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WCAP-14344

SG-95-04-011

SLIDE PRESENTATION MATERIAL
NRC MEETING OF FEBRUARY 23 1995
ALTERNATE PLUGGING CRITERIA WITH TUBE EXPANSION FOR THE BRAIDWOOD 1 AND BYRON 1 MODEL D4 STEAM GENERATORS

APRIL 1995

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Overall Approach to Tube Expansion Based APC

- General Approach
- Tube Repair, Inspection and Analysis Requirements(Q. 1f, 2b)
- Burst Probabilities(Q. 4)

Westinghouse Proprietary

- Functional Requirements and Performance(Q. 1a)
- Tube Expansion Matrix
- Structural Limit Considerations(Q. 2a)

NRC/ComEd/Westinghouse Meeting

February 23, 1995

Presented By:

T. A. Pitterle
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WCAP/Presentation Response to NRC Questions

NRC Question No./Topic	WCAP Section	Presentor
1a. Overall functional requirements Tube expansion requirements	12.1, 12.2 10.1	Pitterle
1b. Tube expansion design and process qualification	10.2 to 10.4	Keating
1c. Exp. tube circumferential cracking assessment	10.6	Pitterle
1d. Potential for ODSCC propagation by tube exp.	10.2	Pitterle
1e. Need for stress relief of expanded tube	10.2	Pitterle
1f. Plugging & monitoring of expanded tubes	12.4	Pitterle
2a. Satisfaction of R.G. 1.121 margins	9.10	Pitterle
2b. NDE methods for higher repair limits	10.4 12.4	Malinowski Pitterle
2c. Assurance of TSP integrity	10.7	Keating
2d. NDE methods for TSP inspection for cracks	10.4	Malinowski
2e. Accuracy requirements for hydraulic calculations • Hydraulic analyses and sensitivity • Displacement analyses and sensitivity	 6.5, 6.6, 5.6 8.4 to 8.8	 Hu Smith
3. Leakage considerations for overpressurized ind. Probability for overpressurized ind. Leakage evaluation of the constrained tube	9.7, 9.8 12.5	Keating
4. Burst probabilities with tube expansion Multiple tube burst probability considerations	11.1 to 11.3, 12.2	Pitterle
5. Structural considerations with locked TSPs • Stress analyses • Locked TSP interaction effects	 8.10 8.11	 Smith Pitterle

Tube Expansion Based APC
Overview

Why Tube Expansion?

- Significantly increases SG safety margins by essentially eliminating the potential for tube ruptures at TSP intersections under accident conditions

- Significantly increases tube repair limits for indications at TSP intersections by eliminating axial tube burst as a basis for limiting repair limits

How Achieved?

- Expanding tubes above and below TSP intersections to limit TSP displacement under accident conditions and, thereby, permit TSP constraint to prevent tube rupture

Tube Expansion Based APC
Overview

How Have Significant Issues Been Resolved?

- Circumferential cracking concerns by plugging expanded tubes to lower temperature, including sleeve stabilizer at expanded tube intersections and adding redundant expansions
- TRANFLO load concerns by applying factor of two on expected hydraulic loads for expansion design analyses
- SLB leak rate for potentially overpressurized indications by including a bounding term for this condition in addition to conservative free span leak rate analysis
- Implications for locked TSP effects from expanded tubes shown to be negligible based on expansions increasing "total stayrod stiffness" by about 10% and:
  - With minimal tube/TSP contact force, no significant change in tube/TSP or tube/TSP/wrapper interactions
  - With tubes "locked" to TSPs, expanded tubes are equivalent to another plugged tube with no new loading conditions

General Approach to Tube Plugging Criteria

Define Acceptable TSP Displacement Requirements

- Achieve burst probability negligible (10^{-5}) compared to NRC 10^{-2} Reporting Guideline

Conservatively Apply Factor of 2 Margin on TRANFLO Hydraulic Loads

- Factor of 2 envelopes collective uncertainties found from TRANFLO sensitivity analyses and independent analyses with MULTIFLEX code

Include Provisions for Postulated Severed Expansions Due to Circumferential Cracking at Expansion Locations

- Obtain tube stabilization with a sleeve stabilizer

- Include redundant expansions at critical TSP locations approaching the 0.31" displacement acceptance limit

Demonstrate that TSP Displacements are Less Than Acceptable Limit for Tube Burst Probability Considerations

- Demonstrate through TSP displacement analyses with factor of 2 on TRANFLO loads and without including redundant expansions

More Limiting TSP Displacement Goal Defined for Tube Expansions to Provide for Option to Implement In Situ Leak Testing

- TSP displacements of about 0.1" or smaller permits direct application of in situ leak rate measurements since these small displacements would not expose significant through wall crack lengths

Braidwood-1 and Byron-1 Tube Repair Limits

For hot leg TSP indications, bobbin flaw indications > 3.0 volts and confirmed by RPC inspection shall be repaired. Bobbin flaw indications > 10.0 volts shall be repaired independent of RPC confirmation.

For indications at cold leg TSP intersections, bobbin flaw indications > 1.0 volt and confirmed by RPC inspection shall be repaired. Bobbin indications greater than 2.7 volts shall be repaired independent of RPC confirmation.

Other tube repair criteria related to cracks outside the TSP, circumferential cracks, indications at dents, etc., are the same as the NRC generic letter.

General Inspection Requirements

The bobbin coil inspection shall include 100% of all hot leg TSP intersections and cold leg TSP intersections down to the lowest cold leg TSP with ODSCC indications.

All bobbin flaw indications exceeding 3.0 volts for hot leg TSP intersections and 1.0 volt for cold leg TSP intersections shall be RPC inspected. In addition, a minimum of 100 hot leg TSP intersections with bobbin voltages less than 3.0 volts shall be RPC inspected. The RPC data shall be evaluated to confirm responses typical of ODSCC within the confines of the TSP.

A RPC inspection shall be performed for intersections with dent signals > 5.0 volts and with bobbin mixed residual signals that could potentially mask flaw responses near or above the voltage repair limits. The RPC inspection sample shall include a minimum of 100 intersections.

Supplemental Inspection Requirements for Tube Expansion

If a 570 mil probe does not pass thru a dented TSP intersection (dent > 65 mils), all surrounding tube locations must be repaired to the free span cold leg TSP criteria

- Braidwood-1 and Byron-1 have no known corrosion induced dents at the TSP intersections. Thus, there is no concern for TSP integrity and there is no need to identify exclusion areas for application of the APC repair limits or for tube expansion candidates.

The tubes selected for expansion and the surrounding tubes shall not have corrosion induced dents > 5.0 volts

- Since Braidwood-1 and Byron-1 have no corrosion induced denting, there are no restrictions on selection of tubes for expansion

Following application of tube expansion, the expanded TSP intersections shall be inspected with a bobbin probe for process verification

- Bobbin profilometry to verify acceptable expansion diameters and to demonstrate proper location relative to the TSP

At every third refueling inspection following tube expansion, a minimum of three expanded tubes shall be deplugged and inspected for circumferential crack indications at the expanded TSP intersections

- If circumferential cracks are found, the adequacy of the expansion sample size and the redundancy in the tube expansion matrix shall be evaluated

SLB Leak Rate and Tube Burst Probability Analyses

SLB leak rates and tube burst probabilities shall be evaluated for the actual voltage distribution found by inspection and for the projected EOC distribution

Acceptance and Reporting Requirements

- The SLB leak rate shall be compared to the allowable limits as given in the Tech Specs and potentially modified by administrative controls
- The SLB tube burst probability for cold leg TSP intersections shall be compared to the reporting value of 10^{-2} and the NRC shall be notified prior to returning the SGs to service if the allowable limits are exceeded
- If the allowable limits are exceeded for the projected EOC distribution, the NRC shall be notified and an assessment of the significance of the results shall be performed

The SLB leak rate analysis can be symbolically represented as:

$$LR_{SLB} = [(1\text{-}POB)^{*}POL^{*}LR_c + POB^{*}LR_b]_{\text{hot leg TSPs}} + [POL^{*}LR_c]_{\text{cold leg TSPs}}$$

Table 11-1
Allowable Model D4 SLB TSP Displacements for Acceptable SLB Tube Burst Probability[1]

No. Hot Leg TSP Intersections	Acceptable SLB TSP Displacement	Burst Probability Per Indication	Total SLB Tube Burst Probability
Uniform TSP Displacements at All TSPs and Tube Locations			
32,046	0.36"	3.1×10^{-8}	1.0×10^{-3}
32,046	0.33"	3.1×10^{-9}	1.0×10^{-4}
32,046	0.31"	3.1×10^{-10}	1.0×10^{-5}
Non-Uniform TSP Displacements			
45 <u>32041</u> 32046	0.434" 0.311"	2.2×10^{-5} 3.1×10^{-10}	0.99×10^{-3} $\underline{0.01 \times 10^{-3}}$ 1.0×10^{-3}
150 <u>31896</u> 32046	0.388" 0.315"	5.7×10^{-7} 4.7×10^{-10}	0.85×10^{-4} $\underline{0.15 \times 10^{-4}}$ 1.0×10^{-4}
10 <u>32036</u> 32046	0.424" 0.282"	1.0×10^{-5} 1.3×10^{-11}	1.00×10^{-4} $\underline{0.004 \times 10^{-4}}$ 1.0×10^{-4}

Notes:

1. Burst probability estimates very conservatively postulate that all hot leg TSP intersections have a throughwall crack length at least equal to the SLB TSP displacement

Table 11-2 Objectives for Model D4 SLB TSP Displacements and SLB Tube Burst Probabilities with Tube Expansion[1]				
No. Postulated Severed Expansions	**SLB TSP Displacement Objective**	**No. TSP Intersections Displaced**	**Single Indication SLB Burst Probability**	**Total SLB Tube Burst Probability**
0	≤ 0.10"	32,046	$\leq 10^{-15}$	$\leq 10^{-10}$
1, 2 or 3 at redundant tube locations	≤ 0.31"	32,046	$\leq 3.1 \times 10^{-10}$	$\leq 10^{-5}$
Any 2 except reference plus its redundant location	≤ 0.31"	32,046	$\leq 3.1 \times 10^{-10}$	$\leq 10^{-5}$

Notes:

1. Burst probability estimates very conservatively postulate that all hot leg TSP intersections have a throughwall crack length at least equal to the SLB TSP displacement

Table 12-1. Overall Requirements for Tube Expansion Application

TSP Displacements and Tube Expansion Process Design Loads Shall be Based on Factor of Two Margin on TRANFLO Hydraulic Loads

- Provides margin against load uncertainties based on TRANFLO uncertainty study and independent analyses with the MULTIFLEX code

Maximum SLB TSP Displacements Shall Be Less Than 0.31" Even if It is Postulated That an Expanded Tube Severs

- Provides redundant tube expansions against a postulated circumferential crack in an expanded tube
- Results in a tube burst probability < 10^{-6} even under extremely conservative assumption of throughwall cracks at all hot leg TSP intersections

As a Design Goal, the Maximum SLB TSP Displacements Shall Be Less Than 0.1" With No Severed Expanded Tubes

- Permits application of in situ leak rate measurements if required to limit leakage to acceptable levels (applied if predicted free span leakage using EPRI correlation exceeds allowable leak rate)
- Expanded tube stiffness shall be sufficient to satisfy this requirement
- Provides tube burst probability < 10^{-10} even under extremely conservative assumption of throughwall cracks at all hot leg TSP intersections

The Tube Expansion Process Shall Provide Adequate Tube Stiffness to Limit TSP Displacements to Acceptable Levels and Shall Provide Tube Stabilization Capability for a Postulated Severed Expansion

- This requirement is further developed into process functional requirements in Table 12-2

Table 12-2. Tube Expansion Process Requirements

Tube Expansion Shall Be Performed with a Hydraulic Expansion Process

- Limits residual stresses compared to alternate expansion processes

Tubes Shall be Expanded Above and Below the TSP

- Provides for uncertainty in the direction of the hydraulic TSP loads

The Expanded Tube Shall Have a TSP Pull Force Capability of [

]^{a,b,c}

- Provides adequate tube stiffness to limit TSP displacements to < 0.1" at design hydraulic loads (twice expected) and to < 0.31" at twice the design loads. The tube stiffness requirement is used in TSP displacement analyses.

A Sleeve Stabilizer Shall be Installed by Hydraulic Expansion at the Expanded Parent Tube TSP Intersections

- Prevents damage to adjacent tubes for a postulated severed tube at the tube expansion

The Maximum Expanded Tube Diameter Increase Shall be [ ]^{a,b,c}

- Limits residual stresses for hydraulic expansions to less than that typical of a tubesheet hardroll expansion. This is a process development goal and not a basis for rejection of field expansions.

Table 12-3. Comparison of Tube Expansion Design Requirements and Demonstrated Performance				
Parameter	Requirement	Design Goal	Demonstrated Performance	
			Result	Report Section
Design Requirements				
Maximum TSP Displacement • All 21 tube expansions functional • 16 tube expansions functional (Excludes redundant exp.)	≤ 0.31" ≤ 0.31"	≤ 0.10" ≤ 0.31"	0.094" 0.094"	8.5 8.6
Expanded tube stiffness				a,b,c
Expanded tube TSP pull force at 3/8" displacement				
Sensitivity Analysis Results				
Maximum TSP displacement with factor of 4 on TRANFLO loads (design basis is factor of 2)	None	≤ 0.31"	0.189"	8.6
Maximum TSP displacement assuming severed expansions for 6 of 8 expanded tubes (excluding redundant locations) at TSPs 3, 5 and 7 (lower 3 TSPs above FDB)	≤ 0.31"	≤ 0.31"	0.097 Note 1	8.6
Maximum TSP displacement assuming severed expansions for 12 of 17 expanded tubes (excluding duplicate nearby locations) at TSPs 8 to 11 (top 4 TSPs)	≤ 0.31"	≤ 0.31"	0.200	8.6
Maximum TSP displacement with only 7 of the 21 expanded tubes functional (duplicate expansions functional)	≤ 0.31"	≤ 0.31"	0.199	8.6

Note 1. The sleeved expansion is fail safe against severed parent tubes at the lower 3 TSPs for which the hydraulic loads act in the downward direction toward the tubesheet.

Table 12-4. Summary of Conservatisms in Application of Tube Expansion for Limited TSP Displacement

Hydraulic Loads for TSP Displacements and Tube Expansion Requirements

- For design and analysis loads, TRANFLO hydraulic loads on TSPs increased by a factor of two to envelope TRANFLO uncertainties and independent analyses with the MULTIFLEX code
- Sensitivity analyses show that acceptable TSP displacements to limit burst probabilities can be obtained with a factor of four on the TRANFLO hydraulic loads

Number of Expansions

- Redundant tube expansions are included at regions of largest TSP displacements without expansion to limit tube burst probabilities even if the reference (excluding redundant expansions) expanded tubes are postulated to sever
- Sensitivity analyses show that acceptable TSP displacements to limit burst probabilities can be obtained with only two expanded tubes limiting displacements

TSP Displacements

- TSP displacements are limited to 0.10" compared to the acceptable 0.31" to limit tube burst probability
- TSP displacement analyses are based on an expanded tube [ ]^{a,b,c} which is exceeded by all acceptable expansions [ ]^{a,c,e} based on process qualification tests
- TSP displacements are essentially independent of a severed expansion at lower three TSPs (3, 5, 7) due to downward loads on the TSPs and lateral restraint to tube motion provided by the sleeve stabilizer

Burst Probability Estimates

- All hot leg TSP intersections postulated to have a throughwall indication at least equal to the TSP displacement at each tube location

SLB Leakage

- SLB leakage initially calculated as free span leakage as long as the conservative results remain within acceptable limits a

Figure 3-1. Model D4 Steam Generator Layout

Table 2-1

Example of Generic Tube Expansion Matrix

a,c

a,c

Figure 2-1. Map of Tube Expansion Locations

Structural Limit with Tube Expansion at TSP Intersections (Q. 2a)

Structural limit of EPRI ARC not applicable due to constraint of TSPs under both normal operating and accident conditions

With tube expansion, potential structural limit is axial tensile tearing resulting from pressure differential across the tube

Data used to assess axial tensile tearing structural limit

- Pulled tubes with cellular corrosion define applicable database since significant IGA has not been found at TSP intersections
- Plant E-4 pulled tube tensile test results for cellular corrosion
- Pulled tubes with measured uncorroded cross section profiles (Braidwood-1, Byron-1, E-4 and L)

Pulled tubes burst tested inside TSP help to define lower bound of the structural limit

- Since the indications opened axially inside the TSP, it is clear that the axial tensile capability is in excess of the burst pressure obtained for these tests

Structural limit at lower 95% confidence for axial tensile tearing found to be > 35 volts based on $3\Delta P_{NO}$ margin of R.G. 1.121

Table 9-3
Summary of Cellular/IGA Corrosion Data

a,c,e

IGADATA.XLSTbl9

Figure 9-9
Residual Strength of Tubes with Cellular Corrosion
(Data Fit Excludes IGA and Burst Data)

Residual Tube Cross Section (%)

Bobbin Volts

a,c,e

Ch-Sumry2IGADATA.XLS

ComEd / NRC
Meeting on

Increased Voltage IPC
for Braidwood 1 & Byron 1
February 23, 1995

Tube Expansion for TSP Restraint

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- **Tube Expansion Design Description**

  - The design consists of converting *out of service* tubes into pseudo-stayrods to prevent significant TSP motion during a postulated SLB event.

  - Conversion is effected by [ ]a,c,e

  - To provide additional structural integrity, the tube is lined with a [ ] a,c,e, Alloy 690 sleeve prior to effecting the expansion.

  - The sleeve provides parent tube constraint in the unlikely event that the tube severs at the Tube/TSP expansion.

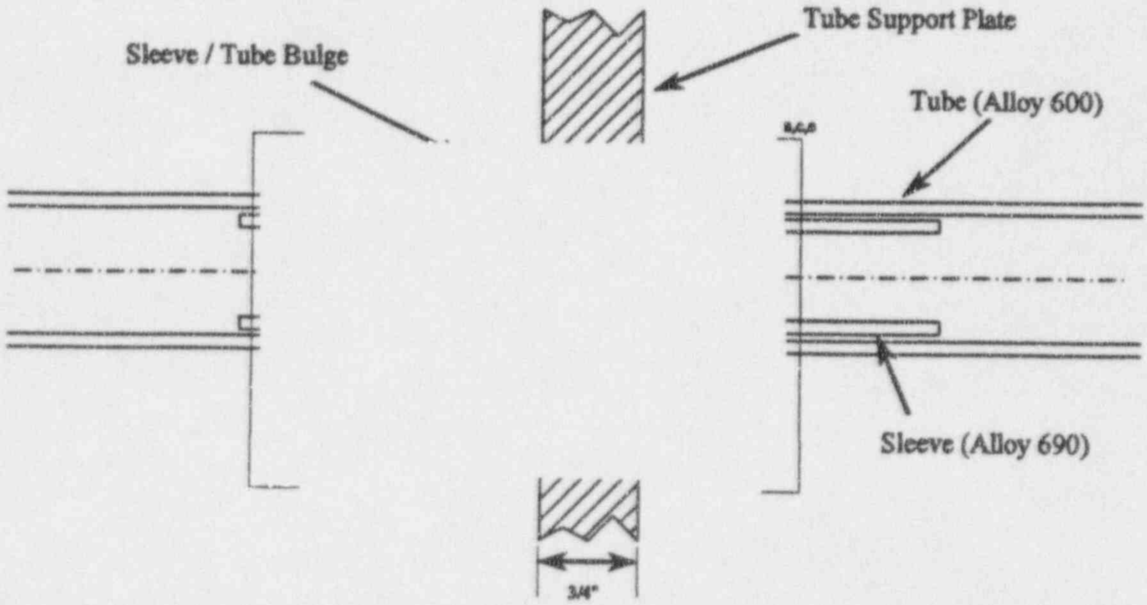

Figure 10-1: Capture of TSP by Tube/Sleeve Combination

NRC Question 1.b)

- **Design Summary**

  - Surrogate sleeve used to bolster stiffness and act as stabilization device.

    - [
    -
    -]a,c,e

  - Special expansion mandrel designed for TSP expansion sleeve length and configuration

    - Similar to LWS mandrel, except only one bladder expansion area provided

NRC Question 1.b (Cont.)

- **Process Description**
  - An existing LWS delivery tool positions the sleeve using an eddy current coil to locate the edge of the TSP, then is stroked a finite distance to position the sleeve.
  - A computer controlled expansion process is used to adequately provide appropriate expansion, [ ]a,c
    - [ ]a,c
  - [ ]a,c

a,c,e

NRC Question 1.b (Cont.)

- **Process Development Testing**
  - Low and high yield strength tubing used
  - "Unit cell" TSP collars used; sized to represent stiffness of actual TSP hole pattern
  - Simulated TSP specimens exhibited no permanent deflection in the radial direction for the maximum expansion pressure.
  - Expanded specimens tensile tested to determine stiffness of expanded joints
    - Bulge size versus pull force curve established
    - Minimum bulge size projected for low and high yield tubing such that minimum acceptable stiffness is provided by minimum acceptable size bulge
  - Implementation qualification in a full scale mockup will be performed at Waltz Mill prior to field installation.
  - Post expansion NDE to include diameter verification of each bulge

a,c,e

NRC Question 1.b) (Cont.)

- **Expansion Design Tests**

  - Pull tests performed in a calibrated tensile testing machine at 0.5" per second. Similar testing at 1.0" per second revealed no change in response.

  - Force versus bulge size curves were established for a variety of expansions at displacements of 0.125", 0.250" and 0.375".

  - Bulge size range of [ ][a,b,c] determined to be acceptable for tubing ranging from [ ][a,b,c]

  - Achieves stiffness of [ ][a,b,c]

    - Force/Deflection curve conservatively includes initial *slack* in the load testing fixture (~20 mils) and tube gripping devices (~30 mils).

    - Actual capability at a *true* TSP displacement of 0.1" could be expected to be 20 to 25% higher.

  - Maximum load of [ ][a,b,c] deflection.

a,c,e

NRC Question 1.b) (Cont.)

- **Expansion Process Tests**

  - Tested *oversized* unpacked and packed crevices with no significant effect on the bulging process.

  - Collars were monitored for permanent changes in diameter. (All collars were new.)

    - All collars remained elastic during the expansion testing.

    - Collars were sized to provide the same *average* radial stiffness as the TSP based on finite element analysis.

  - Testing in a TSP simulant with twenty-five tube holes and flow holes was performed. No changes in any hole or ligament dimensions were observed based on micrometer measurements.

- **TSP Integrity**
  - Elastic-plastic finite element model analyses performed considering:
    - No denting
    - All neighbors dented
    - Four pitch direction neighbors dented
    - Four diagonal neighbors dented
    - Two pitch direction neighbors dented
  - Only about 4 ksi of radial pressure is transmitted to the TSP hole.
  - Peak stresses ranged from 19.4 ksi for no denting to a maximum of 20.1 ksi for four diagonal neighbors dented.
  - **Denting of neighboring tubes has only a minor effect on the peak stress on the ID of the TSP hole.**

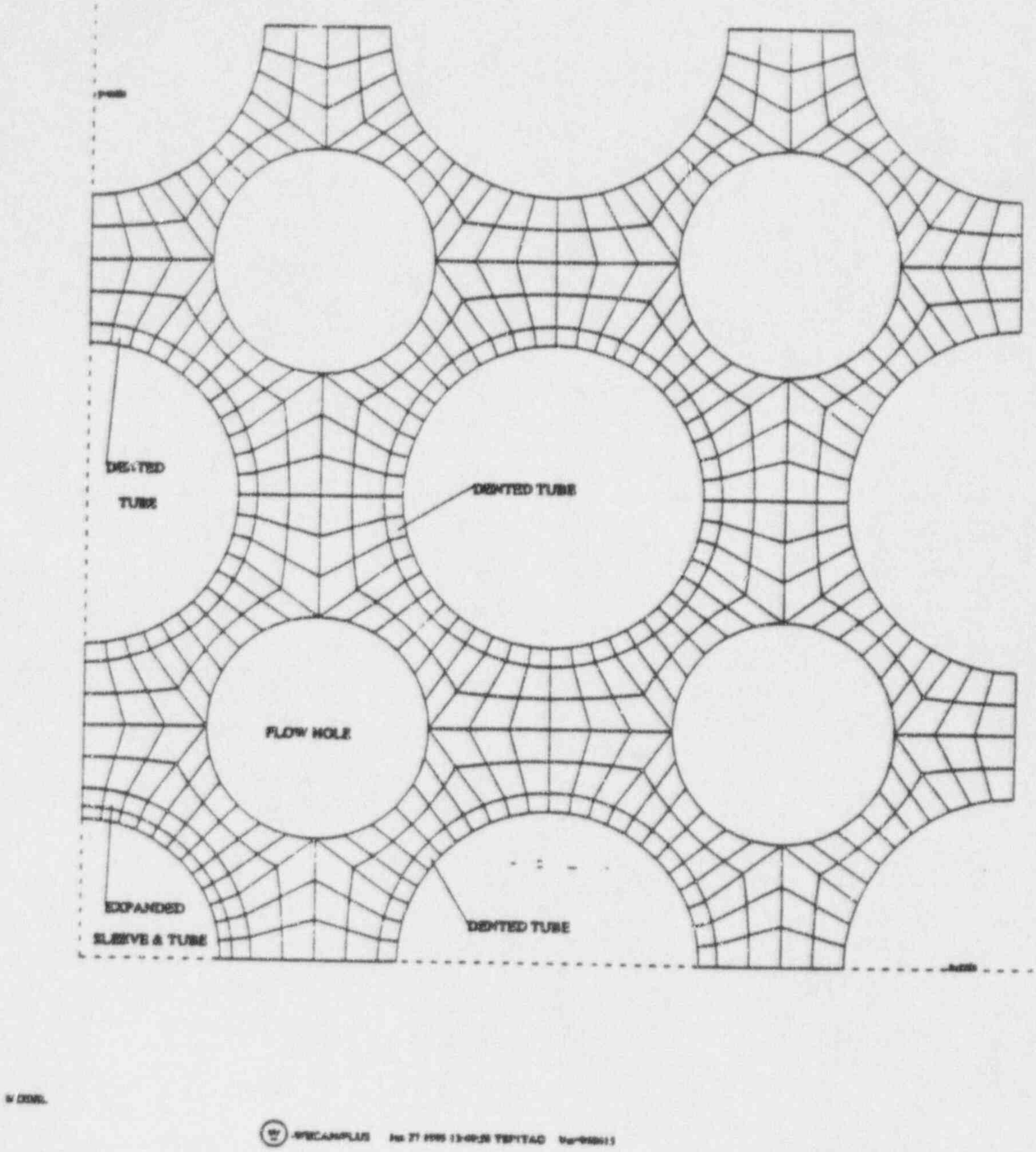

Figure 10-5. Finite Element Model of TSP With Expanded and Dented Tubes

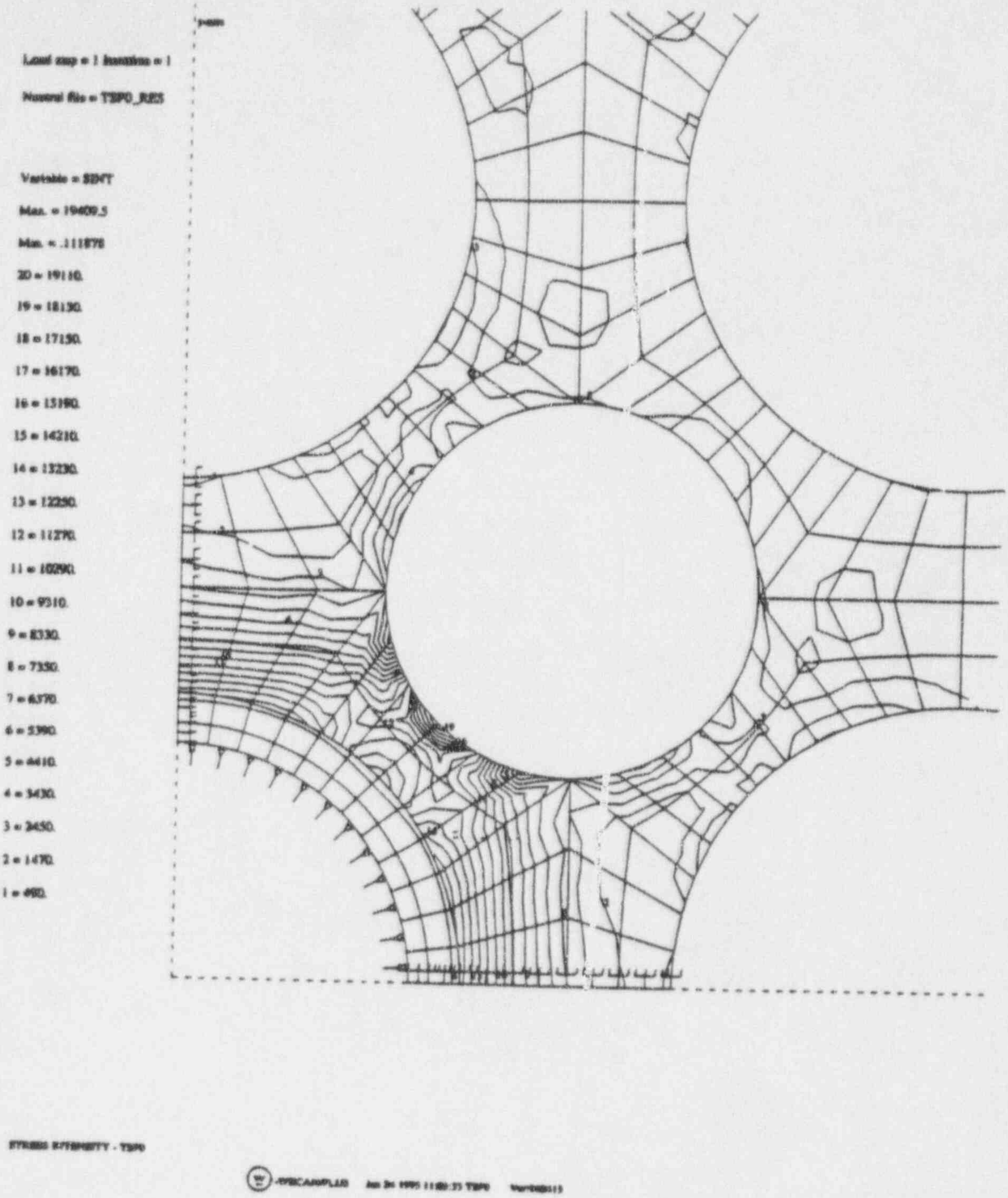

Figure 10-7. Stress Intensity Contours Near Expanded Tube

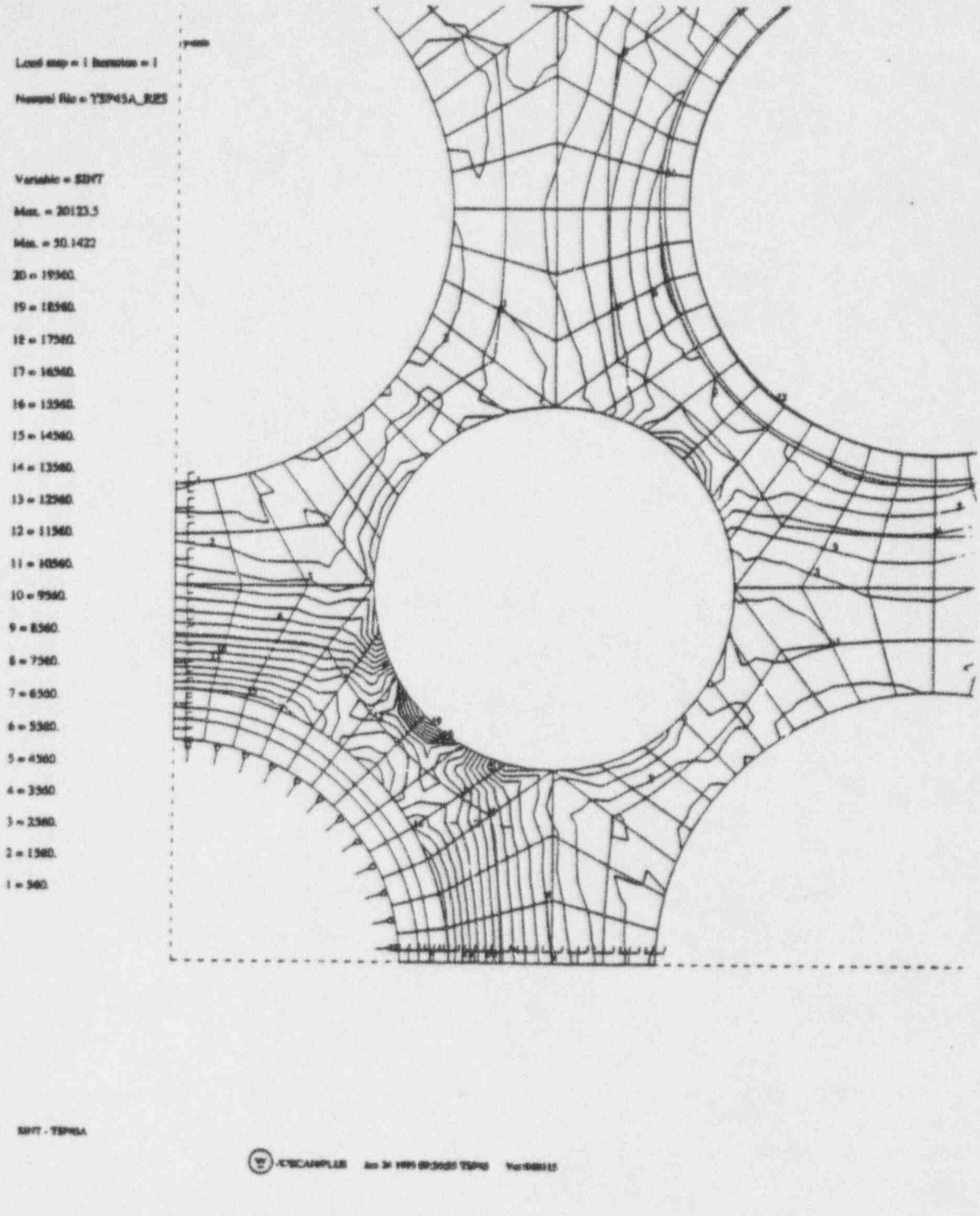

Figure 10-9. Stress Intensity Contours Produced by Tube Expansion With Four Dented Tubes in the Diagonal Direction

- For no denting, a minimum ligament of 0.072" could exist without yielding of the TSP hole at the ID surface for a TSP with minimum structural properties.
- For the worst denting case the minimum allowable ligament is about 0.075" for a TSP with minimum structural properties.
- The minimum ligament for gross yielding could be significantly smaller than those determined for yielding at the peak stress location.
- Nominal ligament is 0.110", hence it is unlikely that a minimum ligament case could occur.

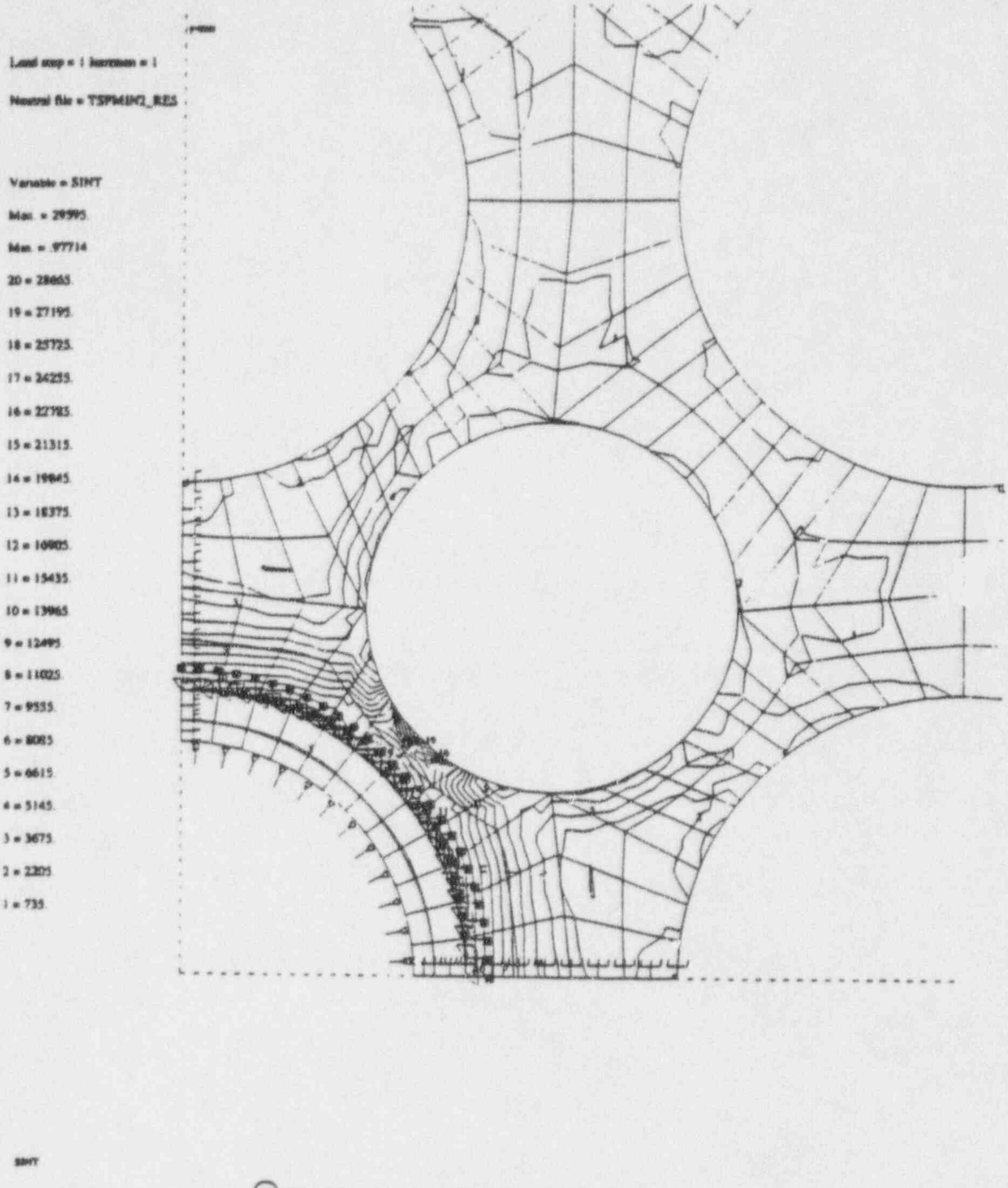

Figure 10-10. Stress Intensity Contours for Minimum Ligament

- **Conclusions**

  - Bulges in the range of [ ]a,c,e will be achieved in the Braidwood and Byron tubes as a result of the expansion process.

  - The bulges [ ]a,c,e will provide the required axial stiffness to restrict motion of the TSPs during a postulated SLB.

  - The Tube/TSP expansion process will not result in any yielding of the TSP ligaments.

Tube Expansion Process Evaluation

- Potential for Circumferential Cracking(Q. 1c)
- Locked TSP Interaction Effects(Q. 5)
- ODSCC Propagation by Tube Expansion(Q. 1d)
- Need for Stress Relief of Expansions(Q. 1e)

NRC/ComEd/Westinghouse Meeting

February 23, 1995

Presented By:

T. A. Pitterle
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Potential for Circumferential Cracking at Tube Expansions (Q. 1c)

Evaluation based upon:

- Operating experience for tubesheet expansions adjusted to plugged tube temperatures
  - Hydraulic expansions with no indications
  - Hardroll expansion time for hot leg circumferential cracking adjusted to plugged tube temperatures and no reported cold leg circumferential cracks
- Operating experience for implemented preheat region hydraulic expansions at cold leg TSPs (including Braidwood-1 and Byron-1) and U-bend repair at Plant G-1
- Laboratory tests on cracking of expanded tubes
  - Temperature sensitivity tests
  - SCC tests of bulged hydraulic expansions
  - Stress indexing tests

Potential for Circumferential Cracking at tube Expansions Conclusions

No occurrences of circumferential cracking in hydraulic tubesheet expansions operating at >615°F, in preheator hydraulic expansions or in field hydraulic expansion repairs

Stress Indexing Test Results

- ID residual stresses typical of normal hydraulic expansion (i.e., minimal sensitivity to diameter up to about [ ]^{a,c}
- ID residual stresses less than or equal to hardroll expansions for range of expanded diameters [ ]^{a,c} for tube expansion process. Therefore, times to crack in hardroll expansions adjusted to plugged tube temperatures provide an acceptable estimate of time to crack for the expanded tubes.
- OD residual stress approximately independent of diameter up to the [ ]^{a,c} Therefore, ODSCC less likely than PWSCC.

SCC tests of bulged hydraulic expansions (TT Alloy 600)

- Bulges up to [ ]^{a,c} exhibit only axial PWSCC and do not progress Throughwall in times equivalent to operating conditions in < 28 years
- Bulges of about [ ]^{a,c} had circumferential cracking in shorter test times

Figure 10-18 Polythionic Stress Index Testing Results for Hydraulically Expanded Tube Specimens

a,b,c

Figure 10-17. PWSCC Test Results for Bulged Hydraulic Expansions in Alloy 600 TT

a,b,c

BULGETST.XLS

Potential for Circumferential Cracking at Tube Expansions
Conclusions

Extrapolation of hard roll expansion time to circumferential cracking (3-4 years minimum) to plugged tube temperatures (<540°F) support time to cracking in expanded tubes that exceed the planned operating periods (i.e., times of about 48 or more years)

Overall Conclusions

- Circumferential cracking in the plugged, expanded tubes would not be expected in the operating period of the plant
- Axial cracking is more likely to occur than circumferential cracking for the expansion diameters of interest
- PWSCC more likely than ODSCC based on residual stresses but ID of plugged tube likely to be dry and less susceptible to PWSCC

Table 10-6

Temperature Based Time Factor for Circumferential Cracking of Plugged Tubes

Plant	Tube Dia.	Ex. Process	Operating Time When Circ. Crack Reported IDSCC (years)	Operating Time When Circ. Crack Reported ODSCC (years)	T_{hot} (F)	T_{sat} (F)	Time Factor (note 1)	Expected Time to Crack Plugged Tube (years)
B-2	0.75	Mech.	-	3	619.9	542.6	16	48
S	0.75	Mech.	4	-	618.8	541	16	64
V-2	0.875	Mech.	-	8	610.9	517	32	128
W-2	0.875	WEXTEX (note 2)	8	-	609.7	524.7	16	128

Note 1: Time factor based on Arrhenius equation

Note 2: No mechanical expanded tube data are available

Locked TSP Interaction Effects (Q. 5)

Potential concerns assessed

- Interaction of tube/TSP or tube/TSP/wrapper/wrapper shell supports when TSPs are "locked" in position
- Assessed nominal tube bundle condition with minimal tube/TSP contact force and tube/TSP lockup condition
  - Both conditions exist without tube expansion. Tube/TSP lockup is the expected condition in most SGs

Background Information

- In Model D4 SGs, TSP axial positions are determined by 13 stayrods/spacers and "backup bars" welded to the wrapper or divider plate above and below the TSP
- Addition of expanded tubes is similar to adding more stayrods except that expanded tubes are an order of magnitude less stiff than a stayrod
- Net effect of adding 21 expanded tubes is to reduce the flexibility of the TSP (increased out-of-plane stiffness). The TSP position and interaction with the wrapper are predominantly determined by the stayrods, backup bars and wedges
- Addition of expanded tubes does not add any significant new loading mechanisms to the TSPs while limiting SLB plate deflections

Locked TSP Interaction Effects

Nominal bundle conditions with minimal tube/TSP contact force

- Tube expansion does not change tube/TSP or tube/TSP/wrapper interactions or loading mechanisms
- If hot and cold TSP positions were determined by tube/TSP contact forces prior to expansion, slippage after expansion may result in some indications extending outside the TSP at cold inspection conditions

Tube/TSP "Lockup" Condition

- Prevalent current condition as indicated by presence of ODSCC within TSPs even for upper TSP indications
- Many tubes participate (denting not required for "lockup" condition) such that TSP elevations follow hot/cold tube expansions. Reference condition for lockup is the hot operating tube/TSP elevation with nominally zero interaction stresses
- Cooldown condition causes interactions among tubes, TSPs, wrapper, wrapper support structure and tubesheet
  - TSP bending occurs with a maximum at the top TSP and minimum at lowest TSP
  - Local bending of the TSPs at stayrod and backup bar locations
  - Since tubes are anchored to the tubesheet, net effect is to load the wrapper to shell support structure to react the wrapper loads and the tubesheet to react the stayrod loads

Locked TSP Interaction Effects

Tube/TSP "Lockup" Condition (Continued)

- With tube expansion implemented at cold conditions, expanded tubes are equivalent to tubes plugged after lockup has occurred. No adverse structural effects have been observed in plugged tubes and none would be expected for expanded tubes

- Tube expansions introduce no new loading mechanisms for SG structural considerations since the tubes are already locked to the TSPs

Conclusions

- Operation with expanded tubes is enveloped by existing conditions with acceptable operating experience and additional analyses are not required to support operation with expanded tubes

Potential for Propagation of Pre-Existing ODSCC by Tube Expansion (Q. 1d)

Expansion process can result in overpressurization of existing indications within the confines of the TSP

- Crack face may open by up to the crevice clearance
  - Burst tests for indications within the TSP generally show small crack extensions and similar results can be expected for the expansion process

- Even if crack tearing from expansion, or corrosion crack growth at pre-existing ODSCC indications would occur, the axial cracks would not significantly affect the stiffness of the expansion for resisting axial displacement of the TSP

Conclusion

- Pre-existing ODSCC is acceptable for expanded TSP intersections and would not significantly affect the functional capability of the expansion

Considerations for Stress Relief of Expansions (Q. 1e)

Very low potential for circumferential cracking at plugged tube expansions

Design margins included for postulated circumferential cracking by implementation of sleeve stabilizers and redundant expansions

- Sleeves result in fail-safe design against severed expansion at lower 3 TSP elevations with downward (toward tubesheet) hydraulic loads

Based on the low potential for circumferential cracking and the expansion process design margins, stress relief to further reduce the potential for circumferential cracking is not necessary

Hydraulic Loads

NRC/ComEd/Westinghouse Meeting

February 23, 1995

Presented By:

M. H. Hu

Westinghouse NSD

HYDRAULIC LOADS

UNDER AN SLB EVENT

- MODELS
- TRANFLO ANALYSIS
- MULTIFLEX ANALYSIS
- SENSITIVITY STUDIES
- CONCLUSIONS

MODELS

- A SCHEMATIC OF SG FLOW CIRCULATION LOOP
  - Pressure Drops along the Loop
  - Unique Features of Moisture Separation
  - Initial Conditions
  - Boundary Conditions

CONDITIONS OF ANALYSES

- VENTURI FLOW LIMITER
- BREAK LOCATION - SG NOZZLE
- BREAK SIZE - GUILLOTINE
- WATER LEVEL - 487"
- TSP LOSS COEFF. - NOMINAL
- DOWNCOMER LOSS COEFF. - NOMINAL
- MOODY DISCHARGE COEFF. - 1.0

COMPARISON OF TRANFLO AND MULTIFLEX RESULTS

- SIMILAR BREAK FLOW RATE
- TSP PRESSURE DROPS
  - Similar Transient within 2 sec
  - TRANFLO > MULTIFLEX
- STILL NO DEFINITE ANSWERS FOR DIFFERENCES BETWEEN CODES

Table 5-1

Hot Standby Pressure Drops Calculated by TRANFLO and MULTIFLEX

a,c

EFFECT OF ACOUSTIC WAVE

- MULTIFLEX CALCULATION
  - With Flow Limiter - Case 31
  - W/O Flow Limiter - Case 31a
- Case 31: Smaller Pressure Drops than TRANFLO
- Case 31a: Similar Pressure Drops like TRANFLO
- BOTH CASES YIELD ONLY 5% PENETRATION OF INCOMING WAVE TO STEAM DOME
- BOTH CASES SHOW NO DISCERNABLE ACOUSTIC WAVE IN TUBE BUNDLE

SENSITIVITY STUDY

- UNCERTAINTY PARAMETERS

  - BREAK LOCATION
  - BREAK SIZE
  - WATER LEVEL
  - TSP LOSS COEFFICIENT
  - DOWNCOMER LOSS COEFFICIENT
  - MOODY DISCHARGE COEFFICIENT

a,c

Table 6-2

SLB Peak TSP Pressure Drops and Ratio of Each Case to Case 1

a,c

CONCLUSIONS

- ACOUSTIC WAVE IS NOT DISCERNABLE INSIDE sg

- EFFECT OF ACOUSTIC WAVE ON TSP PRESSURE DROP IS NOT DISCERNABLE

- TRANFLO CODE HAS BEEN SPECIFICALLY DEVELOPED FOR SG

- TRANFLO BEING PROVEN ACCEPTABLE AND CONSERVATIVE

CONCLUSIONS (CONTINUED)

- A FACTOR OF 2 ON REFERENCE LOADS REPRESENTS A CONSERVATIVE LOAD ADJUSTMENT FACTOR

TSP Displacement Analysis for Model D4 Steam Generators Subject to Steam Line Break Loads With and Without Tube Expansion

Richard E. Smith

February 23, 1995

TSP Displacement Analysis
Presentation Outline

- General Methodology
- Tube Expansion Analysis - Basis for Tube Selection
- Tube Support Plate Support System
- Finite Element Model
- Applied Pressure Loading
- Summary of Displacement Results - With Tube Expansion
    - Comparison of Expanded and Unexpanded Cases
    - Results for Redundant Expansion Case
- Summary of Tube Expansion Locations
    - Sensitivity to Load Amplitude and Postulated Circumferential Cracking
    - Sensitivity to Tube Expansion Position
- Summary of Axial Forces in Expanded Tubes
- Analysis Conclusions

TSP Displacement Analysis
General Methodology

- Transient Dynamic Analysis Approach
- Generate Mass / Stiffness Matrices for all Structures Included in the Analysis
- Account for Plate-to-Plate Variations in Geometry and Support Conditions
- Include Hydrodynamic Mass Effects
- Define Appropriate Dynamic Degrees of Freedom
- Generate Mass and Stiffness Matrices
- Apply Transient Pressure Loads
- Calculate Time History Response of Plates
- Determine Differential Plate / Tube Displacements
- Calculate Displacements as a Function of Tube Position for Limiting plates
- Calculate Number of Tubes for Given Displacement Amplitude
- Evaluate Stresses in Structural Members and Compare to Material Yield Strength

Tube Expansion Analysis
Basis for Tube Selection

- Review Individual Plate Displacements for Case Without Tube Expansion

- Identify Locations of Maximum Displacement as Tube Expansion Positions

- Incorporate Stiffness for Expanded Tubes into Dynamic Solution

- Perform Initial Dynamic Solution

- Iterate on Number and Location of Expanded Tubes Until 0.100 inch Criteria is Satisfied

- Perform Sensitivity Runs for Load / Postulated Circumferential Cracks and Loss of Tube Support

- Define Redundant Tube Expansions at Critical Locations

- Perform Run to Determine Sensitivity to Expansion Position

- Evaluate Stresses in Structural Members and Compare to Material Yield Strength

Tube Support Plate Support System

- Support System is a Combination of Tierods / Spacers, Vertical Bars, Wedges (and Expanded Tubes)

- Tierods are Solid Bars that Run from Tubesheet to Top Support Plate

- One Central Tierod Runs from Top of Preheater (Plate L (8H)) to Top Support Plate

- Spacers are Hollow Cylinders Located on Outside of Tierods, and are Located Between Support Plates

- Spacers are non-linear supports (They are not Rigidly Attached to Support Plates, Except for Central Tierod)

- Vertical Bars are Rectangular Bars Welded to Either Wrapper or Partition Plate Above and Below Tube Support Plates

- Expanded Tubes Provide Both Upward and Downward Support to Plates as a Result of Expansion Above and Below Plates

- Tube / Plate Interaction Due to Plate Rotation Included for Case Without Tube Expansion

Finite Element Model

- Ninety Degree Model
- Includes All Hot Leg Plates, Channel Head, Shell, Tubesheet, and Tierods
- All Components, except Tierods, Modeled using Three-Dimensional Shell Elements
- Tierods Modeled using Beam Elements
- Modeling of Plates Includes Cutouts Along Tubelane, at Outer Edge of Plate for Plates N (10H) and P (11H), and Central Cutout for FDB (Plate A (1H))

a,c

Figure 7-14. Overall Finite Element Model Geometry

Applied Pressure Loading

- Several Different Sets of Loads Considered for Unexpanded Case
  - Variations in Initial Conditions (Full Power versus Hot Standby)
  - Variation in Break Location (S/G Nozzle versus Outside Containment)
  - Application of Uncertainty Factor to Account for Analysis Uncertainties

- Limiting Set of Loads used for Tube Expansion Evaluation
  - Break Location - S/G Nozzle
  - Initial Condition - Hot Standby
  - Uncertainty Factor of 2.0

SUMMARY OF DISPLACEMENT RESULTS
CASE WITH TUBE EXPANSION

COMPARISON OF EXPANDED AND UNEXPANDED CASES

a,c

[ ]

SUMMARY OF DISPLACEMENT RESULTS CASE WITH TUBE EXPANSION

RESULTS FOR REDUNDANT EXPANSION CASE

a,c

Table 8-11

Summary of Tube Expansion Locations

a,c

a,c

Figure 8-26. Map of Tube Expansion Locations

Summary of Displacement Results
Case With Tube Expansion

Sensitivity to Load Amplitude and Potential Circumferential Cracking

a,c

Expanded Tube Loacations

Breaks at All Plates
(Maintain Redundant Expansions)

a,c

DISK 225 - BRDWD\TUBEXP\TBL214 - 01/22/95

Summary of Displacement Results
Case With Tube Expansion

Sensitivity to Tube Expansion Position

a,c

SUMMARY OF DISPLACEMENT RESULTS
CASE WITH TUBE EXPANSION

PLATE P ALONG TUBE LANE

- FINITE ELEMENT MODEL CONSIDERD HOT LEG ONLY
- COLD LEG DOES NOT HAVE TUBE EXPANSION
- DISPLACEMENTS FOR CASE WITHOUT UPPER PLATE EXPANSIONS ALONG TUBELANE APPROXIMATES COLD LEG RESPONSE
- COLD LEG DISPLACEMENTS APPROXIMATELY EQUAL TO [ ]^{a,b,c}
- DISPLACEMENTS ALONG TUBELANE WILL BE APPROXIMATELY EQUAL TO AVERAGE OF THE HOT AND COLD LEG RESPONSES, OR [ ]^{a,b,c}

Table 8-13

Summary of Axial Forces in Expanded Tubes
SLB Transient
Model D4 Steam Generators

a,c

ANALYSIS CONCLUSIONS

- TUBE EXPANSION IS EFFECTIVE IN LIMITING PLATE DISPLACEMENTS, ESPECIALLY FOR THE LOWER PLATES
- LOSS OF SUPPORT OF AN EXPANDED TUBE AT A NON-REDUNDANT LOCATION, MAX PLATE DISPLACEMENTS [ ][a,b,c]
- ELASTIC ANALYSIS PROVIDES A GOOD APPROXIMATION OF THE PLATE RESPONSE UNDER SLB LOADS

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Increased Voltage IPC
for Braidwood 1 & Byron 1
February 23, 1995

Methods for SLB Tube Burst Analyses

R. F. Keating
Steam Generator Technology & Engineering
Nuclear Services Division
Westinghouse Electric Corp.

- **Probability of Burst of Analysis Methods**
  - Correlation of Burst to Crack Length
    - Used for Probability of Overpressurization
  - Correlation of Burst to Exposed Crack Length
    - Used for Probability of Burst
  - Probability of Burst to Crack Length
  - Probability of Burst to Exposed Crack Length

Burst Pressure as a Function of Crack Length

- Non-Linear Regression analysis of database of 206 test results (EPRI, W, NUREG):

$$\left[\qquad\qquad \right]^{a,c,g} \tag{1}$$

where

$$\lambda = \frac{a}{\sqrt{R_m t}} \tag{2}$$

- **Index of Determination of 99.1%**
- **All p Values < 0.1%**
- **For 95%/95% LTL Material:**
  - $a_{critical}$ = 0.75" for 2650 psi @ 650°F
  - $a_{critical}$ = 0.51" for 3657 psi @ 650°F

● Burst Pressure as a Function of Crack Exposure

- Based on constraint offered by the TSP hole clearance as determined by testing.

a,c,e

[ ]

- For small clearances, e.g., 13 mils, the burst pressure is the same as for a throughwall crack with a total length equal to the exposed length of the crack.

- For larger clearances the burst pressure is slightly decreased from that for small clearances. Over the range of interest this amounts to about [ ]^{a,c,e}

• Burst Probability as a Function of Crack Length

- The distribution of the Burst Pressures for a specific crack length is the product of the distribution of the Normalized Burst Pressures for that crack length and the distribution of the Flow Stress of the tube materials:

$$P_B = \frac{2t}{R_m} P_N S_f \tag{3}$$

  where $P_N \sim N(\bar{P}_N, \sigma_P)$ and $S_f \sim N(\bar{S}_f, \sigma_S)$. $\bar{P}_N$ is defined by equation (1).

- The Standard Deviation of the distribution of the Burst Pressures is

$$\sigma_{P_B} = \frac{2t}{R_m}\sqrt{\bar{P}_N^{\,2}\,V(S_f) + \bar{S}_f^{\,2}\,V(P_N) + V(S_f)\,V(P_N)} \tag{4}$$

- The Skewness of the burst pressure is

$$\mathbf{M}_3 \propto \bar{P}_N^{\,2}\,\bar{S}_f^{\,2}\,\mathbf{V}(P_N)\,\mathbf{V}(S_f) \tag{5}$$

M_3 is always > 0, hence the distribution is skewed right.

- The statistic

$$t = \frac{P_B - P_{SLB}}{\sigma_P} \tag{6}$$

may be conservatively assumed to be distributed as a Student's *t* distribution with [ ]g

- The probability of burst is taken as the same as the probability of obtaining a value of *t* equal to or greater than the value from equation (6).

- Since the *t* distribution is symmetrical and the expected distribution is skewed right, the lower tail of the predicted distribution of burst pressures would be expected to be higher than the actual distribution of burst pressures.

- **Monte Carlo verification of deterministic Probability of Burst.**
  - Always conservative over the range of interest.
  - Degree of conservatism increases with decreasing probability of burst.

a,c,e

a,c,e

- **Burst Probability as a Function of Crack Exposure**

  - Adjustment of the t statistic

a,c,e

[ ] (7)

where P_B is from equation (1) and σ_P is assumed to be the same as for free-span indications.

- **Burst Probability for All Indications in the SG**

  - Assume all indications have long TW cracks. The PoB of one or more of m indications is

$$\text{PoB(m indications)} = 1 - \prod_{k=1}^{m} \left(1 - \text{PoB}_k\right) < \sum_{k=1}^{m} \text{PoB}_k \quad (8)$$

  - The PoB of one or more indications in n bins is

$$\text{POB(n bins)} < \sum_{i=1}^{n} m_i \, \text{PoB}_i \quad (9)$$

- **Current Method is Deterministic**
  - Omits uncertainties in the parameters, BUT,
  - ***Judged to be conservative.***
    - Applied to all intersections in the SG.
    - Probability of burst of each indication is overestimated.
    - For the crack exposures of interest, i.e., 0.15" < a < 0.36" the PoB is likely at least an order of magnitude lower than the value being used.

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Methods for SLB Tube Leak Rate Analyses

R. F. Keating
Steam Generator Technology & Engineering
Nuclear Services Division
Westinghouse Electric Corp.

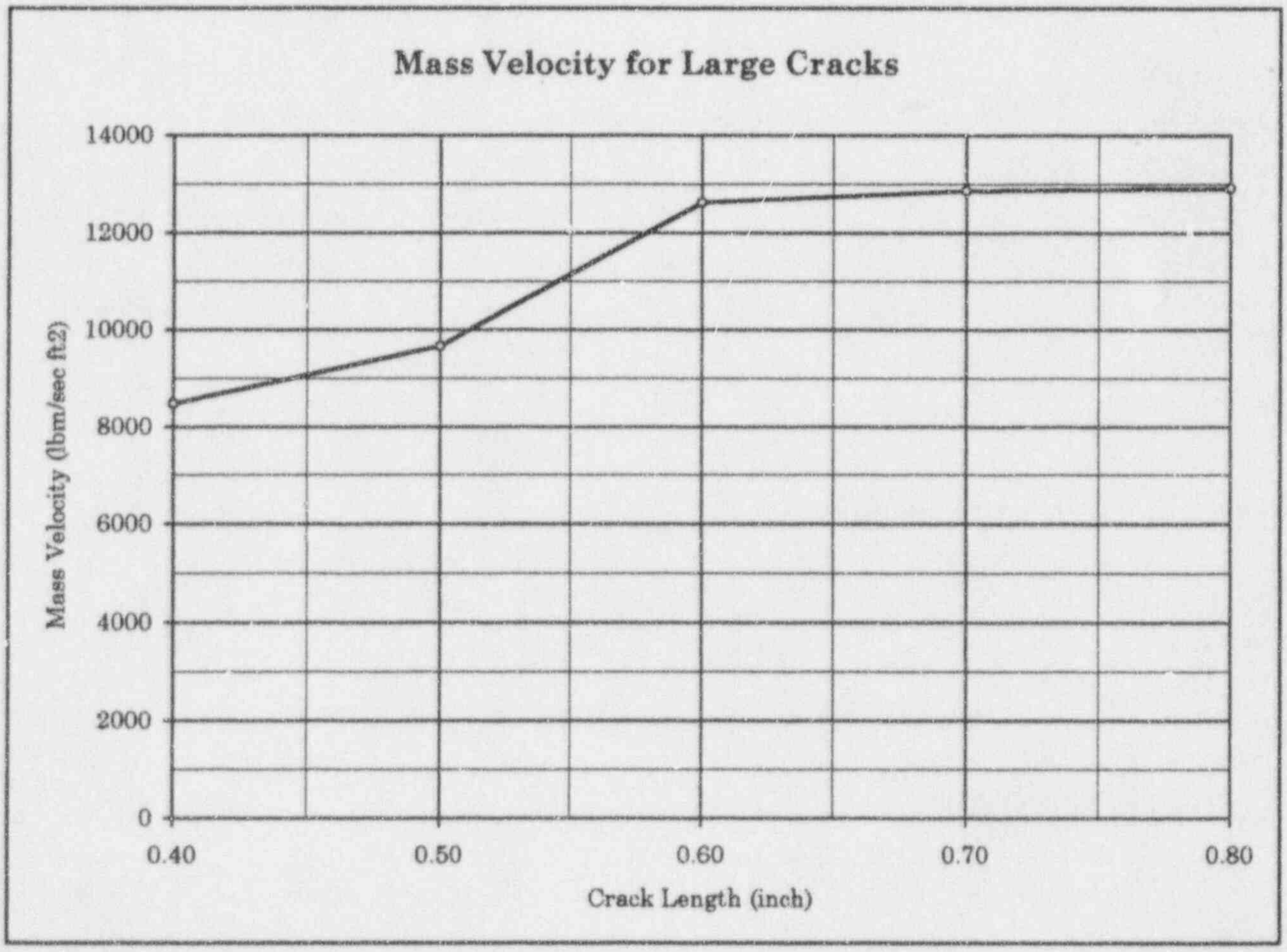
- **Total Leak Rate Analysis Methods**
  - Correlation of Bounding Leak Rate to Crack Length
  - Correlation of Crack Length to Volts
  - Correlation of Bounding Leak Rate to Volts
  - Monte Carlo determination of 95% Confidence Total Leak Rate

Free-Span Leak Rate Analyses

- Correlation of Probability of Leak to the common logarithm of the Bobbin Volts.
- Correlation of the logarithm of the Leak Rate to the logarithm of the Bobbin Volts.

a,c,e

- **Overpressurized Tube Leak Rate Analysis**
  - Limiting mass velocity for large cracks in the free span is the *choke* velocity.
  - Apply to small cracks located within the TSP.
    - Turning, friction and form losses are small, thus the mass velocity is conservatively estimated.



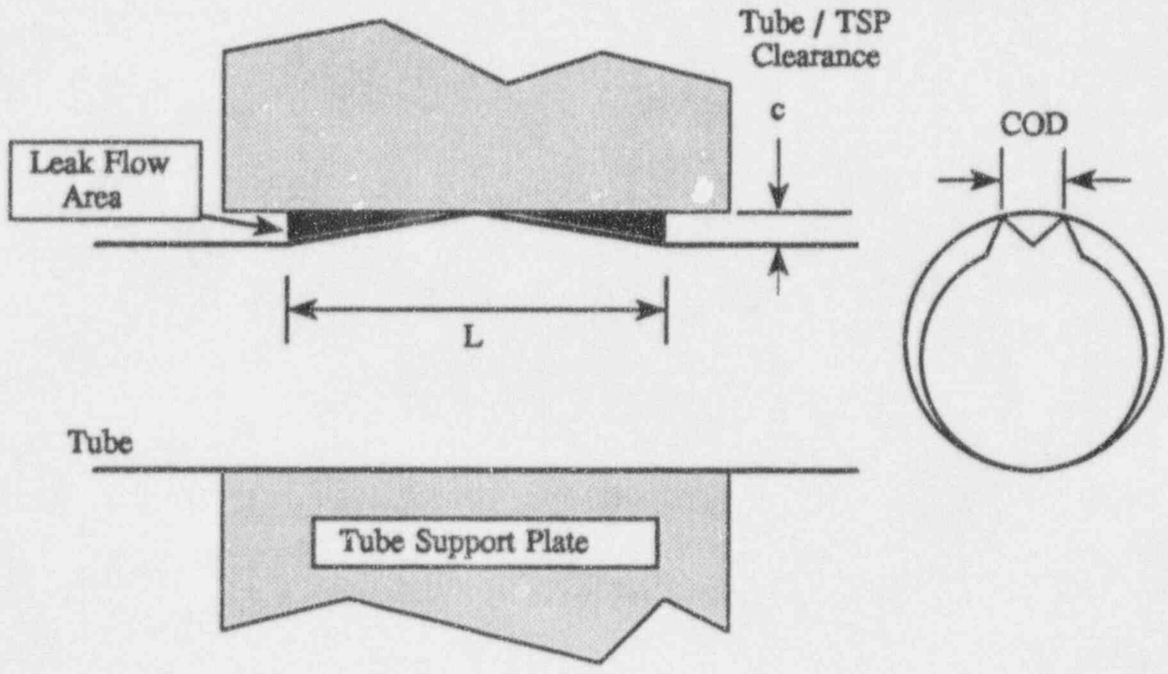
- **Limiting mass velocity is [ ]^{a,c,e} $lb_m/sec\text{-}ft^2$.**

Estimation of Crack Opening Area

- Assumed to contact only at the center of the crack flanks.
- Assumed that no expansion of the tube at the ends of the crack takes place, leading to a crack opening area of

$$A_c = \frac{LC}{2} \approx \frac{\pi c L}{2}$$

where C is the crack center COD.

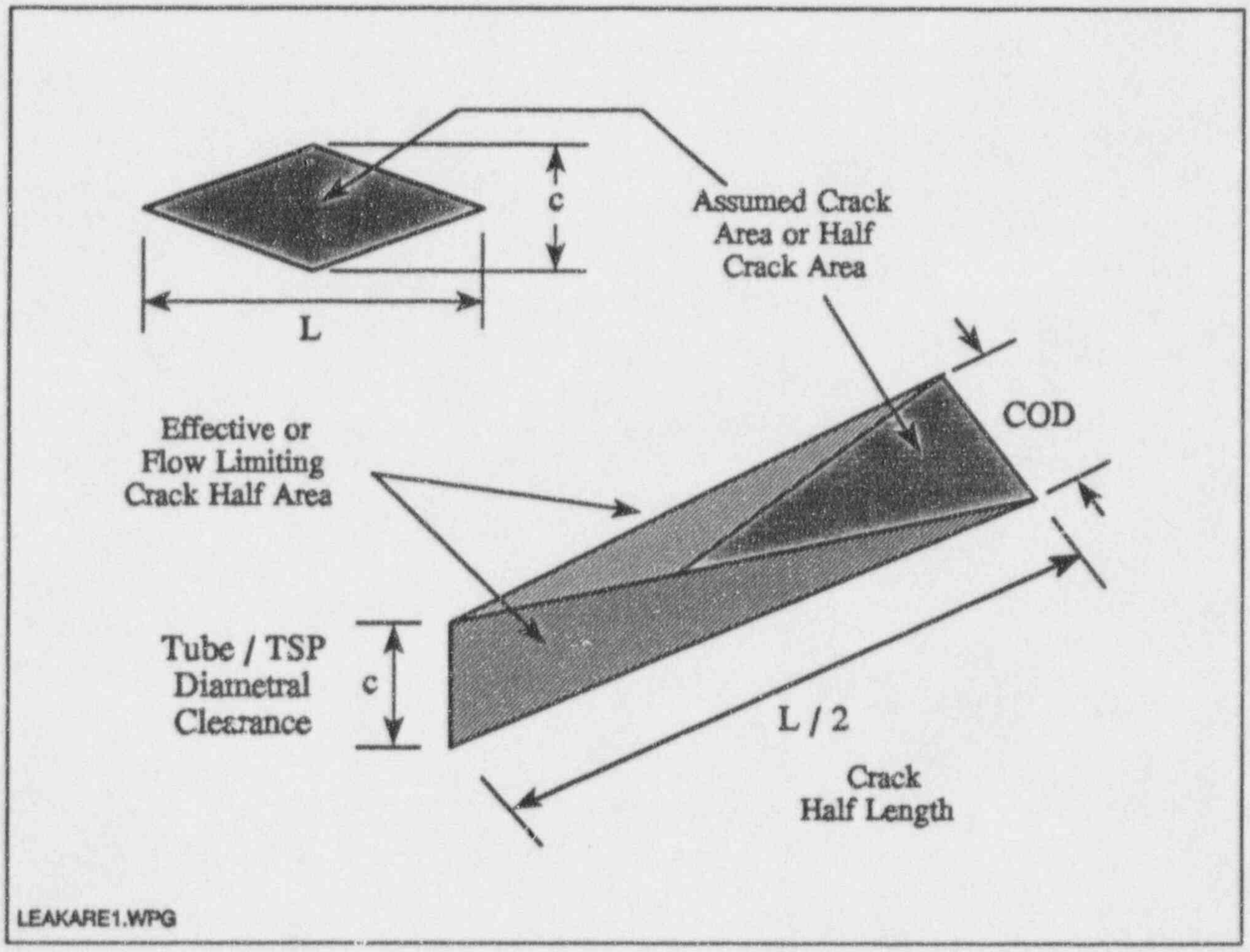


TSP-COD1.WPG

- Flow is really limited by the projected area between the tube and the TSP hole, i.e.,

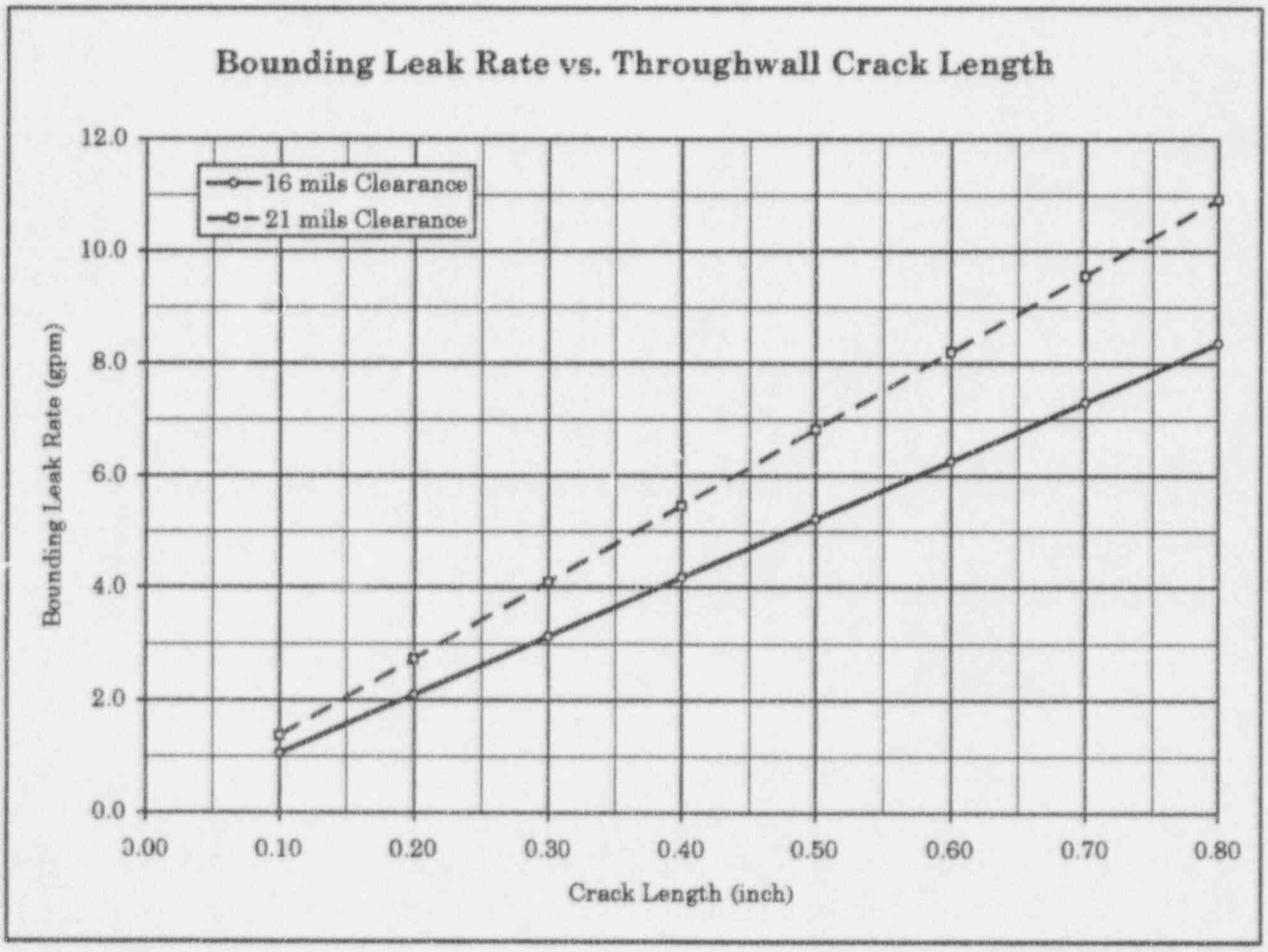
$$A_f = 4\left[\frac{1}{2}\left(c\,\frac{L}{2}\right)\right] = c\,L$$

where A_f is the limiting flow area.



- **Bounding Leak Rate as a Function of Crack Length**
  - Using the appropriate crack opening area, the limiting flow is then

$$Q_{limit} = 2\left(\frac{G_{max}}{\rho}\right)cL$$



• Correlation of Bobbin Amplitude to Crack Length

- Developed for the EPRI database report a,c,e

  [ ]

  where V_∞ and λ are parameters fitted to the data base. a,c,e

[ ]

- In practice, a lower 90% confidence bound on the fitted equation is used to relate bobbin amplitude to crack length.

- **Bounding Leak Rate as a Function of Bobbin Amplitude**

  - The bobbin voltage as a function of crack length is combined with the bounding leak rate as a function of crack length to obtain the bounding leak rate versus bobbin voltage.

  - The bounding leak rates are conservative when compared to the free span leak rates.

a,c,e

[ ]

  - The bounding leak rate is then used in the Monte Carlo analysis for indications simulated to be overpressurized.

NDE Methods Necessary to Support Higher Repair Limits and Tube Expansion (Q.2b, 2d)

Bobbin coil profilometry for post-expansion diameter confirmation

* Profilometry measurements of 3/4" expanded tubes agree with actual IDs within a standard deviation of 2 mils, an uncertainty with negligible influence on the expansion stiffness

Periodic inspections of tube expansions for circumferential cracks

* Existing capabilities (RPC, Cecco) for inspecting sleeves are adequate for expansions since only a severed or near severed expansion will influence expansion stiffness

NDE Capability for Assessing TSP Integrity

* Not required since APC would not be applied to plants with high levels of denting for which TSP integrity might be a concern and tube expansion not applied at TSP intersections with > 5 volts dent which would result in minor TSP stress

* NDE capability not adequate to acceptably discriminate between cracked and normal TSP ligaments

a,b,c

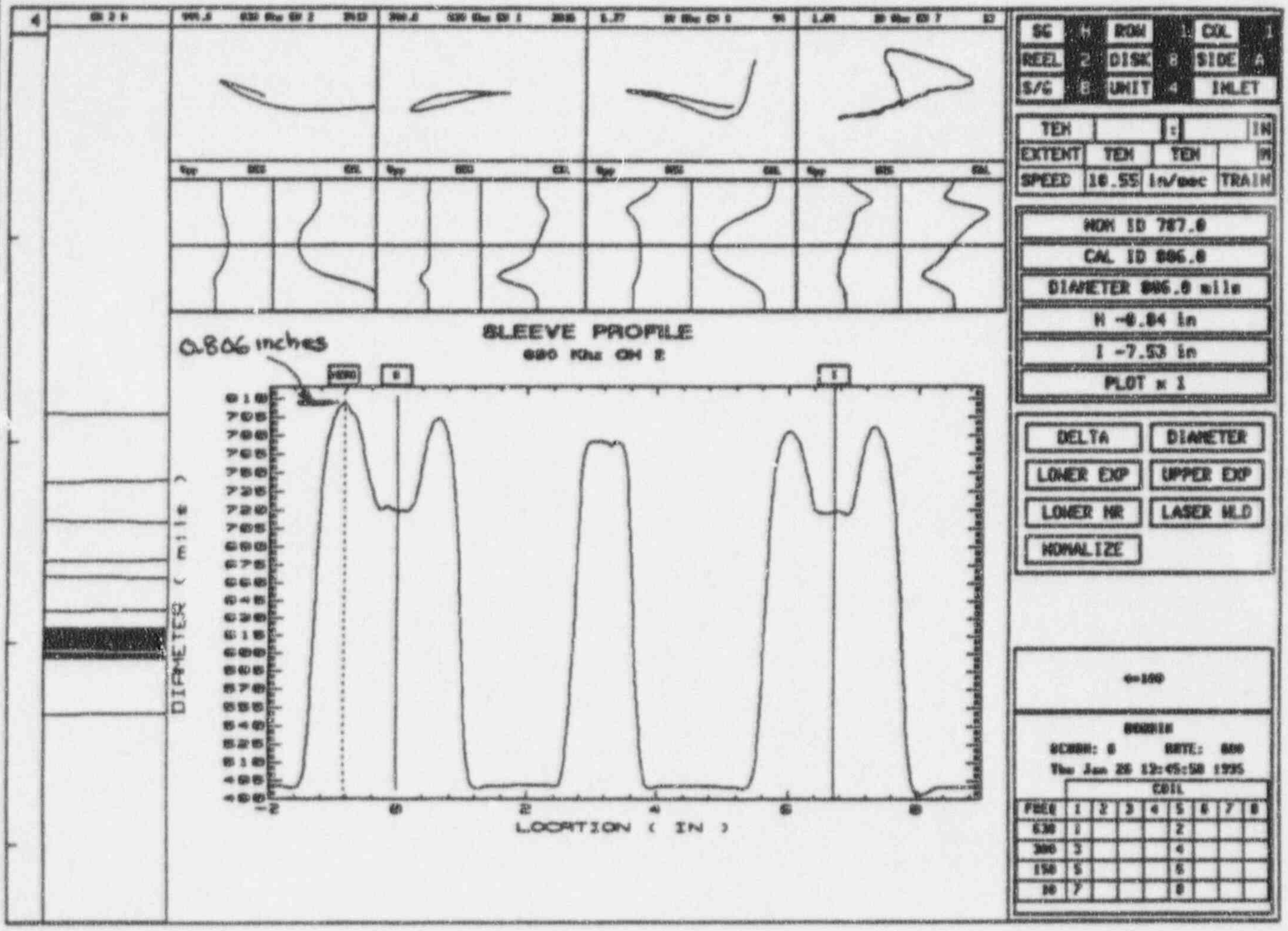


Figure 10-12. Sample with two sleeves expanded at TSP locations. The measured I.D. for the expansion indicated in 0.806 inch. Note: 7/8 inch tube OD

3/4" Tube Samples

Actual vs E/C Measured I.D.

a,c,e

— Ideal

◇ E/C Measurement

··· LSF

R^2 = 0.99

n=15 dx=-0.0008" s=0.0021"

Figure 10-13 a. Bobbin Data for TSP with No Crack

Figure 10-13b. Bobbin Data for TSP with 50% Deep Cracks in Two Ligaments

Figure 10-13a Bobbin Data for TSP with No Crack

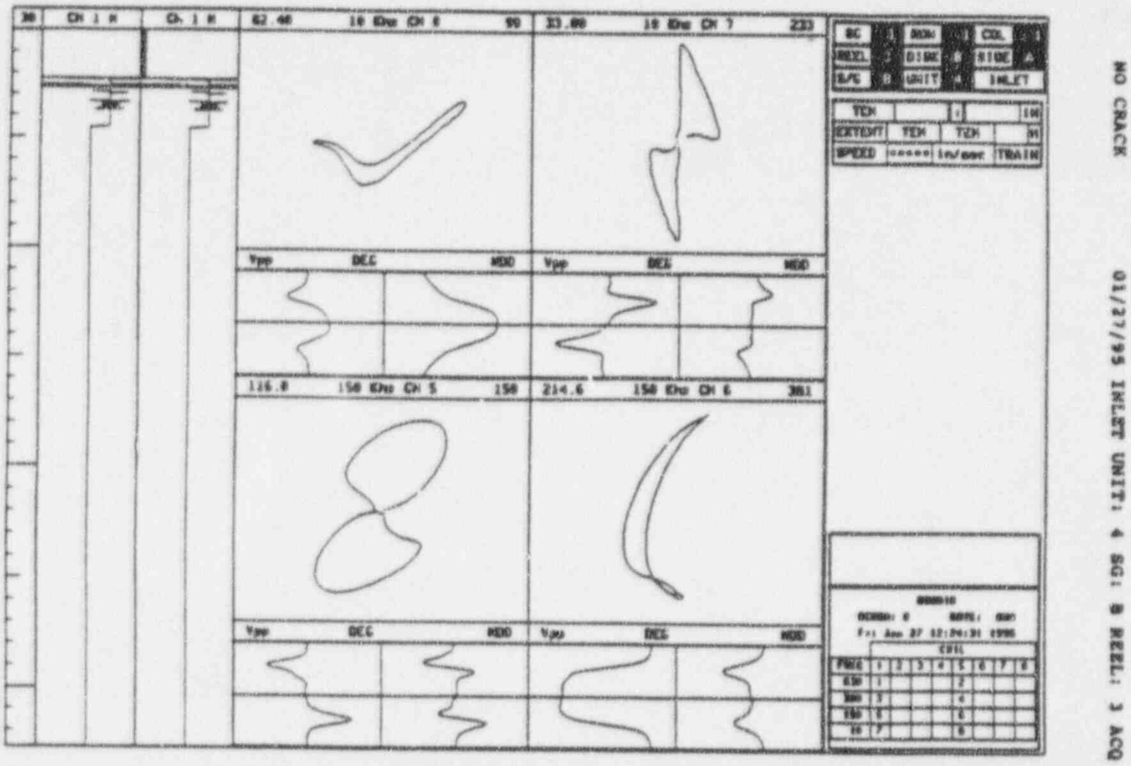


Figure 10-13b Bobbin Data for TSP with 50% Deep Cracks in Two Ligaments

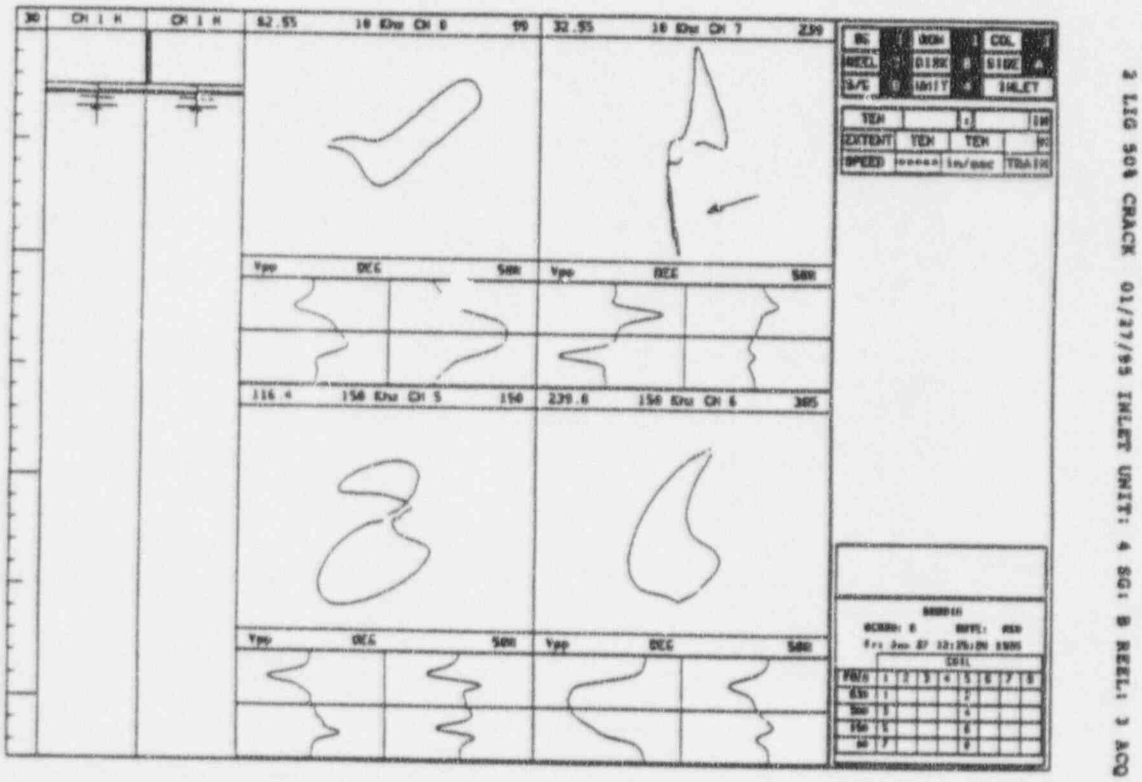


Figure 10-14a. Bobbin Data for TSP with 100% Deep Crack in One Ligament

Figure 10-14b. Bobbin Data for TSP on ASME Standard

Figure 10-14a Bobbin Data for TSP with 100% Deep Crack in One Ligament

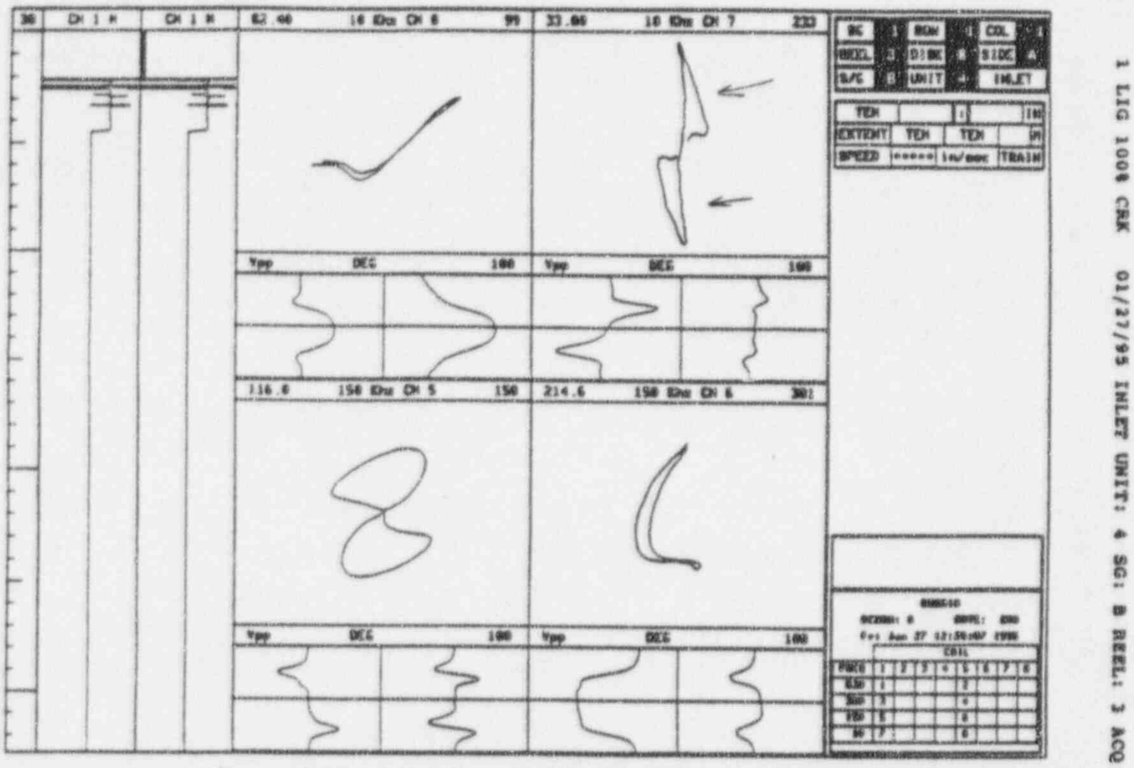


Figure 10-14b Bobbin Data for Field TSP Expansion Candidate

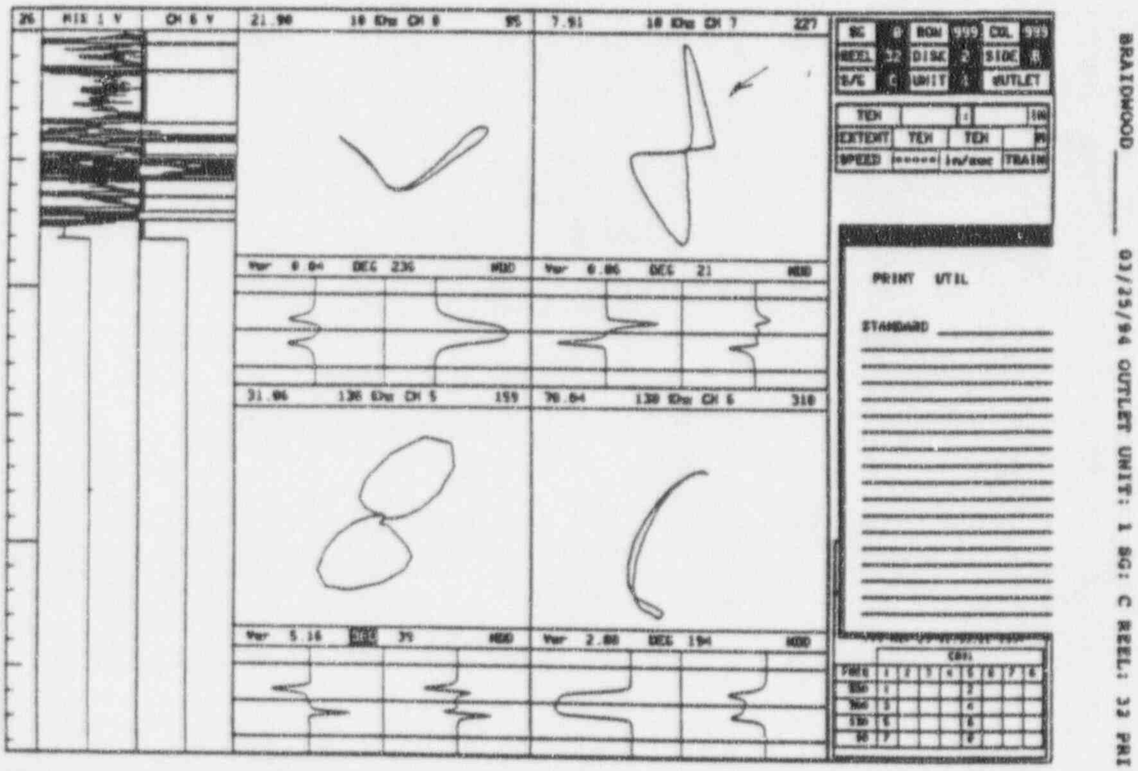


Figure 10-15 Bobbin Data for Typical Field TSP Intersection