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Evaluation of Crystal River Unit 3 (CR-3) Steam Generator Tube Wall Degradation

February 24, 1994

Prepared for

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Crystal River Energy Complex
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Crystal River, Florida 34228-6708

CONTENTS

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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 conservative plugging/sleeving criteria and operating experience of CR-3 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 CR-3 requiring shutdown for a leak rate of 0.3 gpm per steam generator. For CR-3, which has not had major tube degradation, this leak rate limit is considered to provide reasonable assurance of tubing structural adequacy as well as being practical, e.g., in terms of detectability. CR-3 experience and other work supports this.

PURPOSE/SCOPE

The purpose of this report is to address all of the structural requirements in Regulatory Guide 1.121 by conservatively considering any possible defect configuration and location which could occur in the secondary side of the steam generator tubing at CR-3. (About 3% lower defect allowables, in terms of through-wall penetration, per Figure 1 only would be calculated for defects on the primary system side of the tubing).

Method

All possible configurations of defects are covered herein based on evaluations of the following:

- Maximum axial tube stresses (which tend to part the tube, especially for the case of a circumferential defect). The limiting axial tube load in this case is due to a LOCA and is 2641 lbs tension (per Reference 2). Notably, the steam line break load per Reference 2 has since been reduced per Reference 3, and is no longer the limiting load.

- Maximum tube hoop stresses (which tend to burst the tube especially for the case of a defect with substantial axial length). The limiting load (i.e., pressure) in this case per Regulatory Guide 1.121 (which includes substantial margin as desired) is 3 times normal operating pressure difference which results in a value of 4050 psi (per Reference 4).

The above two cases are considered separately, because of the following:

- Stresses are produced in the axial direction only by axial loads and in the hoop direction only by pressure loads.

- Even when the axial and pressure loads occur simultaneously, the resulting stresses are principal stresses, and there is no intermediate direction which would have a greater stress. Hence, failure would be expected to occur whenever one of these stresses exceeded the critical value.

The worst case defect location[1] for the bounding analyses in this report is a defect located in a peripheral tube. A peripheral tube sees the maximum axial tube stresses, due to axial differential expansion between the tubes and the vessel (as a result of tubesheet stiffness being greater at the periphery), during a LOCA. The elevation location of the defect has no effect on the tube burst analyses herein since no credit is taken for support from e.g., a support plate or tubesheet in resisting tube burst from an axial defect.

The configuration of the defect can be either symmetrical or nonsymmetrical about the tube axis because the primary stresses of concern (axial stress due to differential expansion effects during a LOCA) are not affected by asymmetry of the defect. As indicated in Figures 3 and 4, all pertinent loads are reacted by either the tube or its supports without the need for any bending moment capability of the tube at the defect (i.e., a plastic hinge can be assumed at the defect).

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[1]Notably, no ECT detectable tube imperfections are considered acceptable (without plugging/stabilizing or sleeving) at the top support plate or the bottom of the upper tubesheet for certain tubes adjacent to the open lane (considered susceptible to vibration/fatigue), because of the potential for fatigue in these areas (see Reference 2).

To reduce the complexity of the analysis, all defects will be considered as planer defects, with no credit taken for ligaments between micro cracks (see Figure 5). Based on operating experience thus far, the extent and rate of occurrence of defects at CR-3 are sufficiently small that such a conservative and simplifying approach can be taken at this time.

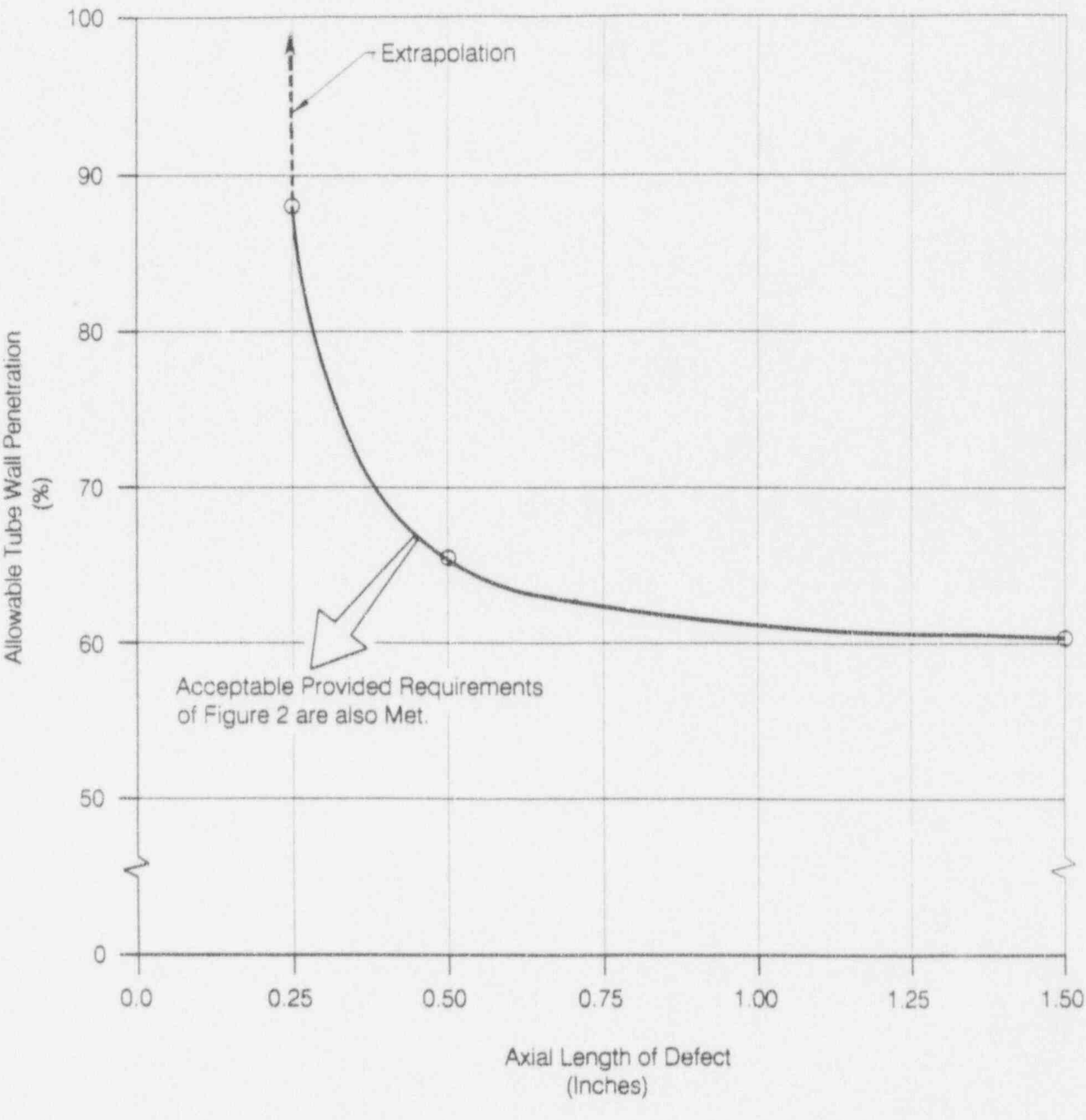

Figure 1. Allowable Tube Wall Penetration
For Axial Slot Type Defects (Axial Cracks)

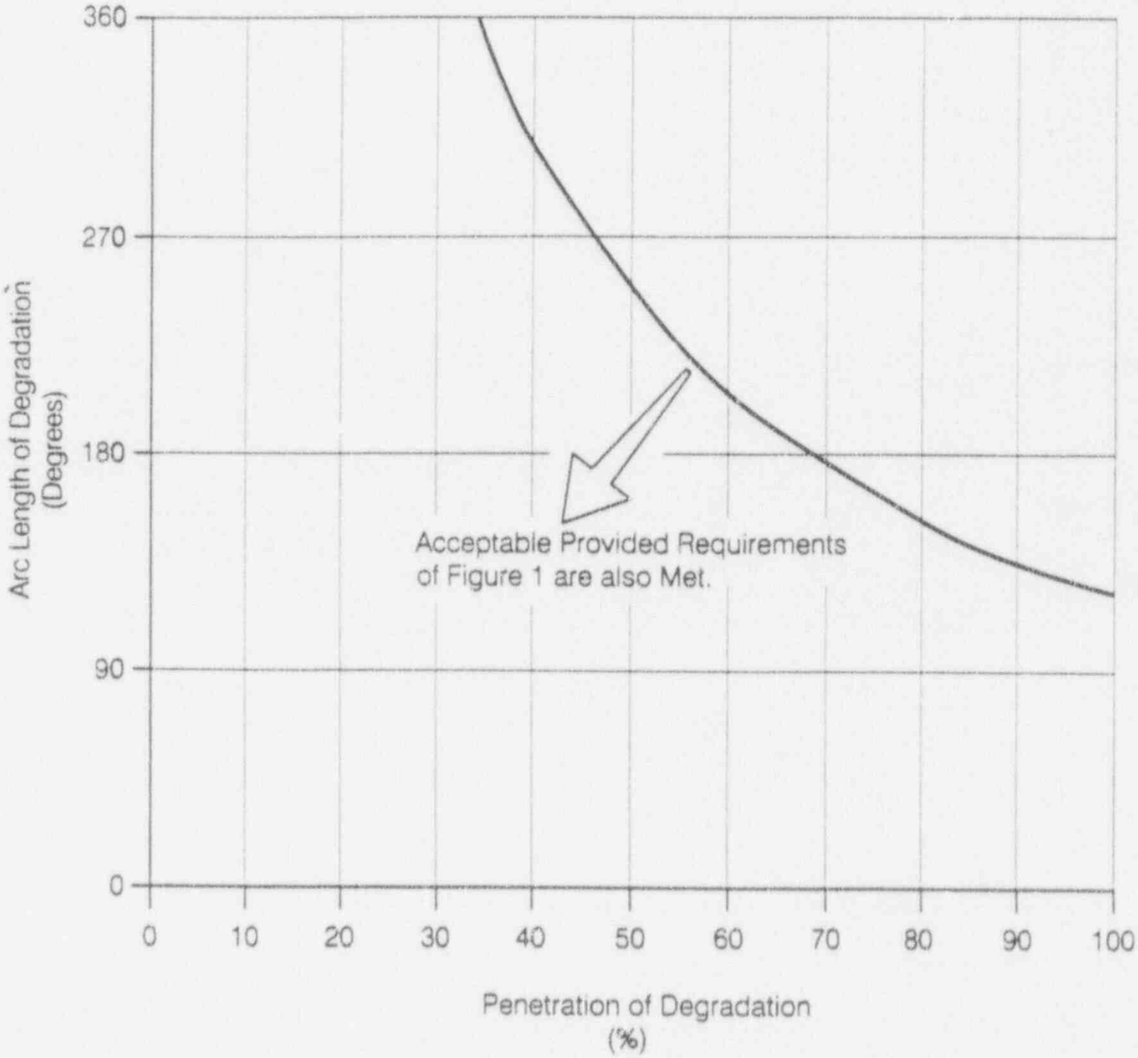

Figure 2. Maximum Allowable Penetration Versus Arc Length for 34.1 % Maximum Allowable Area of Degradation

Section 2

SUMMARY

The maximum allowable tube wall degradation determined herein is summarized in Tables 2-1 for "probable" material properties and 2-2 for Code minimum material properties . 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 (i.e., per a 95% probability of occurrence at a 95% confidence level, per Reference 2), as appropriate, rather than ASME Code minimums. Accordingly, we consider the maximum allowable degradation as shown in Table 2-1 to be appropriate and conservative.

The results in Table 2-1 are presented graphically in Figure 1 (for axial slot-type defects) and in Figure 2 (for circumferential defects) which covers the effects of arc length of the defect as well as penetration. Based on tube burst test data in Reference 5, the analysis in this report for axial slot-type defects is reasonable and conservative for other axial defects of interest as well (e.g., any substantial size uniform wastage or elliptical wastage defect). The circumferential defects analyzed herein apply for defects up to 360° of arc length and are limited to an axial height of 1.5-in. To be acceptable per Regulatory Guide 1.121, a defect must be within allowables of both Figure 1 and Figure 2, since different configurations of defects are limited by different criteria.

Table 2-1

Allowable Steam Generator Tube Wall Degradation for Various Degradation Configurations (For Probable Tubing Material Properties)

Configuration Type of Degradation	Allowable Tube Wall Degradation
1. Circumferential (up to 1.5 in. axial length and 360° arc length)	34.1% of tube cross-sectional area (see Figure 2)
2. Axial slot-type	See Figure 1
a. Less than 0.25 in. long	See Figure 1
b. 0.50 in. long	65.6% Penetration
c. 1.5 in. long	60.3% Penetration

Table 2-2

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

Configuration Type of Degradation	Allowable Tube Wall Degradation
1. Circumferential (up to 1.5 in. axial length and 360° arc length)	23.0% of tube cross-sectional area
2. Axial slot-type	
a. 0.25 in. long	86.3% Penetration
b. 0.50 in. long	60.1% Penetration
c. 1.5 in. long	53.8% Penetration

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 Section 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)).

  CR-3—Experience at CR-3 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).

  CR-3—This requirement is addressed by the current practice at CR-3 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 CR-3 and others) indicates sufficiently rapid degradation should be expected (e.g., for certain tubes adjacent the open lane with degradation at the top support plate or at the bottom of the top tubesheet). Also, experience (at CR-3 and others) is used to ensure degradation between NDT examinations will not exceed structural allowables. Finally, an evaluation of fatigue is discussed in the CR-3 comments for Regulatory Guide 1.121 Section C.3 as follows.

From Section 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)).

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IMAGE EVALUATION TEST TARGET (MT-3)

150mm

6"

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IMAGE EVALUATION TEST TARGET (MT-3)

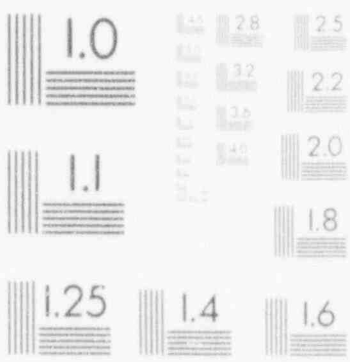

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IMAGE EVALUATION TEST TARGET (MT-3)

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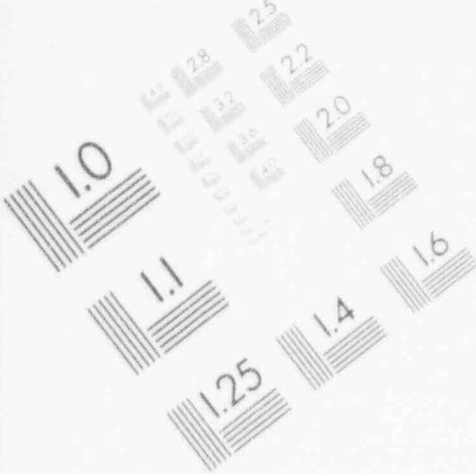
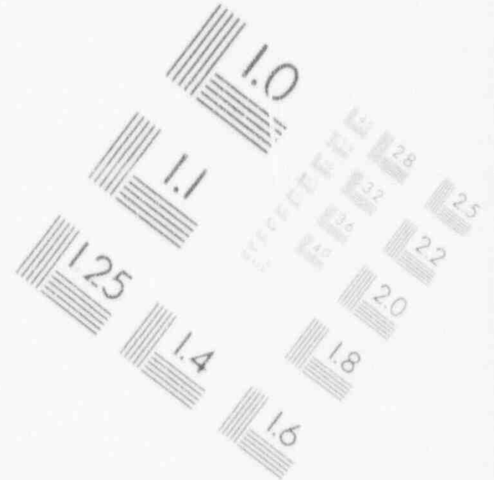
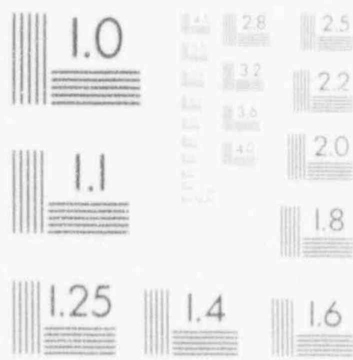
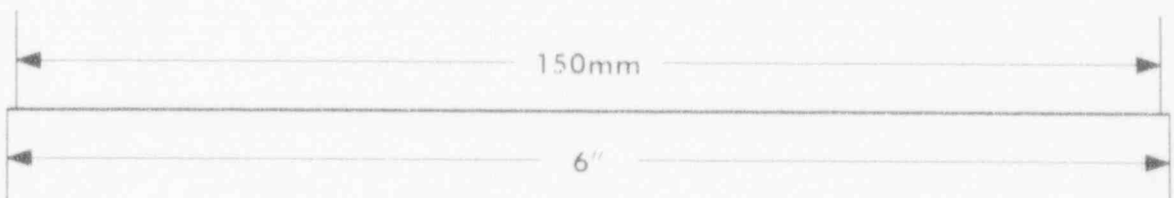
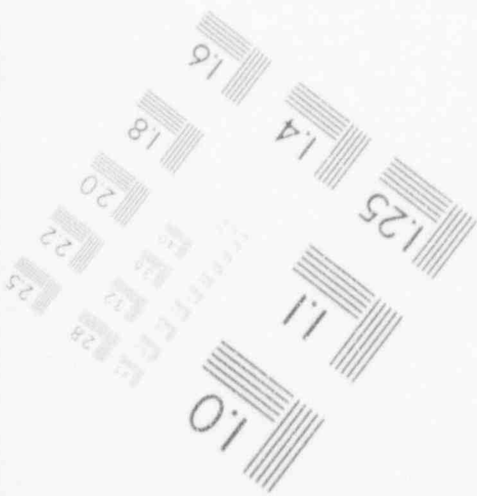
IMAGE EVALUATION TEST TARGET (MT-3)

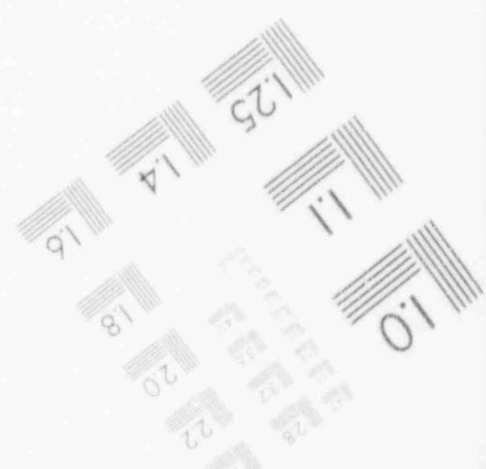












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- "The fatigue effects of cyclic loading forces should be considered in determining the minimum tube wall thickness. The transients considered in the original design of the steam generator tubes should be included in the fatigue analysis of degraded 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)).

  CR-3—This requirement is addressed by the current practice at CR-3 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 CR-3 and others) indicates sufficiently rapid degradation should be expected (e.g., for certain tubes adjacent the open lane with degradation at the top support plate or at the bottom of the top tubesheet). Also, experience (at CR-3 and others) is used to ensure degradation due to fatigue between NDT examinations will not exceed structural allowables.

  In essence, crack growth between tube inspections due to either corrosion or fatigue has not been a problem at CR-3 or other once-through steam generators(OTSGs) with the exceptions of fatigue defects in certain tubes adjacent to the open tube lane near the upper tubesheet and a small number of other incidents where the cause of the degradation has been found and resolved. Since the appropriate "lane" tubes at CR-3 are plugged or sleeved irrespective of size of degradation and since operating experience indicates no significant growth of other degradation, crack growth between inspections is not significant for CR-3. For completeness; however, a fatigue evaluation has been performed for this report.

  Specifically, crack growth due to fatigue is evaluated herein for a worst-case circumferential crack based on a 100% through-wall defect per Figure 2. For this evaluation, the controlling cyclic loads are due to startup/shutdown/operation with little effect from tube vibration (see Reference 6). Based on calculations used for Reference 6 and assuming design basis loads, a crack growth rate of only about .9° of arc length per startup/shutdown/operation load cycle (up to 1107-lb tube tension) is predicted even for the above worst-case crack size per Figure 2. We understand that subsequent to Reference 6, the above design basis load has been increased slightly; therefore, a somewhat greater than (.9°/ cycle) would be calculated. However, the actual expected tube load cycle (more like half the design basis load cycle) would result in essentially no crack growth. Accordingly, such crack growth due to fatigue is not significant since the number of cycles between inspections is not large; and, only small growth rates if any are indicated.

Crack growth due to fatigue between inspections for axial cracks (per Figure 1) can also be evaluated in a similar manner as for circumferential cracks discussed above. Specifically, a worst-case axial crack (maximum length of 1.5 in. per Figure 1) would grow only about .006% through wall per startup/shutdown/operation cycle. Accordingly, such crack growth due to fatigue is not significant since the number of cycles between inspections is not large; and, only small growth rates if any are indicated.

Accordingly, and in overall summary, degradation and crack growth due to corrosion or fatigue between inspections is small (if any) and not significant for CR-3 (based on evaluations herein and operating experience thus far).

- "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)).

  <u>CR-3</u>—This requirement is addressed by an administrative limit requiring shutdown for a leak rate of 0.3 gpm per steam generator. For CR-3, which has not had major tube degradation, this leak rate limit is considered to provide reasonable assurance of tubing structural adequacy as well as being practical, e.g., in terms of detectability. CR-3 experience and other work supports this.

Crack opening displacements and resulting leakages have been analyzed in a number of cases, including for OTSGs such as at CR-3 (see Reference 6). However, experience has shown that sometimes even substantial tube defects do not exhibit much leakage (apparently due to tight cracks being stopped up with magnetite). Accordingly, CR-3 uses an administrative leakage acceptance criteria mentioned above based on engineering judgment and satisfactory past operating experience.

- "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.).

  CR-3—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 Section 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 Section 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 normal operating pressure difference across the tube wall. This is the limiting requirement for normal operating conditions (see calculation in Appendix B); the results of this limit are shown in Figure 1.

For Accident Conditions:

- The tube burst stress should be greater than the pressure difference across the tube wall.

- 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 0.7 ultimate stress requirement is the limiting requirement for accident conditions (see calculation in Appendix A); the results of this limit are shown in Figure 2.

ALLOWABLE TUBE WALL DEGRADATION

Based on the evaluations and calculations herein, the allowable tube wall degradation for various types of degradation of the CR-3 steam generator tubing was determined. The results of the evaluations are summarized in Tables 2-1 and 2-2 and in Figures 1 and 2, based on the calculations presented in Appendices A and B.

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Section 4

REFERENCES

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

2. "Determination of Minimum Required Tube Wall Thickness for 177-FA Once-Through Steam Generators," Babcock & Wilcox, No. 10146. April, 1980.

3. "Review and Update of OTSG Tube Loads, Task 1 Summary," Babcock & Wilcox No. 51-1202303-00, February 28, 1991.

4. "Crystal River Unit 3 Tube Pull Project Summary Report," Attachment 1 to Florida Power Corporation letter to U.S. Nuclear Regulatory Commission—Document Control Desk, dated July 29, 1993.

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. "Assessment of TMI-1 Plant Safety for Return to Service after Steam Generator Repair Topical Report 008, Rev.3, August 19, 1983.

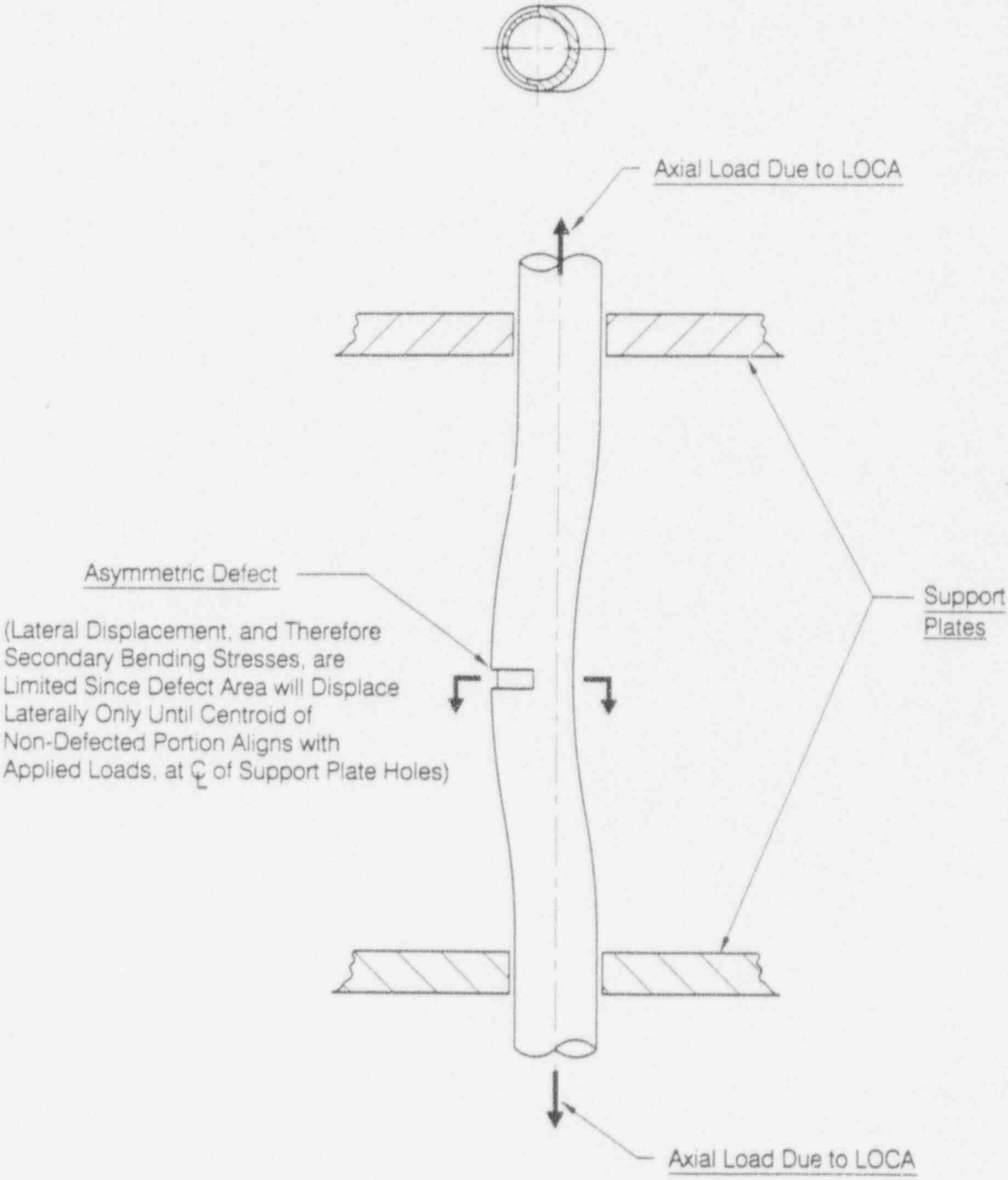

Figure 3. Schematic Load Diagram with Asymmetric Defect Between Supports

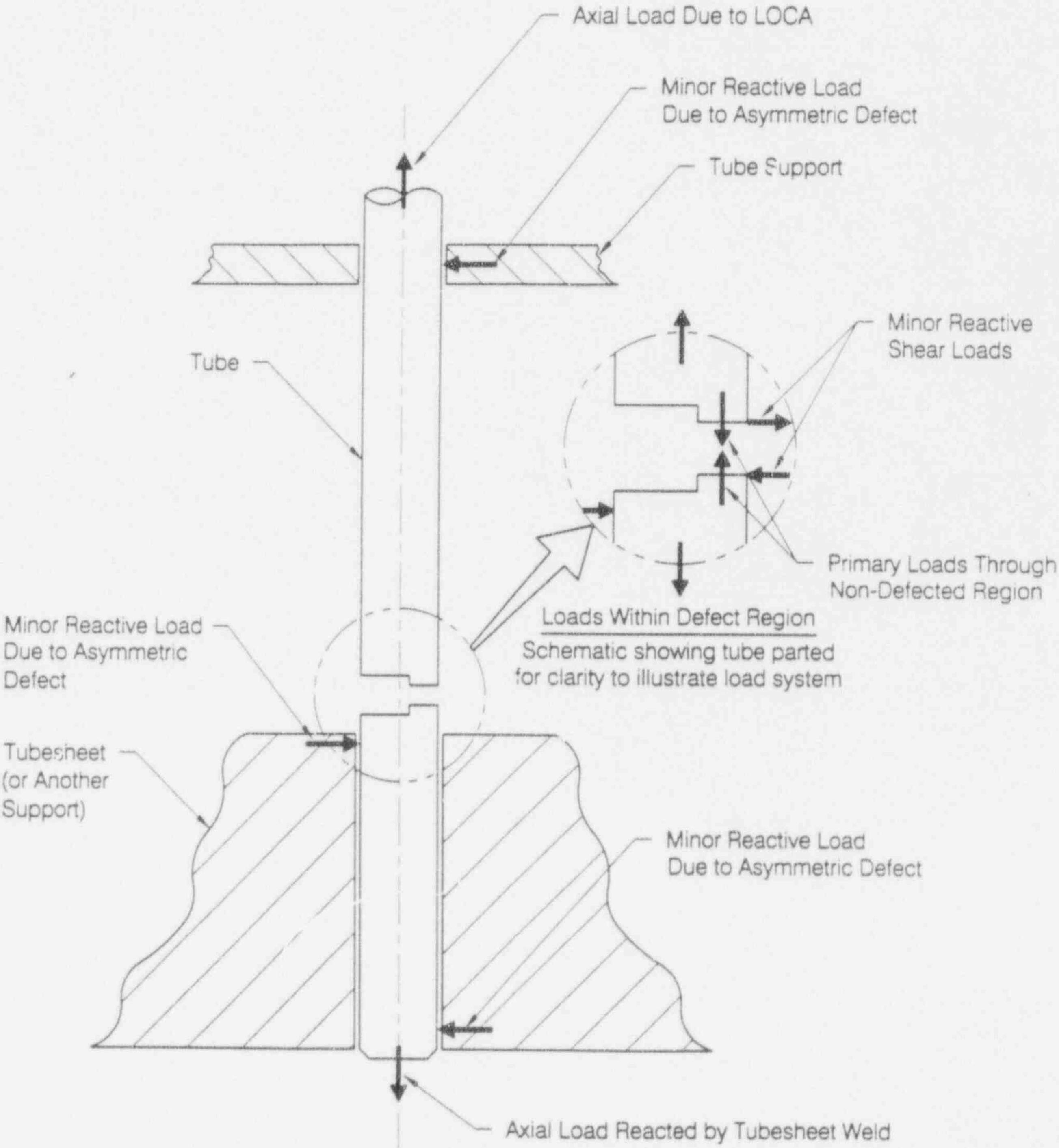

Figure 4. Free Body Schematic Load Diagram for Asymmetric Defect at Top of Tubesheet (or at a Support)

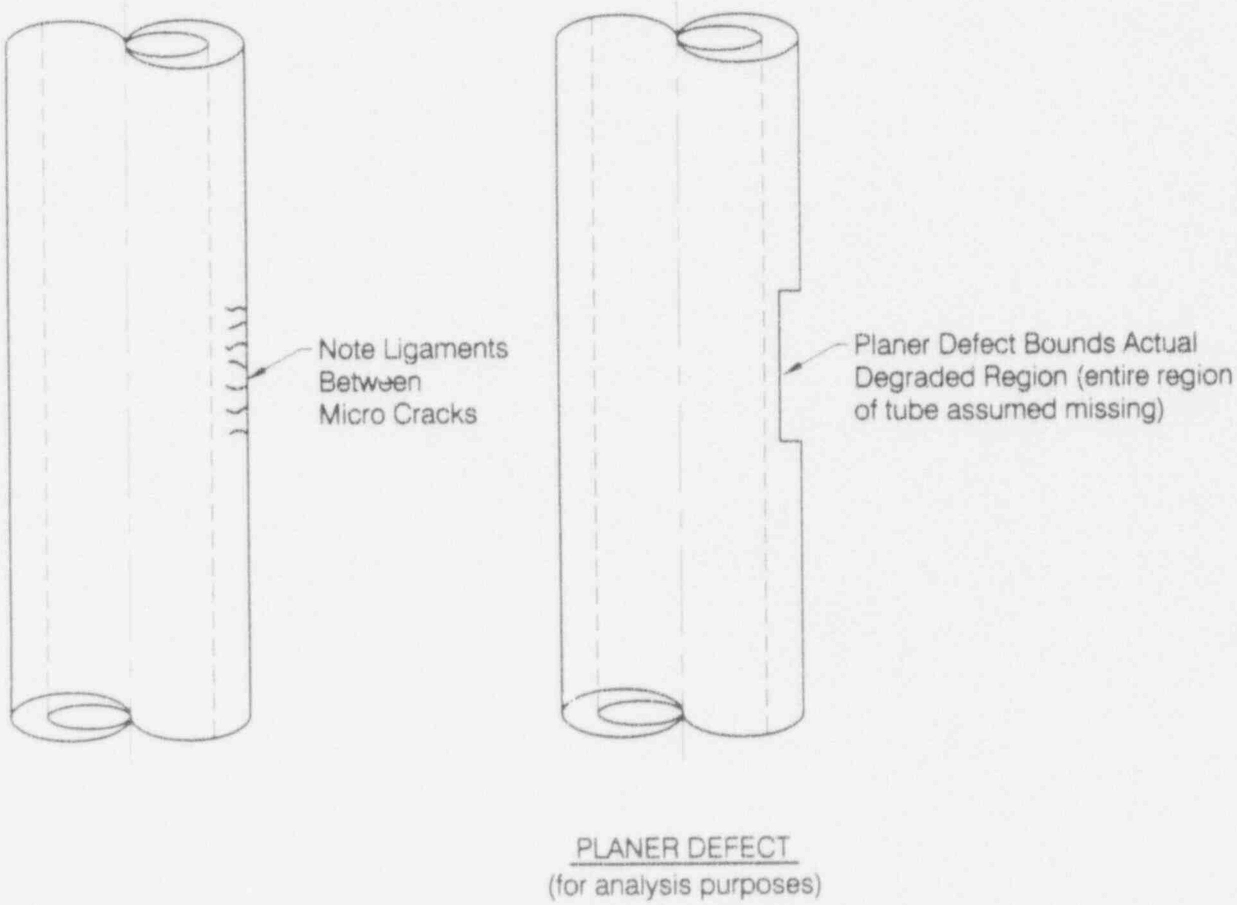

Figure 5. Illustration of Planer Defect Used in Analysis to Conservatively Bound Actual Degraded Region

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Appendix A

**MPR Calculation 102-071-HWM2,
"Allowable Tube Wall Degradation
for 1.5 in. Axial Length, 360° Defects"**

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CALCULATION TITLE PAGE

Client FLORIDA POWER	Page 1 of 14
Project CRYSTAL RIVER UNIT 3 STEAM GENERATOR	Task No. 102-071
Title ALLOWABLE TUBE WALL DEGRADATION FOR 1.5 IN. AXIAL LENGTH, 360° DEFECTS	Calculation No. 102-071-HWM2

Preparer/Date	Checker/Date	Reviewer/Date	Rev. No.
HWMcCURDY 1-14-94	A. ZARECHNAK 1-17-94	A. ZARECHNAK 1-17-94	0

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RECORD OF REVISIONS

Calculation No.	Prepared By	Checked By	Page
102-071-HWM 2	HW McCURDY	A Zarechnak	2

Revision	Description
0	ORIGINAL ISSUE

MPR

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Calculation No.	Prepared By	Checked By	Page
102-071-HWM2	HWMcCURDY	A. Zarechnak	3

SUMMARY

THIS CALCULATION DETERMINES THE ALLOWABLE WALL DEGRADATION FOR CR UNIT 3 STEAM GENERATOR TUBES FOR 1.5 IN. AXIAL LENGTH, 360° CIRCUMFERENTIAL DEFECTS.

BASED ON THE LIMITING REGULATORY GUIDE 1.121 LIMITS AND CODE MINIMUM AND ACTUAL CR UNIT 3 TUBING MATERIAL PROPERTIES, THE REQUIRED WALL AREA AND ALLOWABLE DEGRADATION ARE,

TUBING PROPERTIES	REQUIRED WALL AREA (IN^2)	DEGRADATION (% WALL)
CODE MINIMUM	0.0486	23.0
ACTUAL CR UNIT 3	0.0416	34.1

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Calculation No.	Prepared By	Checked By	Page
102-071-HWM2	HWMcCURDY	A Zarechnak	4

THE PURPOSE OF THIS CALCULATION IS TO DETERMINE THE ACCEPTABLE AMOUNT OF WALL DEGRADATION FOR CRYSTAL RIVER (CR) UNIT 3 STEAM GENERATOR TUBES.

THE CALCULATION CONSIDERS DEGRADATION UP TO 1.5 IN. AXIAL LENGTH AND 360° IN CIRCUMFERENTIAL EXTENT.

THIS CALCULATION CONSIDERS THE FOLLOWING STRUCTURAL LIMITS PER NRC REGULATORY GUIDE 1.121:

A. FOR NORMAL OPERATION:

1. THE TUBE STRESS INTENSITY SHOULD BE LESS THAN THE MATERIAL YIELD STRESS.
2. THE TUBE BURST PRESSURE SHOULD BE GREATER THAN 3x THE NORMAL OPERATING PRESSURE DIFFERENCE ACROSS THE TUBE WALL.

B. FOR ACCIDENT CONDITIONS:

1. THE TUBE BURST PRESSURE SHOULD BE GREATER THAN THE PRESSURE DIFFERENCE ACROSS THE TUBE WALL FOR THE ACCIDENT.

2. THE TUBE STRESS INTENSITY SHOULD BE LESS THAN THE LESSER OF 2.4x THE DESIGN STRESS INTENSITY (S_M) OR 0.7x THE ULTIMATE STRESS.

EACH OF THESE STRUCTURAL LIMITS IS ADDRESSED IN THE FOLLOWING CALCULATION. THE PERTINENT PARAMETERS ARE,

- TUBING OUTSIDE DIAMETER – 0.625 IN. (REF. 2, TABLE 3-4)
- TUBING WALL THICKNESS – 0.034 IN. (REF. 2, TABLE 3-4)
- TUBING MATERIAL – INCONEL 600 (SB163) (REF. 5)
- OPERATING PRESSURE DIFFERENCE – 1350 PSI (REF. 2, PG. 6-3)
- ACCIDENT PRESSURE DIFFERENCE – 2672 PSI (REF. 2, PG. 6-6)
- AXIAL FORCE ON TUBE:
  -- FOR NORMAL OPERATION – 1255 LB (REF. 4)
  -- FOR ACCIDENT – 2641 LB. (REF 4 FOR LOCA)

FOR CODE MINIMUM TUBING PROPERTIES:

FOR LIMIT A.1.

THE AXIAL STRESS IS,

$$\sigma_A = \frac{F_A}{A_R}$$

WHERE,

F_A = AXIAL FORCE ON TUBE, LB

A_R = REMAINING (UNDEFECTED) TUBE AREA, IN^2

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

$$\sigma_R = -\frac{P_I + P_O}{2}$$

WHERE,

P_I = PRESSURE INSIDE TUBE, PSIA

P_O = PRESSURE OUTSIDE TUBE, PSIA

THE PARAMETERS ARE,

F_A = 1255 LB. (SEE PARAMETER LIST ABOVE)

P_I = 2250 PSIA (REF. 2, PG. G-3)

P_O = 900 PSIA (REF. 2, PG. G-3)

THE TUBE STRESS INTENSITY IS,

$$S = \sigma_A - \sigma_R$$

NOTE THAT THE CIRCUMFERENTIAL STRESS IS POSITIVE SO THAT THIS COMBINATION GIVES THE LARGEST STRESS INTENSITY.

$$S = \frac{1255}{A_R} + \frac{2250+900}{2} = \frac{1255}{A_R} + 1575$$

THE YIELD STRESS FOR INCONEL 600 (SB163) AT 600°F (MAXIMUM TUBE OPERATING TEMPERATURE) IS,

$$S_Y = 27.9 \text{ KSI} \quad \text{(SEE REF. 3, TABLE I-2.2)}$$

THE REQUIRED REMAINING AREA IS,

$$A_R = \frac{1255}{27{,}900 - 1575}$$

$$A_R = 0.0477 \text{ IN}^2$$

THE UNDEFECTED TUBE AREA IS,

$$A_o = \frac{\pi}{4}\left(0.625^2 - (0.625 - 2 \cdot .034)^2\right)$$

$$A_o = 0.0631 \text{ IN}^2$$

THE PERCENT DEGRADATION IS,

$$\frac{A_o - A_R}{A_o} = \frac{0.0631 - 0.0477}{0.0631} \cdot 100 = 24.4 \text{ PERCENT}$$

FOR LIMIT A.2.

FROM THE ABOVE PARAMETER LIST, THE REQUIRED BURST PRESSURE IS,

$P_B = 3 \cdot (1350) = 4050$ PSI

BURST TEST DATA IS PROVIDED IN REFERENCE 1 FOR VARIOUS TUBING SIZES. ALTHOUGH THERE IS NO DATA FOR A 0.625 IN. × .034 IN. TUBE WITH A 360° - 1.5 IN. LONG DEFECT, THE DATA FOR A 0.875 IN. × .050 IN. TUBE CAN BE USED SINCE IT HAS A SIMILAR DIAMETER/THICKNESS RATIO.

FROM FIGURE 12 OF REFERENCE 5, THE ALLOWABLE WALL DEGRADATION IS,

$$\frac{A_R - A_O}{A_O} = 62 \text{ PERCENT}$$

THE REMAINING WALL IS 38 PERCENT.

THE REQUIRED REMAINING WALL MUST BE ADJUSTED FOR THE DIFFERENCE BETWEEN THE ULTIMATE STRESS OF THE TESTED TUBING AND THE CODE MINIMUM ULTIMATE STRESS.

FROM TABLE 3 OF REFERENCE 1, THE AVERAGE ULTIMATE STRESS FOR THE TESTED TUBING IS,

$$(S_U)_T = 93.9\ KSI$$

FROM TABLE I-3.2 OF REFERENCE 3, THE CODE MINIMUM ULTIMATE STRESS IS,

$$(S_U)_{CODE} = 80\ KSI$$

SINCE THE REQUIRED REMAINING WALL IS INVERSELY PROPORTIONAL TO THE ULTIMATE STRESS, THE REQUIRED WALL IS,

$$\frac{A_R}{A_O} = 38 \cdot \frac{93.9}{80} = 44.6 \text{ PERCENT (55.4 PERCENT DEGRADATION)}$$

FOR LIMIT B.1.

FOR THE ACCIDENT, THE PRESSURE DIFFERENCE ACROSS THE TUBE WALL IS 2672 PSI (SEE PARAMETER LIST ABOVE). SINCE THIS IS LESS THAN THE 4050 PSI ΔP CONSIDERED ABOVE FOR LIMIT A.2, THE ALLOWABLE DEGRADATION WOULD BE GREATER THAN DETERMINED FOR LIMIT A.2.

FOR LIMIT B.2.

THE AXIAL TUBE STRESS IS,

$$\sigma_A = \frac{2641}{A_R}$$ (SEE PARAMETER LIST)

THE AVERAGE RADIAL STRESS IS,

$$\sigma_R = -\frac{2250+900}{2}$$ (NOTE THAT FOR THE LOCA BOTH THE PRIMARY AND SECONDARY PRESSURES WILL DECREASE. HOWEVER, USE OF THE NORMAL OPERATING PRESSURES IS CONSERVATIVE.)

$$\sigma_R = -1575 \text{ PSI}$$

THE TUBE STRESS INTENSITY IS,

$$S = \sigma_A - \sigma_R$$

$$S = \frac{2641}{A_R} + 1575$$

(AS DISCUSSED IN THE CALCULATION FOR LIMIT A.1 ABOVE, THIS COMBINATION GIVES THE LARGEST STRESS INTENSITY.)

THE ALLOWABLE STRESS IS THE LESSER OF,

$$2.4 S_M = 2.4 \cdot 23.3 \text{ KSI} = 55.9 \text{ KSI}$$ (SEE TABLE I-1.2 OF REF. 4)

$$0.7 S_U = 0.7 \cdot 80 \text{ KSI} = 56 \text{ KSI}$$ (SEE TABLE I-3.2 OF REF. 4)

THE REQUIRED REMAINING AREA IS,

$$A_R = \frac{2641}{55{,}900 - 1575}$$

$$A_R = 0.0486 \text{ IN}^2$$

THE PERCENT DEGRADATION IS,

$$\frac{A_o - A_R}{A_o} = \frac{0.0631 - 0.0486}{0.0631} \cdot 100 = 23.0 \text{ PERCENT}$$

BASED ON THE ABOVE, THE MOST RESTRICTIVE R.G. 1.21 LIMIT IS THAT THE TUBE STRESS INTENSITY FOR ACCIDENT CONDITIONS SHOULD BE LESS THAN 2.4x THE DESIGN STRESS INTENSITY. THE RESULTING ALLOWABLE TUBE WALL DEGRADATION IS 23.0 PERCENT.

FOR ACTUAL CR-3 TUBING PROPERTIES:

FOR LIMIT A.1.

FROM REFERENCE 2, PG. G-3, THE ACTUAL YIELD STRESS AT 600°F IS 34.2 KSI. THE REQUIRED REMAINING AREA IS,

$$A_R = \frac{1255}{34{,}200 - 1575}$$

$$A_R = 0.0385 \text{ in}^2$$

THE ALLOWABLE DEGRADATION IS,

$$\frac{A_o - A_R}{A_o} = \frac{0.0631 - 0.0385}{0.0631} \times 100 = 39.0 \text{ PERCENT}$$

FOR LIMIT A.2.

FROM REFERENCE 2, PG. 6-5, THE ACTUAL ULTIMATE STRESS OF THE CR UNIT 3 TUBING IS,

$$(S_U)_{CR\text{-}3} = 92.9 \text{ KSI}$$

THE ADJUSTED REQUIRED REMAINING WALL IS,

$$\frac{A_R}{A_o} = 38 \cdot \frac{93.9}{92.9} = 38.4 \text{ PERCENT (61.6 PERCENT DEGRADATION)}$$

FOR LIMIT B.1.

THE ALLOWABLE DEGRATION WOULD BE GREATER THAN FOR LIMIT A.2. ABOVE, AS INDICATED ON PG. 9.

FOR LIMIT B.2.

FROM REFERENCE 2, PG. 6-5, THE ALLOWABLE STRESS IS,

$$0.7 (S_U)_{CR\text{-}3} = 65.0 \text{ KSI}$$

THE REQUIRED REMAINING AREA IS,

$$A_R = \frac{2641}{65{,}000 - 1575}$$

$$A_R = 0.0416 \text{ IN}^2$$

THE PERCENT DEGRADATION IS,

$$\frac{A_o - A_R}{A_o} = \frac{0.0631 - 0.0416}{0.0631} \times 100 = 34.1 \text{ PERCENT}$$

BASED ON THE ABOVE, THE MOST RESTRICTIVE R.G. 1.121 LIMIT IS THAT THE TUBE STRESS INTENSITY FOR ACCIDENT CONDITIONS SHOULD BE LESS THAN 0.7× THE ULTIMATE STRESS. THE ALLOWABLE TUBE WALL DEGRADATION IS 34.1 PERCENT.

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Calculation No. 102-071-HWM 2	Prepared By HW McCurdy	Checked By A. Zarechnak	Page 14

REFERENCES:

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

2. BAW-10146, "DETERMINATION OF MINIMUM REQUIRED TUBE WALL THICKNESS FOR 177-FA ONCE-THROUGH STEAM GENERATORS," BABCOCK + WILCOX, APRIL 1980.

3. ASME SECTION III, 1989 EDITION, DIVISION 1, APPENDICES.

4. B+W NUCLEAR TECHNOLOGIES DOCUMENT 51-1202303-00, "REVIEW AND UPDATE OF OTSG TUBE LOADS, TASK 1 SUMMARY," 2/28/91 (SEE TABLE 1).

5. CRYSTAL RIVER UNIT 3 FINAL SAFETY ANALYSIS REPORT, TABLE 4-9.

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Appendix B

MPR Calculation 102-071-HWM1, "Allowable Tube Wall Degradation for Axial, Slot-type Defects"

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CALCULATION TITLE PAGE

Client	
FLORIDA POWER	Page 1 of 8

Project	Task No.
CRYSTAL RIVER UNIT 3 STEAM GENERATOR	102-071

Title	Calculation No.
ALLOWABLE TUBE WALL DEGRADATION FOR AXIAL, SLOT-TYPE DEFECTS	102-071-HWM1

Preparer/Date	Checker/Date	Reviewer/Date	Rev. No.
HW McCURDY 1-12-94	A. ZARECHNAK 1-17-94	A. ZARECHNAK 1-17-94	0

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RECORD OF REVISIONS

Calculation No.	Prepared By	Checked By	Page
102-071-HWM1	HW McCurdy	A. Zarechnak	2

Revision	Description
0	ORIGINAL ISSUE

MPR	MPR Associates, Inc. 320 King Street Alexandria, VA 22314		
Calculation No. 102-071-HWM 1	Prepared By HW McCORDY	Checked By A. Zarechnak	Page 3

SUMMARY

THIS CALCULATION DETERMINES THE ALLOWABLE TUBE WALL DEGRADATION FOR CR UNIT 3 STEAM GENERATOR TUBES FOR AXIAL, SLOT-TYPE, OUTSIDE-DIAMETER INITIATED DEFECTS. THE REQUIRED REMAINING WALL AND ALLOWABLE WALL DEGRADATION FOR TUBE MATERIAL ULTIMATE STRESSES OF 80 KSI (CODE MINIMUM) AND 92.9 KSI (ACTUAL FOR CR UNIT 3 TUBING) ARE,

DEFECT	ULTIMATE STRESS (KSI)	REQUIRED WALL (IN.)	DEGRADATION (% WALL)
1/4" SLOT	80	.0046	86.3
	92.9	.0040	88.2
1/2" SLOT	80	.0133	60.1
	92.9	.0117	65.6
1 1/2" SLOT	80	.0157	53.8
	92.9	.0135	60.3

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102-071-HWM1	HWMcCURDY	A. Zarechnak	4

THE PURPOSE OF THIS CALCULATION IS TO DETERMINE THE ALLOWABLE WALL DEGRADATION FOR CRYSTAL RIVER (CR) UNIT 3 STEAM GENERATOR TUBES FOR AXIAL, SLOT-TYPE, OUTSIDE-DIAMETER (OD) INITIATED 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 DIFFERENCE IN THE MATERIAL ULTIMATE STRESS BETWEEN THE TESTED TUBING AND THE CR UNIT 3 STEAM GENERATOR TUBING.

BURST PRESSURE RESULTS FOR 0.625 IN. × .034 IN. TUBING ARE SHOWN IN FIGURE 28 OF REFERENCE 1. (CR UNIT 3 TUBING IS THE SAME 0.625 IN. × .034 IN. PER REFERENCE 2, TABLE 3-4). FIGURE 28 IS

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SHOWN BELOW INCLUDING "BEST-FIT" STRAIGHT LINES FOR 1/4", 1/2" AND 1 1/2" SLOT-TYPE DEFECTS.

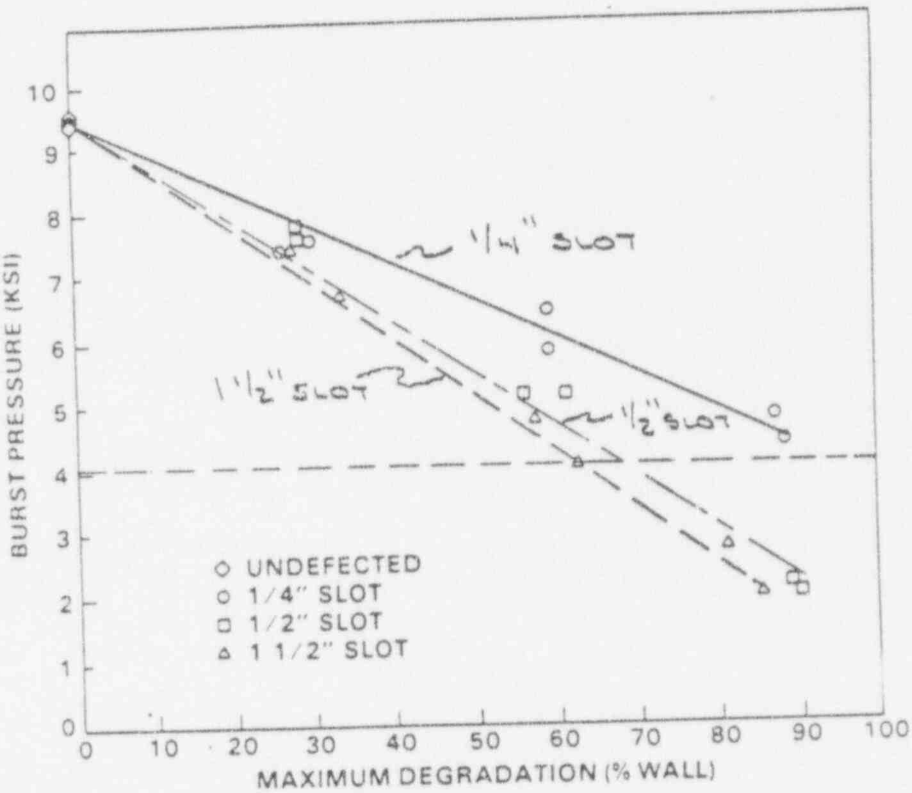

FIGURE 28. Burst Pressures for 0.625 x 0.034 in. EDM Slots

FROM THE ABOVE FIGURE FOR A BURST PRESSURE OF 4050 PSI (FROM REFERENCE 2, PAGE 6-3) THE ALLOWABLE DEGRADATION AND REMAINING WALL THICKNESS ARE,

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DEFECT	DEGRADATION (% WALL)	REMAINING WALL (% WALL)	REMAINING WALL (IN)
1/4" SLOT	89*	11	.0037
1/2" SLOT	68	32	.0109
1 1/2" SLOT	63	37	.0126

* THIS IS THE LARGEST DEGRADATION FOR WHICH BURST PRESSURE DATA IS PROVIDED IN FIGURE 28. FOR THIS TEST POINT, THE BURST PRESSURE IS 4300 PSI AND THEREFORE ITS USE IS CONSERVATIVE.

FROM TABLE 3 OF REFERENCE 1, THE TUBING USED FOR THE BURST TESTS HAD AN AVERAGE ULTIMATE STRESS OF 99.8 KSI. FROM TABLE I-1.2 OF REFERENCE 3 FOR INCONEL 600 (SB163)* TUBING, THE ASME CODE MINIMUM ULTIMATE STRESS IS 80 KSI. FROM REFERENCE 2 (PAGE 6-5), THE ACTUAL ULTIMATE STRESS OF THE CRUNIT 3 TUBING IS 92.9 KSI. SINCE FOR A GIVEN BURST PRESSURE, THE WALL THICKNESS WOULD BE INVERSELY PROPORTIONAL TO THE

* SEE REFERENCE 4

TUBING ULTIMATE STRESS, THE REMAINING WALL THICKNESS VALUES GIVEN IN THE PRECEDING TABLE MAY BE ADJUSTED FOR THE CODE MINIMUM OR ACTUAL MATERIAL ULTIMATE STRESSES. THESE ADJUSTED WALL THICKNESSES ARE GIVEN IN THE FOLLOWING TABLE.

DEFECT	ULTIMATE STRESS (KSI)	REQUIRED WALL (% WALL)	(IN)
1/4" SLOT	80	13.7	.0046
	92.9	11.8	.0040
1/2" SLOT	80	39.9	.0136
	92.9	34.4	.0117
1 1/2" SLOT	80	46.2	.0157
	92.9	39.7	.0135

REFERENCES:

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

2. BAW-10146, "Determination of Minimum Required Tube Wall Thickness for 177-FA Once-Through Steam Generators," Babcock + Wilcox, April 1980.

3. ASME Section III, 1989 Edition, Division 1, Appendices.

4. Crystal River Unit 3 Final Safety Analysis Report, Table 4-9.

APPENDIX C

MPR STATISTICAL ANALYSIS