results from Sec. 4.3.31 (p. 4-20) of the NNECO report are $E^* = 3.76$ ksi, $\nu^* = 0.322$. In view of the significant large discrepancy between the two E^* values, it seems possible that a factor of 10^3 was omitted in the NNECO report.

Comment 2: Since the tubes are bonded to the plate through the magnetite, the resultant stiffening effect should be considered in generating the perforated plate stiffness properties.

Comment 3: It is apparent by comparing results from the elastic analyses of different constraints that considerable relief on secondary (restraint induced) stresses can be achieved by removing the lug supports (Sec. 4.3.4.3, NNECO report). However, the elastic analysis method is not adequate to predict support plate behavior under constrained configurations because the perforated support plate has already yielded at an early denting state (at about 5 mils), and the consideration of plasticity must be included in the analysis. Without such an analysis, it is difficult to determine whether further support plate fracture will occur in support plate No. 10 for the projected denting growth in operation Cycle 2.

Comment 4: An explanation is required as to how the following conclusion was reached: "Considering the lower support plate No. 10, the rim is essentially against the shroud at 10-mil denting."

Comment 5: The effect of existing crack openings resulting from support plate shifting was not considered in the analysis of the secondary stress in support plate No. 10.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The important conclusions from reviewing the tube support analysis completed by NNECO are listed below:

- The relationship between the amount of support plate corrosion and tube denting needs further examination, as it is not consistent with the magnetite growth assumption. Using a consistent relationship (Eq. 2) will lead to the conclusion that at a denting level of 15 mils (projected maximum value for Cycle 2 operation), the ligament local stress should have exceeded the ultimate strength and, hence, failed. To understand the exact mechanism of magnetite growth, further investigations are needed. So far NNECO has proposed laboratory inspection of dented tube/support plate samples.
- Further guidance on code classification of dent-related stresses is needed for ASME code evaluation.
- The analysis procedure for predicting deformations in the restraint-free perforated support plate (support plate No. 11 without lug and rim restraints) is generally acceptable. An improved analytical model to account for the gradual reduction of the ligament resulting from support plate corrosion would be more desirable.
- The effect of restraining the perforated support plate was studied by comparing elastic analysis results of unrestrained and restrained models. It failed to account for the fact that the support plate will reach yielding at an early stage of denting. As a result, support plate behavior should be predicted incrementally to account for the plasticity after yielding.

4.2 RECOMMENDATIONS

An expanded and modified analysis program is recommended for the prediction of support plate/tube deformations at different stages of magnetite growth. The program effort can be divided into three areas:

- Denting modeling studies.
- Tube stress analysis.
- Plate stress analysis.

The long-term objectives of these analytical studies are to:

- Develop analytical capabilities to assess the safety impact of denting-related support plate/tube deformations in existing nuclear power plants.
- Assist in arriving at a design that will minimize or eliminate the adverse structural effect of magnetite growth.
- Investigate the possibility of reducing the tendency for magnetite growth by controlling water chemistry and by choosing proper structural materials.

4.2.1 Denting Modeling Studies

The objective is to identify the parameters and to develop a model that can predict the shape and volume of tube denting by studying the mechanics and chemistry of magnetite growth.

4.2.2 Tube Stress Analysis

The objective is to determine stresses in a cylindrical shell (tube) under a prescribed external pressure (or displacement) loading. Once the denting-induced pressure or displacement function is known, the analysis can be solved by available computer programs for such as MARC³ (for axisymmetrical denting, linear or nonlinear analysis) and STAGSC⁴ (for nonaxisymmetric, linear or nonlinear analyses).

Several cases of probable denting shapes could be studied, which include:

- Axisymmetric denting.
- Nonaxisymmetric denting: elliptical shape, peanut shape.
- Nonaxisymmetric denting resulting from support plate shifting.

The experimentally obtained load vs denting curves in Fig. 4.3-7 of the NNECO report can be used for verifying the axisymmetrical denting case.

4.2.3 Support Plate Stress Analysis

Support plate response can be reasonably predicted for the case of uniform or nearly uniform magnetite growth in the tube holes by considering a local ligament piece as described in Sec. 4.3.2.3 of the NNECO report and in the paper by Thomas et al.⁵ For the nonuniform case, depending on the distribution and the variation in denting sizes, a general support plate analysis considering the entire support plate may be required to make an accurate prediction.

In a perforated support plate restrained by lugs or solid-rim sections, the internal stress distribution in the support plate is not uniform. This condition requires a general plate analysis. If all the hole geometries of the plate were modeled in this general analysis, the resulting computational effort would be extremely high and economically impractical. As an acceptable alternative, the perforated support plate can be modeled by a manageable number of equivalent perforated support plate elements. The properties of these support plates are chosen to simulate the average behavior of representative perforated support plate regions.

For the start, the property of the equivalent support plates can be assumed to be isotropic. This assumption is more valid for the triangular-hole penetration pattern (i.e., in the Millstone Unit II tube support plates) than for the square-hole pattern considered by Thomas.⁵ To illustrate this point, the degrees of anisotropy in different types of plate are compared below:

The same stiffness property occurs after the axis rotates the following degrees in the plane

Support plate type	
Isotropic support plate	0°
Triangular-hole penetration	60°
Square-hole penetration	90°
Orthotropic	180°

Two phases of analytical work are proposed:

- Elastic analysis phase.
- Inelastic analysis phase.

During the elastic analysis phase, equivalent perforated support plate constants, E^* and ν^* , will be derived by studying the response of the local perforated region, modeled in detail by finite elements. A reasonable number of holes could be included in this finite element model to ensure the results are not dependent on the size of perforated region used. The results will be checked with ASME III code, A-8000, Fig. A-8131-1,² for verification.

During the inelastic analysis phase, the von Mises yield criterion with isotropic strain hardening model could be used to define the onset of yielding and strain hardening stiffness properties under general loading. Usually this relationship is obtained from the uniaxial tension test. For the perforated (triangular pattern) support plate case, uniaxial stress strain results will vary somewhat depending on the orientation of the loading axis. Therefore, it would be better to use the results from biaxial tension loading.

The support plate model will consist of a perforated region which is represented by an assemblage of the equivalent perforated support plate elements, and a rim portion represented by regular plane stress elements. The lug restraints (if any) will be modeled by applying the appropriate boundary conditions. The magnetite-induced stresses in a region of comparable magnetite growth will be simulated by applying a set of self-equilibrating boundary forces around the region. These forces will increase with each magnetite growth and will apply in an incremental manner.

5. REFERENCES

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