APPENDIX A

GPU Nuclear
TECHNICAL DATA REPORT

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PROJECT: OTSG Tube Plugging

DOCUMENT TITLE: Assessment of 50% TW Repair Limit with respect to Reg. Guide 1.121 Guidelines.

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ABSTRACT:

PURPOSE

Analytical results, provided by several different methods, show that tubes with deep local flaws need not be treated the same as tubes with shallower but more extensive flaws. A comprehensive plugging criteria should disposition tubes based on ECT characterization of both depth and circumferential extent for circumferential defects and depth and length for axial defects.

A comprehensive tube plugging criteria is developed here which meets or exceeds NRC guidelines on structural margin, as per the guidelines of Reg. Guide 1.121, addresses ECT accuracy, and provides a basis that an additional thickness degradation allowance is not necessary.

METHODS:

Structural

Analytical results, some described in earlier reports, were compared against guidelines for establishing a steam generator tube plugging criteria contained in Reg. Guide 1.121. These guidelines addressed, among other things, providing a margin of 3.0 on normal loads and 1.428 on upset to prevent ductile failure (circumferential defect) or burst (axial).

METHODS: Cont'd

Margin against plastic collapse was met by using a non-linear strain analysis and exceeded by an elastic plastic fracture mechanics analysis. The margin to burst was shown to be exceeded by net section collapse methods and by actual test data.

ECT Accuracy

ECT accuracy was demonstrated with metallurgical samples. The recently qualified conversion curve was used in conjunction with the .540 SD probe.

RESULTS:

The following results were derived:

Defect size

A defect of 50% TW with a continuous length of 0.55" is acceptable.

ECT Accuracy

The proposed tube plugging criteria contains a margin of ten percentage points on throughwall extent out of recognition of possible ECT error. For a 50% throughwall defect, this represents a 20% margin for error.

Using the mean and standard deviation obtained from metallurgical samples the percent error due to undercall is 3.3%.

Additional thickness degradation allowance

An additional thickness degradation allowance, as suggested in Reg. Guide 1.121, has not been included because, first, the mechanism for continued chemical attack from the inner surface has been arrested and, second, the TMI-1 OTSG's do not have a history of either significant tube problems because of wear on the outer surface at the elevations of the lateral support plates or secondary side chemical attack. Both the NRC staff and the Atomic Safety and Licensing Board have concurred that primary side corrosive attack is not ongoing.

CONCLUSIONS:

1. Comparison of the present results with the results from previous analysis, albeit that methods differed, shows that they are nearly the same.

   This comparison allows the conclusion that fatigue, plastic collapse and burst concerns are all satisfied. Plastic collapse and burst are addressed for the first time herein.

2. The proposed tube plugging criteria contains margins to failure equal to or greater than those recommended in Reg. Guide 1.121.

3. The percent error due to undercall is less than that previously assumed.

4. The tube plugging criteria developed here is applicable to flaws on the inner surface of the tube only. In addition, it is applicable to the free span portion of the tube only, away from entrance effects associated with support plates.

   Tubes with defects on the OD surface will be dispositioned at 40% TW. Tubes with indication of nearby OD and ID flaws will be dispositioned on a case-by-case basis in a conservative manner consistent with the nature of the degradations involved and the uncertainties of the ECT call.

PURPOSE

The proposed GPUN OTSG tube plugging criteria provides for the structural integrity of tubes with defects against fatigue failure mechanisms and against failure in single application of large loads.

The latter condition, based in ASME Code practice, is recommended in Reg. Guide 1.121, Basis for Plugging Degraded PWR Steam Generator Tubes (Ref. 2). This source recommends a margin of safety against ductile failure equal to 3.0 x normal loads and 1.428 x upset loads. In addition, identification of error associated with ECT is also necessary as is a discussion of an additional thickness degradation allowance.

Reg. Guide 1.121 does not recognize the demonstrated capability of ECT in characterizing both depth and extent of circumferential defects nor does it make a distinction between circumferential and axial defects. A comprehensive plugging criteria should disposition tubes based on ECT characterization of both depth and circumferential extent for circumferential defects and depth and length of axial defects.

A comprehensive tube plugging criteria is developed here which meets or exceeds NRC guidelines on structural margin, identifies a probability of ECT error, and provides basis that an additional thickness degradation allowance is not necessary.

METHODS

The approach used to demonstrate structural margin, as recommended in Reg. Guide 1.121, is described first. The approaches to address ECT error and additional thickness degradation allowance will follow.

1. Structural Margin

Structural margin is demonstrated in "Evaluation of GPUN proposed OTSG Tube Plugging Criteria" (Ref. 3) prepared by Structural Integrity Associates.

Conceptual Overview
Loads

A factor of 3x normal loads (ASME Code, Sect. III). and 1.428 x upset loads (ASME Code, Sect. III, App. F) is recommended by Reg. Guide 1.121. The basic loads originate in a B&W generic document on tube plugging (Ref. 4). That report not only provides identification of loads under anticipated design basis conditions, it also provides the thermal/hydraulic methodology for deriving those service loads. The dominant component in the tube axial load is thermally induced, as would occur when the OTSG shell is hotter than the tubes. The resulting load is due to thermal growth difference, or, in other words, displacement control. If displacements of interacting members are reduced, reactions are reduced. This is in opposition to load control where reactions are independent of displacement.

Non-linear Strain Analysis

Applying large factors to relatively large loads produces stresses in the region of the material stress-strain curve where displacement and load are no longer linearly related. Resistance to displacement decreases as material response becomes non-linear. Reaction loads decrease as the more flexible tubes are stretched, or displaced, to conform to the growth of the OTSG vessel shell. Loads less than what are predicted by linear proportionality are actually generated. Invoking the tube material actual stress-strain response shows that lower internal reactions should be used in the evaluation. The loads that are actually developed on the OTSG tubes are identified. This is discussed in Ref. 3, Sec. 2-1; please see Fig. 2-1, specifically.

This effect is particularly important when considering circumferential defects. No such benefit exits for axial defects, however, because large strains are only possible in the longitudinal tube direction.

Failure Criteria: Net Section Collapse, Tearing Instability, and Burst.

Net section collapse (NSC) has been used by EPRI to gauge the structural integrity of pipes with circumferential defects (Ref. 5). A defect is unacceptably large where a point on the cross-section reaches the material flow stress. This condition is equated to ductile failure. The flow stress condition represents the departure from uniform material elongation and the on-set of neck-down deformation prior to reaching the ultimate tensile strength. The analysis of NSC proceeds from principles of solid mechanics.

The analysis for tearing instability, however, proceeds from principles of elastic plastic fracture mechanics (EPFM). A crack in a structure may propagate a small distance and then arrest or it may tear through the material without arresting if the combination of load and crack size is sufficiently damaging. EPFM predicts the onset of the latter condition, i.e., tearing instability. The tearing modulus and applied J are computed for this purpose. See Sect. 4.1 of Ref. 3. Burst is the failure mode for tubes with axial defects. No benefit can be taken here for actual material response to reduce reaction loads because burst is load, not displacement, controlled. Analytically, flow stress is taken to govern prediction of burst. A comparison of predicted burst behavior with experimental data shows that analysis contains inherent conservatism. See Sect. 5.3 of Ref. 3.

Failure by Fatigue Mechanisms and the MSLB

Analyses demonstrating the serviceability of flawed tubes against fatigue failure mechanisms have been previously reviewed and endorsed by the NRC staff. These analyses included ASME Section III and Section XI fatigue evaluations, and a solid mechanics single accident load (Main Steam Line Break, MSLB) analysis conducted as part of GPU Nuclear's response to the 1981 tube cracking experience, as presented in TR-008 (Ref. 1).

GPUN can now take credit for that previous work in identifying minimum required tube wall thickness. Inherent in the previous work was the capability to establish that a) by fatigue analysis that inservice tubes would not develop cracks under normal operating conditions, even in areas of suspected degradation and b) that existing cracks, should they go undetected, would not propagate throughwall under normal operating conditions.

GPUN's evaluation combines the methodology of both ASME Sections III and XI in order to assess the reduction in fatigue resistance caused by identified or hypothetical ECT indications. ASME Section III provides guidance for designing nuclear pressure components against failure; ASME Section XI provides guidance for evaluating the impact of suspected flaws in pressure retaining components inservice.

The Section III fatigue failure analysis uses crack initiation as the criterion for loss of fatigue resistance of the material; therefore, design using this approach assumes only a degraded material condition and not outright structural failure. The approach used to enter the ASME III design fatigue curve was originally discussed in TDR-421 (Ref. 11) and is summarized in TR-008 (Ref. 1), which formed a basis for NRC conclusions in NUREG-1019.

In ASME Section XI, 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. As discussed previously in TDR-388 (Ref. 10) and TR-008 (Ref. 1), 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 ID circumferential crack under applied axial load, internal pressure, and bending stress due to flow induced vibration. The aim of this analysis originally was to demonstrate the adequacy of the threshold of ECT detection sensitivity.

The rupture strength of a flawed tube to the maximum axial load, applied one time only, was evaluated under the faulted condition of a main steam line break (MSLB). The tube response was 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.

2. ECT Accuracy

ECT accuracy was demonstrated with metallurgical samples. The recently qualified conversion curve was used in conjunction with the .540 SD probe to generate 6 data points for defects.

The approach taken here utilizes percent error of the ECT call with respect to actual flaw size, as shown by metallurgical examination, to establish relative error. This approach allows conclusions concerning ECT overcall or undercall.

The margin separating the fatigue analysis results and the proposed plugging criteria is at least ten percentage points (10%) on throughwall out of recognition of possible ECT error.

3. Additional Thickness Degradation Allowance

Additional material allowance out of recognition of both a primary side attack combined, at the same elevation, with mechanical wear from the outer surface, as at the elevation of the upper lateral support plate, is addressed in two ways. First, primary side chemical attack was arrested by chemical cleaning and is prevented from reoccurring by plant chemistry procedures involving pH and lithium addition (Ref. 8).

Second, plant engineering records of the tube plugging on account of wear on the outer surface (Ref. 7) indicate that cross-flow patterns for the generators at TMI-1 do not promote this mode of degradation. Six lane tubes were plugged on account of wear at the 15th lateral support plate as a precautionary measure. ECT techniques now in place will be employed to examine these areas.

RESULTS

1. Structural Margin

The results of the non-linear strain analysis are shown in Figure 1. Tube load versus displacement, assuming linearity, is shown as the bold straight line. The parallel dashed line is the 0.2% offset yield line. The curved dashed lines are the actual material temperature dependent engineering stress-strain curves. As the material strains, the predominately thermal loads are reduced. Dropping down from the pseudo-elastic response to the actual non-linear material response (intersection at circles) gives the true tube load by reading back to that axis. The applied axial loads are shown multiplied by the factors of safety recommended by Reg. Guide 1.121.

The results of the NSC and EPFM structural analyses for circumferential defects in tubes are shown in Fig. 2. The analytical results are shown with respect to a piece-wise linear expression of the proposed plugging criteria. The two NSC curves (dotted) reflect the two conditions of flawed tube structural response; that the tube is flexible (triangle) and that it is inflexible. The EPFM result is indicated as: J-T, 42 KSI. The 42 KSI follows from the industry practice for 360°, 40% TW defects.

In the area of the proposed plugging criteria, both NSC models produce results well removed from the 10% TW zone. The EPFM results are in a region well removed from the proposed plugging criteria. These results are nowhere within 10% TW of the criteria. The NSC results for a flexible tube model (triangles), where the centroids of the defective and non-defective cross-sections tend to line-up under load reducing the internal moment reactions, come within 10% TW of the plugging criteria only for defects of very large circumferential extent. Results for an inflexible tube (squares) come within 10% TW over a broader region of circumferential extent. Inflexible tube response is less likely than flexible response.

The results shown in Fig. 2 are all within the proposed plugging criteria.

Figures 3 and 4 show NSC results for tubes with axial defects. The normal and upset loads are multiplied by the factors of safety recommended by Reg. Guide 1.121. The figures indicate that the proposed plugging criteria bounds the analytical results. Figures 5 and 6 compare actual burst tests results for INCO 600 with analytical prediction. The latter are always conservative when compared to burst test results.

Except for a small region, these results are not within 10% TW of the plugging criteria. Where there is a small discrepancy there is margin in the analysis methods to compensate. For example, using Figures 5 and 6 and equations 5-4 and 5-5 in Ref. 3, the actual burst pressure by test, is about 22.5% greater than predicted burst pressure.

The results of the previous fatigue and MSLB analyses are provided in (Ref. 1) TR-008. The proposed plugging criteria bounds the results of these analyses. In the area of the proposed plugging criteria, there is at least a margin of 20% TW or greater. (The margin increases with decreasing length.) Margin of this magnitude occurs when stable crack growth and not fatigue resistance are governing.

ECT Accuracy

ECT accuracy was demonstrated with metallurgical samples using the recently qualified conversion curve (6). The mean of six data points (Ref. 6) was 13.4% overcall. The standard deviation was ± 16.7%. On this basis, a 3.3% undercall was observed. This is less than the 20% undercall, on a 50% throughwall indication, already included in the proposed criteria.

Previously, (Ref. 6), a statistical presentation was made regarding differences between ECT sizing and metallurgical results. The approach taken here utilizes percent error of theECT call with respect to actual flaw size as shown by metallurgical examination. The approach allows conclusions concerning ECT overcall or undercall. Previous work discusses accuracy in terms of per cent throughwall units. That approach gauges error against the total throughwall dimension. The previous work does not include an assessment of relative error, as presented above.

In the region of the proposed plugging criteria, the margin against ECT is at least 10% on throughwall as seen by inspection of Figure 2 and TR-008 (Ref. 1). These analyses represent distinctly different solutions but allow the same conservative conclusions with regard to margin against ECT error.

DISCUSSION

Application of Plugging Criteria

In a strict sense, the structural model used here was that for a ID surface flaw. The applicability of the results will be limited to that geometry only. Defects on the OD surface will be dispositioned in accordance with the existing Tech Spec repair criterion.

The ECT sizing accuracy is established for defects on the ID surface in the free span. Applicability of these structural results will be limited to these regions.

The structural problem of OD and ID surface flaws at the same elevation has not been solved here. Tubes having this type of defect combination will be dispositioned on a case-by-case basis in a conservative manner consistent with the nature of the degradations involved.

IGA/IGSAC

Previous work (Ref. 8) provided an explanation of the November, 1984, tube defects. What was proposed was, essentially, that previously existing IGA/IGSAC was mechanically exercised into ECT detectability. Additionally (Ref. 9), it was found from pulled tube specimens that IGA could exist apart from IGSAC.

The structural results discussed above apply to defects whose origination is from either mechanism. Inability to call IGA defects would impact only the statistics associated with ECT. If necessary, the issue of ECT margin will be revisited should there be a deficiency in ECT with regard to detection and sizing of IGA alone.

CONCLUSIONS:

1. Comparison of the present results with the results from previous analysis, albeit that methods differed, shows that they are nearly the same.

   This comparison allows the conclusion that fatigue, plastic collapse and burst concerns are all satisfied. Plastic collapse and burst are addressed for the first time herein.

2. The previous tube plugging criteria contains margins to failure equal to or greater than those recommended in

   Reg. Guide 1.121.

3. The percent error due to undercall based on an assessment of metallurgical data is less than that assumed in GPUN structural analyses.

4. The tube plugging criteria developed here is applicable to flaws on the inner surface of the tube only. In addition, it is applicable to the free span portion of the tube only, away from entrance effects associated tube support plates.

   Tubes with defects on the OD surface will be dispositioned at 40% TW. Tubes with indication of nearby OD and ID flaws will be dispositioned on a case-by-case basis in a conservative manner consistent with the nature of the degradations involved.

References

1. TDR 008 Assessment of TMI-1 Plant Safety for Return to Service after OTSG Repair, Rev. 3, 8/83.

2. Regulatory Guide 1.121, Basis for Plugging Degraded PWR Steam Generator Tubes, 8/70.

3. J.F. Copeland and T.L. Gerber, Evaluation of GPUN Proposed OTSG Tube Plugging Criteria, S.I. Report No.: SIR-85-017, May, 1985.

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

5. B.J.L. Darlaston, Some Aspects of Leak-Before-Break; Their Quantification and Application, Nuclear Eng'g & Design 84 (1985) 225-232, North-Holland, Amsterdam.

6. TDR 642, Qualification of Conversion Curve for Inner Diameter Discontinuities, Evaluation of Eddy Current Indicators During the 1984 Tech., Rev. 2.

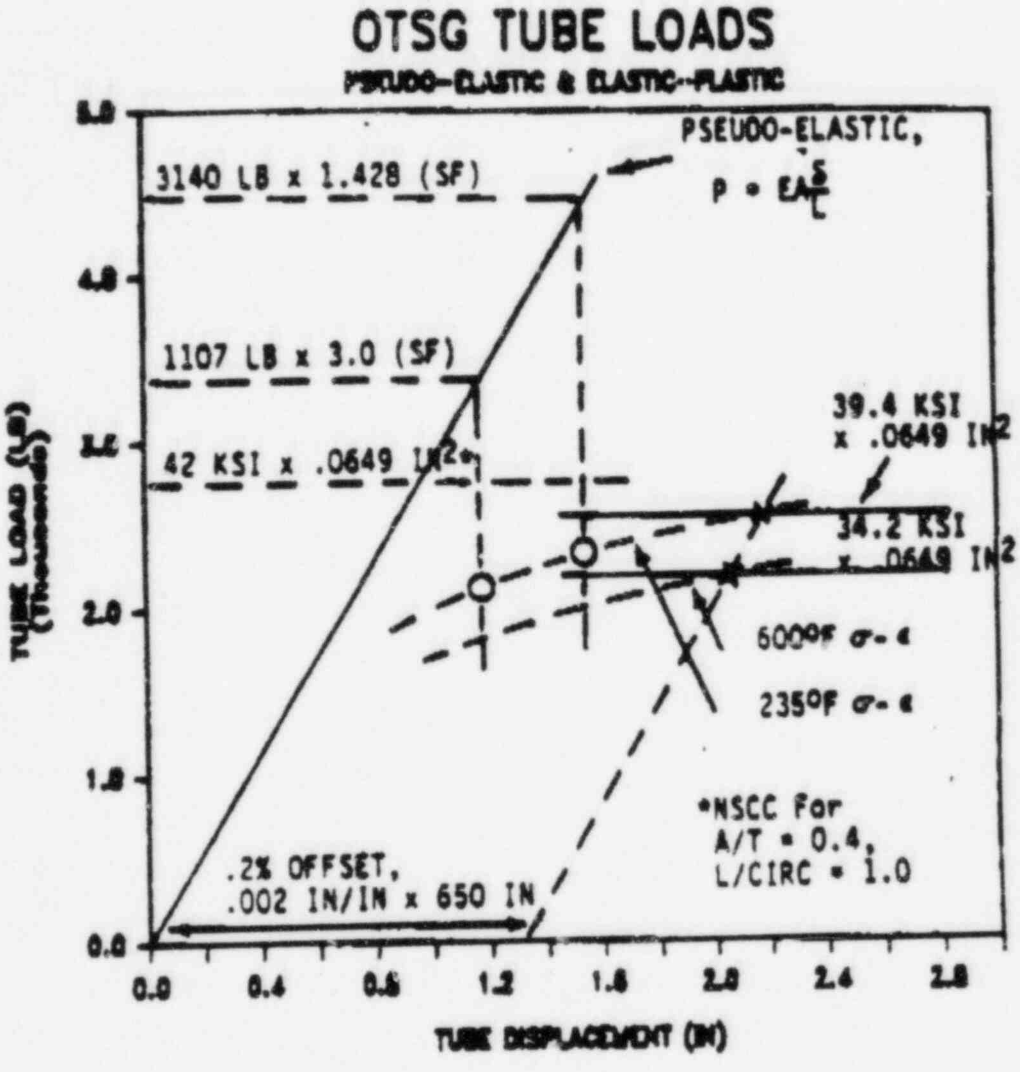
7. Record of Telephone Conversation, R. O. Barley to S. D. Leshnoff, OTSG Tubes Plugged Because of Wear on the O.D. Surface, 5/7/85.

8. TDR 638, Rev. 0 Evaluation of Eddy Current Indications Detected During the 1984 Tech. Spec. Inspection.

9. TDR 686, Rev. 1, Characterization of IGA in TMI-1 OTSG Tube Samples.

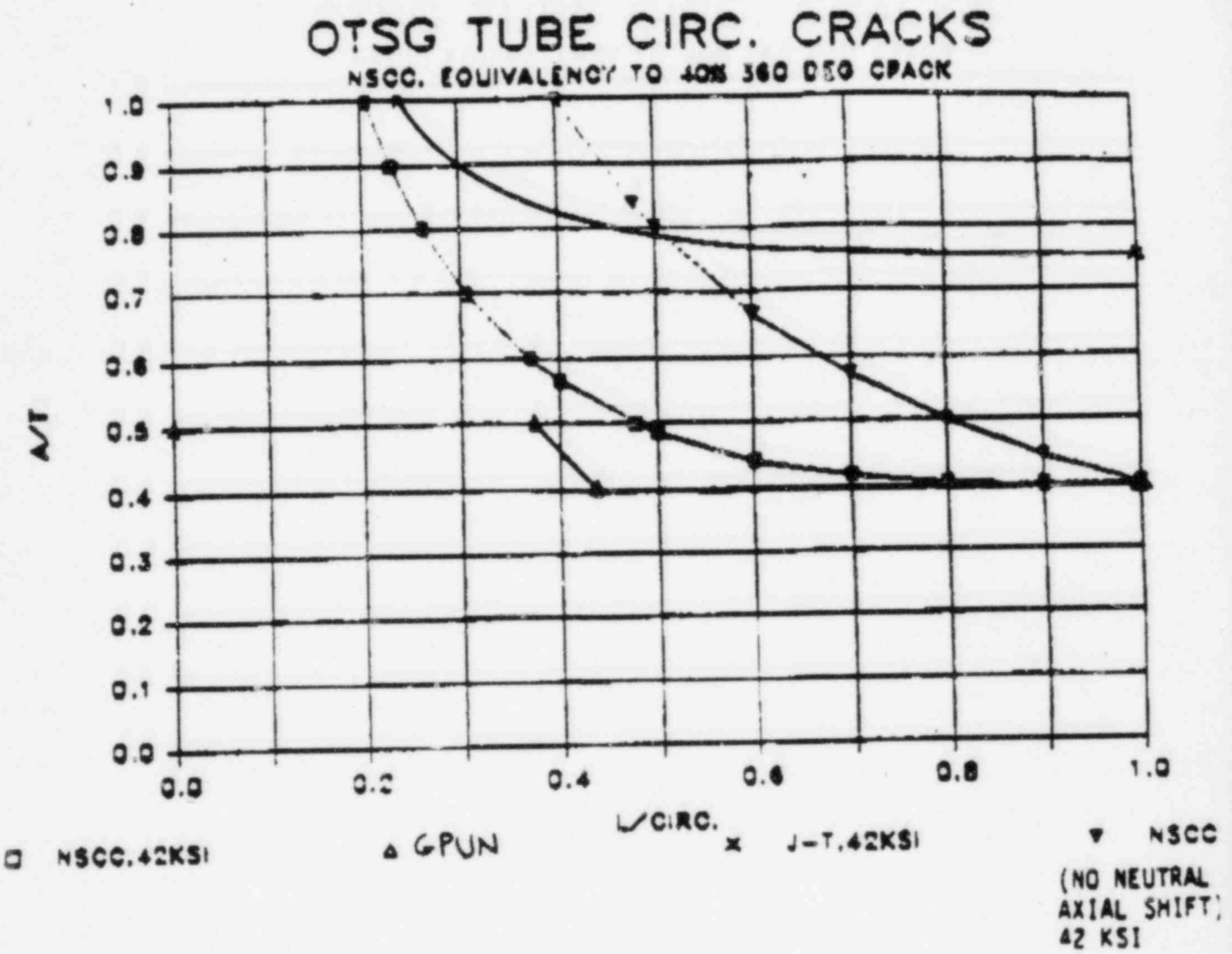
10. TDR 388, Rev. 3, Mechanical Integrity Analysis of TMI-1 OTSG Unplugged Tubes.

11. TDR 421, Rev. 0, Steam Generator Adequacy of Tube Plugging and Stabilizing Criteria.



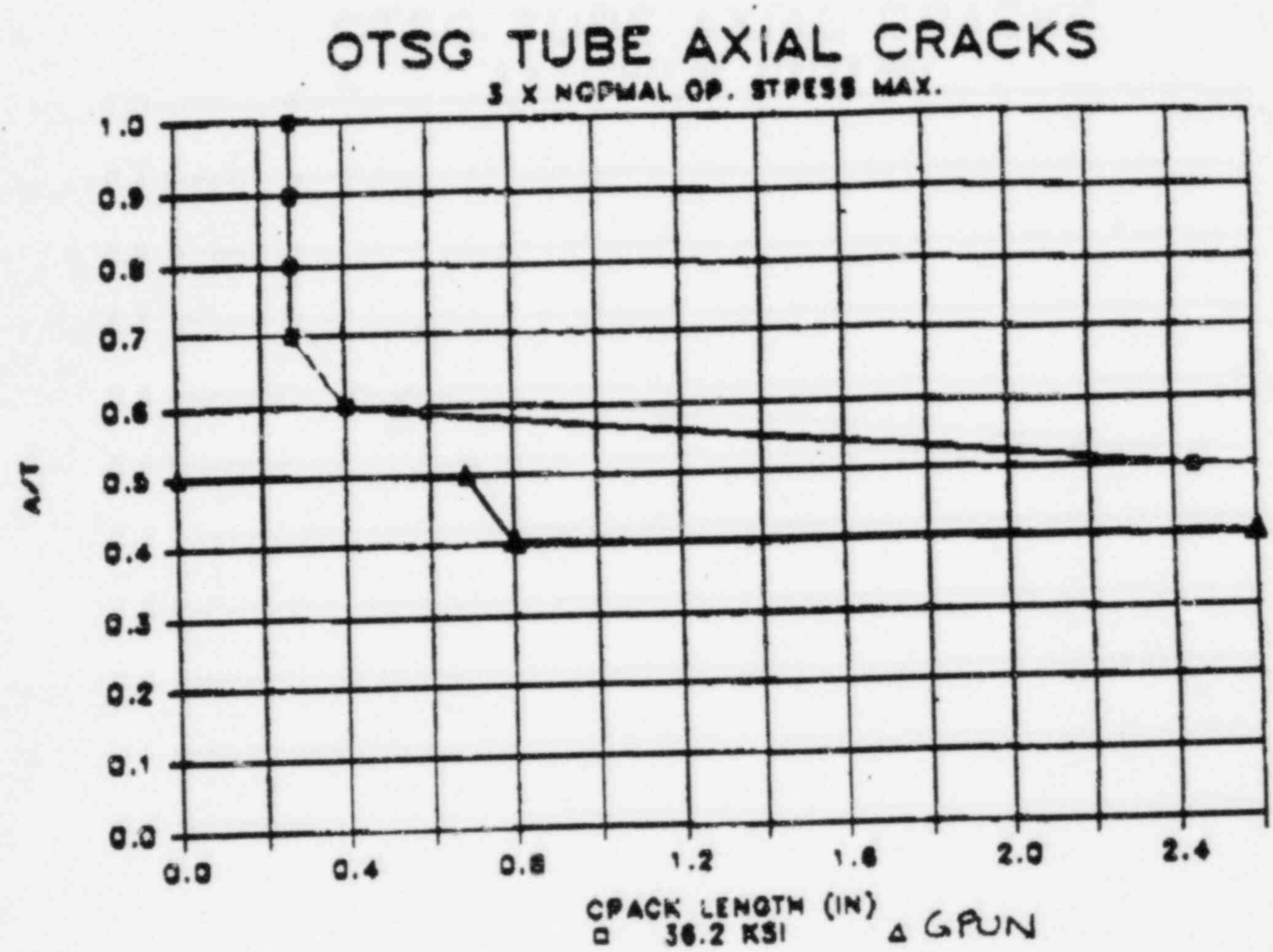
OTSG Tubing Elasticity Calculated and Expected Load Displacement Behavior

FIG 1



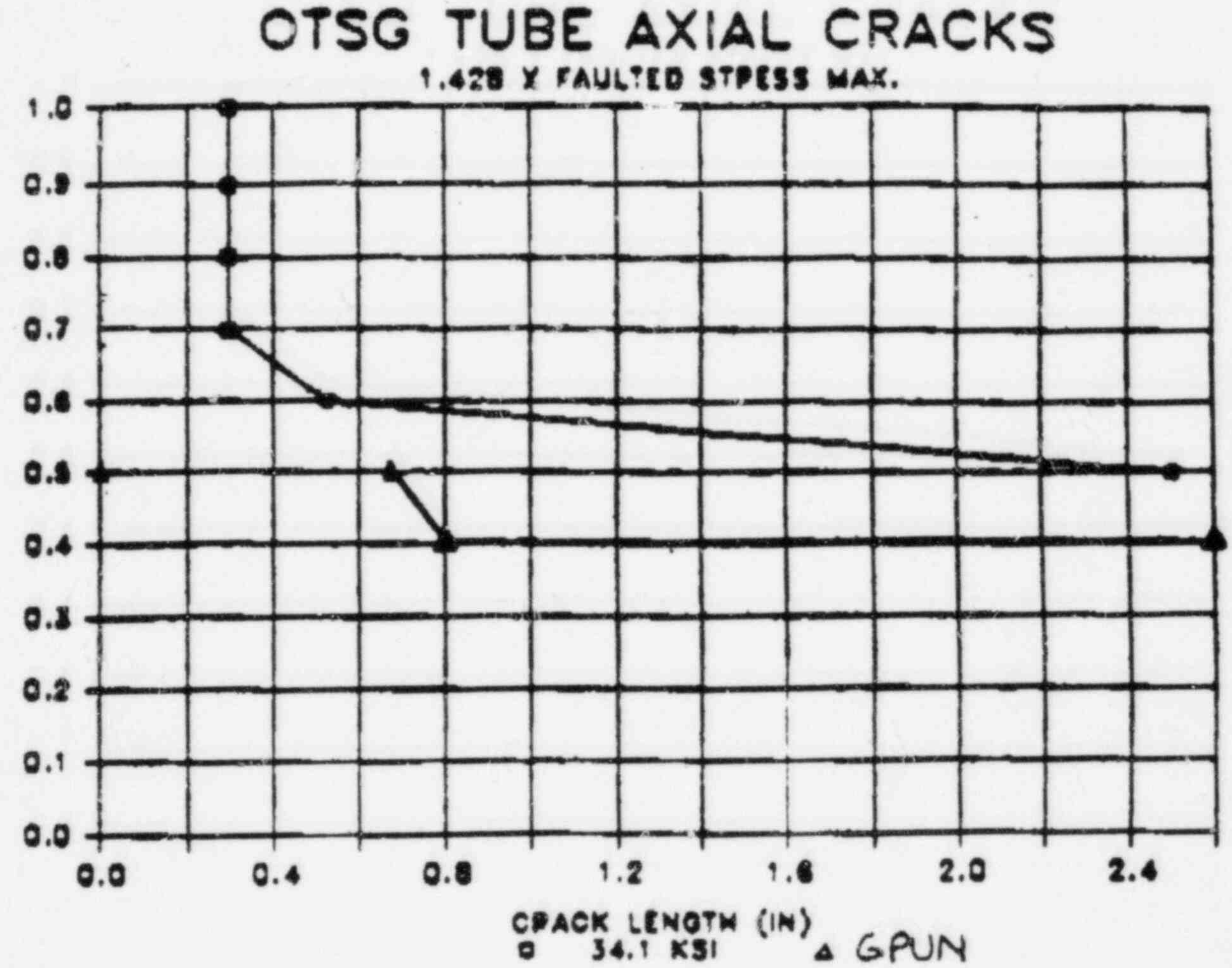
Net Section Collapse Criterion and J-T Instability Results for Circumferential Cracks in Tubes with an Axial Stress of 42.0 Ksi which Permits a 360°, 40% Through the Tube Wall Crack

FIG 2



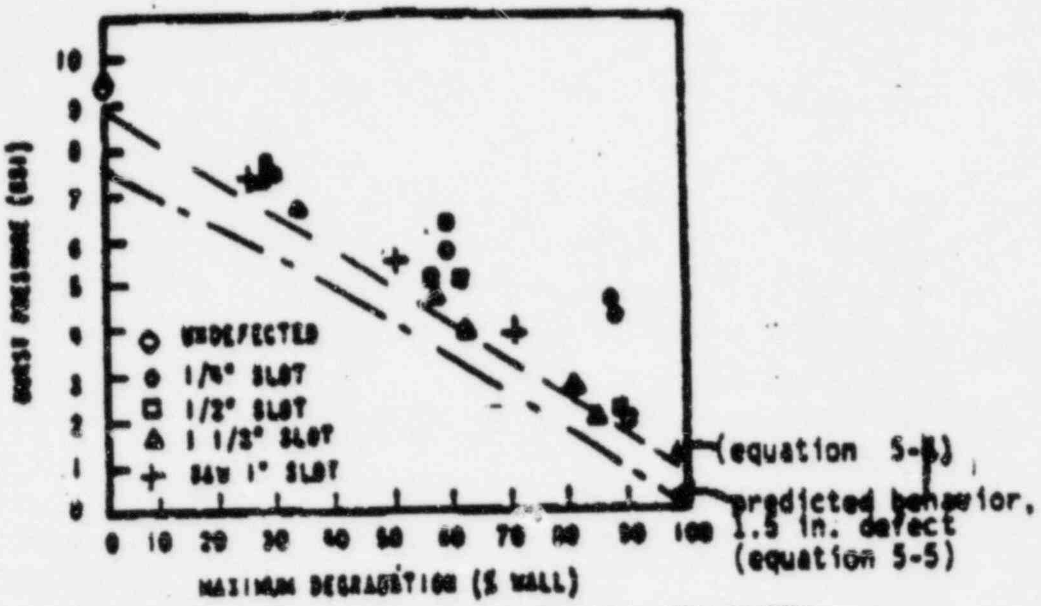
Net Section Collapse Criterion Results for Axial Cracks in Tubes at Three Times Normal Operating Stress (36.161 Ksi)

FIG 3

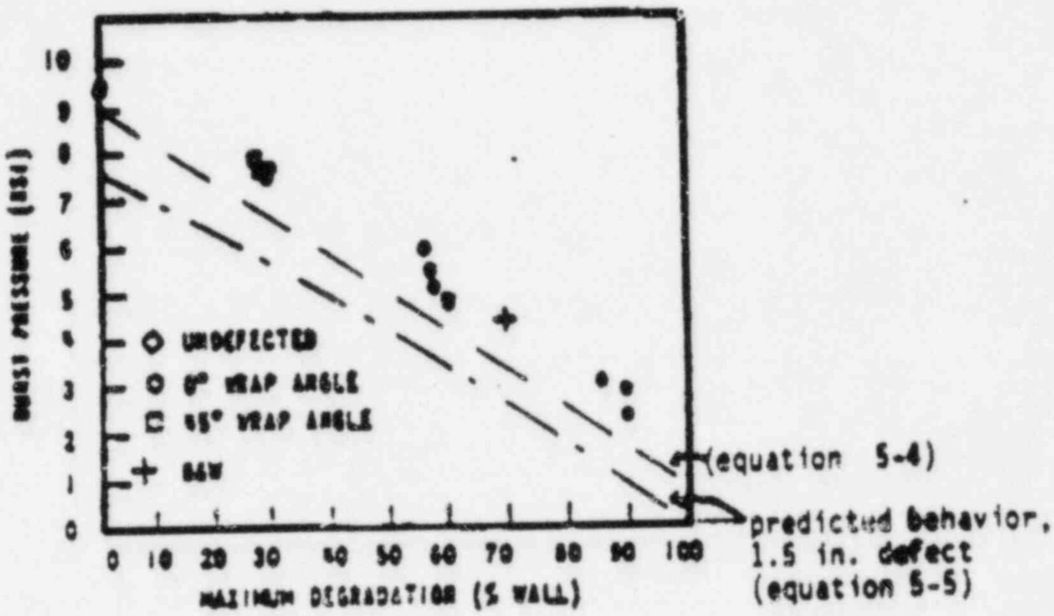


Net Section Collapse Criterion Results for Axial Cracks in Tubes at 1.428 Times Faulted Stress (34.068 Ksi)

FIG. 4



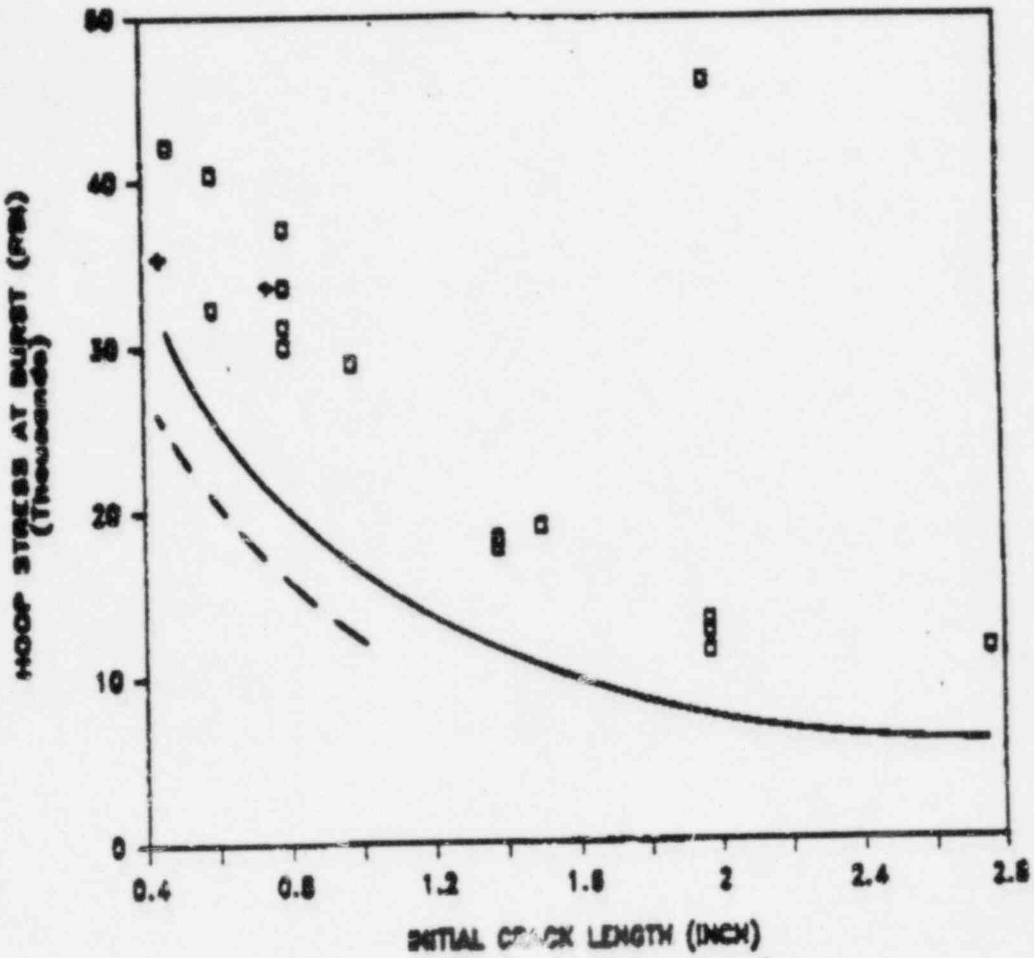
BURST PRESSURES FOR 0.625 x 0.034 IN. EDM SLOTS



BURST PRESSURES FOR 0.625 x 0.034 IN. ELLIPTICAL WASTAGE

Burst Test Results (3) and Predictions for Tubes with Part Through-Wall Defects

FIG. 5



□ 0.050 inch wall thickness data [11]
— 0.050 inch wall thickness prediction
+ 0.030 inch wall thickness data [12]
--- 0.030 inch wall thickness prediction

Comparison of Thru-Wall Crack Burst Test Data with Predicted Behavior

FIG. 6