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ENTERGY OPERATIONS INCORPORATED
ARKANSAS NUCLEAR ONE

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ENGINEERING REPORT
FOR
ARKANSAS NUCLEAR ONE
RUSSELLVILLE, ARKANSAS

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TITLE: ANO-2 STEAM GENERATOR DEGRADED TUBE ANALYSIS PER REG GUIDE 1.121

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1.0 PURPOSE

In March 1992, ANO-2 was shut down as a result of a tube leak in the "A" steam generator (one of two steam generators: 2E24 A & B). Inspections were performed to determine the extent of degradation associated with the leaker. These inspections revealed significant degradation in the expansion transition region of the tubing, just above the tubesheet, on the hot leg side, primarily in the "A" generator, but also in the "B" generator. This degradation was essentially circumferential in nature, with axial extent limited to less than 0.25 inch, based on eddy current testing. This is also consistant with the limited axial extent of the expansion transition where the residual stresses imposed on the tube by the expansion contribute to the stress corrosion cracking which caused the defects, based on tubes pulled from the generators for examination. Due to the large size of the defects (both circumferential and thru-wall extent), an evaluation of the allowable tube wall degradation was performed. The purpose of this report is to document the evaluation done to determine the maximum allowable tube wall degradation in accordance with (draft) Reg Guide 1.121. This allowable degradation is used to support the tube plugging criteria and related safety margins for ANO-2 steam generators.

2.0 SUMMARY OF APPROACH

A structural evaluation of maximum allowable degradation was performed by Combustion Engineering (C-E) in accordance with the Reg Guide requirements, as interpreted by C-E. The report of this work is contained in Attachment A. This report was then independently reviewed by MPR Associates, Inc. Their review, along with their interpretations of the requirements of the Reg Guide, were factored into their report, Attachment B. In addition, since axial cracking in the egg crate support region is also an emerging issue for ANO-2, MPR was tasked to expand their results to include additional information to support criteria specifically for axial cracks.

2.1 C-E Approach

C-E evaluated the structural integrity of the flawed tubing for normal operating conditions including flow induced vibration, and accident loads coincident with Safe Shutdown Earthquake (SSE) loads. These loads were considered for three cases:

1) Unlimited axial and circumferential extent,
2) A limited axial extent of 0.25 inch maximum and unlimited circumferential extent, and

3) A limited axial extent of 0.25 inch maximum, and the maximum allowable 100% thru-wall defect was determined.

The analysis considered both Code required mimimum material strength, and a conservative estimate of actual material strength expected in ANO-2 based on yield strengths of typical tubing supplied to C-E in accordance with their tubing specifications. In addition, the analysis also considered degradation initiating on both the inside and outside of the tubing.

2.2 MPR Approach

MPR provides a point by point discussion of the Reg Guide requirements, compares the C-E analysis to them, and provides additional evaluations where necessary, based on their interpretation of the Reg Guide. Significant items from the report are:

1) MPR agrees with the results of the first case for unlimited axial and circumferential extent.

2) The C-E evaluation uses the tube burst data directly to estimate the allowable degradation for the second case defect. The MPR evaluations also utilize the burst test data, but account for differences in tubing and defect parameters between the burst test tubing and the ANO-2 tubing.

3) The results for C-E's third case of limited axial extent and 100% thru-wall are misleading, as they actually apply to slot type defects rather than a defect which is 0.25 inch wide. However, based on burst tests for other tubing with defects similar to ANO-2, it is expected that ANO-2 tubing will behave such that average remaining wall thickness is the appropriate criteria. See Attachment B, pages 3-6 and 3-7, for additional information.

3.0 SUMMARY OF RESULTS

The overall results are summarized in Table 1, below.

TABLE 1

Types of Degradation[1]	C-E Results[2]	MPR Results[2]
Unlimited axial and circumferential extent	65.8%	66%
0.25 inch max axial length at 360° circ extent	77%	79%
axial slot type	NA	See Attach. B, Fig. 1

[1]asymmetrical defects at the tubesheet or tube support elevations, or symmetrical defects at any location

[2] conservative best estimate tubing properties

Based on a detailed review of Attachments A and B, Design Engineering considers a limit of 79 % through wall to be appropriate for the pertinent defects of current interest (0.25 inch maximum axial length, 360 degree circumferential extent). Notably, this 79% value is based on calculations/tests for planar defects and is, therefore, conservative with regard to actual ANO-2 defects which have ligament strength between microcracks.

ABB COMBUSTION ENGINEERING NUCLEAR POWER
Combustion Engineering, Inc.

EVALUATION OF
CIRCUMFERENTIAL DEFECTS AT THE
EXPANSION TRANSITION IN ARKANSAS NUCLEAR ONE
UNIT 2 STEAM GENERATOR TUBES

CR-9417-CSE92-1102, REV. 0

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NCS ENGINEERING CALCULATION REPORT

CR-9417-CSE92-1102, REV. 0

EVALUATION OF CIRCUMFERENTIAL DEFECTS AT THE EXPANSION TRANSITION IN ARKANSAS NUCLEAR ONE - UNIT 2 STEAM GENERATOR TUBES

PREPARED BY: C.L. Stubbs Cheryl L. Hatke DATE: 4/23/92

VERIFICATION STATUS: COMPLETE

The Safety-Related design information contained in this document has been verified to be correct by means of Design Review using Checklist(s) 2 of QAM-101.

Name B.A. Bell Signature B.A. Bell Date 4/23/92
Independent Reviewer

APPROVED BY: J.H Sodergren J.H. Sodergren DATE: 4/23/92

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RECORD OF REVISIONS

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0	04/23/92	Original Issue	C. L. Stubbs	B.A. Bell	J. H. Sodergren

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1.0 INTRODUCTION

The analysis presented herein is performed to establish the maximum allowable tube wall degradation for the Arkansas Nuclear One - Unit 2 steam generator tubes per the requirement of NRC Regulatory Guide 1.121. The results of this analytical study will be used in conjunction with prior pressure testing results to assess the steam generator tube integrity when subjected to either inner diameter or outer diameter circumferential cracking at the tube expansion transition region.

This report addresses the structural aspects of NRC Regulatory Guide 1.121 regarding the minimum wall thickness of steam generator tubing. The report does not address the primary to secondary leakage rate data used in meeting Regulatory Position C.3.(d)(3). The structural integrity of the flawed tubing is evaluated based on normal operating conditions and possible accident conditions such as Loss of Coolant Accidents (LOCA) plus Safe Shutdown Earthquake (SSE) loads and Main Steam Line Break (MSLB) plus SSE loads. Since the tubes containing flaws may be located near the outer periphery of the tube bundle the tubes will also be evaluated for flow induced vibration due to the recirculating fluid.

The report also considers two tube cases with localized defects. The first case has an axial defect of 0.25 in. maximum and an unlimited circumferential extent. The second case also has an axial defect of 0.25 in. maximum, but the allowable circumferential extent for 100% thru-wall defect is determined.

2.0 SUMMARY OF RESULTS

This analysis evaluates the loading of a flawed tube due to normal operation, Loss of Coolant Accident (LOCA), Main Steam Line Break (MSLB), and Safe Shutdown Earthquake (SSE). The allowable tube wall degradation is established to be 61.5% for the case of unlimited axial and circumferential extent of defect in accordance with the stress allowed by the ASME Code Section III and the structural integrity margins required by NRC Regulatory Guide 1.121. When the probable tube material properties are used in place of the ASME Code allowables, the allowable tube wall degradation can be increased to 65.8% for the case of unlimited axial and circumferential extent of defect and still meet the structural integrity margins required by NRC Regulatory Guide 1.121.

The maximum stress intensity due to a 61.5% degraded tube was found to be 26.75 ksi and 30.24 ksi for a 65.8% degraded tube, which is less than the allowable of 56 ksi for the steam generator tube material, Inconel SB-163.

For the two tube cases with specific defects, the maximum allowable tube defect per NRC Regulatory Guide 1.121 tube burst requirements is 77% tube wall degradation for an axial extent of 0.25 in. maximum and unlimited circumferential extent. With 100% thru-wall defect, the maximum allowable circumferential extent is 274°, with 86° of the total circumference having no tube wall degradation.

3.0 REFERENCES

3.1 U.S NRC Regulatory Guide 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes", August 1976.

3.2 Analyses to Determine Allowable Tube Wall Degradation for Palisades Steam Generator, CENC-1264, Revision 03, January 1976.

3.3 Arkansas Steam Generator Structural Analysis of Tubes for Pipe Rupture Accidents, CENC-1262-1, September 23, 1977

3.4 Maine Yankee Steam Generator Analysis of Circumferentially Flawed Tubes at Tubesheet, CENC-1934, January 1991.

3.5 ASME Boiler and Pressure Vessel Code, Section III for Nuclear Power Plant Components.

3.6 Connors, H.J., Jr., "Fluidelastic Vibration of Tube Arrays Excited by Nonuniform Cross Flow", Flow-Induced Vibration of power Plant Components, ASME, PVP-41, p. 93.

3.7 Heilker, W.J. and Vincent, R.Q., "Vibration in Nuclear Heat Exchangers Due to Liquid and Two-Phase Flow", Engineering for Power, April 1981, Vol.103, No.2.

3.8 ANSYS Engineering Analysis System, Finite Element Computer Program, Revision 4.1, March 1, 1983, John A. Swanson, Ph.D.

3.9 Lowry, J.C. memo to J.H. Sodergren on "Hydraulic Conditions at the Tube Bundle Entrance for Arkansas Steam Generator," ATH-92-069, April 10, 1992.

3.10 Heilker, W.J. and Beard, N.L., "Flow Induced Vibration Analysis in Support of the Design of the Yongwang Units 3 and 4 Steam Generators", Proceeding of the International Symposium on Pressure Vessels Technology and Nuclear Codes and Standards, April 19-21, 1989, Seoul, Korea.

3.11 Drawing E-234-825, "Baffle and Tube Support Assembly, Rev. 04.

3.12 Engineering Specification for a Steam Generator Assembly, Specification No. 06370-PE-120.

3.13 Analytical Report for Arkansas Nuclear One Unit 2 Steam Generator, CENC-1223, July, 1974.

3.14 Roark, R.J. and Young, W.C., "Formulas for Stress and Strain", Fifth Edition, 1975.

3.15 "Design Guide for Calculating Hydrodynamic Mass Part I: Cylindrical Structures", Chen, S.S. and Chung, H., June, 1976, Argonne National Laboratory.

3.16 Main Steam Line Break Analysis of Palisades Steam Generator Internals (Including Tube Sleeves), CENC-1288, June 3, 1977.

3.17 Analytical Report for Arizona Public Service Company Palo Verde Unit No. 3 Steam Generators, CENC-1479, August, 1981.

3.18 Annual Progress Report for Steam Generator Tube Integrity Program, NUREG/CR-0277, PNL-2684, R5, January 1-December 31, 1977.

4.0 GEOMETRY DESCRIPTION OF S/G TUBE BUNDLE

The Arkansas steam generator tube bundle is comprised of 0.75 inch diameter tubes with 0.048 inch wall thickness which are supported by grid type ("egg-crate") tube supports in the axial flow region. In the cross flow region the tube bundle is supported by three different types of supports. Two of these, drilled plates and "egg-crates", support the vertical portion of the tubes and "batwing" configurations support the horizontal section. This report is concerned only with the stresses occurring in the tube expansion region of the bundle and is therefore only considering forces acting on the vertical portion of the tube bundle.

The egg-crate and drilled support plates are spaced incrementally up the tube bundle as shown in Figure 5.4-1. The first support is located at 28.125 inches above the tube sheet. The remaining full and partial supports are located vertically in the following increments (all in inches), 30, 33, 35, 30, 33, 35, 25.5, 26.5, 22. The last three increments correspond to locations of partial supports. (Reference 3.11)

Tube Row 110 is modeled in ANSYS to be evaluated throughout this report. This tube row is chosen as a bounding condition and corresponds to the location evaluated in the Palisades steam generator report (Reference 3.2). Resulting time history displacements from this Palisades report will be applied to the ANO2 steam generator and it is necessary that the identical location in the ANO2 generator be modeled to produce compatible results.

5.0 STRUCTURAL ANALYSIS

5.1 LOADINGS TO BE CONSIDERED

5.1.1 LOCA Rarefaction Wave

A Loss-of-Coolant Accident (LOCA) produces a rarefaction wave which propagates at the speed of sound away from the break location. As the rarefaction wave passes through the tubes in the bend region of the steam generator, it imparts a lateral pressure loading on the tube bundle. The pressure loading on a particular tube is proportional to the pressure difference acting between the midpoints of the bends. Fluid friction and the centrifugal forces generated as the fluid negotiates the bends also contributes to the lateral loading on the tube bundle. The net force on a particular horizontal section of the tube is the algebraic sum of the pressure, friction, and centrifugal forces.

5.1.2 Pipe Break Impulse Response

A LOCA accident produces an externally applied impulse to the steam generator caused by the fluid escaping from its respective loop. A detailed system LOCA analysis has been done for the Palisades steam generator, Reference 3.2. The results of this analysis were time history displacements at the steam generator uppermost full eggcrate tube support. These displacements were used in a dynamic ANSYS finite element analysis on a model of the Maine Yankee steam generator to calculate the tube stresses near the secondary face of the tubesheet and at the uppermost eggcrate support. The following discussion will show that these results can be conservatively applied to the ANO2 steam generator tubes.

Palisades analyzed the stress at the uppermost eggcrate while Maine Yankee (MY) calculated this stress as well as the stress at the secondary tubesheet face. The stress calculated for both plants at the uppermost eggcrate was the same. The steam generators for these two plants are compared with ANO2 on the bases of volume and geometry. The volume of the Maine Yankee generator is smaller than Palisades and ANO2 (the volume of ANO2 is similar to Palisades), but the geometry of MY is more unstable than Palisades. Since the resulting stress calculated at the uppermost eggcrate for both plants was the same and the geometry of ANO2 is more stable than that for Palisades and MY, it is assumed that the results obtained by MY for the stresses at the tubesheet are conservative for ANO2.

5.1.3 MSLB Secondary Side Blowdown

A Main Steam Line Break (MSLB) produces a transient pressure loading on the steam generator internals. The pressure loading results from the relative rates at which the secondary fluid leaves adjacent region. In general, the blowdown rate following a main steam line break depends upon the steam generator geometry, the secondary pressure, the secondary mass, and the nozzle area.

Previous analyses of a main steam line break for a wide range of operating conditions and different steam generator geometries (References 3.16 and 3.17) indicate that peak pressure loads on steam generator internals are realized at either zero or low power operation. This is due to the fact that the secondary pressure increases to near 900 psi under zero and low power operation, from 825 psi during normal operation. The pressure load across the tube bend region caused by this blowdown is maximized at zero percent power. During the main steam line break, the rapid depressurization of the secondary fluid and its acceleration toward the break location are unaffected by the primary system.

5.1.4 Flow Induced Vibration

A tube placed perpendicular to a flowing fluid tends to extract energy from the fluid and vibrate with some amplitude. The steam generator tubes in the tubesheet region are affected in this manner by the recirculating fluid in the generator. Reference 3.7 gives a method of calculating an equivalent static loading using flow induced vibration evaluation methods which are based on the velocity of the fluid cross flow, the natural vibration frequencies of the tube, and the mode shapes of the tube vibration.

5.1.5 Differential Pressure (ΔP)

During the MSLB event a tube is subjected to a net pressure force which produces an axial force in the vertical straight portion of the tube. With the primary pressure remaining approximately constant during the secondary side blowdown at a maximum of 2500 psia, a differential pressure stress is developed which increa[illegible] from normal operating differential stress to some maximum value which varies from plant to plant. In order to select a conservative value, it will be assumed that the secondary side has dropped to atmospheric pressure while the primary side is at design condition.

During the LOCA event a tube is subjected to a net pressure force which produces an axial force in the vertical straight portion of the tube. With the

secondary pressure remaining approximately constant during the LOCA event at 900 psia, a differential pressure stress is determined based on this pressure and the primary pressure at the time of maximum LOCA stresses. Since the pressure in the primary side will not exceed 2500 psia, the maximum ΔP caused by LOCA will be less than that caused by MSLB. Therefore, the stress caused by the ΔP due to the MSLB will be evaluated in this report and will envelope that caused by the LOCA. The analysis concludes that tube buckling is not a concern, with the higher ΔP being outside the tube, due to the circumferential nature of the defects.

5.1.6 Safe Shutdown Earthquake (SSE)

The project specification for the ANO2 unit states that the steam generator shall be capable of withstanding a maximum seismic loading equivalent to a 1.5G lateral and 1.4G vertical simultaneously applied static loading (Reference 3.12).

5.2 ASSUMPTIONS APPLICABLE TO STRUCTURAL LOADINGS

5.2.1 The stresses in the tube at the tubesheet expansion location caused by LOCA Impulse response as calculated by Maine Yankee in Reference 3.4 are conservatively assumed to apply to the ANO2 steam generator tubes

5.2.2 The velocity flow in the tubesheet region due to recirculating fluid is constant over the vertical span of 0-15 inches above the tubesheet and zero from there to the top of the tube.

5.2.3 The maximum amount of degradation for the unlimited axial and circumferential extent of defect is calculated for both the ASME Code allowables and the "probable" tube material properties.

5.2.4 The stress caused by ΔP due to a main steam line break envelopes that caused by a LOCA event.

5.2.5 Where exact data and equations are not applicable, the stress caused by the degradation of the tube will be estimated from the stress resulting on the healthy tube, using a factor based on the percent of degradation.

5.3 NRC REQUIRED STRUCTURAL INTEGRITY MARGINS

In Section 5.1, various loadings including postulated pipe break accident, earthquake, flow induced vibration, and operational differential pressure were identified as

conditions which in combination must satisfy appropriate ASME Code, Section III allowable stresses. In addition to those requirements, the NRC Regulatory Guide 1.121 requires that certain structural integrity margins be satisfied for flawed tubes which have not been removed from service:

These criteria include:

1. Tubes with detected acceptable defects will not be stressed during the full range of normal reactor operation beyond the elastic range of tube material.

2. The factor of safety against failure by bursting under normal operating conditions is not less than three at any tube location where defects have been detected.

These criteria represent margins of safety which are inherent in the design rules of Section III of the ASME Code. It is possible for flawed tubes to meet these requirements because steam generator tubes are designed with margins much larger than the minimum ASME Code requirements.

The following sections verify that a 61.5% degradation for unlimited axial and circumferential extent of defect irrespective of O.D. or I.D. initiation when using the ASME Code allowables for S_y and S_u. The minimum required thickness is based on pressures, temperature and material properties at normal operating conditions.

Dimensions of a healthy tube are $R_i = 0.327$, $R_o = 0.3750$, and $t = 0.048$ inches

5.3.1 Tube Degraded from the Inside

New dimensions: $R_i = 0.3565$, $R_o = 0.3750$, and $t = 0.0185$ inches

1. Flawed tube not stressed beyond elastic limit

The code equation for required minimum tubewall thickness (t_r) in cylindrical shells is used with the most conservative combination of pressure loadings. S_y is used to evaluate the required thickness with respect to the elastic limit of the material.

$$t_r = \frac{(P_1 - P_2)\ Ri}{Sy - 0.5(P_1 + P_2)} = \frac{(2.25 - 0.900)(.3565)}{27.9 - 0.5(2.25 + 0.900)} = 0.0183\ in. \quad \text{Equation 1}$$

2. Flawed tube maintains a safety factor of 3

The code equation for required minimum tubewall thickness in cylindrical shells is used with the most conservative combination of pressure loadings. S_U is used to show that the factor of 3 is maintained with regard to the ultimate strength of the material.

$$t_r = \frac{3(P_1 - P_2)R_i}{S_u - 0.5(P_1 + P_2)} = \frac{3(2.25-0.900)(.3565)}{80 - 0.5(2.25 + 0.900)} = 0.0184\ in. \quad \textit{Equation 2}$$

5.3.2 Tube Degraded from the Outside

New dimensions: $R_i = 0.327$, $R_o = 0.3455$, and $t = 0.0185$ inches

1. Flawed tube not stressed beyond elastic limit

The code equation for required minimum tubewall thickness (t_r) in cylindrical shells is used with the most conservative combination of pressure loadings. S_y is used to evaluate the required thickness with respect to the elastic limit of the material.

Using Equation 1, $t_r = 0.0168$ in

2. Flawed tube maintains a safety factor of 3

The code equation for required minimum tubewall thickness in cylindrical shells is used with the most conservative combination of pressure loadings. S_U is used to show that the factor of 3 is maintained with regard to the ultimate strength of the material.

Using Equation 2, $t_r = 0.0169$ in

5.4 STRESS EVALUATION OF TUBE WITH UNLIMITED AXIAL AND CIRCUMFERENTIAL DEFECTS

The following analyses will be discussed based on three states of the tube: healthy, degraded on the inside, and degraded on the outside. The individual loading conditions may have been evaluated for one, two or three of these cases. Where only the healthy tube was analyzed, a factor based on the percent degradation will be applied to estimate

the stress in the degraded cases. Where the degraded cases were analyzed the actual resulting stress is known. However, this factor of degradation will be also applied to the healthy case and the largest of the actual and estimated stress will be used.

Factor of Degradation:

maximum allowable percent degradation = 61.5%

factor = 1/(1-.615) = 2.60

5.4.1 LOCA RAREFACTION WAVE

The LOCA rarefaction wave can cause severe lateral loading at the top of the tube bundle, as described in Section 5.1.1. However, the tube flaws being evaluated in this study occur exclusively in the tube expansion region. Therefore, the rarefaction wave produces no stress at the location of interest in this analysis.

5.4.2 PIPE BREAK IMPULSE RESPONSE

The postulated LOCA event causes a shock loading to the steam generator which causes the steam generator shell to deflect as a rigid body about the bottom of the sliding base (Figure 5.4-2). The time history displacements of the steam generator shell at the uppermost full eggcrate support locations are calculated in Reference 3.2 and shown in Figure 5.4-3. These displacements were applied to an ANSYS finite element model of the vertical portion of a Maine Yankee steam generator tube in a dynamic analysis of the tube (Reference 3.4). The results showed that the maximum stress at the tubesheet was 0.5 ksi, Figure 5.4-4, and the maximum stress, occurring at the uppermost eggcrate was 2.0 ksi. This stress at the uppermost eggcrate is consistent with the results of the Palisades steam generator report. (Note: the input data for the MY analysis was taken from the Palisades report) The volume of ANO2 is similar to that of Palisades and the geometry of ANO2 is more stable, with the tube supports being closer together. Therefore, the results of the MY analysis showing the maximum stress at the tubesheet to be 0.5 ksi can be conservatively applied to the ANO2 steam generator tubes.

The previously mentioned analysis was done for a healthy tube. As discussed above a factor based on the percent degradation will be applied to this value to estimate the stress which would occur on a degraded tube. This stress will be applicable to degradation on the inside or outside of the tube. Stress on degraded tube = 0.5 x 2.60 = 1.3 ksi.

5.4.3 MSLB SECONDARY SIDE BLOWDOWN

The tubes in the cross-flow region are subjected to an external flow induced loading during the MSLB event. The loading imposed on the horizontal span of each tube is based on the assumption that the force acting is proportional to the ratio of an individual tube's projected area to the total cross-flow tube area of the bundle. Since the tube flaws being evaluated in this study occur exclusively in the expansion region just above the tubesheet, the flow forces described above produce no significant primary loading at this location.

5.4.4 FLOW INDUCED VIBRATION

An ANSYS model of the straight portion of a Row 110 ANO2 steam generator tube was created. It consists of 109 STIF16, 3-D pipe elements with supports at 10 locations above the tube sheet, Figure 5.4-5. The boundary conditions are: (1) the model is fixed at Node 1, the tubesheet face, and (2) the tube is simply supported at each tube support location. This model was used to generate an Eigenvalue analysis to give frequencies and mode shapes which are required to evaluate the flow induced vibrations loading.

The resulting Eigenvalues are listed in Table 5.4-1 for a healthy tube and for a tube degraded on the outside. Mode 9 is the critical mode for both cases, since the maximum displacement in this mode occurs in the first span. The mode shape plot is similar for both cases and is shown in Figure 5.4-6 for Mode 9. Table 5.4-2 and 5.4-3 give the expanded Eigenvector for Mode 9 for the healthy tube and tube degraded outside, respectively.

The effective mass is required for this analysis and is calculated as follows:

$$\rho_{eff} = (1/A_t g)(\rho_t A_t + \rho_{pf} A_i + C_m \rho_{sf} A_o) \quad \text{Equation 3} \quad \text{(Reference 3.15)}$$

Where:

- g = Acceleration due to gravity (in/sec^2)
- A_t = Area of tube wall per inch of tube (in^2)
- ρ_t = Density of tube (lb/in^3)
- A_i = Area of displaced flow based on inside radius per inch of tube (in^2)
- ρ_{pf} = Density of primary fluid (lb/in^3)
- A_o = Area of displaced flow based on outside radius per inch of tube (in^2)
- ρ_{sf} = Density of secondary fluid (lb/in^3)
- C_m = Virtual mass coefficient

When tubes in a heat exchanger are subjected to a fluid cross flow, there is a threshold velocity where the onset of fluid-elastic unstable vibrations occur. This is defined as the critical velocity and is given by the equation:

$$Vcr = fn\ Kd\ \left[\frac{M_o\ \delta_o}{\rho_o\ d^2}\right]^{1/2} \quad \text{Equation 4}$$

(Reference 3.7)

Where:

- f_n = Natural frequency of nth mode of vibration (Hz)
- K = Threshold of instability constant
- d = Tube O.D. (in)
- M_o = Reference mass of tube per unit length (lb/in)
- δ_o = Logarithmic decrement = $2\pi\xi$
- ξ = Damping ratio of tube in fluid
- ρ_o = Reference fluid density (lb/in^3)

The above parameters are obtained from the tube geometry and from test and operating plant data.

A comprehensive flow test program was conducted by Combustion Engineering to evaluate the vibration behavior of various tube bundle arrangements when subjected to liquid cross flow (References 3.7 and 3.10). The triangular pattern with 0.75 O.D tubes used in the CE generators was one of those evaluated. The tubes were driven to instability and critical velocities were determined for various flow orientations. The K value for the subject tube geometry was determined to be 3.2 (Reference 3.10).

If the cross flow velocity is not constant over the entire tube span, an effective velocity must be determined. Reference 3.10 presents a method for calculating V_{eff}. The equation is:

$$V_{eff}^2 = \frac{\int (\rho(x)/\rho_o)\ \ V^2(x)\ \ \phi^2(x)\ \ dx}{\int (M(x)/M_o)\ \ \phi^2(x)\ \ dx} \quad \text{Equation 5}$$

Where:

- ρ = Density of secondary fluid
- M = Effective mass of tube
- ϕ = Modal displacement (in)
- V = Cross flow gap velocity (in/s)

All parameters vary with distance along the tube, x.

The onset of instability occurs when the stability ratio reaches 1. This is based on a procedure of defining, from test data, critical velocity corresponding to the onset of instability to be the velocity at which the tube response suddenly deviates from linearity or exceeds an rms displacement of 10 mils. Stability ratio is defined as :

$$S.R = V_{eff} / V_{cr} \qquad \text{(Reference 3.10)}$$

The flow data for the tube span between the tubesheet and the first tube support is taken from Reference 3.9. The velocity profile is assumed to be constant over the flow region. Although this results in a lower maximum velocity than a linear distribution, the equation for effective velocity is such that velocity and modal displacement are related. The velocity corresponding to the maximum modal displacement for constant velocity distribution is larger than that for a linear distribution. Therefore, the constant velocity distribution is conservative.

5.4.4.1 Flow Induced Vibration for Healthy Tube

Effective Mass:

Substituting the following values into Equation 3 gives,

ρ_{eff} = 0.001948 lb-sec²/in⁴

Where:

G	= 386 in/sec²
A_t	= 0.106 in²
ρ_t	= 0.305 lb/in³
A_i	= 0.336 in²
ρ_{pf}	= 0.026 lb/in³
A_o	= 0.442 in²
ρ_{sf}	= 0.0282 lb/in³
C_m	= 3.1

Critical Velocity:

Substituting the following values into Equation 4 gives,

V_{cr} = 364.7 in/s

Where:

f_n = 191 Hz
K = 3.2
d = 0.75 in
M_o = 0.0797 lb/in
δ_n = $2\pi\xi$ = 0.126
ξ = 0.02
ρ_o = 0.0282 lb/in^3

Effective Velocity:

Using the equation previously defined with the effective mass of the tube and the density of the secondary fluid constant over the tube span, a velocity of 11.44 ft/s from 0-15 inches above the tubesheet, and modal displacements from Table 5.4-2, the effective velocity is calculated to be 83.8 in/s.

Stability Ratio:

S.R. = 83.8 / 364.7 = 0.23

Tube Loading:

$F_p = C_f\, d\, (\rho V_{eff}^2 / 2g) = 0.0770$ lb/in Equation 6

Where:

C_f = 0.4 (Reference 3.7)
d = 0.75 in
ρ = 0.0282 lb/in^3
V_{eff} = 83.8 in/s
g = 386 in/sec^2

This loading of .077 lb/in is inputted as static load to the previously described ANSYS model, Figure 5.4-5. The maximum stress is calculated to be less than a .1 ksi at the tubesheet face.

5.4.4.2 Flow Induced Vibration for Tube Degraded Outside

Effective Mass:

Substituting the following values into Equation 3 gives.

ρ_{eff} = 0.003225 lb-sec^2/in^4

Where:

g	= 386 in/sec^2
A_t	= 0.0447 in^2
ρ_t	= 0.305 lb/in^3
A_i	= 0.336 in^2
ρ_{pf}	= 0.026 lb/in^3
A_o	= 0.3807 in^2
ρ_{sf}	= 0.0282 lb/in^3
C_m	= 3.1

Critical Velocity:

Substituting the following values into Equation 4 gives,

V_{cr} = 292.5 in/s

Where:

f_n	= 183.3 Hz
K	= 3.2
d	= 0.696 in
M_o	= 0.05565 lb/in
δ_n	= $2\pi\xi$ = 0.126
ξ	= 0.02
ρ_o	= 0.0282 lb/in^3

Effective Velocity:

Using the equation defined above with the effective mass of the tube and the density of the secondary fluid constant along the tube span, a velocity of 11.44 ft/s from 0-15 inches above the tubesheet, and modal displacements from Table 5.4-3, the effective velocity is calculated to be 83.8 in/s.

Stability Ratio:

S.R. = 83.8 / 292.5 = 0.29

Tube Loading:

Substituting the following values into Equation 6 gives,

$F_F = 0.0803$ lb/in

Where:

C_F	= 0.45 (Reference 3.7)
d	= 0.696 in
ρ	= 0.0282 lb/in^3
V_{eff}	= 83.8 in/s
g	= 386 in/sec^2

This loading of 0.080 lb/in is inputted as a static load to the previously described ANSYS model, Figure 5.4-5. The maximum stress is calculated to be less than .1 ksi at the tubesheet face. Since the healthy tube had a stress of 0.10 ksi at the tubesheet, a degradation factor of 2.60 is applied to this value, thus producing an estimated stress of 0.260 ksi for the degraded cases.

5.4.5 DIFFERENTIAL PRESSURE

As discussed in Section 5.1.5, the differential pressure for MSLB will be conservatively assumed to be the difference between the primary side pressure remaining constant at a maximum of 2500 psia and the secondary side dropping to atmospheric pressure, 0 psia. The resulting pressure differential is:

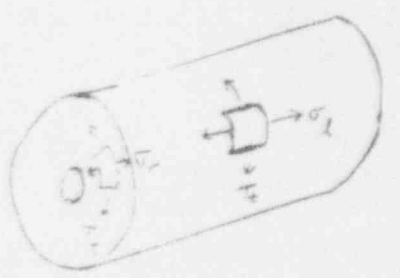
$\Delta P = (P_1 - P_2) = 2500 - 0 = 2500$ psia

The membrane stress intensity associated with this pressure differential is calculated below. The coordinate system used is shown below:

$$\sigma_t - \sigma_r = \frac{(P_1 - P_2) R_i^2}{2 R_m t} + \frac{(P_1 + P_2)}{2} \qquad \textit{Equation 7}$$

Where:

σ_t	= tangential (circumferential) stress
σ_l	= longitudinal stress
σ_r	= radial stress
R_i	= inner radius (in)
R_m	= mean radius (in)
t	= average wall thickness (in)
P_1	= primary side pressure (ksi)
P_2	= secondary side pressure (ksi)



Healthy Tube:

Dimensions: R_i = 0.327, R_o = 0.3750, and t = 0.048 inches

Substituting these dimensions into Equation 7 gives,

$\sigma_t - \sigma_r$ = 9.18 ksi

Degraded Outside:

Dimensions: R_i = 0.327, R_o = 0.3455, and t = 0.0185 inches

Substituting these dimensions into Equation 7 gives,

$\sigma_t - \sigma_r$ = 22.74 ksi

Degraded Inside:

Dimensions: R_i = 0.3565, R_o = 0.375, and t = 0.0185 inches

Substituting these dimensions into Equation 7 gives,

$\sigma_t - \sigma_r$ = 24.73 ksi

Since these stresses are calculated using code equations with actual plant specific data, the actual stresses will be used, and the degradation factor will not be applied to the case of the healthy tube to estimate the stress for the degraded cases.

5.4.6 SAFE SHUTDOWN EARTHQUAKE (SSE)

The model as described in Section 5.4.4 is utilized to apply a 1.5G lateral, 1.4G vertical static seismic loading to the steam generator tube. This loading is applied in ANSYS as an acceleration and produces the stress at each nodal location. This loading was applied to all three tube cases, with the maximum stress at the tubesheet being 0.178 ksi and the overall maximum stress occurring at the uppermost full eggcrate and being 0.302 ksi. Both of these maximums are from the case of degradation from the outside

The healthy tube had a stress of 0.177 ksi at the tubesheet. Applying the degradation factor to this value produces 0.460 ksi for the estimated stress of the degraded cases.

5.4.7 COMBINED STRESSES ON TUBE WITH ASME CODE ALLOWABLES

The resulting stress acting on the tube at the tubesheet interface is compared to the guidelines as specified in Appendix F of Section III. This Appendix F of the ASME Code defines the allowable membrane stress allowable for the faulted conditions considered in this report as $S_{memb} = 0.7\ S_U$. The ultimate strength for the SB-163 Inconel is $S_U = 80.0$ ksi ar the maximum operating temperature of 600°F. Therefore, the allowable membrane stress in the steam generator tube is:

$$S_{memb} = 0.7\ S_U = 56.0 \text{ ksi}$$

The resulting stress intensities from the loadings of the previous sections are combined arithmetically as follows:

Loading Condition		Healthy Tube	Degraded Outside	Degraded Inside
Pipe Break Impulse Response (ksi)	=	0.5	1.30	1.30
Flow Induced Vibration (ksi)	=	0.1	0.260	0.260
Maximum ΔP During MSLB (ksi)	=	9.18	22.74	24.73
Safe Shutdown Earthquake (ksi)	=	0.177	0.460	0.460
Total Stress Intensity	=	9.96	24.76	26.75

Maximum S.I. = 26.75 < 56.0 ksi

Therefore, 61.5% degradation of the steam generator tubes is allowable and fulfills both NRC and ASME requirements.

5.4.8 COMBINED STRESSES ON TUBE WITH "PROBABLE" TUBE MATERIAL PROPERTIES

When the "probable" tube material properties for S_y and S_u are used in place of the ASME Code allowables mentioned earlier, a 65.8%, degradation can be considered for unlimited axial and circumferential extent of defect irrespective of O.D. or I.D. initiation. The Factor of Degradation = 1/(1-.658) = 2.92. The minimum required thickness is based on pressures and temperature at normal operating conditions.

A. Dimensions of a healthy tube are $R_i = 0.327$, $R_o = 0.3750$, and $t = 0.048$ inches.

B. Tube Degradation From the Inside

New dimensions: R_i = 0.3586, R_o = 0.3750, and t = 0.0164 inches

1. Flawed tube not stressed beyond elastic limit using Equation 1 with S_y = 35.2 ksi, t_r = 0.0144 in.

2. Flawed tube maintains a safety factor of 3 using Equation 2 with S_u = 90.0 ksi, t_r = 0.0164 in.

C. Tube Degraded From the Outside

New dimensions: R_i = 0.327, R_o = 0.3434, and t = 0.0164 inches

1. Flawed tube not stressed beyond elastic limit using Equation 1 with S_y = 35.2 ksi, t_r = 0.0131 in.

2. Flawed tube maintains a safety factor of 3 using Equation 2 with S_u = 90.0 ksi, t_r = 0.0150 in.

5.4.8.1 LOCA Rarefaction Wave

As mentioned earlier there is no stress at this location of interest.

5.4.8.2 Pipe Break Impulse Response

Stress on degraded tube = 0.5 x 2.92 = 1.46 ksi.

5.4.8.3 MSLB Secondary Side Blowdown

There is no significant primary loading at this location.

5.4.8.4 Flow Induced Vibration

Stress on degraded tube = 0.10 x 2.92 = 0.292 ksi.

5.4.8.5 Differential Pressure

A. Degraded Outside:

$\sigma_t - \sigma_r$ = 25.56 *ksi* *Using Equation* 7

B. Degraded Inside:

$\sigma_t - \sigma_r = 27.97\ ksi$ *Using Equation 7*

5.4.8.6 Safe Shutdown Earthquake (SSE)

Stress on degraded tube = 0.177 x 2.92 = 0.517 ksi.

5.4.8.7 Summary of Stresses

The resulting stress intensities from the previous loading are combined arithmetically as follows:

Loading Condition		Healthy Tube	Degraded Outside	Degraded Inside
Pipe Break Impulse Response (ksi)	=	0.5	1.46	1.46
Flow Induced Vibration (ksi)	=	0.1	0.292	0.292
Maximum ΔP During MSLB (ksi)	=	9.18	25.56	27.97
Safe Shutdown Earthquake (ksi)	=	0.177	0.517	0.517
Total Stress Intensity	=	9.96	27.83	30.24

Maximum S.I. = 30.24 < 56.0 ksi

Therefore, 65.8% degradation of the steam generator tubes is allowable when the probable tube material properties are used.

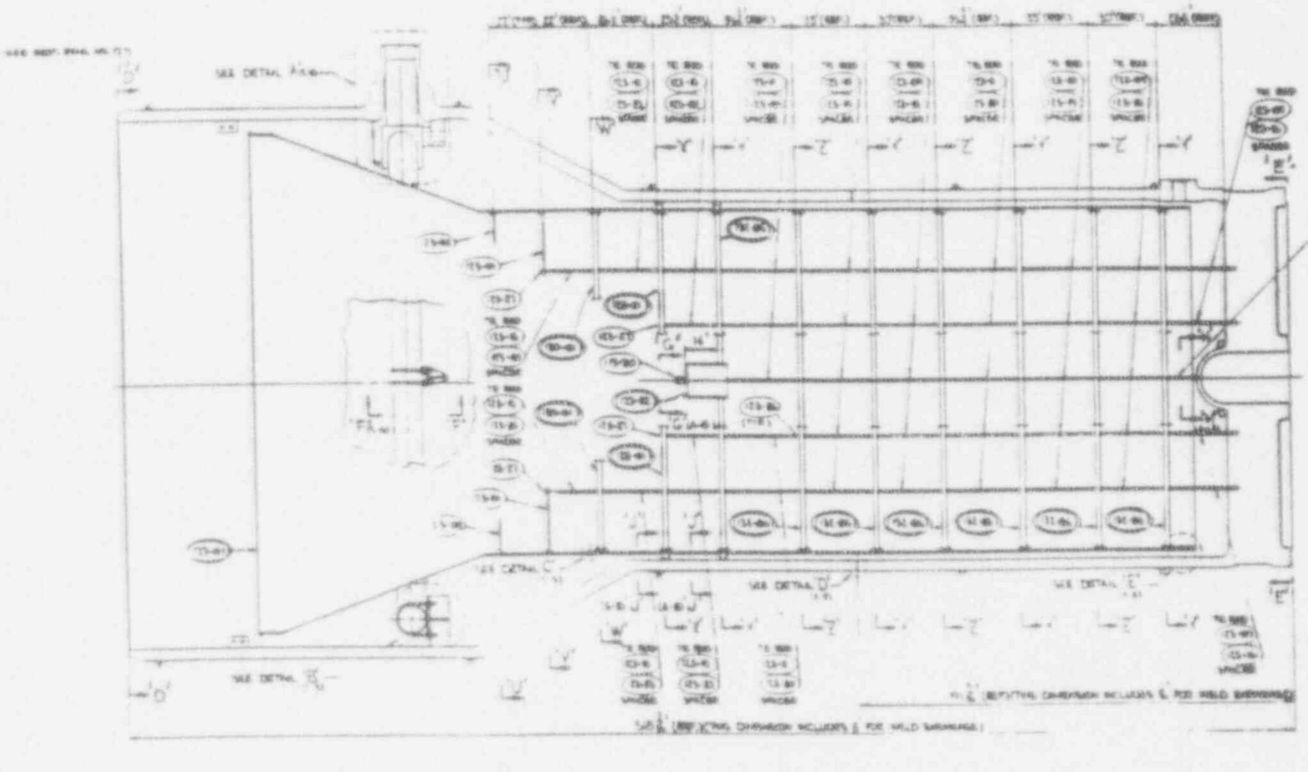


Figure 5.4.1
Location of Support Plates
for ANO2 Steam Generator

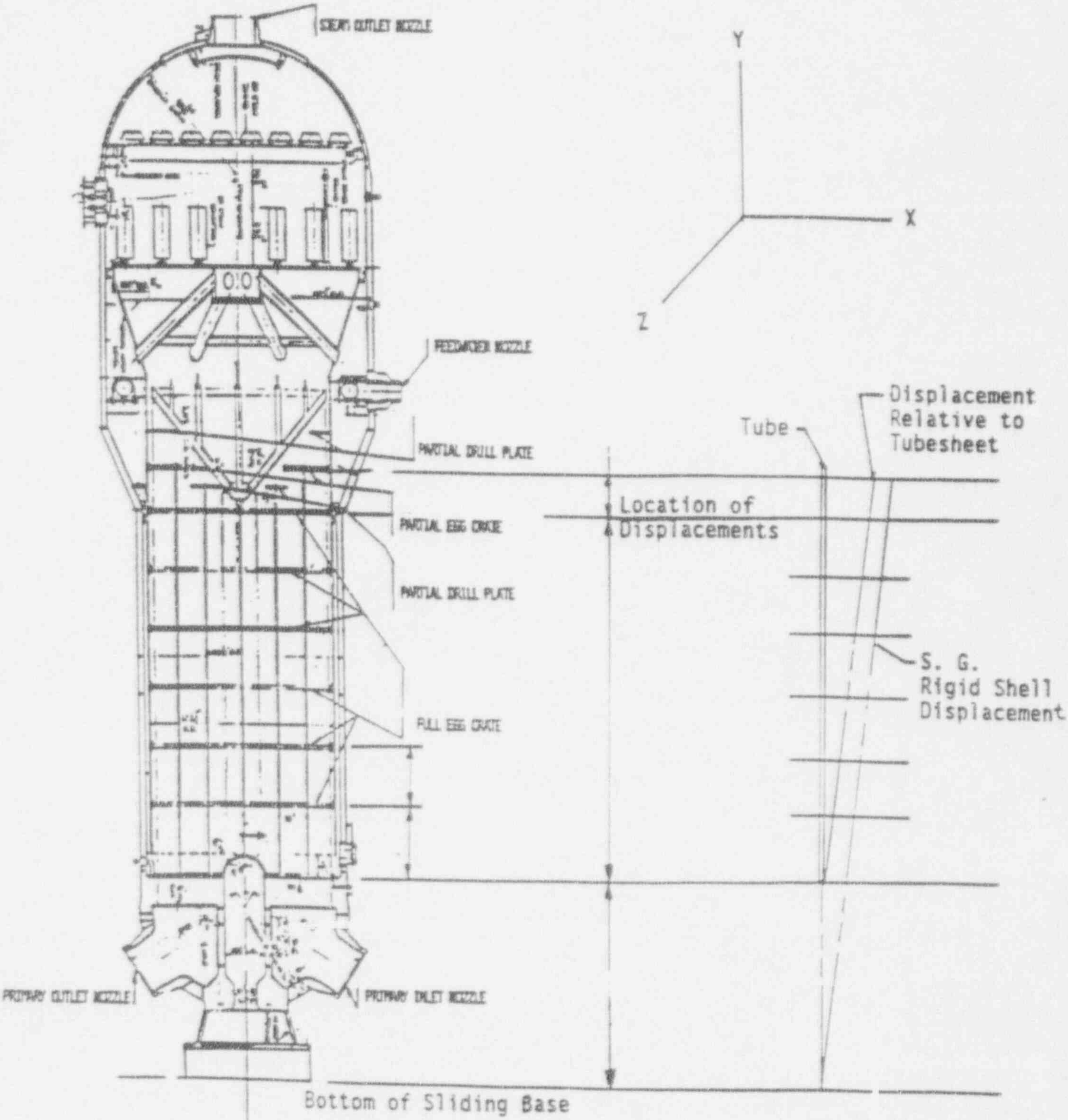


Figure 5.4-2
Displacement of Steam Generator Tube

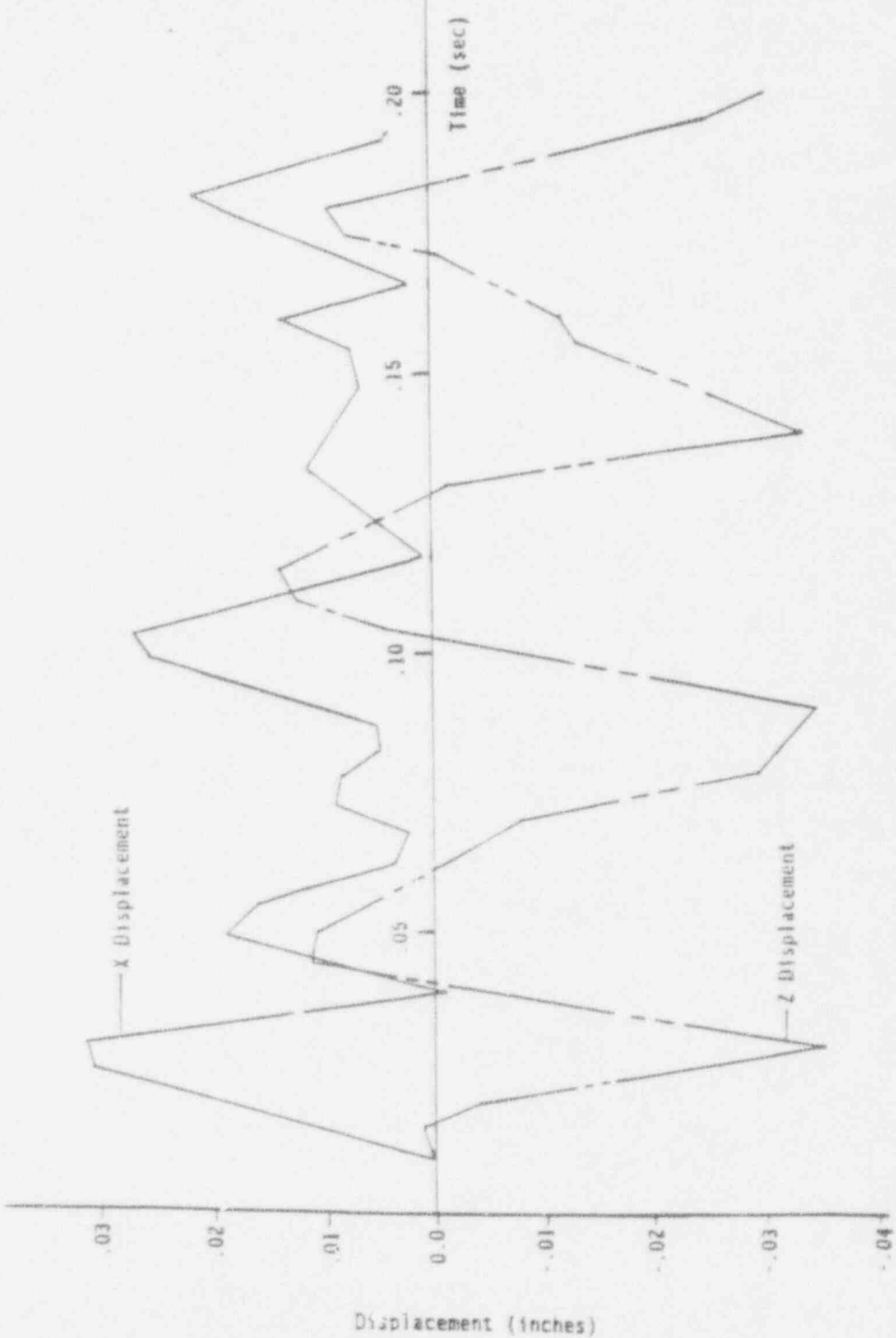


Figure 5.4-3
Applied Time History Displacements
Due to LOCA Impulse Response

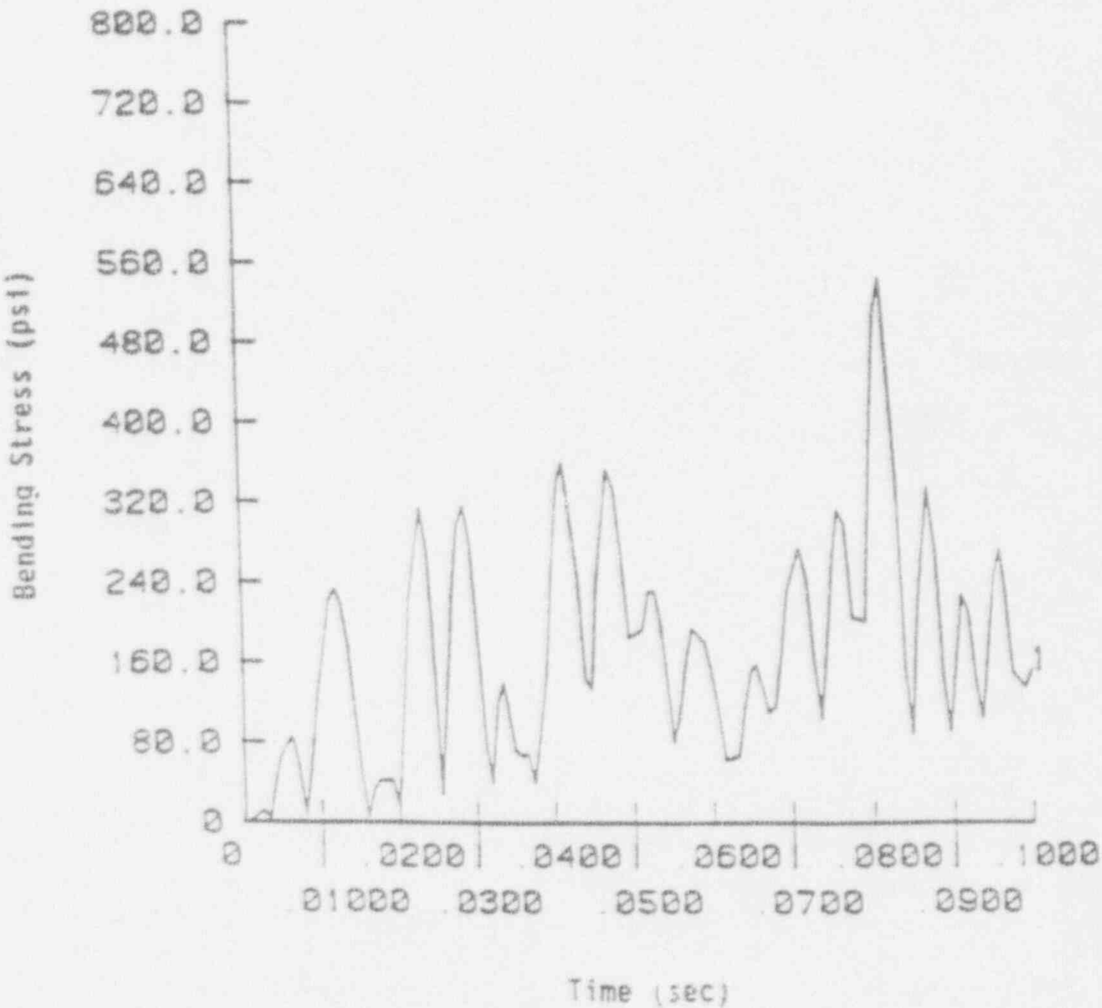


Figure 5.4-4
Resultant Time History Bending
Stress at the Tubesheet

Figure 5.4-5
ANSYS Model of ANO2 Steam Generator Tube

Figure 5.4-6
Mode Shape 9 for ANO2 Steam Generator Tube

HEALTHY TUBE		DEGRADED OUTSIDE	
1	70.5	1	67.6
2	77.9	2	74.7
3	98.2	3	94.2
4	110.9	4	106.4
5	113.6	5	126.2
6	136.4	6	130.8
7	154.1	7	147.8
8	186.3	8	178
9	191.0	9	183.3
10	234.6	10	225.1
11	293.0	11	281.1
12	381.2	12	366.0
13	391.9	13	376.3
14	504.7	14	484.7
15	526.4	15	505.8

Table 5.4.-1
Eigenvector for Healthy and Degraded
ANO2 Steam Generator Tube

Healthy tube

node	mode displ.	node	mode displ.	node	mode displ.
1	0.0000	41	5.0110	81	0.3220
2	0.1998	42	3.4786	82	0.4705
3	0.7189	43	2.1087	83	0.5060
4	1.5213	44	0.9375	84	0.4041
5	2.5717	45	0.0000	85	0.1756
6	3.8344	46	-1.1805	86	0.0000
7	5.2733	47	-0.3321	87	0.0855
8	6.8546	48	1.9417	88	0.2473
9	8.5441	49	5.0432	89	0.3297
10	10.3057	50	8.4260	90	0.2521
11	12.1096	51	11.5491	91	0.0185
12	13.9242	52	13.9026	92	0.0000
13	15.7151	53	15.2720	93	0.2879
14	17.4581	54	15.4738	94	0.5752
15	19.1260	55	14.3653	95	0.7306
16	20.6881	56	12.1952	96	0.6673
17	22.1271	57	9.2530	97	0.3516
18	23.4223	58	5.8548	98	0.0000
19	24.5481	59	2.5713	99	-0.1653
20	25.4959	60	0.0000	100	-0.1279
21	26.2523	61	-1.2420	101	0.0124
22	26.7988	62	2.4087	102	0.1453
23	27.1359	63	5.9409	103	0.1664
24	27.2587	64	5.5407	104	0.0000
25	27.1570	65	2.6731	105	-0.2922
26	26.8403	66	0.0000	106	-0.5573
27	26.3126	67	-0.3940	107	-0.7039
28	25.5727	68	0.8394	108	-0.6635
29	24.6382	69	1.9751	109	-0.3956
30	23.5219	70	1.7268	110	0.0000
31	22.2314	71	0.7152		0.0000
32	20.7918	72	0.0000		
33	19.2230	73	0.2177		
34	17.5415	74	0.8153		
35	15.7773	75	1.2176		
36	13.9570	76	1.0045		
37	12.1041	77	0.4543		
38	10.2522	78	0.0000		
39	8.4322	79	-0.0535		
40	6.6734	80	0.1037		

Table 5.4-2
Expanded Modal Displacements for Mode 9
on a Healthy Tube

Degraded Outside

node	mode displ.	node	mode displ.	node	mode displ.
1	0.0000	41	7.6997	81	0.4930
2	0.3041	42	5.3442	82	0.7221
3	1.0997	43	3.2390	83	0.7777
4	2.3315	44	1.4396	84	0.6217
5	3.9450	45	0.0000	85	0.2706
6	5.8854	46	-1.8224	86	0.0000
7	8.0970	47	-0.5216	87	0.1287
8	10.5280	48	2.9739	88	0.3770
9	13.1254	49	7.7445	89	0.5046
10	15.8342	50	12.9483	90	0.3869
11	18.6081	51	17.7527	91	0.0294
12	21.3985	52	21.3756	92	0.0000
13	24.1528	53	23.4835	93	0.4384
14	26.8334	54	23.7939	94	0.8770
15	29.3986	55	22.0914	95	1.1144
16	31.8013	56	18.7542	96	1.0178
17	34.0147	57	14.2280	97	0.5365
18	36.0067	58	9.0021	98	0.0000
19	37.7386	59	3.9528	99	-0.2530
20	39.1966	60	0.0000	100	-0.1965
21	40.3600	61	-1.9167	101	0.0176
22	41.2010	62	3.7006	102	0.2207
23	41.7198	63	9.1350	103	0.2536
24	41.9087	64	8.5235	104	0.0000
25	41.7528	65	4.1120	105	-0.4457
26	41.2660	66	0.0000	106	-0.8504
27	40.4544	67	-0.6079	107	-1.0743
28	39.3168	68	1.2902	108	-1.0126
29	37.8798	69	3.0376	109	-0.6039
30	36.1629	70	2.6567	110	0.0000
31	34.1786	71	1.1003		
32	31.9647	72	0.0000		
33	29.5520	73	0.3340		
34	26.9663	74	1.2529		
35	24.2535	75	1.8716		
36	21.4542	76	1.5448		
37	18.6050	77	0.6988		
38	15.7575	78	0.0000		
39	12.9592	79	-0.0833		
40	10.2552	80	0.1576		

Table 5.4-3
Expanded Modal Displacements for Mode 9
on a tube Degraded from the Outside

5.5 NRC REGULATORY GUIDE 1.121 EVALUATION OF TUBE WITH AXIAL DEFECT OF 0.25 INCH MAX. AND UNLIMITED CIRCUMFERENTIAL DEFECT

Section 5.4 verified that tubes with unlimited axial and circumferential extent of defects up to 65.8% of the wall thickness satisfy the Reference 3.1 safety factor against tube failure for operational and accident loadings.

This section will show that the Regulatory Guide 1.121 margin against burst is satisfied for a 77% uniformely degraded tube with a limited (1/4" max.) axial defect.

Figure 13 of Reference 3.18 presents burst pressure test data for various thinning defects. These tests were performed on 0.875" diameter x .050" wall tubing.

The aforementioned Figure 13 indicates that a tube with a .25 long uniform defect with a wall thinning of 75-80% can withstand a burst pressure up to 5100 psi.

The ratio of wall thickness/diameter for the test specimen is:

$$\frac{0.050}{.875} = .057$$

By comparison the ratio for the ANO-2 tubes is,

$$\frac{.048}{.750} = .064$$

It can be therefore be concluded that at ANO-2 the burst pressure for a .25 inch long uniform defect with a 75-80% wall thinning will exceed 5100 psi.

The operational ΔP for ANO-2 is 1350 psi.

$(3)(1350) = 4050 < 5100$ psi

The ANO-2 tubes are structionally adequate to meet the Regulatory Guide 1.121 safety margin against burst with uniform (360°) defects that are .25 inches long and 77% degradation.

5.5.1 Differential Pressure

The maximum pressure differential loading will occur during a postulated MSLB event. The membrane stress intensity associated with this pressure differential is calculated below:

$$\sigma_t - \sigma_r = \frac{(P_1 - P_2)\ Ri^2}{2\ Rmt} + \frac{(P_1 + P_2)}{2} \qquad \text{Equation 7}$$

Where:

P_1 = 2500 psia
P_2 = 0 psia
Ri = 0.327 in
Rm = 0.3325 in
t = .0110 in

Therefore:

$$\sigma_t - \sigma_r = 37.8\ ksi$$

5.5.2 LOCA Rarefaction Wave

The rarefaction wave produces no stress component at the secondary face of the tube sheet. This loading condition produces no stress component affecting tube burst.

5.5.3 Pipe Break Impulse Response

It was determined in section 5.4.2 that a pipe break shock loading would incur a maximum 0.5 ksi at the tubesheet elevation. This stress was for a healthy (not degraded) tube and adjusting for a 77% degraded tube results in 2.2 ksi.

$$0.5\ \left(\frac{1}{1-.77}\right) = 2.2\ ksi$$

5.5.4 MSLB Secondary Side Blowdown

This loading condition will cause a drag load on the horizontal leg of the tube bundle. The load produces an axial stress component only and hence will have no influence on the tube burst.

5.5.5 Safe Shutdown Earthquake (SSE)

The distance between the tubesheet and the first tube support is 28.125". Calculating the weight of the tube and the fluid inventory in this span yields.

W = 1.15 lbs

F_{SSE} = 1.5 x 1.15 = 1.7 lb.

The resultant moment from this force is.

$$M = 1.7\ \frac{28.125}{2} = 23.9\ in\text{-}lb$$

The stress produced at the tubesheet elevation from this moment is in significant and hence can be neglected.

5.5.6 Flow Induced Vibration

The minute flow forces will not produce significant stresses in the tubes at the tubesheet elevation.

5.5.7 Inside Flow Inducement

This loading only produces an axial stress component at the tubesheet elevation and therefore will have no influence on the tube burst.

5.5.8 Combined Stresses On Tube

The resulting stress intensities from the loadings of the previous sections are combined arithmetically as follows:

LOADING CONDITION	STRESS INTENSITY
Maximum ΔP During MSLB (ksi)	37.8
LOCA Rarefaction (ksi)	0
Pipe Break Impulse Response (ksi)	2.2
MSLB Secondary Side Blowdown (ksi)	0
Safe Shutdown Earthquake (ksi)	0
Flow Induced Vibration (ksi)	0
Inside Flow Inducement (ksi)	0
Total Stress Intensity	40.0 ksi

Maximum S.I. = 40.0 ksi < 56.0 ksi

Therefore, 77% tube wall thickness degradation will not be subject to burst and its maximum stress intensity is below 56.0 ksi.

5.6 NRC REGULATORY GUIDE 1.121 EVALUATION OF TUBE WITH AXIAL DEFECT OF 0.25 INCH MAX. AND ALLOWABLE CIRCUMFERENTIAL 100% THRU-WALL DEFECT

Figure 5.6-1 shows the type of defect that will be considered in this section. "F" represents the total axial force pulling on the tube.

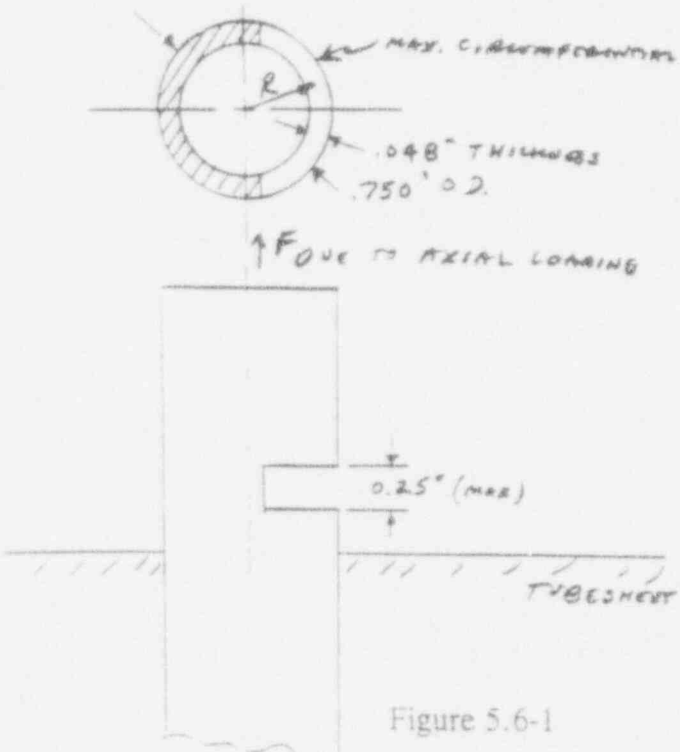


Figure 5.6-1

$$R = \frac{0750 - 0.048}{2} = 0.351 \text{ in.}$$

$t = 0.048$ in

$R_i = 0.327$ in

For SB-163 (600) Inconel Tubing at 650°F

$S_m = 23.3$ ksi

$S_U = 80.0$ ksi

$S_y = 27.9$ ksi

5.6.1 LOADINGS TO BE CONSIDERED FOR THE AXIAL FORCE

5.6.1.1 Differential Pressure during MSLB

During a main steam line break, the differential pressure creates two types of axial loads on the tube. The first one is a drag load and the second, an internal piston load. The drag load will be discussed in Paragraph 5.6.1.4.

The internal piston load occurs when the maximum pressure difference of 2500 psi is pushing on the I.D. of the tube. This load is:

$$= 2500 \text{ psi} \times \pi (R_i)^2$$
$$= 2500 \text{ psi} \times \pi (.327)^2$$
$$= 839.8 \text{ lbs.}$$

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5.6.1.2 LOCA Rarefaction Wave

As mentioned earlier, the rarefaction wave produces no stress at the location of interest in this analysis. Thus, the axial loading is zero.

5.6.1.3 Pipe Break Impulse Response

Since there is no Y - Displacement for the pipe break impulse response (Reference 3.4), the axial loading is zero.

5.6.1.4 MSLB Secondary Side Blowdown

Reference 3.3 determined that this type of pressure differential due to secondary side blowdown resulted in a total drag load of 113, 290 lbs. across the cross flow region of the tube bundle. Since there are 8411 tubes in the steam generator, the drag load/tube is 113.290 lbs/8411 tubes or 13.5 lbs.

5.6.1.5 Safe Shutdown Earthquake (SSE)

Using the 1.4 G vertical applied static loading (Reference 3.12) results in the following equation for the SSE contribution to the total axial load.

$$F_S = 1.4 \times W \text{ (Weight of tube)}$$

Where: W = (Density of Primary Fluid) x (Volume of Fluid) + (Density of Tube) x (Volume of Tube)

Substituting:

$$W = (0.0260 \times \pi/4 \times 0.654^2 \times 326.7) + (0.305 \times \pi/4 \times ((0.75)^2 - (0.654)^2) \times 326.7)$$

$$= 2.85 + 10.55$$

$$= 13.4 \text{ lbs.}$$

Therefore, $F_S = 1.4 \times 13.4 = 18.8$ lbs.

5.6.1.6 Flow Induced Vibration

Since the flow forces do not produce a significant loading at the tubesheet interface, the axial loading is zero.

5.6.1.7 Inside Flow Inducement

The axial loading due to inside flow inducement is dependent upon the fluid velocity and the pressure drop through one third of the total tube bend length. The equation for this type of loading is:

$$F_7 = \frac{\rho A\ V^2}{g} + \Delta P \times \pi (Ri)^2$$

Where :

F_7 = force due to inside flow inducement, lbf
ρ = Density of fluid = 44.928 lb/ft
A = Cross flow area = 0.336 in
V = Fluid velocity, ft/sec
= (Primary Flow Rate/Tube)/ ρA
= (60.2 x 10^6 lb/hr/ 8411 tubes)/ ρA
g = gravity = 32.2 ft/sec
ΔP = Pressure drop through one third of total tube bend length
= 36 psi/3 (Page A-1014 of Reference 3.13)
R = 0.327 in

Substituting:

$$F_7 = \rho A \frac{\left[\frac{60.2 \times 10^6}{8411} \times \frac{1}{3600}\right]^2}{32.2 \quad \rho A \times 44.928 \times .\frac{336}{144}} + 12 \times \pi (.327)^2$$

= 1.2 + 4.0
= 5.2 lbs

Therefore, the total axial force is :

F = 839.8 + 0 + 0 + 13.5 + 18.8 + 0 + 5.2
= 877.3 lbs

5.6.2 STRESS DUE AXIAL LOADING

The equation for calculating the stress due to the axial loading is:

$$\sigma = F / 2 \pi R t$$

Where:

σ = Stress, psi
F = Total Axial Load, 877.3 lbs
R = Mean Radius of healthy tube, 0.351 in
t = tube wall thickness, 0.048 in

Substituting:

$\sigma = 877.3 / 2\pi \times 0.351 \times 0.048$

σ = 8287.4 psi < 1.0 S_m or 23,300 psi, the allowable value of the General Primary Membrane Stress Intensity (NB-3221.1 of reference 3.5) for the average stress across the solid section excluding discontinuities and concentrations.

5.6.3 ALLOWABLE CIRCUMFERENTIAL 100% THRU-WALL DEFECT

For a solid section which considers discontinuities, the allowable value for the local membrane stress intensity (NB-3221.2 of Reference 3.5) is 1.5 S_m or 34,950 psi. The NRC Regulatory Guide 1.121 (Reference 3.1) refers to NB-3225 of Reference 3.5 for Level D Service Limits which also refers to Appendix F of Reference 3.5. Paragraph F-1331.1(b) of Appendix F supports the 1.5 S_m value for the localized membrane stress intensity of the case in Figure 5.6-1.

$$\sigma_{max} = 1.5\ S_m = \frac{F}{2\pi Rt\ \left(\frac{360 - \theta}{360}\right)}$$

Where:

θ = Circumferential extent of thru-wall defect

Substituting,

$$34{,}950 = \frac{877.3}{2\pi \times .351 \times .048\ \left(\frac{360 - \theta}{360}\right)}$$

$\theta = 274°$

Therefore, the maximum circumferential extent of 100% thru-wall defect is 274°.

MPR ASSOCIATES, INC.

August 26, 1992

Evaluation of Arkansas Nuclear One Unit 2
Steam Generator Tube Wall Degradation

Prepared for

Entergy Operations
Arkansas Nuclear One Unit 2
Russellville, Arkansas 72801

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CONTENTS

Section 1

INTRODUCTION

BACKGROUND

NRC Regulatory Guide 1.121 (Reference 1) describes a method for determining allowable limits for degradation of steam generator tubing. Tubes with degradation beyond these limits are required to be removed from service by the installation of plugs at each end of the tube (or modified to be acceptable for further service by the installation of suitable sleeves which meet Regulatory Guide 1.121 requirements).

As part of the technical justification for continued safe operation, structural adequacy of the tubing can be demonstrated by showing that tube degradation will not exceed Regulatory Guide 1.121 allowables at any time during plant operation. This report calculates maximum allowable degradation. Suitable NDT (sensitivity and frequency), conservative plugging/sleeving criteria and operating experience of Arkansas Nuclear One Unit 2 (ANO-2) and other similar plants can then be used to ensure tube degradation will not exceed the allowable degradation determined herein.

To further ensure tubing structural adequacy during plant operating periods between NDT inspections, an administrative limit is imposed at ANO-2 requiring shutdown for a leak rate of 0.1 gpm per steam generator. For ANO-2, this leak rate limit is estimated to provide reasonable assurance of tubing structural adequacy as well as being practical, e.g., in terms of detectability. ANO-2 experience and other work supports this.

In Reference 2, ABB Combustion Engineering (ABB CE) performed an evaluation of certain types of tube wall degradation recently found in the ANO-2 steam generators. The ABB CE report considered three bounding configurations of possible degradation as follows:

- Unlimited axial and circumferential extent and partially through-wall.
- Axial length of 0.25 in. maximum, unlimited circumferential extent and partially through-wall.
- Axial length of 0.25 in. maximum, essentially through-wall and limited circumferential extent.

These evaluations utilized what ABB CE considered to be the limiting requirements of Regulatory Guide 1.121 which pertain to the structural integrity of the tubing for normal operating and accident conditions.

PURPOSE

The purpose of this report is to address all of the structural requirements in Regulatory Guide 1.121, utilizing the ABB CE evaluations of Reference 2, as applicable, and additional MPR structural evaluations as needed based on our review of Reference 2. These additional evaluations included consideration of axial, slot-type defects (axial cracks). Consistent with NDT findings and expectations for ANO-2 this report is limited (except as discussed herein) to tube degradation either within or close to a tube support or at the top of the tube sheet.

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Section 2

SUMMARY

The evaluations in this report address the structural requirements of NRC Regulatory Guide 1.121 for certain types of degradation in the Arkansas Nuclear One Unit 2 steam generator tubing. The evaluations are based on the structural analyses performed by ABB Combustion Engineering and additional MPR structural evaluations and calculations. The tubing degradation considered is either within or close to a tube support or at the top of the tube sheet. Slightly reduced values would be calculated for allowable tube wall degradation for non-axisymmetric degradation configurations at other locations due to tube bending stresses resulting from less lateral support of the tube, e.g., in areas between supports. For tubing degradation configurations which are axisymmetric and therefore do not result in tube bending stresses, the degradation allowables in this report are also applicable at areas away from tube supports (as well as at supports).

The maximum allowable tube wall degradation determined herein is summarized in Tables 2-1 and 2-2. For the intended purpose of determining the maximum allowable tube degradation per Regulatory Guide 1.121, we consider use of the "probable tubing material properties", as appropriate, rather than ASME Code minimums. Further, if desired, Entergy could possibly obtain as-built materials properties which we believe would allow even greater degradation than indicated herein for "probable" material properties. Accordingly, we consider the maximum allowable degradation as shown in Table 2-1 to be appropriate and conservative.

Notably, the values for maximum allowable degradation calculated herein are somewhat different from the values calculated in Reference 2 by ABB CE. The main causes of these differences are discussed later in this report. Other differences are in the details of the calculations, also presented later in this report. For convenience, Table 2-3 shows a comparison of the ABB CE and MPR calculated values for the case of a .25 in. maximum axial, 360° circumferential, part through-wall tube degraded area. Also shown is the value from public documents (Reference 3) for Millstone 2 (which has the same tubing size as ANO-2).

As indicated, the values in Table 2-3 are similar as they should be. Notably a lower value (59%) has been published for Maine Yankee (Reference 4); however, this is not applicable since this (lower) value was based on a defect of unlimited axial extent along with some other minor differences in calculations. Accordingly, we conclude the value of 79% as computed herein is appropriate for ANO-2.

Table 2-1

Allowable Steam Generator Tube Wall Degradation for Various Degradation Types (For Probable Tubing Material Properties)[1]

Type of Degradation[2]	Allowable Tube Wall Degradation
Unlimited axial and circumferential extent	66% maximum
0.25 in. maximum axial length, 360° circumferential	79% average around the tube circumference[3]
Axial slot-type defect	
- Less than 0.25 in. long	100%[4]
- 0.25 - 0.50 in. long	84%[5]
- 0.50 - 1.5 in. long	73%[5]
- Longer than 1.5 in.	66%

[1] Mill test certificates with actual properties were not available for use at this time, otherwise, actual materials properties would have been used.

[2] Any of the types of degradation indicated herein can be considered applicable to either a support location or a location at the top of the tubesheet. If the degradation is symmetric about the tubing axis, the specified degradation allowable is also applicable at locations away from support locations.

[3] As an example, this 79% <u>average</u> value equates to an <u>accumulated</u> total of 234° of 100% deep defect penetration together with the remainder at 40% deep. As discussed later in this report, burst test data for actual defect configurations confirm that the accumulated average penetration is the controlling parameter for these defects at ANO-2.

[4] Burst pressure data is available for tube wall degradation to 84%. Extrapolation of this data indicates that the allowable slot depth would be 100% (i.e., essentially through-wall).

[5] These values actually apply for the maximum of the slot defect lengths indicated. Other values can be obtained from Figure 1 if desired.

Table 2-2

Allowable Steam Generator Tube Wall Degradation for Various Degradation Types (For ASME Code Minimum Tubing Material Properties)

Type of Degradation[1]	Allowable Tube Wall Degradation
Unlimited axial and circumferential extent	62% maximum
0.25 in. maximum axial length, 360° circumferential	76% average around the tube circumference
Axial slot-type defect	
- Less than 0.25 in. long	100%[2]
- 0.25 - 0.50 in. long	77%
- 0.50 - 1.5 in. long	67%
- Longer than 1.5 in.	62%

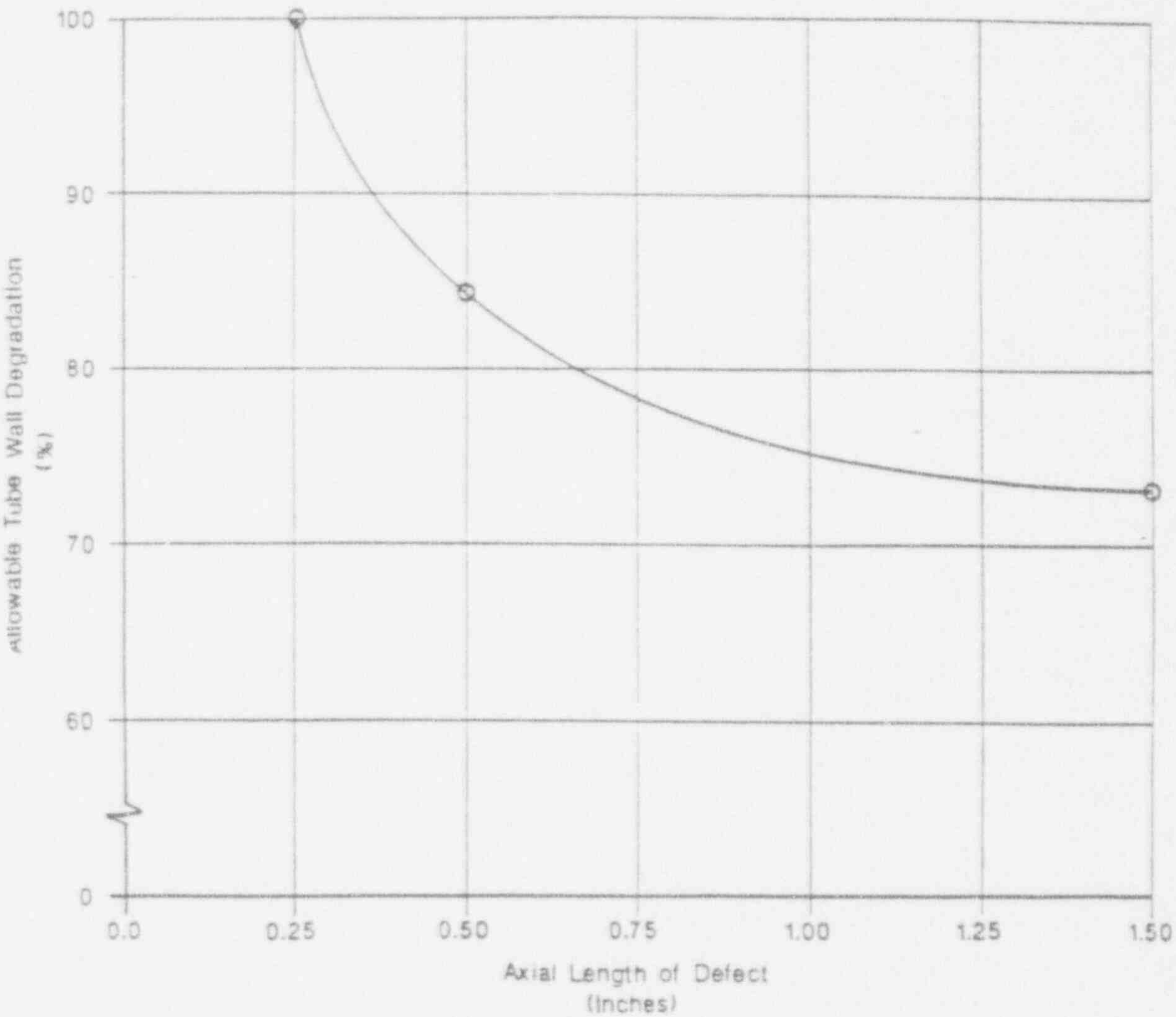
1 Any of the types of degradation indicated herein can be considered applicable to either a support location or a location at the top of the tubesheet. If the degradation is symmetric about the tubing axis, the specified degradation allowable is also applicable at locations away from support locations.

2 Burst pressure data is available for tube wall degradation of 84%. Extrapolation of this data indicates that the allowable slot depth would be 100% (i.e., essentially through-wall).

Table 2-3

Average Percent Through-Wall Defect Penetration
Allowable per Regulatory Guide 1.121 for
Degradation of Tube at Top of Tube sheet

For ANO-2		For Millstone-2
ABB-CE	MPR	Per Reference 3
77	79	79



ALLOWABLE TUBE WALL DEGRADATION
FOR AXIAL SLOT TYPE DEFECTS (AXIAL CRACKS)

FIGURE 1

Section 3

DISCUSSION

NRC REGULATORY GUIDE 1.121 REQUIREMENTS

Regulatory Guide 1.121 provides requirements for evaluating the allowable wall degradation of steam generator tubing, beyond which the defective tubing must be removed from service. As stated, the Regulatory Guide requires the consideration of three factors: (1) the wall thickness required to sustain the imposed loadings under normal and accident conditions; (2) an allowance for further degradation during operation until the next inservice inspection; and (3) the crack size permitted to meet the primary-to-secondary leakage limit allowed by the plant's technical specifications.

Section C of Regulatory Guide 1.121 provides the specific structural requirements which must be satisfied for degraded steam generator tubing for normal operation and accident conditions. Most of these requirements can be bound by a reduced set of requirements at the end of this section; and, others are shown to be not pertinent as follows:

For normal operation, the requirements from NRC Regulatory Guide 1.121 are:

From C.2., "Minimum Acceptable Wall Thickness,"

- "Tubes with detected part through-wall cracks should not be stressed during the full range of normal reactor operation beyond the elastic range of the tube material" (C.2.a.(1)).

- "Tubes with part through-wall cracks, wastage, or combinations of these should have a factor of safety against failure by bursting under normal operating conditions of not less than three at any tube location" (C.2.a(2)).

- "The margin of safety against tube rupture under normal operating conditions should be not less than three at any tube location where defects have been detected" (C.2.a(4)).

- "Any increase in the primary-to-secondary leakage rate should be gradual to provide time for corrective action to be taken" (C.2.a(5)).

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Experience at ANO-2 and at other similar plants has demonstrated this requirement to be met; accordingly, this requirement is not included in the reduced set of requirements at the end of this section.

- "An additional thickness degradation allowance should be added to the minimum acceptable tube wall thickness to establish the operational tube thickness acceptable for continued service. An imperfection that reduces the remaining tube wall thickness to less than the sum of the minimum acceptable wall thickness plus the operational degradation allowance is designated as an unacceptable defect. A tube containing this imperfection has exceeded the tube wall thickness limit for continued service and should be plugged before operation of the steam generator is resumed" (C.2.b).

  This requirement is addressed by the current practice at ANO-2 of sufficient NDT examinations and sleeving or plugging (and stabilizing) for any actual indicated degradation (irrespective of tube wall penetration) for tube locations where experience (at ANO-2 and others) indicates sufficiently rapid degradation should be expected. Also, experience (at ANO-2 and others) is used to ensure degradation between NDT examinations will not exceed structural allowables.

From C.3, "Analytical and Loading Criteria Applicable to Tubes with either Part Thru-wall or Thru-wall Cracks and Wastage,"

- "Loadings associated with normal plant conditions, including start up, operation in power range, hot standby, and cooldown, as well as all anticipated transients (e.g., loss of electrical load, loss of offsite power) that are included in the design specifications for the plant, should not produce a primary membrane stress in excess of the yield stress of the tube material at operating temperature" (C.3.a.(1)).

- "The margin between the maximum internal pressure to be contained by the tubes during normal plant conditions and the pressure that would be required to burst the tubes should remain consistent with the margin incorporated in the design rules of Section III of the ASME Code" (C.3.a.(2)).

- "The fatigue effects of cyclic loading forces should be considered in determining the minimum tube wall thickness. The transients considered in the original design of the steam generator tubes should be included in the fatigue analysis of degraded tubes corresponding to the minimum tube wall thickness established. The magnitude and frequency of the temperature and pressure transients should be based on the estimated number of cycles anticipated during normal operation for the maximum service interval

expected between tube inspection periods. Notch effects resulting from tube thinning should be taken into account in the fatigue evaluation" (C.3.b(2)).

This requirement is addressed by the current practice at ANO-2 of sufficient NDT examinations and sleeving or plugging (and stabilizing) for any actual indicated degradation (irrespective of tube wall penetration) for tube locations where experience (at ANO-2 and others) indicates sufficiently rapid degradation should be expected. Also, experience (at ANO-2 and others) is used to ensure degradation due to fatigue between NDT examinations will not exceed structural allowables.

- "The maximum permissible length of the largest single crack should be such that the internal pressure required to cause crack propagation and tube rupture is at least three times greater than the normal operating pressure. The length and geometry of the largest permissible crack size should be determined analytically either by tests or by refined finite element or fracture mechanics techniques. The material stress-strain characteristics at temperature, fracture toughness, stress intensity factors, and material flow properties should be considered in making this determination" (C.3.d(1)).

- "The primary-to-secondary leakage rate limit under normal operating pressure is set forth in the plant technical specifications and should be less than the leakage rate determined theoretically or experimentally from the largest single permissible longitudinal crack. This would ensure orderly plant shutdown and allow sufficient time for remedial action if the crack size increases beyond the permissible limits during service" (C.3.d(3)).

  This requirement is addressed by an administrative limit requiring shutdown for a leak rate of 0.1 gpm per steam generator. For ANO-2, this leak rate limit is estimated to provide reasonable assurance of tubing structural adequacy as well as being practical, e.g., in terms of detectability. ANO-2 experience and other work supports this.

- "Conservative analytical models should be used to establish the minimum acceptable tube wall thickness generally applicable to those areas of tube length where tube degradation is most likely to occur in service due to cracking, wastage, intergranular attack, and the mechanisms of fatigue, vibration, and flow-induced loadings. The wall thickness should be such that sufficient tube wall will remain to meet the design limits specified by Section III of the ASME Boiler and Pressure Vessel Code for Class 1 components, as well as the following criteria and loading conditions" (C.3.a.).

This requirement is interpreted as being covered by other requirements in Regulatory Guide 1.121 as discussed herein. The only conflict is per requirement C.3.a(1) which limits to yield stress versus a lower limit per Section III of the ASME Code. In this case we consider the stated Regulatory Guide limit per C.3.a.(1) of yield stress to be appropriate and note that others have done the same.

For accident conditions, the requirements from NRC Regulatory Guide 1.121 are:

From C.2, "Minimum Acceptable Wall Thickness,"

- "If through-wall cracks with a specified leakage limit occur either on a tube wall with normal thickness or in regions previously thinned by wastage, they should not propagate and result in tube rupture under postulated accident conditions" (C.2.a(3)).

- "The margin of safety against tube failure under postulated accidents, such as a LOCA, steam line break, or feedwater line break concurrent with the SSE, should be consistent with the margin of safety determined by the stress limits specified in NB-3225 of Section III of the ASME Boiler and Pressure Vessel Code" (C.2.a(6)).

From C. 3, "Analytical loading criteria applicable to tubes with either part through-wall or through-wall cracks and wastage,"

- "Loadings associated with a LOCA or a steam line break, either inside or outside the containment and concurrent with the SSE, should be accommodated with the margin determined by the stress limits specified in NB-3225 of Section III of the ASME Code and by the ultimate tube burst strength determined experimentally at the operating temperature" (C.3.a.(3)).

- "The stress calculations of the thinned tubes should consider all the stresses and tube deformations imposed on the tube bundle during the most adverse loadings of the postulated accident conditions. The dynamic loads should be obtained from the modal analysis of the steam generator and its support structure. All major hydrodynamic and flow-induced forces should be considered in this analysis" (C.3.b.(1)).

- "The combination of loading conditions for the postulated accident conditions should include, but not be limited to, the following sources:

  - Impulse loads due to rarefaction waves during blowdown,
  - Loads due to fluid friction from mass fluid accelerations,
  - Loads due to the centrifugal force on U-bend and other bend regions caused by high velocity fluid motion,
  - Seismic loads,
  - Transient pressure load differentials" (C.3.c).

- "Adequate margin should be provided between the loadings associated with a large steam line break or a LOCA concurrent with an SSE and the loading required to initiate propagation of the largest permissible longitudinal crack resulting in tube rupture. The loadings associated with the postulated accident conditions should include the transient hydraulic and dynamic loads listed in C.3.c." (C.3.d.(2)).

The pertinent NRC Regulatory Guide 1.121 tube structural requirements as stated above can be reduced to the following set of requirements:

For Normal Operation:

- The tube stress intensity should be less than the tube material yield stress.
- The tube burst pressure should be greater than three times the pressure difference across the tube wall.

For Accident Conditions:

- The tube stress intensity should be less than the lesser of 2.4 times the design stress intensity (S_m) or 0.7 times the ultimate stress.
- The tube burst stress should be greater than the pressure difference across the tube wall.

ABB COMBUSTION ENGINEERING EVALUATIONS

In Reference 2, ABB Combustion Engineering performed an evaluation of ANO Unit 2 steam generator tubing structural adequacy for degradation in the expansion transition

region (at the top of the tube sheet). For each type of degradation the ABB CE evaluations considered the requirements of NRC Regulatory Guide 1.121 and determined the allowable tube wall degradation. Based on our review of this work, we have the following comments:

- The tubing degradation in the expansion transition region is in close proximity to the tube sheet. As a result of the constraint to tubing lateral displacement due to the close clearance between the tubing outside diameter and the tube sheet bore, and as a result of lateral support of the tube from the adjacent tube support grid, the axial load on the tube for accident conditions does not result in primary bending stresses in the tubing even for a non-uniform degradation profile around the tubing circumference. As a result, the average cross-sectional area of the degraded area of the tube determines its axial load capability. This is based on the results of tube burst tests with typical degradation profiles which are reported in References 4 and 6.

- The pressure difference calculations across the tube for the case of a steam line break do not include stress amplification due to rapid depressurization of the steam line. We consider this appropriate based on previous MPR calculations which demonstrate that the pressure around the tubes inside the steam generator does not fall rapidly (relative to the appropriate natural frequency of the tubes) and no amplification of tube stress will occur. In essence, even though the pressure will fall rapidly within the steam line, it does not fall rapidly within the steam generator -- because the resulting boiling of the water tends to hold the pressure up inside the steam generator (as in a pressurizer).

- The ABB CE evaluations considered degradation which originated either from the tubing outside diameter or inside diameter. In all cases, the required tubing remaining wall thickness is greater for the degradation which originates from the tubing inside diameter.

- The ABB CE evaluations considered both ASME Section III minimum tubing properties (yield and ultimate stress) as well as "probable" material properties. We consider this appropriate as discussed herein.

- The ABB CE evaluations for 0.25 in. axial-length, through-wall, partial-circumference defects are not applicable if the defects are actually .25 in. long for their full penetration (up to 100%) extent, since premature failure would occur within the essentially 100% through-wall portion of the .25 in. long defect due to circumferential stresses from internal pressure.

However, this would not be the case for a circumferential slot-type defect (due to support of the defected portion of the tube from non-defected adjacent areas). Accordingly, these evaluations are applicable to circumferential slot-type defects (circumferential cracks) with essentially no axial extent. This ABB CE analysis may be applicable for actual defect areas .25 in. long in the steam generator (e.g., with ligaments between cracks); however, burst tests would be needed to demonstrate this.

Notably, the circumferential defects found thus far at ANO-2 are not of the type which need to be covered by the ABB CE analysis mentioned above (.25 in. long, 100% through-wall, partial circumference). Instead, all circumferential defects found thus far at ANO-2 can be covered by the case analyzed herein for .25 in. maximum axial length, 360° circumferential extent with average penetration of 79% per Table 2-1. Accordingly, there is no need to use the above mentioned part of the ABB CE analysis (which otherwise requires either limiting to a slot-type defect or tube burst tests).

- For the case of interest for circumferential defects (.25 in. maximum axial extent, 360°, partial through-wall, i.e., 79% average per Table 2-1), local areas around the defected portion of the tube may be degraded greater than the 79% average value. This is acceptable based on burst tests from tube pulls with similar defects at another plant (Reference 6). These tests show that the average (and not maximum) penetration is the pertinent parameter to establish structural adequacy; and, in any event, even in the worst-case, only a tube leak would result if a local area of a defect goes through wall. Accordingly, the 79% average defect case is considered the controlling case for circumferential defects at ANO-2.

MPR STRUCTURAL EVALUATIONS

MPR performed additional tubing stress analyses based on the tubing loads determined by ABB CE in order to adjust certain ABB CE evaluation results based on our interpretation of Regulatory Guide 1.121 requirements. (See Appendices A and B of this report.) The following should be noted:

- The ABB CE evaluations for 0.25 in. long 360° circumferential degradation utilized burst test data to determine the allowable degradation. This burst test data was obtained for simulated degradation originating from the tube outside diameter. In addition, the measured burst pressure for the tested 77 percent defect was significantly greater than the required pressure of 4050 psi. The MPR evaluations in Appendix A estimate the permitted wall degradation from the inside diameter which would provide a margin of three to burst based on the tubing wall differential pressure during normal

plant operation. The calculations consider code minimum and probable tubing material properties.

- Evaluations are provided in Appendix B for axial, slot-type defects of lengths 0.25 in., 0.50 in. and 1.5 in. These evaluations used burst-test data from Reference 5. The calculations consider code minimum and probable tubing material properties.

ALLOWABLE TUBE WALL DEGRADATION

Based on the ABB CE and MPR evaluations, the allowable tube wall degradation for various types of degradation of the ANO Unit 2 steam generator tubing was determined. The results of the evaluations in Table 3-1 and Table 3-2 show the permitted degradation extent for the types of degradation which were addressed.

Table 3-1

Allowable Steam Generator Tube Wall Degradation
For Various Degradation Types
(For Probable Material Properties)[1]

Type of Degradation[2]	Limiting Regulatory Guide 1.121 Structural Requirement	Allowable Tube Wall Degradation
Unlimited axial and circumferential extent	Burst pressure should be greater than $3x(p_{rcs}-p_{sec})$	66% maximum
0.25 in. axial length, 360° circumferential	Burst pressure should be greater than $3x(p_{rcs}-p_{sec})$	79% average around the tube circumference
Axial slot-type defect	Burst pressure should be greater than $3x(p_{rcs}-p_{sec})$	
- Less than 0.25 in. long		100%[3]
- 0.25 - 0.50 in. long		84%
- 0.50 - 1.5 in. long		73%
- Longer than 1.5 in.		66%

---

1 Mill test certificates with actual properties were not available for use at this time, otherwise, actual materials properties would have been used.

2 Any of the types of degradation indicated herein can be considered applicable to either a support location or a location at the top of the tubesheet. If the degradation is symmetric about the tubing axis, the specified degradation allowable is also applicable at locations away from support locations.

3 Burst pressure data is available for tube wall degradation to 84%. Extrapolation of this data indicates that allowable slot depth would be 100% (i.e., essentially through-wall).

Table 3-2

Allowable Steam Generator Tube Wall Degradation
For Various Degradation Types
(For ASME Code Minimum Tubing Material Properties)

Type of Degradation[1]	Limiting Regulatory Guide 1.121 Structural Requirement	Allowable Tube Wall Degradation
Unlimited axial and circumferential extent	Burst pressure should be greater than $3x(p_{rcs}-p_{sec})$	62% maximum
0.25 in. axial length, 360° circumferential	Burst pressure should be greater than $3x(p_{rcs}-p_{sec})$	76% average around the tube circumference
Axial slot-type defect	Burst pressure should be greater than $3x(p_{rcs}-p_{sec})$	
- Less than 0.25 in. long		100%[2]
- 0.25 - 0.50 in. long		77%
- 0.50 - 1.5 in.long		67%
- Longer than 1.5 in.		62%

---

[1] Any of the types of degradation indicated herein can be considered applicable to either a support location or a location at the top of the tubesheet. If the degradation is symmetric about the tubing axis, the specified degradation allowable is also applicable at locations away from support locations.

[2] Burst pressure data is available for tube wall degradation to 84%. Extrapolation of this data indicates that the allowable slot depth would be 100% (i.e., essentially through-wall).

Section 4

REFERENCES

1. US Nuclear Regulatory Commission Regulatory Guide 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes," August 1976.

2. ABB Combustion Engineering NCS Engineering Calculation Report CR-9417-CSE 92-1102, Rev. 0, "Evaluation of Circumferential Defects at the Expansion Transition in Arkansas Nuclear One-Unit 2 Steam Generator Tubes," April 23, 1992.

3. US Nuclear Regulatory Commission Docket No. 50-336, "Summary of Meeting with Representatives of Northeast Utilities Concerning the Assessment of the Steam Generators at Millstone 2, August 28, 1991," September 23, 1991.

4. Maine Yankee letter from S. E. Nichols, Manager Nuclear Engineering & Licensing, to Document Control Desk, US Nuclear Regulatory Commission dated June 20, 1991, "Maine Yankee Steam Generator Tube Evaluation (RG 1.121 Report)".

5. PNL-2684 (NUREG/CR-0277), "Steam Generator Tube Integrity Program - Annual Progress Report for January 1 - December 31, 1977," Battelle Pacific Northwest Laboratory, August 1978.

6. US Nuclear Regulatory Commission Docket No. 50-336, "Summary of Meeting with Representatives of Northeast Utilities Concerning the Assessment of the Steam Generators at Millstone 2, February 22, 1990," March 22, 1990; and Summary of Meeting with Representatives of Northeast Utilities Concerning the Assessment of the Steam Generators at Millstone 2, August 28, 1991, September 23, 1991.

APPENDIX A

MPR Calculation 62-81-HWM-1, "Acceptable Tube Wall Thinning for 0.25 in. Axial Length, 360° Circumferential Degradation"

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION TITLE PAGE

CLIENT	
ENTERGY OPERATIONS	PAGE 1 OF 10
PROJECT: ANO UNIT 2 STEAM GENERATOR	TASK NO. 62-81
CALCULATION TITLE: ACCEPTABLE TUBE WALL THINNING FOR 0.25 IN. AXIAL LENGTH, 360° CIRCUMFERENTIAL DEGRADATION	CALCULATION NO. (OPTIONAL) 62-81-HWM1

PREPARER(S)/DATE	CHECKER(S)/DATE	REVIEWER(S)/DATE	REV. NO.
HWMcCURDY 6-30-92	Michael Francis 6-30-92	Scott Bowen 6-30-92	0
			1

SUMMARY

THIS CALCULATION DETERMINES THE ACCEPTABLE AMOUNT OF WALL DEGRADATION FOR ANO UNIT 2 STEAM GENERATOR TUBES FOR WALL DEGRADATION WHICH IS 0.25 IN. AXIAL LENGTH AND 360° IN CIRCUMFERENTIAL EXTENT.

THE LIMITING STRUCTURAL REQUIREMENT FROM NRC REGULATORY GUIDE 1.121 IS THAT A MARGIN OF 3 EXIST TO BURST PRESSURE FOR THE NORMAL OPERATION TUBE WALL PRESSURE DIFFERENCE. RESULTS ARE,

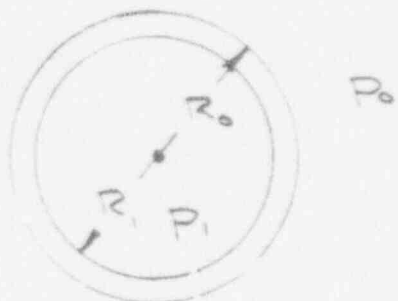
ULTIMATE STRESS (PSI)	REQUIRED WALL (IN)	ALLOWABLE WALL THINNING (%)
80,000*	.0115	76.0
90,000*	.0102	78.8

* AT 650°F

THE PURPOSE OF THIS CALCULATION IS TO DETERMINE THE ACCEPTABLE AMOUNT OF WALL DEGRADATION FOR ANO UNIT 2 STEAM GENERATOR TUBES. THE CALCULATION CONSIDERS DEGRADATION WHICH IS 0.25 IN. IN AXIAL LENGTH AND 360° IN CIRCUMFERENTIAL EXTENT.

BECAUSE OF THE SHORT AXIAL EXTENT OF THE DEGRADATION, THE CAPABILITY OF THE TUBING TO SUSTAIN THE CIRCUMFERENTIAL PRESSURE FORCES IS NOT AFFECTED SIGNIFICANTLY, I.E. THE FORCES ARE REDISTRIBUTED TO THE TUBING MATERIAL ABOVE AND BELOW THE DEGRADATION. AS A RESULT, THE AXIAL STRESSES IN THE TUBING DUE TO PRESSURE, OR AN APPLIED AXIAL FORCE, ARE THE ONLY TUBING STRESSES SIGNIFICANTLY AFFECTED BY THE 0.25 IN. LONG DEGRADATION.

THE GEOMETRY OF THE TUBE AT THE DEGRADATION IS SHOWN HERE,



NOTE THAT FOR THE TUBE THE PRESSURE FORCE ACTS ON THE U-BEND END OF THE TUBE. THE AXIAL FORCE BALANCE GIVES,

$$\sigma_A \pi (R_0^2 - R_1^2) = (P_1 - P_0) \cdot \pi R_1^2$$

WHERE,

R_1 = TUBE INSIDE RADIUS, IN.

R_0 = TUBE OUTSIDE RADIUS, IN.

P_1 = PRESSURE INSIDE TUBE, PSIA

P_0 = PRESSURE OUTSIDE TUBE, PSIA

σ_A = TUBE AXIAL STRESS, PSI

THE AXIAL STRESS IS,

$$\sigma_A = \frac{\pi R_i^2 (P_i - P_o)}{\pi (R_o^2 - R_i^2)}$$

THE AVERAGE RADIAL STRESS IN THE TUBE DUE TO PRESSURE IS,

$$\sigma_R = -\frac{P_i + P_o}{2}$$

THE TUBE STRESS INTENSITY IS,

$$S = \sigma_A - \sigma_R$$

$$S = \frac{\pi R_i^2 (P_i - P_o)}{\pi (R_o^2 - R_i^2)} + \frac{P_i + P_o}{2}$$

FROM SECTION 5.3 OF REFERENCE 1, THE LIMITING REQUIREMENT FROM REGULATORY GUIDE 1.121 IS THAT THE DEGRADED TUBE HAVE A MARGIN TO BURST OF 3 BASED ON THE PRESSURE DIFFERENCE FOR NORMAL OPERATION. ALSO, SECTION 5.5 OF REFERENCE 1 STATES THAT BURST TEST DATA EXISTS FOR A STEAM GENERATOR TUBE (0.875 IN. × .050 IN) WITH A 0.25 IN. AXIAL LENGTH

DEGRADED SECTION WITH 75-80% WALL REDUCTION. THE ABOVE EQUATION WILL BE USED TO DETERMINE THE STRESS INTENSITY AT WHICH THE FAILURE OCCURRED IN THIS TEST. NOTE FROM FIGURE 11 OF REFERENCE 2 (SAME AS REFERENCE 3.18 IN REFERENCE 1) THAT THE DEGRADATION WAS MACHINED IN THE TUBE FROM THE OUTSIDE DIAMETER.

SPECIMEN NUMBER 3-35-7 (SEE APPENDIX E OF REF. 2) IS USED FOR THE CALCULATION SINCE IT HAS A REPRESENTATIVE DEFECT (UNIFORM THINNING, 73% WASTAGE, .1825 IN. DEFECT LENGTH). PARAMETERS ARE,

$R_i = \frac{.875}{2} - .0514 = .3861$ in. (REF. 2, APPENDIX E AND TABLE 3)

$R_o = \frac{.875}{2} - .0375 = .400$ in. (REF. 2, APPENDIX E)

$P_i = 7700$ PSIA (REF. 2, APPENDIX E)

$P_o = 2250$ PSIA (REF. 2, APPENDIX E)

$$S = \frac{.3861^2(7700-2250)}{.400^2 - .3861^2} + \frac{7700+2250}{2} = 79{,}300 \text{ PSI}$$

THIS STRESS AT FAILURE IS ABOUT 85% OF THE ULTIMATE STRESS OF ~93,000 PSI FOR THE 0.875 IN × .050 IN. TUBING (SEE REF. 2, TABLES 3 AND 4). THEREFORE, THE CONCLUSION IS THAT THE TUBING BURSTS WHEN THE AXIAL PRESSURE STRESS IS EQUAL TO 0.85 TIMES THE MATERIAL ULTIMATE STRESS.

NEXT, SOLVE THE TUBE STRESS INTENSITY RELATIONSHIP FOR THE INSIDE RADIUS (R_i),

$$R_i = R_o \cdot \left(\frac{S - \frac{P_i + P_o}{2}}{P_i - P_o + S - \frac{P_i + P_o}{2}} \right)^{1/2}$$

THE PARAMETERS FOR THE ANO-2 STEAM GENERATOR TUBES ARE,

R_o = 0.375 IN. (REF. 1, PAGE 12)

P_i = 2250 PSIA (REF. 1, PAGE 12)

P_o = 900 PSIA (REF. 1, PAGE 12

THE TUBING RADIUS IS GIVEN BY,

$$R_1 = 0.375 \cdot \left(\frac{S - \frac{2250+900}{2}}{2250 - 900 + S - \frac{2250+900}{2}} \right)^{1/2}$$

$$R_1 = 0.375 \cdot \left(\frac{S - 1575}{S - 225} \right)^{1/2}$$

TO PROVIDE THE REQUIRED MARGIN OF 3 TO BURST PRESSURE, THE ALLOWABLE STRESS IS EQUAL TO $\frac{1}{3}$ × BURST FAILURE STRESS. TWO CASES ARE CONSIDERED - WITH THE ASME CODE MINIMUM ULTIMATE STRESS OF 80,000 PSI* (SEE REF. 1, PAGE 13) AND WITH THE PROBABLE ULTIMATE STRESS OF 90,000 PSI* (SEE REF. 1, PAGE 23). FOR S_{ULT} = 80,000 PSI, BURST FAILURE WILL OCCUR AT A STRESS OF .85 · 80,000 = 68,000 PSI. THE REQUIRED TUBING INSIDE RADIUS IS,

$$R_1 = 0.375 \cdot \left(\frac{\frac{68,000}{3} - 1575}{\frac{68,000}{3} - 225} \right)^{1/2}$$

R_1 = 0.3635 IN. (WALL THICKNESS IS 0.375 - 0.3635 = 0.0115 IN.)

* AT 650°F

FOR S_{ULT} = 90,000 PSI, BURST PRESSURE WILL OCCUR AT A STRESS OF .85·90,000 = 76,500 PSI.

THE REQUIRED TUBING INSIDE RADIUS IS,

$$R_i = 0.375 \cdot \left(\frac{\frac{76,500}{3} - 1575}{\frac{76,500}{3} - 225} \right)^{1/2}$$

R_i = 0.3648 IN. (WALL THICKNESS IS 0.375 - 0.3648 = 0.0102 IN.)

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CALCULATION NO.	PREPARED BY	CHECKED BY	
G2-81-HWM1	HWMcCURDY	M Francis	PAGE 10

REFERENCES:

(1) ABB CE, NCS ENGINEERING CALCULATION REPORT CR-9417-CSE92-1102, REV. 0 DATED 4/23/92.

(2) PNL-2684, "STEAM GENERATOR TUBE INTEGRITY PROGRAM", ANNUAL PROGRESS REPORT JANUARY 1 - DECEMBER 31, 1977.

APPENDIX B

MPR Calculation 62-81-HWM-3, "Allowable Tube Wall Degradation for Axial, Slot-type Defects"

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CALCULATION TITLE PAGE

CLIENT ENTERGY OPERATIONS	PAGE 1 OF 9
PROJECT ANO UNIT 2 STEAM GENERATOR	TASK NO. 62-81
CALCULATION TITLE ALLOWABLE TUBE WALL DEGRADATION FOR AXIAL, SLOT-TYPE DEFECTS	CALCULATION NO. (OPTIONAL) 62-81-HWM3

PREPARER(S)/DATE	CHECKER(S)/DATE	REVIEWER(S)/DATE	REV. NO.
H W McCURDY 7-27-92	Michael Francis 7-29-92	[signature] 7-29-92	0

92-R-2025-01
ATTACH. B PAGE 33 OF 41

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CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 2
62-81-HWM3	H W McCurdy	Michael [illegible]	

SUMMARY

THIS CALCULATION DETERMINES THE ALLOWABLE TUBE WALL DEGRADATION FOR ANO UNIT 2 STEAM GENERATOR TUBES FOR AXIAL, SLOT-TYPE DEFECTS. THE REQUIRED REMAINING WALL AND ALLOWABLE WALL DEGRADATION FOR TUBE MATERIAL ULTIMATE STRESSES OF 80 AND 90 KSI ARE:

DEFECT LENGTH (IN.)	ULTIMATE STRESS (KSI)	REQUIRED WALL (IN.)	DEGRADATION (%)
1/4	80	<.0075	>84.4
	90	<.0075	>84.4
1/2	80	.011	77.1
	90	.0078	83.8
1 1/2	80	.016	66.7
	90	.013	72.9

NOTE: UNDEGRADED WALL THICKNESS IS .048 IN.

THE PURPOSE OF THIS CALCULATION IS TO DETERMINE THE ALLOWABLE WALL DEGRADATION FOR ANO UNIT 2 STEAM GENERATOR TUBES FOR AXIAL, SLOT-TYPE DEFECTS.

BURST-TEST DATA IS CONTAINED IN REFERENCE 1 FOR TUBES WITH AXIAL SLOTS WHICH WERE MACHINED PART WAY THROUGH THE WALL USING EDM. THIS DATA IS CLOSELY APPLICABLE BUT MUST BE ADJUSTED FOR THE FOLLOWING:

- THE ULTIMATE STRESS FOR THE TESTED TUBING WAS HIGHER THAN THAT OF THE ANO UNIT 2 TUBING.
- THE WALL THICKNESS OF THE TESTED TUBING WAS GREATER THAN THAT OF THE ANO UNIT 2 TUBING.

BURST PRESSURE RESULTS FOR 0.750 × .050 IN. TUBING ARE SHOWN IN FIGURE 26 OF REFERENCE 1. (ANO UNIT 2 TUBING IS 0.750 × .048 IN. PER REFERENCE 2, PAGE 21.). FIGURE 26 IS SHOWN

BELOW INCLUDING "BEST-FIT" STRAIGHT LINES RELATING BURST PRESSURE TO WALL DEGRADATION FOR THE 1/4", 1/2" AND 1 1/2" SLOT DEFECTS.

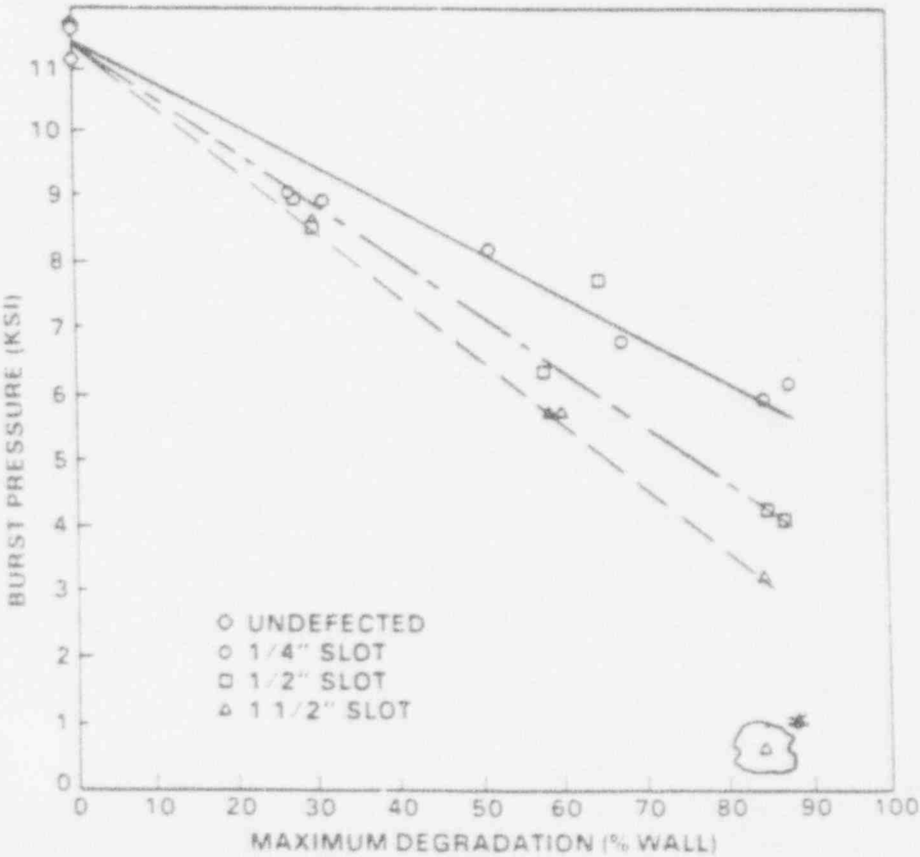

FIGURE 26. Burst Pressures for 0.750 x 0.050 in. EDM Slots

* NOTE THAT THIS DATA POINT IS NOT CONSIDERED VALID AS DISCUSSED ON PAGE 46 OF REFERENCE 1.

BURST PRESSURE DATA POINTS ARE:

DEFECT LENGTH (IN.)	MAXIMUM DEGRADATION (%)	REMAINING WALL (IN.)	BURST PRESSURE (KSI)
1/4	0	.050	11.4
	85	.0075	6.0
1/2	0	.050	11.4
	85	.0075	4.3
1 1/2	0	.050	11.4
	85	.0075	3.3

"BEST-FIT" STRAIGHT LINES ARE AS FOLLOWS:

FOR 1/4 IN. DEFECT:

$$P_B = 11.4 - \frac{11.4 - 6.0}{.050 - .0075} \cdot (.050 - t_w)$$

$$P_B = 5.05 + 127\, t_w$$

WHERE,

P_B = BURST PRESSURE (KSI)

t_w = REMAINING TUBE WALL (IN.)

FOR 1/2 IN. DEFECT:

$$P_B = 11.4 - \frac{11.4 - 4.3}{.050 - .0075} \cdot (.050 - t_w)$$

$$P_B = 3.05 + 167 t_w$$

FOR 1 1/2 IN. DEFECT:

$$P_B = 11.4 - \frac{11.4 - 3.3}{.050 - .0075} \cdot (.050 - t_w)$$

$$P_B = 1.87 + 191 t_w$$

FROM TABLE 3 OF REFERENCE 1, THE TUBING USED FOR THE BURST TESTS HAD AN ULTIMATE STRESS OF 96.5 KSI. FROM PAGE 13 OF REFERENCE 2, THE ANO-2 TUBING HAS A CODE MINIMUM ULTIMATE STRESS OF 80 KSI. FROM PAGE 23 OF REFERENCE 2, THE "PROBABLE" ULTIMATE STRESS IS 90 KSI. SINCE BURST PRESSURE IS DIRECTLY PROPORTIONAL TO ULTIMATE STRESS, THE BURST PRESSURE VS. REMAINING WALL RELATIONSHIPS CAN BE ADJUSTED AS FOLLOWS:

$$P_B(@S_u) = \frac{S_u}{96.5} \cdot P_B(@96.5\text{ ksi})$$

DEFECT LENGTH (IN.)	S_u (KSI)	P_B (KSI)
1/4	80	$4.19 + 105\,t_w$
	90	$4.71 + 118\,t_w$
1/2	80	$2.53 + 138\,t_w$
	90	$2.84 + 156\,t_w$
1 1/2	80	$1.55 + 158\,t_w$
	90	$1.74 + 178\,t_w$

FROM PAGE 13 OF REFERENCE 2, THE REQUIRED BURST PRESSURE IS --- $3 \cdot (2.25 - 0.90) = 4.05$ KSI

THE REQUIRED REMAINING WALL THICKNESS IS,

DEFECT LENGTH (IN.)	S_u (KSI)	t_w (IN.)
1/4	80	<.0075
	90	<.0075
1/2	80	.011
	90	.0078
1 1/2	80	.016
	90	.013

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NOTE THAT NO BURST PRESSURE DATA IS AVAILABLE FOR A TUBE WALL LESS THAN .0075 IN. THICK. THEREFORE, THE REQUIRED REMAINING TUBE WALL THICKNESS IS CONSERVATIVELY LIMITED TO THIS VALUE.

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CALCULATION NO. 92-81-HWM3	PREPARED BY HW McCURDY	CHECKED BY Michael Francis	PAGE 9

REFERENCES:

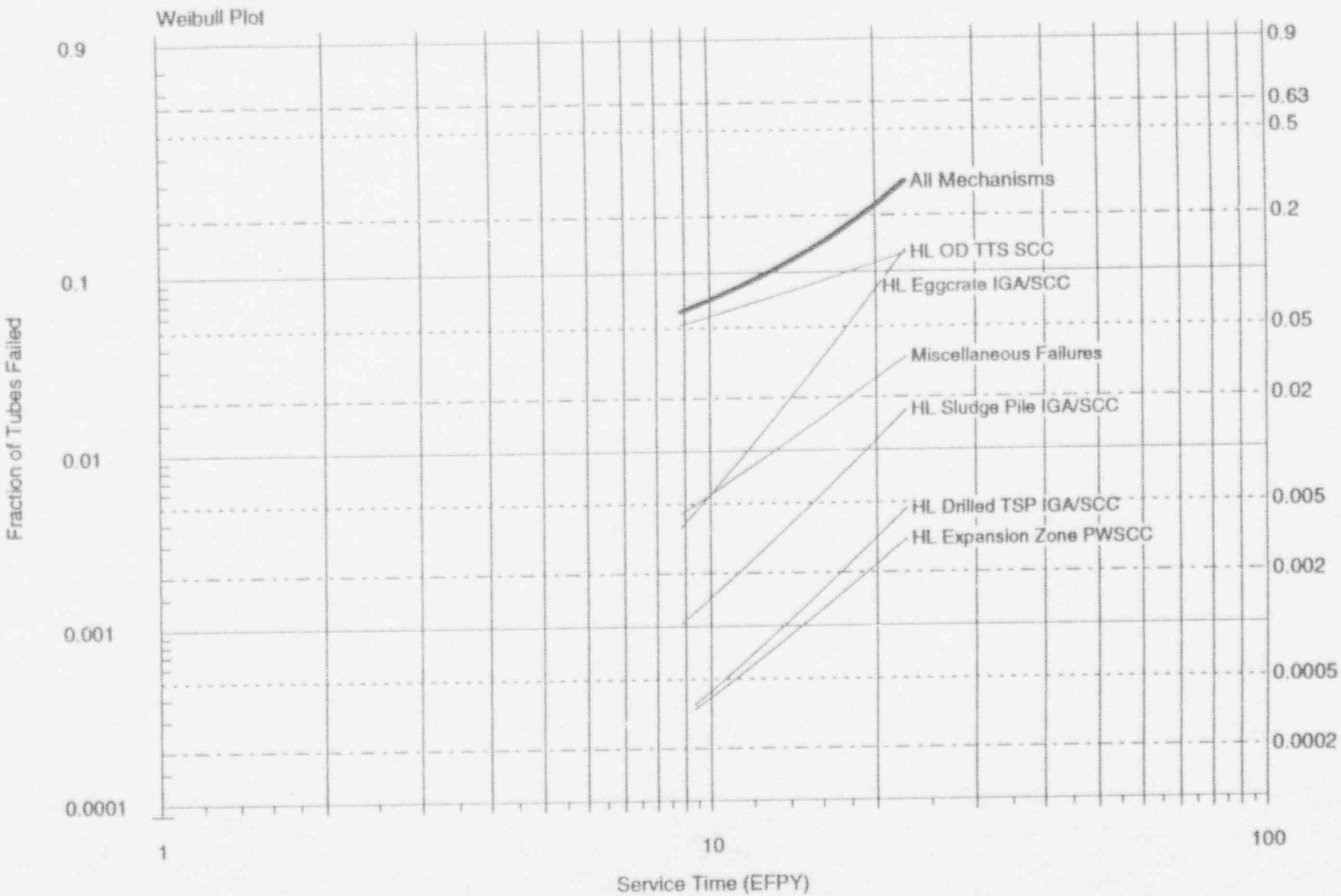
1. NUREG/CR-0277 (PNL-2684), "STEAM GENERATOR TUBE INTEGRITY PROGRAM - ANNUAL PROGRESS REPORT - JANUARY 1 - DECEMBER 31, 1977," BATTELLE PACIFIC NORTHWEST LABORATORY, AUGUST 1978.

2. ABB CE ENGINEERING CALCULATION REPORT CR-9417-CSE92-1102, REV. 0, APRIL 23, 1992.

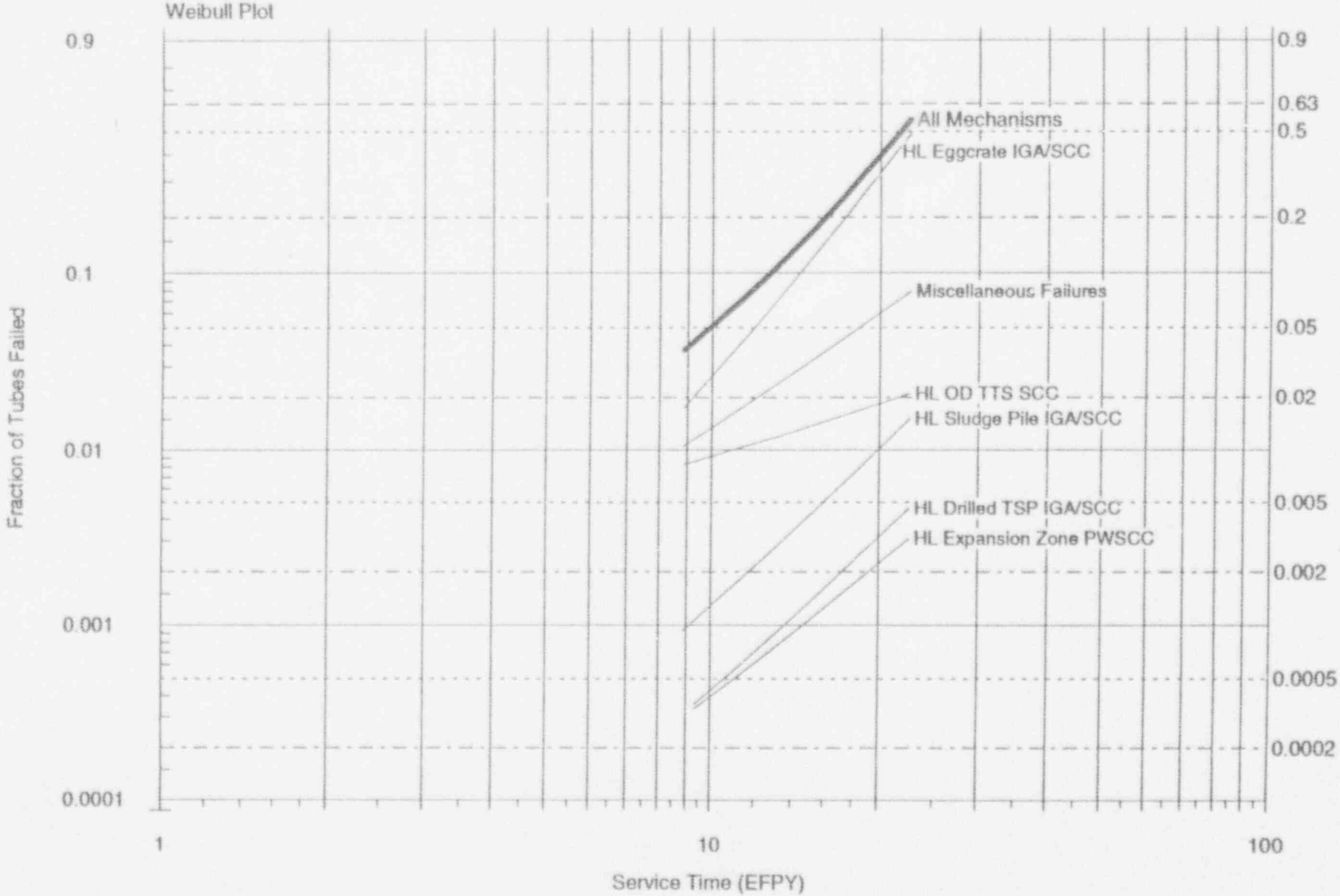
ATTACHMENT 2

ANO-2 Predicted Tube Repair Curves

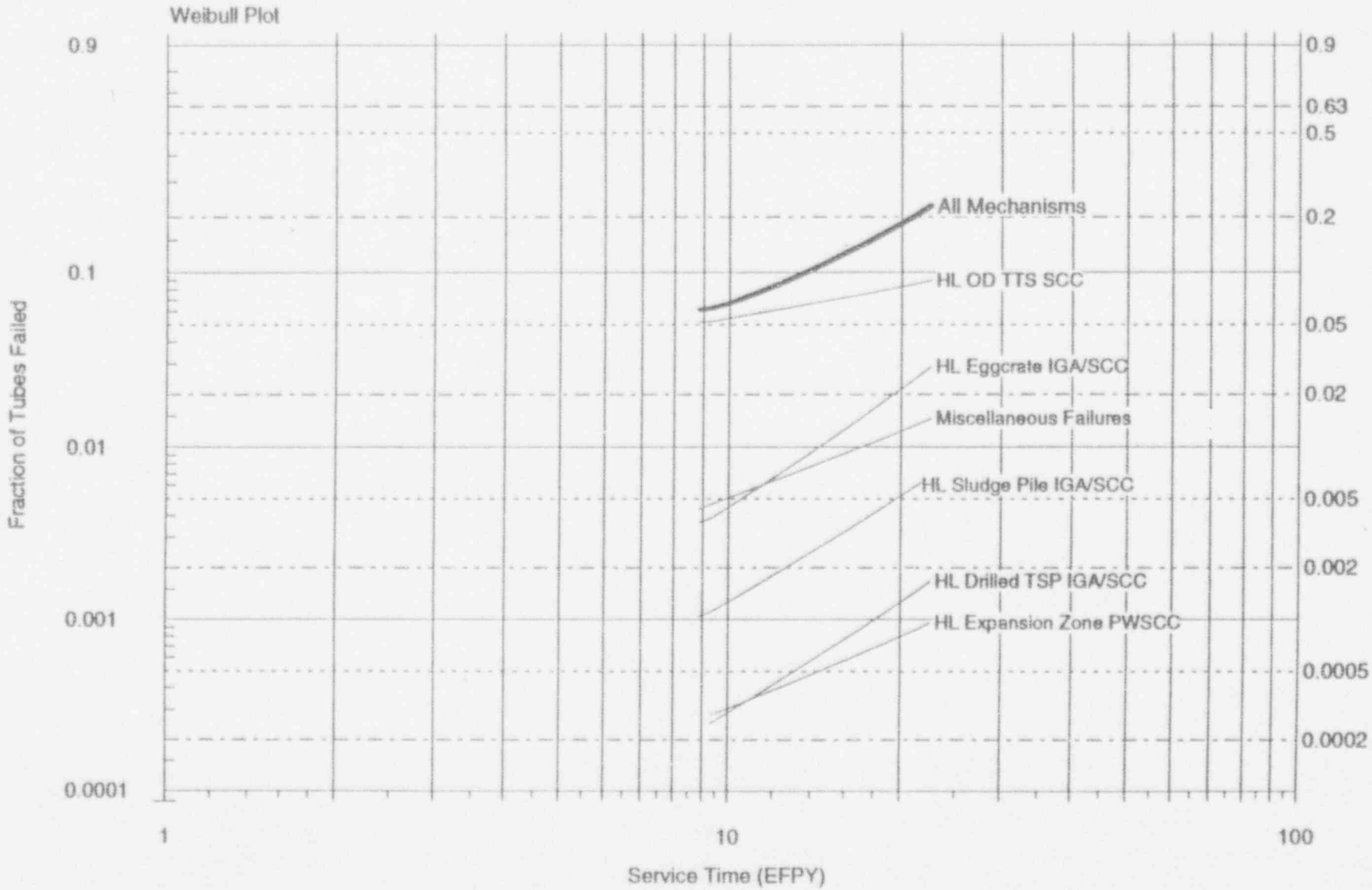
ANO 2 - SG A - PREDICTED TUBE REPAIRS - BEST ESTIMATE - REDUCED Thot (case 1)



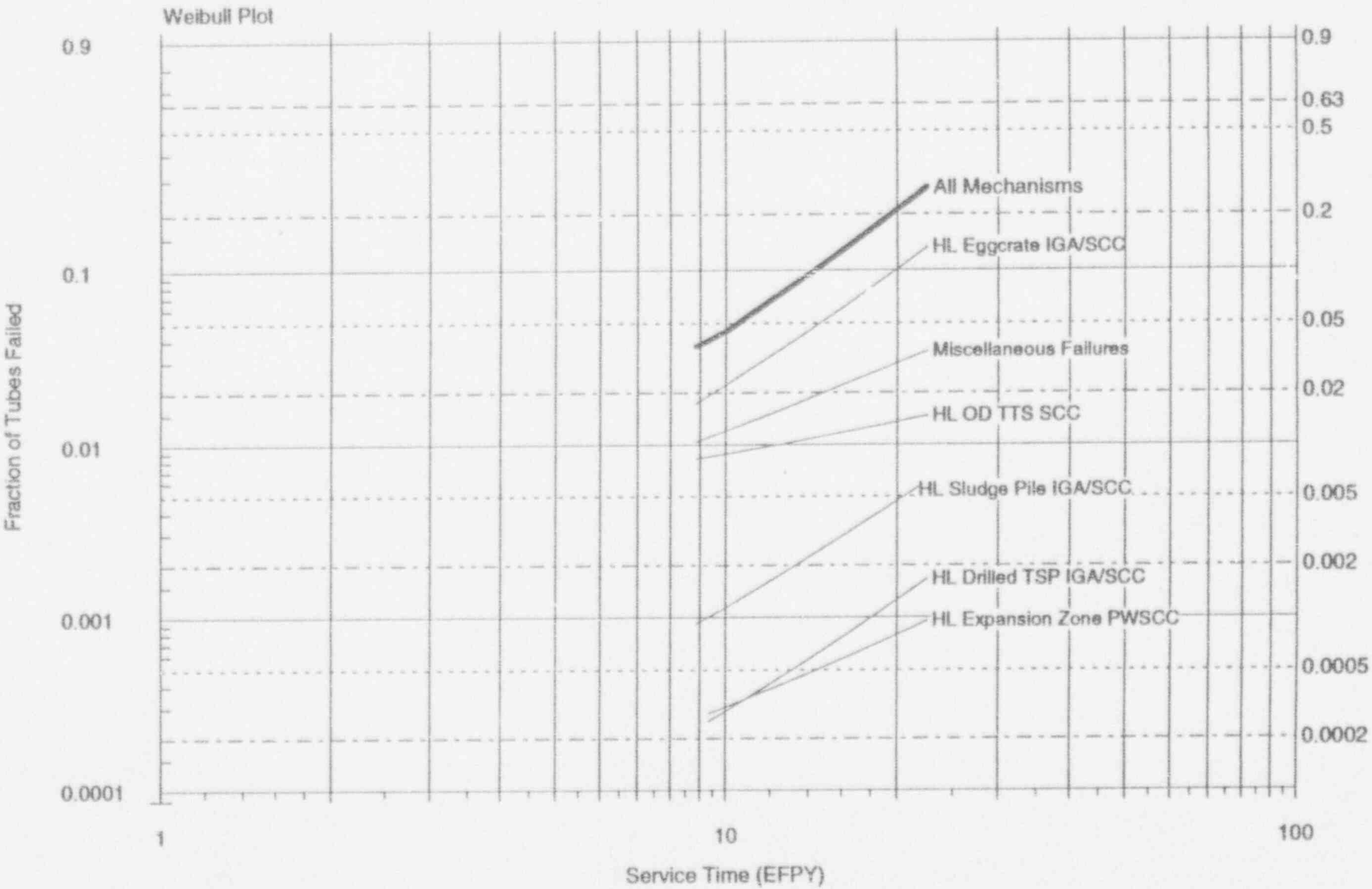
ANO 2 - SG B - PREDICTED TUBE REPAIRS - BEST ESTIMATE - REDUCED Thot (case 1)

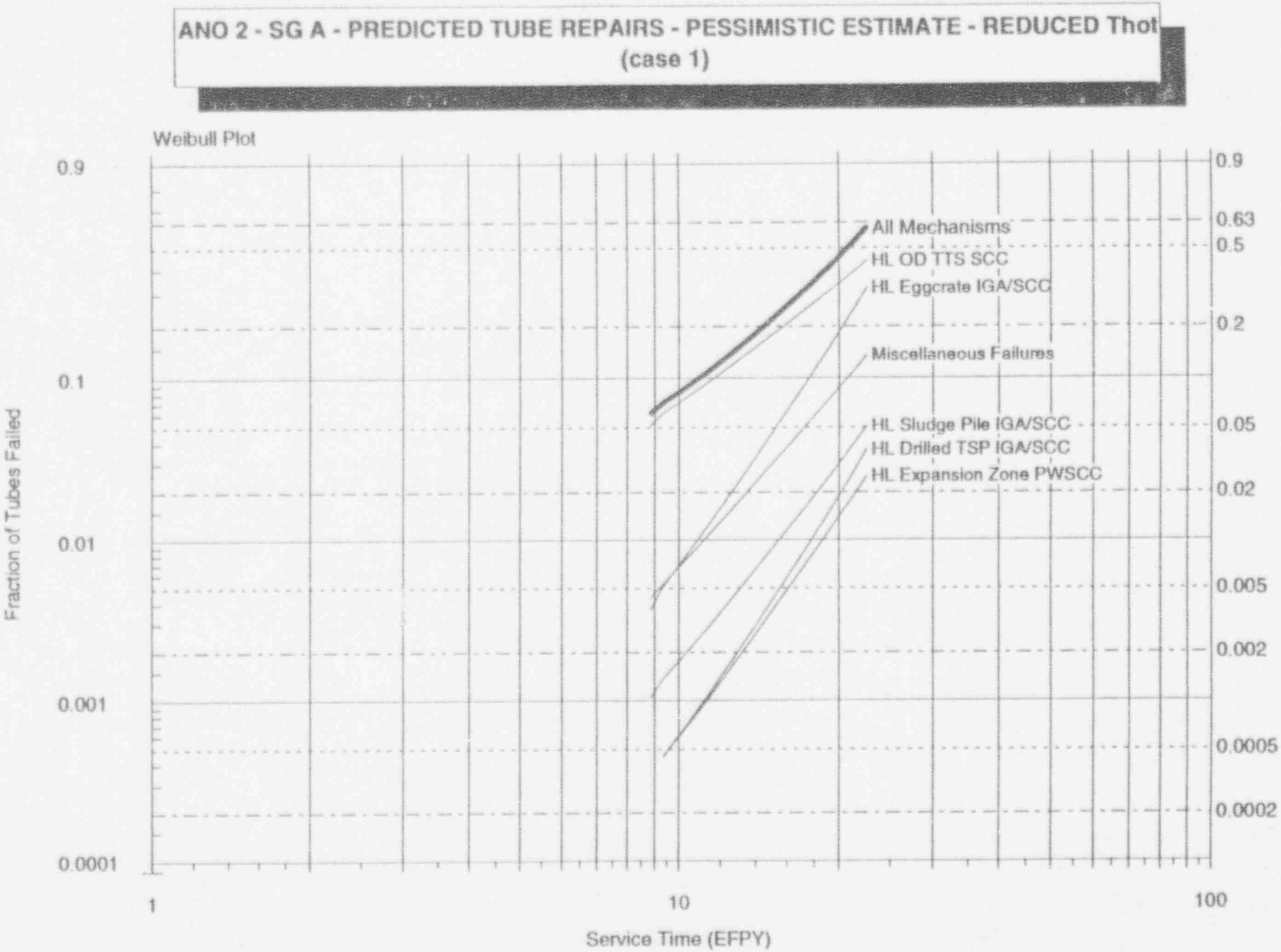


ANO 2 - SG A - PREDICTED TUBE REPAIRS - OPTIMISTIC ESTIMATE - REDUCED Thot (case 1)



ANO 2 - SG B - PREDICTED TUBE REPAIRS - OPTIMISTIC ESTIMATE - REDUCED Thot (case 1)

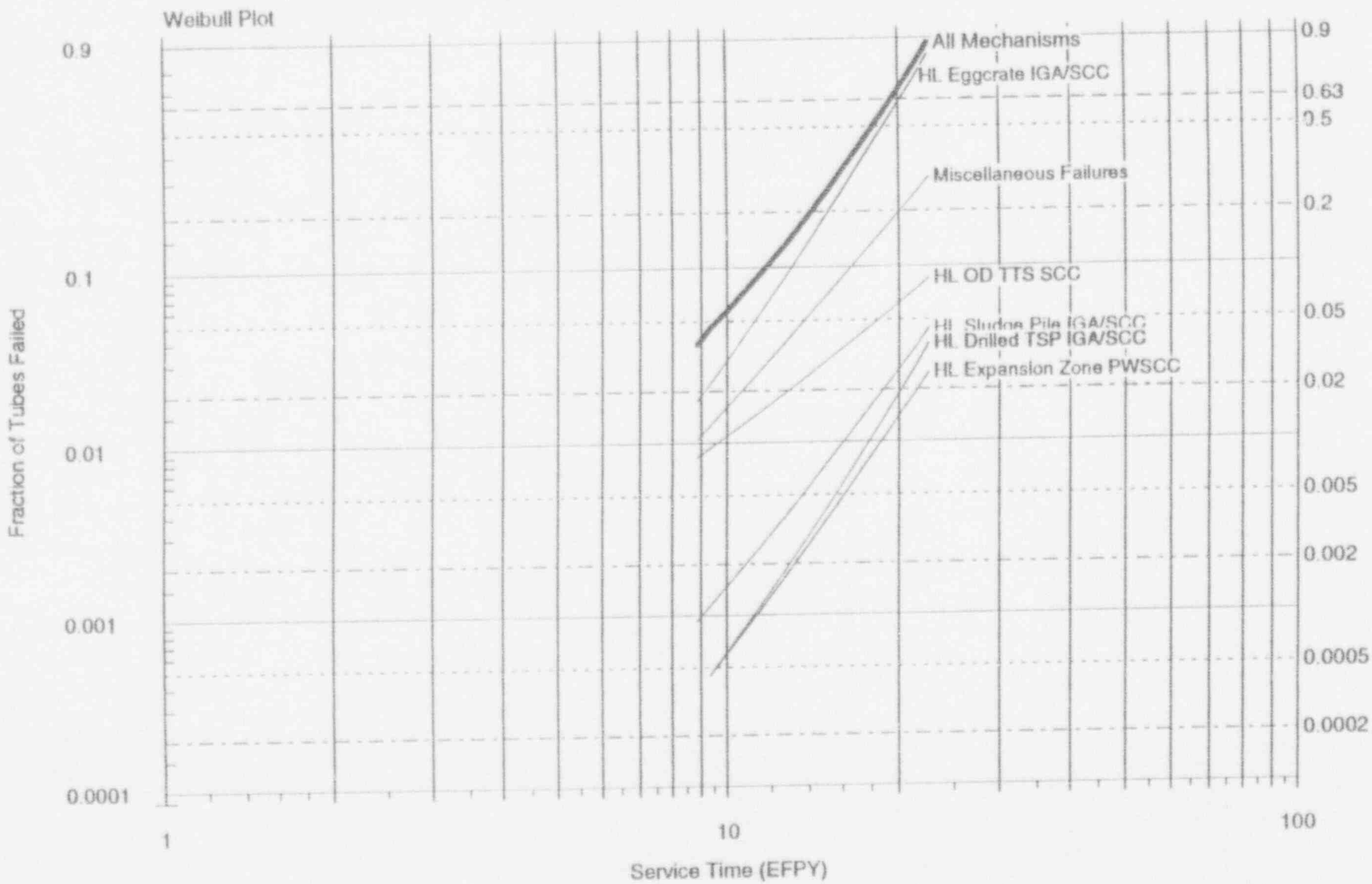




ANO 2 - SG A - PREDICTED TUBE REPAIRS - PESSIMISTIC ESTIMATE - REDUCED Thot (case 1)
Weibull Plot
0.9
0.1
0.01
0.001
0.0001
0.9
0.63
0.5
0.2
0.05
0.02
0.005
0.002
0.0005
0.0002
All Mechanisms
HL OD TTS SCC
HL Eggcrate IGA/SCC
Miscellaneous Failures
HL Sludge Pile IGA/SCC
HL Drilled TSP IGA/SCC
HL Expansion Zone PWSCC
Fraction of Tubes Failed
1
10
100
Service Time (EFPY)

Dominion Engineering, Inc.

ANO 2 - SG B - PREDICTED TUBE REPAIRS - PESSIMISTIC ESTIMATE - REDUCED Thot (case 1)



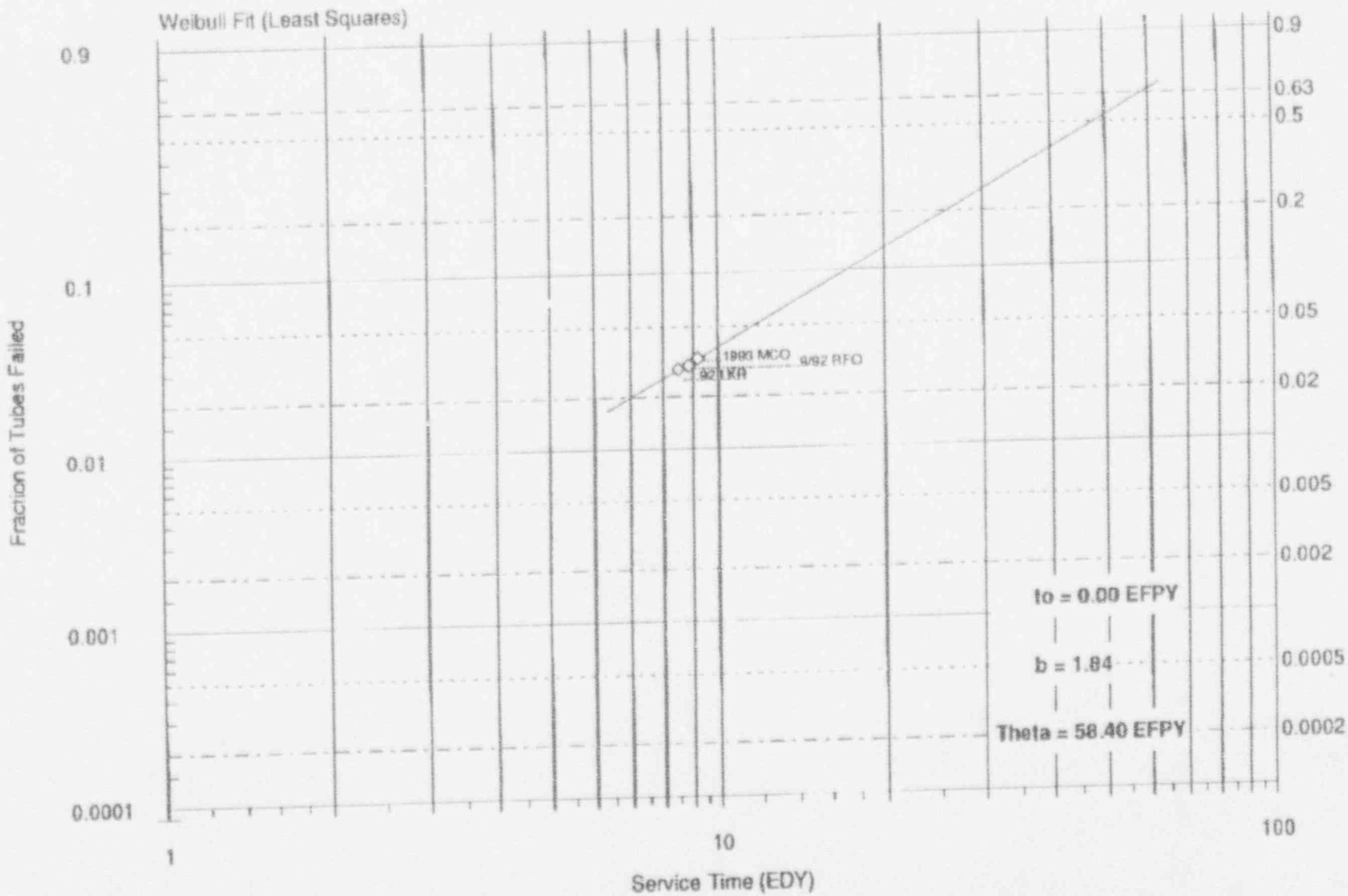
FS UB SGB TR1 WP-90%

1/15/93

Dominion Engineering, Inc.

DRAFT

ANO 2 - Both SGs - OD TTS SCC



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