Westinghouse Nuclear Energy Systems

WCAP-9989

STEAM GENERATOR TUBE PLUGGING MARGIN ANALYSIS FOR THE VIRGIL C. SUMMER NUCLEAR POWER PLANT UNIT NO. 1

M. R. PATEL, Ph.D.

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APPROVED: J. L. Houtman
J. L. Houtman, Manager
Applied Structural Mechanics

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WESTINGHOUSE ELECTRIC CORPORATION
Nuclear Energy Systems
P.O. Box 355
Pittsburgh, Pennsylvania 15230

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ABSTRACT

This report describes the analyses and testing used for determining the plugging margin for the Virgil C. Summer Nuclear Power Plant (CGE) steam generator (Model D3) tubing. Based on the results, a minimum tube wall thickness requirement [ ] of the nominal (0.043 inch) wall is established in accordance with the guidelines of USNRC Regulatory Guide 1.121. Assuming [ ] a,b,c for continued corrosion and eddy-current measurement uncertainties, a plugging margin of 55% of the nominal wall is recommended. a,b,c

The loss in the primary flow area resulting from the localized tube-to-tube support plate deformation due to the maximum postulated [ ] a,c loading was calculated [ ] a,b,c

[

NOMENCLATURE

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

f = natural frequency, Hz

g = gravitational constant

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 = leak rate, 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

R_T = Room Temperature (~75°F)

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

S_u = material ultimate strength, psi or ksi

NOMENCLATURE (CONTINUED)

S_y = material yield strength, psi or ksi

T = temperature, °F. Subscripts h, c, and s refer to hot leg, cold leg and steam, respectively.

t = tube wall thickness, inch

t_{min} = minimum required thickness

ΔP_i = primary-to-secondary pressure differential, psi

ΔP_o = secondary-to-primary pressure differential, psi

λ = normalized crack length, $L/\sqrt{R_m t}$

Abbreviations:

AVB = Antivibration bars

ECT = Eddy-Current test

FDB = Flow distribution baffle

FIV = Flow induced vibrations

FLB = (main) feedline break (accident)

FS = Factor of Safety

LOCA = Loss-of-coolant Accident

LTL = (Statistical) Lower Tolerance Limit

NSSS = Nuclear steam supply system

PCT = Peak clad temperature

PWR = Pressurized Water Reactor

SI = Stress Intensity

SLB = (main) steam line break (accident)

SSE = Safe shutdown earthquake

T/H = Thermal-Hydraulic

TSP = Tube support plate

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SECTION 1

INTRODUCTION

1.1 Regulatory Requirement for Tube Plugging

The heat transfer area of steam generators in a PWR nuclear steam supply system (NSSS) can comprise well over 50% of the total primary system pressure boundary. The steam generator tubing therefore represents an integral part of a major barrier against the release of activity to the environment. Accordingly, conservative design criteria have been established to assure structural integrity of the tubing under the postulated design-basis accident condition loadings [1]*.

However, over a period of time under the influence of the operating loads and environment in the steam generator, some tubes may become defective due to localized wall degradation or cracking. In order to safeguard against the failure of degraded tubes, inservice inspection using eddy-current (EC) techniques is performed in accordance with the guidelines of USNRC Regulatory Guide 1.83 [2]. Partially degraded tubes with a wall thickness greater than the minimum acceptable tube wall thickness are acceptable for continued service, provided the minimum required tube wall thickness, is adjusted to account for the EC probe error and an operational allowance for continued degradation until the next scheduled inspection.

The USNRC Regulatory Guide 1.121 [3] describes an acceptable method for establishing the limiting safe conditions of tube degradation beyond which defective tubes as established by the EC inspection must 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.

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* Numbers in brackets designate references at the end.

1.2 Program Scope and Summary

This report describes the results of analyses and testing performed on the Virgil C. Summer Nuclear Power Plant (CGE) steam generator tubing for establishing the tube plugging margin. The CGE unit has a 3-loop NSSS which includes Model D3 steam generators.

A sectional view of a Model D3 steam generator is shown in Figure 1-1. Figure 1-2 shows a schematic drawing of the tube bundle which consists of 4674 U-tubes made of mill-annealed Inconel-600 (SB-163) alloy. Lateral support for the tube is provided by the seven (7) tube support plates (TSP) in the straight region. In the U-bend region, the out-of-plane motion of tube bends is limited by coupling the U-bends with two (2) sets of anti-vibration bars. The nominal tube dimensions are: 0.75" OD x 0.043"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) Verifying that, in the case of tube thinning, the remaining tube wall can 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 limited to assure leak-before-break. Additional requirements consist of verifying the margin to burst under normal operation and margin against collapse during a LOCA.

Thus, the program requirements consisted of:

1) Analyses to establish applicable loads and integrity evaluations for tubes subjected to these loads, and

2) Leak rate and burst pressure tests to establish the maximum allowable leakage during operation consistent with the leak-before-break requirement.

In connection with the tube bundle integrity evaluation, it should be noted that both the safety and functional requirements must be satisfied. The safety requirement which, in fact, is the basis of the Regulatory Guide 1.121 criteria, governs the limiting safe condition of (localized) tube degradation beyond which defective tubes, as established by in-service inspection, should be repaired or removed from service. The functional requirement, on the other hand, 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 (to be evaluated in conjunction with SSE). Although both the safety and functional requirements were 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 the next section. In the two sections after that, details of tube loadings during the various plant conditions are discussed and related analyses, results and evaluations are given. Section 5 contains the discussion of burst strength requirements and leak-before-break verification. Finally, the recommended tube plugging margin is provided in Section 6.

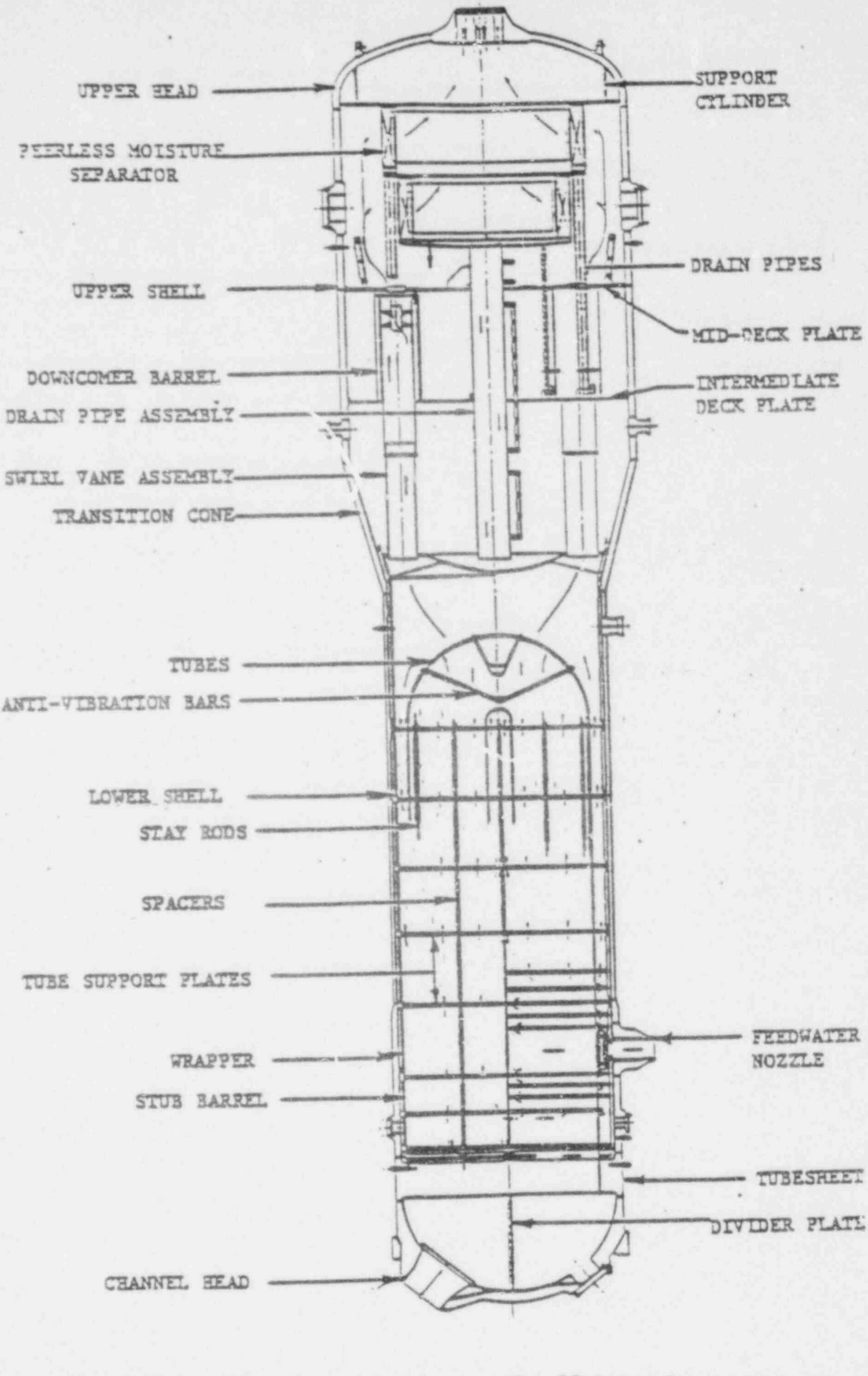

Figure 1-1. Typical Sectional View of a D3 Steam Generator

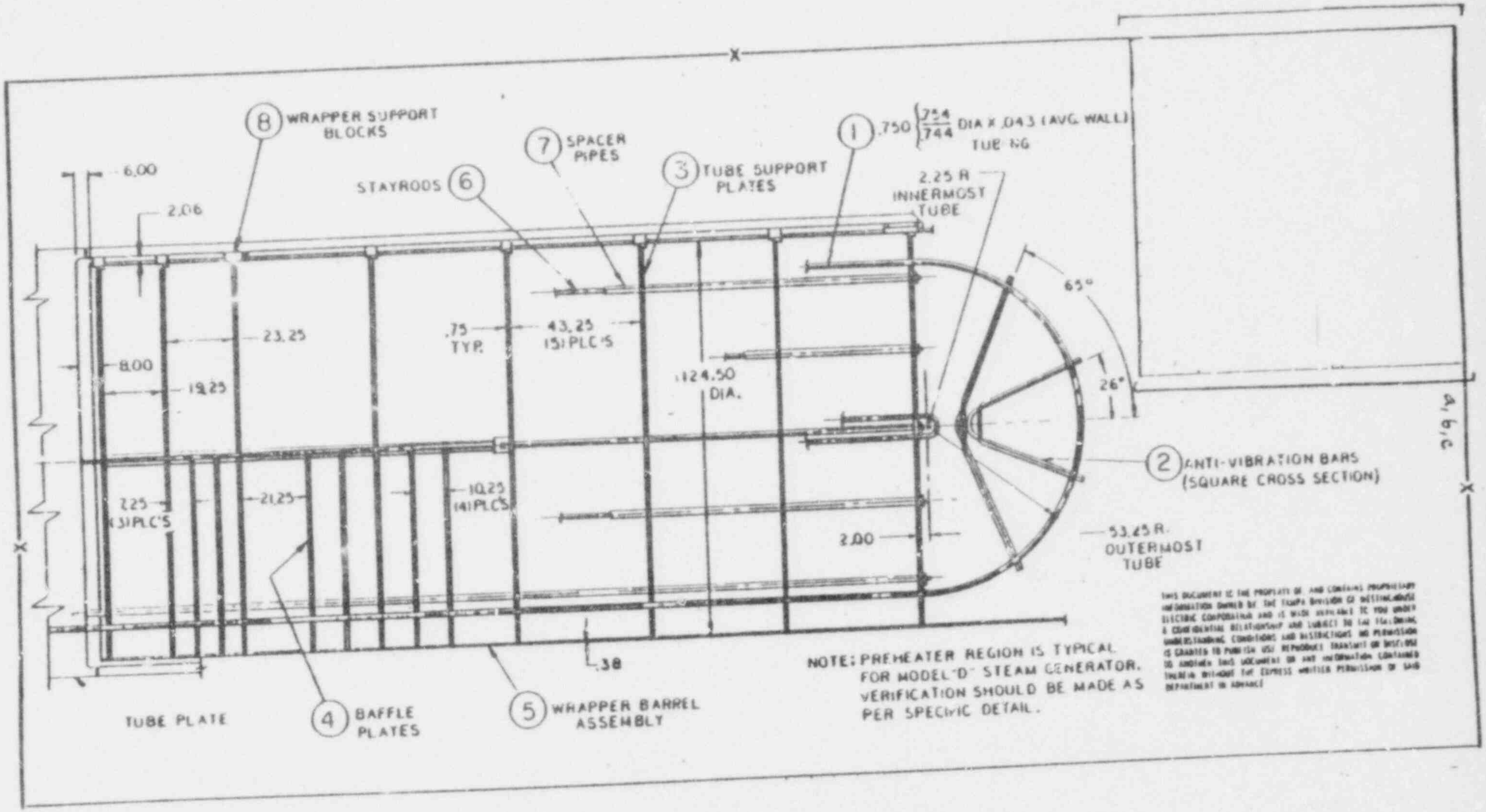

Figure 1-2. Schematic of a Model D3 SG Tube Bundle Internals

SECTION 2

INTEGRITY REQUIREMENTS AND CRITERIA

The steam generator tubing represents an integral part of a barrier against the release of radioactivity into the atmosphere. In the event of a primary loss-of-coolant accident (LOCA), the tubing also provides the necessary heat sink, intially for the core cooldown and later on, for maintaining the plant in the safe shutdown condition. Thus, it is important to establish the structural integrity of the steam generator tubing. This is accomplished based on analyses, testing and in-service inspection. The tube bundle can therefore sustain the loads during normal operation and the various postulated accident conditions without a loss of function or safety.

2.1 Functional and Safety Requirements

Tube wall degradation is caused by a number of different factors such as environment-induced corrosion (includes intergranular attack and stress-corrosion cracking), erosion due to the fluid friction, and fretting wear from the mechanical and flow-induced vibrations. [ ] a,c [ ] However, a potential for additional wall degradation may exist locally in some tubes, at the top of the tubesheet* and in the region of tube-TSP (tube support plates) intersections. This is due to the combination of the fretting wear and corrosion-induced defects and the higher potential of chemical and heat flux concentrations in these regions.

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* Tubes in these units are full-depth expanded within the tubesheet.

Based on steam generator operational history, the whole tube bundle is subjected to only a small, but probably a more or less uniform, tube wall loss over the design total operating period of the unit. On the other hand, a few tubes within 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 rather 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.

In the subsequent discussions, tubes associated with the above two modes of degradation are referrred to as the "median" and the "thinned or locally degraded" tube. The median tubing corresponds to the minimum expected strength properties of the overall tube bundle. That is, a median tube represents a tube with the a,b,
end-of-design life minimum wall [

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*. Specifically, the following two criteria are to be satisfied assuming the median tube properties, that is, end-of-design period thinning concurrent with the drawing minimum tube wall.

1) For Level D Service Conditions, the primary stresses do not exceed the stress limits specified in Appendix F of Section III of the ASME B&PV Code (hereinafter referred to as 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

---

* In the event of extensive tube plugging, plant derating and/or reanalyses associated with functional requirement verification may be necessary. [ ]

a,c

2.3 Locally Degraded Tube Integrity Requirements

As previously indicated, potential for tube wall degradation other than due to nominal erosion-corrosion could exist at certain typical 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 objectionable from the viewpoint of a potential tube rupture if the associated depth of penetration is relatively large. Therefore, to assure that there are no safety consequences as a result of random tube failures, 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 defected tubes. Guidelines in Regulatory Guide 1.83 [2] for EC inspection and Regulatory Guide 1.121 [3] for tube plugging margin calculations provide the bases for determining the limiting safe condition of a locally degraded tube.

The remainder of the report describes the analyses and testing performed to establish the tube plugging margin in accordance with the intent of Regulatory Guide 1.121 [3]. For tube degradation in excess of the established plugging margin, it is required that the tube be repaired or removed (by plugging or otherwise) from service in order to assure 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, the remaining tube wall must be shown to be capable of meeting the applicable strength requirements with adequate allowance for the EC measurement errors and continued erosion-corrosion until the next scheduled outage. The strength requirements are specified in terms of allowable primary stress limits and margins to failure by burst during normal operation and by 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

The most limiting loads for establishing the tube integrity are imposed during the Level D service conditions, [

] a,b
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,b,c

] The tube stress classification for various locations in the tube bundle under the different types of loadings 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 (AVB's) 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-exicted flow induced vibration (FIV) stresses and flow induced vibration from other causes. A self-excited vibration mechanism could be established if flow velocities exceed critical 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

2.5 Criteria and Stress Limits

a,c

Summary of these calculations is given in Table 2-2. Detailed calculations are included in Appendix A.

a,c

- Normal Plant Conditions:

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

$$P_m \le S_y = \left[\qquad \right]^{a,b,c}$$

- 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. That is, during LOCA+SSE, FLB+SSE, and SLB+SSE:

For Locally-Thinned Tubing

$$P_m \le \text{smaller of } (2.4\ S_m,\ 0.7\ S_u) = \left[\qquad \right]^{a,b,c}$$

$$P_m + P_b \le \left[\qquad \right]^{a,b,c}$$

For the Median Tubing $\left[\qquad \right]^{a,b,c}$

$$P_m \le \left[\qquad \right]^{a,b,c}$$

$$P_m + P_b = \left[\qquad \right]^{a,b,c}$$

The shape factor k is a function of the cross-section of the component being evaluated: $\left[\qquad \right]^{a,b,c}$

$\left[\qquad \right]$

As far as the consideration of the secondary and peak stresses in the evaluation of the 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, b, c

TABLE 2-1

TUBE STRESS CLASSIFICATION

a, b, c

TABLE 2-2

CGE TUBE STRENGTH PROPERTIES FOR RG 1.121 ANALYSES
(0.75" OD x 0.043" WALL MILL-ANNEALED I-600)

a, b, c

Temperature, °F
Yield Strength, S_y ksi
Code Value
Lower Tolerance Limit (LTL)
Ultimate Strength, S_u ksi
Code Value
Lower Tolerance Limit
Allowable Stress Intensity, S_m ksi
Code Value
Lower Tolerance Limit

a, b, c

NOTES:
1.
2.
3.

SECTION 3

LOADS AND ASSOCIATED ANALYSES

In establishing the safe limiting condition of a degraded tube in terms of its remaining wall thickness, 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 pressure and thermal conditions are as follows [5].

Primary Side:

[ ] a,b,c.

Secondary Side:

a,b,c

a,b,c

3.2 Accident Condition Loads

For the faulted plant condition evaluation, the postulated Level D Service Condition events are: Safe Shutdown Earthquake (SSE), Loss-of-Coolant Accident (LOCA), main Steam Line Break (SLB) and main Feed Line Break (FLB) accidents. The tube integrity evaluation is performed for the SSE loads in conjunction with the blowdown loads, that is, LOCA+SSE, FLB+SSE, and SLB+SSE loads. Mathematical models, analyses and resulting tube bundle loadings are discussed separately for each of these events.

3.2.1 SSE Loads

Seismic (SSE) loads are developed as a result of the motion of the ground during an earthquake. Plant specific response spectra for CGE were used to obtain the loads and stresses in the tube bundle internals.

a,c

Input Excitations

The seismic excitation for the linear analysis was in the form of response spectra at the steam generator supports. The three orthogonal components of the earthquake were applied simultaneously to perform the analysis. Figure 3-1 shows the three components for the OBE case. The SSE analyses for this study used 150% of the OBE accelerations. The X-direction is along the hot leg, positive toward the reactor vessel; Y is vertical, positive upward and Z is by right hand rule, in the general direction of the crossover leg.

a,c

[ ] The synthesized SSE acceleration time history for the X-direction is shown in Figure 3-2. Figure 3-3 shows the corresponding acceleration time history spectrum superimposed on the specified floor response spectrum in the X-direction.

Modeling Details

The analyses were performed using the WECAN Computer Code. The mathematical model consisted of three-dimensional lumped mass, beam, and pipe elements as well as general matrix input (STIF27) to represent the CGE specific steam generator upper lateral and lower support stiffnesses and the reactor coolant loop piping stiffness. [ ]

a,b,c

[ ]^{a,c} For the rest of the structure, mass and structural damping coefficients were input to realize [ ]^{a,} damping at the lowest and highest significant frequencies of the structure.

Figure 3-4 shows the mathematical model with selected node numbers. The primary loop piping and the lower column support stiffnesses were input as 6x6 STIF27 matrices as given in Tables 3-1 and 3-2, respectively. The upper and lower lateral support restraints were represented by compression-only (single-acting) gap-spring elements in the nonlinear analysis. The upper and lower lateral support configurations and the associated stiffnesses are given in Tables 3-3 and 3-4, respectively. [

]^{a,c}

The modeling of the tube bundle internals-to-shell connections is shown schematically in Figure 3-5. The TSP-local shell stiffness combinations were obtained from detailed finite element analyses and are summarized in Table 3-5. The local shell stiffness at the top TSP location is higher than at lower TSP locations because of its proximity to the upper lateral supports. [

]^{a,b,}

Analysis Output

The analysis output pertinent to the subject evaluation consists of the tube bundle stresses and the maximum in-plane TSP loads.

[ ] a,b,c

As expected, the nonlinear analysis yields higher stresses and loads because of the amplification effect due to the gap between the tube bundle internals and the shell. [ ] a,c

3.2.2 LOCA Loads

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

a,c

LOCA Rarefaction Wave Analyses

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

a,b,c

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

a,b c

For the rarefaction wave induced loadings, the predominant motion of the U-bends is in the plane of the U-bend. [

a,c

] The WECAN Program was used for these dynamic analyses. Figure 3-7 shows the node and element numbering for a typical single tube model.

The tube model consisted of three-dimensional straight pipe and elbow elements. [ ] a, b

[ ] a,c

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.

Rarefaction Wave Induced Tube Loads

The peak tube responses subject to the LOCA rarefaction wave induced loading are summarized in Table 3-8 for the various cases analyzed. Time-history plots of some of the more important response variables are shown in Figures 3-9 thru 3-12. Comparison of these results lead to the following two major inferences.

a
c

The maximum axial stresses in the U-bends are summarized in Table 3-9. As pointed out earlier, the significant stresses result from the pressure differential across the U-bend as the rarefaction wave passes through it.

Rarefaction Wave Induced TSP Loads

The tube motion due to the LOCA rarefaction wave induced loading is restrained at the TSP locations, thus resulting in reaction forces in the plates. [redacted] a,c A summary of the peak reactions for the cases analyzed is included in Table 3-10.

[redacted] a, c

[ ] a,c

For a given tube group, the resultant TSP force was calculated by multiplying the single tube force (from both tube ends) with the number of tubes in that group. The total TSP load at a given time was then obtained by combining the resultant forces [ ] a,c

The maximum loads were calculated [ ] a,b,c

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 coolant loop motion. [ ] a,c

---

* [ ] a,c

The tube U-bend stresses due to LOCA shaking were determined in a previous analysis [5]. Figure 3-15 shows the stress history at approximately the location of the maximum rarefaction wave induced stresses. It is to be noted that the stresses in Figure 3-15 represent the resultant of both the in-plane and out-of-plane stress components, and that the peak magnitude does not occur at the same time as the rarefaction wave induced peak stresses (given in Table 3-8).

3.2.3 FLB/SLB Loads

During the postulated FLB/SLB accidents, the predominant primary tube stresses result from the ΔP_i loading. The peak differential pressure for these events were first determined.

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

] 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,b,c

[redacted]

TABLE 3-1

PRIMARY LOOP PIPING STIFFNESS MATRIX

(lbs/in, in-lb/rad)

a,b

UX
UY
UZ
RX
RY
RZ

TABLE 3-2

STEAM GENERATOR LOWER COLUMN SUPPORT STIFFNESS MATRIX

(lbs/in, in-lb/rad)

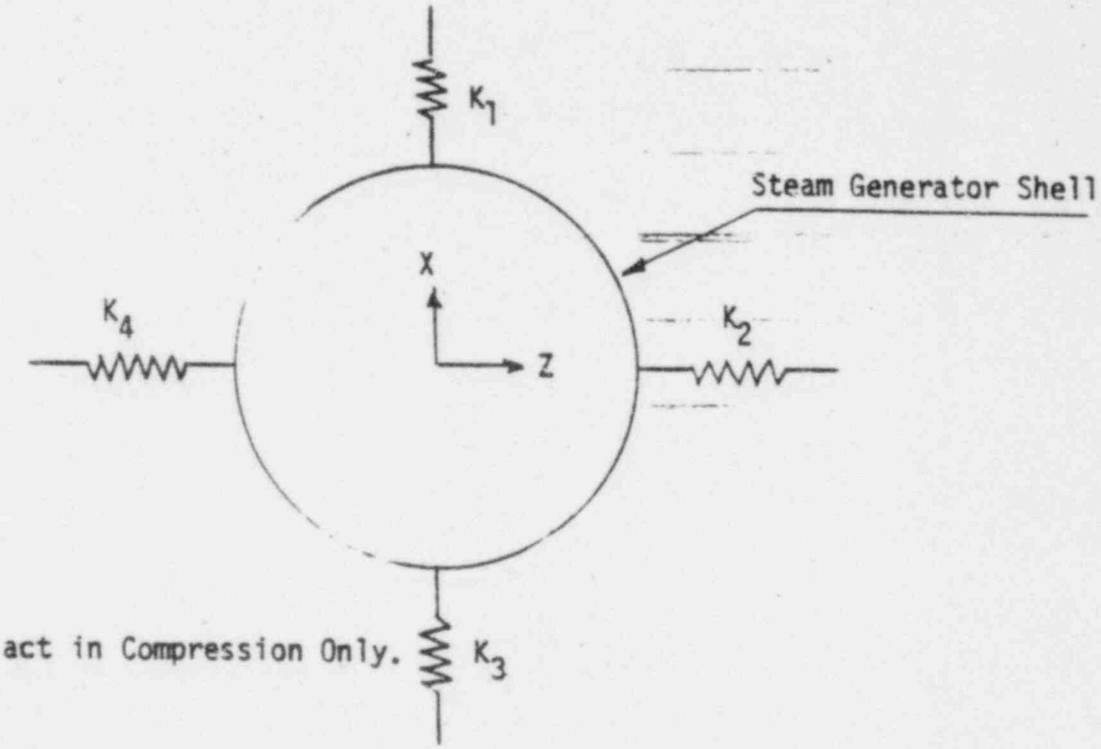
$$\begin{array}{c|c|} \text{UX} & \\ \text{UY} & \\ \text{UZ} & \\ \text{RX} & \\ \text{RY} & \\ \text{RZ} & \end{array}\;{}^{a,b}_{c}$$

TABLE 3-3

STEAM GENERATOR UPPER LATERAL SUPPORT STIFFNESSES

a, b, c

Support Stiffness (lb/in)	Series Combination of Local Shell Stiffness and Support Stiffness (lb/in)



Springs act in Compression Only.

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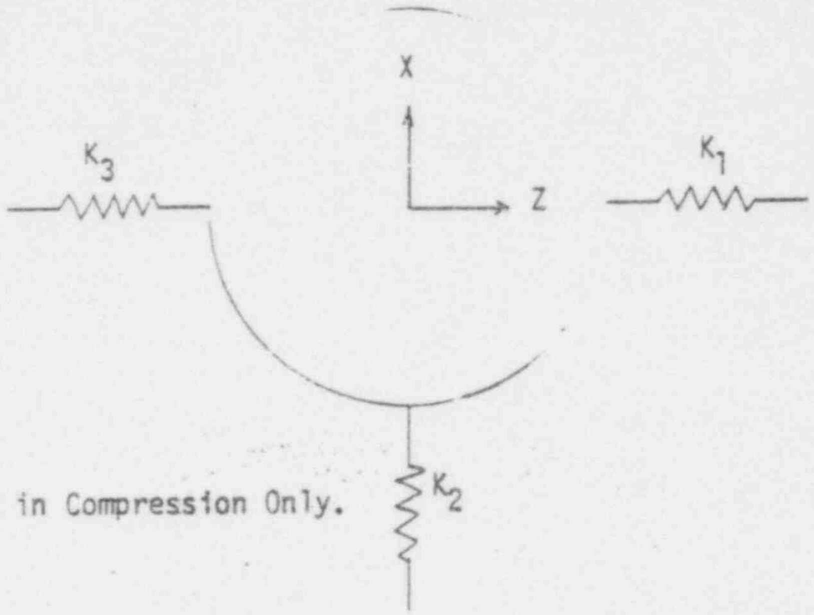
* Spring K_3 includes the tension stiffness of the snubbers.

TABLE 3-4

STEAM GENERATOR LOWER LATERAL SUPPORT STIFFNESSES



Springs Act in Compression Only.

a, b, c

TABLE 3-5

IN-PLANE TUBE SUPPORT PLATE - LOCAL SHELL STIFFNESSES

TSP Location	K_{TSP}, lbs/in.	K_{shell}, lbs/in.	$K_{eq.}$ lbs/in.

a,b,c

TABLE 3-6

MAXIMUM AXIAL TUBE STRESSES DUE TO SSE LOADING

Tube Location	Nonlinear Time History Analysis			Response Spectrum Analysis		
	In-Plane Bending	Out-of-Plane Bending	Direct	In-Plane Bending	Out-of-Plane Bending	Direct

a,b,c

NOTES: (1) In-plane and out-of-plane references for tube stress components are with respect to the plane of the tube U-bends.

(2) Stresses are in psi.

TABLE 3-7

MAXIMUM IN-PLANE TUBE SUPPORT PLATE SSE LOADS

a,b,c

TSP Number	Nonlinear Analysis	Response Spectrum Analysis

NOTES: (1) In-plane loads are loads in the plane of the plate (horizontal plane).

(2) Loads are in kips.

TABLE 3-8

PEAK TUBE RESPONSES DUE TO THE LOCA RAREFACTION WAVE LOADING

a,b,c

---

* Numbers in parentheses refer to node locations in Figure 3-7.

TABLE 3-9

MAXIMUM AXIAL STRESSES IN THE TUBE U-BEND DUE TO THE LOCA RAREFACTION WAVE LOADING

a,b,c

---

* Rarefaction wave ΔP loading. Maximum total stress also occurs at these nodes.

\+ Primary-to-secondary ΔP_i cap force plus fluid friction and centrifugal forces. The maximum stress is more or less uniform around the bend and is mainly due to the ΔP_i cap force which rapidly drops due to the primary side depressurization.

TABLE 3-10

MAXIMUM TUBE SUPPORT PLATE LOADS DUE TO LOCA RAREFACTION WAVE LOADING OF INDIVIDUAL TUBES

a, b, c

[illegible]	[illegible]		[illegible]	
	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]				
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]				
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

a, b, c

a, b, c

a, b

Figure 3-1. CGE Response Spectra for OBE Analysis [5] (X direction is along hot leg, Z by RH Rule)

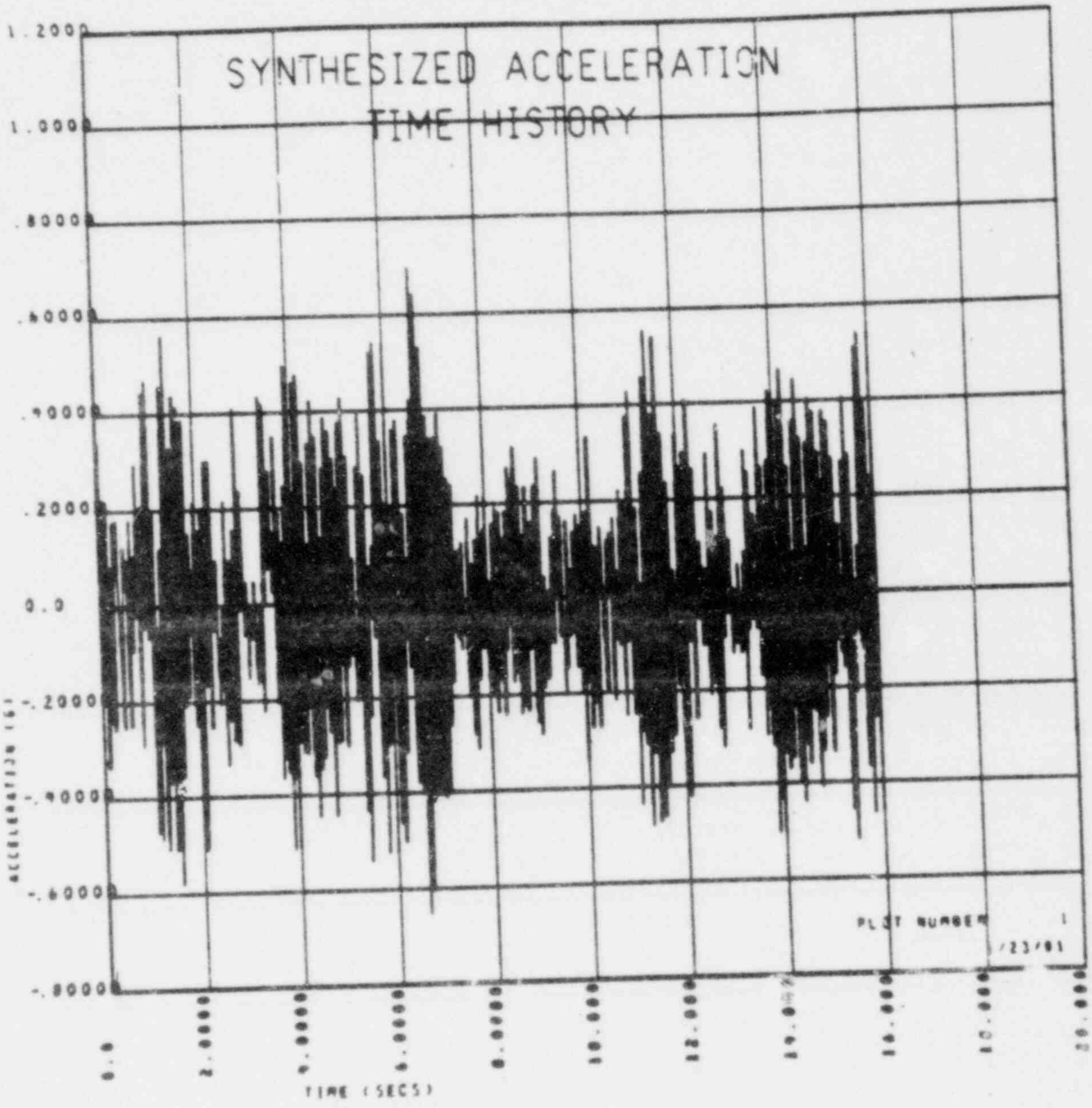


Figure 3-2. Synthesized SSE Acceleration Time History for the X-Direction

a,b,

Figure 3-3. Specified Floor Response Spectrum and the Acceleration Time History Response Spectrum for X-Direction

a,b,c

Figure 3-4. Mathematical Model for the Seismic Analyses

a,b,c

Figure 3-5. Schematic of Tube Bundle Internals-to-Shell Connections in the Seismic Analysis Model

a,b,c

Figure 3-6. Typical Primary Fluid Pressure Time Histories Following a LOCA - Nodes 11 thru 15,[ ] a,b,c
a,b,c [ ] (See Figure 3-7 for Node Locations)

a,b,c

Figure 3-7. LOCA Rarefaction Wave Analysis Model

a, b, c

Figure 3-8. Horizontal Displacements of Node 12 Due to LOCA Rarefaction Wave Loading

a, b, c

a, b,

Figure 3-9. In-plane Bending Moments at Node 15 Due to LOCA Rarefaction Wave Loading -

a, b, c

a, b, c

Figure 3-10. In-plane Rotation of Node 12 Due to LOCA Rarefaction Wave Loading

a, b, c

a, b

Figure 3-11. Horizontal Displacement of Node 12 Due to LOCA Rarefaction Wave Loading -

a, b, c

[ ]a,b,c

Figure 3-12. Tube End Reactions at the Top TSP Due to LOCA Rarefaction Wave Loading - [ ]a,b,c a,b

Figure 3-13. Resultant of LOCA Rarefaction Wave Induced Tube End Reactions at the Top TSP - [ ]a,b,c

a,b,c

Figure 3-14. Resultant of LOCA Rarefaction Wave Induced Tube End Reactions at the Top TSP - [ ] a,b,c

a,b,c

Figure 3-15. Tube Stresses From LOCA Shaking [9] (These stresses are approximately at Nodes 13 and 15 in Figure 3-7)

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) Safety requirements on a locally degraded tube, viz.,

a, b, c

(2) Functional requirements associated with the overall tube bundle integrity (assuming median tubes)* during and following the Level D Service Condition loadings, that is:

a, c

a, b, c

Although the tubing was evaluated for acceptance for both the functional and safety requirements, as indicated earlier, only details of evaluations to the Regulatory Guide 1.121 criteria (that is, degraded tube safety requirements) are discussed in this report. However, for completeness, the following summary of evaluations to verify compliance to the functional requirements is included. The remainder of the section deals with the minimum required tube wall thickness calculations. The discussion of allowable leak rate limit and verification of leak-before-break is contained in the next section.

4.1 Functional Integrity Evaluation

[ ]^{a,b} 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,} 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 (of a degraded tube).

[ ]^{a,} Results of the LOCA and SSE analyses discussed in the previous section were used to compute the maximum $P_m + P_b$ stress intensity in the tube U-bends. Results of this computation are summarized in Table 4-1.

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 support wedges resulting in local distortion and/or collapse of distorted tubes (due to external ΔP_0 following a LOCA).

a,b,c

The TSP reactions due to the LOCA and SSE loads were obtained using elastic analyses described in the previous section.

a,c

a, b,

Figure 4-3 shows the test correlation between the ΔD's and corresponding collapse pressures P_c in a nondimensionalized form. The tests were run at room temperature with tubes inserted into drilled collars simulating the TSP. The tube-collar assemblies were deformed in a vise to obtain various tube ΔD's to be tested.

a, b

---

* a

[ ]a,b,c

The resultant increase in the tube bundle primary flow resistance represents a very small percentage increase in the overall system resistance and, therefore, will not impair the intended function of the steam generator [ ]a,c

4.2 Minimum Wall Requirements for Degraded Tubes

[ ]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 the ovality. An analytical correlation between the collapse pressure and the tube ovality was developed using a large deformation, lower bound limit analysis. The validity and conservatism of the analytical correlation was verified against the results of room temperature collapse pressure tests, conducted in-house and elsewhere [6], on mill-annealed 0.75" OD x 0.043" t oval tubes. Figure 4-4 shows the comparison of analytical predicted (normalized) collapse pressures with those obtained from the tests.

a,

Burst strength requirements associated with leak-before-break and margin to burst under normal operating ΔP_i are discussed in the next section.

TABLE 4-1

SUMMARY OF MAXIMUM STRESS INTENSITY CALCULATIONS

a,b,c

a,b,

Figure 4-1. Schematic of a Tube-Tube Support Plate Crush Test

a,b,c

Figure 4-2. Tube Distortion Data Obtained From the Tube - TSP Crush Test

a,b,c

Figure 4-3. Results of Pressure Collapse Tests on Distorted Tube - TSP Collar Assemblies

a,b,c

Figure 4-4. Correlation Between Tube Ovality and Collapse Pressure

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 must also be shown to be satisfied.

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 assured that an unstable crack growth leading to tube rupture would not occur in the unlikely event of the limiting accident.

For the CGE units, the maximum technical specification allowable leak rate is 0.33 gpm per steam generator. Results of the leak rate tests were used to determine the maximum allowable crack length during normal operation corresponding to this Tech. Spec. limit. [ ]a,c

] From this correlation, the largest permissible crack length (associated with Tech. Spec. limit of 0.33 gpm leak rate) during normal operation is ~0.44 inch. Beyond this length, the leakage would exceed the Tech. Spec. limit, requiring a plant shutdown for a corrective action.

[ ]a,b

] A data base much larger than in Table 5-1 is required for a meaningful statistical evaluation. Such a data base was created by compiling the results of a large number of burst pressure tests performed on various Westinghouse steam generator tubing, within Westinghouse and elsewhere [7]. Because of the variations in tube sizes and mechanical properties, the data was non-dimensionalized and is shown in Figure 5-3. Results for the CGE tests in Table 5-1 were included in Figure 5-3 to verify that the lower bound (shown by the solid line) established by broad data base is applicable to the CGE tubing evaluation.

a,b,
c

Applicability to Thinned Tubing

The applicability of leak-before-break is also required to be verified for the case of a tube with cracking superimposed on thinning. In connection with the burst pressure and leak rate behavior of a tubing, the following should be noted.

a,b
c

5.2 Margin to Burst Under Normal ΔP

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

5.2.1 Tube with Thru-Wall Degradation

a, b, c

For a thinned tube with a superimposed crack, the value of FS would be even higher as indicated by the results in Figure 5-5.

5.2.2 Thinned Tube

For the case of a predominantly thinning mode of tube degradation (that is no thru-wall cracking and hence no leakage prior to failure), the minimum tube wall thickness must be established

a,b.

TABLE 5-1

SUMMARY OF BURST PRESSURE AND LEAK RATE TEST MATRICES FOR CGE TUBING

Burst Pressure Tests[1]

Specimen ID No.	Axial Crack Length, L inch
3900-JAB-81 #1	
#2	
#6	
#7	
#8	
#9	
#10	
#11	

a,b,c

Leak Rate Tests[2,3]

Specimen ID No.	Axial Crack Length, L inch
SGTLR-39 #3	
SGTLR-29	
SGTLR-40 #4A	
SGTLR-41 #5	

a,b,c

a,b,c

a,b

Figure 5-1. Results from a Typical Leak Rate Test (Test #SGTLR-40, [ ] a,b,c

a,b,c

Figure 5-2. Correlation Between Crack Length vs. Leak Rate During Normal Operation (0.75" OD x 0.043" Tubing, [ ] a,b,c

Figure 5-3. Relationship Between Normalized Burst Pressure and Axial Crack Length of SG Tubing

a,b,c

a,b,c

Figure 5-4. Minimum Expected Burst Strength of 0.75"OD x 0.043"Wall I-600 MA Tubing a, b

Figure 5-5. Variation in Margin to Burst as a Function of Mean Radius-to-Thickness Ratio of The Tube

SECTION 6

PLUGGING MARGIN RECOMMENDATION

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

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

Thus, the recommended tube plugging margin for CGE is 55% of nominal wall.

SECTION 7

REFERENCES

1. "ASME Boiler and Pressure Vessel Code, Section III, "Rules, For Construction of Nuclear Power Plant Components", The American Society of Mechanical Engineers, New York, N.Y., 1977.

2. USNRC Regulatory Guide 1.83, "In-Service Inspection of Pressurized Water Reactor Steam Generator Tubes", July 1975.

3. USNRC Regulatory Guide 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes (For Comment)", August 1976.

4. Timoshenko, S., "Strength of Materials - Part II", Third Ed., Von Nostrand Reinhold Co., New York, N.Y., 1958, p. 353.

5. DeRosa, P.P., et. al., "Evaluation of Steam Generator Tube, Tubesheet and Divider Plate Under Combined LOCA plus SSE Conditions", WCAP-7832, Westinghouse Nuclear Energy Systems, Pittsburgh, PA., April 1978.

6. Small, N.C., "Plastic Collapse of Oval Straight Tubes Under External Pressure", ASME Paper #77-PVP-57, June 1977.

7. Vagins, M., et. al., "Steam Generator Tube Integrity Program - Phase I Report," NUREG/CR-0718, September 1979.

APPENDIX A

DERIVATION OF LOWER BOUND TOLERANCE LIMITS FOR STRENGTH PROPERTIES OF 0.75" OD x 0.043" WALL MILL-ANNEALED I-600 TUBING

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

a,b
c

Table A-1 summarizes the calculations of statistical analyses of test data of the mill-annealed Inconel-600 tubing for CGE. The LTL's for the allowable design stress intensity were obtained from the LTL's on yield and ultimate strengths in accordance with the rules in Appendix III of Section III of the ASME Code. Details of these calculations are given in Table A-2.

TABLE A-1

LOWER TOLERANCE LIMITS FOR MODEL D MILL-ANNEALED TUBING STRENGTH PROPERTIES

a,b,c

TABLE A-2

CGE TUBE STRENGTH PROPERTIES FOR RG 1.121 ANALYSES
(0.75" OD x 0.043" WALL MILL-ANNEALED I-600)

a,