Oconee Nuclear Station
Unit #1 Steam Generator
Discussion with NRC
Washington, DC
June 22, 2005

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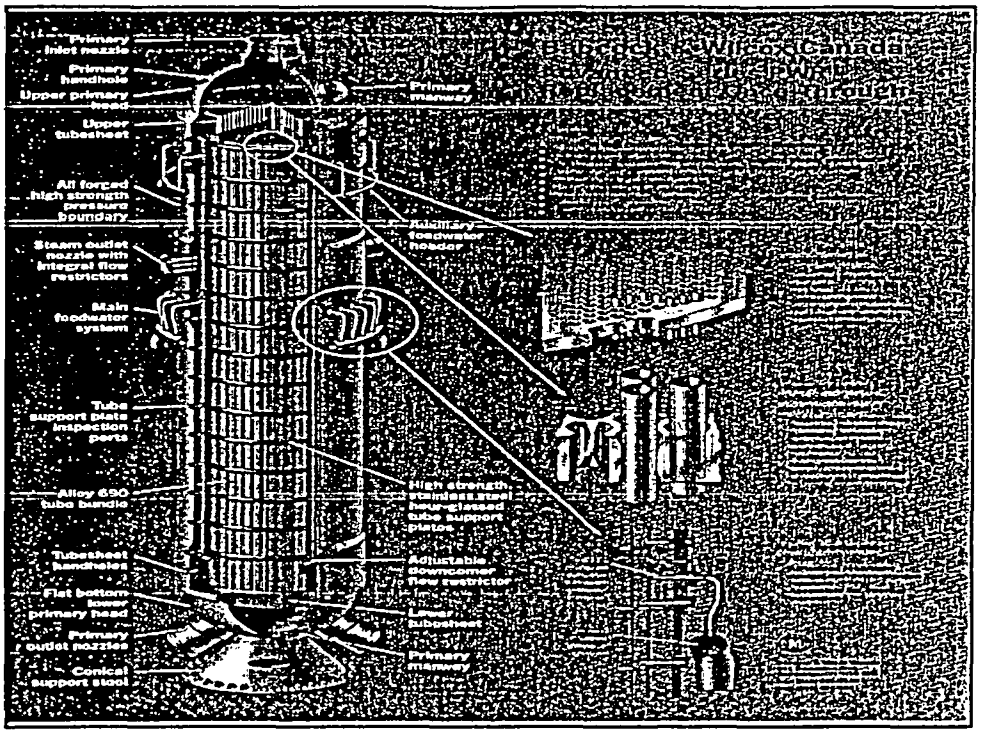
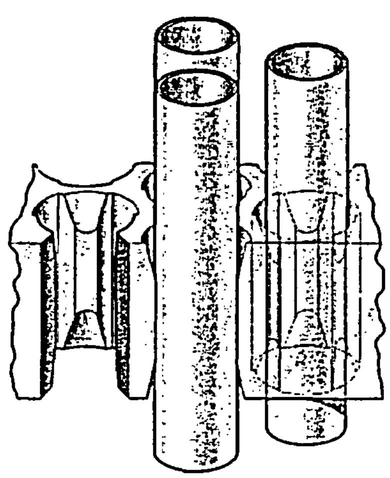
Introduction

- Design comparison of the ONS OTSG and ROTSG
- Spring Inspections Results for ONS #1 SGs
- Wear Indications and Probable Causes
- Duke's Response to the Wear Issue
- Future Impact
- Summary

Attachment 2



Hourglass Broached Hole



Significant Differences in Design between OTSG and ROTSG

Oconee ROTSG
Comparison between Original and Replacement OTSG
with respect to Tube / Tube Support Plate

Description	Original OTSG	Replacement OTSG
Tube material	I 600	I 690
Tube size	5/8" OD (+0.005 -0), 0.034" 1min 0.037" 1nom	5/8" OD (+0.005 -0), 0.034" 1min 0.038" 1nom
Tube free lane	Yes	No
Tube support plate material	SA-212 B [illegible] SA-515 Gr 70)	SA-240 Type 410S
Tube support plate thickness	1.5"	1.5"
Tube support plate spacing	Varying (upper and lower [illegible] ~45", balance at 35"-40")	40.425" – (upper at 22.525") See attached
Plate drilled hole diameter	0.640" min 0.646" max, no hour-glass	0.640" min - 0.646" max, hour glass - See attached
Tube support plate axial length of tube contact	1.5"	0.75" (nom.) - 1.125" (nom. - [illegible])
Broached Hole Land	concave	flat
Avg. tube to hole clearance	0.0155"	0.0155" (non-electropolished), 0.018" (electropolished)
Min. hole clearance	0.021" on corner	0.021" on corner
Off Center Tube to Land Clearance	≈ 0.023" (nom hole, nom tube 0), ≈ 0.0315" (max hole, min tube 0)	0.023" (nom hole, nom tube 0); 0.0315" (max hole, min tube 0)
Peripheral gap between tube support plate and shroud	Yes, at all except TSPs 1 and 15	Yes and no - See attached
Upper shroud to shroud ring connection (above lower [illegible])	Straight cylindrical juncture ~4" gap	Conical juncture ~5.485" diagonal spacing
Tube preload	6 - 15 lbs. depending on source	4.7 lbs
Tube stress at full power condition	[illegible]	See attached
Assembly Technique	Shroud barrels inserted into	TSPs installed sequentially into shroud from bottom up
	shells - lower barrel from lower end, upper barrel from	Tubes installed with larger force
	upper end. Tubes installed with manual strain inside	
	shroud can providing guiding assistance) and forceful	
	(hammering) assistance	

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Operational Comparison OTSG to ROTSG, and "A" to "B"

- FDW Flow (ROTSG Limit = 6.0 X 106 #/hr)
  - A FDW Mass Flow (avg): ~ 5.42x106 #/hr
  - B FDW Mass Flow (avg): ~ 5.35x106 #/hr

  (compared to previous cycle these values are slightly lower, ~0.05 x 106 #/hr)
- MS Outlet Temperature
  - MS Temperature increased from ~592F on A side & ~582F B side to ~595F on both S/Gs

  (with cleaner tube surfaces and better heat transfer performance, this was expected)
- RCS
  - Flow Increased ~3% on A side compared with previous cycle
  - Flow Increased ~5% on B side compared with previous cycle
  - Rx Delta T decreased accordingly

  (Total RCS performance remained constant from previous cycle)
- Water level
  - Water level was lowered ~180" to ~140" (as expected, better heat transfer)

Other Items Reviewed Did Not Indicate Any Operational Abnormalities
(Final FDW Flow, RCS Press, FDW Pump Press, Aux Fdw Flow, MS Press, Vibrations, etc.)

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Definition of the Issue

- A significant number of tubes in the ONS ROTSG were found with wear indications after 14 months of operation.
- 100% eddy current inspection of Oconee Unit #1 "A" and "B" steam generators was conducted at the end of the initial operating cycle as recommended by industry guidance. (15,631 tubes per generator)
- Eddy current inspection scope included 100% bobbin inspection, "X" probe inspection of all tubes showing indications ~3250 tubes

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Oconee Unit 1 EOC-22
Steam Generator Inspection Observations

- Identification of widespread tube wear - confirmed with multiple ECT techniques (bobbin and "X" probe)
- Tube wear statistics
  - 1,800 tubes with wear indications in 1A SG
  - 1,450 tubes with wear indications in 1B SG
  - maximum wear depth observed = 42% TW in the "A" SG
  - 80% wear indications were between 5% and 15% TW
  - wear indications primarily in peripheral regions at 9th, 10th, and 11th TSPs
  - most tubes had single indication; some had indications at multiple locations
  - wear indications were small (generally < 0.5 inch axial, < 35° circumferential)
  - wear indications had a tapered depth profile
  - minimum detectability is 4% TW

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Oconee Unit 1 EOC 22 Steam Generator Inspection Observations

- Most indications (~95%) appear in the superheated steam region in the periphery of the bundle
- Highest population of indications is at the 10th TSP followed by the 11th and the 9th
- Population of indications in the 12th TSP in the "B" SG is low but in the "A" SG 12th TSP the population is 4th highest
- The 15th TSP shows only a few indications (single side chamfer broached hole on the outer tubes ~10 inches)
- The outermost 4 tubes at the 14th TSP in both SGs has only 2 indications (1st four outer tubes are drilled not broached)
- 11th 12th and 13th TSP have same broached hourglass holes with ½ inch bypass between the plate and the shroud blocked. The pattern of indications are similar with two exceptions
  - The lack of indications at the 12th TSP of the "B" SG
  - Higher number of large indications at the 11th TSP in the "B" SG
- The 9th TSP is located just below the bleed port has broached single sided chamfer for ~14 outer tube rows. In the "A" SG this TSP has the most significant non-peripheral population of wear indications
- The single sided chamfer pattern for the 15th, 10th, and 9th TSP covers ~10 inches of the periphery. Indications at the 9th, and 10th TSP occur in both the single sided and hourglass broached holes

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Oconee 1A SG Wear Size Distribution

	Support															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
%TW</=5					1			4	24	15	21	17	6	13		101
%TW>5</=10	4	5	5		2		9	46	318	384	344	228	110	121	1	1577
%TW>10</=15	1	2	2				1	8	89	157	102	83	49	50	4	548
%TW>15</=20									13	47	31	16	8	14	1	130
%TW>20</=25									1	19	15	3		2		40
%TW>25</=30										15	3	1				19
%TW>30</=35										8	4					12
%TW>35</=40										2	2					4
%TW>40</=45										2						2
%TW>45</=50																0
%TW>50																0
Total/Support	5	7	7	0	3	0	10	58	445	649	522	348	173	200	6	2433

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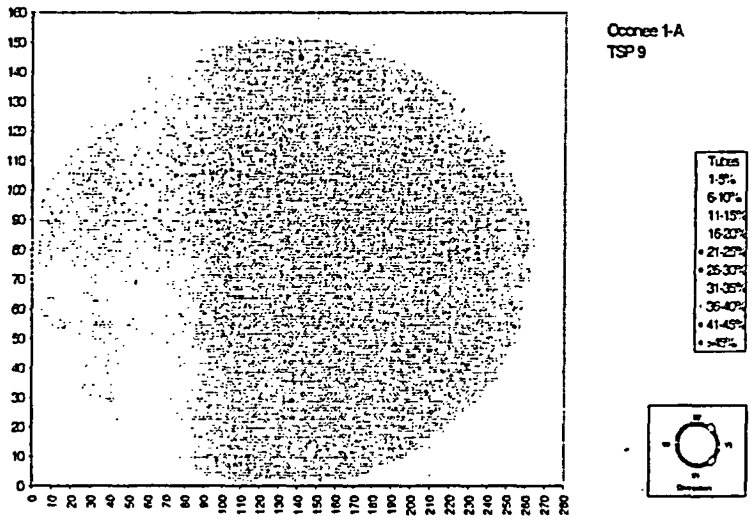
Wear Indications "A" Generator



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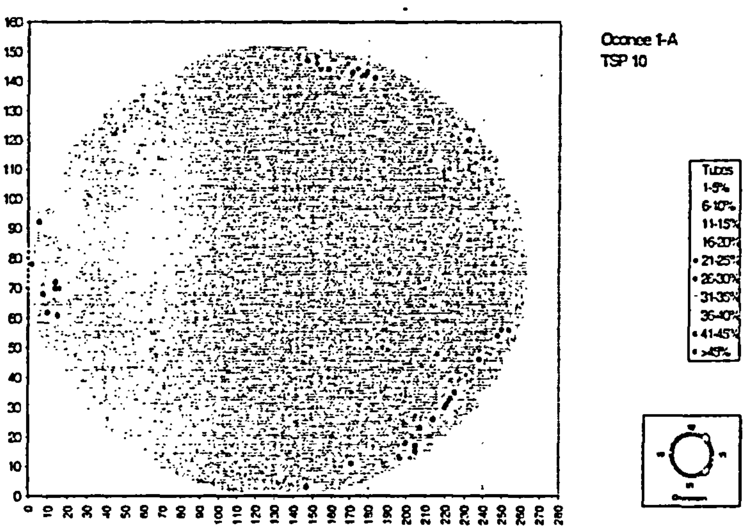
Wear Indications "A" Generator



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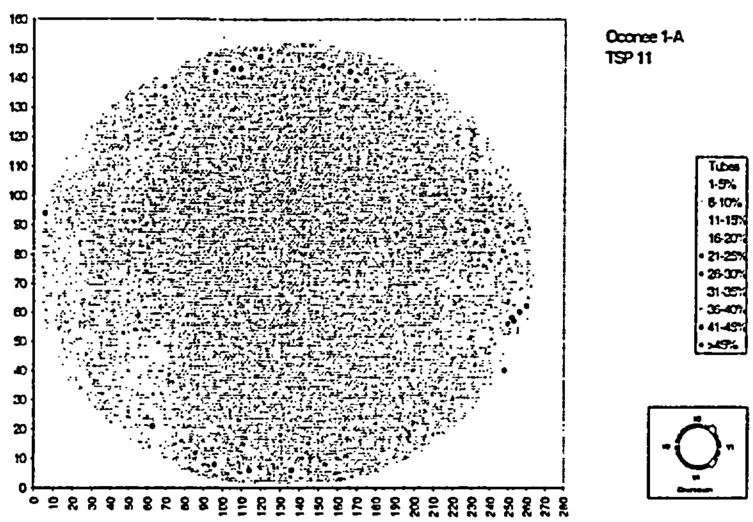
Wear Indications "A" Generator



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Oconee 1B SG Wear Size Distribution

	Support															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
%TW</=5		3	2		1		6	13	19	34	11	2	6	17	1	115
%TW>5</=10	1	9	6	5	2	1	32	34	254	407	177	6	57	178	10	1179
%TW>10</=15	1		1				4		28	131	83	2	5	68	2	325
%TW>15</=20									7	40	36			17	1	101
%TW>20</=25	1								2	16	14		1	3		37
%TW>25</=30										16	6					22
%TW>30</=35										5	4					9
%TW>35</=40										3	2					5
%TW>40</=45											3					3
%TW>45</=50																0
%TW>50																0
Total/Support	3	12	9	5	3	1	42	47	310	652	336	10	69	283	14	1795

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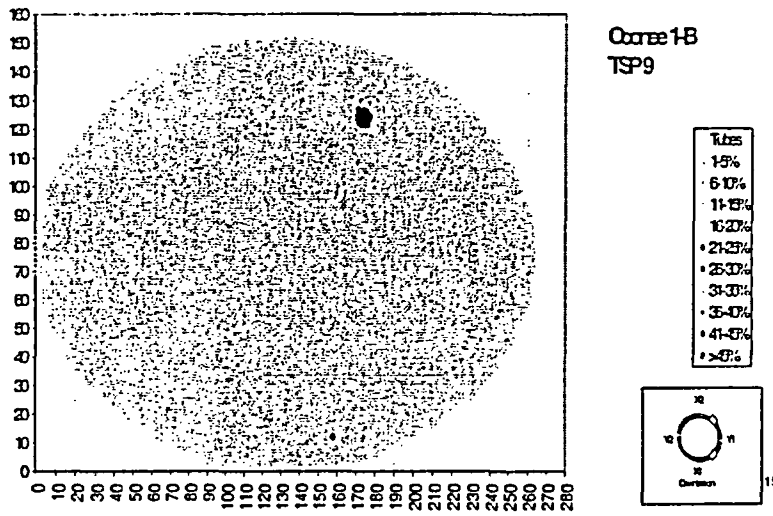
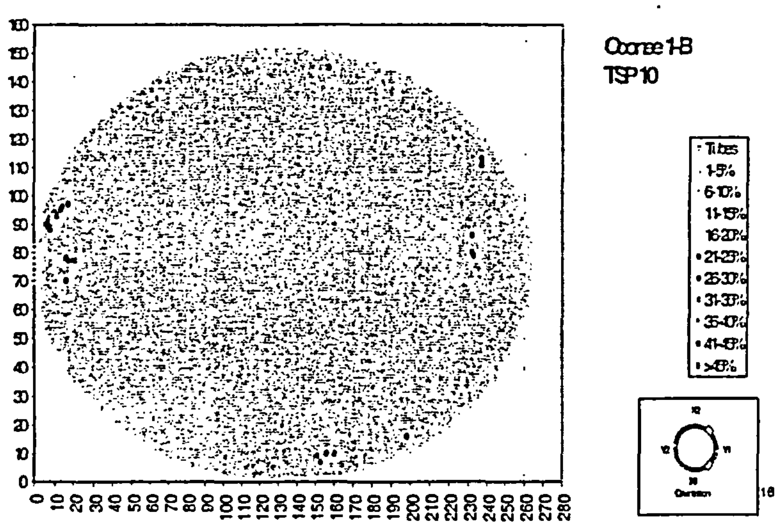
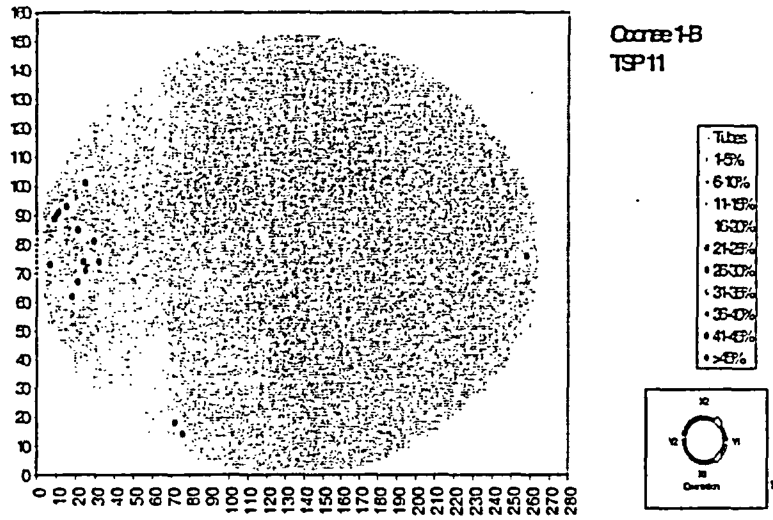
Wear Indications "B" Generator



Wear Indications "B" Generator



Wear Indications "B" Generator



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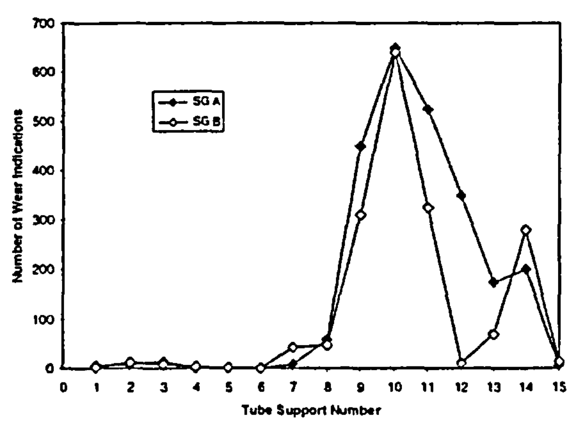
Wear Distribution by Support Location



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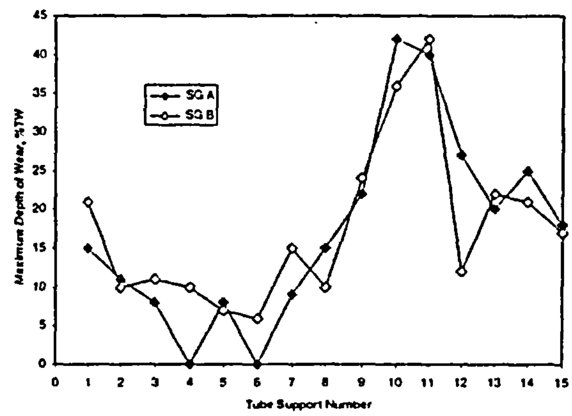
Wear Depth Distribution by Support Location



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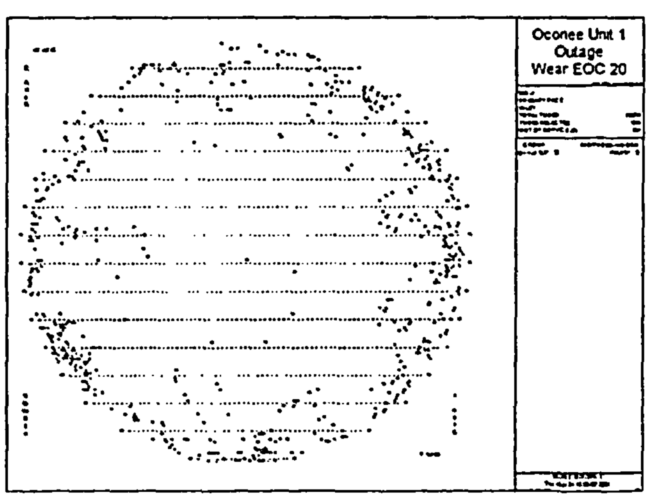
Oconee 1A OTSG Wear Indications After 20 Cycles of Operation (all elevations)



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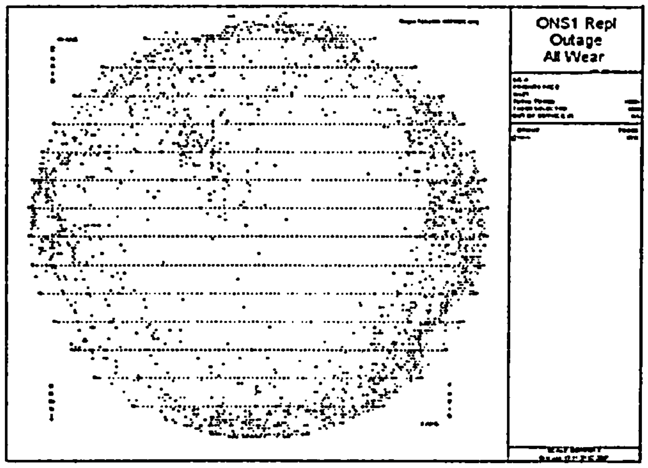
Oconee 1A ROTSG Wear Indications After First Cycle of Operation (all elevations)



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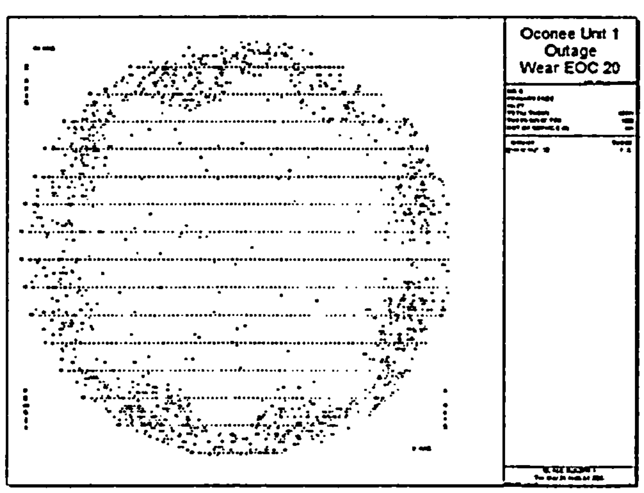
Oconee 1B OTSG Wear Indications After 20 Cycles of Operation (all elevations)



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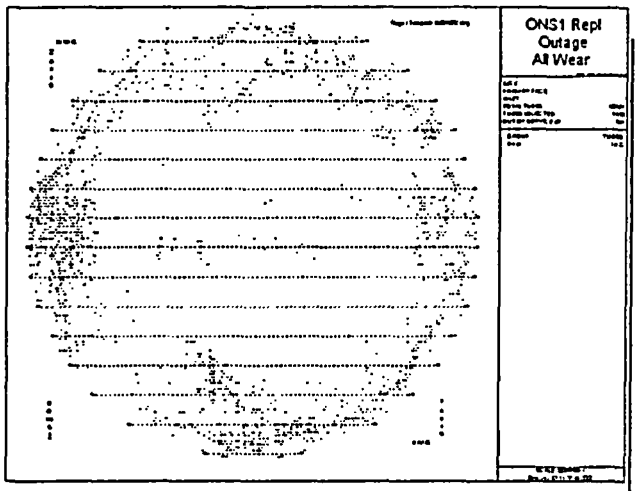
Oconee 1B ROTSG Wear Indications After First Cycle of Operation (all elevations)



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Tube Wear Cause Analysis

- Root cause evaluation being performed by BWC, with Duke oversight
- Both analytical work (calculations, modeling) and mock-up testing being used to investigate possible causes (work currently in progress)
- *Field testing to determine or evaluate wear damage causes*
- Outside consultants being used by Duke for independent investigation (Framatome, MPR, EPRI)
- Probable cause list developed

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Excessive Wear Probable Causes

- Tube Vibration Induced by ROSTG Motion
- Excessive Compressive Load in Tubes
- High Wear Rate Coefficient for Inconel 690 with 410 SS TSP
- Acoustically Induced Tube Vibration
- Broached Hole Surface Finish Roughness
- Hourglass Broached Hole Divergent Nozzle

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Tube Vibration Induced by ROTSG Motion with Primary or Secondary Pipe Flow

- Wide distribution of wear
- Pedestal is less resistant to rocking motion
- Factors to Consider:
  - Upper restraint may have gaps – beyond assembly concerns
  - Flow in the Hot Leg (Candy Cane) can cause ROSTG vibration
  - Main Steam flow restrictor can cause pressure pulsation
- Actions:
  - Verify gap measurements during RSG outage
  - Review loose parts monitoring data
  - Mount accelerometers on ONS Unit #2 during Fall 2005 outage
  - Contingency to mount instrumentation on ONS Unit 1

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Excessive Compressive Load in Tubes

- Wide distribution of wear
- Wear marks on opposite sides of a tube at different TSPs
- Historical data suggest the OTSG tubes were sensitive to FIV when loads exceeded 300 lbs compression.
- Factors to Consider:
  - Most wear marks are at the periphery, compressive loading is highest in the center
- Actions:
  - MPR to conduct 3rd party review of BWC calculations and assumptions on tube loading both preload and operation state
  - Evaluate feasibility of installing strain gauges in/on a tube prior to pulling during Unit #2 outage
  - Evaluate feasibility of installing strain gauges in a tube in operation – Unit #2 or Unit #3

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High Wear Rate Inconel 690 Tube to 410 Stainless Steel Support Plate

- Wide distribution of wear
- 410 stainless steel is harder than original carbon steel
- Factors to consider:
  - BWC wear rate coefficients seem conservative compared to values utilized by others
- Actions:
  - BWC / McMaster University is evaluating out wear testing
  - BWC has AECL performing independent wear simulations using VIBIC and H3DMAP
  - BWC review of EC results and development of gap correlations
  - Place accelerometers inside a tube to measure data
  - Duke and EPRI are evaluating wear rate coefficients

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Acoustically Induced Tube Vibration

- Wide distribution of wear
- *Significant amount of wear appears at the aspirator port and above where fluid medium is steam*
- Wear did not occur in top span where the acoustic response is likely suppressed
- Factors to consider:
  - Original OTSG top span did not pass current industry guidance for acoustic suppression however no wear was observed
  - No unusual noise was reported
  - Slender structures are not typically prone to acoustic excitation
- Actions:
  - Place microphones or AE listening devices on or around the ROTSG
  - Install accelerometers inside a tube during operation
  - Review loose parts monitor data for vibration response
  - Investigating two mock-ups for laboratory studies

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Broached Holes Surface Finish Roughness

- The majority of the wear is less than 0.007 inch deep
- Factors to consider:
  - Only a few tubes had wear greater than 40% Thru wall ~0.014 inch deep
  - Units 2 and 3 have electro-polished holes which should have smoother surfaces
  - Surface imperfections should rub out without wear reaching the depths reported
- Actions:
  - Perform future inspections which should show decrease in wear rate

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Hourglass Broached Hole

- Divergent nozzles have inherent flow instabilities due to jet switch from an imperfect configuration - tube is elastic
- Factors to consider:
  - Flow through a divergent cone can cause tube instability – prior worldwide experiences
- Actions:
  - BWC (M. Pettigrew) construct mock-up and perform tests
  - CFD model of tube to TSP interface

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What We Theorize is Not Causing Wear

- Fluid Elastic Instability
  - No ring wear patterns
  - No mid-span wear
  - Lasted 14 months
- Near Instability Threshold
  - Statistically not valid for 3000 tube to be close with not one tube entering instability
- Classic Vortex Induced Vibration
  - No mid-span wear
  - Wear predominately confined to one location round the circumference at the broached hole
  - Wear noted in interior tubes where vortex shedding is not possible due to very low velocities
- High Turbulence Level
  - Cross flow in aspirator area too low
  - Wear rates are too low unless wear rate coefficient is found in error

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What We Theorize is Not Causing Wear

- Axial Flow
  - Very little lateral energy in the power spectral density from axial flow
- Cross Flow in the Axial Region
  - Very little energy
- Flow Regime Instability
  - Low probability issue based on cross-flow regime maps

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Other Possible Causes / Investigations

- Cross flow in the bundle periphery / gaps
  - 2D CFD model completed matches THEDA model fairly well
  - 3D CFD model underway
  - PORTHOS modeling by Areva/Framatome
  - Thermal expansion of the 410 SS TSP when compared to original carbon steel TSP, differential expansion may increase lateral contact load between the tube and TSP

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Preliminary Conclusions

- No identified design errors – inputs and outputs of models appear reasonable this time
- Expert consensus that the ONS Unit #1 ROTSG are experiencing some flow induced wear – we do not understand excitation force
- Root cause work is continuing

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Industry Experts Engaged Currently

- BWC design engineering organization
- Duke Technical Services/ ONS Engineering
- Areva / Framatome
- Dr. M K Au-Yang, formerly B&W Areva/Framatome
- Dr. M Pettigrew, Ecole Polytechnique
- Dr. John Luxat, McMaster University
- Dr. N Mureithi, Ecole Polytechnique
- Dr. E. de Langre, Ecole Polytechnique
- E. Blandford, G Srikantiah, EPRI
- M. Rao, Stress Technology – EPRI
- Various EPRI SGMP personnel
- MPR Associates
- N. Fisher, AECL (Chalk River)
- Y. Han, AECL (Chalk River)
- Dr. Alan Bilanin, Continuum Dynamics

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Plugging Criteria

- Plug and stabilize all tube with wear indications $\geq$ 28% thru wall - 30 tubes plugged "A" 18 tubes plugged in "B"
  - Wear rate assumed to be linear and based upon the highest rate observed in Unit #1 results 42% (average wear rate approximately 9.8%)
  - Wear rate used in the evaluation was increased based upon the NDE sizing uncertainty of 7.4% thru wall
  - 3ΔP pressure drop of 3930 psi
  - Material properties were evaluated by Monte Carlo analysis which is industry practice
  - Physical dimension of the flaws were adjusted to take into account linear taper, maximum length of the contact area is 1 inch
  - Allowable EOC maximum depth is 80.6% thru wall for a tapered flaw
  - Plugged tubes were stabilized
  - Plugging criteria was reviewed and accepted by BWC

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Corrective Actions

Formal Corrective Actions will be detailed in the final root cause report; however, several CAs are evident including:

- Plug tubes on Unit #1 "A" and "B" SG that exceeded that plugging criteria of wear $\geq$ 28% thru wall
- Refine plugging criteria for Units #2, #3
- Completed installation of the N-16 radiation monitors on each ONS unit
- Review operator actions for N-16 monitors and existing actions for tube leakage and rupture events

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Corrective Actions

Unit 2 Outage (Oct. 2005)

- Pull two tubes for metallurgical examination
- Determine stress loadings on tubes when pulled
- Install instrumentation (accelerometers, acoustic monitoring)
- Prepare to plug up to 200 tubes

Unit 1 Forced Outage

- Install instrumentation

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Future Impact

- Duke needs additional EC data to confirm results and validate models and assumptions. ONS will need to accumulate several cycles of data.
- Future inspections and wear rate analyses may result in three possible conclusions:
  - Wear rates higher than expected leading to mid cycle inspection outages
  - Wear rates follow the expected model leading to plugging tubes and more frequent inspections, every outage
  - Wear rates are less than expected and inspection schedule requires more than one additional 100% inspection to accomplish basis for returning to normal inspection frequency
- Possible impact on unit up-rate
- Possible impact on 24 month fuel cycles
- Possible modification to the existing ROTSGS

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Summary

- Duke and BWC continue to evaluate generator wear using enhanced analysis methods
- BWC will be conducting experiments utilizing mock-ups to prove analysis assumptions, output, and results
- We remain confident the mechanism is fretting wear. We are still searching for the excitation force
- Duke is supplementing in-house expertise with a variety of consultants to ensure that testing plans and analyses are meaningful and lead to corrective actions that will resolve the issue
- This issue is not simple. Considerable effort expended and no "smoking gun" identified
- Expect root cause investigations and research to continue through summer
- Will keep NRC informed of root cause progress and any conclusions

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