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STEAM GENERATOR TUBE PLUGGING MARGIN ANALYSIS FOR THE WESTINGHOUSE STANDARDIZED NUCLEAR POWER PLANT SYSTEM (SNUPPS)

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ABSTRACT

This report describes the analysis to determine the plugging margin for the Westinghouse Standardized Nuclear Power Plant System (SNUPPS) steam generator (Model F) tubing. Based on the results, a minimum tube thickness requirement [ ] of the nominal wall is established in accordance with the guidelines of USNRC Regulatory Guide 1.121. Assuming [ ] allowance for continued tube wall degradation, a plugging margin of 53% of the nominal wall is recommended. a,b,c a,b,c

With discrete wedges used to support the TSPs, the effective tube bundle flow area is reduced [ ] in the faulted steam generator [ ] a,c However, [ ] non-faulted units remain unaffected and the overall system resistance is slightly increased with hardly any effect on the steam generator function. a,b,c a,c

NOMENCLATURE

e = tube ovality, $(OD_{max}-OD_{min})/OD_{nom}$

ID = inside diameter, inch

K = shape factor

L = crack length (axial), inch

OD = outside diameter, inch

P = burst pressure, psi or ksi

$\overline{P}$ = normalized burst pressure, $PR_m/(S_y+S_u)t$

P_c = collapse pressure, psi or ksi

$\overline{P}_c$ = normalized collapse pressure, P_cR_m/S_yt

P_b = primary bending stress (intensity), psi or ksi

P_i = primary side or tube inside pressure, psi

P_m = primary membrane stress (intensity), psi or ksi

P_o = secondary side or tube outside pressure, psi

Q = leakrate, gpm or secondary stress (intensity), psi

R = mean radius of tube U-bend, inch

R_i = inside radius of tube, ID/2, inch

R_m = mean radius of tube (ID+OD)/2, inch

R_o = outside radius of tube, OD/2, inch

S_m = code allowable stress intensity for design, psi or ksi

S_u = material ultimate strength, psi or ksi

S_y = material yield strength, psi or ksi

t = tube wall, inch

t_{min} = minimum required thickness

NOMENCLATURE (CONTINUED)

ΔP_i = primary-to-secondary pressure differential, psi
ΔP_o = secondary-to-primary pressure differential, psi
λ = normalized crack length, $L/\sqrt{R_m t}$

SNUPPS = Standardized Nuclear Power Plant System
ASME = American Society of Mechanical Engineers
AVB = Antivibration bars
EC = Eddy-Current
FDB = Flow distribution baffle
FIV = Flow induced vibrations
FLB = (main) Feedline break (accident)
FS = Factor of Safety
LOCA = Loss-of-Coolant Accident (primary)
LTL = (Statistical) Lower Tolerance Limit
NSSS = Nuclear Steam Supply System
PCT = Peak clad temperature
PWR = Pressurized Water Reactor
SG = Steam Generator
SLB = (main) Steam line break (accident)
SRSS = Square Root of the Sum of the Squares
SSE = Safe Shutdown Earthquake
T/H = Thermal-Hydraulic
TSP = Tube support plate
USNRC = United States Nuclear Regulatory Commission
W = Westinghouse Electric Corporation

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SECTION 1

INTRODUCTION

1.1 Regulatory Requirements for the Plugging

The heat transfer area of steam generators in a PWR nuclear steam supply system (NSSS) comprises over 50% of the total primary system pressure boundary. The steam generator tubing therefore represents a major barrier against the release of radioactivity to the environment. For this reason, conservative design criteria have been established for structural integrity of the tubing under the postulated design-basis accident condition loadings in accordance with Section III of the ASME Boiler and Pressure Vessel Code (hereinafter designated as the Code).

Over a period of time under the influence of the operating loads and environment in the steam generator, some tubes may become degraded in local areas. To determine the condition of the tubing, inservice inspection using eddy-current (EC) techniques is performed in accordance with the guidelines of USNRC Regulatory Guide 1.83. Partially-degraded tubes with wall thicknesses greater than the minimum acceptable tube wall thickness are satisfactory for continued service. Also, the minimum required tube wall thickness is adjusted to take care of possible discrepancies in the EC probe and to annular an operational allowance for continued tube degradation until the next scheduled inspection.

The USNRC Regulatory Guide 1.121 describes an acceptable method fo establishing the limits of tube degradation beyond which tubes will be repaired or removed from service. The amount of degradation as recorded by the EC testing is customarily expressed as a percentage of the design nominal tube wall thickness, and the acceptable degradation is referred to as the tube plugging margin.

1.2 Scope of the SNUPPS Plugging Margin Analysis

This report describes the results of analysis performed for the Westinghouse Standardized Nuclear Power Plant System (SNUPPS) steam generator tubing in order to establish the tube plugging margin. Each SNUPPS unit has a 4-loop NSSS which includes the Model F steam generator.

A cutaway view of a Model F steam generator is shown in Figure 1-1. Figure 1-2 shows a schematic drawing of the tube bundle which consists of 3626 U-tubes made of Inconel-600 (SB-163) alloy. Some of the earlier SNUPPS units have both the mill-annealed and thermally-treated tubing. Lateral support for the tube is provided by the seven (7) tube support plates (TSP) approximately 40 inches apart in the straight region of the bundle. In the U-bend area, the out-of-plane motion of tube bends is limited by coupling the U-bends with three sets of

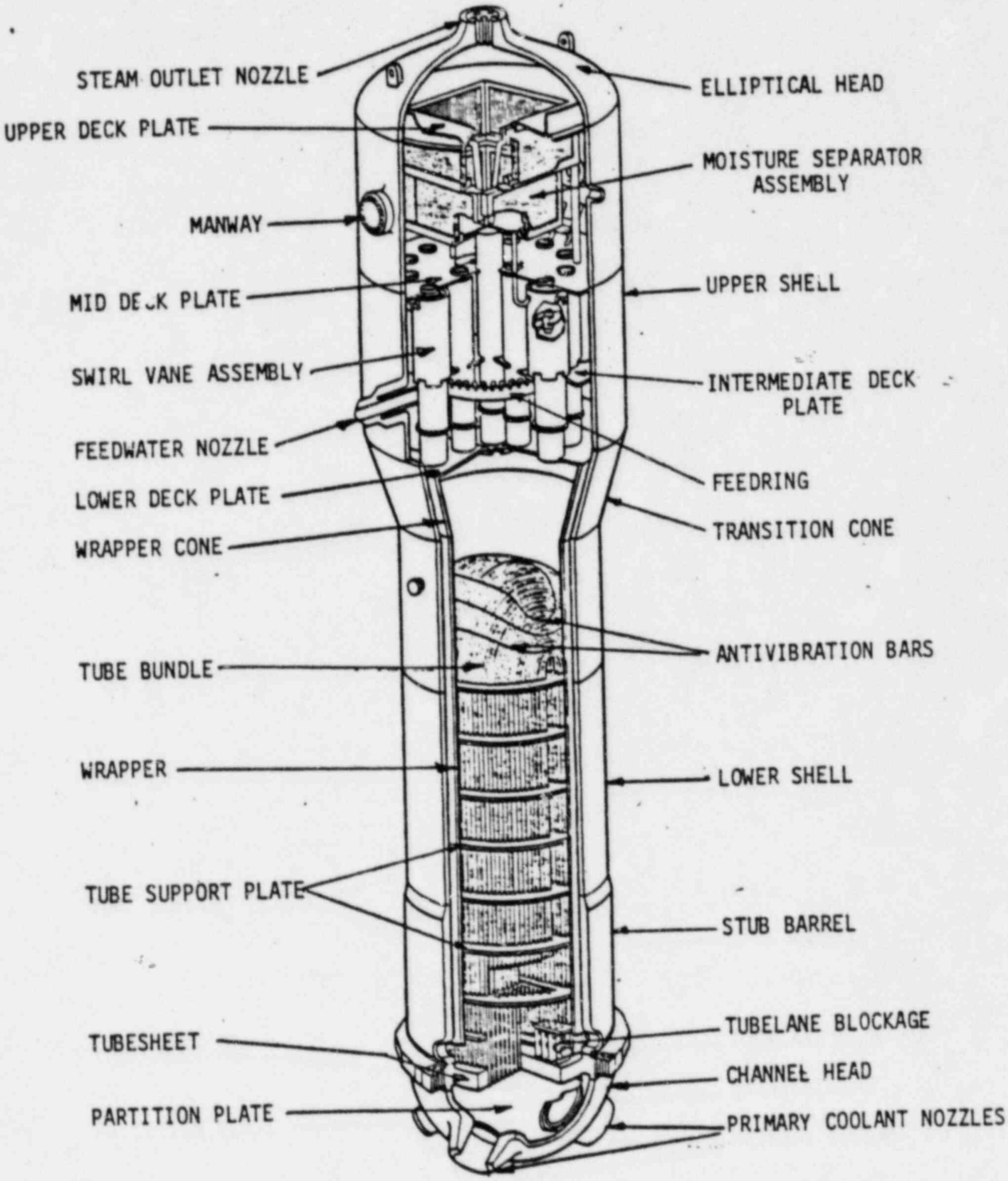

FIGURE 1-1: CUTAWAY VIEW OF A MODEL F STEAM GENERATOR

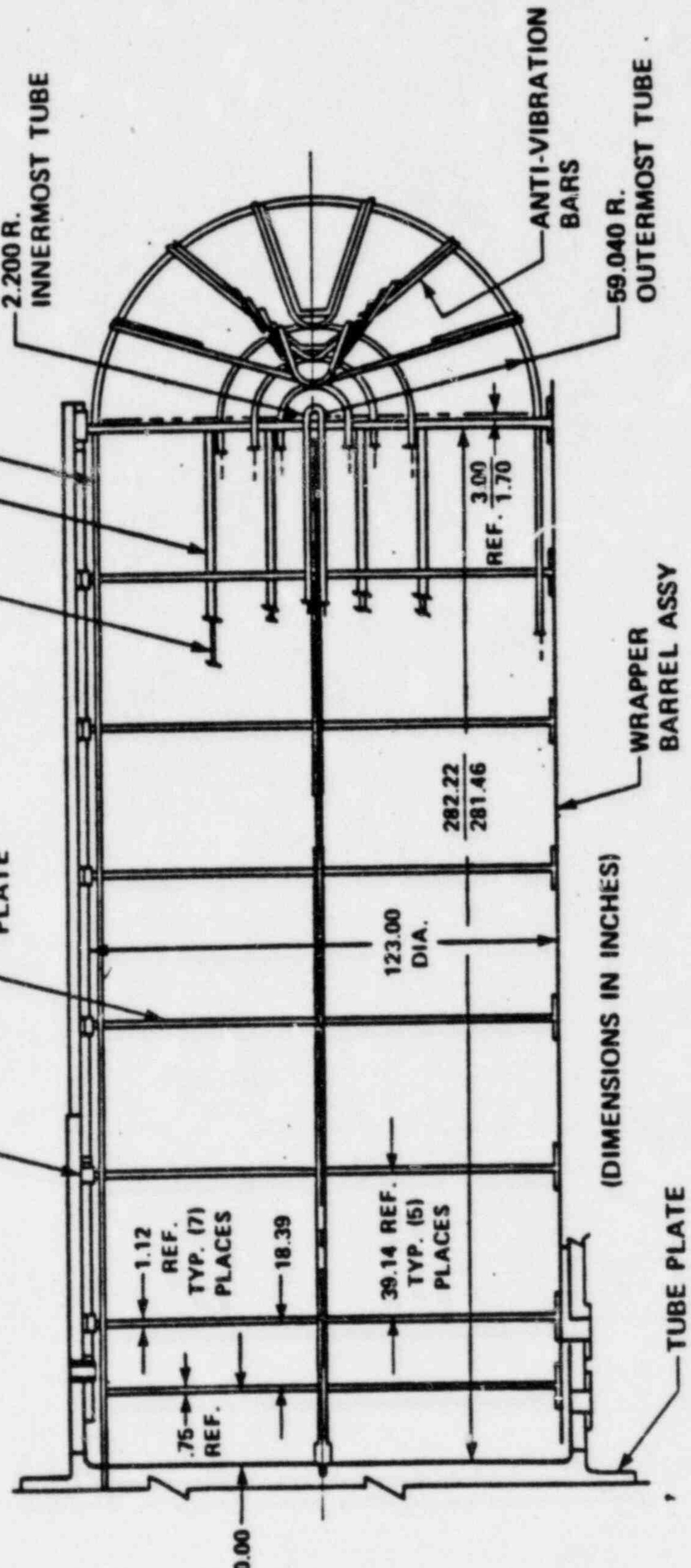

FIGURE 1-2: SCHEMATIC OF A MODEL F STEAM GENERATOR TUBE BUNDLE GEOMETRY

anti-vibration bars (AVB). The nominal tube is 0.688" OD x 0.040" t.

The minimum tube wall requirements were calculated in accordance with the criteria of USNRC Regulatory Guide 1.121, entitled "Bases for Plugging Degraded PWR Steam Generator Tubes". The basic requirements consist of:

1) In the case of tube thinning, stresses in the remaining tube wall are to meet applicable stress limits during normal and postulated accident condition loadings, and

2) In the case of tube cracking, with or without any thinning, the maximum allowable leakage during normal operation is to be limited consistent with leak-before-break criteria.

Additional requirements consist of verifying the margin to burst under normal operation and margin against collapse during a LOCA. The question of fatigue failure under cyclic bending stresses is covered in the validation of leak-before-break.

In connection with the tube bundle integrity evaluation, it should be noted that both the safety and functional requirements are to be satisfied. The safety requirement which is the basis of the Regulatory Guide 1.121 criteria governs the limiting safe condition of localized tube degradation, as established by inservice inspection, beyond which tubes should be repaired or removed from service. In contrast, the functional requirement applies to the overall degradation of the tube bundle in terms of its heat removing capability and the impact on the peak clad temperature due to the primary coolant flow restriction through the tube bundle following a LOCA, which is evaluated in conjunction with SSE. Although both the safety and functional requirements were found satisfied, the subject matter of this report deals mainly with the safety requirements associated with the plugging margin criteria in Regulatory Guide 1.121.

Specific criteria and the corresponding allowable limits and/or margins associated with the safety and functional requirements are discussed in Section 2. Details of tube loadings during the various plant conditions are discussed in Sections 3 and 4 with the related analytical results and evaluations. Section 5 contains the discussion of leak-before-break verification and burst strength requirements. Finally, the recommended tube plugging margin is set forth in Section 6.

SECTION 2

INTEGRITY REQUIREMENTS AND CRITERIA

The steam generator tubing represents an integral part of the primary system. In the event of a primary loss-of-coolant (LOCA), the tubing provides the necessary heat sink, initially for the core cooldown and later for maintaining the plant in the safe shutdown condition. Thus, it is important to establish the structural integrity of the steam generator tubing so that the tube bundle can sustain the loads during normal operation and the various postulated accident conditions without a loss of function of safety.

2.1 Functional and Safety Requirements

Tube walls may be affected by a number of different factors such as environment-induced corrosion (including intergranular attack and stress-corrosion cracking), erosion due to the fluid friction, and fretting wear from mechanical and flow-induced vibrations. The wall loss due to general erosion or corrosion has been conservatively established and is assumed to be more or less uniform for the entire tube bundle during the plant operating period. However, a potential for additional wall degradation may exist locally in some tubes, near the top of the tubesheet and in the region of tube-tube support plates (TSP) intersections, because of a higher potential for chemical concentrations and/or relative motion in these regions.

Based on steam generator operational history, the whole bundle may be subjected to only a small, but probably a more or less uniform, tube wall loss over the total operating period of the unit. On the other hand, some tubes of the bundle may degrade locally to the extent that either the removal of these tubes from service or local repair to restore integrity is sufficient for continued safe operation of the unit. Because of these two distinct modes of tube degradation, it is possible to separate the functional and safety requirements into those affecting the integrity of (1) the overall tube bundle, and (2) a locally-thinned or degraded tube. Tube associated with these modes of degradation are referred to as the "median" and the "locally-degraded" tube. The median tubing corresponds to the minimum expected strength properties of the overall tube bundle and represents a tube with the end-of-design life minimum wall, which may be the drawing minimum less the design basis erosion/corrosion allowance. The end-of-design life conditions assume a general corrosion on the outside of tubes [ ] and a general erosion on the inside of tube [ ] a,b, a,b,

2.2 Tube Bundle Integrity Requirements

These requirements are based on the assumption that removal of a small number of tubes from service does not impair the structural and functional capability of the overall tube bundle. In the event of extensive tube plugging, plant derating and/or reanalyses associated with functional requirement verification may be necessary. However, reanalyses for the verification of structural integrity of the tube bundle as a whole will not be required since almost all of the deactivated tubes would physically remain in the tube bundle, thus maintaining the structural characteristics of the tube bundle practically intact. Specifically, the following two criteria are to be satisfied, assuming the median tube properties:

1) For Level D Service Conditions, the primary stresses do not exceed the stress limits specified in Appendix F of Section III of the Code.

2) The loss of tube bundle flow area due to the combination of the cross-sectional distortion and/or collapse of a limited number of tubes due to the postulated [ ] loads does not increase the primary flow resistance of the system [ ] a,c

a,c

2.3 Locally-Degraded Tube Integrity Requirements

As previously indicated, the potential for tube wall degradation other than due to nominal erosion-corrosion may exist at certain locations in the tube bundle. Even though such localized degradation is known to be confined over a small portion of the tubing (and hence of no adverse consequence to the functional capability of the bundle), it is to be assessed from the viewpoint of a potential tube rupture, if the associated depth of penetration is relatively large. Therefore, to show that there are no safety consequences as a result of random tube bursts, a conservative bound on acceptable degradation for continued operation must be established along with the in-service inspection and leakage monitoring requirements for the detection of degraded tubes. Guidelines in Regulatory Guide 1.83 for EC inspection and Regulatory Guide 1.121 for tube plugging margin calculations provide the bases for determining the limiting safe condition of a locally-degraded tube. For tube degradation in excess of the established plugging margin, it is required that the tube be repaired or removed from service (by plugging or otherwise) in order to provide continued safe operation.

The intent of Regulatory Guide 1.121, as applicable to this analysis, is summarized below:

- In the case of tube thinning due to the mechanical and chemical wastage, and generalized intergranular attack, stresses in the remaining tube wall are shown to be capable of meeting the applicable requirements with adequate allowance for the EC measurement uncertainties and assumed continued erosion-corrosion until the next scheduled outage. The strength requirements are specified in terms of allowable primary stress limits and margins against burst during normal operation and collapse following a LOCA.

- For tube cracking due to fatigue and/or stress corrosion, a specification on maximum allowable leak rate during normal operation must be established such that the associated crack will not lead to a tube rupture during a postulated worst case accident condition pressure loading. If the leak rate exceeds the specification, the plant must be shutdown and corrective actions taken to restore integrity of the unit.

2.4 Tube Stress Classification

For plants in seismic regions, the most limiting loads for establishing the tube integrity are imposed during the Level D service conditions; [ ] a,c

There are two general considerations which must be accounted for in determining the classification of stresses; namely, the location in the structure and the nature of the loading.

[ ] a,c The tube stress classification for various locations in the tube bundle under the different types of loadings

TABLE 2-1: TUBE STRESS CLASSIFICATION

[ ] a,b,c

(1) Median Tube

(2) Thinned Tube

is summarized in Table 2-1. The notation P_m refers to general primary membrane stress, P_b refers to primary bending stress and Q refers to secondary stress. At the top TSP, a distinction is made between bending stresses in median tubes and locally-thinned tubes. In the U-bend region the anti-vibration bars couple the tubes for motion out of the plane of the U-bend so that out-of-plane bending is resisted by the entire bundle.

a,c

a,c

A distinction is made between self-excited, flow-induced vibration (FIV) stresses and flow-induced vibration from other causes. A self-excited vibration mechanism could be established if flow velocities exceed criteria values for fluidelastic vibration. When the vibration amplitude increases, however, the amount of damping in the vibrating tube also increases. The vibration amplitude of cyclic bending stresses are limited by the amount of damping in the system. [

a,c

TABLE 2-2: SNUPPS TUBE STRENGTH PROPERTIES FOR R.G. 1.121 ANALYSES (0.688" OD x 0.040" t)

a,

a,c

2.5 Criteria and Stress Limits

a,c

A summary of these calculations is given in Table 2-2.

a,c

[ ] a,b,c

- Normal and Upset Plant Conditions

  The primary-to-secondary pressure differential P_i should not produce a primary membrane stress in excess of the yield stress of the tube material at operating temperature; that is,

$$P_m \leq S_y = [\quad]^{a,b,}$$

- Postulated Accident Conditions

  Loadings associated with a primary (LOCA) or a secondary side (SLB/FLB) blowdown, concurrent with the SSE, should be accommodated with the margin determined by the stress limits specified for Level D Service Conditions in Appendix F of the Code. [ ] a,c

For Locally-Thinned Tubing

$P_m \leq$ smaller of $(2.4\ S_m,\ 0.7\ S_u) = [\quad]^{a,b,c}$

$P_m + P_b \leq [\quad]$

a,b,c

<u>For the Median Tubing</u> [

$P_m \leq$ [

$P_m + P_b =$ [ ]

Since the tube has regions of plastic deformations, the shake factor K is introduced in determining the allowable stress. This constant is a function of the cross-sectional dimensions of the tube. [ ] a,b,c

As far as the consideration of the secondary and peak stresses in the evaluation of a locally-thinned tube is concerned, it is noted that the effects of these stresses will be manifested into racheting, fatigue and/or corrosion-fatigue types of mechanisms associated with tube cracking if that should occur. [ ] a,c

SECTION 3

LOADS AND ASSOCIATED ANALYSES

In establishing the safe limiting condition of a tube in terms of its remaining wall thickness, the effects of loadings during both the normal operation and the postulated accident conditions must be evaluated. [

]^{a,c}

3.1 Normal Operating Loads

The limiting stresses during normal and upset operating conditions are the primary membrane stresses due to the primary-to-secondary pressure differential ΔP_i across the tube wall. During normal operation at 100% full power, the pressures are as follows:

Primary Side:

Reactor coolant pressure, P_i = 2250 psia

Secondary Side:

Steam pressure, P_o = 1000 psia

The pressure differential ΔP_i at 100% power is thus 1250 psi.

3.1.1 Upset Load

However, the maximum operating condition ΔP_i occurs during a loss-of-load transient when:

Primary side pressure, P_i = 2650 psia
Secondary side pressure, P_o = 975 psia

Hence, $\Delta P_i = P_i - P_o$ = 1675 psi.

3.2 Accident Condition Loads

For the faulted plant condition evaluation, the postulated Level D Service Condition events are: Loss-of-Coolant Accident (LOCA), main Steam Line Break (SLB), main Feed Line Break (FLB) and Safe Shutdown Earthquake (SSE). The tube integrity evaluation is performed for the blowdown loads in conjunction with the SSE loads; [ ]^{a,c} [ ]^{a,c} The tube loadings were maximized by assuming these events to initiate when the plant is operating at 100% full power condition.

3.2.1 LOCA Loads

LOCA loads are developed as a result of transient flow and pressure fluctuations following a postulated main coolant pipe break. [

]a,c

a,c

3.2.1.1 LOCA Rarefaction Wave Analyses

The principal tube loading during a LOCA is caused by the rarefaction wave in the primary fluid. [

a,c

a,b,c

FIGURE 3-1: TUBE MODEL FOR LOCAL RAREFACTION WAVE ANALYSIS

a,c

Figure 3-1 shows the node and element numbering for a typical single tube model which was analyzed using the WECAN program.

a,c

a,c

a,c

a,b,c

The pressure-time histories to be input in the structural analyses were obtained from transient thermal-hydraulic (T/H) analyses using the MULTIFLEX Code.

a,b,c

[ ]a,b,c

FIGURE 3-2: DIFFERENTIAL PRESSURE TIME-HISTORIES AT VARIOUS NODES FOLLOWING A LOCA

a,c

In addition to the pressure bending loads, the rarefaction wave analysis includes the pressure membrane stresses due to the primary-to-secondary ΔP_i and the effect of fluid friction and centrifugal forces.

3.2.1.2 Rarefaction Wave Induced Tube Loads

The maximum tube bending stresses and rotations at the top TSP are summarized in Tables 3-1 and 3-2, respectively, for the various cases analyzed. Figures 3-3 and 3-4 show the time-history variations of the in-plane horizontal displacements and bending moments, respectively, at selected nodes of the largest bend radius tube. Comparison of these results lead to the following two major inferences.

a,c

TABLE 3-1: LOCA RAREFACTION TUBE BENDING STRESSES

a,b,c

* Due to pinned boundary assumption, no bending stresses result at this location.

TABLE 3-2: LOCA RAREFACTION TUBE ROTATIONS AT TOP TSP

a,b,c

a,b,c

FIGURE 3-3: LOCA RAREFACTION WAVE TUBE HORIZONTAL DISPLACEMENT (UX) VS TIME FOR NODE 6 TO NODE 9, INCLUSIVE

a,b,c

FIGURE 3-4: LOCA RAREFACTION WAVE TUBE BENDING MOMENT (MZ) VS TIME IN ELEMENT 2 TO ELEMENT 5, INCLUSIVE

[ ]a,c

3.2.1.3 Rarefaction Wave Induced TSP Loads

The tube motion due to the LOCA rarefaction wave induced loading is restrained at the TSP locations, resulting in reaction forces in the plates. [

]a,c

[ ]a,b,c

3.2.1.4 LOCA Shaking Loads

Concurrent with the rarefaction wave loading during a LOCA, the tube bundle is subjected to additional bending loads due to the shaking of the steam generator caused by the break hydraulics and reactor

a,b,c

FIGURE 3-5: REACTOR COOLANT LOOP MODEL FOR LOCA ANALYSIS

a,b,c

FIGURE 3-6: STEAM GENERATOR DISPLACEMENTS DUE TO A STEAM GENERATOR OUTLET NOZZLE BREAK coolant loop motion. [ ] a,c

[ ] a,b,c

[ ] a,c

a, b, c

FIGURE 3-7: MODEL OF THE TUBE BUNDLE FOR LOCA SHAKING ANALYSIS WITH NODE NUMBERING

a,b,c

FIGURE 3-8: MODEL OF THE TUBE BUNDLE FOR LOCA SHAKING ANALYSIS WITH ELEMENT NUMBERING

TABLE 3-3: LOCA SHAKING TUBE STRESSES

a,b,c

* Due to pinned boundary assumption, no bending stresses result at this location.

TABLE 3-4: LOCA SHAKING TUBE ROTATIONS AT TOP TSP

a, b, c

The WECAN model with the node and element numbering used for the LOCA shaking analysis of the tube bundle is shown in Figure 3-7 and in Figure 3-8.

The maximum bending stresses in the tube U-bends (both the nominal and median geometries) and the maximum tube rotations at the top TSP are summarized in Tables 3-3 and 3-4, respectively. [ ] a,b,c

3.2.2 FLB/SLB Loads

During the postulated FLB/SLB accidents, the predominant primary tube stresses result from the P_i loading. The peak differential pressures for these events were obtained from the results of transient blowdown analyses. [ ] a,b,c

These secondary side blowdown transients are based on an instantaneous full double-ended rupture of the main feedline/steamline. [ ] a,c

[ ]a,b,c

In addition to the primary pressure stresses, axial bending stresses in the tubes are developed as a result of flow-induced vibrations and tube-baffle interaction. [ ]a,c

[ ]a,c

[ ] a,b,c

FIGURE 3-9: SNUPPS SSE RESPONSE SPECTRA [ ] a,b,c

[ ] a,c

3.2.3 SSE Loads

Seismic (SSE) loads are developed in the steam generator as a result of the motion of the ground during an earthquake. [ ] a,b,c Because of the differences in the SNUPPS peripheral support designs for the tube support plates (TSP), two separate analyses were performed: designated Plant 1 Site and Plant 2 Site. The response spectra used in these analyses are shown in Figure 3-9.

3.2.3.1 Seismic Model

The analyses were performed using the WECAN computer code. [ ] a,b,c

19,547-11

a, b, c

FIGURE 3-10: SEISMIC MODEL OF THE SNUPPS STEAM GENERATOR WITH NODE NUMBERING

19,547-12

a,b,c

FIGURE 3-11: SEISMIC MODEL OF THE SNUPPS STEAM GENERATOR WITH ELEMENT NUMBERING

a,b,c

FIGURE 3-12: SEISMIC MODEL OF THE U-BEND SHOWING ELEMENT NUMBERING

[ ]a,c The node and element numbering details of the model are shown in Figures 3.10 and 3.11, respectively.

[ ]a,b,c Details of the element numbering of the mathematical model of the U-bend region are shown in Figure 3.12. The node numbering is the same as was shown in Figure 3-7.

3.2.3.2 Seismic Analysis Output

In addition to the displacements, velocity and acceleration of each node point, the seismic solution provides the stresses in each element as well as support wedge reaction loads on the TSP's. [ ]a,b,c

TABLE 3-5: SSE TUBE BENDING STRESSES

[ ]^{a,b,c}

TABLE 3-6: MAXIMUM TUBE SUPPORT LOADS DUE TO SSE

a,b,c

a,c

The analysis output pertinent to the subject evaluation consists of the tube bundle stresses and the in-plane TSP loads. The maximum (axial) stresses in both the nominal and median tube, and the TSP loads are summarized in Tables 3-5 and 3-6. respectively. [

]a,c

SECTION 4

RESULTS OF ANALYSES AND EVALUATION

Loads and stresses generated from the analyses described in the previous section were used to verify the following requirements:

(1) Functional requirements associated with the overall tube bundle integrity during and following the Level D Service Condition loadings, that is:

a,c

(2) Safety requirements on a locally-degraded tube; viz.,

a,c

4.1 Functional Integrity Evaluation

a,c

[ ] The evaluation consisted of verifying that the tube primary stresses and the reduction in the primary flow area of the tube bundle under the limiting faulted loads were within the specified acceptance limits.

4.1.1 Level D Service Condition Stresses

a,c

[ ] This loading condition is most limiting for the case of locally-degraded (thinned) tubing and is considered later in the determination of the minimum required thickness.

a,c

[ ]

Results of the [ ]^{a,c} analyses discussed in the previous section were used to compute the maximum stress intensity in the tube U-bends.

a,c

[ ]

19,547-17

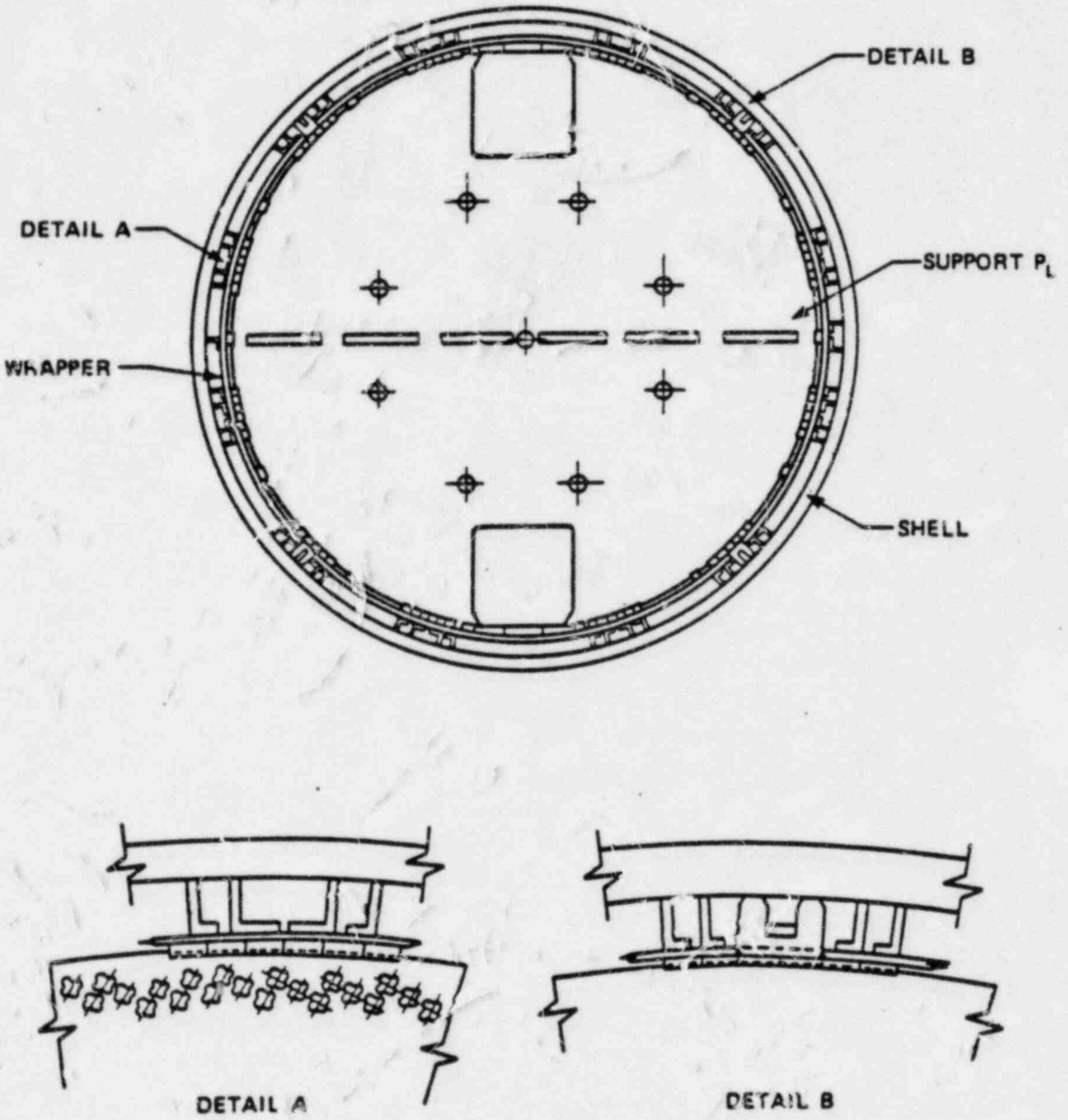

FIGURE 4-1: TYPICAL WEDGE GROUP ARRANGEMENT FOR TUBE SUPPORT PLATE

19,547-16

a, b, c

A – PLATE SOLID RIM
B – PLATE BROACHED PERFORATED REGION
C – PLATE FIXTURE (OUT-OF-PLANE RESTRAINT)
D – DIAL INDICATOR GAGE
E – 12" WEDGING

FIGURE 4-2: SCHEMATIC OF A TUBE-TUBE SUPPORT PLATE CRUSH TEST

a,b,c

4.1.2 Primary Flow Area Reduction

The in-plane TSP loads due to LOCA and SSE are transmitted to the shell through the supports of the tube support plates. [

a,b,c

a,b,c

---

* Originally, there were 4 plant orders for SNUPPS. Only the earlier two, Callaway No. 1 and Wolf Creek, are being built. The other two were cancelled.

TABLE 4-1: SUMMARY OF MAXIMUM TUBE SUPPORT PLATE WEDGE LOADS

a,b,c

a,c

a,b,c

Table 4-1 summarizes the individual wedge loads along with the contact loads. [

a,c

a,c

a, c

a, b, c

a, b, c

a,c

] Thus, the functional requirements are met by the SNUPPS Model F steam generators.

4.2 Minimum Wall Requirements for Degradation Tubes

a,b,c

a,b,c

4.2.1 Normal Plant Conditions

a,b,c

4.2.2 FLB/SLB+SSE

a,b,c

[ ]^{a,b,c}

4.2.3 LOCA+SSE

[ ]^{a,b,c}

The collapse pressure is significantly affected by tube ovality. A number of correlations using limit analysis theory have been developed to predict collapse strength of ovalized tubes. A correlation was found to be quite accurate for the thermally-treated (or stress-relieved) tubing, believed to be due to its less anisotropic yield properties compared to that of as-manufactured tubing. The validity and conservatism of this

19,547-19

a,b,c

FIGURE 4-3: CORRELATION BETWEEN TUBE OVALITY AND COLLAPSE PRESSURE analytical correlation was verified against the results of room temperature collapse pressure tests on mill-annealed 0.75 in. OD x 0.043 in. t, and 0.875 in. OD x 0.050 in. t oval tubes. Figure 4-3 shows the comparison of analytically predicted (normalized) collapse pressures with those obtained from the tests.

a,b,c

SECTION 5

BURST STRENGTH REQUIREMENTS

In addition to the limits on allowable stresses and margin to collapse due to external pressure discussed previously, the following requirements on the burst (pressure) strength capability of the degraded tubing is also to be shown as satisfied:

[ ]^{a,b,c}

TABLE 5-1: SUMMARY OF LEAKRATES OF AXIALLY-CRACKED MODEL F TUBING UNDER NORMAL OPERATING ΔP; [ ] a, b, c

[ ] a, b, c

19,847-30

[ ]^{a,b,c}

FIGURE 5-1: PLOT OF A TYPICAL LEAKRATE TEST (SGTLR #30, [ ]^{a,b,c}

10,847-31

[ ] a, b, c

FIGURE 5-2: CORRELATION BETWEEN AXIAL CRACK LENGTH VERSUS LEAKRATE FOR MODEL F TUBING UNDER NORMAL OPERATING ΔP; [ ] a, b, c

[ ]a,b,c

5.1 Leak-Before-Break Verification

The rationale behind this requirement is to limit the maximum allowable (primary-to-secondary) leak rate during normal operation such that the associated crack length (through which the leakage occurs) is less than the critical crack length corresponding to the maximum postulated accident condition pressure loading. Thus, on the basis of leakage monitoring during normal operation, it is assumed that an unstable crack growth leading to tube burst would not occur in the unlikely event of the limiting accident.

For the SNUPPS units, the maximum technical allowable leakrate is 0.35 gpm per steam generator. Results of four leakrate (Q) tests in Table 5-1 were used to determine the maximum allowable crack length (L) through the nominal wall during normal operation corresponding to this specified limit, conservatively assuming that the entire leakage is associated with a single crack. [ ]a,b,c

[ ] Beyond this crack length, the leakage would exceed the

TABLE 5-2: BURST PRESSURE TEST DATA ON AXIALLY-SLOTTED MODEL F TUBING AT ROOM TEMPERATURE

a,b,c

10,847-22

a,b,c

FIGURE 5-3: RELATIONSHIP BETWEEN NORMALIZED BURST PRESSURE AND AXIAL CRACK LENGTH OF SG TUBING

19,847-28

a,b,c

FIGURE 5-4: MINIMUM EXPECTED BURST STRENGTH OF MODEL F INCONEL 600 THERMALLY-TREATED TUBING technical specification limit, requiring a plant shutdown for a corrective action.

[ ]a,b,c

] The results are plotted in Figure 5-3. Since all previous tests were on mill-annealed material, the results in Table 5-2 of testing on thermally-treated tubing was included in Figure 5-3 to verify that the lower bound (shown by the solid line) established by the broad data base is applicable to the evaluation of thermally-treated SNUPPS tubing.

[ ]a,b,c

Applicability to Thinned Tubing

The applicability of leak-before-break is also to be verified for the case of a tube with cracking superimposed on thinning. [

[ ]a,c

19,547-24

a, b, c

FIGURE 5-5: VARIATION IN MARGIN TO BURST AS A FUNCTION OF R_m/t FOR THERMALLY-TREATED 0.688"OD x 0.040"t TUBING

a,c

a,b,c

5.2 Margin to Burst Under Normal P_i

According to the Regulatory Guide 1.121 guidelines, a factor of safety (FS) of 3 is required against bursting under the normal operating pressure differential. [

a,b,c

a, b, c

a, c

5.2.1 Effect of Bending on Burst Strength of Tube

a, c

a,c

5.2.2 Tube with Thru-Wall Degradation

a,b,c

5.2.3 Thinned Tube

For the case of a predominantly thinning mode of tube degradation; i.e., no thru-wall cracking and hence no leakage, the minimum tube wall thickness is established [ ] a,b,c

[ ]

Thus, the previously established minimum tube wall [ ] a,b,c [ ] meets the applicable burst strength requirement.

SECTION 6

PLUGGING MARGIN RECOMMENDATION

Based on analyses in the previous sections, a minimum wall [ ] a,b,c is necessary to satisfy the stress limit and strength requirements of USNRC Regulatory Guide 1.121. [ ] a,b,c

The allowable degradation incorporates additional allowances for any additional degradation under continued operation until next scheduled inspection and the measurement uncertainties using the EC probes. An estimate of the degradation allowance can be made based on the history of similarly designed and operated units and the projected inspection interval. [ ] a,b,c

Thus, the recommended tube plugging margin for SNUPPS is 53 percent of nominal wall; i.e.; 0.021 inch, which exceeds the plugging margin of 40% (0.016 in.) allowed by the ASME Code Section XI, Paragraph IWB 3521.1 in lieu of analyses.

SECTION 7

APPENDIX

7.1 Deviation of Lower Bound Tolerance Limits for Strength Properties

Expected strength properties to be used for the SNUPPS tubing evaluation were obtained from statistical analyses of tensile test data of actual production tubing. [

a,b,c

a,b,c

Table 7-1 [illegible]zes the calculations of statistical analyses of test data of the mill-annealed and thermally-treated Inconel-600 tubing for SNUPPS.

TABLE 7-1: LOWER TOLERANCE LIMITS OF STRENGTH PROPERTIES FOR THE SNUPPS TUBE

a.b.c