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Duke Energy - Oconee Nuclear Station Steam Generator Wear Root Cause Update with NRC
April 10, 2006

C Thomas Alley

ENCLOSURE 2

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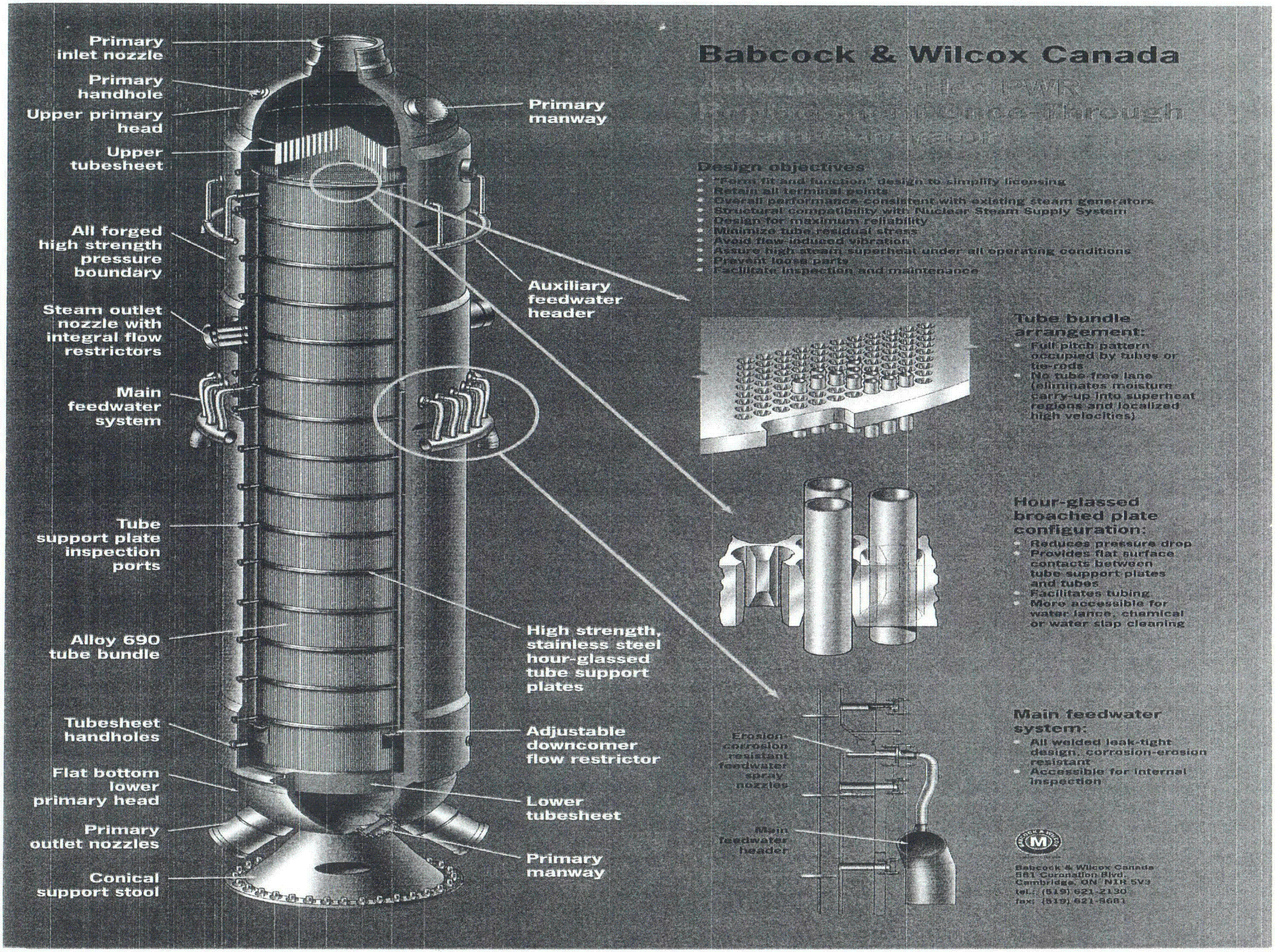
Topics of discussion

- Introductions
- Review of Unit 1 and 2 ROTSG Wear
- Preliminary Probable Causes
  - Alloy 690 / 410S Tube Support Plate (TSP) material couple and Increased Wear Coefficient
  - Tube to TSP relative rotation and reduced contact area
  - Steam Nozzle Flow Restrictor Acoustic Excitation
  - Low Frequency Pressure Pulse
  - Hourglassed Broach Plate Annular Flow Instability
- Preliminary Metallurgical Observations
- Plan for Future Activities
- Conclusions


Babcock & Wilcox Canada
Design objectives
"Form fit and function" design to simplify licensing
Retain all terminal points
Overall performance consistent with existing steam generators
Structural compatibility with Nuclear Steam Supply System
Design for maximum reliability
Minimize tube residual stress
Avoid flow-induced vibration
Assure high steam superheat under all operating conditions
Prevent loose parts
Facilitate inspection and maintenance
Primary inlet nozzle
Primary handhole
Upper primary head
Upper tubesheet
Primary manway
All forged high strength pressure boundary
Auxiliary feedwater header
Steam outlet nozzle with integral flow restrictors
Main feedwater system
Tube support plate inspection ports
Alloy 690 tube bundle
High strength, stainless steel hour-glassed tube support plates
Tubesheet handholes
Adjustable downcomer flow restrictor
Flat bottom lower primary head
Lower tubesheet
Primary outlet nozzles
Primary manway
Conical support stool
Tube bundle arrangement:
Full pitch pattern occupied by tubes or tie-rods
No tube-free lane (eliminates moisture carry-up into superheat regions and localized high velocities)
Hour-glassed broached plate configuration:
Reduces pressure drop
Provides flat surface contacts between tube support plates and tubes
Facilitates tubing
More accessible for water lance, chemical or water slap cleaning
Erosion-corrosion resistant feedwater spray nozzles
Main feedwater header
Main feedwater system:
All welded leak-tight design, corrosion-erosion resistant
Accessible for internal inspection
Babcock & Wilcox Canada
581 Coronation Blvd.
Cambridge, ON N1R 5V3
tel.: (519) 621-2130
fax: (519) 621-9681

ONS 1 Wear Distributions

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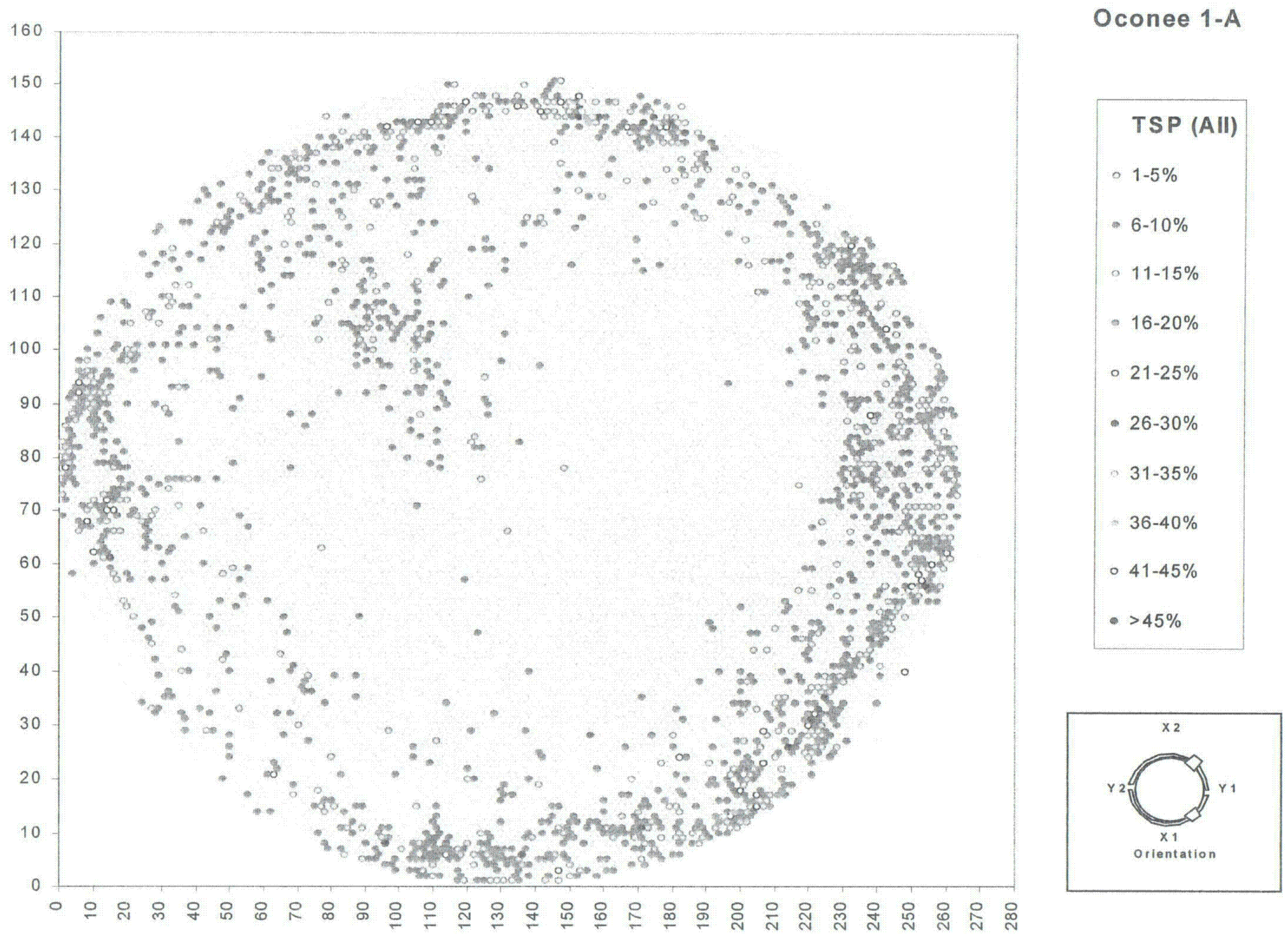
ONS1 A	Tube Support Plate														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
%tw<=5					1			4	23	15	21	17	6	13		100
5<%tw<=10	4	5	5		2		9	46	318	383	344	228	110	121	1	1576
10<%tw<=15	1	2	2					8	89	157	102	83	49	50	5	548
15<%tw<=20									13	47	31	16	8	14	1	130
20<%tw<=25									1	19	15	3		2		40
25<%tw<=30										15	3	1				19
30<%tw<=35										8	4					12
35<%tw<=40										2	2					4
40<%tw<=45										2						2
45<%tw<=50																0
50<%tw<=55																0
55<%tw<=60																0
%tw>60																0
Total/Support	5	7	7	0	3	0	9	58	444	648	522	348	173	200	7	2431

ONS1-B	Tube Support Plate														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
%tw<=5		3	2		1		5	12	19	31	11	2	5	15	1	107
5<%tw<=10	1	9	6	5	2	1	30	34	253	402	174	4	55	174	10	1160
10<%tw<=15	1		1				4		28	130	80	2	5	68	2	321
15<%tw<=20									7	40	35			17	1	100
20<%tw<=25	1								2	15	11		1	3		33
25<%tw<=30										12	4					16
30<%tw<=35										5	3					8
35<%tw<=40										1	1					2
40<%tw<=45											2					2
45<%tw<=50																0
50<%tw<=55																0
55<%tw<=60																0
%tw>60																0
Total/Support	3	12	9	5	3	1	39	46	309	636	321	8	66	277	14	1749

ONS 1 Wear Distributions



ONS 1 Wear Distributions

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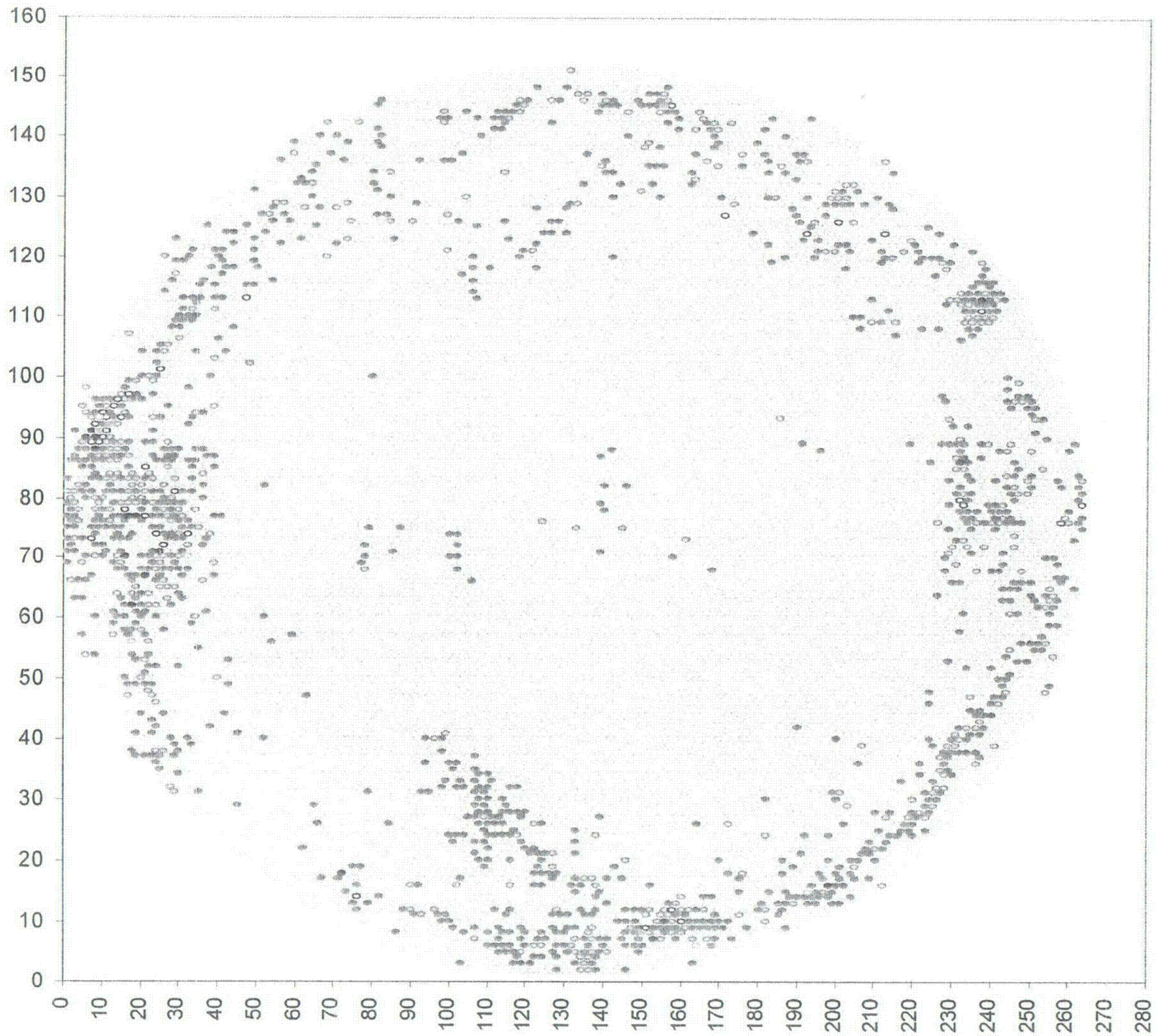
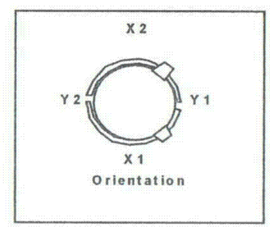
Oconee 1-B



TSP (All)

- 1-5%
- 6-10%
- 11-15%
- 16-20%
- 21-25%
- 26-30%
- 31-35%
- 36-40%
- 41-45%
- >45%



ONS 2 Wear Distributions

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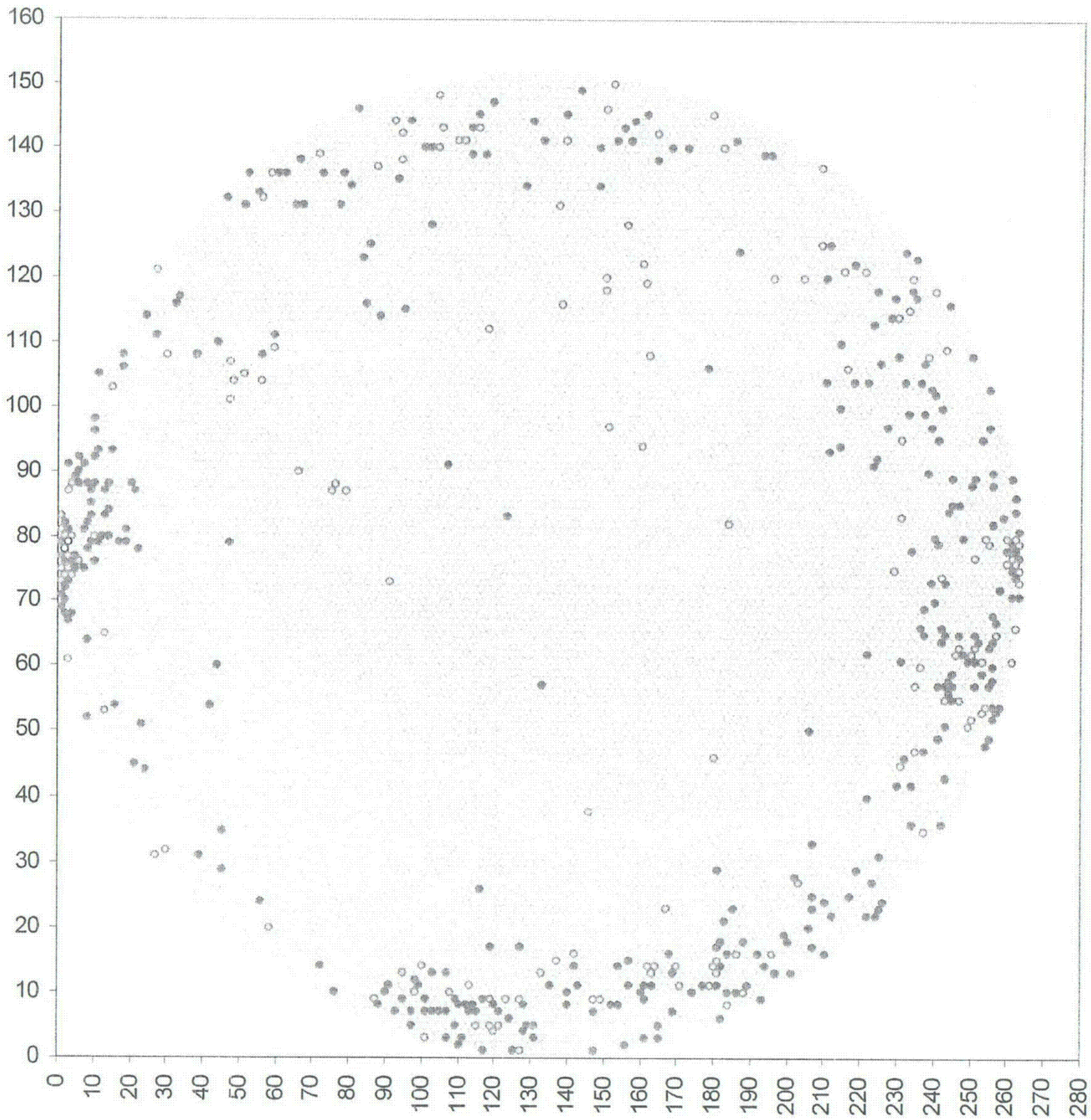
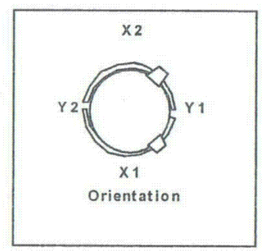
ONS2-A
11-01-05





ONS 2 Wear Distributions

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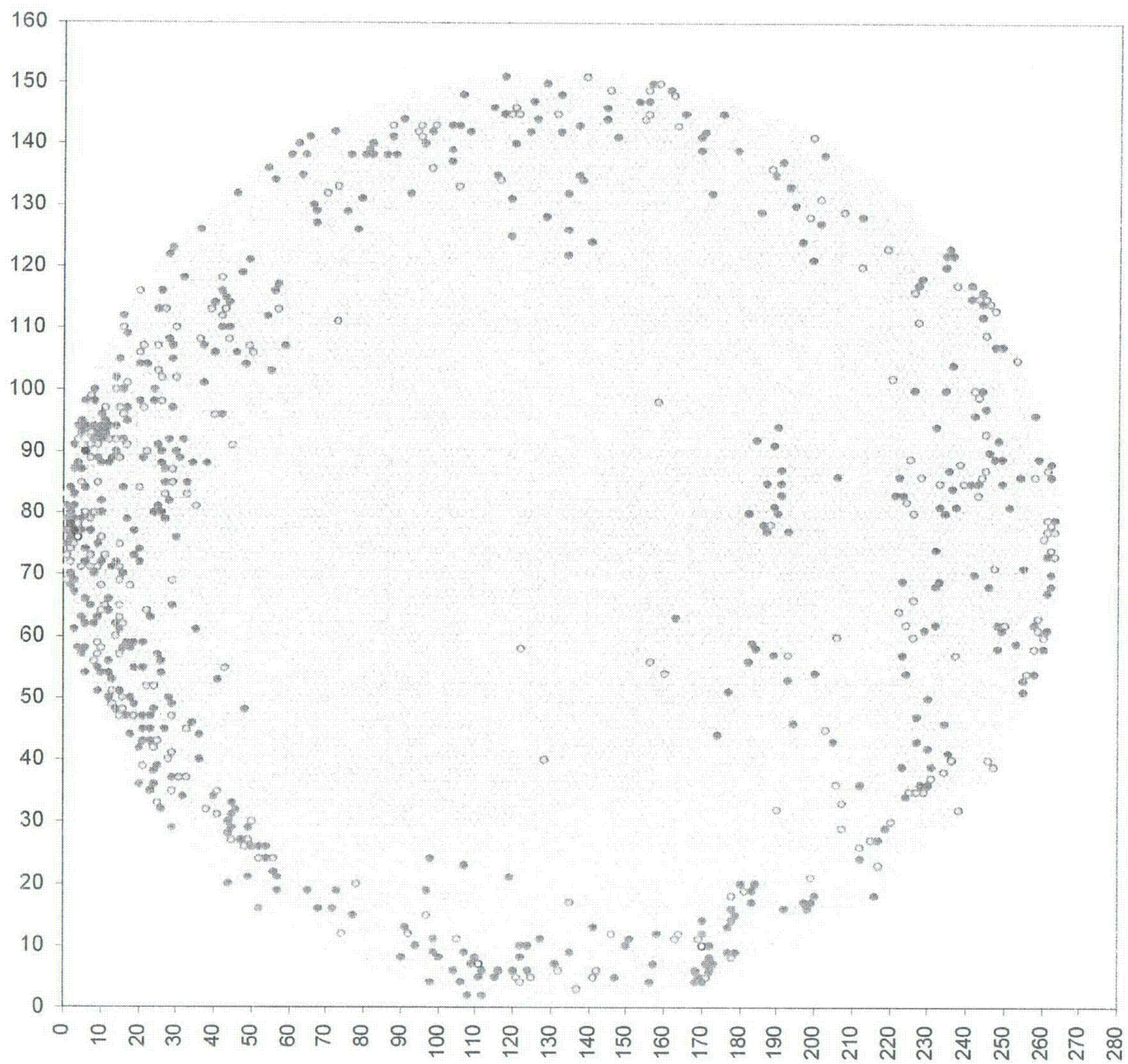
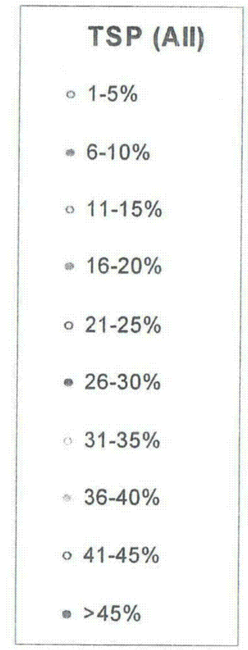
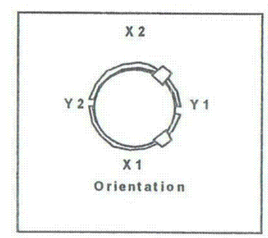


ONS2-B
11-04-05





Wear Indications per Steam Generator

		Original OTSG	Replacement OTSG
Oconee Unit 1	SGA	555	1797
	SGB	1232	1450
Oconee Unit 2	SGA	428	498
	SGB	566	699
Oconee Unit 3	SGA	350	Scheduled April/May 2006
	SGB	280	Scheduled April/May 2006

ONS 1 & 2 TSP Wear Frequency Comparison

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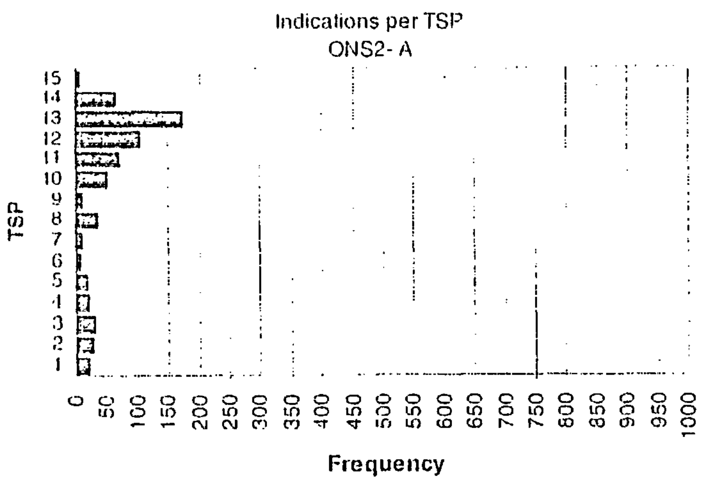

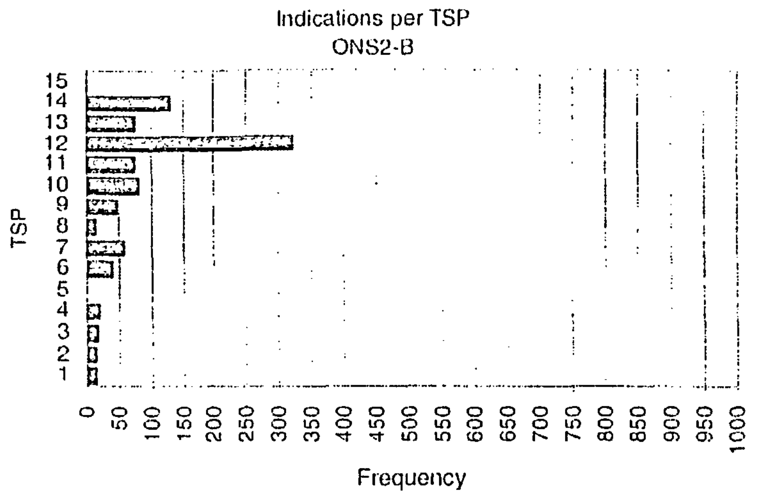

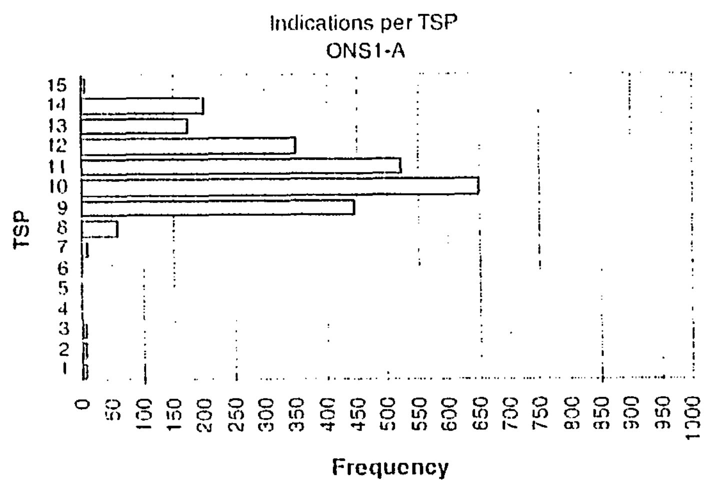

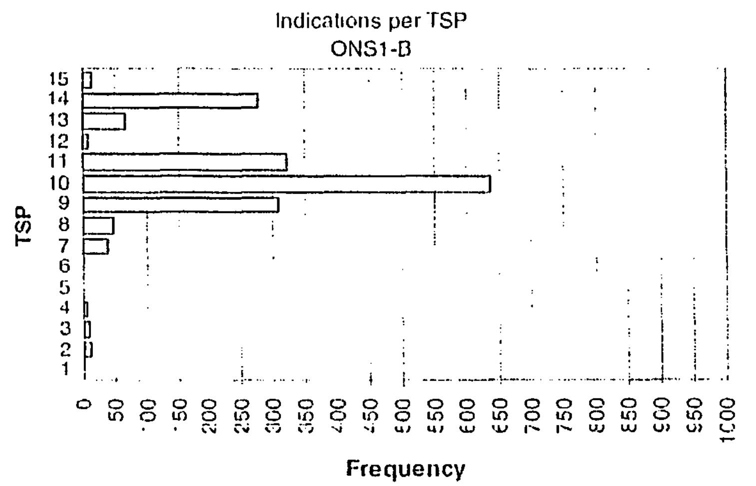

Summary of Review of Eddy Current Data

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- <u>ONS 1 Summary</u>
  - ONS1A, 2431 indications were found on 1797 tubes
  - ONS1-B, 1749 indications were found on 1450 tubes
  - Both ROTSGs 90% of the indications are less than or equal to 15% of the through wall thickness
  - 50% of the indications are under 10% of the through wall thickness
  - The vast majority of indications (≈95%) are present in the superheated steam region on the 9^{th} tube support plate and above
  - All indication above the 9^{th} support plate are predominately on the outer region of the bundle.

ONS1 Summary (cont'd)

- The highest frequency of indications is at the 10th support plate, with the 11th and 9th showing the next highest population,
  - The bleed port is located between the 9th and 10th support plate
  - the steam outlet nozzles are located at the elevation of the 11th support plate.
- Peripheral indications at the 10th TSP on both ROTSGs are more tightly distributed and show a tendency to form a "line" oriented relative to the steam nozzle orientation
- There is also a heavy defect concentration directly opposite the steam nozzles on the Y2 axis.
- The 15th support plate, which is directly below the high cross flow steam outlet region and has very few indications.
- For support plates 10 and above, there are very few indications in the interior with increasing occurrences towards the periphery
- The peak density of tube wear is typically a few rows away from the periphery edge
- Support plate 9 has a significant percentage of indications in the interior of the bundle.

ONS1 Summary (cont'd)

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- Virtually all indications are tapered wear marks with an angle nominally between 0.3 and 1.2 degrees.
- Analysis of tube to TSP land clearances indicate no clear relationship between the size of the clearances and incidence of indications.
- The original OTSGs tube wear is compared against the replacements in which the distribution of the tube wear in the upper TSPs is similar; although there are more indications for the replacements during the first fuel first cycle, than the life span of the original units.
- The original OTSGs the 9th and 10th TSP have the most indications followed by the 8th and the remainder in the upper TSPs.
- The peak counts occur in the 10th and 11th TSP for the replacements followed by the remainder of the upper TSPs.
- Only TSPs 7 and 8 differ with significantly more indications in the OTSGs than the ROTSGs.

ONS2 Summary

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- ONS2-A, 633 indications were found on 498 tubes
- ONS2-B, 903 indications were found on 699 tubes
- Both ROTSGs 90% of the indications are less than or equal to 13% of the through wall thickness and 50% of the indications are under 8% of the through wall thickness
- There are significantly less indications than ONS1 with a less severe wear depth distribution.
- The highest frequency of indications is at the 13^{th} support plate for ONS2-A and the 12^{th} support plate for ONS2-B. There is low incidence of indications on the 9^{th}, 10^{th} and 11 support plates when compared with ONS1.
- Relative to ONS1 there are an increased number of indications in the vicinity of the inspection ports in the lower bundle region below the 9^{th} TSP.
- Based on ECT, wear is predominately single lobe contact similar to ONS1
- Preliminary review of X-Probe data shows no discernable orientation pattern .

Oconee Tube Wear Probable Cause

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- To date, no singular technical root cause has been isolated, but five contributing causes have been identified by the Root Cause Team (BWC and Duke Energy)

- **Probable Technical Causes:**

  1) Alloy 690 / 410S tube support plate (TSP) material couple and increased wear coefficient
  2) Tube to TSP relative rotation and reduced contact area
  3) Main steam nozzle flow restrictor acoustic excitation
  4) Low frequency pressure pulse
  5) Hourglassed broach plate annular flow instability

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Factors Investigated

Factors Investigated

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- **Dynamic Pressure Induced Vibration**
  - Feedwater Spray Nozzle Dynamic Excitation of Lower Shroud
  - Feedwater Spray Nozzle Dynamic Pressure Excitation of Tubes
- **Acoustic Induced Vibration**
  - Axial Acoustic Standing Waves between TSPs
  - Acoustic Resonance with Cross Flow Vortex Shedding
  - Steam Nozzle Flow Restrictor Acoustic Excitation of Tubes
  - Feedwater Spray Nozzle Acoustic Excitation of Tubes

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- **Structural Vibration**
  - Steam Nozzle Flow Restrictor Dynamic Excitation of Piping, Shell or Shroud
  - Structural Vibration of Shell due to Mechanical Excitation of System including change in stiffness of ROTSG
  - Structural Vibration of Shell due to Ineffective Upper Lateral Restraint
  - Structural Vibration of Shell due to RCP excitation / unbalance
  - Structural Excitation of Hot Leg (180° bend) due to RCS flow perturbations

Factors Investigated (cont'd)

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Flow Induced Vibration

- Hourglassed Broached Hole Annular Flow Instability
- O.D. Axial Flow Turbulence Induced Excitation
- Axial flow inside tube causing lateral vibration
- Localized cross flow excitation at TSPs within a nominally axial flow field
- High Cross Flows and FIV loading in bleed port and steam exit region
- Localized 'jet pump' effect of feedwater spray nozzles
- Excessive Bleed Flow attributed to steam carryunder in lower feedwater downcomer
- Downcomer flow leakage through lower inspection port sleeves
- Flow Regime Instability

Factors Investigated (cont'd)

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Flow Induced Vibration (cont'd)

- Porosity Related Flow Maldistribution at Tube Support Plates
- Correctness of standard FIV analysis addressing fluid-elastic instability (FEI), random turbulence (RT) and vortex shedding
- Effects of linear versus non-linear FIV analysis including 'clearance limited FEI'
- Unbalanced feedwater flow through spray nozzles
- 'U-tube' flow oscillations in lower bundle and downcomer

Factors Investigated (cont'd)

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Mechanical / Material Interaction

- Effect of broached hole clearances
- Effect of tube tension including confirmation of prestrain
- Effect of damping in superheat region
- Relative mechanical interaction between tubes, TSPs, shroud and shell
- Effect of curved versus flat land
- Effect of improved tube / TSP alignment
- Material couple wear coefficient

Plant Operational Thermal Hydraulic Conditions and Geometry

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Discussion of Probable Causes

Alloy 690 / 410S TSP Wear Coefficient

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- A literature search of wear coefficients was conducted and found a wide variation of results for the same materials
- Comparison of the original material combination to the ROTSG material combination was initiated
- Room temperature sliding tests in a dry environment have provided repeatable consistent results showing that the wear coefficient for Alloy 690 / 410S is about an order of magnitude higher than Alloy 600 / carbon steel
- Comparative simultaneous testing in autoclave fretting machines at super heated conditions has been initiated to confirm the differences between the original material and ROTSG material combinations

Tube to TSP Relative Rotation and Reduced Contact

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- Volumetric wear rate is proportional to work rate but through wall wear rate is related to the contacting surface area
- Dynamic contact between the tube and tube support 'land' should engage the full length of the land
- Relative angular rotation due to tube dynamic motion or rotation of the TSPs can increase the wear rate
- The Oconee ROTSGs TSPs are vertically positioned by both tie rod spacers starting from the lower tubesheet and by support blocks around the outer edge of the TSPs which are welded to the shroud I.D.

Tube to TSP Relative Rotation and Reduced Contact cont'd)

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- Relative thermal expansion of the tie rods and the upper and lower shrouds, which are anchored at their bottom ends, cause vertical loads at the outer support blocks. These loads result in a dishing of the support plates
- The angular rotation of the support plate edge may be detrimental to wear due to the possibility of reduced contact area
- A relationship between the locations of the tapered wear marks and the angular rotation of the TSPs is still under review

Main Steam Nozzle Flow Restrictor Acoustic Excitation

- Any sudden shock loss in a steam system is a potential source of acoustic energy
- An illustration of acoustic energy generation and transmission in a piping system is shown in Figure 10-10 of Blevins (1994)

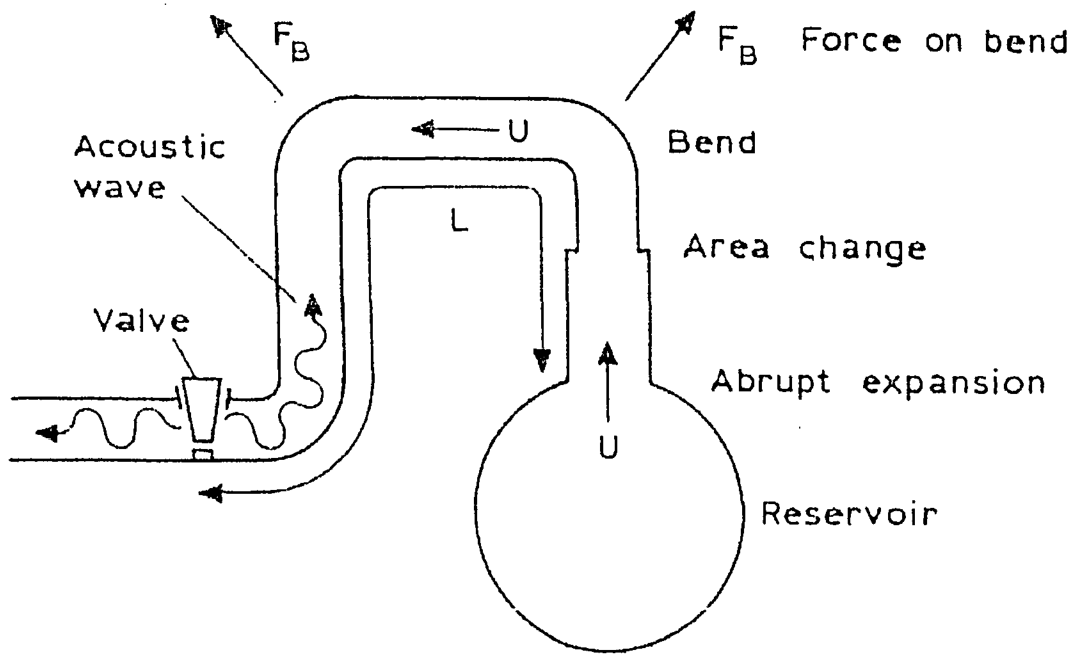

Fig. 10-10 A pipe run with an acoustical source at a valve.

Main Steam Nozzle Flow Restrictor Acoustics cont'd

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Analytical Acoustic Analysis

- Determined acoustic energy from steam nozzle flow restrictor pressure drop and velocity using conventional analytical analysis
- Predicted ROTSG acoustic modes
- From acoustic sound pressure levels and mode shapes determined magnitude and frequency of tube lateral loads
- Applied acoustic loading as forced vibration on tubes along with FIV loads and support contact forces
- Based on analysis, acoustic energy maybe significant, especially in areas away from cross flow loads and generally covers regions where wear was observed

Main Steam Nozzle Flow Restrictor Acoustics cont'd

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Search for acoustics

- Original and Replacement OTSG Loose Part Monitoring System spectral content reviewed
- Steam line piping (outside of containment) instrumented to measure pipe wall accelerations at Units 1, 2 and 3
- Microphone sound measurements taken around steam line
- Direct pressure transducer measurements taken at ROTSG inspection ports during power escalation following Unit 2 outage
- More pressure transducer measurements planned for Unit 3 outage as well as containment microphone being installed

Main Steam Nozzle Flow Restrictor Acoustics cont'd

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Search for acoustics cont'd

- Unit 2 pressure transducer acoustic frequencies were detected but the amplitudes were not as intense as those from predictive analysis
- Steam line piping acceleration measurements detected the same acoustic frequencies as those measured by the ROTSG pressure transducers. Steam line piping accelerations are largest at Unit 1 followed by Unit 2 followed by Unit 3

Main Steam Nozzle Flow Restrictor Acoustics cont'd

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Acoustic analysis conclusions

- Predictive analysis based on the pressure drop of the steam line flow restrictor and acoustic modal analysis indicates that the flow restrictor maybe an acoustic source that may explain the wear distribution within the bundle
- Field measurements and analysis of steam line accelerations indicate a potential that acoustic frequencies exists that may have potentially high energy levels
- Pressure transducer measurements at ONS-2 detected acoustic frequencies at intensities less than expected from ONS-1 investigations.

Low Frequency Pressure Pulse

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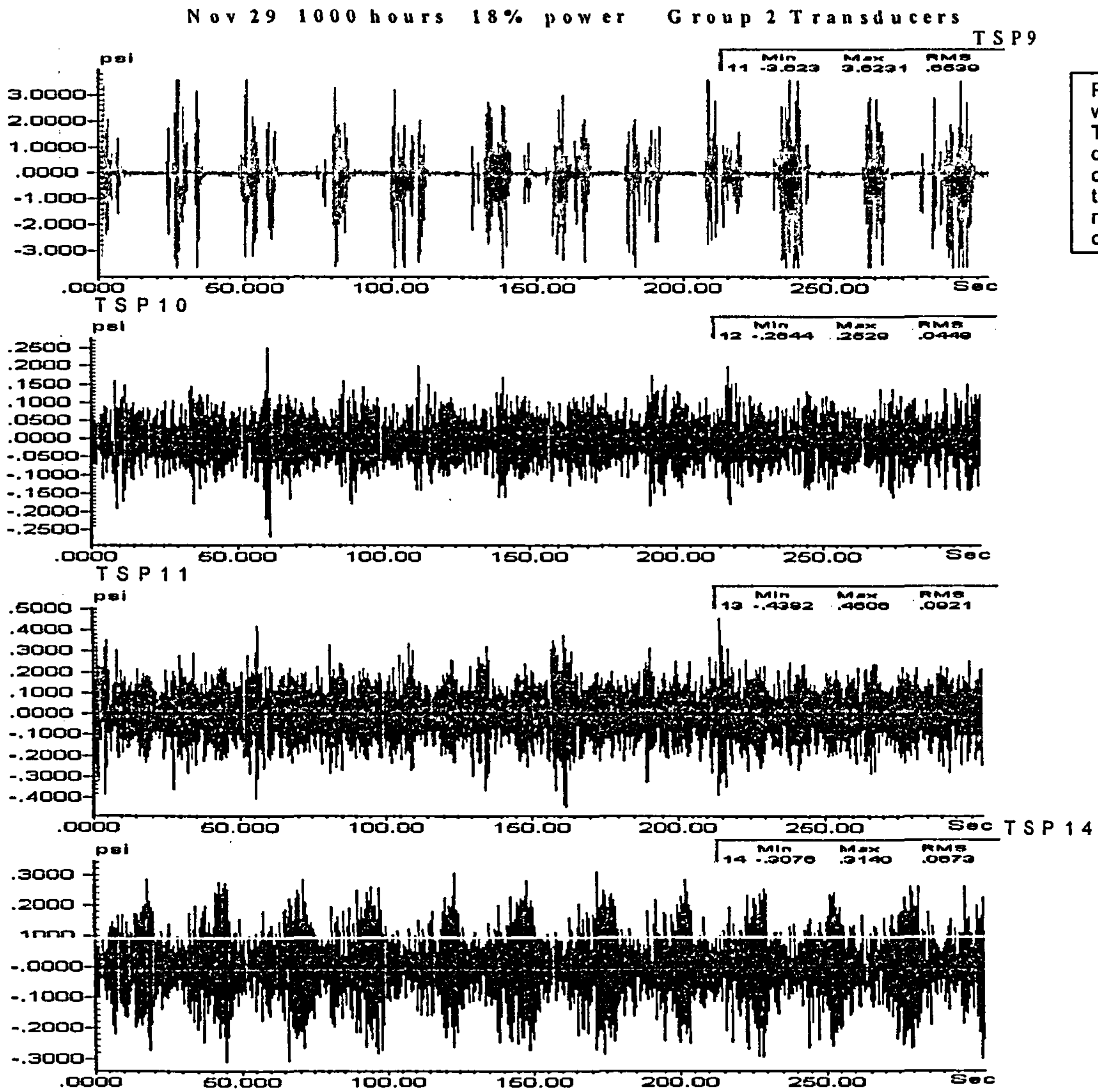
- Unexpected high pressure, low frequency signals were observed at the 9th and 10th TSP, especially at lower power during startup of unit #2 in the fall 2006
- Signals still being evaluated. There is concern that they may not represent real pressure
- Calculations by consultant indicate that energy is sufficient to cause damage if signals are real.
- Signals at low power may be related to control valve operations.

Low Frequency Pressure Pulse

Low Frequency Pressure Transients during Low Power Operations



Pressure transients were initiated at TSP9 but were detected also at the other TSP transducers. Note the magnitudes at the other locations were

Low Frequency Pressure Pulse

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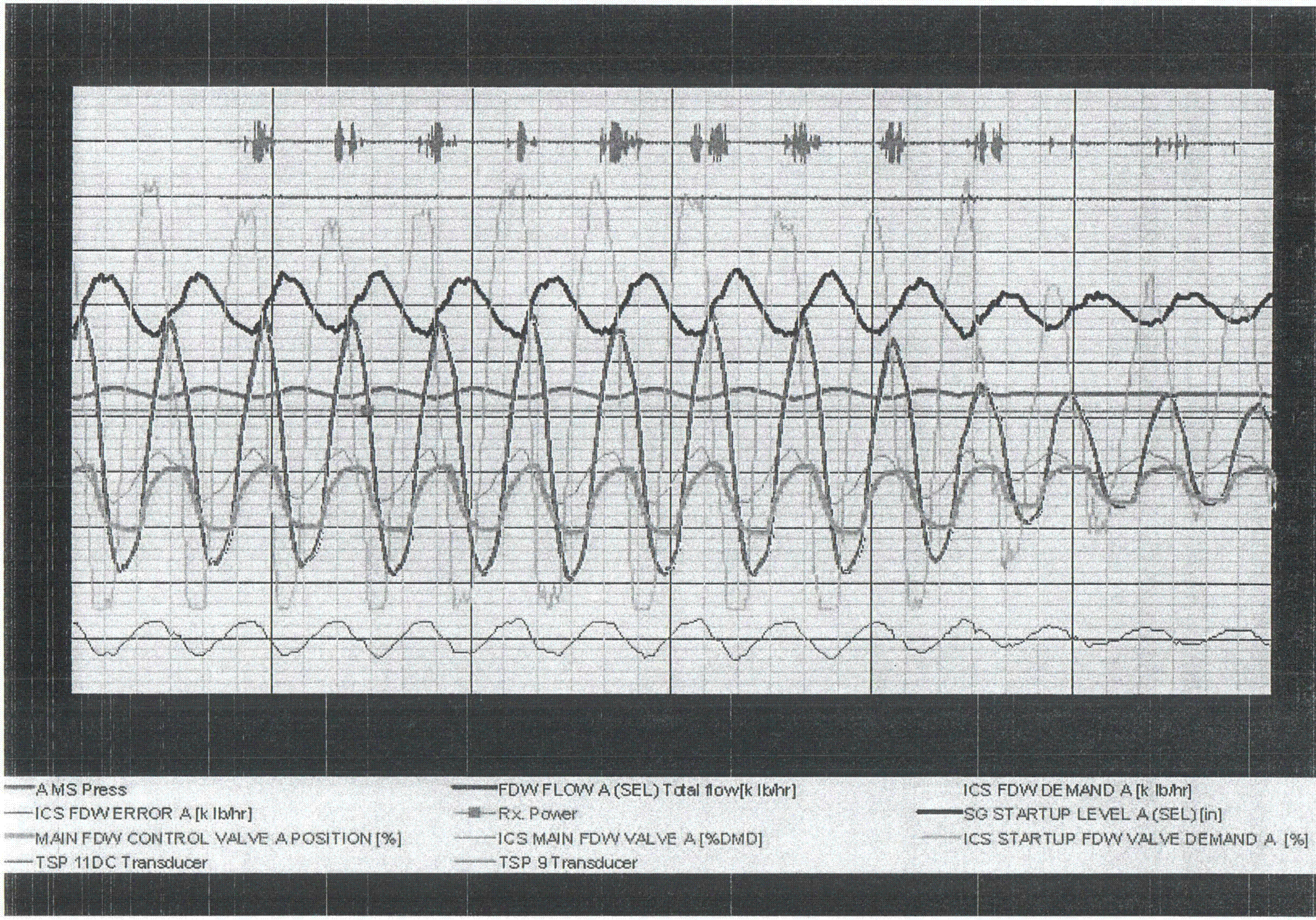
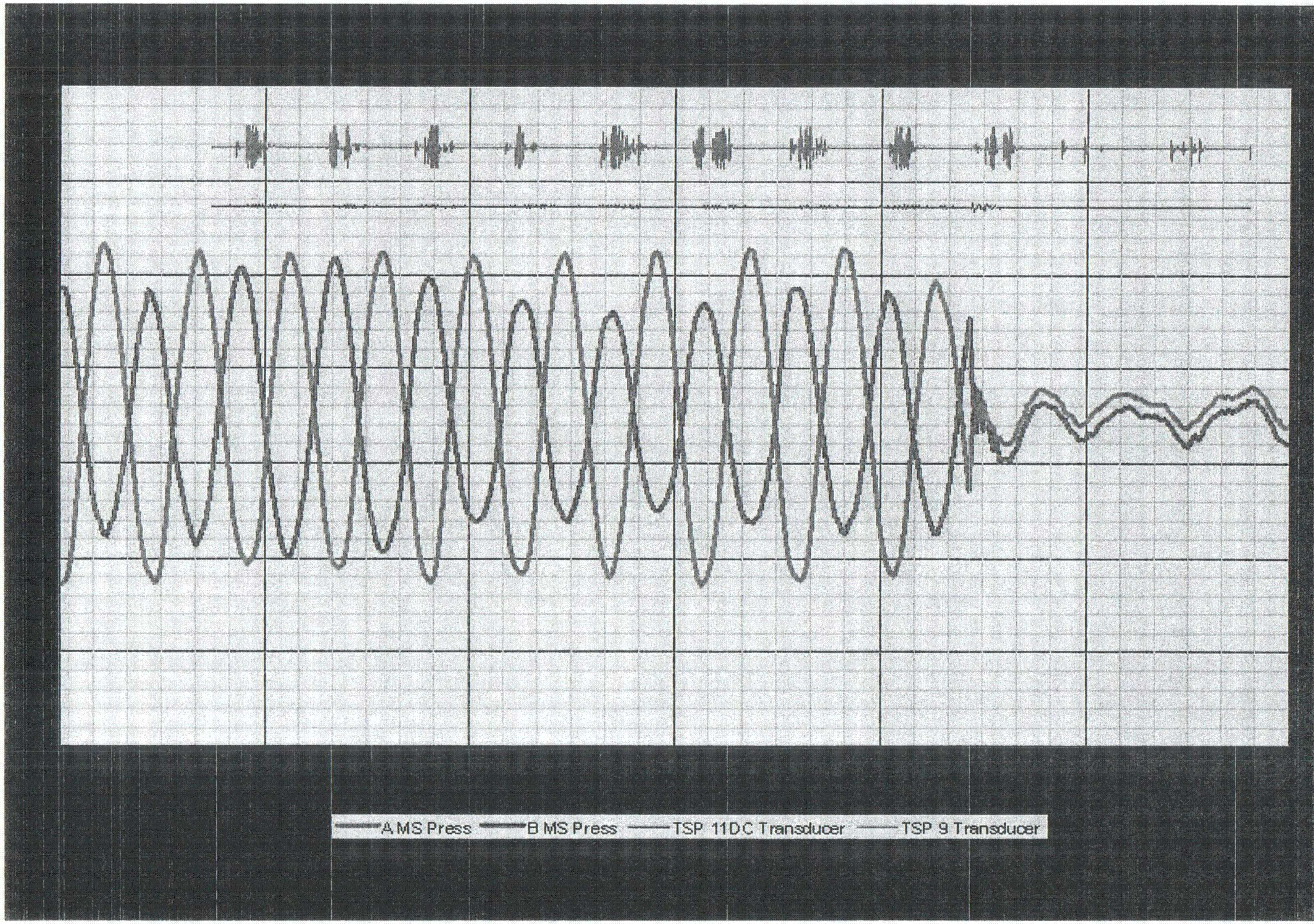
Low Frequency Pressure Transients during Low Power Operations



Low Frequency Pressure Pulse

Low Frequency Pressure Transients during Low Power Operations



Annular Flow Instability of Hourglassed Broached Hole

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- Annular flow instability, also known as 'leakage-flow-induced' vibration, typically occurs in cases where a flexible object is situated within an annular flow passage
- Either the dynamics of the flow field or the varying position of the flexible object within the flow passage can cause a variation in the dynamic pressure around the central object
- The difference in dynamic pressure around the perimeter of the central object causes a net lateral pressure force which may be destabilizing. The motion caused by the lateral force may increase the dynamic pressure imbalance and cause further lateral motion, hence creating instability.

Annular Flow Instability of Hourglassed Broached Hole

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Industry Experience with Annular Flow Instability

- Laboratory experiments of divergent nozzle annular flow instability show that a symmetric annular gap with divergent (expansion) angles of 5 to 15° can cause lateral vibration
- In some cases where the divergent profile had non-symmetric relief passages, annular flow instability was still observed
- Some research has shown that inlet convergent profiles are a stable configuration
- The Oconee ROTSG configuration does not match the profile of a classic unstable profile but has some features that make it suspect and consequently a test program in air and water flows was initiated

Annular Flow Instability of Hourglassed Broached Hole

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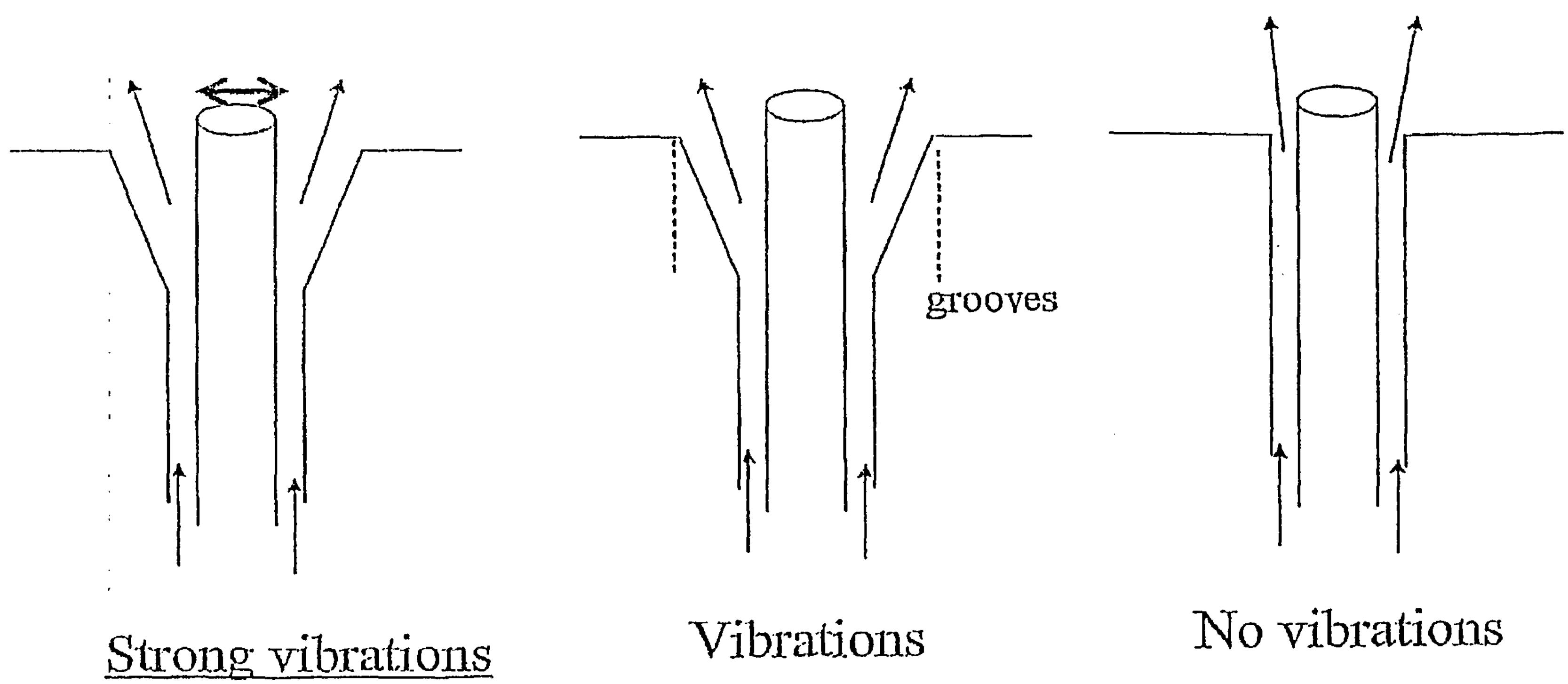
3. Laboratory experiments

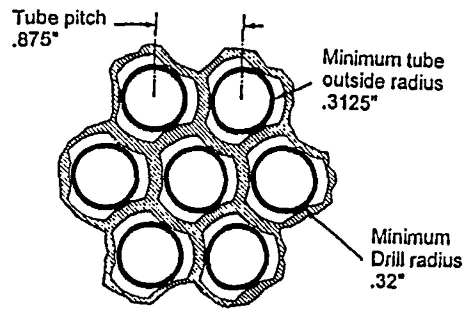
Water
Angle=15°

a) Gorman & al. 1987 (at EdF,in relation with PWR in-core)



Annular Flow Instability of Hourglassed Broached Hole

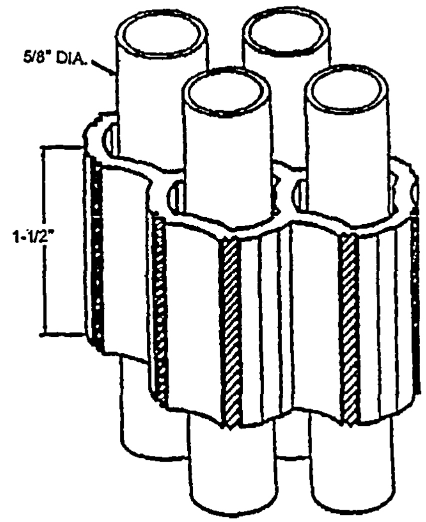
Original Broached Hole



Note: Plate thickness 1.5"

OTSG broached plate tube support

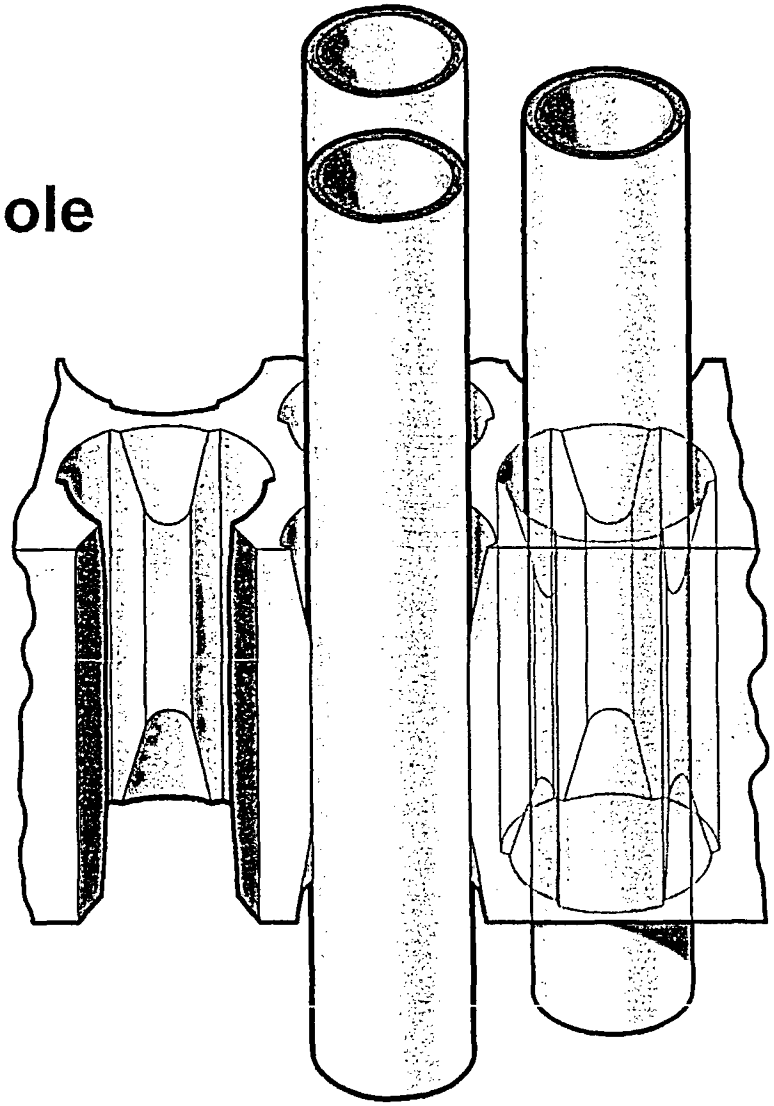
Original TSP Design



B&W Tube Support Plate Design

Annular Flow Instability of Hourglassed Broached Hole

ROTSG Broached Holed Hole



Annular Flow Instability of Hourglassed Broached Hole

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Results of Analysis and Testing

- Air flow tests at hydraulic conditions equivalent to full power operation indicate that the hourglassed profile causes increased tube response relative to the original non-tapered flow passages
- The vibratory motions and frequencies measured do not result in an exceedingly high work rate at the support interface but are similar to those from cross flow FIV mechanisms
- Field data does not support annular flow instability as a singular root cause since axial flow is uniform at all radial positions while wear predominantly occurs around the periphery

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Preliminary Metallurgical Studies

ONS 2 Tube Pulls

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Two full length tubes were removed from ONS 2 during outage for metallurgical analysis

Westinghouse performing met exam

- Macro photography -complete
- Lab ECT - complete
- SEM/EDX – in progress
- Laser profilometry – in progress
- Meeting 4/11/05 to discuss results to date and future plans
- Wear tapered consistent with field ECT
- Sliding marks evident on upper bundle defects
- Preliminary observations of wear surface suggest more than one mode of tube motion likely

ONS 2 Tube Pulls

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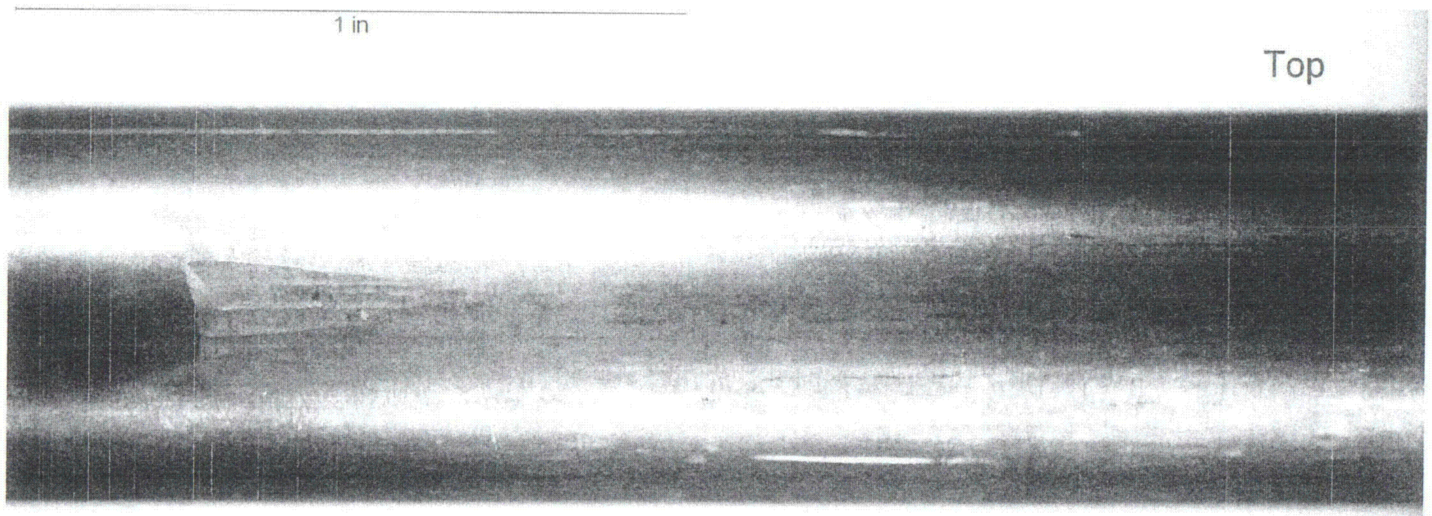
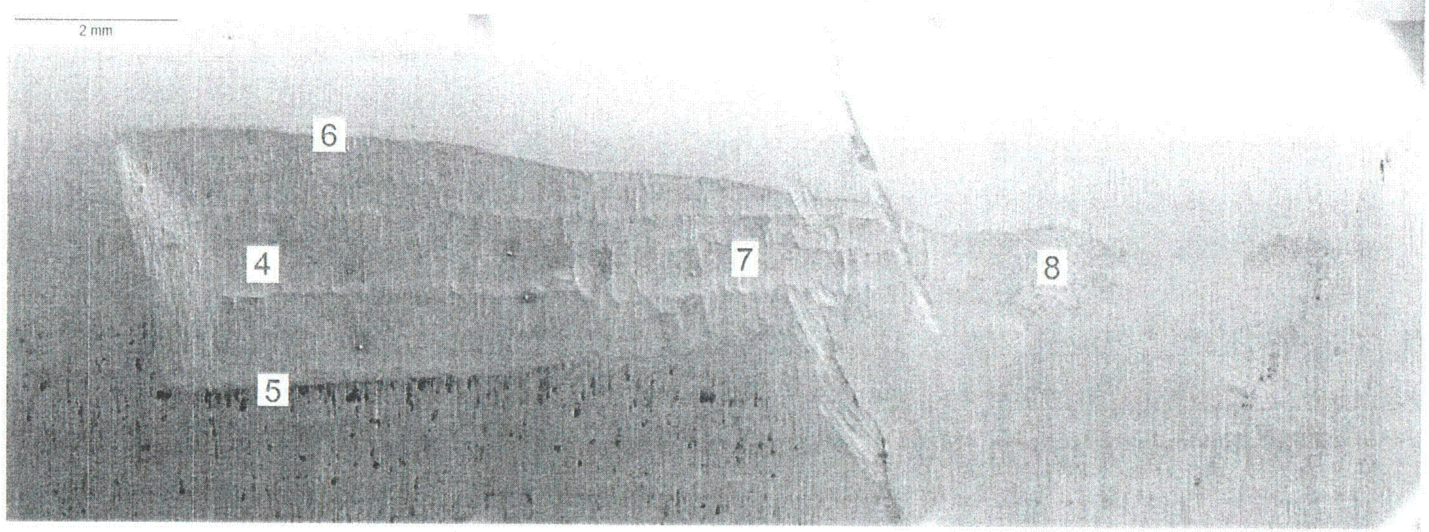
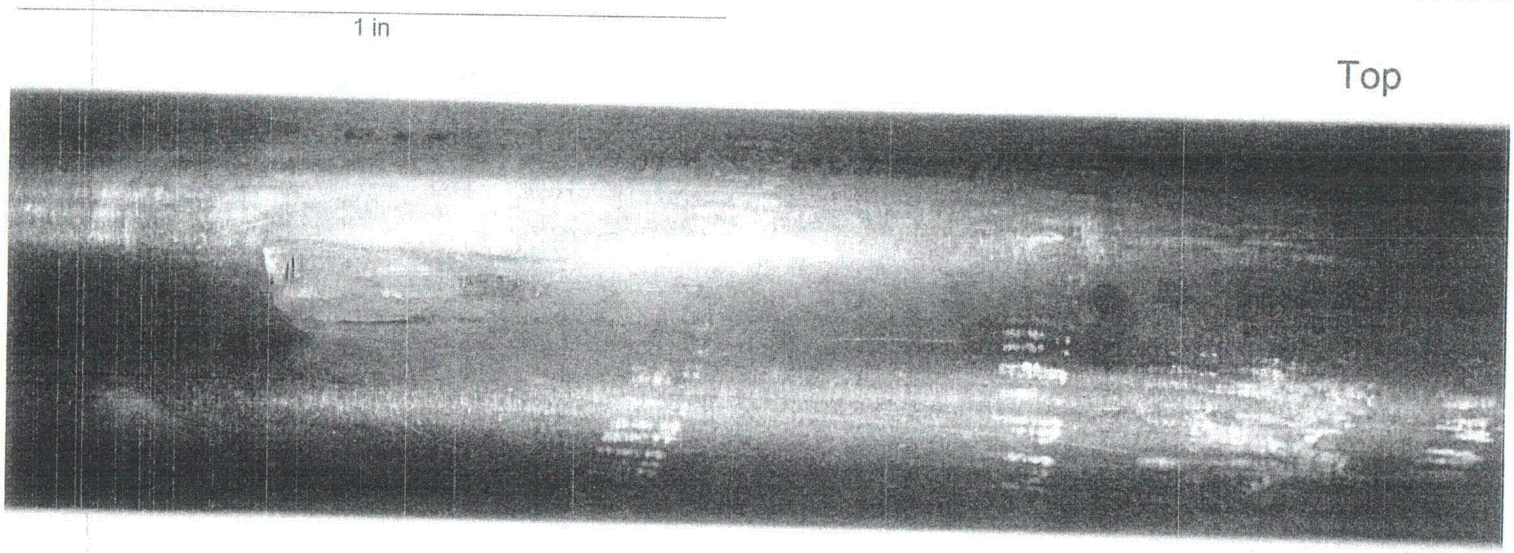


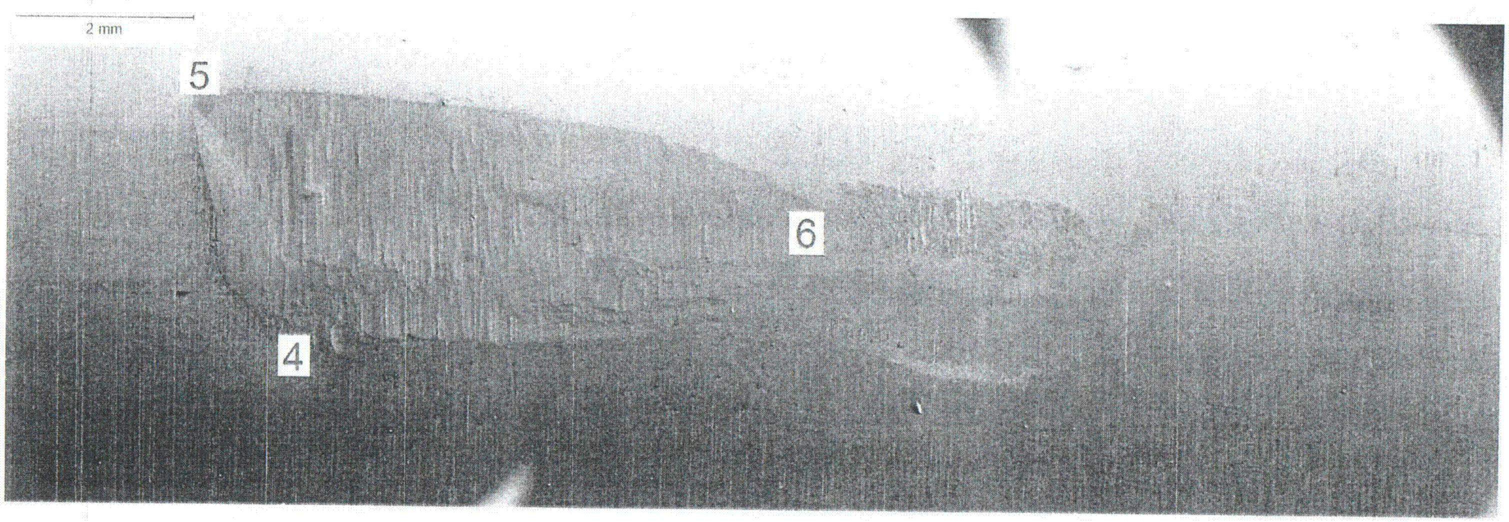
53-114, Pce 32,TSP 14, 110 Deg.



ONS 2 Tube Pulls



53-114, Pce 28,TSP 12, 120 Deg.



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Future direction and conclusions

Status of ONS Steam Generator Root Cause Investigation

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- Install instrumentation package during spring 06 unit #3 outage, perform analysis of data and compare to unit #2, update root cause report/assumptions
- Install instrumentation package during fall 06 unit #1 outage, perform analysis of data and compare results of all testing update root cause report/assumptions
- Perform 100% eddy current inspection of unit #1, establish time rate of wear, validate models and assumptions used in operability assessments and evaluations, update root cause report/assumptions
- Transition to corrective actions for probable causes

TEST INSPECTION PORT LOCATIONS

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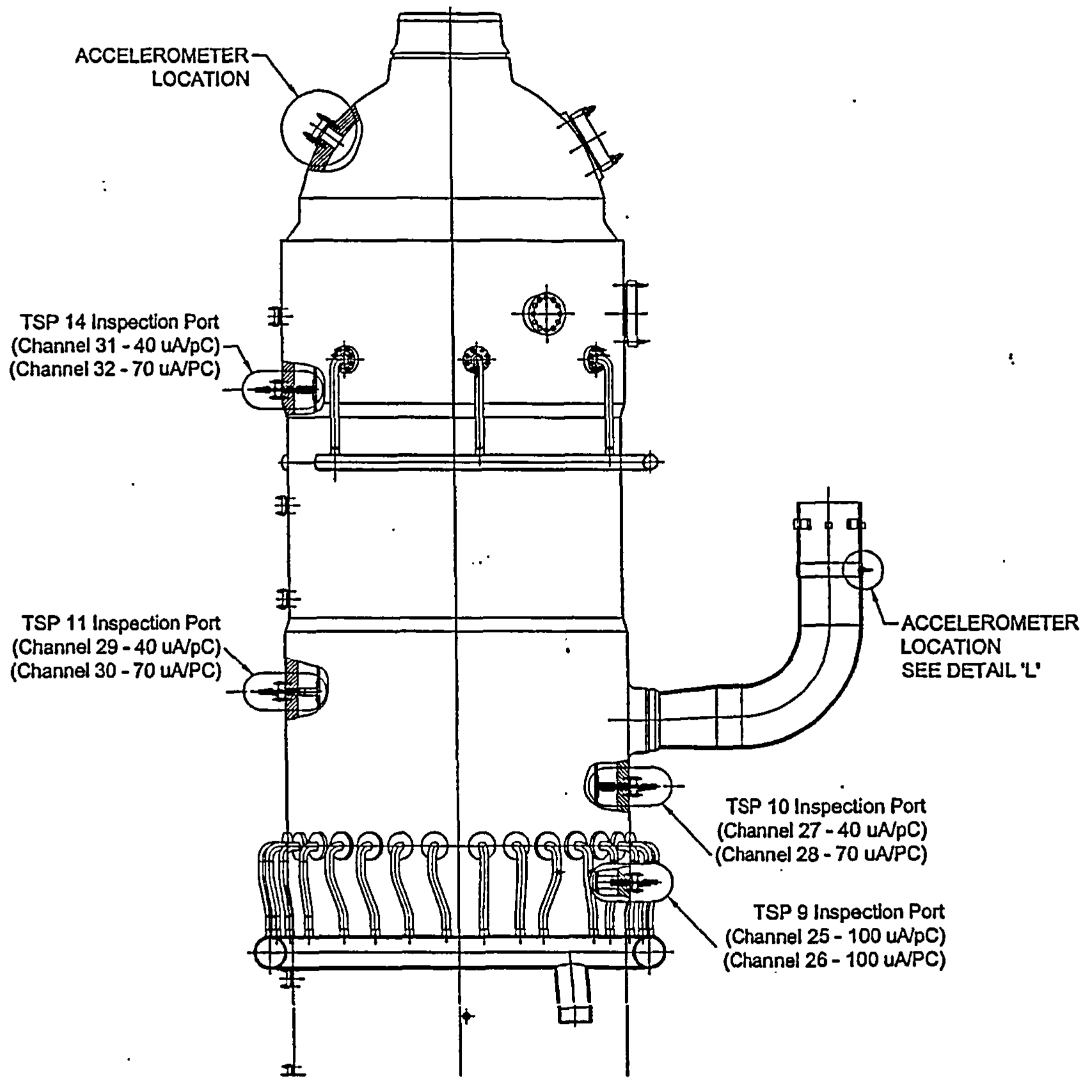

Concluding Remarks

- Root cause teams have been meeting on a regular basis and will continue through out the summer
- We now know more about what is not causing the wear scars and have 4-5 probable causes
- Testing and data analysis efforts will continue for units #3 this spring and unit #1 this fall
- Eddy current results for the fall 2006 outage on unit #1 will give us our first clues as to the time rate of wear and the if new wear scars have initiated
- Root cause effort should come to some conclusions and begin winding down by the end of the year unless unexpected results are found during the unit #1 re-inspection
- ECT will continue on each unit for the foreseeable future