GPU Nuclear

TECHNICAL DATA REPORT

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DOCUMENT TITLE Basis for Revised Plugging and Stabilizing Criteria for OTSG Tubes

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ABSTRACT

Problem Statement
Recent ECT inspection has identified indications not previously seen in 1982. Additional mechanical analysis of flawed tubes since the development of the original tube plugging and stabilizing criteria provides the basis for a revision.

Result
A revised tube plugging and stabilizing criteria is developed here. The revised criteria will be applied to disposition tubes with indications identified in the recent and future ECT examination.

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TMI-1 Basis for Plugging and Stabilizing Criteria for OTSG Tubes

I. Statement of the Problem

Recent ECT inspection, performed as required by Technical Specifications, has identified indications not seen in 1982. New chemical attack is not the cause, as is discussed elsewhere (Ref. 1). Mechanical factors, enabled enhanced ECT detectability of previously initiated defects.

Additional evaluation of earlier mechanical analyses of flawed tubes (performed in evaluating the 1981 tube cracking) provide the basis for tube plugging and stabilization criteria. These plugging and stabilizing criteria are developed here. The tube plugging and stabilizing criteria will be used to disposition tubes with indications identified in the recent (11/84) and future ECT examinations.

II. Methods of Analyses

A. Plugging Criteria

Several existing analyses of the serviceability of flawed tubes under normal, transient, and accident conditions were considered. These analyses included ASME Section III and Section XI fatigue evaluations and a solid mechanics single accident load analyses conducted as part of GPU Nuclear's response to the 1981 tube cracking experience. Also considered was the Babcock and Wilcox ASME Section III evaluation used to support the original generic evaluation of OTSG tubing satisfies Reg. Guide 1.121.

GPUN's evaluation combines the methodology of both ASME Sections III and XI in order to obtain the widest range of solutions for the reduction in fatigue resistance caused by identified or hypothetical ECT indications whether they are intergranular attack (IGA) or intergranular stress assisted cracking (IGSAC) in origin.

1. ASME Section III

ASME Section III provides guidance for designing nuclear pressure components against failure. This ASME design criteria is based on several layers of conservatism (Ref. 2). ASME fatigue data is corrected to account for the difficulty in computing residual stress in complex welded pressure vessels. The correction for this effect is to shift the curve to the left a factor of 20 on cycles and downward a factor of 2 on stress. Because OTSG tubes are not welded nor complex in the free span then the utilization of Figure I.9.2 of Section III, Appendices (Figure I) is conservative. This fatigue failure analysis, Sectoin III, uses crack initiation as criteria for loss of fatigue resistance of the material, therefore designs using this approach insures only a degraded material condition and not outright structural failure.

The approach used to enter the design fatigue curve was originally discussed in TDR 421 (Ref. 3) and as summarized in TR 008 (Ref. 12), the document on which the OTSG tube plugging and stability criteria is partly based. Treating the indication as a straight-sided notch and using the methods of solid mechanics, it is possible to derive an equation for axial stress range as a function of crack length and depth. The applied loading was axial force and flow induced vibration combined as appropriate, for a Section III evaluation (Section VIII, Part D, Appendix A, Ref. 3). The allowable stress for 240 Heatup/Cooldown cycles anticipated in 40 years of service (design basis) from the design fatigue curve is reduced by a fatigue strength reduction factor (FSRF) equal to 5.0 due to stress concentration.

2. ASME Section XI

ASME Section XI provides guidance for evaluating the impact of suspected flaws in pressure retaining components inservice. The methods of linear elastic fracture mechanics (LEFM) are recommended. In this approach the presumed crack is analytically interacted with the local stress field in order to predict enlargement and propagation as service loads (both mechanical and thermal) are cycled in the anticipated manner. Since the data base predicts the material response more closely than Section III, this analysis is more exact. The range over which the analytical fracture mechanics solutions are available is narrower than that covered by solid mechanics for Section III.

As discussed previously (Ref. 4), a particular fracture mechanics solution was used by GPUN in order to properly model the response of a thin tube to the presence of an I.D. circumferential crack under applied axial load, internal pressure, and bending stress due to flow induced vibration. The aim of the analysis in Ref. 4 was to demonstrate the adequacy of the threshold of ECT detection sensitivity. The results of that analysis also satisfy the Section XI flaw acceptance criteria (above) when integrated with the results of the MSLB analysis, also in the same reference.

3. Main Steam Line Break

The rupture strength of a flawed tube to the maximum axial load, applied one time only, is evaluated under the faulted condition of a main steam line break (MSLB). The tube response is analyzed by methods of solid mechanics capturing the increased flexibility of the tube at the elevation of the flaw and utilizing the flow stress as the limiting material condition (Ref. 4). The flow stress reflects the load at which the gauge length of a test specimen departs from a uniform strain response, i.e., the onset of localized necking. The flow stress is less than the ultimate tensile strength and occurs at much less than total strain at rupture.

4. The above methods, addressing plugging only, provide the framework for the results described below.

B. Stabilizing Criteria

The need to stabilize a plugged tube is based on an analysis of tube vibration characteristics. Those areas in the steam generator where high cross flow would occur are first identified. The vortex shedding frequency is calculated in each span of concern and compared to the analytical fundamental frequency to see if a resonant condition is possible. Vibration amplitudes of a few configurations (unsevered, stabilized severance in the T/S and in the 16th span) are calculated and form the basis for determining whether wear of neighboring tubes can be expected due to cross-flow.

III. Results

A. Plugging and Stabilizing Criteria

The plugging and stabilizing criteria for the disposition of 11/84 OTSG tube ECT indications are shown in Figure 2 and Table 1. This criteria is an envelope around previously presented analyses. A fracture mechanics analysis using ASME, Section XI methods, was reported in Reference 4. An ASME, Section III evaluation, was reported in Reference 3 and as summarized by TR 008 (Ref. 12). The results of these analyses are shown in Figure 3. The criteria of Figure 2 bound the Section XI LEFM results, Section III fatigue evaluation, and the MSLB solid mechanics analysis.

The plugging and stabilizing criteria also address the problem of disposition of multiple indications located within a 1" axial region. The indications within this region can be combined to find an equivalent size. The method of combination is derived out of recognition of the structural impact of both circumferential (in the sense of cross-influence) and axial flaw alignment (See Note 1 of Table 1).

Where an unacceptable analytical result for 40 years of service is obtained the tube is removed from service by plugging and then stabilized through the span of the indication when necessary. The flaw is characterized by penetration (percent throughwall), using the .540 standard differential probe at high gain and by circumferential extent (arc length) using the (8x1) absolute probe.

Stabilization, in general, is intended to mitigate the consequences of wear on adjacent active or plugged tubes, which could occur following the severance of a tube. Retention of a minimum of 4" of unexpanded tube within the tubesheet allows plugging without stabilizing.

Lane/Wedge tubes are treated separately. High cross-flow local to these tubes is a concern for all tube spans. Historically, the industry has seen more problems in this area than in any other. Consequently, all pluggable indications are stabilized through to the span of the indication.

The following is a discussion of margin of safety either inherent in the analytical methods and the ECT detection method or added as additional conservatism.

B. Margins of Safety

The governing condition for margin of safety for existing Technical Specifications occurs when approaching the 360° circumferential defect and up to 40% throughwall. This was previously summarized in TR 008, Section IX, Part D (Ref. 12), in Figure 1 of TDR 388 (Ref. 4) and approved by NUREG 1019, page 12 (Ref. 13). The plugging and stabilizing criteria of this TDR is superimposed against the serviceability of flawed tubes analyses in Figure 4. It is clear from this figure that the limiting analyses for the existing licensing basis is Main Steam Line Break (MSLB).

It has been previously pointed out that MSLB is conservative since the structural limit is taken to be the flow stress of the material rather than rupture stress. In addition, this approach also accounts for a thermal stress resulting from the MSLB which according to ASME Section III, NB-32213.9 does not result in failure after one application. Because of the ductility of the structure (OTSG tubes) thermal stress is strain limited and therefore applied load goes down as the more flexible part of the structure (tubes) elongate. Both considerations continue to justify the acceptability of the MSLB analysis.

The criteria of this TDR does not alter the licensing basis for existing Technical Specification. For each coil the margin separating the fatigue analysis results and the criteria of this TDR is ten percentage points (10%) on throughwall.

The limiting margin of safety approved by the NRC is not affected or reduced. Therefore, the probability of occurrence of an accident or malfunction is not increased.

1. <u>Plugging Criteria</u>

   a) ASME Section III: Analytical Margin

      The prescribed Section III methods and material performance data base are intended to be conservative. For the type of material and condition of TMI-1 OTSG's certain aspects of Section III analytical methods provide additional conservatism:

      (1) Thumb nail cracks were modeled as full rectangular notches. For the same percent throughwall indication the model assumes more material is missing from the cross section than actually exists.

      (2) A fatigue strength reduction factor equal to 5.0 is conservatively applied before using the code data base.

      (3) Forty years of anticipated service is the period over which the loading is applied. The technical specifications are interested in growth between inspections only, thus a number of inspection cycles could have been used less than the 240 design number.

      (4) Crack appearance is taken as a failure in the analysis whereas tube severance is the structural concern, providing additional conservatism.

(b) ASME Section XI: Analytical Margin

LEFM is a conservative method for evaluating propagation of part through wall cracks in steam generator tubes. 10 CFR 50.55a(g) requires in-service nuclear power plant components be inspected and evaluated according to the methods of ASME, Section XI. The LEFM method has been successfully applied throughout the industry.

(c) ECT Detection Margin

The sensitivity of an 8x1 absolute probe has been demonstrated to detect a notch of 80% through wall extent by 0.194" arc length on a single coil. (Ref. 5). Anything larger would appear on more than one coil. Therefore, multi-coil calls are possibly overcalls. Treating all multi-coil calls, for purposes of analysis, as always coinciding in arc length with the 8x1 identification, is conservative.

d) Margin with axial alignment

The 1984 higher voltage .540 SD results, coupled with single (8x1) coil response may be indicative of axial alignment within an IGA patch.

The axial and circumferential alignments, can be treated independently analytically because each is acted on by a different principle stress. By comparison, the stress intensity for an axial throughwall crack in a pressurized OTSG tube is less than that for the same size circumferentially oriented crack under axial load. The results obtained for circumferential through wall cracks bound those for similar sized axial cracks, formed out of IGA link-up.

For IGA patches, the axial dimension is generally comparable to the circumferential component on the surface (Ref. 1). Even though the axial component would be predicted to propagate more slowly than the circumferential component, potential consequences of axial progation were also considered. Severance of a tube by axial growth is not possible, but leakage up to that predicted for severence due to a circumferential flaw, could occur if the axial flaw were large enough. Since leakage from an axially-oriented defect would not be load-dependent, a small through wall defect, propagating axially, would be detectable by leakage long before reaching a size comparable to a double ended rupture. Leakage detection, by present leakage monitoring equipment and off-line primary-to-secondary leakage assessment procedures (Ref. 11), will detect Primary to Secondary leakage through an axial defect in the same way as for circumferential cracks.

e) Margin due to residual structural strength

It is of interest to note that severe pitting in steam generator tubes did not significantly reduce steam generator burst strength. This was demonstrated by a pressure test of an actual pulled tube specimen that exhibited 83% TW ECT indication while in the generator. "This tube exhibited a burst pressure in excess of 9000 psi, which is close to the strength of as-manufactured tubing and indicative of the high residual strength associated with even severely pitted tubes" (Ref. 8). GPUN also performed a pull to rupture test on a OTSG tube specimen with a known crack (Ref. 3). The rupture of the tube occurred in a ductile manner. This demonstrated that tubes have high structural strength even with the presence of cracks. These tube tests continue to support the residual structural margin.

f) Results of Babcock and Wilcox Analysis Performed to Guidelines of Reg. Guide 1.121

Analyses for patches of mechanical wear are applicable to the present situation.

Mechanical wear was considered in previous B&W work (B&W 10146, Ref. 6) performed which satisfies Reg. Guide 1.121 (Ref. 7). A comparison of B&W 10146 with the GPUN analyses of this TDR demonstrates that this plugging criteria is reasonable because of the similarity of the two results.

Table 2, which is identical to Table 6-3 in Ref. 6, shows that the usage factor for a 79% throughwall defect evaluated for an inspection period of 40 months is much less than one. (It should be noted that a usage factor equal to 1 signals that the fatigue limit has been reached.) This fatigue evaluation used design basis anticipated transients such as heat-ups, cool-downs, and load changes. Based on the Technical Specification OTSG inspection frequency, the results of the plugging criteria of this TDR bound the B&W results.

It is important to note that while the Primary-Plus-Thermal allowable defect depth is >70%, when in fact it can be shown to be larger. This is because a secondary (thermal) stress is involved and as indicated in ASME Sect. III, NB-3213.9 (ASME, Sec. III) one application of a secondary stress is not expected to cause failure. These results are developed for tube OD defects which, after removal and laboratory examination, are characterizable as erosion/corrosion or wear over an area of 1.5" axially and 45° circumferentially. The present circumferential indications are within the bounds of this analysis. It is conservative to do this. Reduction in fatigue resistance and load carrying capacity were addressed by using the appropriate axial load associated with each transient. As pointed out in B&W 10146, their results do not include allowances for inspection technique inaccuracies or for defect growth rate.

2. Stabilizing Criteria
Analytical Results

Analytical prediction of radial velocity during steady-state operations has become available (Ref. 9). The THEDA computer code, a Babcock and Wilcox 3D thermal hydraulic code, provided radial cross velocities including the effects of the current plugging pattern. Only the inlet, operating, and steam dome regions are significant. Results are shown in Table 4. These results allow the conclusion that FIV of an intact tube is significant only in one (steam dome) region of those where cross-flow is likely to occur.

Recently, B&W calculations have identified the vortex shedding frequencies in these zones as well as the natural frequency of our unflawed tube, including cross span effects (Ref. 10). Vibration amplitudes were also calculated for the worst case. These results are given in Table 5. These results do not change significantly even when the displacements for the first 20 modes are combined.

These results indicate that it is only important to stabilize the 16th span against flow induced vibration (FIV) due to cross-flow. In terms of potential to wear neighboring active or plugged tubes, upper span tubes are stabilized not only because of the high energy imparted to the severed ends by the cross-flow, but also because of the absence of the mitigating effect of damping that is gained if a severance occurs in the liquid phase (at a lower span) as opposed to superheated steam, as in the top span. Margin is obtained by stabilizing a pluggable tube all the way through the span of the indication.

A severed tube could conceivably wear against neighboring tubes even in regions of low cross flow. High axial velocity in the region can be expected. The ends of a severed plugged tube will be driven by turbulent parallel flow. Each of the severed ends is driven by a different forcing function. The principal difference is the orientation of the severed end with respect to the parallel flow. The lower piece moves like a string. The upper part presents a high drag cross-section to the flow and behaves differently.

Also, it is evident from these results that Connor's instability in the 16th span will not cause wear of neighboring tubes. A minimum of 4" of unexpanded tube within the tubesheet is required to provide that a severance will not wear neighboring tubes (Ref. 3).

Therfore stabilizing plugged tubes provide assurance of structural integrity of neighboring plugged or inservice tubes.

IV. Comparison with Previous Criteria

Table 6 provides a basis for comparison between the plugging and stabilizing criteria of TR 008 Ref. 12 to the criteria in this TDR. As stated in TR 008, less than 40% TW indications which are also two coils or less are acceptable except if the indications are in the upper span in which case the tube is taken out of service and stabilized. Tubes with greater than 40% TW indications and more than 2 coils on the absolute probe are plugged and stabilized to the span of the defect. Tubes with greater than 40% TW indications but with 2 coils or less are plugged only if the indication elevation is between the 15th SP (support plate) to LS-4. Tubes with indications less than 40% TW but larger than 2 coils are taken out of service by plugging only as specified by Table 6.

Using the criteria of this TDR tubes in the lane/wedge area are taken out of service by plugging and stabilizing, through the span of indication if the indications equal or exceed 40% TW.

Additionally, multiple indications are addressed in the revised criteria. Indications located within a 1" axial region centered at an indication, are combined in a fashion to maximize arc length out of consideration of axial interaction (one on the other in a circumferential sense). The combination rule is also intended to be an envelope around possible axial link-up (Note 1 of Table 1).

Safety Analysis using 10 CFR 50.59

10 CFR 50.59 provides that unreviewed safety questions do not arise if a change does not introduce a new accident, increase the probability of an accident occurring or increase its consequences, or decrease the licensed margin of safety.

It is maintained that no unreviewed safety questions are involved in the plugging and stabilizing criteria presented here. In fact, there are no new issues of any kind. Enhanced detectability of IGA initiated at the time of the original chemical event has lately enabled the indentification of additional indications. These indications are of a size not previously visible by ECT. GPUN had previously demonstrated that such indications were of a size that did not need to be plugged or stabilized. Thus it has already been demonstrated that no safety considerations require that they be removed from service.

While the proposed plugging criteria represent a new application of the previous analyses, their validity is unchanged. This criteria provide for 40 years of service. At the same time, the bases for procedural action levels after the detection of primary-to-secondary leakage is unchanged (Ref. 11). It should be noted that leak detection capability and procedures provide operational safety protection.

Structural resistance to accident loads is not reduced.

This evaluation does not provide results which reduce margins of safety. An accident is no more likely. The consequences of an accident are not greater having applied the plugging and stabilizing criteria than they were with the original criteria.

References

1. TDR 638, J. Janiszewski, "Evaluation of Eddy Current Indications Detected During the 1984 Tech Spec Inspection", Jan. 11, 1985.

2. Background of the Factors of Safety Used in Divisions 1 of Sections III and XI of the ASME Rules for Nuclear Vessels, prepared for the ASME Section XI Special Working Group on Operating Plant Criteria by W.E. Cooper, 10/84.

3. TDR 421, TMI-1 Steam Generator Adequacy of Tube Plugging and Stabilizing Repair Criteria, March 1983

4. TDR 388, Rev. 3, Mechanical Integrity Analysis of TMI-1 OTSG Unplugged Tubes, May 1983

5. TDR 401, Task IV Report on Eddy Current Indications Found Subsequent to Kinetic Expansion of TMI-1 OTSG Tubes, 4/83.

6. BAW Report 10146, Determination of Minimum Required Tube Wall Thickness for 177-FA Once Through Steam Generators, 1980.

7. Regulatory Guide 1.121, Basis for Plugging Degraded PWR Steam Generator Tubes, 8/76.

8. NUREG 1063, Steam Generator Operating Experience Update, 1982-1983, by L. Frank

9. IOM, N.G. Trikouros to S.D. Leshnoff, OTSG Cross-flow Velocities, SAPC-265, 11/28/84.

10. Babcock and Wilcox Document No. 51-114-1502-00, 177FA OTSG Flexible Stabilize Design Verification Report, B&W Proprietary, March 1984.

11. TDR 624, "Bases for Procedural Action Levels Concerning Measured Primary-To-Secondary Leakage", November 1984.

12. T.M. Moran, "Assessment of TMI-1 Plant Safety for Return to Service After Steam Generator Repair," GPUN Topical Report 008, Rev. 3, August 19, 1983.

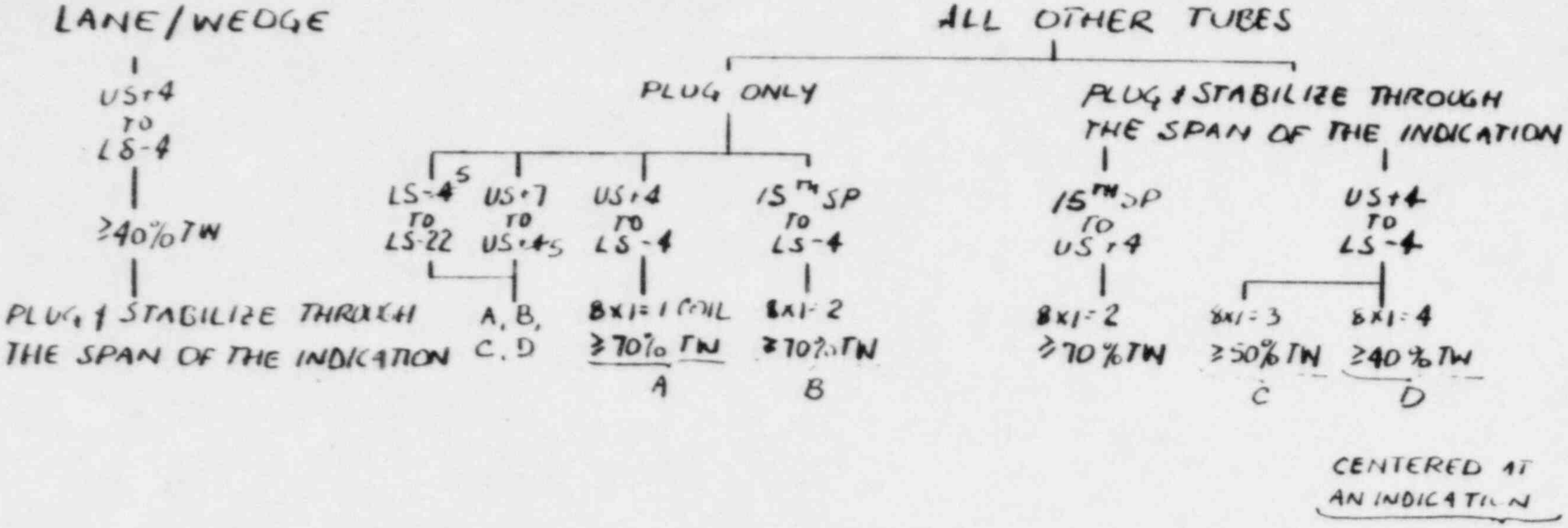
13. NUREG 1019, Supplement 1, "Safety Evaluation of TMI Unit 1 Steam Generator Tube Repair and Return To Operation."

GPU Nuclear Calculation Sheet

Subject PLUGGING & STABILIZING OTSG TUBES
Calc No TDM E&D/TMI-2010
Rev No 1
Sheet No ATT 2 of 2
Originator SD LESHNOFF
Date 1/17/85
Reviewed by
Date

TDR 645

DISPOSITION OF OTSG TUBES WITH ECT INDICATIONS



NOTE: 1. THE EQUIVALENT SIZE OF MULTIPLE INDICATIONS LOCATED WITHIN A 1" AXIAL REGION IS OBTAINED BY USING THE MAXIMUM DEPTH OF ANY INDICATION AND THE SUM OF THE INDIVIDUAL ARC LENGTHS, BY (8x1), AS THE CIRCUMFERENTIAL EXTENT, NOT TO EXCEED FOUR COILS.

2. STABILIZING GUIDANCE IS FOR MINIMUM STABILIZER LENGTH. IT IS RECOMMENDED THAT THE STABILIZER EXTEND TO THE NEXT SUPPORT PLATE BEYOND THE SPAN OF THE INDICATION.

TABLE 1

Calculation of Fatigue Usage Factor Based on 79% Through-Wall Defect

		S_{12} stress differences				
Stress cycle	n	Maximum	Minimum	S_{alt}[a]	N[b]	n/N
1	17	22,653	-61,256	186,781	190	0.0895
2	1	22,653	-57,886	179,280	220	0.0045
3	74	-42,471	-57,886	34,314	2.2×10^5	0.0003
4	1	-47,443	-57,886	23,240	$>10^6$	0.0
5	2804	-47,443	-55,368	17,641	$>10^6$	0.0028
6	12.5	-47,443	-47,443	0	∞	0.0
					Usage =	0.097

[a] $S_{alt} = \frac{26.0 \times 10^6}{29.2 \times 10^6}(5)(\frac{1}{2})$ (stress difference range).

[b] From Figure I-9.2 of reference 11.

TABLE 2

Allowable Depths for OTSG Defects

Criterion	Minimum thickness, in.	Defect depth, % of wall in 0.0375-in. tube	Critical accident condition
Normal Operation			
$P_m \le S_y$	0.0114	70	--
$3\Delta p \le p_b$	0.0103	73	—
$\left\{\begin{array}{l}\Delta(P_m + P_b + Q) \le 3S_m \\ \text{usage factor} \le 1.0\end{array}\right\}$	<0.0079	>79	—
Faulted Conditions			
$P_m \le 2.4S_m,\ 0.7S_u$	0.0116	69	FWLB
$\Delta p \le p_b$	0.0046	88	FWLB
$\Delta p \le 0.9p_c$	<0.0050	>85	LOCA
$P_m + P_b \le 3.6S_m$	<0.0079	>79	FWLB + SSE
Primary Plus Thermal			
$\left(\frac{\Delta p}{p_b}\right)^2 + \left(\frac{P_{ax}}{P_u}\right)^2 \le 1$	<0.0114	>70	MSLB

Note: Nomenclature not specifically defined in this section is from the ASME Boiler and Pressure Vessel Code.

TABLE 3

Table 4

OTSG Radial Velocity (as plugged)

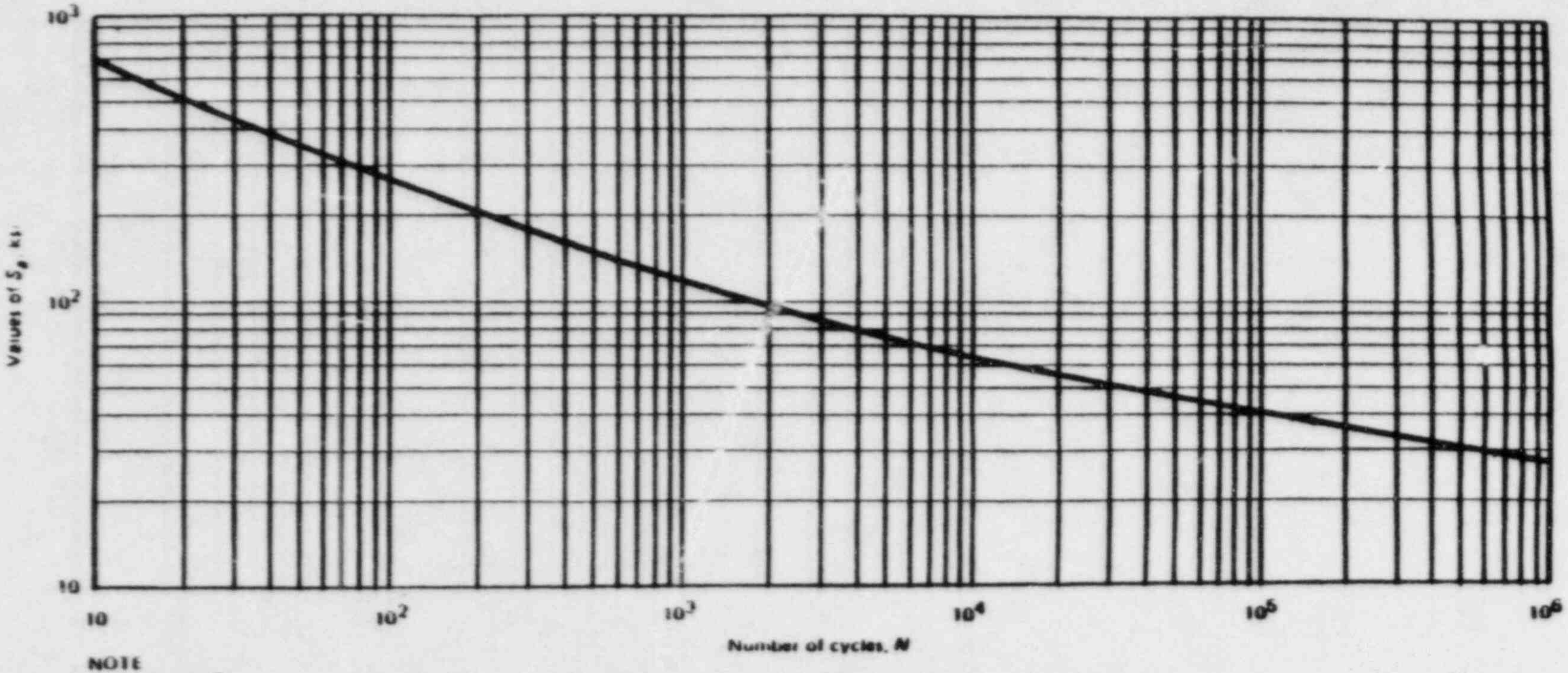
Lane Tubes

Elevation 4[ft.]	Peripheral [ft./sec.]	Core [ft./sec.]
Inlet	0.395	3.5
32 Aspirator	2.69	1.1
54 Steam Dome	51.4	3.87

Table 5

Span	Vortex Shedding Frequency (Hz)
16	39.4
10	4.6
1	5.4

Tube Configuration	Analytical Frequency	Amplitude of Vibration (0-peak, inches)
Tube only	42.2	0.026
Laminated stabilizer, T/S severance	20.2	0.041
Laminated stabilize, severance at 15th lateral support plate	26.8	0.041



NOTE
E = 28.3 × 10^6 psi

FIG. I-9.2.1 DESIGN FATIGUE CURVE FOR AUSTENITIC STEELS, NICKEL–CHROMIUM–IRON ALLOY, NICKEL–IRON–CHROMIUM ALLOY, AND NICKEL–COPPER ALLOY FOR $S_a > 28.2$ ksi, FOR TEMPERATURES NOT EXCEEDING 800°F
(For $S_a \leq 28.2$ ksi, use Fig. I-9.2.2.)
Table I-9.1 Contains Tabulated Values and a Formula for Accurate Interpolation of This Curve

FIG. 1

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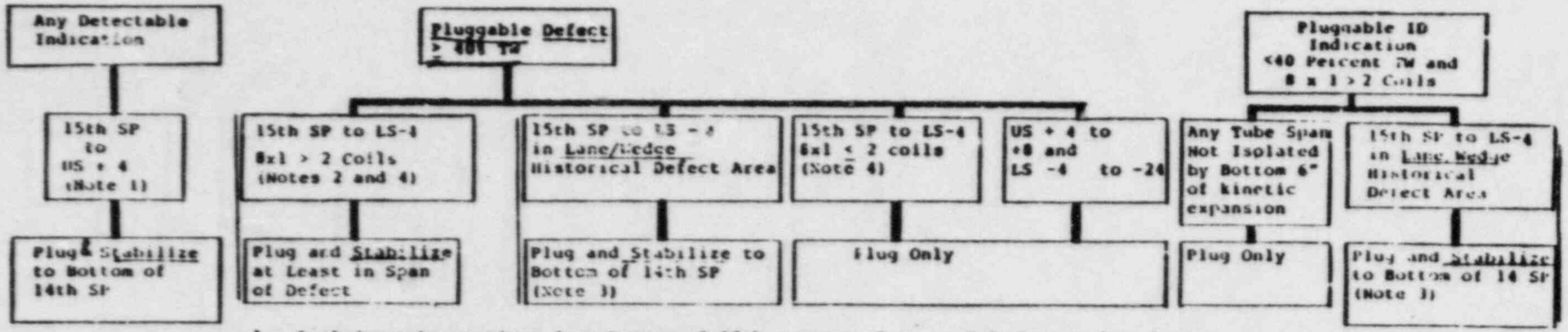
OUTLINE OF BASIC TUBE PLUGGING/STABILIZING PLAN



1. Includes tube sections from bottom of 15th support plate to 4-inches up into bottom of upper tubesheet.
2. Includes tube section from bottom of 15th support plate to 4 inches down from the top of the lower tubesheet.
3. See Figure IV-1 for tubes in Lane/Wedge area.
4. 8x1 is ECT probe with 8 absolute coils and 360° circumferential coverage.

TABLE 6
(FIG. VII-1 OF TR-008)

CALC. NO. ....

SHEET NO. .... OF ....

SUBJECT ....

DATE ....

COMP. BY/DATE S.D. LESHNOFF 1/11/85

CHK'D. BY/DATE ....

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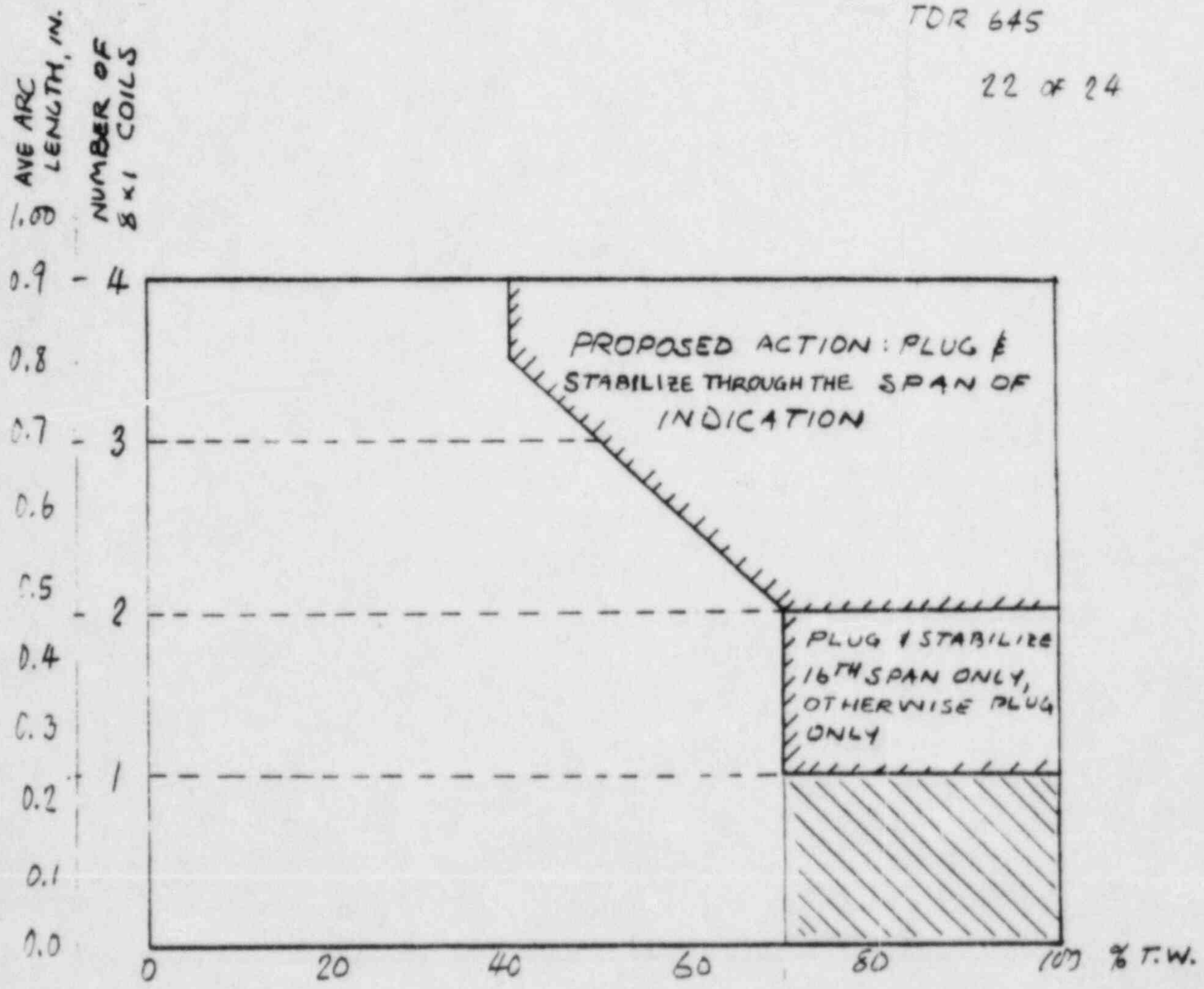

DISPOSITION OF 11/84 TUBE ECT INDICATIONS

FIG. 2

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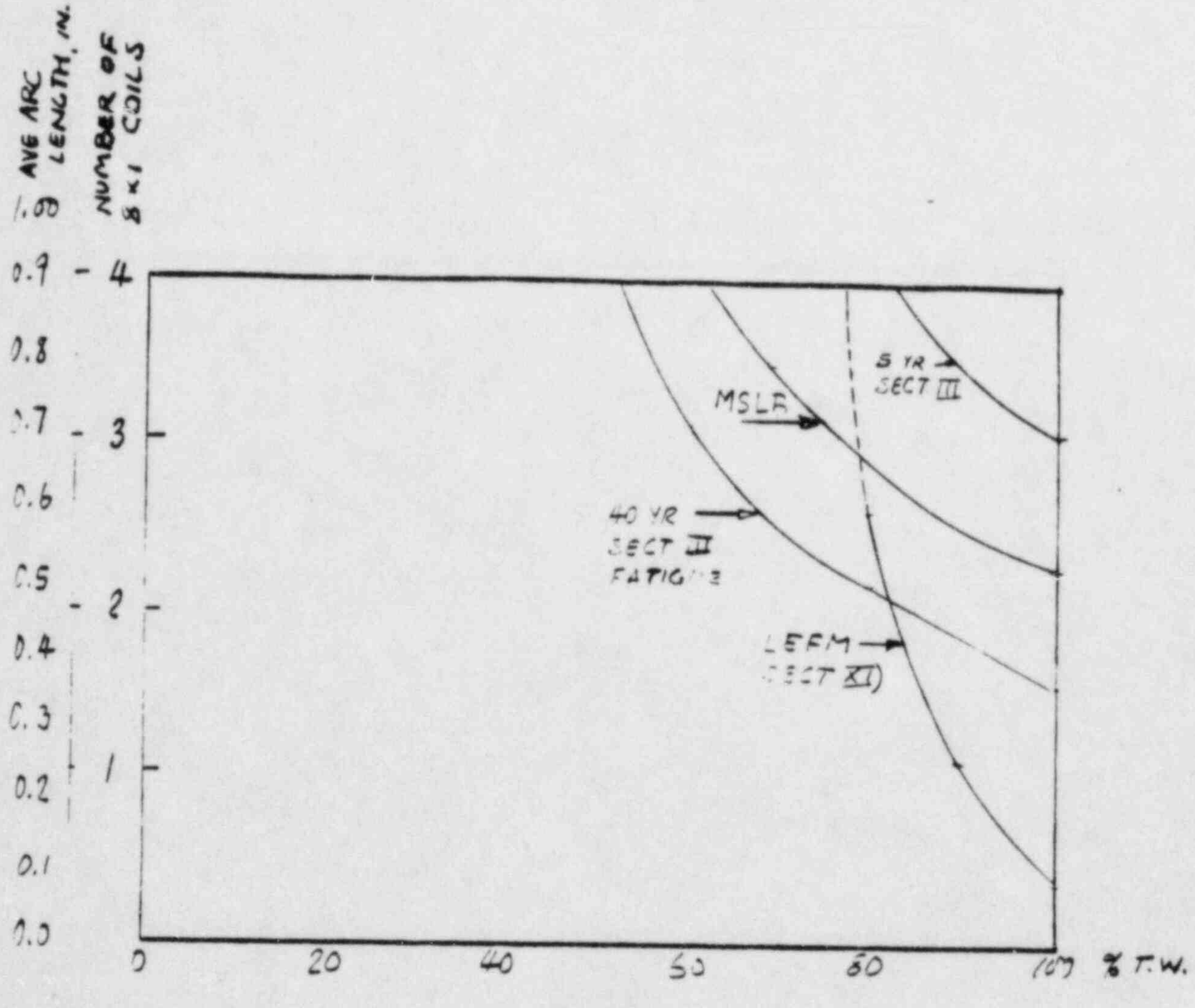

RESULTS OF PREVIOUS ANALYSES

FIG. 3

GPU Nuclear Calculation Sheet

Subject	Calc No	Rev No	Sheet No ___ of ___
Originator S D LESHNOFF	Date 1/30/85	Reviewed by	Date

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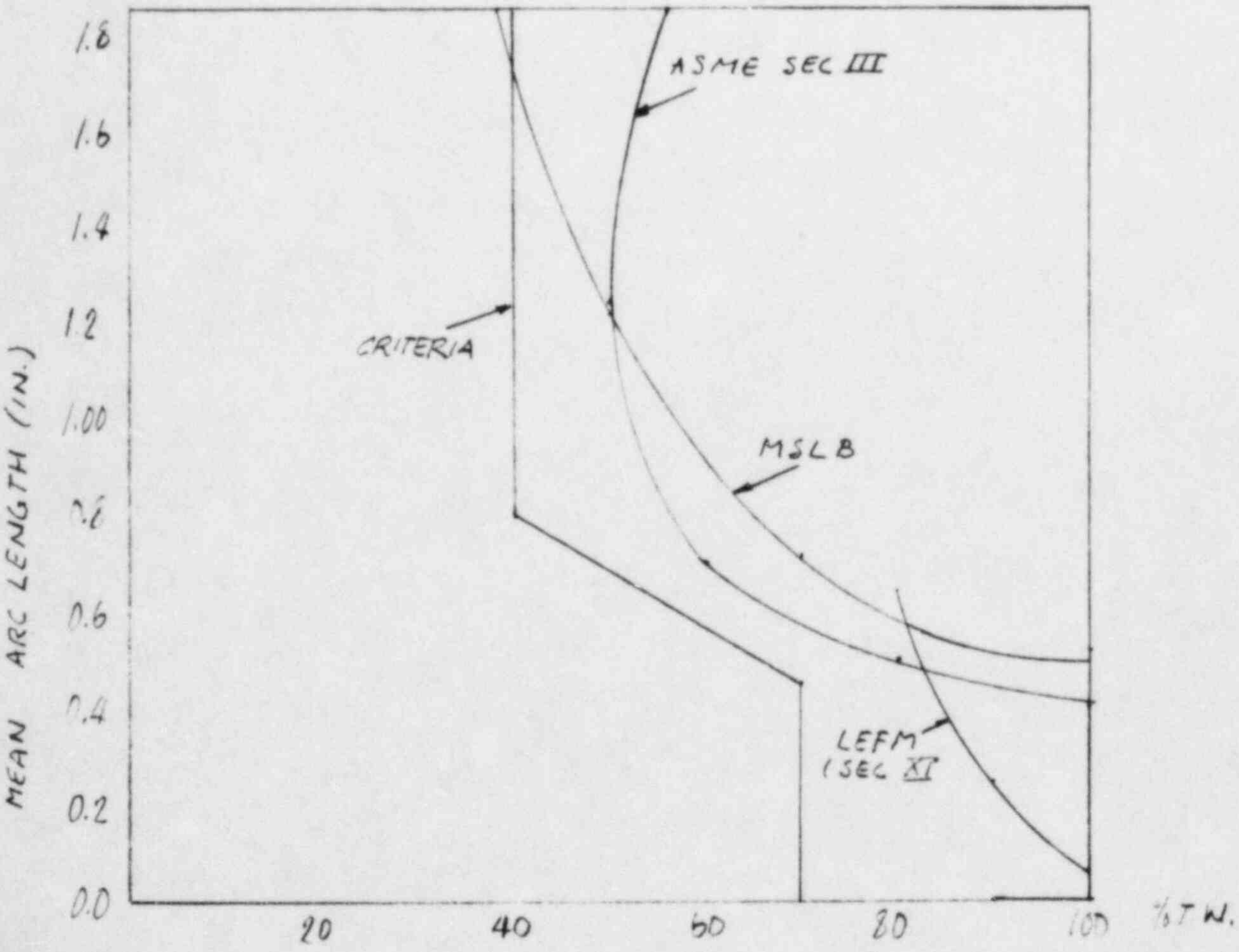

FIG. 4

COMPARISON OF ANALYSIS RESULTS WITH CRITERIA.