GPU Nuclear

TECHNICAL DATA REPORT

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PROJECT:

TMI-1
OTSG Repair

DEPARTMENT/SECTION E&D/Consulting Engineering

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DOCUMENT TITLE: TMI-1 OTSG Tube Axial Loads and Leakage Monitoring

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ABSTRACT:

SEE PAGES 1b and 1c ATTACHED

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DOCUMENT NO.
TDR-417 pg 1a

TITLE TMI-1 OTSG Tube Axial Loads & Leakage Monitoring

REV	SUMMARY OF CHANGE	APPROVAL	DATE
1	Revised document title. Complete revision to TDR contents as a result of re-calculation of OTSG tube loads and additional information regarding the plant variables which affect tube axial loads.		8-15-83 (same)
2	Revised section 3.1.1 to include B&W's comments in added ref. No. 16. Also revised Fig. No. 3 to avoid confusion regarding intent of 6 GPH.	[signature] [signature]	9-14-83 9-14-83

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STATEMENT OF PROBLEM

Analysis [TDR 388 (Ref. 1)] identified the size of an OTSG tube circumferential crack (defined as a critical crack) which would propagate by net section collapse to a double ended tube rupture under the most severe design basis loads (MSLB axial tube loads). Other analysis [TDR 421 (Ref. 5)] identified the fact that the primary contribution to crack propagation during normal operation was from axial tube loads during heatup/cooldown transients. The purpose of this TDR was to; 1) provide justification for an administrative leakrate limit which would provide reasonable assurance that any individual tube would be removed from service by plugging before a leaking circumferential crack reached a critical crack size; and 2) establish operating guidelines for cooldowns which would minimize tube axial loads.

SUMMARY AND KEY RESULTS

Tube leakrate from circumferential cracks was calculated utilizing a formulation (Ref. 12) developed by FAA for the Nuclear Safety Analysis Center (NSAC), a division of EPRI. The analysis was based on the concept of crack opening displacement (COD) and flow area being a function of tube axial load. Considerations provided by Professor Erdogan of Lehigh University (Ref. 11) were also utilized in analyzing leakrates. Specifically, the fact that circumferential cracks in tubes which have previously been subjected to axial tensile loads retain a residual crack opening displacement (CODR) was utilized to assess expected leakrates. Additional considerations including the dropout of intergrannulary attacked grains, and the erosion of the crack surface by cavitation were utilized in establishing an administrative leakage limit.

The magnitude of tube axial loads was a significant variable in both the NSAC leakrate analysis and the crack propagation evaluation. In addition to utilizing the generic tubeload analysis (Ref. 2), a TMI-1 specific tube axial load analysis was completed. The analysis was done for 100% power operation, cooldown and the most severe (as far as tube axial loads) design basis accident (MSLB). The results of these analyses were utilized to evaluate the TMI-1 administrative limits and reassess previous fatigue/fracture mechanics analyses. The variables which affect tube axial load and the sensitivity of tube loads to these variables were also documented.

The results of the analysis described can be summarized as follows:

1) The differential temperature between the tube and shell is the variable which has the greatest affect on tube axial load. It readily lends itself to an operating guideline aimed at reducing tube axial tensile loads.

2) Tube axial tensile load is greatest during cooldown and may range from compression to tension at power operating conditions.

3) Although the NSAC leakrate analysis predicts zero leakage from a crack with no tensile axial load, the residual crack opening displacement (CODR) and other factors can reasonably be expected to produce leakrates in excess of 6 gph from thru wall cracks which are not yet of a critical size (pre-critical crack).

4) Since tube axial tensile loads are maximized during cooldowns leakrate would also be maximized during these periods.

5) The TMI-1 specific tube load analysis during cooldowns predicts higher tube axial tensile loads than the generic analysis for a shell-to-tube differential temperature of 140°F. Limiting the TMI-1 shell-to-tube differential temperature to 70°F results in tube axial tensile loads during cooldown comparable to the generic loads on which the fatigue/fracture mechanics analysis was based.

6) The TMI-1 specific evaluation of tube loads during MSLB predicts lower tube axial tensile loads than the generic analysis. This results in larger critical cracks and greater margin in the administrative leakrate limit.

CONCLUSIONS

1. An operating guideline limiting the shell-to-tube differential temperature to a maximum of 70°F wil reduce tube axial tensile loads by approximately half compared to our predicted tensile load attained during a generic cooldown (140°delta-T). The 70°F delta-T limit will ensure that the load cycle used for the fatigue/fracture mechanics analysis in TDR 421 remains a bounding case.

2. An administrative limit on leakrate of 6 gph above a previously established baseline provides reasonable assurance that tubes with leaking thru wall cracks will be removed from service before the crack reaches a critical size.

3. Leakrate measurements should be made during cooldown as well as during normal operations to provide additional information for evaluation of the OTSG tube status.

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1.0 PURPOSE:

The purpose of this report is to evaluate the ability to detect critical circumferential cracks in the TMI-1 OTSG tubes by leak monitoring. Such cracks are sufficiently large tube defects which had been missed by ECT inspections and post-repair OTSG cold and hot leak testing programs and then propagated by mechanical load cycling. A critical crack is defined as a defect which is sufficiently large to result in tube failure by net section collapse when it is subjected to the design basis tube axial loads. The design basis tube axial loads are defined as those which are generated by a postulated generic main steam line break (MSLB) accident.

This evaluation also provides the basis for an administrative limit for OTSG leakage during plant power operating conditions which provides the ability to detect potential critical circumferential cracks in OTSG tubes as a result of mechanical fatigue crack propagation of the repaired and post repair tested OTSG.

2.0 METHOD

This evaluation utilizes the results of various reports, evaluations and calculation, which are identified in the list of references, in combination with predictions of tube loads and crack leakrates to provide the basis for leak monitoring guidelines and a conclusion on the ability to detect defects which have been mechanically propagated to critical circumferential crack sizes.

The evaluation addresses the tube loading during the heatup/cooldown cycles and the effect of these load cycles in the crack propagation mechanism; the tube loading during postulated accident conditions and their corresponding critical crack sizes; the predicted tube loading at 100% power operating conditions and the sensitivity of tube load predictions to assumed variables. The evaluation then utilizes the geometry of the defects which were generated by the sulfur induced IGSA process and the results of the mechanical crack propagation mechanism analysis to define pre-critical crack sizes which must be detected by a leak monitoring program. Leakrate predictions from pre-critical cracks during plant cooldowns and during power operating conditions were made. The leakrate predictions during power operation being based on residual COD's in pre-critical crack sizes which result from the tube loads during a previous plant cooldown. The leakrate from pre-critical cracks are then demonstrated to be detectable and result in OTSG tube leakage in excess of the selected 6 gph administrative limit for power operating conditions. Leakage from pre-critical crack sizes during a plant cooldown are shown to be significantly in excess of 6 gph. Conclusions on the ability to detect critical cracks are reached as well as recommendations for leak monitoring guidelines.

The OTSG tube axial load predictions presented in this report were all calculated by a computer model of the OTSG, called OTSG1, which is described in reference No. 8. This model accounts for the tube pre-load, which is discussed in Section 5.1 of this report, shell and tube thermal growth, primary and secondary pressures, including the Poisson effect on the tubes and shell, and tubesheet temperature and primary to secondary differential pressures as they effect the tubesheet deflection. The model thus provides different load values for peripheral and center tubes in the OTSG.

3.0 HEATUP/COOLDOWN CYCLES

The following discussion addresses the cyclic loading of the OTSG tubes resulting from plant heatup/ccoldown cycles. Specifically it addresses the generic evaluation (Ref. No. 2), the GPUN calculated loads based on a revision to the operating procedures and the effect of the loading cycle on the fatigue/fracture mechanics analysis of crack propagation due to these load cycles. A discussion of the tube pre-load is found in Section 5.1.

3.1.0 Generic Evaluation Results

The heatup/cooldown cycle tube loads which form the generic evaluation of the OTSG tube integrity is presented in B&W topical report BAW-10146, Oct., 1980, Ref. No. 2. These loads are summarized as follows:

Transient	Tube Load(lbs.)	
	Center	Peripheral
Cooldown from 15% power	649	1107 (w/142°F shell to tube delta-T)
Heatup to 15% power	-670	-775 (w/(-)65°F shell to tube delta-T)
Total cycle range	1319	1882

3.1.1 Review of the Generic Evaluation Cooldown Tube Loads

During on GPUN's review of reference No. 2 and the OTSG shell & tube temperature versus time during a 100°F/Hr cooldown (Ref. No. 3) we found two assumptions, one non-conservative and one conservative, which are:

1. Note(b) to Table 5-2 in BAW-10146 (Ref. No. 2) states that by assuming no primary to secondary pressure differential the tube loads would be lower than those which were reported for the cooldown transient. This assumption is non-conservative in that a primary to secondary pressure differential results in a tensile load due to membrane and Poisson effects. Assuming no tube pre-load (no load at cold conditions) with RCS pressure equal to 2250 psig and OTSG pressure equal to 119 psig at the critical time of 2.025 hrs, our current prediction is that the tube loads would be approximately 1700 lbs. and 535 lbs. for peripheral and center tubes respectively. If a pre-load of 280 lbs. is also assumed, then the loads increase to approximately 1965 lbs. and 800 lbs. respectively.

A benchmark calculation using the GPUN model (Ref. 8) and the generic evaluation assumptions of no primary or secondary pressure and no pre-load has also been performed with resulting loads of approximately 1182 lbs. and 653 lbs. for peripheral and center tubes respectively. These results compare favorably to the respective generic values of 1107 lbs. and 649 lbs. to conclude that our OTSG model is reasonable.

2. The OTSG temperature history in the referenced B&W calculation seems to be indicative of the upper shell temperature (steam space) instead of the overall average shell temperature which is used to calculate the delta-T between the shell and tubes. Based on steady state conditions at 15% power versus the OTSG temperature history in the calculation, the temperature history is approximately 30°F higher than the overall average shell temperature. We have calculated (see Section 6.0) that 1°F change in shell to tube delta-T results in approximately a 10 lb. change in the tube axial load. Thus, the calculated loads stated in item 2.1.1.1 above would all be reduced by approximately 300 lbs.

The Reference No. 2 analysis results are also based on a requirement for a 2 hour hold period at the conditions which permit initiation of the D.H. system before the D. H. system is actually placed in service. During this period, core heat is removed by continued steaming of the OTSG's which provides forced cooling of the OTSG upper shell and allows the OTSG shell temperature to approach the tube temperature. Reference No. 4 states that this hold period is required in order not to exceed the design basis cooldown tube loads once the D. H. system is placed in service and the shell no longer cools at the same rate as the RCS and OTSG tubes.

It is recognized that this TDR presents values for tube loads during cooldowns which are larger than those documented in B&W topical report BAW-10146 (ref. No. 2). B&W's approach in BAW-10146, as stated in reference No. 16, was to maximize the stress intensity range for a tube wall thinning phenomenon fatigue analysis. Thus, by neglecting the pressure effects during a cooldown but including them during a heatup results in maximizing the stress intensity range. GPUN's approach in this TDR is to develop the best and maximum prediction of axial tube tensile loads because these loads act to propagate tube cracks. Thus, each of these approaches is appropriate and conservative in meeting the objective of their respective aims. 2

3.1.2 GPUN Proposed Changes to Cooldown Procedures

In anticipation of reducing the OTSG tube loads to approximately one half of the design basis values, GPUN had proposed to limit the shell to tube delta-T to a value of 70°F during a normal plant cooldown. Based upon calculations which include a tube pre-load of approximately 280 lbs., the effects of primary and secondary pressures on the tubes, and a maximum shell to tube delta-T of 70°F we have predicted that the tube loads are approximately equal to, the generic loads during a cooldown which limits the shell to tube delta-T to 140°F. The peak loads occur before the decay heat removal system is initiated and while the RCS pressure is being maintained at high values in order to satisfy the fuel clad compression limits and RC pump normal NPSH requirements yet not exceed the NDT limits (see O.P. 1102-11 Fig. 1 & 1A, Plant Cooldown procedure).

Once the D.H. system is placed in service, the RCS pressure is limited to approximately 335 psig. We have calculated that a 1 psi change in RCS pressure results in an approximate 0.2 lbs. change in axial tube load. Thus, with a 70°F shell to tube delta-T limit, the OTSG tube loads are substantially reduced once the RCS is depressurized from the high pressure band during the initial phase of the cooldown.

3.1.3 OTSG Tube Loads Based on Proposed Cooldown Procedure Changes

The proposed changes to the cooldown procedure address only a portion of the OTSG conditions which are required to calculate the tube loads. The other limitations are the RCS pressure versus temperature limits provided by Fig. 1 & 1A in the cooldown procedure and the OTSG shell and RCS temperatures versus time data. Since the temperature versus time data for a cooldown with the proposed limitations was not available, we have utilized the same temperature history as the referenced B&W calculation (Ref. No. 3) up to a time at which the shell to tube delta-T reached 70°F. At this point we assumed that the shell cooldown with respect to time will follow the B&W shell cooldown curve, however, we assumed that the RCS temperature will be controlled in accordance with the cooldown procedure to remain within 70°F of the shell average temperature. The assumption regarding the shell cooldown rate is considered to be valid on the basis that the steam flow rate will be equal or greater than that which has been utilized to develop the B&W shell cooldown curve. Although the steam temperature will be approximately 70°F higher, it will still result in an equivalent heat transfer rate to cool the shell. If the assumption is incorrect, then there will still be no effect on tube loads, but the length of time that the tube is subjected to the load will be increased as will the period required to cooldown. We have also modified the B&W shell cooldown curve by lowering it by 30°F to reflect the overall average OTSG shell temperature versus the upper shell temperature, per the basis described in section 3.1.1.2 above.

We have calculated OTSG tube loads based on the proposed procedure changes. For this calculation we utilized both the original B&W OTSG shell temperature history and the modified shell cooldown curve. The results are almost identical with either set of curves except that the peak loads occur approximately one-half hour earlier and decay more slowly with the original OTSG shell cooldown curve.

With a 70°F delta-T limit between the OTSG shell and tubes, the tube loads are calculated to be approximately:

	Tube Load (lbs.)		
	Center	Peripheral	
Peak	510	1200	(before D.H. is in service)
D.H. in service	510	860	(based on 70°F delta-T, without 2 hr. "Hold" period)

Although our proposed procedure for plant cooldown will limit the shell to tube temperature difference to 70°F for the entire cooldown and will also provide a two hour "hold" period before the D.H. system is initiated, this evaluation of cooldown tube loads conservatively assumes no two hour hold period.

3.1.4 PLANT COOLDOWN CURVES:

Attached figures No. 1 and 2 show the plant variables and OTSG tube loads as a function of time. The tube loads are shown for peripheral, average and core tubes. Each of the identified tubes has an upper and lower bound axial load curve. The bounding axial load curve is a function of the RCS pressure during the cooldown. The upper axial load curve for the peripheral and average tube and lower axial load curve for a core tube represent the tube loads during a cooldown wherein the RCS pressure is maintained at its upper limit. The other axial load bounding curve represents the tube loads during a cooldown wherein the RCS pressure is maintained at a minimum value along its lower limit. Both curves represent cooldowns from operating condition at 15% power. Figure No.1 utilizes the OTSG shell and tube average temperatures obtained from Reference No. 3. Figure No. 2 utilized a shell average temperature which is 30°F lower than in Figure No. 1 but the same tube average temperature until the shell to tube temperature difference equals 70°F.

Note that if a cooldown is performed from Hot Standby conditions with minimal decay heat from the RCS, then the OTSG shell will cool more slowly and the sehll to tube delta-T limit will be reached earlier. The resultant tube loads will reach their peaks more quickly and remain there for a longer period but will not exceed the calculated peak values provided the delta-T limit is not exceeded.

3.1.5 OTSG Tube Loads During Plant Heatup

In order to establish the total tube load cycle range for the heatup/cooldown cycles, one must know what the tube loads are during a plant heatup. GPUN is relying on the values reported in Reference No. 2. In order to account for the difference between the tube pre-load assumed in calculating these loads, and the tube pre-load that we have utilized for the balance of cur calculations, we have simply substracted the difference from the previously calculated tube loads.

	Tube Loads (lbs.)	
	Center	Peripheral
Ref. No. 2 calculated load (assumed 100 lbs. pre-load)	-670	-775
TMI-1 tube load (assumed 280 lbs. pre-load)	-490	-595

3.1.6 Heatup/Cooldown Total Cycle Loads

Utilizing peak calculated cooldown loads and heatup loads both based on a tube pre-load of 280 lbs., the total load cycle are:

	Tube Loads lbs.	
	Center	Periphery
Cooldown Peak Loads	510	1200
Heatup Loads	-490	-595
Total Loads Cycle	1000	1795

3.2 Effect of the Calculated Total Cycle Loads on Fatigue/Fracture Mechanics Analyses.

The calculations and results of the ASME code fatigue analysis and the linear fracture mechanics analysis to determine the maximum initial thru-wall crack size which could sustain 40 years of FIV cyclic loading plus 240 cycles of heatup/cooldown loads without failure in a subsequent cooldown was initially prepared and included in (Ref. No. 5) TDR-421 Rev. 0, Vol. II, sections C&D. These calculations were based on heatup/cooldown loads of (-)775 lbs./1107 lbs. which are the generic values for axial tube loads during a cooldown. Based on the previous discussion in this report, (section 3.1) these tube loads are more appropriately applied to the calculated loads during a normal cooldown which is being limited by a 70°F delta-T criteria.

The ASME code fatigue analysis calculation method utilizes the total stress (load) range rather than the maximum absolute stress (load). Therefore, the maximum calculated crack size which satisfies the criteria does not change if there is no change to the total load range. Since the total load cycle for a normal heatup/cooldown has been recalculated to be approximately 1795 lbs. versus the 1832 lbs. which was utilized for the earlier calculation the conclusions are unchanged.

The linear fracture mechanics analysis utilizes the maximum tensile stress (load) to calculate the maximum crack size that would satisfy the 40 year normal heatup/cooldown load cycling plus FIV cycling. Thus, we have recalculated the crack size which satisfies the criteria based on a load in excess of the expected maximum normal cooldown tensile load of 1200 lbs. The results of this calculation (Ref. No. 6) with an assumed tube tensile load of 1580 lbs. is that a thru-wall crack with arc length of 0.34 inches satisfies the failure criteria.

Although the fatigue evaluation is now being presented on the basis of the normal cooldown loads which are administratively limited by a 70^{o}F delta-T criteria versus the generic evaluation cooldown, tube failure is not predicted if the plant is subject to such a transient with an initial crack size which is smaller than the critical crack size for an MSLB.

Reference 7 concluded that non-thru-wall cracks of sizes that are smaller than those shown by Fig. 1, curve "A", in Reference No. 7 would not grow to become thru-wall within 40 years of normal load cycling. Since the assumptions regarding tube loads during power operation and heatup/cooldown cycles have now been calculated to be different, curve "A" may shift either to the right or to the left. Since thru-wall cracks smaller than the critical thru-wall crack size for an MSLB grows stabily and such a crack will be detected by leakage, it becomes unnecessary to revise curve "A" on Fig. 1.

3.3 CONCLUSION

The conclusion that may be reached at this point regarding tube loads resulting from heatup/cooldown transients and their effect on failure analysis are:

1. The tubes can safely sustain the loads resulting from heatup/cooldown transients although these loads have been calculated to be higher than previously reported.

2. If existing flaws, which have gone undetected by the ECT inspection or by the cold and hot OTSG testing programs, are subject to the transient loads, they will be detected before they propagate to a size which may result in tube failures during plant cooldowns including design basis cooldowns.

3. Possible existing undetected flaws will propagate to thru-wall and then increasing arc lengths as had been concluded in Reference No. 7 but with a slight shift in Fig. 1, curve "A" in Ref. 7. This conclusion does not negate the ability to cooldown without incurring tube failures.

4.0 OTSG Tube Loads During Postulated Accidents

The postulated main steam line break (MSLB) accident was selected as the event which produces the highest OTSG tube loads. The basis for this selection is Reference No. 2 which provides a summary of tube loads during postulated accidents.

The basis for the generic and TMI-1 specific MSLB calculated OTSG tube loads, the resultant load values and the corresponding critical crack sizes to demonstrate the conservatism in the generic MSLB evaluation compared to the TMI-1 specific MSLB event is provided in this section.

As can be seen from Figures 1 and 2 for plant cooldowns, and the discussion in Section 6.0 on tube load sensitivity to the value of assumed variables, the OTSG tube loads are most greatly affected by the shell to tube temperature difference. In terms of OTSG tube loads, a MSLB is initially a very rapid cooldown transient until the OTSG's either are placed in or reach a mode where-in they remove heat from the RCS in a controlled manner. The MSLB will cool the RCS to a final temperature which is dependent upon the mass of the secondary side inventory that is available for cooling and the mass of cold primary water that is injected, if one assumes that the total amount of sensible heat in the RCS and core decay heat are equal. Since the initial cooldown transient is so rapid, it is assumed that the thick OTSG shell average temperature does not decrease significantly from its condition at 100% power. Thus, if the RCS and tube temperatures are arrested at a higher value than the generic MSLB evaluation, the shell to tube temperature difference and resultant OTSG tube loads will be to lower.

4.1 Generic MSLB

4.1.1 Basis

The generic MSLB evaluation is based on a plant configuration wherein the main steam isolation valves (MSIV's) must be manually initiated to close them in order to prevent reverse flow; the main steam lines are interconnected downstream of the MSIV's and the assumed pipe break location is at a 36 inch diameter steam line nozzle on one OTSG. This configuration allows both OTSG's to be blown down very rapidly thru a double ended rupture of a 36 inch diameter steam line.

In terms of system flow performance to provide additional heat removal fluids, the generic MSLB evaluation assumed:

1. Main feedwater was terminated by a low steam pressure (600 psig) ESFAS signal at 17.5 seconds.

2. The 1600 psig RCS pressure ESFAS signal initiated HPI flow at 170 lbs/sec (approx. 1220 gpm) to the RCS.

3. EFW flow was assumed to runout the pumps at a total flow of 1650 gpm to the OTSG with the ruptured main steam line nozzle for 20 minutes. A second case assumed 1600 gpm total to both OTSG's for 20 minutes. A third case assumed 2900 gpm to the unaffected OTSG and was terminated at 5 minutes.

4. Cases were run with and without the Reactor Coolant Pumps in operation.

5. Core power at the time of the MSLB was assumed at 102% of 2568 Mwt.

6. RCS and OTSG pressures were assumed to be 2500 psig and zero respectively.

The results of these evaluations indicate that with EFW flow to the OTSG(s) for 20 minutes, equilibrium between the primary and secondary side was reached at an RCS and tube temperature of approximately 234°F. With EFW terminated at 5 minutes equilibrium was reached at an RCS and tube temperature of 473°F.

4.1.2 Generic OTSG Tube Loads During a MSLB:

The exact MSLB scenario and assumptions that were utilized to generate the B&W generic OTSG tube loads during and MSLB were not available to GPUN. We have performed an independent verification of the calculation of generic MSLB tube loads.

Our asumptions for the independent calculation are:

1-	Tube average temperature	234.8°F
2-	OTSG shell average temperature	520.7°F
3-	Tubesheet average temperature	275.0°F
4-	RCS Pressure	2500 PSIG
5-	OTSG Pressure	0 PSIG
6-	Tube tensile pre-load	100 LBS.

OTSG Tube Loads

Tube Location	Generic MSLB	GPUN Recalculated MSLB
Peripheral tube	3140 lbs.	3430 lbs (tension)
Core tube	1408 lbs.	1420 lbs (tension)

These results confirm the reasonableness of the new analytical model.

4.2 TMI-1 Specific MSLB

4.2.1 Basis

The TMI-1 specific MSLB is based on the TMI-1 plant configuration and system flow performance.

The TMI-1 configuration does not allow both OTSG's to be blown down by a single main steam line break since the steam lines from their respective OTSG's do not have a large common node which is located upstream of the turbine stop-control valve chest. A MSLB will result in a turbine trip and close the turbine stop valves to prevent reversal of steam flow from the non-affected to the affected OTSG. If the break is located upstream of the MSIV's and two turbine stop valves fail to close then reverse flow is prevented by the MSIV's, which are stop-check type valves, . Plant emergency procedures require the oerator to close the MSIV's during a MSLB to isolate the OTSG's and we have not postulated a failure of both the turbine stop valves to close concurrently with the inability to close the MSIV's for postulated steam line breaks downstream of the MSIV's. Thus for the TMI-1 specific MSLB, the initial energy removal capacity is reduced to one half of the generic MSLB value.

The TMI-1 OTSG's each have two 24 inch main steam line nozzles and are routed in two parallel steam leads to the turbine stop valve chest. The two steam leads from each OTSG have a comon node point upstream of the MSIV's thru an 8 inch diameter cross-connect pipe. Even with this cross-connect, the blowdown rate of an OTSG thru a MSLB would be less rapid than thru the generic 36 inch nozzle.

In terms of other assumptions and system flow performance, we have utilized the following for the TMI-1 specific MSLB evaluation.

1- Main feedwater is terminated to the depressurized OTSG by a low steam pressure (600 psig) signal and by high level signal and/or low steam pressure in the unaffected OTSG.

2- HPI is initiated by the 1600 psig RCS pressure ESFAS signal. The HPI flow, with both HPI trrains in service, is limited by the cavitating venturies at a total flow of 1100 gpm. This flow is slightly less than that assumed in the generic analysis.

3- It is assumed that all EFW pumps are successfully started. The unaffected OTSG initially contains sufficient secondary inventory so that its EFW regulating valve remains closed and the EFW flow to the affected OTSG is limited to 600 gpm by its cavitating venturi. Thus the TMI-1 specific MSLB limits the rate of energy removal from the primary by the EFW system to less than one half of the B&W generic analysis.

4- We have assumed that the RC pumps are operating to provide forced circulation cooling.

5- TMI-1 is licensed for only 2535 Mwt compared to 2568 Mwt for the generic asumption of 2568 Mwt.

6- Assumptions regarding RCS and OTSG pressures are dependent on the accident scenario. If it is assumed that EFW is terminated by the operator within 5 minutes, based on recognition of the transient, the RCS would be repressurized to 2500 psig and reheated and result in zero pressure in the affected OTSG and 1050 psig in the unaffected OTSG. If EFW were not terminated for 20 minutes, then it is assumed that the operator would control the RCS pressure and temperature based on the lower RCS pressure-temperature limits at that time.

7- Tubes have a tensile pre-load of 280 lbs. see Section 5.1 for a discussion of pre-load.

The TMI-1 plant specific analysis used the TMI-1 Basic Principles Training (BPT) computer and confirmation of these results from a simplified one loop model of the RCS and OTSG's which utilized more conservatisms than are described above as plant system limitations. The more conservative assumptions that are included in the BPT are:

1- EFW flow to the affected OTSG was allowed to reach 2000 gpm compared to the 600 gpm limitation due to the cavitating venturi.

2- The HPI flow based on this larger overcooling event reached 1200 gpm.

The resultant RCS and OTSG condition are then as follows:

	Affected OTSG @ 20 min W/EFW	Terminated EFW @ 5 Min. Affected OTSG	Terminated EFW @ 5 Min. Unaffected OTSG
Case No.	1	2	3
1- Tube average temp., (°F)	363	386	560
2- OTSG shell ave. temp., (°F)	563	563	563
3- Tubesheet ave. temp., (°F)	570	400	600
4- RCS pressure, (psig)	470	2500	2500
5- OTSG pressure, (psig)	0	0	1050
6- Assumed tube tensile pre-load, (lbs.)	280	280	280

4.2.2 TMI-1 Specific Tube Loads During a MSLB

Based on the OTSG and RCS conditions resulting from our evaluation we have then calculated the TMI-1 specific OTSG tube loads for each of the cases.

	OTSG Tube Loads (Lbs.) Case		
Tube Location	1	2	3
Peripheral tube	2200	2425	365
Core tube	1200	975	60

We have selected the following values as being representative for the TMI-1 specific MSLB which is the most severe OTSG tube load producing accident.

Tube Location	TMI-1 Specific MSLB OTSG Tube Loads
Peripheral Tube	2450 lbs (tension)
Core Tube	1000 lbs (tension)

4.2.3 Critical Crack Sizes for TMI-1 Specific MSLB Tube Loads

Based on the TMI-1 specific MSLB tube loads, the critical thru-wall crack sizes which could sustain such loading on a one time basis were calculated to be:

Tube Location	Critical Crack Arc Length for TMI-1 Specific MSLB Tube Loads
Peripheral Tube	0.65 inches
Core Tube	1.53 inches

4.3 CONCLUSION

The generic evaluation for a MSLB is overly conservative in predicting this overcooling event for the TMI-1 specific plant configuration and system limitations. The results of our evaluation utilizing the TMI-1 BPT and a single loop model provide an indication of the magnitude that the generic evaluation overestimates the MSLB overcooling event for TMI-1.

The OTSG tube loads that have been selected to represent the most severe accident loading seem to have reasonable values. Thus, the lower values for the maximum tube loads yield larger allowable thru-wall cracks before they become critical during postulated accidents.

5.0 TMI-1 PREDICTED OTSG TUBE LOADS @ 100% POWER

This section addresses the basis and uncertainties in the system and loading conditions at 100% power, and section No. 6 addresses the sensitivity of tube loads to assumptions.

5.1 OTSG Tube Pre-Load

The tube pre-load is the tensile load that exists in the OTSG when it is at ambient temperature and pressure conditions. It is the residual pre-stress on the tubes which was purposely induced during the OTSG tubing process.

One indication of tube pre-load came from measurement of a fiber optic examination of OTSG tube B-22-30 which had severed prior to the bulk sulphur induced stress corrosion cracking at TMI-1. The measurement indicated a separation of the tube surfaces (jump-down gap) of approximately 3/32 inch. This may be calculated in terms of a residual tube pre-load of approximately 280 lbs.

3. TMI-1 performance data at full power was obtained from historical tapes of the plant "Modcomp" computer.

This data is summarized with the OTSG conditions which were utilized in the original hand (ref. 15) calculation:

Parameter	Orig. Calc.	THEDA-I Prediction	THEDA-II Prediction	TMI-1 Data
RCS Pressure(psig)	2195	2200	2155	2147
OTSG Pressure(psig)	950	925	910	914
Tube Avg.Temp(°F)	580	577.8	573.5	576.3
OTSG Shell Avg.Temp(°F)	580	556.4	553.3	554.7
Wetted Tube Length (in)	300	331	336	336
Tubesheet Avg.Temp(°F)	580	582	579	579

5.3 OTSG Tube Loads at 100% Power

The computer program was utilized to calculate the OTSG tubes axial loads for each of the cases in Section 5.2 with a tube pre-load of 280 lbs. In order to benchmark the computer program for this calculation, Poisson effect on the OTSG shell was deleted. The result of the benchmark calculation produced tensile tube loads of approximately 500 lbs. and 200 lbs. for peripheral and core tubes respectively.

The summary of calculated tube loads, including the Poisson effect on the OTSG shell, for the cases presented in Section 5.2 with a tube pre-load of 280 lbs. is:

Tube Location	OTSG Tube Loads (Lbs.) Orig. Calc.	THEDA-I Prediction	THEDA-II Prediction	TMI-1 Data
Peripheral Tube	290	56	60	44
Core Tube	57	(-)70	(-)63	(-)70

Note: (-) Indicates tube is in compression

6.0 SENSITIVITY OF OTSG TUBE LOADS TO ASSUMED OPERATING VARIABLES

In order to evaluate the approximate effect of changes to the assumed values for the operating variables on the OTSG calculated tube loads, the following table has been prepared. This table was developed from the tube load calculations that were performed to evaluate the tube loads during a plant cooldown that are shown in Figures No. 1 & 2 and should not be utilized to yield exact correlations.

EFFECT ON OTSG TUBE LOADS
DUE TO CHANGES IN VARIOUS VARIABLES

	Variable	Change	Effect on Tube Load
1.	Shell to tube ave. temp. diff.	1°F	10 lbs. change
2.	RCS & OTSG Pressure	1 psig	0.21 lbs. change
3.	Secondary Water Level	50 inches	35 lbs. change
4.	RCS to OTSG Pressure Diff.	1 psid	(-) 0.176 lbs. on core tubes. Variable affects tubesheet deflection with major effect noted in core tubes and minimal change in opposite direction noted in peripheral tubes.
5.	Tubesheet Temperature	-	Minimal effect on peripheral tubes and only minor effect on core tubes. Higher tubesheet temperatures relieve core tube loads.
6.	Tube Pre-load	1 lb.	Approximately a 1 lb. change.

7.0 DEFINITION OF UNDETECTED CRACKS AND CRACK GROWTH MECHANISM:

The following discussion presents the basis and definition of existing tube cracks which may have been undetected by the ECT inspection of the OTSG tubes, and the cold and hot OTSG testing programs and which may present a concern if they propagate to a larger size in the future. The mechanism for tube crack growth is mechanical load cycling.

7.1 Basis & Definition of Existing Undetected Tube Cracks

This evaluation deals only with existing undetected OTSG tube defects which were produced by the sulphur induced stress attack in the bulk of the TMI-1 OTSG's.

Based on laboratory examination of TMI-1 OTSG tubes and evaluations of the ECT inspection data, the geometry of tube defects was defined by an aspect ratio. The aspect ratio is defined simply as the ratio of the defect arc length to the thru-wall depth of the defect. The maximum aspect ratio found in any TMI-1 tube sample is 8.9 (Ref. 5, part I, table III-A) for cases with less than 100% thru-wall penetration. It may thus be assumed that the majority of non-thru-wall defects have a maxiumum aspect ratio of 8.9. The cycle fatigue analysis also demonstrates that non-thru-wall defects will grow thru-wall before they start to grow circumferentially (Ref. 7). Thus, the probable maximum existing defect which may not be thru-wall can be defined by the aspect ratio and tube wall thickness.

$$\text{Max Possible Non-Thru-Wall Crack Arc Length} = A_{max.} = \text{Max. Aspect Ratio} \times \text{Tube Wall Thickness} = (8.9)\times(0.034)$$

$$A_{max.} = 0.3026 \text{ inches}$$

Thus, missed tube defects will already be through wall or they will be non-thru-wall with a probable maximum arc legnth of 0.3026 inches and would become thru-wall with the same arc length that they presently have.

This narrows the range of thru-wall crack sizes for which leak detection is desired from a minimum arc length of 0.3 to 0.52 inches for peripheral tubes and from 0.3 to 1.28 inches for a core tube. These values being based on an assumed minimum thru-wall crack size to one that is critical for the tube loading during a postulated MSLB.

7.2 Crack Growth Mechanism:

The crack growth mechanism is cycle fatigue of the crack tip due to the combined operating load with FIV loading and the larger plant heatup/cooldown loading cycles. The cycle fatigue analysis has shown that thru-wall cracks in the range of 0.3 to 0.52 inch are length grow very stabily. Such analysis has also demonstrated that an initial 0.34 inch arc length thru-wall crack will require in excess of 40 year of operation with load cycles in excess of the expected TMI-1 normal load cycles to propagate to an approximate 0.54 inch arc length (Ref. No. 6).

One may also conclude from the load cycle fatigue analysis that until the crack arc length becomes very large, the operating loading with FIV loading produce negligible crack growth and the crack growth is controlled by the heatup/cooldown load cycle. This is the case for peripheral tubes with crack sizes between 0.3 and 0.52 inches. Core tubes are not subject to either high operating nor high FIV loads and therefore their crack growth is also controlled by the heatup/cooldown load cycle which is approximately one-third of the load utilized in the fatigue analysis (Ref. 6 and Section 3.1.3 of this report). Therefore, core tubes may have even larger circumferential defects before they become critical.

7.3 CONCLUSION

Based on the discussion in Sections 7.1 and 7.2 we have concluded that the maximum crack sizes that must be detectable by leak monitoring are:

Tube Location	Max. Crack Sizes to be Detected(Inches)	
	Generic MSLB	TMI-1 Specific MSLB
Peripheral Tubes	0.5	0.63
Core Tubes	1.25	1.50

8.0 PREDICTION OF TUBE LEAKAGE FROM THRU-WALL CRACKS:

8.1 Basis for Leakrate Predictions:

OTSG tube leakage is a function of the flow area and the fluid properties and flow regime.

The flow area of a tube crack is a function of the crack arc length and crack width or crack opening displacement (COD). The concept of COD as a function of tube tensile load is discussed in reference No.7. For a given tube tensile load, the COD increases linearly for small crack arc lengths and then non-linear once the membrane stress at the crack tip exceeds approximately 22.5% of the material flow stress value.

Based on the concept of COD and flow area being a function of tube tensile load and crack arc length, Nuclear Safety Analysis Center (NSAC), a division of EPRI, and FAA developed the values for tube leakrates as a function of crack arc lengths with tubes subject to 1107 lbs. and 500 lbs. tensile loads. Since the leakrate for a given crack arc length is a function of tube tensile load, assuming fixed fluid flow condition the functional relationship was developed for the linear and non-linear change in COD portions of the leakrate versus crack arc length.

These relationship are:

Eq. 1

$$(LR_L)_1 = (0.07)\ (60)\left(\frac{L}{500}\right)^{1.0915} \times (A)$$

Eq. 2

$$(LR_L)_2 = [(2.2633)\ (A-0.3802)\ (L)^{1.373} - 627.47] \times 10^{-4} \times (60)$$

where:

LR_L = Leakrate, (gph)
L = Tube tension (lbs.)
A = Crack arc length (inches)
Subscript: 1 = Linear change in COD with tube tension
2 = Non-linear change in COD with tube tension

The tube leakrate is then the higher value between $(LR_L)1$ and $(LR_L)2$.

8.2 Effect of Cooldown on Operating Leakrate

The effect of a plant cooldown on existing thru-wall cracks is an insignificant increase in the crack arc length and an increase in the crack COD duing the cooldown due to the tube loads being higher during the cooldown than during normal power operation. An additional effect, which is observed as common occurrence (ref. No. 10), is that some plastic deformation has taken place which does not return the COD to its original size when the axial load is removed. Thus, a plant cooldown increases the COD plastically so that the crack leakrate during a return to power will have increased from its leakrate prior to the cooldown. This phenomenon is not included in the leakrate predictions and could result in a substantial increase above the predicted values. Thus, even if the operating tube loads are low, such an increase in leakrate from one or several tubes could result in exceeding the 6 gph administrative leakrate limit.

Although data is not available in order to quantify this phenomenon we have approximated (from ref. No. 12) the required residual COD of the crack COD during a cooldown that will result in a 6 gph leakrate from the crack during the next return to power.

Tube Location	Periphery		Core	
Crack Arc Length (Inches)	0.5		1.25	
Required Residual Crack Opening(mils)	0.45		0.2	
Cooldown Tube Load Max/Min (lbs)	1050	800	400	250
COD @ Cooldown (mils)	1.13	0.9	1.0	0.5
Req'd Residual Opening to COD @ Cooldown (%)	40	50	20	40

Since the crack tip will experience some localized plastic strain plus some crack surface grain loss as a result of the cooldown it is quite conceivable that the residual crack opening will be as large as 50 percent of the crack COD during the cooldown. Therefore, we expect sub-critical cracks to leak at or in excess of 6 gph as soon as the RCS is repressurized during the next plant heatup and be detectable by RMA-5 once the OTSG's start steaming to the condenser.

Thus, a defect which has grown to a critical size during a plant cooldown, would yield an operating leakrate increase of 6 gph or more during the next return to power.

8.3 Conservatisms and variables in Predicting Leakrates

We've reviewed the referenced NSAC leakrate prediction method and have concluded it contains some offsetting assumptions which still provide fairly accurate predictions at given axial tube loads.

The following is a brief review of the NSAC leakrate prediction method:

1. Size of Crack Opening Displacement (COD)

   The NSAC values of COD should be increased by 30% for 0.5" circumferential cracks because of recognized inaccuracy for larger cracks (ref. 11 & 12). The equation used for COD, here called δ , is:

$$\delta = \frac{4ka}{E'\sqrt{\pi a}} \cdot \frac{F_1(a,t)}{F(a,t)}$$

   where, a, dimension of crack in circumferential
   k, stress intensity for circumferential crack in cylinders
   F(a,t) function of crack length and cylinder thickness, t.
   $F_1(a,t)$, second function of same vaiables as above
   $E' = \frac{E}{1-\nu^2}$

   The equation uses the flat slate value for the ratio of functions. For a flate plate, $\frac{F_1(a,t)}{F(a,t)} = 1$.
   For large cracks a cylinder will buldge. This feature is not part of the flate plate solution. The use of a unity value of this ratio for large "a" valves ignores this bulding and leads to an underestimation of COD for large "a".

   Using ref. 12, the COD for an 0.5" circumferential crack under 500 lbs. tensile operating load is 0.586 mils. EPRI/NSAC predicts 0.44 mils for the same conditions

2. Wear of COD profile

   Wear of the crack profile will increase COD as leakage proceeds. Flashing of coolant involves local cavitation. Cavitation is recognized as a material wear mechanism. This entrance effect causes a pressure drop due to acceleration. Fluid shearing forces will wear the profile due to the associated force. Wear mitigates pressure drop due to flow meandering around transgranular roughness. This pressure drop term was not considered in the EPRI/NSAC report (ref. 13).

3. Conclusion regarding NSAC Leakrate Calculations

   a. EPRI methodology contains an appropriate accounting of pressure drop terms. (ref. 12).
   b. The EPRI methodology tests for flashing.

   c. Differences in assumptions are mitigated by off-setting effects; recognized simplifications in crack model uses a parallel sided slot;

typical through-wall convergence is offset by knowlingly ignoring buldging.

The NSAC method for predicting leakrate does not account for a circumferential tube crack to remain open after it has been subjected to a large load. This occurs when the crack tip has been plastically strained to result in a residual COD (see Section 8.2). We have applied this concept to evaluate leakage from pre-critical cracks at power operating conditions and bewlieve it to be a valid and reasonable approach. Note that the OTSG hot testing program and successive plant cooldowns will produce such a residual COD in pre-critical cracks.

GPUN's application of the NSAC leakrate prediction at tube loads other than the 1107 lbs. and 500 lbs. was conservative in the transition region where the COD and leakrate change from a linear to non-linear function of crack arc legnth. The conservatism comes from linearizing the NSAC predictions in both regions, utilizing the greatest slope of the non-linear portion and then utilizing the higher leakrate value resulting from the two equations. Thus, in the leakrate transition region, GPUN's leakrate predictions will be conservatively lower than those predicted by NSAC.

8.4 Predicted Leakrate During Plant Cooldown

Leakrates from thru-wall defects approaching the critical crack sizes for both a generic MSLB and TMI-1 specific MSLB were calculated on the basis of tube loads that represent a normal cooldown with a 70^{o} delta-T limit and loads that represent a cooldown with a 140^{o}F delta-T limit. We also calculated the predicted leakrates from tubes which had lost their pre-load. Table 8-1 summarizes the results and figure No. 3 provides a graphical summary.

This table demonstrates that during a plant cooldown, the predicted leakrate from a crack that is not yet of critical size for either the generic or TMI-1 specific MSLB tube loads, will leak in excess of the 6 gph administrative limit. These predictions include tubes that have a pre-load and also tubes that have jumped down during the kinetic expansion repair process. Since we have not identified any tubes in the core region which have jumped down, one may safely conclude their leakrate during a cooldown to be significantly in excess of 6 gph. The lowest predicted leakrate from a peripheral tube during cooldown is based on a pre-critical crack for the generic MSLB tube loads and that the tube has lost its pre-load. Even with these conservative assumptions, such a tube will have a crack leakrate which is predicted to be twice the value of the administrative limit.

Table No. 8-1

OTSG Tube Leakrates

During Plant Cooldown

Tube Location	Core				Periphery			
Crack Size Basis	Generic MSLB		TMI-1 Specific MSLB		Generic MSLB		TMI-1 Specific MSLB	
Crack Size (inches)	1.25		1.5		0.5		0.63	
Cooldown Tube Load Basis(see note below)	A	B	A	B	A	B	A	B
<u>Cooldown w/140°F T Limit</u>								
Cooldown Tube Load (Lbs)	600	800	600	800	1500	1750	1500	1750
Leakrate @ cooldown (GPH)	73	110	96	144	34	42	74	92
<u>Cooldown w/70°F T Limit</u>								
Cooldown Tube Load (Lbs)	150	400	150	400	800	1050	800	1050
Leakrate @ Cooldown (GPH)	8	40	11	52	12	19	29	44

Note:

A = Tubes which have jumped down in the upper tubesheet.

B = Tubes with pre-load

8.5 Conclusion

The review of the NSAC method for predicting leakrates from OTSG tube cracks indicated that the method provides predicted values which do not overestimate the leakrate. GPUN's adaptation of the NSAC results for other tube load conditions yields crack leakrate values which are conservatively lower than the NSAC predictions, especially in the transition region where plastic flow start to occur at the crack tip. Thus, the leakrate predictions presented in this evaluation are not over-estimate but are reasonable and expected values.

The effect of a plant cooldown to open a crack and leave a residual but somewhat smaller crack opening after the cooldown load is removed is discussed and provides a reasonable approach for predicting the leakrate from cracks during power operation. Such an effect is expected to leave a sufficiently large residual opening in pre-critical cracks to result in crack leakage in excess of 6 gph during power operation when the tube load may be non-existant. Thus, tube defects which are pre-critical for the generic MSLB tube loads would be detected at the next return to power.

Leak monitoring during a plant cooldown provides the greatest sensitivity for detecting pre-critical cracks in the OTSG tubes. Such leakage can be expected to be at least twice the 6 gph administrative leakrate limit value, even with the most conservative assumptions regarding crack size, tube pre-load and leakrate predictions.

9.0 Results and Conclusion on Detection of Critical Cracks by Leak Monitoring

This evaluation has addressed circumferencial IGSAC cracks in the TMI-1 OTSG tubes which may have been missed by the ECT inspection and OTSG hot and cold testing programs, the mechanism by which such defects propagate, the calculated tube loads at power, during plant cooldowns, and during postulated accidents, the predictions of crack leakrates and the differences in assumptions and sensitivities that may exist. In the previous sections conclusions were reached regarding the various aspects affecting the ability to monitor leakage from tube cracks before they propagate to a critical size.

9.1 RESULTS:

These individual conclusions are summarized at this point as the results of this evaluation.

1. The defects which may have been missed by the ECT inspection has a maximum size of 0.3026 inches arc length, if the defect is not yet thru-wall. Thru-wall cracks of this size would have been detected by the cold OTSG drip and bubble tests and by the OTSG hot testing program.

2. Crack propagation during normal operating conditions, for sizes up to the critical crack size for normal plant cooldowns, is stable (not rapid) and results from the heatup/cooldown load cycle. Defects with 0.34 inch thru-wall cracks can sustain 40 years of normal load cycling without failure during the final cooldown. Small thru-wall cracks do not propagate as a result of axial tube loads during power operation including FIV loads.

3. Tube load predictions contain some variables which are dependent on assumed operating conditions and tube pre-load. In terms of critical crack size detection by leak monitoring, these variables have greater significance during power operation than during plant cooldowns. The generic evaluation predictions of tube loads during a cooldown seem to be unconservatively low. GPUN has therefore utilized our own predictions of cooldown tube loads.

4. Pre-critical cracks subject to cooldown load cycles are stable and require numerous heatup/cooldown cycles to become critical for postulated generic MSLB tube loading.

5. Pre-critical cracks which have been subjected to cooldown loads will probably produce leakage in excess of 6 gph during power operating conditions. Thus, affording a means of detection at oprating conditions.

6. Leak monitoring during a plant cooldown will provide a very measurable indication of pre-critical cracks for MSLB loading even in the absence of tube pre-load.

9.2 Conclusion:

These results indicate that the plant can be operated safely at power without propagating a crack to a critical size for MSLB loading before the next plant cooldown. The normal cooldown tube loading will not result in a tube failure nor propagate a pre-critical crack to a critical size for the generic MSLB tube loading. The cooldown tube loading will provide a residual crack opening displacement which allows monitoring and detection of pre-critical crack sizes during power operation even in the absence of tensile tube loads during power operation.

Additional margin is provided by an expectation that leakage would most probably originate from a number of tubes, with each one contributing to the aggregate which is being monitored and limited to 6 gph.

Therefore, the ability to detect a critical size crack in the TMI-1 OTSG tubes has been demonstrated to exist with a 6 gph leakrate administrative limit.

Monitoring and evaluation of leakrate during plant cooldowns will provide additional information regarding the existance of pre-critical circumferential defects.

10.0 REFERENCES

1- GPUN TR-008 Rev. 2, "Assessment of TMI-1 Plant Safety for Return to Service After Steam Generator Repair".

2- B&W report BAW-10146, Oct. 1980, "Determination of Minimum Required Tube Wall Thickness for 177-FA Once-Through Steam Generators"

3- B&W Calc. No. 32-20068 Rev. 0

4- B&W letter (L.J. Stanek) to GPUN (D.G. Slear) No. GPUN-83-194 dated 4/25/83 "TMI-1 Cooldown Basis for 1107 lb. OTSG Tube Load"

5- GPUN TDR-421 Rev. 0, "TMI-1 Steam Generator Adequacy of Tube Plugging and Stabilizing Repair Criteria".

6- MPR Assoc. Calc. "Maximum Crack for 1580 lb. Cyclic Tensile Load", by P.S. Damerell, dated 5/26/83.

7- GPUN TDR-388 Rev. 3 "Mechanical integrity Analysis of TMI-1 OTSG Unplugged Tubes"

8- GPUN TDR-459 Rev. 0 "TMI-1 OTSG Tube Axial Load Calculation Model"

9- GPUN memo No. MTI-1286, dated 3/15/83, J. A. Janiszewski to G. L. Lehmann "Measurement of Tube Gaps after Explosive Expansion"

10- GPUN memo No. 3310-83-177, dated 6/29/83, "A and B OTSG Gap Measurements" F. W. Paulewicz to R. o. Barley

11- Report by F. Erdogan, "The Residual Crack Opening Displacement in Tubes and Pipes" transmitted by letter dated 8/2/83, F. Erdogan to S. D. Leshnoff.

12- EPRI/NSAC report, "Leak-Before-Break in Once-Through Steam Generator Tubes", presented at the Steam Generator Owners Group Technical Advisory Committee meeting on 5/12/83.

13- F. Erdogan, "Fracture Analysis of Steam Generator Tubes, Part II. Stress Intensity Factor and COD Calculations", prepared for GPUN

14- GPUN memo No. EM-83-732, dated 7/5/83, J. P. Sheu to S. D. Leshnoff, Review Calculation of Leak Rates from Cracks in Steam Generator Tubes by EPRI/NSAC (ref. No. 12).

15- GPUN, EM Calc. No 1101X-5320-A49 by S. D. Leshnoff

16- B&W letter (J. F. Pearson) to GPUN (D. G. Slear) No. SGS/TMI-83-127, dated 9/6/83 "Review of GPUN TDR-417 Rev. 1". 2

Fig. No. 1

TDR-417

100°F/Hr. Cooldown; 140°F △ T Limit w/280# Tube Pre-load

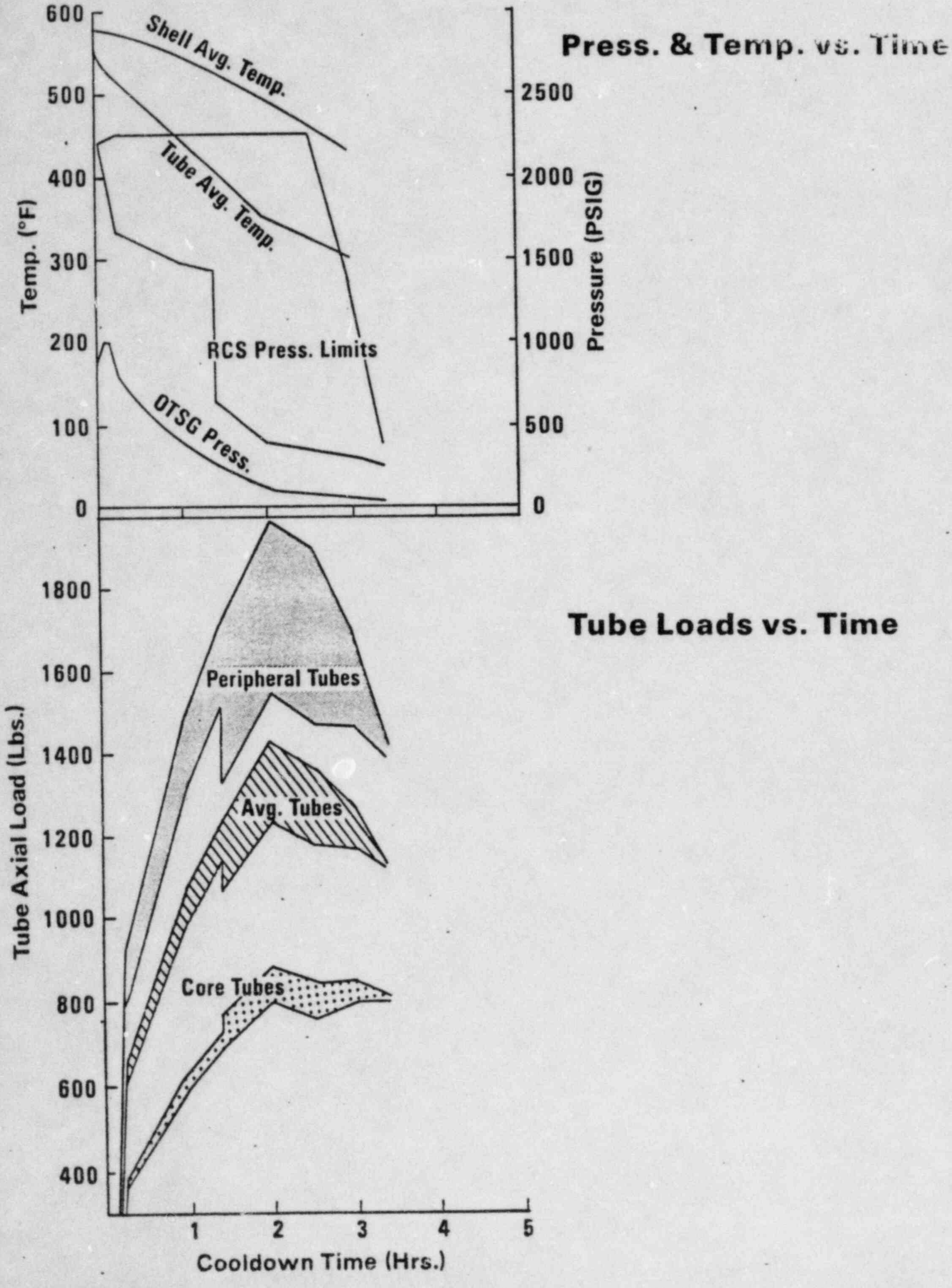
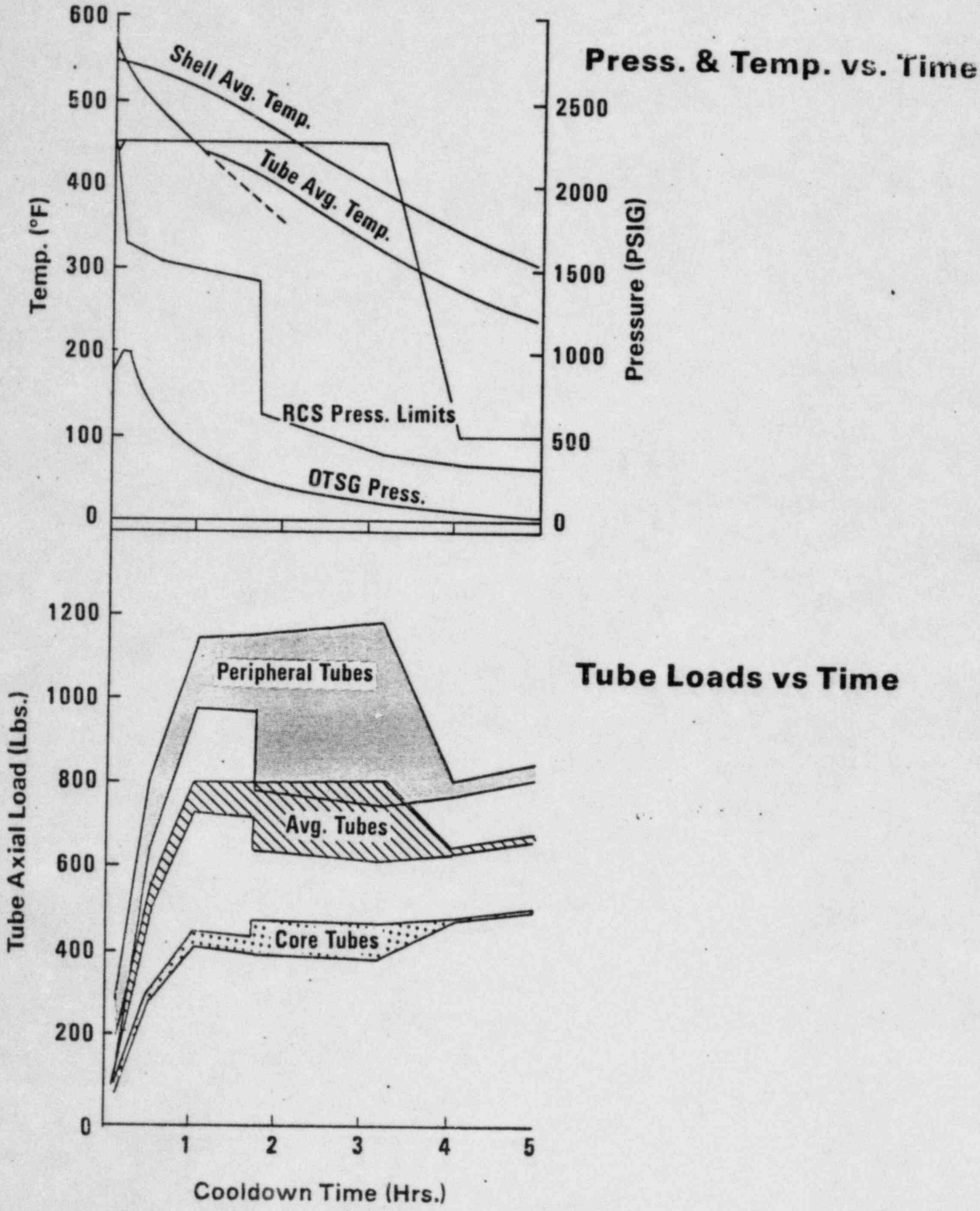


Fig. No. 2

Cooldown; 70°F △ T Limit w/280# Tube Pre-load



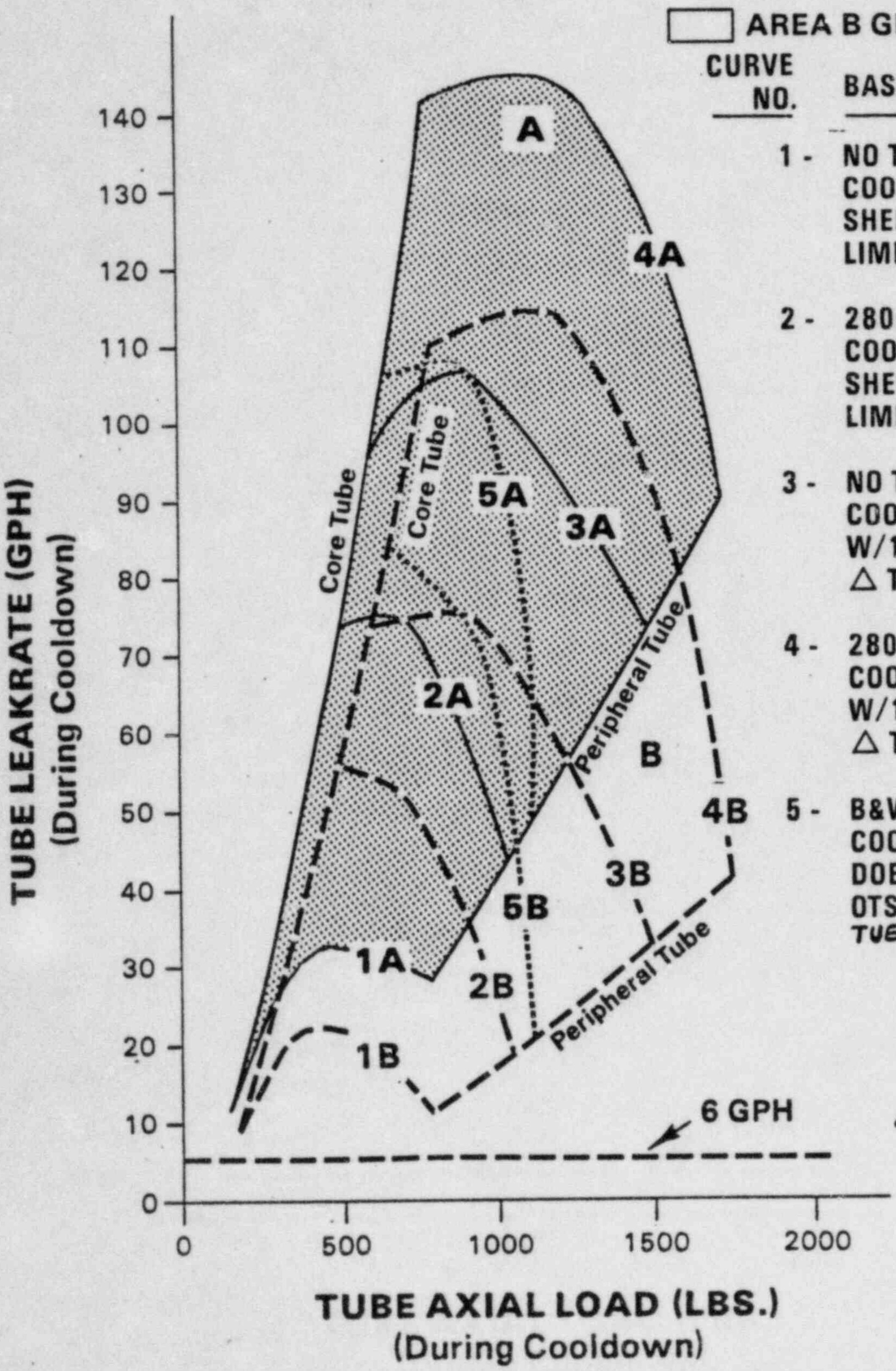
T DR-417

Fig. No. 3

TMI-1 OTSG
Tube Leakrate During Plant Cooldown From MSLB Pre-Critical Crack in One Tube at Various Cooldown Conditions

AREA A TMI-1 SPECIFIC MSLB

AREA B GENERIC MSLB



CURVE NO.	BASIS
1 -	NO TUBE PRE-LOAD: COOLDOWN W/70°F SHELL TO TUBE △ T LIMIT.
2 -	280# TUBE PRE-LOAD: COOLDOWN W/70°F SHELL TO TUBE △ T LIMIT.
3 -	NO TUBE PRE-LOAD: COOLDOWN AT 100°F/HR W/140°F SHELL TO TUBE △ T LIMIT
4 -	280# TUBE PRE-LOAD: COOLDOWN AT 100°F/HR W/140°F SHELL TO TUBE △ T LIMIT
5 -	B&W GENERIC COOLDOWN TUBE LOADS. DOES NOT INCLUDE RCS & OTSG PRESSURE LOADS *OR TUBE PRE-LOAD*

△2

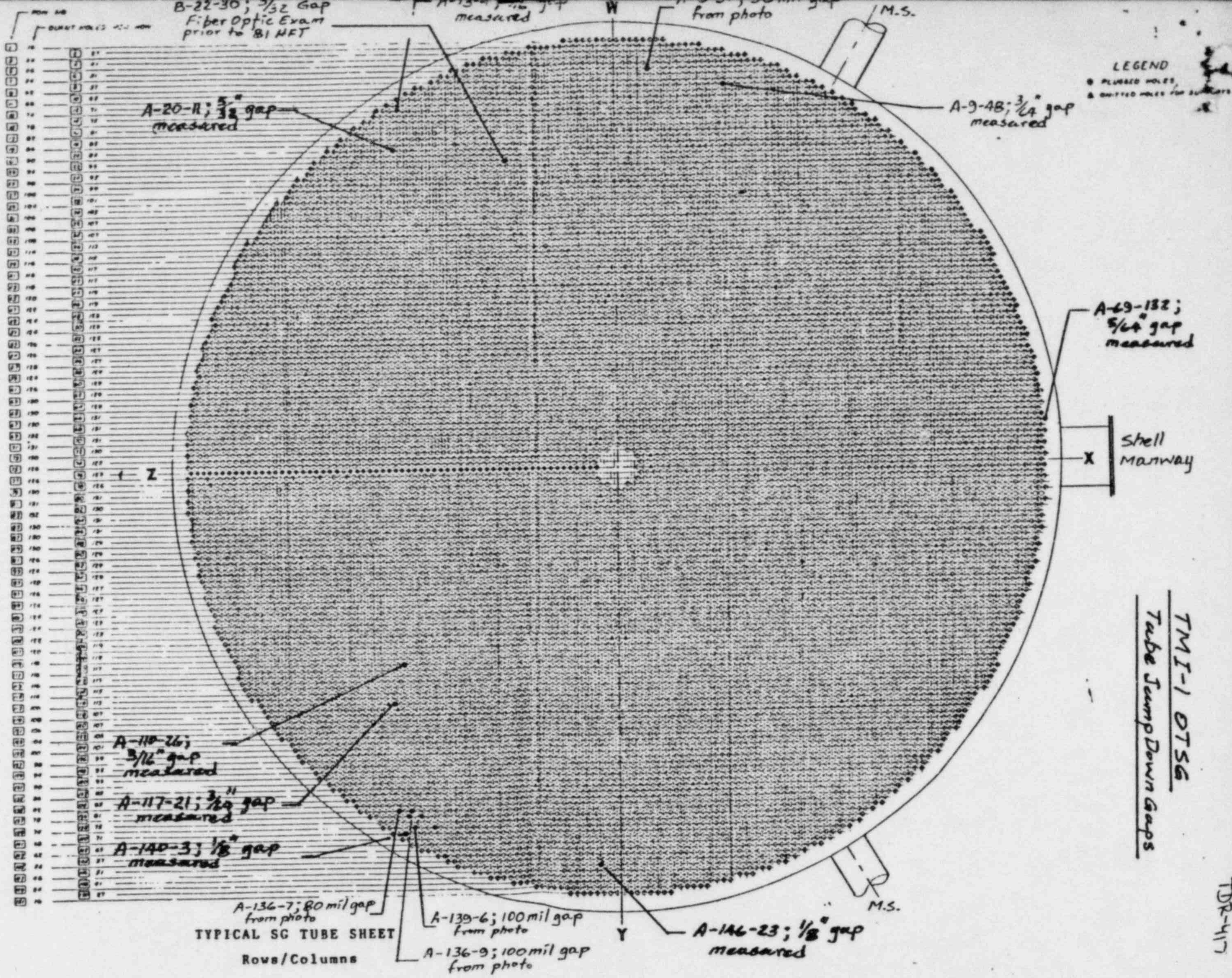


Fig. No. 4

TMI-1 OTSG
Tube Jump Down Gaps

TDR-417