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CONFIDENTIAL

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(CONFIDENTIAL) Hearing Exhibit No. 102 from 2/5/20 DOAH Hearing. [CLK Note: See DN 10935-2019 for Exh Nos. 1, 68-75, 80, 82, 100]

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EXHIBIT NO. 102

CONFIDENTIAL

DOCKET NO: 20190001-EI

WITNESS: Jeffrey Swartz

PARTY: Duke

DESCRIPTION: Late filed deposition Exhibit No. 4

DOCUMENTS: Panel deposition of Jeffrey Swartz, Anthony Salvarezza and C. Wayne Toms, August 30, 2019.

PROFFERED BY: Office of Public Counsel

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BRR 4S L-0 Background rev 10-15-16hmc

The Bartow Combined Cycle Steam Turbine 4s (COE mid-2009) last stage blade (L-0) issues started with a routine visual inspection that lead to a forced outage in 2012 after just 3 years of in service time. Several cracks and chips were found on the blade mid-span snubbers and tip z-notches of the turbine end row. The generator end was undamaged and turbine end L-0's were replaced. The OEM concluded in a root cause investigation the cause of the issue was last stage steam flow rates beyond their design limits forcing non synchronous blade vibrations and subsequent wear and fatigue of the mating blade contact surfaces. At that time, the OEM required a limit to the IP exhaust pressure to limit steam flow into the LP section to the original design limit thus restricting output. The unit continued to run at the original design conditions until a more rugged design upgrade was developed and made available.

It is important to note that this turbine was originally designed for another project and built by the OEM, but not shipped. It was subsequently reapplied to the Bartow project with the limitations in turbine output shown on the heat balances and other documentation provided. However, it was much less clear about the exhaust flow limit the output limit implied since this pressure and flow limit is not clearly stated on the documentation given.

In spring 2015 a planned outage replaced the original design blades with blades having several improvements that included hard facing of the mid-span snubber wear surfaces. It should be noted that the original generator end blades, and the 2nd set of turbine end blades, looked to be in good condition and suitable for continued operation.

Information presented by the OEM showed test data indicating an improvement of wear rate and fatigue life by a factor of x10 with the addition of a hard face coating, as well as a significant reduction in contact stresses the revised design promised. Previous to the application of the revised blades, the OEM root cause was questioned and challenged. Two Japanese executives that made a presentation at site and their openness for questions and data presented allowed the Legacy Progress team to conclude that if we had a three year life blade and improvements could give more that x10, the goal a reasonable life (> 15 yrs) was very likely. A contract for procuring and testing this revised upgraded blade also added protection and reduced risk with a 6 yr warranty 3 yr full remainder prorated, a significate upgrade from 1 or 2 yr full warranty. This seemed an adequate choice to justify the decision to plan and schedule this 2015 outage with the upgraded blade.

The test plan for the new blades included strain gage testing in the OEM facility, which we witnessed, and in-situ strain gage testing at site with full load steam. All steps reasonable and practical were taken to assure the design was going to be successful, and the team performed due diligence with the choice to select the redesigned blade and validate it without waiting 3 years for run experience. The testing did reveal an "avoidance zone" or combination of steam flow and condenser backpressures that was a driver for blade stresses above desirable levels. When the unit was returned to service and released for operation with this "avoidance zone", it was intended that the unit not be run with these combinations of flow and backpressures.

In early spring 2016, an inspection that was expected to be routine and have no findings revealed damage at a blade tip z-notch that rendered the unit at a high risk to return to service by the OEM. The blades were

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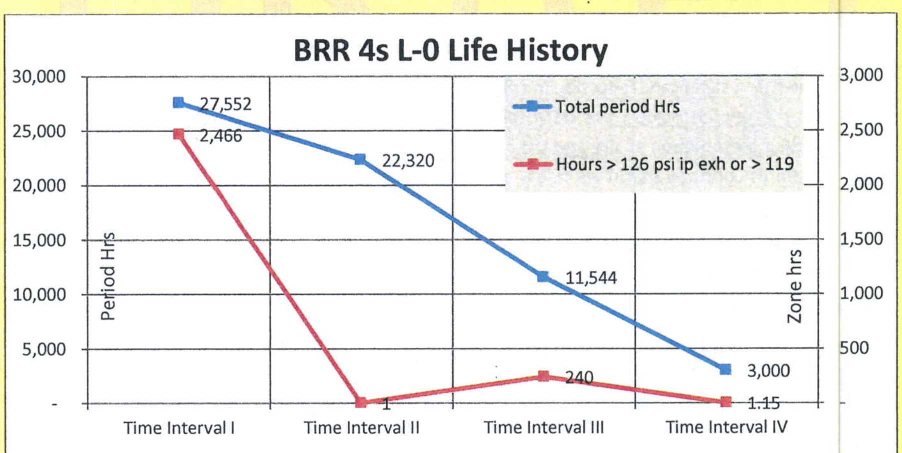
replaced in May 2016 with a second OEM design modification that included adding more hard facing to the tip z-notch contact surfaces.

The unit restarted in June 2016 and ran until July 2016 when a step change in vibration of approximately 0.5 mils at the LP bearings occurred. The unit continued to run and an additional small step change occurred in Aug 2016. The OEM was consulted and they felt the vibration changes were due to changes in bearing stiffness. The Duke team was not completely comfortable with the OEM's explanation and while we felt that rotor mass loss may not be likely, it was possible, and therefore the unit needed to be shut down for a visual inspection. Commercial load demands, two hurricanes and other unit outages postponed this inspection until mid-Oct 2016.

This recent inspection revealed the cause of the vibration changes to be significant mass loss of three separate L-0 blade tip z-notches – one on the turbine end row, and two on the generator end row. In addition, at least one mid-span snubber has failed. The data indicate one of the blades only ran 30 days prior to failing.

The expected blade life predictions of the latest blade configuration compared to the actual field experience is the driver for the study in attachment A of steam turbine output and operating pressures versus time. There is one particular fact and clear apparent path forward that can bee seen in this data. The Table below from the attachment presents the fact that the more we modified the blades, the shorter the time before contact surface failure despite the fact we have continued operate the unit with lower steam flows that fall mostly within the OEM limits for the original design.



Inspection of the data reveal that the original design in time intervals 1 and 2 only had the mid-span snubber failure of the original turbine end (TE) blades – and the 1st time interval nearly 2500 hours of operation was above the OEM limit. In time interval 2, no failures occurred and there was only 1 hours of operation slightly above the limit. This means that the generator end (GE) blades ran nearly 50,000 hours with no failures.

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This is in contrast to time interval 3 where failures occurred after only 11.5 khrs of operation with only 240 hours above the original limit – and interval 4 with only 3 khrs of operation and just over only 1 hour above the original flow limit. The data clearly suggest that returning to the original design, and limiting the IP exhaust pressure to 123 psig (not sure I'm reading that right off the graph), which will give approximately 400 to 405 MW with 4x1 operation, will give much more acceptable life than the modified design.

Summary of Data

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While there are many significant points and facts to be concluded from the data being presented, a glaring fact that surfaces is the more we improved the blade design (two modifications, three versions tested) and simultaneously reduce the time at excessive flows, the shorter the blade service interval has become. It was never obvious earlier in the spring 2016 failure because the time operations exceeded the pressure was the focus of the second yet incomplete RCA. No one knew the first service run had so many hours above the later imposed pressure limit.

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While in the period I there were 33K hrs available and 2600 hrs with high pressure operation. There were no blades found with complete z-notch lug loss and no step changes in vibration were encountered.

Compare this to period III with 11k hrs and 240 hrs with high pressure. This is the first design modification compared to the original design we were trying to improve. The life decreased by x 1/3 rather than increase by x10 . The high pressure hours did decrease from 9% of the time period to 2%, but the blade service life still decreased. This is counter to the expected result.

In period IV the unit ran 3k hrs with 1.15 hrs at high pressure. This is the second design modification. The life decreased to ~ x 1/10 not x10 as advertised. If you consider the unit actually failed a blade 30 days after restart when the vibration changed ~ 700 hours the decrease in life is even less x 1/10 to approx. x 0.2. Or effectively the second design modification, with pressure restrictions, gave 2% of the life of the original design with no pressure restriction.

For these reasons the recommended direction on the current repair (fall 2016) is to return to the original blade design (no hard facing) with reasonable operational restrictions on steam flows and pressure limits. These restrictions need to be part of the control logic and not an operator or supervision option to interpret.

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If this style blade is not quickly available the option of inspecting and installing the blades removed in 2012 should be evaluated against an extended outage waiting for blades. This is not the first recommendation.

Opinion

These facts supported by actual experienced field data suggest the proposed OEM root cause may not be inclusive of all interactions possible. It also suggests the following points need to be investigated for a better RCA

- Quality of coating (workmanship)
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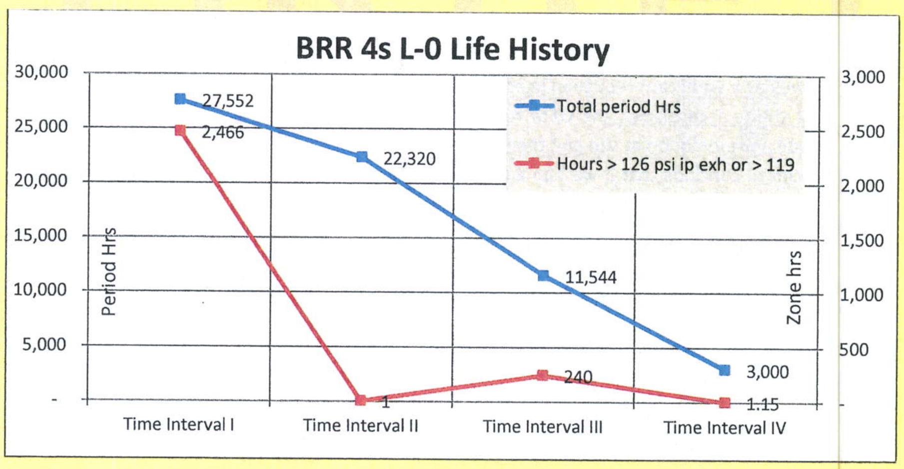

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Bartow Steam Turbine

RCA Review

Nov 9th 2016

MITSUBISHI HITACHI POWER SYSTEMS

Agenda

- Goal of the Meeting
- RCA
  - RCA Action Items
  - Fleet History
  - Blade Metallurgical Evaluation
  - Manufacturing and Assembly Data
  - Telemetry Test Data Review
  - Operation Data Analysis
  - RCA Conclusion

Goal of the Meeting

- Review RCA evaluation of blade damage found in April 2016 and provide root cause of shroud chipping

Note : Blades were Type 3 Blades with mid-span snubber HVOF used in the telemetry test to understand the blade response and operating capability.

RCA Team

Muhammad Riaz	RCA Lead	MHPSA
Nick Porteous	MHPSA RCA Sponsor + Technical Contributor	MHPSA
Ikushima-san	MHPSA Communications Lead	MHPSA
Ryan Paulson	Inspection	MHPSA
Ruban Amirtharajah	Operating Data Review	MHPSA
Balaji Jayaraj	Metallurgist	MHPSA
Miyajima-san	Lead Analyst	MHPS
Enomoto-san	MHPS RCA Sponsor	MHPS
Osaki-san	MHPS RCA Lead	MHPS
Jon Hopkins	Blades Scan	MHPSA
Jake English	Duke RCA Lead	Duke
David Brown	Operations specialist	Duke
Chris Holland	Engineering	Duke
John Burney	Engineering	Duke
Additional Resources		
Harry Carbone	Duke Technical Consutant	Duke
John Huls	Duke ST SME	Duke

RCA Team members from Duke Energy, MHPSA USA and MHPS Japan
Multiple working meetings were held to work on the RCA Actions

Blade Shroud Chipping RCA – Fish Bone

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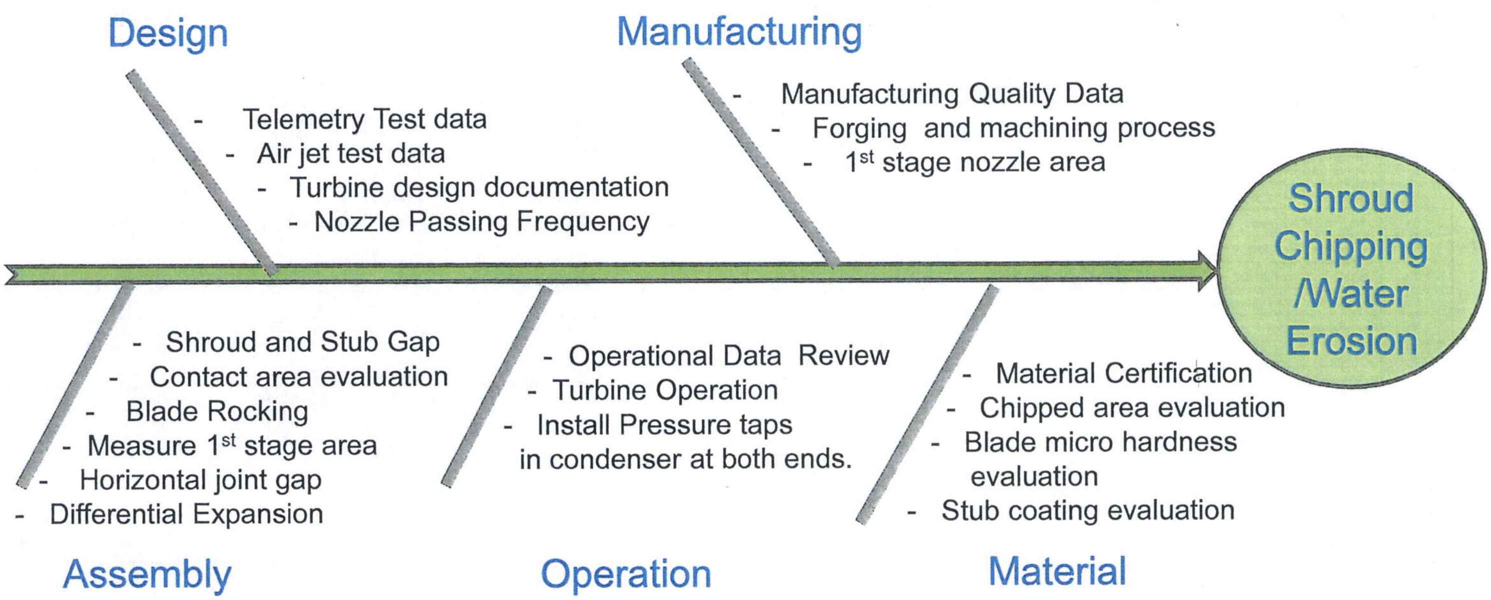


Key Areas of Investigation

Blade Shroud Chipping RCA

Detailed Actions Tracked (1 of 2)
Reviews conducted with RCA Team

Influence

Low
Medium
High

		Actions	Conclusions
Design	1	Independent Review of Bartow 2015 Telemetry Test Stress Analysis and Operating Limits Provided	Telemetry Test Data review completed by team in MHPS in Japan.
	2	Confirmation of frequency margins identified in Air Test Data, comparing with original design / other air jet tests	All synchronous vibration frequencies are within design range.
	3	Re-evaluation of the Telemetry Test Data in the light of Bartow Tip Damage	Completed by team in MHPS in Japan.
	4	FEA Review of shroud face movement at high load compared to observed damage	FEA Analysis performed by MHPS in Japan.
	5	Confirm MHPS Mass Flow Calculation Method used in evaluating Telemetry Test Data	Mass flow measurements are no more used as evaluation parameter
	6	Telemetry Test Data Shroud Fretting Calculation sim too Snubber Calculations	Fretting evaluation completed by MHPS in Japan.
	7	Revisit Bartow / Tenaska design torsional margins	Torsional design calculations show acceptable design margins
	8	Research overall exhaust pressure limits for 40" L-0 compared to this unit	Bartow Exhaust pressures limits are standard limits
	9	Review Axial Rotor Position relative to asymmetry from Gen/Gov end	Rotor axial position reviewed and recommended to use as is original design.
Manufacturing	1	Request Forging Material Test Certs for existing installed blades	Material Certs show correct material used and meet design material properties and chemistry.
	2	Request Forging Material Test Certs for replacement blades	Material Certs show correct material used and meet design material properties and chemistry.
	3	Moment Weights for existing installed blades	Row of blades is balanced with acceptable unbalance residual
	4	Request Moment Weights Test Certs for replacement blades	Row of blades is balanced with acceptable unbalance residual
	5	Request Machining Manufacturing Quality Records (Including Box Gap Data + Single Blade Freq Data) New Blades	Data reviewed and blades are with in acceptable criteria
	6	Request Machining Manufacturing Quality Records (Including Box Gap Data + Single Blade Freq Data) Existing Blades	Data reviewed and blades are with in acceptable criteria
	7	Request Record of as Built Area Nozzle Check	Data not located by Japan.
	8	Field Measurements of LP 1st Stage Nozzle Area (Throat / Base Dia / Nozzle Height @ both ends)	1st stage nozzle area is within less than 0.5% on both ends.
Material	1	On site review of fracture surfaces and wear	Review of rotor, blades and casing on site.
	2	Characterize Cracking / Chipping on Tip - Fretting Fatigue?	Metallurigical Evalaution of blades performed in US and Japan included - Visual Inspection - Material Composition -Microscopic evaluation - Hardness evaluation - SEM evaluation - EPMA evaluation
	3	Characterize Cracking / Chipping on Tip Wear Surface - Fretting Fatigue?	
	4	Characterize Hardness throughout tip and wear surface	
	5	Characterize microstructure throughout tip and wear surface	
	6	Evaluate Wear on Mid Span Snubber	
	7	MHPS TGO Lab Review - Establish blades to be sent	
	8	TGO Evaluation	

Blade Shroud Chipping RCA

Influence

Influence
Low
Medium
High

Detailed Actions Tracked (2 of 2)
Reviews conducted with RCA Team

		Actions	Conclusions
Assembly	1	On Site 4 Point Check of Snubber and Shroud (as found + as left)	Gap Data recorded and analyzed. Data within tolerance
	2	Blue / White Light Scan for sample of replacement blades	3 blades (Light/Medium/heavy) were scanned and compared with nominal model after HVOF. No differences identified.
	3	Geometry overlay and review	
	4	Blue / White Light Scan for sample of existing installed blades	7 Blades were scanned and compared with nominal model. No differences identified.
	5	Geometry overlay and review	
	6	Confirm amount of rocking on existing blades / and replacement installed blades	Small rocking was observed on few existing blades. No rocking observed on new blades.
	7	Measure HJ Gap at Diffuser	HJ gap measured at unit assembly and found to be within tolerance.
	8	Review wear profile across single tip during early damage	Wear profile checked with replica and by sectioning and reviewed under microscope.
	9	Measure shroud contact surface (L,W,Depth at 4 points)	Contact surface data collected
	10	Wear and Chipping Documented with photos and scale	Pictures taken for all contact surfaces and documented.
	11	Record water erosion at leading edge and under the shroud	Data recorded and minimum to no erosion observed.
	12	Stationary blade surface finish review	L0 Stationary blade surface finish was checked and no issue is observed.
Operation	1	Map Operating Data to LP Loading and Summarize	Operation data reviewed
	2	Install Pressure Taps / and re-evaluate exhaust flow on return to service	Additional pressure taps are installed.
	3	Operational Data Review of exhaust pressure taps on return to service	Data received and reviewed.
	4	Provide summary of LP Pressure Measurement Location and LP Admission Flow	Locations provided to Bartow
	5	Start-Up Review for Cold, Warm and Hot Starts.	Data not received from Bartow
	6	Characterization of operation from Log Book	Data not received from Bartow
	7	Operation review to determine expected moisture and sensitivity to flow and exhaust pressure changes	Asymmetric condenser circulating water flow at both ends
	8	Provide details or pictures of April 2015 Blade Inspection	Few pictures provided
	9	Provide report of Dynamic Pressure Study from ~2012 for evaluation	Summary provided- No vibration response was observed.

Team Meetings focused on methodical execution of actions and opportunity for questions / discuss of details

40” Fleet Operating Experience

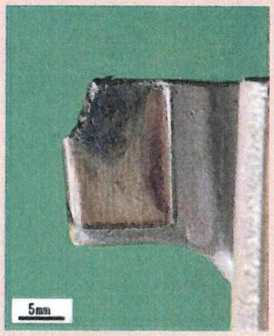
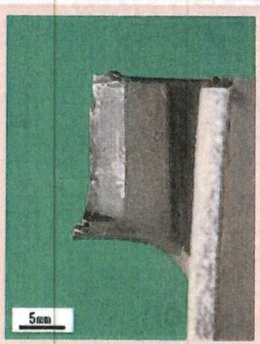
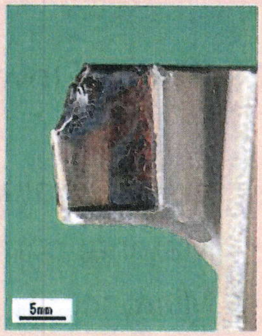
- There are 57 rows of 40” L0 blades operating in the world. 9 Single flows, 22 double flow and 1 four flow LP sections.
- There are 31 rows of type 3 blades (same blades as Bartow except no HVOF coating/ chamfer on midspan snubber). 14 double flows and 3 single flow LP sections.
- Type 3 blades have Stellite material welded under the shroud for water erosion protection.
- Oldest Type 3 blade in operation since 2008.
- Bartow steam turbine have the highest L0 Blade loading amongst the fleet.

Metallurgical Evaluation of Blades Operating from December 2014 to April 2016

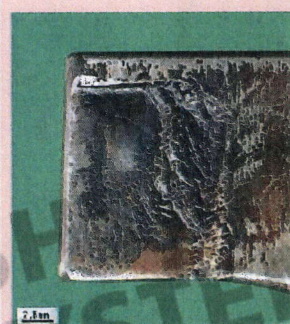
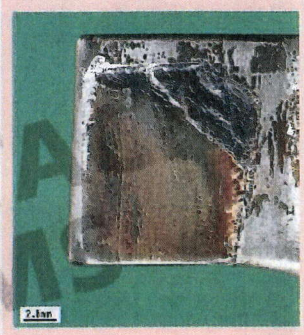
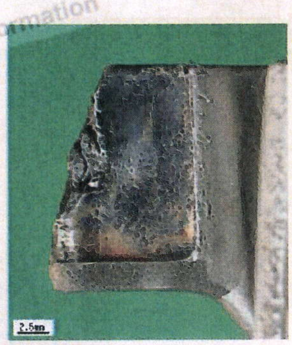
Methods of Investigation :

- Visual Evaluation of Blades
- Material composition
- Microscopic evaluation
- Hardness evaluation
- SEM evaluation (Scanning Electron Microscope)
- EPMA evaluation (Electron probe micro analyzer)

Blade Inspection Results

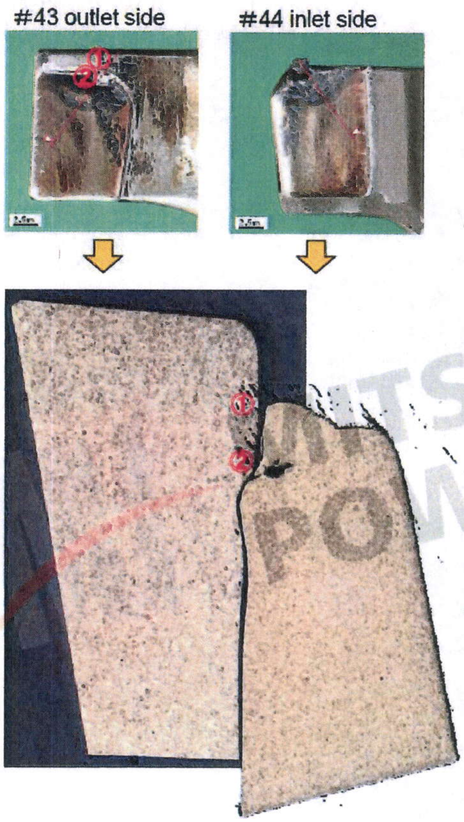
	#39	#40	#41	#42
Contact Surface Leading Edge				
Chipped Surface				

Blade Inspection Results

	#42 outlet #43 inlet	#43 outlet #44 inlet	#44 outlet #45 inlet	#45 outlet -----
Outlet side contact surface				
Inlet side contact surface				-----

Shroud Chipping is starting at same location for all blades

Metallurgical Evaluation of Blades

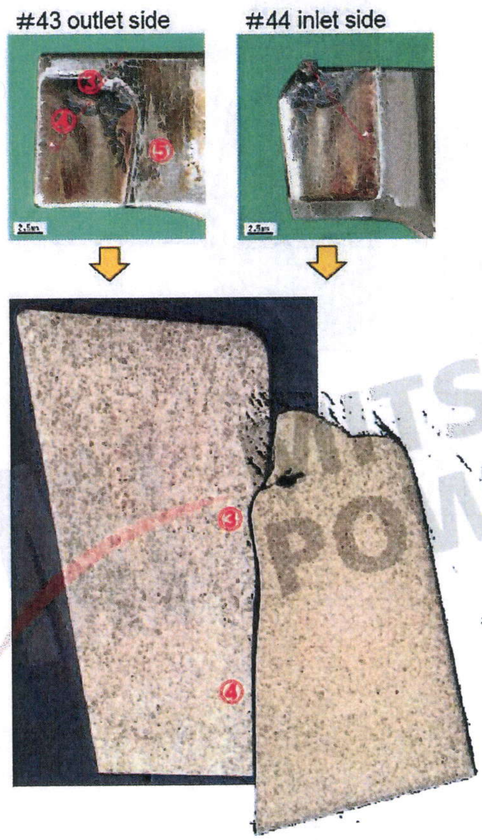


Microscopic observation was performed on the same sections in contact condition for each of outlet side of #43 blade and inlet side of #44 blade.

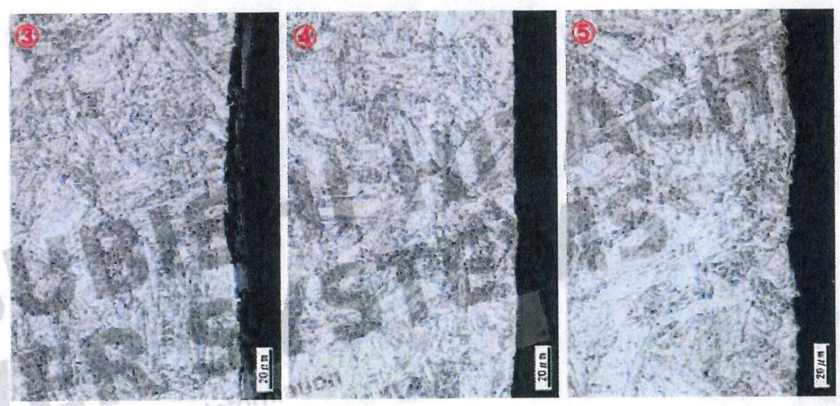
- Fine cracks, caused by fretting fatigue, are found near the end of contact part with local deformation of inlet side of #44 blade.
- Plasticity is found in concave part of local deformation.

Fretting fatigue identified as crack initiation source.

Metallurgical Evaluation of Blades



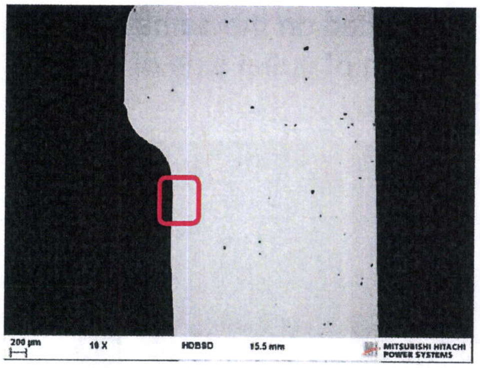
Microscopic observation was performed on the same sections in contact condition for each of outlet side of #43 blade and inlet side of #44 blade.

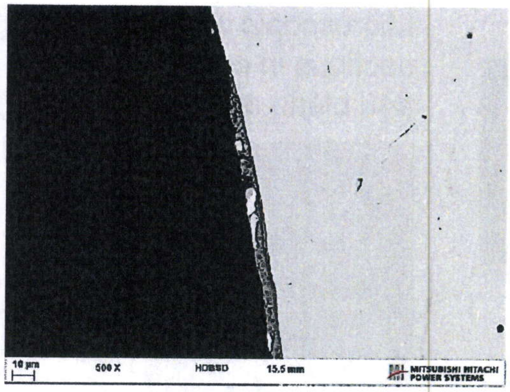


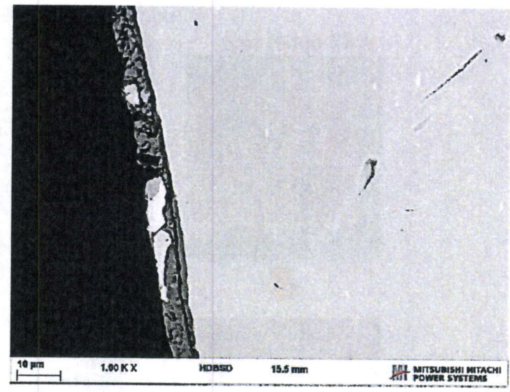
- ③: Oxide scale was found on black surface of local deformation area.
- ④: Dark brown surface of worn and thinned part is free of oxide scale and smoother than non-contact surface of ⑤.

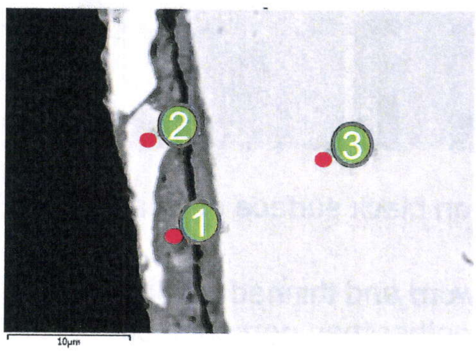
Oxide scale with local deformation observed on black surface

Metallurgical Evaluation of Blades









Location	Semi-Qualitative EDS analysis of elements detected (wt%)							
	O	Si	Cr	Mn	Fe	Ni	Cu	Nb
1	25.97	0.44	7.67	0.41	61.59	1.84	1.18	0.00
2	0	0.35	18.15	0.95	70.12	9.35	0.08	1.00
3	0	0.33	15.86	0.54	73.65	4.91	3.58	1.14

- Oxidation/corrosion was observed on the trailing edge contact surface of the tip shroud.
- Material removal from wear is from abrasion.

Material chemistry matched with blade original material

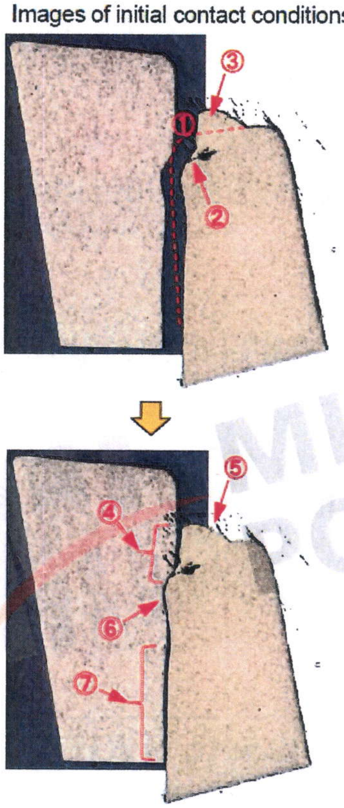
Metallurgical Evaluation of Blades - Hardness

- Hardness measurements are taken at the shroud contact surface, fracture surface, base material and below the shroud on 8 blades.
  - The results show hardness close to original materials (Base Material and Stellite welding).
- Hardness measurements also taken at stub contact area and away from contact surface on base material.
  - The results also show Hardness within criteria at the contact surface and away from contact surface.

No hardening is transferred to base material due to HVOF, contact surface rubbing or welding Stellite material.

Damage Mechanism

Images of initial contact conditions



① Partial local contact at the top and tip of blade

↓

② Fretting fatigue crack generated in local area

↓

③ Local deformation is generated along with the crack

↓

④ Excessive local surface pressure (adhesion) & vibrational stress are applied.

↓

⑤ HCF crack is generated.

↓

⑥ Local wear generated by high surface pressure & excessive sliding. Oxide scale developed by heat generation (black surface).

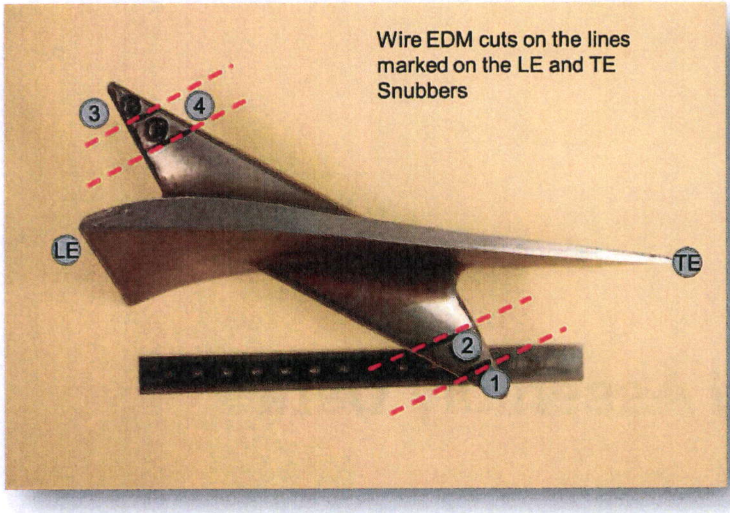
↓

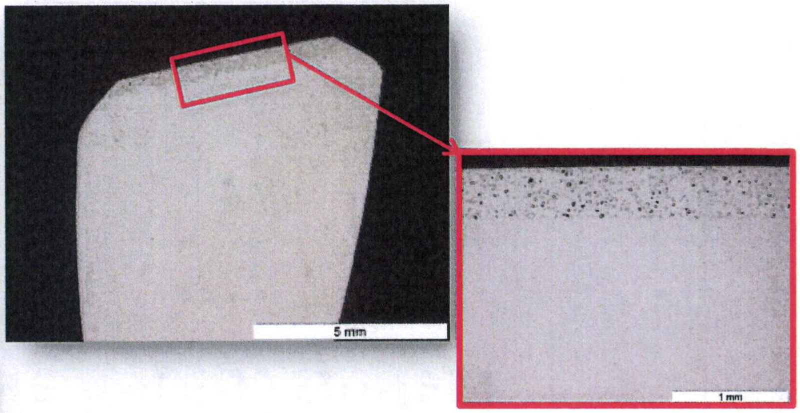
⑦ Worn by wear debris

⑧ Partial defect was caused by fretting fatigue crack which was generated and propagated in high surface pressure and sliding area (black surface).

※⑦ & ⑧ progressed at the same time

Stub Evaluation



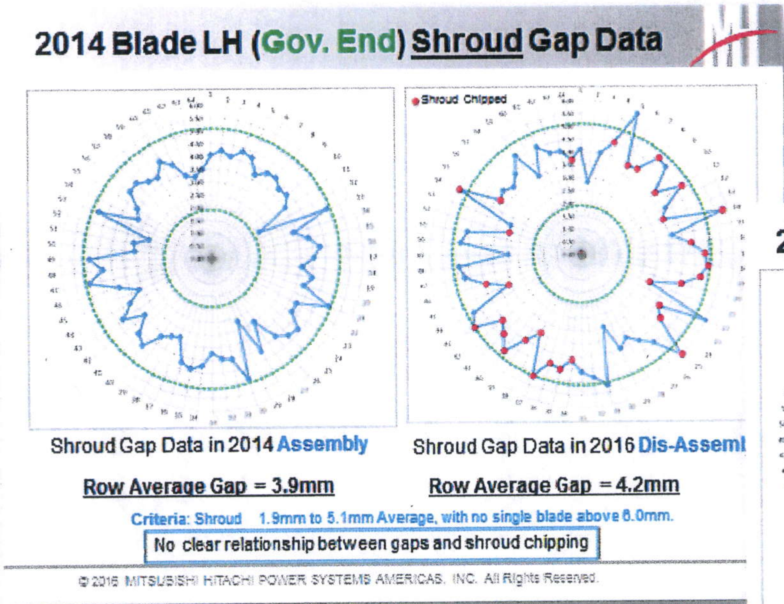


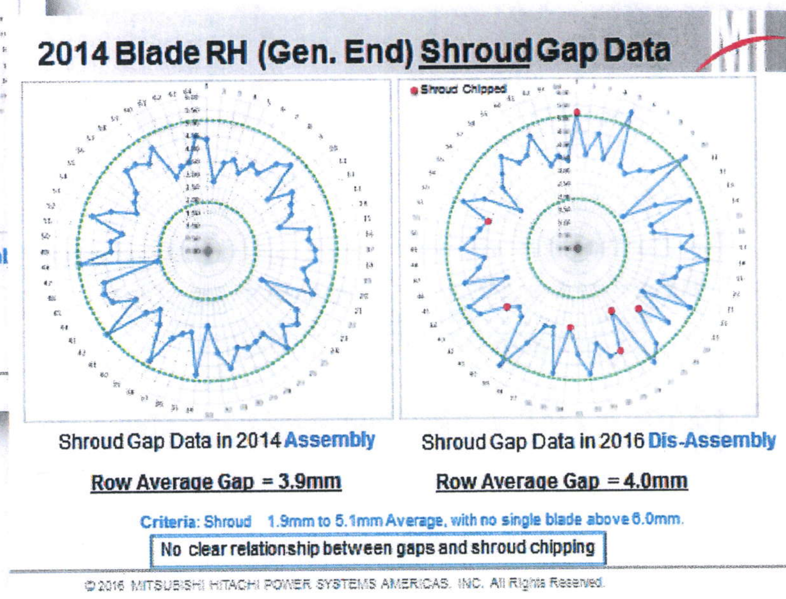
- The contact surface coating did not show any cracks, deformation or wear.
- Uniform thickness was measured on the areas of contact between the LE and TE snubbers.

HVOF coating on the stub prevented fretting or any other surface damage

Manufacturing and Assembly Data

Shroud Gap Data





LH and RH shroud average gaps are nearly same
No clear relationship between gap and shroud chipping

Stub Gap Data

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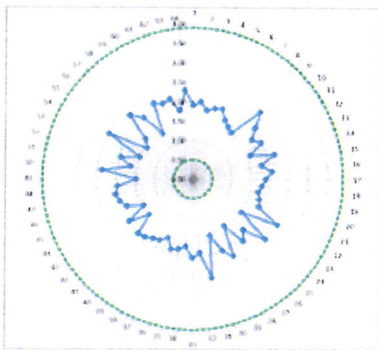
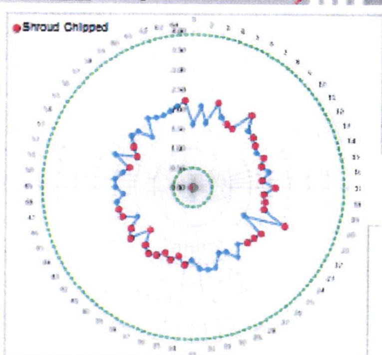
2014 Blade LH (Gov. End) Stub Gap Data





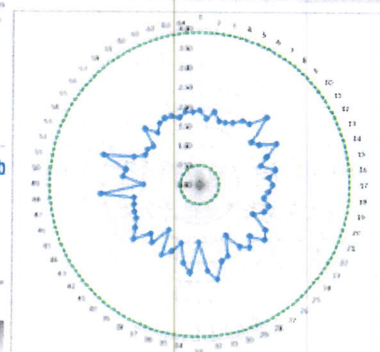
Shroud Gap Data in 2014 Assembly — Shroud Gap Data in 2016 Dis-Assemb

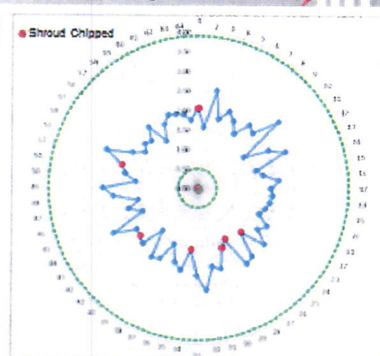
Row Average Gap = 1.9mm — Row Average Gap = 1.9mm

Criteria: Stub 0.5mm to 3.9mm Average, with no single blade above 4.8mm.

No clear relationship between gaps and shroud chipping

2014 Blade RH (Gen. End) Stub Gap Data





Shroud Gap Data in 2014 Assembly — Shroud Gap Data in 2016 Dis-Assembly

Row Average Gap = 1.9mm — Row Average Gap = 1.9mm

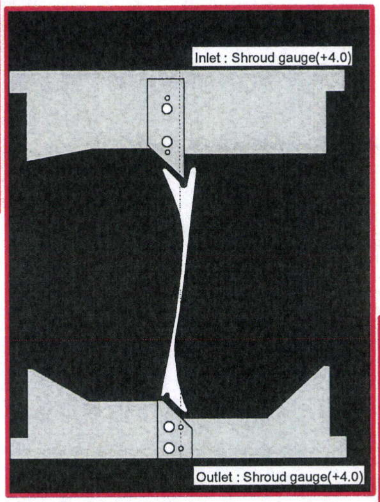
Criteria: Stub 0.5mm to 3.9mm Average, with no single blade above 4.8mm.

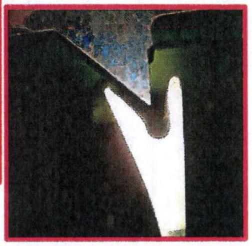
No clear relationship between gaps and shroud chipping

LH and RH stub average gaps are nearly same.
No clear relationship between gap and shroud chipping.

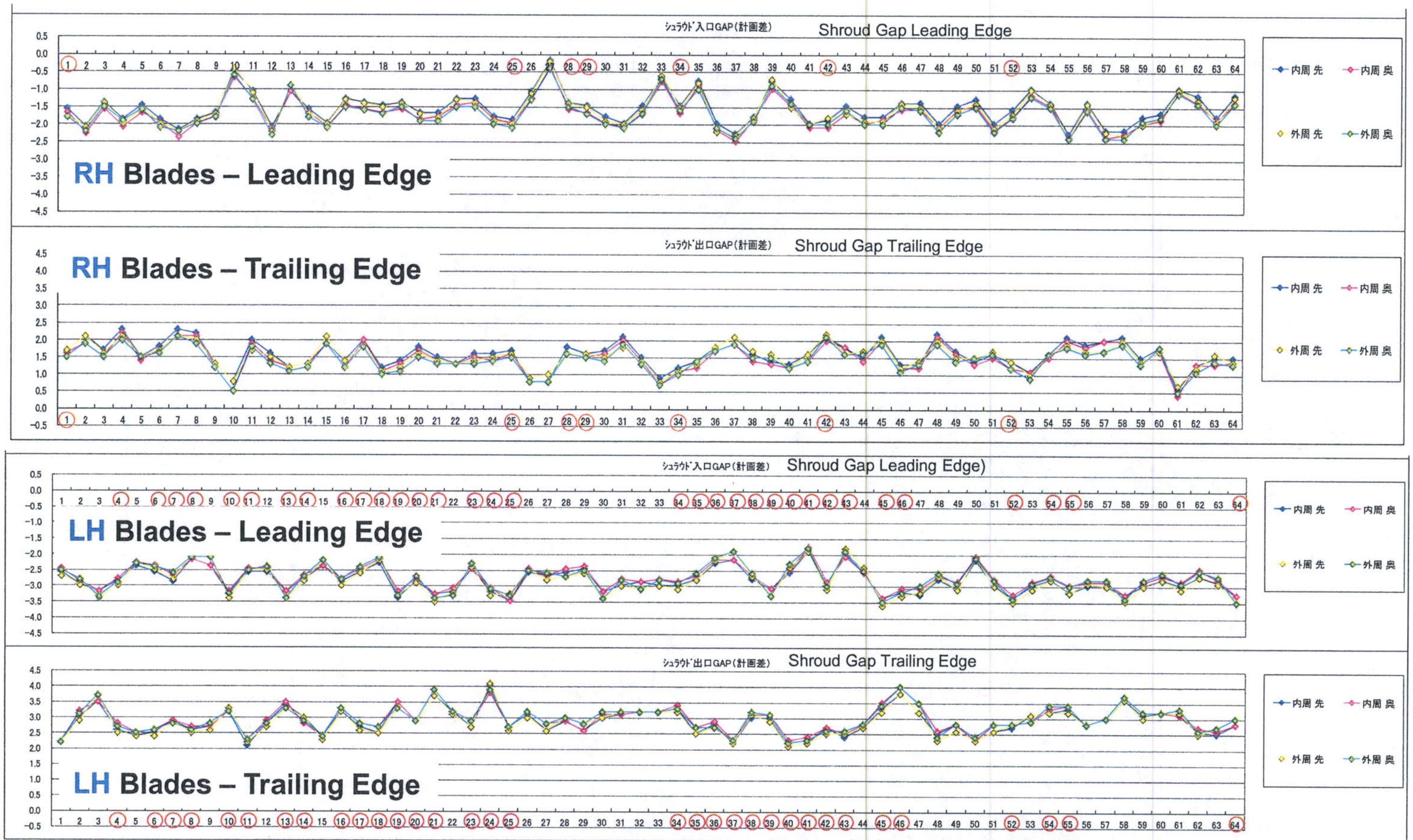
Manufacturing Quality Data - Box Gauge

Box Gauge with 40" L0 Blade





Box Gauge Measurement Results - 2014 blades



Blade manufacturing data show variation within criteria

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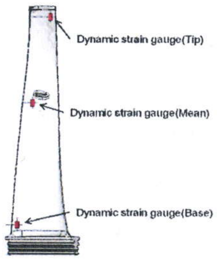
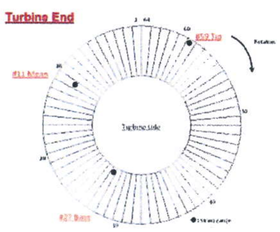
Telemetry Test Data Analysis

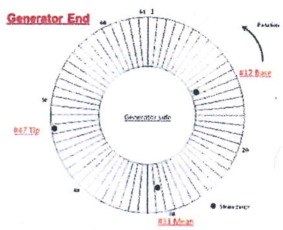
Telemetry Test Results

Strain Gage Locations

- Six strain gage were installed on LH and RH blades.
- Strain gage locations were selected
  - ➢ High Response sensitivity for vibration modes.
  - ➢ MHPS Experience

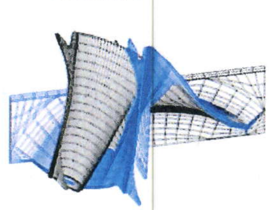




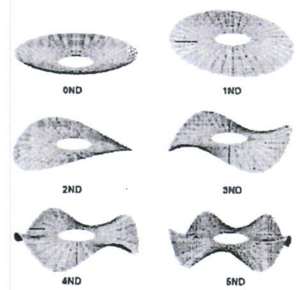


Test Results

- Analysis of Non-synchronous response show frequencies close to 200Hz region and composed of axial mode shape with higher nodal diameter.
- Fretting at stubs was evaluated with the telemeter test results.



Similar to 1st Mode Shape

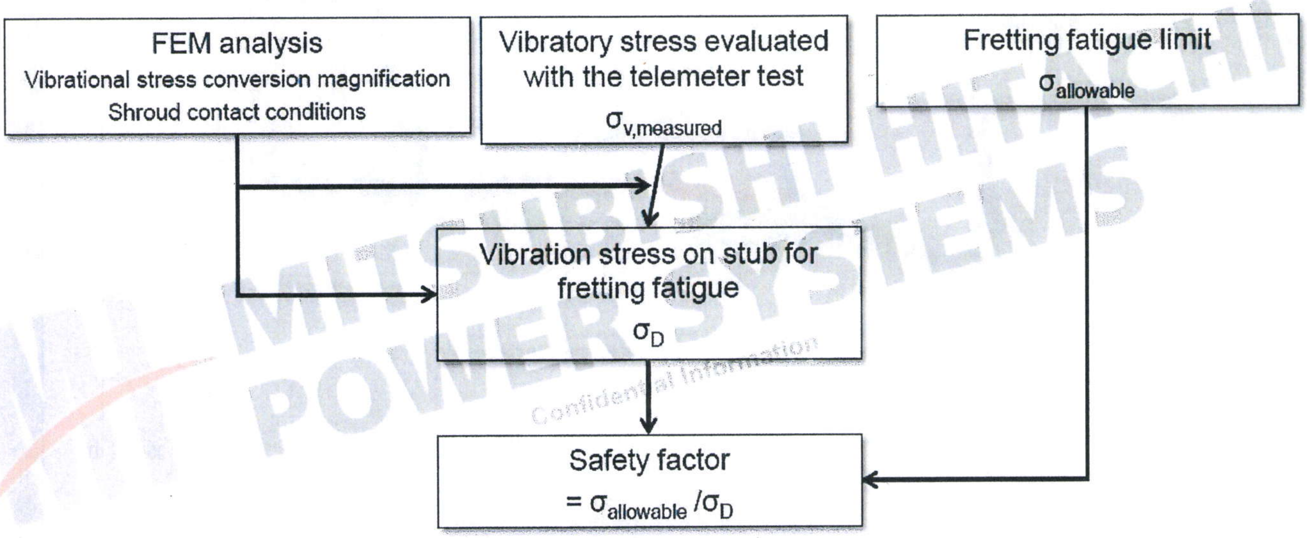


Nodal Diameters

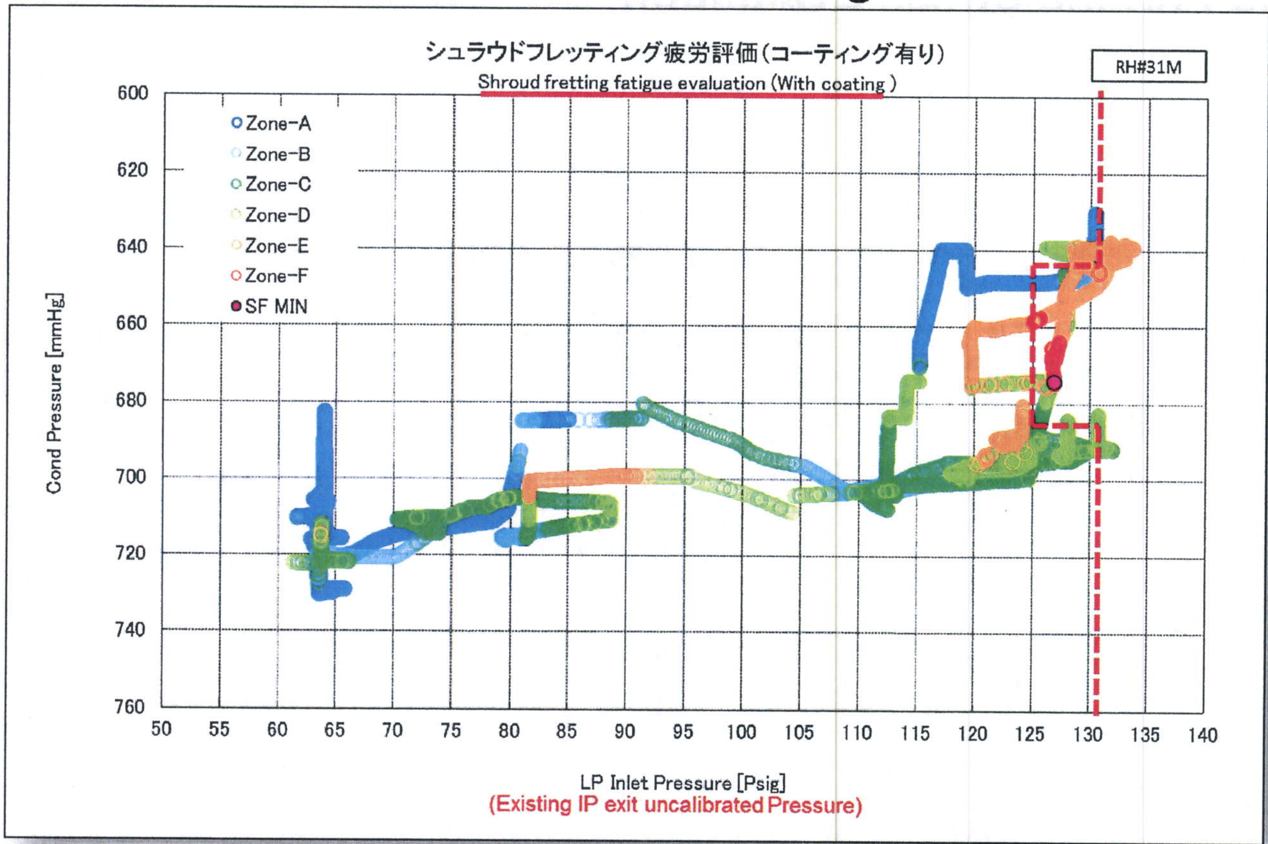
Telemetry Testing 2014 -
To understand dynamic blade response during operation

Shroud Fretting Stress Evaluation

- Evaluation method is the same as stub fretting evaluation.
- Vibrational stress is evaluated, with FEM analysis, primarily for effect of shroud contact condition (partial contact) based on actual telemeter measurement result of 2014.

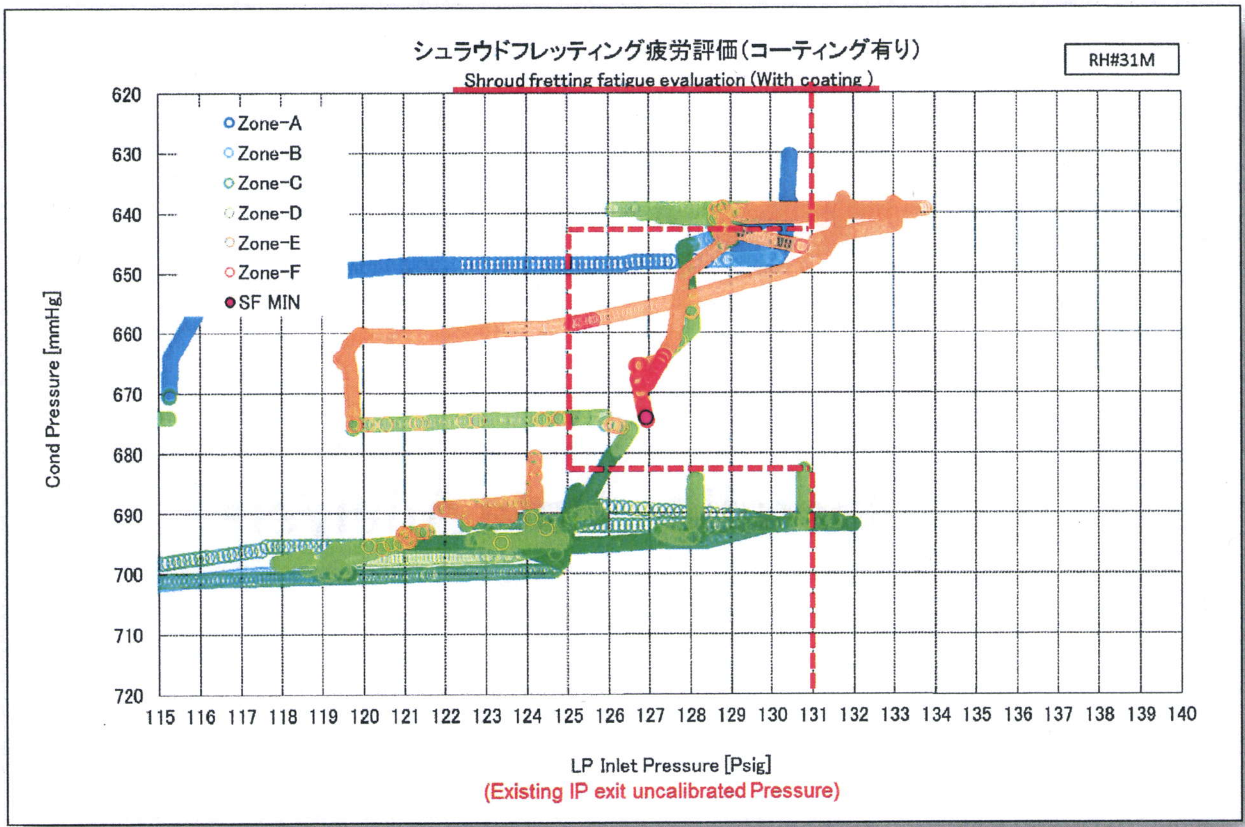


Telemetry Test Results – Shroud Fretting



Fretting fatigue calculations for shroud with coating show acceptable margins outside avoidance zone

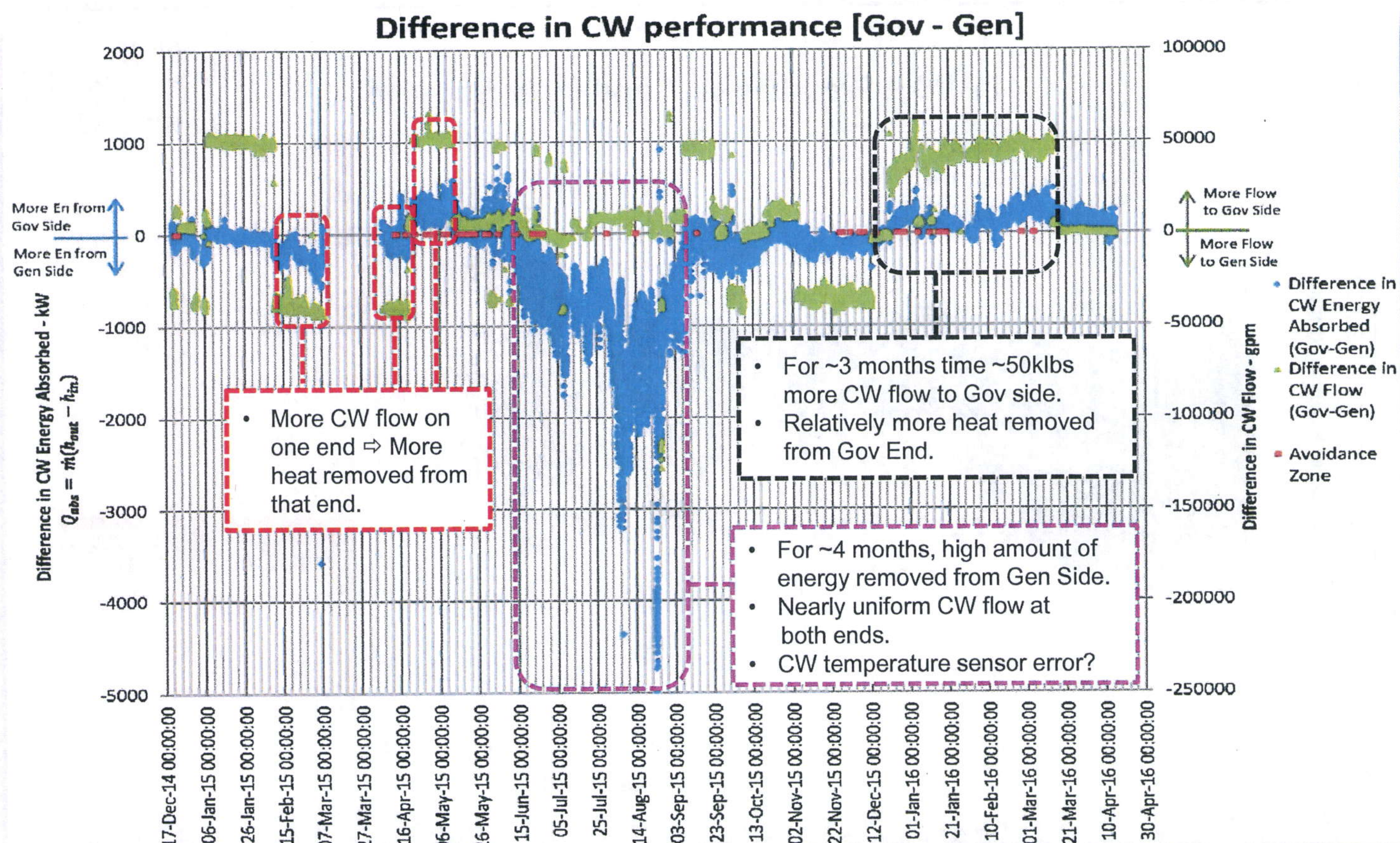
Telemetry Test Data – Shroud Fretting



Fretting fatigue calculations for shroud with coating show acceptable margins outside avoidance zone

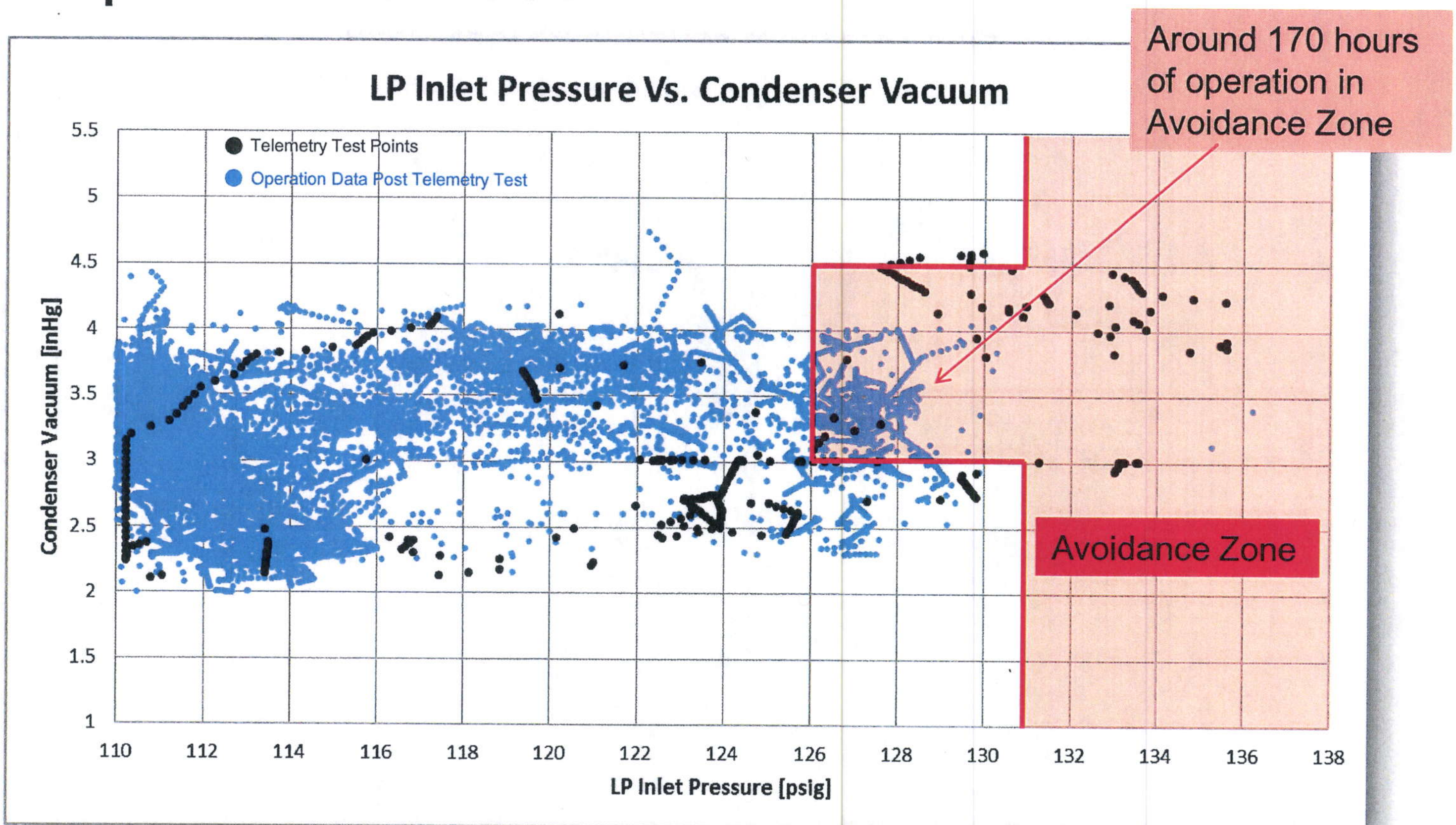
Operation Data Analysis

Condenser Circulating Water (CW) flow analysis



Asymmetric circulating water flow may explain difference in water erosion observed
Not enough data to draw any conclusion on blade shroud damage

Operation Data Review



170+ hours of operation in avoidance zone with a response frequency ~200Hz = 1.2E8 Cycles

RCA Conclusions

Blade Shroud Cause and Effect Diagram

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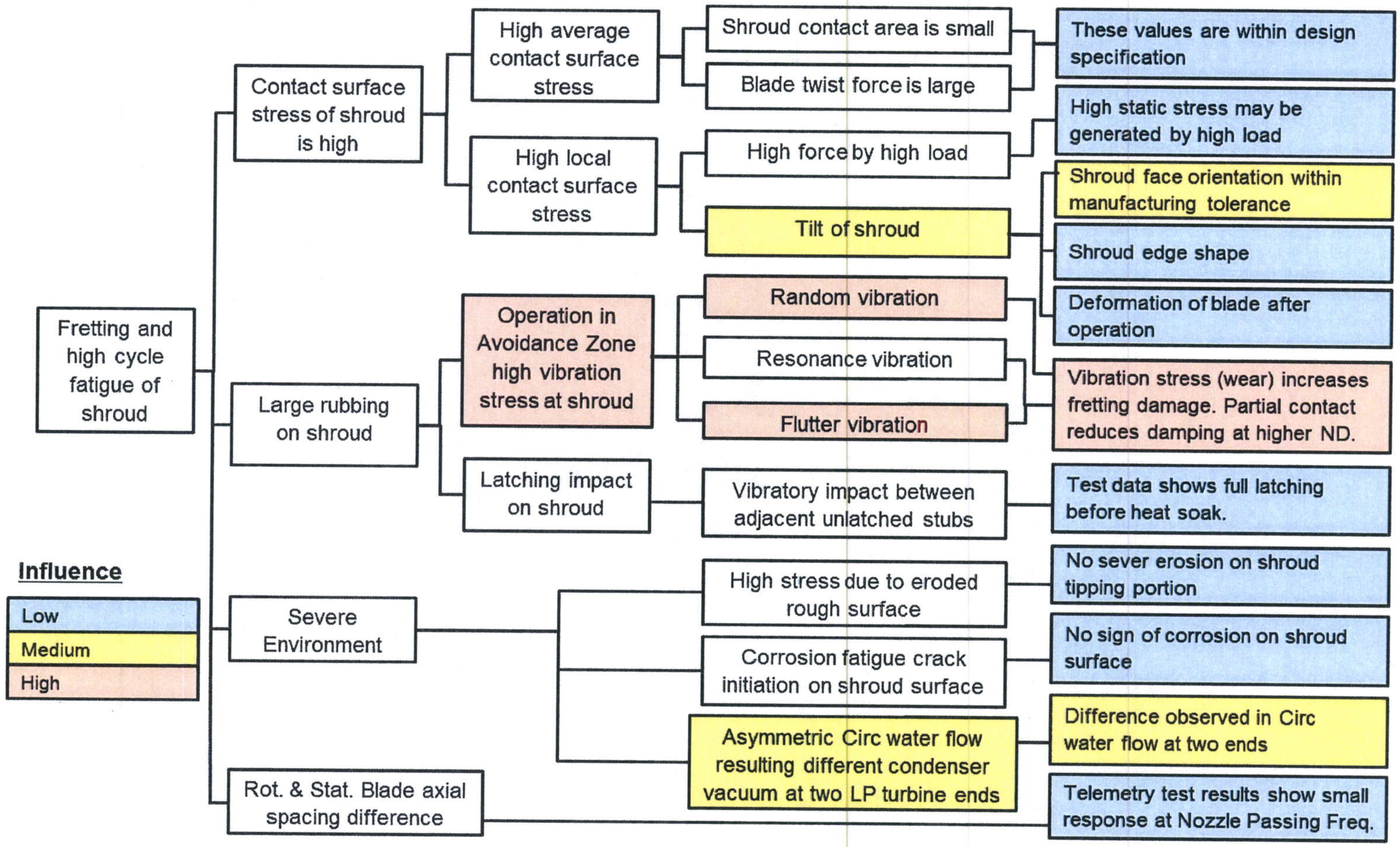
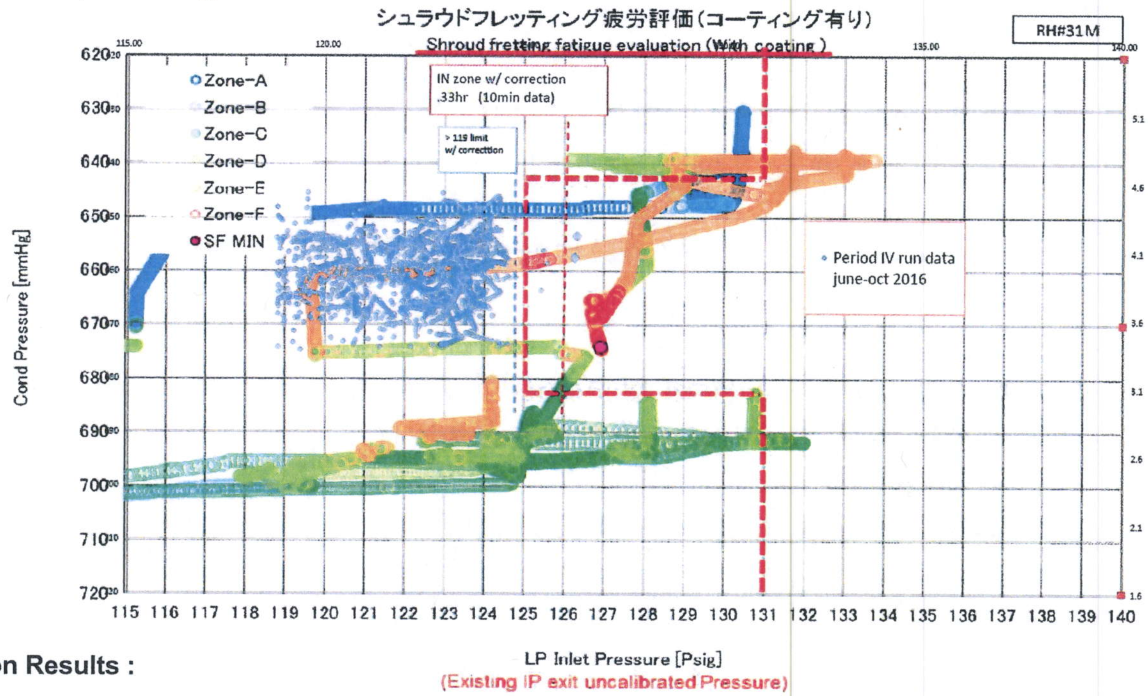


RCA Conclusion

- The root cause for start of shroud chipping has been identified as operation in the avoidance zone.
- Within the avoidance zone, high local contact pressure is developed due to partial contact.
- After initial chipping, nearly uniform wear of contact surface indicate progression of chipping due to operation at resonance (avoidance zone).
- Stellite coating on stub has proven its effective at protecting surfaces from fretting damage.

1.4) Operating Time 4 : Jun 2016 to Oct 2016



Inspection Results :

Location	Blades	Service	Mid Span Snubber	Shroud	Disposition
Gen End	Type 3 + HVOF++	4 Months	1 Liberation	3 Shroud Liberations	Replace Row
Gov End	Type 3 + HVOF++	4 Months	No significant damage	1 Shroud Liberation	Replace Row

Bartow Steam Turbine
RCA Review
Addendum Presentation
Nov 17th 2016

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Purpose of Presentation

Provide responses to open items / questions during the Nov 9th RCA Report Out Meeting

Subjects :

1) Demonstrate that operating data from 2009 to 2014 is consistent with the RCA conclusions.
2) Provide hardness results not presented in Nov 9th .
3) Provide parallelism data not presented in Nov 9th.
4) Provide responses to prior questions from Harry Carbone.

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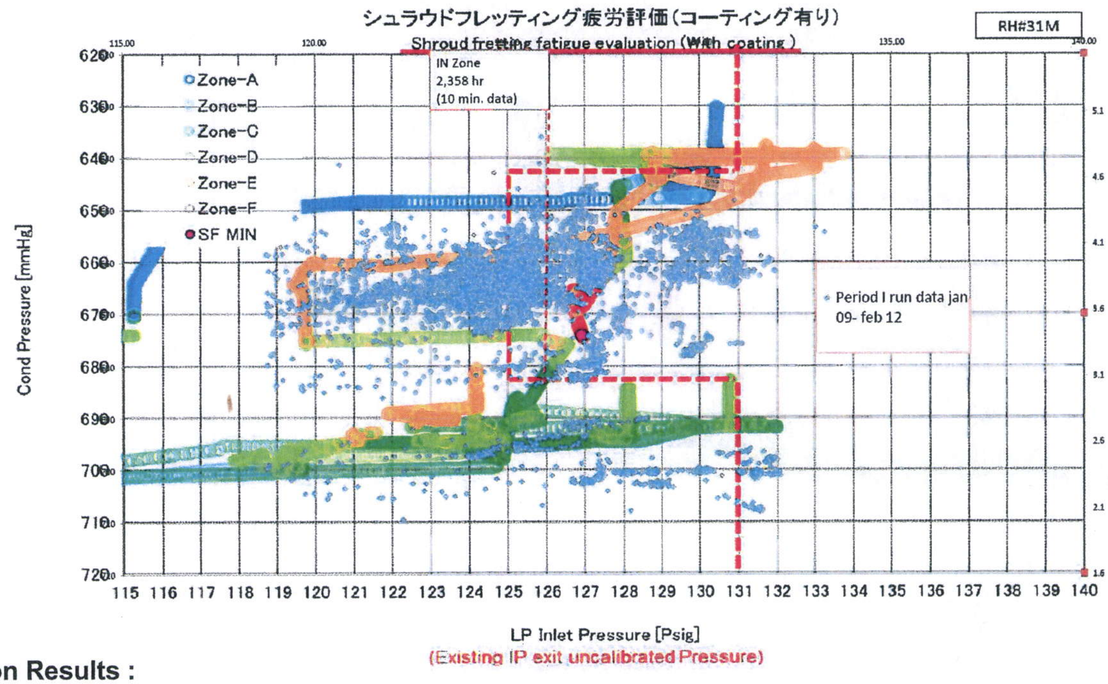
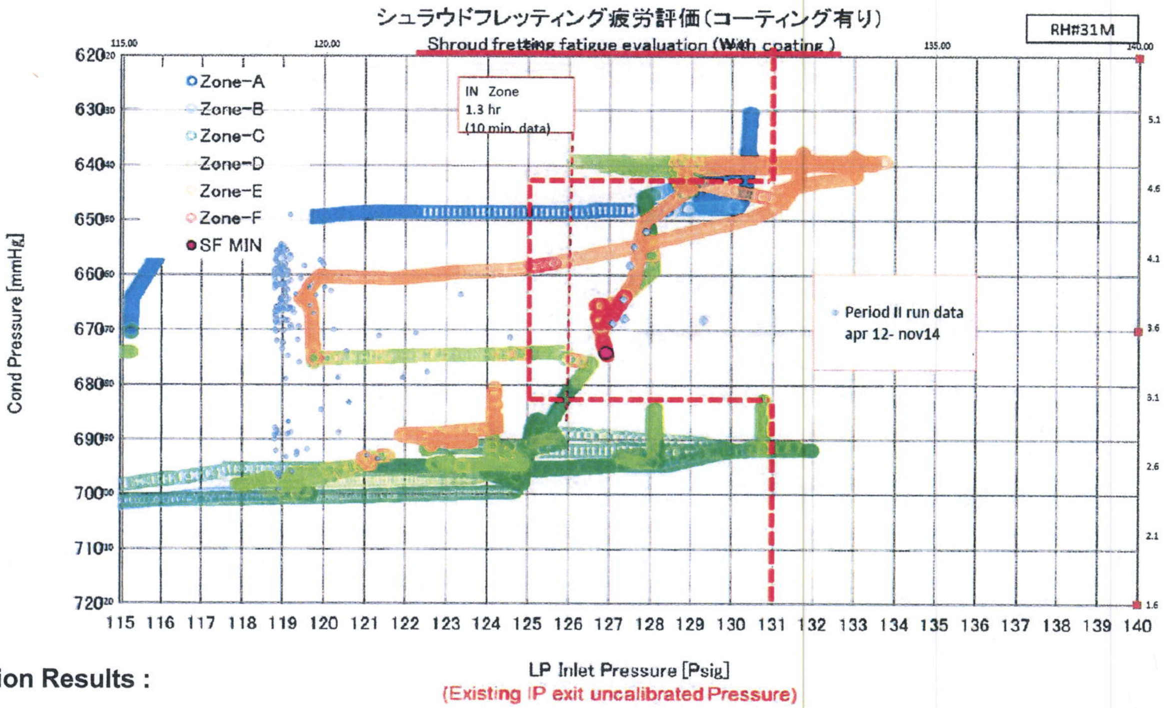
1.1) Operating Time 1 : Jan 2009 to Feb 2012



Inspection Results :

Location	Blades	Service	Mid Span Snubber	Shroud	Disposition
Gen End	Type 1	3 yrs	No significant damage	No significant damage	Continue operation until 2014 planned replacement
Gov End	Type 1	3 yrs	5 Major Chip	3 minor chips	Replace blades as continues midspan chipping could results in a free standing blade

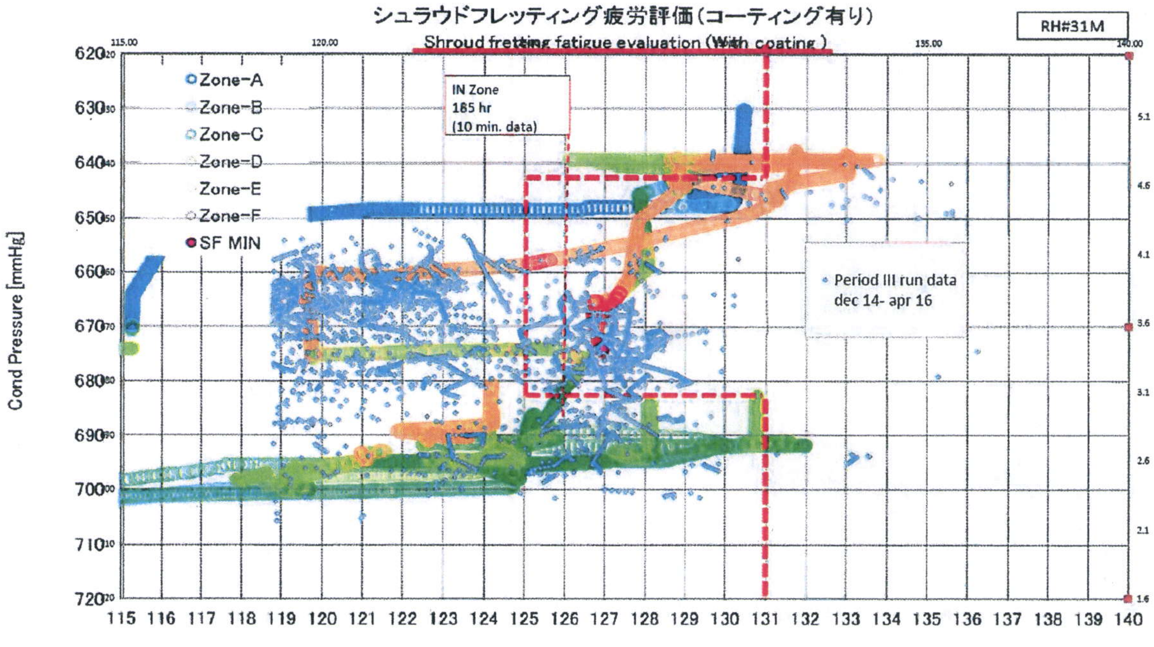
1.2) Operating Time 2 : Apr 2012 to Nov 2014



Inspection Results :

Location	Blades	Service	Mid Span Snubber	Shroud	Disposition
Gen End	Type 1	5 yrs	No significant damage	12 minor chips	Scheduled change out to blades with midspan HVOF
Gov End	Type 1	2 yrs	No significant damage	3 minor chips	Scheduled change out to blades with midspan HVOF

1.3) Operating Time 3 : Dec 2014 to Apr 2016



Inspection Results :

Location	Blades	Service	Mid Span Snubber	Shroud	Disposition
Gen End	Type 3 + HVOF	15 Months	No significant damage	7 minor chips	Fit for continued operation. Shroud contact on all blades.
Gov End	Type 3 + HVOF	15 Months	No significant damage	33 chips including significant damage	Replace row as free shroud contact has bee lost on 1 blade.

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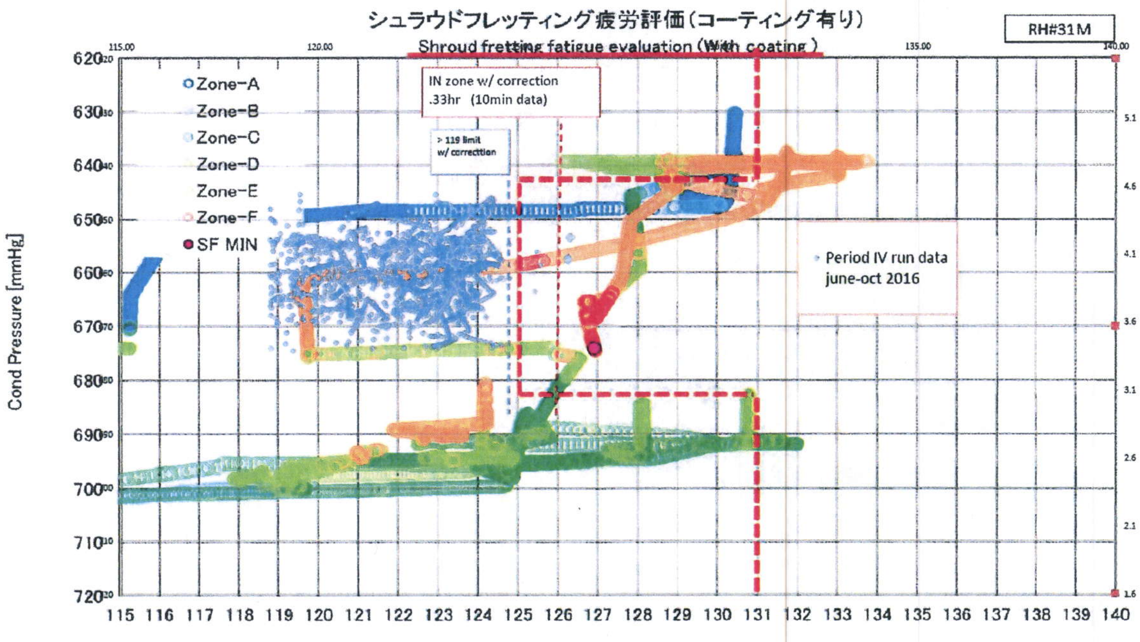
1.4) Operating Time 4 : Jun 2016 to Oct 2016



Inspection Results :

Location	Blades	Service	Mid Span Snubber	Shroud	Disposition
Gen End	Type 3 + HVOF++	4 Months	No significant damage	7 minor chips	Fit for continued operation. Shroud contact on all blades.
Gov End	Type 3 + HVOF++	4 Months	No significant damage	33 significant damage	Replace row as free shroud contact has bee lost on 1 blade.

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Conclusions of LP Blade Loading Review

- Telemetry test results show that once in the avoidance zone, small changes in operating conditions can produce a large change blade response magnitude.
- Damage accumulates at 200Hz (720,000 cycles every hour)

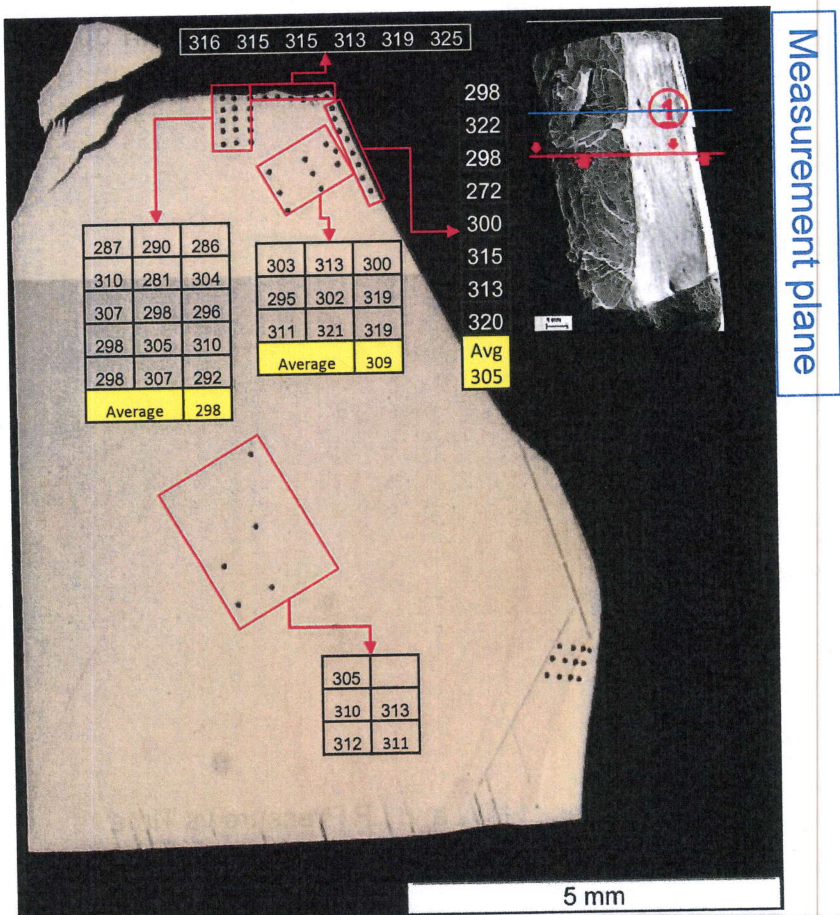
1.1) Operating Time 1 : Jan 2009 to Feb 2012
Significant operation in the avoidance zone.
Significant damage observed on the blades.

1.2) Operating Time 2 : Apr 2012 to Nov 2014
Minimal operation in the avoidance zone.
Minor chipping observed.

1.3) Operating Time 3 : Dec 2014 to Apr 2016
Significant operation in the avoidance zone.
Significant damage observed on the blades.

1.4) Operating Time 4 : Jun 2016 to Oct 2016
RCA evaluation has not been completed.
Operating data has not bee provided beyond, only summaries of MW and LP Pressure vs Time.

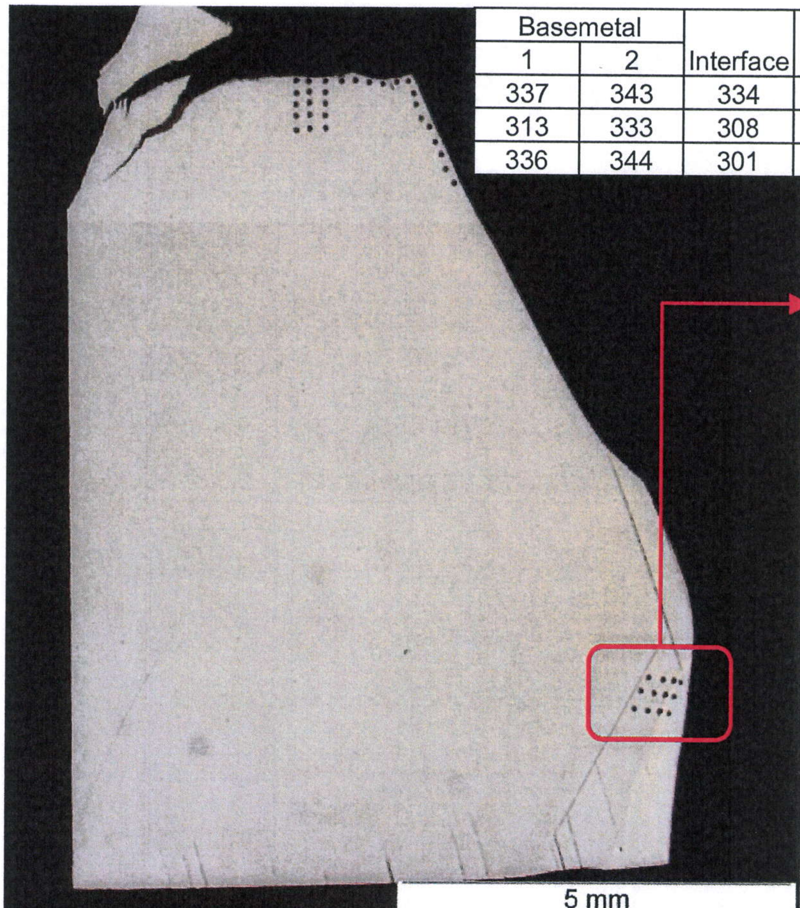
2 - Hardness Variation – Presented

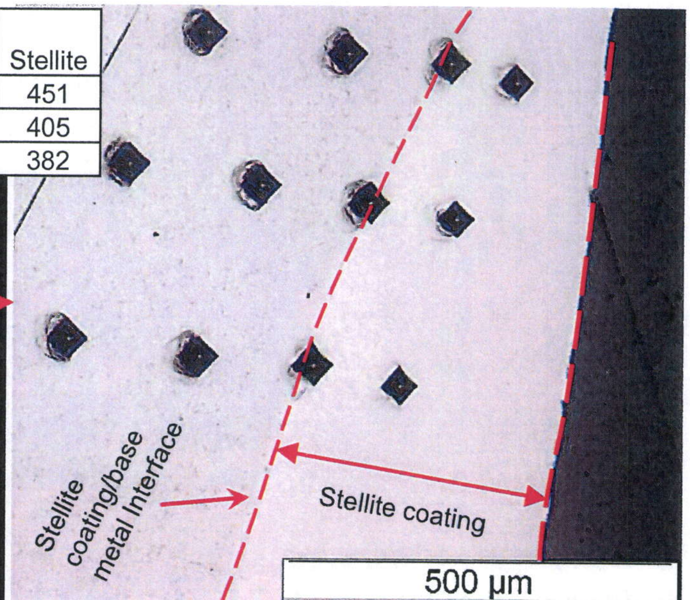


- From hardness observation no significant decrease was observed where the crack initiated.
- A decrease in hardness was observed on the contact surface.

2- Hardness Variation basemetal, Interface and Stellite Coating

Basemetal		Interface	Stellite
1	2		
337	343	334	451
313	333	308	405
336	344	301	382

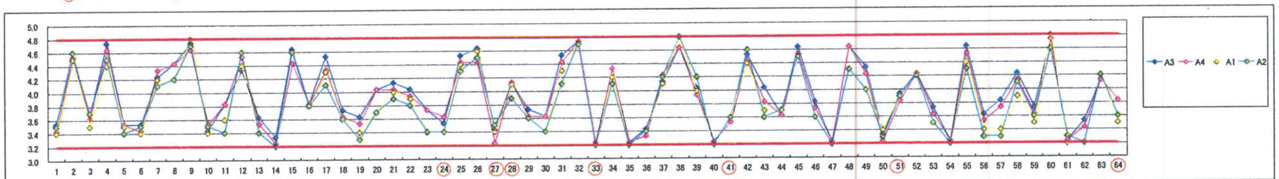


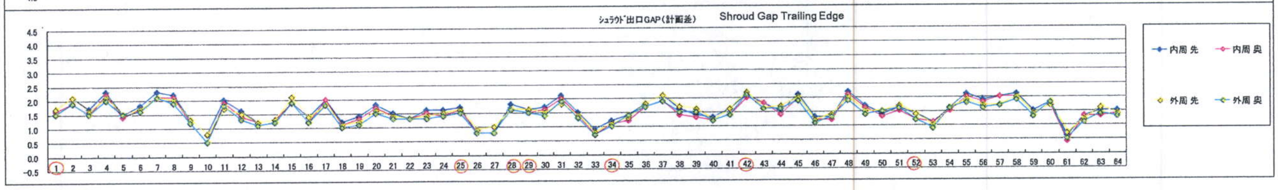


- No significant hardness variation was observed within the base metal as a result of stellite welding.

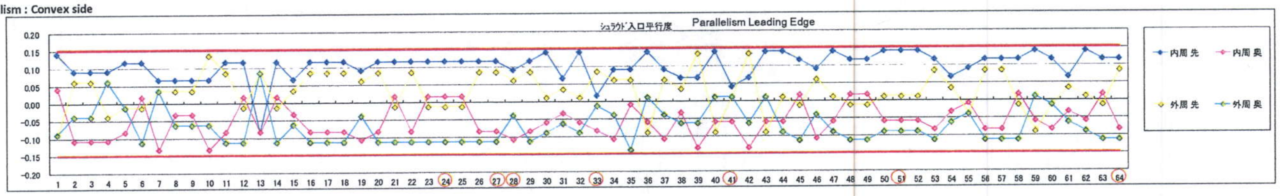
3.1) Measurement Results RH (Gen End) 2014 blades

Shroud GAP ○: Shrouds with Damage

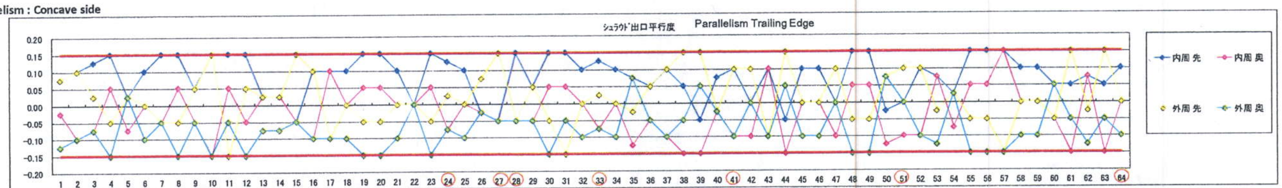




Parallelism : Convex side

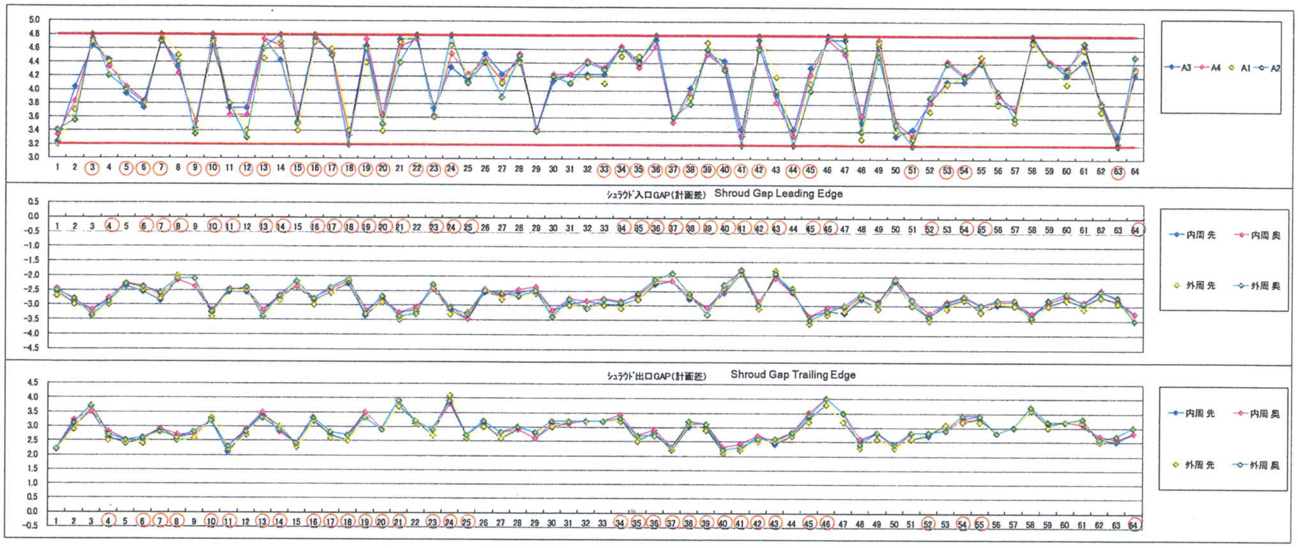


Parallelism : Concave side

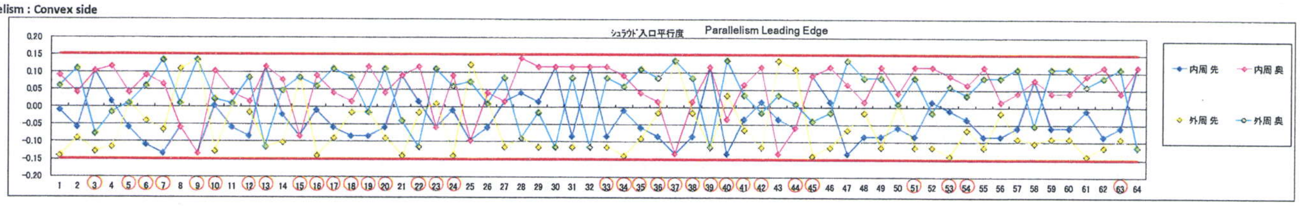


3.2) Measurement Results LH (Gov End) 2014 blades

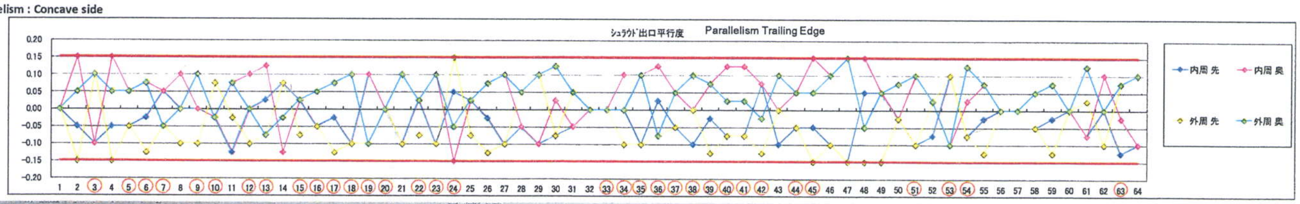
Shroud GAP ◯: Shrouds with Damage



Parallelism : Convex side



Parallelism : Concave side



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Duke Questions (From 10/26/16 Meeting):

1. Current draft of time line of blade outages
2. Updated Vibration change dates To understand the

Operating data from the operating from June 2016 to October 2016 has been requested on multiple occasions since the change in vibration was brought to the attention of MHPSA in August 2016.
To understand the operation of the unit, this information is required to provide an objective data driven assessment of the operation.

3. The mw correction factors issue

Conflicting information is being given. It is no longer clear whether during the telemetry test there was an offset MW. The operating data requested is required to understand the relationship between steam conditions and load.

4. New LP inlet pressure gage 3.7 psi zero offset error

Following the finding that the IP Exhaust Pressure Tap had not been calibrated with its water leg, the same issue has now occurred on the new LP Admission.
There is currently a lack of clarity on the calibration of the pressure taps which is critical to understanding the steam loading seen by the blades which can hopefully be addressed by review of the latest operating data.

5. Chart of blade options

An updated chart is attached.

6. Duke requested strain gage data

Results of the telemetry test have been shared during the RCA meetings. Face to face meetings were held in May 2016 specifically for the purpose of being able to openly share information which would normally not be available to share due to being business confidential information. During these reviews the nature of the none synchronous response was described identifying that the blade response is not being excited by single modes. A single stresses cannot be evaluated against a single allowable in a Goodman diagram, but a range of modes is being excited within a frequency range. The magnitude of blade response is integrated over a frequency range to determine an overall response level compared to successfully validated response levels. This is not data which can be sent directly as a file to Duke Bartow.

7. Confirm material is 17-4

Similar too material designations are provided for reference only and do not support reverse engineering of the blade design which is subject to multi-year development programs and continuous improvement by the MHPS-Japan development team.
Hardness was reviewed in detail during the face to face RCA meetings.
The RCA reports are intended to be presented in person to ensure that they are correctly interpreted due to the complex nature of the RCA investigation.

8. Supply Goodman Diagram

OEM Last Stage Blade materials are not per industry standards, with the material development being critical to achieving competitive designs. The Goodman Diagrams for MHPS developed materials is proprietary.

Summary of Blade Types

DEF20190001BARTOW LFE4-000055

	Base material	Brazed in Stellite Leading edge erosion strip	Spray Stellite under Z notch Leading edge	Welded Stellite Under Z notch Leading edge	Polish off shot peening after welding	Spray Stellite .3 mm on snubber contact faces	Spray Stellite .3mm on Z notch contact faces	Chamfer 1 x 0.5 mm & 2 mm radius on snubber	Corner cut on Z notch ~3mm x 3mm
Type 1		Yes	Not Applicable	No	n/a	No	No	No	No
~~Type 2~~		Note : Type 2 is a welded field modifcation provided as a temporary measure while awaiting replacemetn blades. No Type 2 Blades are operating in the fleet.							
Type 3		Yes	Not Applicable	Yes	No	No	No	No	Yes
~~Newer Type 3~~		Note : No blade type - "Newer Type 3"							
Installed 2014 (Typ3 + HVOF))	Proprietary Sim to 17-4 PH Proprietary HT	Yes	Not Applicable	Yes	No	Yes	Yes	Yes	Yes
Installed 2016 spring (Typ3 + HVOF)		Yes	Not Applicable	Yes	No	Yes	Yes	Yes	Yes
Proposed now Fall '16(Typ1)		Yes	Not Applicable	No	n/a	No	No	Yes	Yes

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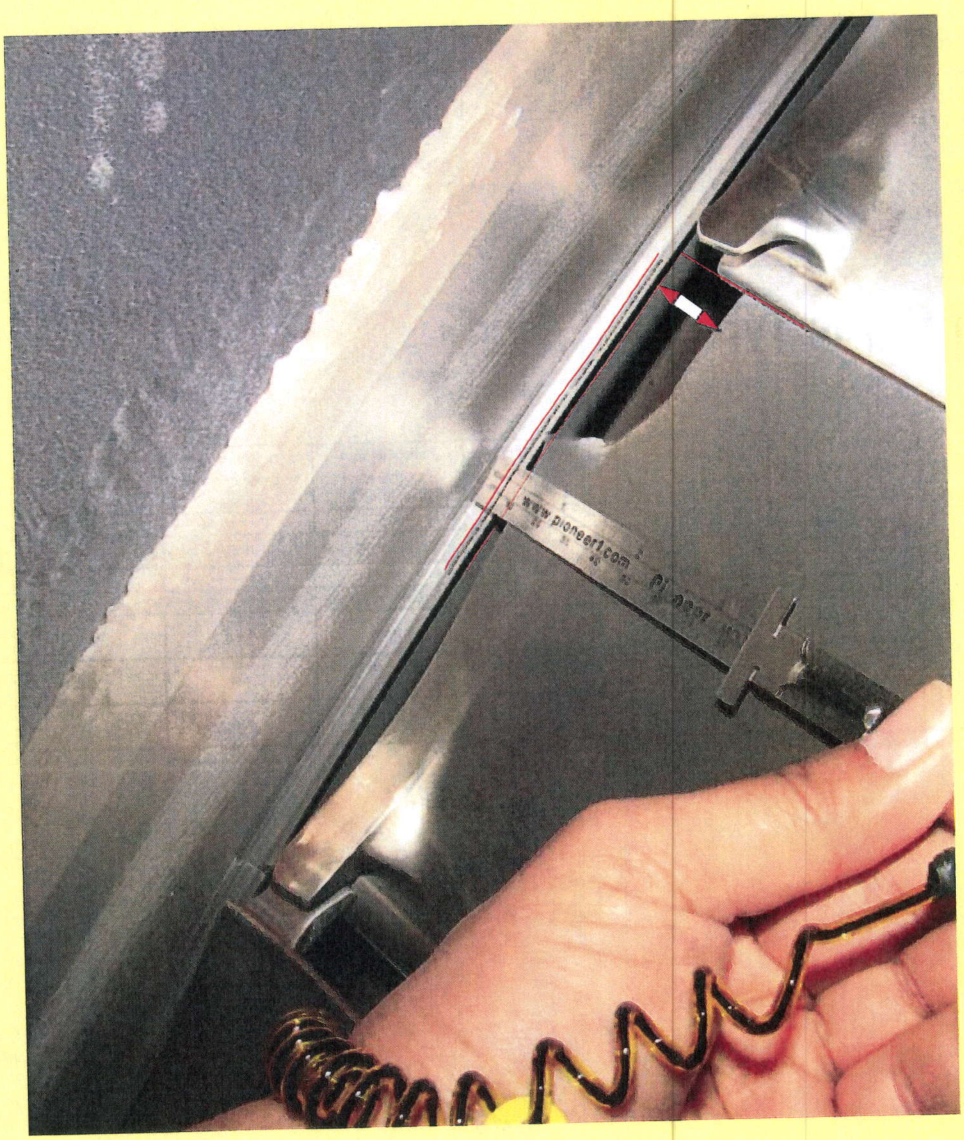
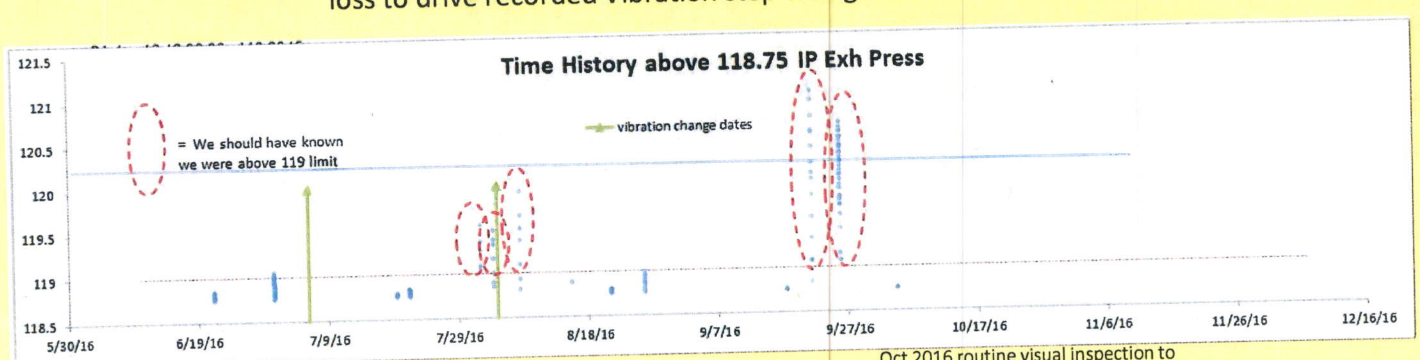


Oct 2016 photo of gen end #22. Three blades failed similar this GE # 13 and TE #2. Adequate mass loss to drive recorded Vibration step changes below.



June 2016
Blades New
both ends

Oct 2016 routine visual inspection to verify OEM eng. opinion that vibration changes were NOT caused by mass loss . Outage resulted in replacement of both rows of blades. Returned to service Dec 2016

HMC 1-20-17

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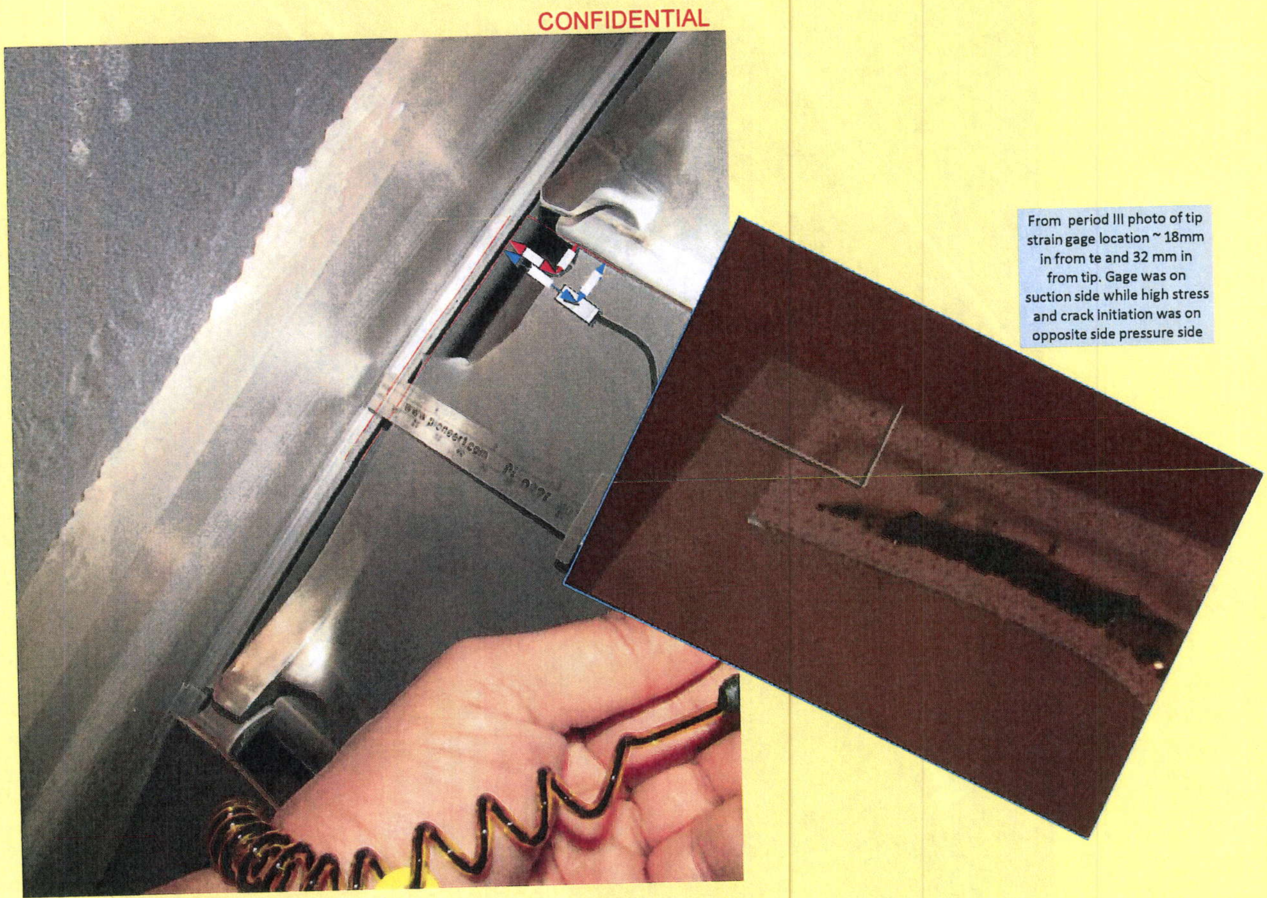
From Harris Lab work Gen End blade #22 crack initiation sites(in zone 1) ~ 13 mm in from te and 23 mm in from tip. Cracks started on pressure side. Opposite side from what is visible in blade #22 in situ photo below Oct 2016

Harris lab work identifies crack as three zones. Initial zone 1 (sem photo above) was high cycle fatigue that started at possibly more that one site ~ 13 mm from trailing edge and joined to grow to zone 2. It was suspected crack started at trailing edge and grew. NOT true started at 13 mm from edge, on the pressure side (opposite side that's shown in photo) and trailing edge failed by ductile overload. Dental molds taken from other two failed blades TE #2, GE #13 show consistent failure mechanisms.

HMC 1-20-17



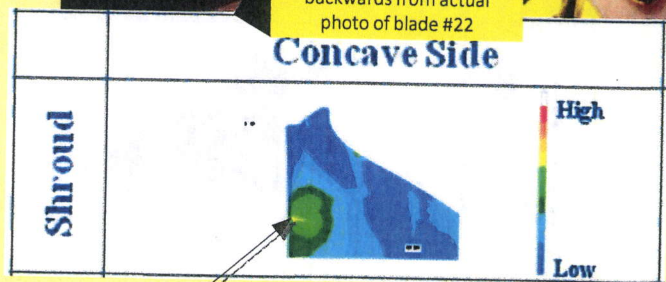
From period III photo of tip strain gage location ~ 18mm in from te and 32 mm in from tip. Gage was on suction side while high stress and crack initiation was on opposite side pressure side

The blades at Bartow were standard MHI type 3(welded) , but had design modifications of that included chamfers, radius, and HVOF hard face on mating surfaces. MHI tested an earlier version in the field (dec 2014) with strain gages at three locations each end. They were at the base, the middle near the snubber, and at the tip shown above near the z lock latch or lock up tip shroud. MHI knew this was a high stress area. They approved limited operation in an identified " zone" from this testing. In fact the testing included > ~ 10 hours in the zone to properly map it with steam flows and condenser back pressures. The original supplied blades, post run, were analyzed for amount of time in the zone. Period I 2009-2012 ran 2,466 hrs in the "zone" and had blade tip damage but never a material loss as large as Period IV Jun-Oct 2016 shown above.

HMC 1-20-17

15mm

From Accttech report 2012 peak static stress ~ 160ksi trailing edge pressure side ~ 6 to 15mm from te and ~ 23 mm in from tip. This view is backwards from actual photo of blade #22



From MHI 2012 Period I RCA presentation. Confirming high static stress area where Period IV cracks initiated.

Finite element analysis performed after 2012 failure showed the crack starting point area had stresses above yield and the design would need to be "yielded down". This is possible because full section of blades was not above yield. This was not a concern with earlier failures, because the air foil was not liberating just contact face wear on mid span snubber and z lock tip. Partial tip and snubber loss was possible. The 2016 work re confirmed the high stress area and an earlier presentation 2012 by MHI supports the pressure side of the blade tip below the latch has high stress. The crack started at nearly the same spot as the predicted high stress area.

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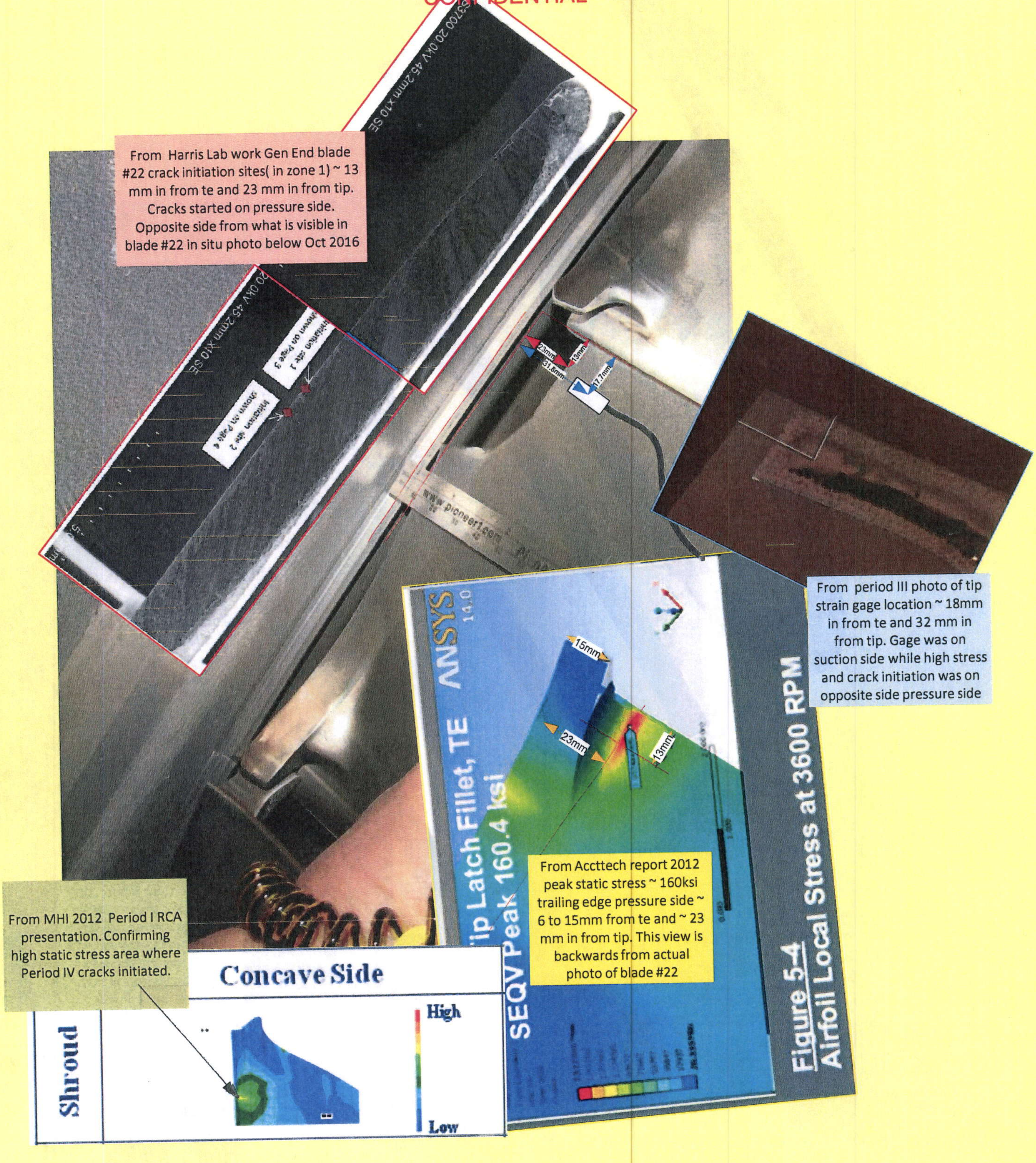

Photo montage of period IV trailing edge complete lug loss failure confirm hi stress area as crack initiation point(s)

- Oct 2016 Generator end Blade slot # 22 Serial 4697Y
- Linear calculated stress was locally most likely above yield, and part yielded back with compressive surface stress at no speed.
- Part saw 2 start cycles to 3600 rpm before first vibration change. Overspeed was on new org bladed and shop test of period III blds.
- Part never saw overspeed as may have been incorrectly stared earlier. Overspeed may allow more yield down and more alt margin
- Part ran between 700 to 1400 hours prior to vibration changes
- Full run cycle on part was ~ 3000 hrs
- MHI 2012 RCA FEA confirms high stress area, but they stated stress below yield in orange color. It may be with full heat treat, but its doubt the min yield for heat affected zones can be significantly above 160ksi. Est yield 110k to 140ksi

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Executive Summary

Duke Energy (Duke) and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 18 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation.

Duke's position is as follows: The Bartow steam turbine (ST) 40" L-0 blade failures are being driven by a non-synchronous self-excited vibration (flutter) of the L-0 blades during operation. In our and MHPS's evaluation of the root cause neither party has been successful in conclusively identifying the factor(s) that are causing the failures. There are a series of contributing factors that have been identified but the correlation and predictability of these contributing factors and the magnitude of their interactions has been difficult if not impossible to predict without having conducted further instrumented testing of the L-0 blades in operation. Any conclusions derived from our efforts and discussed in this document are based on our best ability to correlate data with events in operation and findings with L-0 blade inspections/failures. that the OEM designed last stage blades had little or no design margins for the actual operating conditions that exist for the overall Bartow Combine Cycle Unit.

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It should also be stated that there is no industry experience with a 4x1 configuration like Bartow...which leads to MHPS not fully understanding the operating conditions, thus having a L-0 blade that we are now determining un-fit for operation with not enough design margin for this station configuration.

Duke Engineering believes the root cause for Periods 1-5 involves more than one driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS also indicated that there may have been more contributing factors for various Periods of failure rather than just excessive steam flow through the LP section above the MHPS design limit of 15,000 lb./hr./ft.^{2}. Excessive steam flow, or "operation in the avoidance zone", had been previously communicated by MHPS as the sole root cause back during a presentation made at Bartow Station on 15 March 2017. MPHS has since changed its position and today there is agreement between both parties that there is not just one simple root cause.

After months of study (and with input from MHPS) Duke Engineering believes the following to be the most significant contributing factors toward root cause of the history of Bartow Unit 4S L-0 events:

- Low Pressure (LP) Turbine Excessive Steam Flow
- Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

Duke believes that the contributing factors presented in this paper – or during MHPS presentations – are postulations and may possibly be correct. Most of the MHPS postulations are derived from strain gauge data taken during the telemetry test conducted during December 2014 – blade response data that is then extrapolated to develop potential root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil itself that were seen during Periods 1-5.

The long-term solution for the Bartow LP section is to replace the L-0 blades or retrofit of the LP steam path with a more capable/reliable design. With either scenario, blade telemetry instrumentation and blade vibration

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monitoring will be necessary to conclusively determine and eliminate the magnitude and impact of the identified contributing factors.

Deleted: and subsequent field measurements taken following various operating configurations/scenarios that are integral to unrestricted 4 x 1 combined cycle operation will be necessary to confirm the contributing factor postulations. In other words, the correctness of the Duke and/or MHPS root cause position(s) can only be confirmed with the successful field operation of the unit.

This technical paper will speak briefly of the history of L-0 blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above.

Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration.

Since commissioning there have been five (5) events triggered by L-0 blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-0 blade in efforts to address the failures (see Appendix B for L-0 modifications). To date, the modifications have not resulted in improved reliability or performance of the L-0 blades in service at Bartow. The number of blade failures and problems with ST L-0 blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-0 fleet. The most common reported issue from the MHPS 40" L-0 blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-0 rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

Root Cause Contributing Factors

Low Pressure (LP) Turbine Excessive Steam Flow

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data analysis – learned (and made it known to Duke) that a significant contributing factor toward root cause of the L-0 blade failures was extremely high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40" L-0 fleet with several operating hours above the design limit of 15,000 lb./hr./ft.^{2} (the MHPS 40" L-0 fleet average was closer to 12,000 lb./hr./ft.^{2}). Duke was issued an "avoidance zone" chart with instructions from MHPS not to run to the right side of the curve – the lone exception being "brief" operation during transient conditions.

While Duke Engineering agrees that back-end loading should be considered a significant contributing factor toward root cause, one cannot definitively conclude that it has been the root cause of all five (5) of the documented L-0 events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the "avoidance zone" of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

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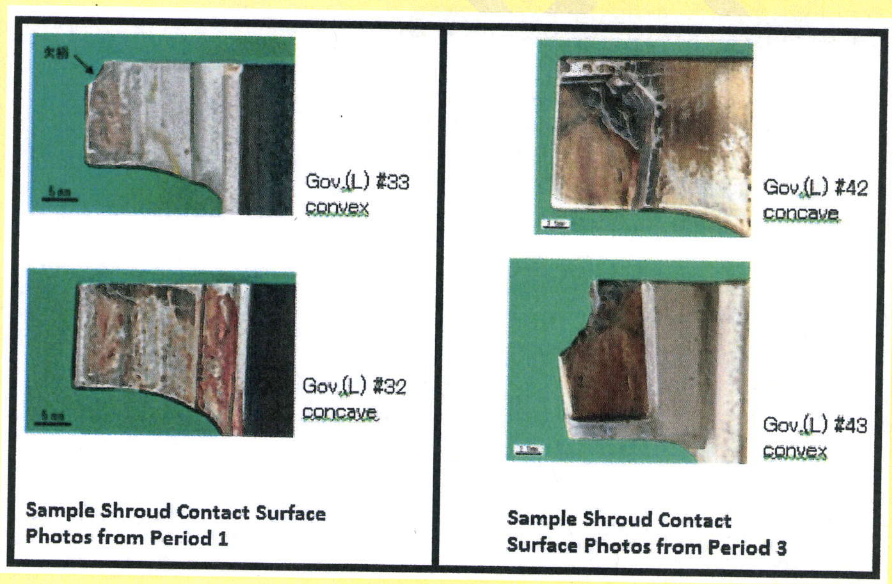
By a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the "avoidance zone" relative to total operating hours – 2,466 out of 21,734 total hours. However, blade damage was relegated to five (5) broken mid-span snubbers on the turbine end of the machine and a minimal degree of fretting on the shroud Z-Lock contact surfaces for both turbine and generator ends of the machine.

Conversely, during Period 3, there were only 240 hours (out of 10,286 total hours) of operation in the "avoidance zone", approx. 11 hours of which occurred during the instrumented blade telemetry test performed by MHPS in December 2014. Even with a significantly fewer number of "avoidance zone" hours for Period 3 relative to Period 1 – a factor of 10 fewer hours for Period 3 – there was significantly greater amounts of blade damage and fretting on both ends of the machine. While the amount of Z-Lock wear is not quantified for Periods 1 and 3, photographic evidence suggests that the amount of wear is much greater for Period 3, as shown below in Figure 1. It is therefore difficult to conclude that damage to the L-0 blades in Period 3 is solely due to unit operation above the exhaust flow limit.

Figure 1 -- Comparative Photos of Shroud Contact Surface Wear for Periods 1 and 3



Sample Shroud Contact Surface Photos from Period 1

Sample Shroud Contact Surface Photos from Period 3

With the L-0s currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern at the current LP inlet operating limits. MHPS Engineering does not have enough technical data to support releasing Duke to operate the machine beyond the current LP inlet operating limits due to concerns for impacts to upstream blading – i.e. the L-1 blade sets.

Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust

During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to include all aspects that might impact the L-0 blades. Since the design of the condenser includes spargers, or "dump tubes", for the hot reheat (HRH) and LP bypass steam flows from each of the four combustion turbines (CT), and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

A set of criteria and an automated process using Excel and PI Datalink were developed that allow large amounts of data (stored in the PI historian) to be quickly reviewed for each Period 1-5. Blends that met the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. This process involved extracting PI data, calculating a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values, or "counts". "Counts" are defined as the number of measureable blends where there was a slope change (+/-) in greater than (20 degrees superheat / min) at the hood spray thermocouples. The data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW. The limits of 20 degrees F (superheat) and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow for a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify specific points/periods in time to look at additional blend parameters.

Table 1 -- Quick Comparison of the Number of "Counts" that Meet the Criteria for Periods 1-5.

	Number of Operating Hours in Each Period	Number of Blends (or "Counts") Meeting Criteria
Period 1	21,734	13
Period 2	21,284	7
Period 3	10,286	37*
Period 4	2,942	3
Period 5	1,561	5

*Includes 6 blends that meet the criteria during strain gauge testing in December 2014

Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is

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programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

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A review of the OEM-provided instructions requires use of hood sprays during the following conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

During a review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found to date. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM-provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or unit trip event when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an instrumentation issue).

Careful attention was also paid to the hood spray pressure over time. This was found to steadily decrease over successive Periods. Maintenance of the hood sprays control valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the same control valve had filled with debris in prior years' operating.

Figure 2, below, demonstrates what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will yield reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization thru centripetal force. The effect of reduced atomization was verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-0 blades might see as large water droplets evaporate in the exhaust stream.

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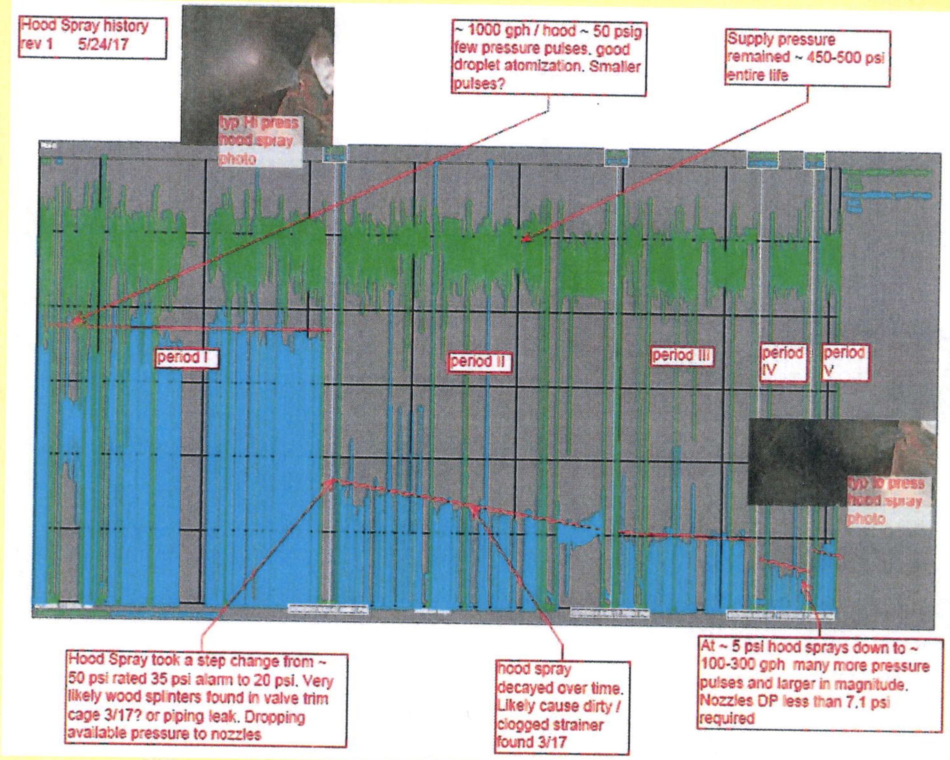
Figure 2 -- Hood Spray Pressure Degradation Over Periods 1-5



Zone Analysis – Shroud Fretting Fatigue

Based on data from the Period 3 blade strain gauge test in December 2014, MHPS identified areas (referred to as "Zones") where blade response was high, but still below the OEM design limit in the normal operation range of the LP turbine. The Duke RCA team defined these zones as Zone F1 through Zone F3 (shown by the red rectangles in Figure 3, below) and based on the PI historical data, calculated the amount of time the turbine spent in each zone for each period.

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Figure 3 -- Data Presented by MHPS During a Presentation Dated 15 March 2017

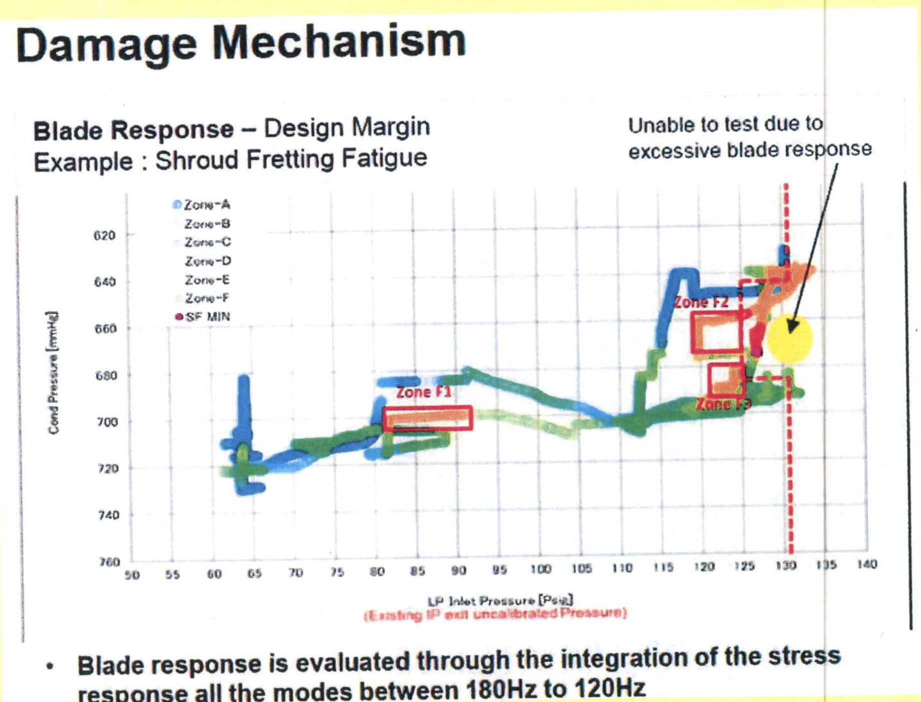

Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined as Zone F1.

Table 2 -- Time (in Hours) Spent in Each Zone and the Total Compared with Operating Time

	Time in Zone				Total Turbine	% Time
	F1	F2	F3	Total	Operating Hours	in Zone F
Period 1	901.2	257.5	23.9	1182.6	21734	5.4%
Period 2	1521.9	10.0	0.2	1532.1	21284	7.2%
Period 3	513.8	257.5	23.9	795.2	10286	7.7%
Period 4	1.3	407.8	0.0	409.1	2942	13.9%
Period 5	419.0	0.0	0.0	419.0	1561	26.8%

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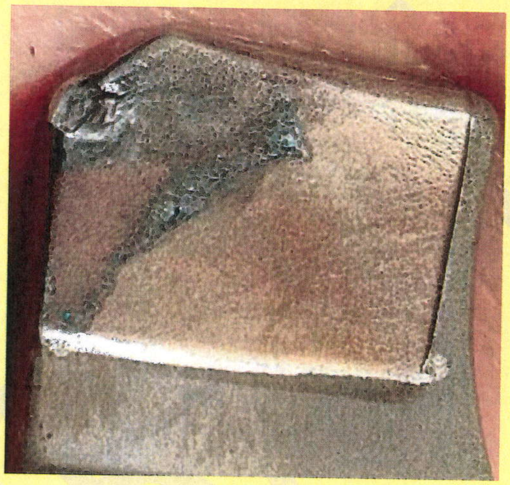
The main reason for conducting this analysis stems from the observed amount of wear seen on the contact surfaces for Period 5. Period 5 did not have any operation time in the exclusion zone and the amount of wear for the amount of operation time seems excessive. A photo showing the amount of wear seen is shown in Figure 4. There was a varying degree of wear seen on the Period 5 Z-notches, however, the wear is higher than what one would expect given the relatively low operating hours.

Figure 4 -- Photo of an L-0 blade Z-Lock from Period 5 Showing Contact Surface Wear



Period 5 did have its share of higher energy blends as detected by the blend energy method. However, in terms of operating hours in blend mode, Period 5 is not excessive in terms of percentage time blending. The total of 20 hours of blend time does not appear to justify the wear seen.

Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

The loss of dampening phenomena was a contributing factor during Periods 3 and 4.

For Period 3, there was hard-facing on the mid-span snubber ONLY. Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was due to loss of dampening at the snubbers, which were HVOF-coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

For Period 4, there was hard-facing on both the mid-span snubbers and the shroud Z-Lock contact surfaces. With both the mid-span and shroud contact surfaces being HVOF-coated, the limiting factor became the blade itself. In addition to mid-span snubber and shroud Z-Lock damage similar to what was encountered during previous Periods 1-3, one (1) of the TE L-0 blade also exhibited tip liberation at the airfoil trailing edge.

Further discussion of loss of dampening and its role as a contributing factor toward root cause will continue in the next section that speaks to blade fitment.

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

During the course of the root cause investigation between Periods 3 and 4, technical questions arose relative to "as left" blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. The basis for these questions was the potential concern that if the blade gaps at both the mid-span snubber interface and the shroud Z-Lock weren't both taken into consideration together, then as the blades began to "untwist" as the machine came up in temperature and load, adjacent mid-span snubbers would achieve greater surface-to-surface contact (especially with the HVOF coating applied) before the shroud Z-Lock contact surfaces could do the same. Consequently, reduced contact surface at the shroud Z-Lock would yield reduced mechanical damping, which is a function of both contact surface area and vibratory stresses (e.g. flutter).

Per the OEM, the Type 3 L-0 blades were used to establish a baseline blade response from the telemetry and strain gauge testing that was conducted in December 2014 at the beginning of Period 3. The intent of the blade response analysis was to capture "worst case" geometry variations. The OEM concluded that the dimensional tolerance between the Type 3 blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 (Periods 3 and 4) blade shows greater distortion than the Type 1 blade (Periods 1, 2 and 5). These findings by the OEM are consistent with independent analysis of the blades by Duke via 3rd party scanning. With a greater geometry variation, the Type 3 blade provided less mechanical damping (relative to the Type 1 blade) because of the smaller contact area – a result of greater contact misalignment.

While the OEM contends that geometry variation on the Type 3 blade are not significant enough to negatively impact blade stress/response, the OEM has acknowledged blade fitment/geometry is important enough to consider in their ongoing R&D relative to a Type 5 blade redesign. The planned design changes are intended to reduce blade response and dynamic stresses that in the past were negatively impacted by decreased contact surface area between the shroud Z-Locks.

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Appendix A: Bartow L-0 Event Summary

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 Months	~28 Months	~17 Months	~5 Months	~2 Months
L-0 Blade Configuration	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	420 MW (Nameplate)	420 MW	450 MW	450 MW	390 MW
Operating Restrictions	None – MHPS Intent Was to Follow Heat Balance Diagrams.	118 psig Limit on IP Exhaust	126 psig Limit on IP Exhaust	119 psig Limit on IP Exhaust	111 psig Limit on IP Exhaust
Blade Overspeed Condition	Overspeed Testing in MFG		Overspeed Tested in Japan	No Overspeed Testing	No Overspeed Testing
Avoidance Zone Exceedance	2,466 hrs. (of 21,734 hrs.)	1 hr. (of 21,284 hrs.)	240 hrs. (of 10,286 hrs.)	1.15 hrs. (of 2,942 hrs.)	0 hrs. (of 1,561 hrs.)
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-Locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE *Z-Lock and airfoils	0 TE / 8 GE
Worn Z-Locks	Moderate Amount of Surface Fretting and Galling Observed	Moderate Amount of Surface Fretting and Galling Observed	High Degree of Wear Observed	Evidence of Poor Contact Alignment Observed	High Degree of Wear (for Hours Run) Observed
Key Notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) and to continue the warranty. MHPSA was storing for Tenaska (purchased grey market, stored by OEM). ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mpph LP exhaust flow).	Not a forced outage. Outage planned to upgrade to "heavy duty" blades. Some blade damage (e.g. chipping at contact corners) was observed from removed service blades. Blade telemetry instrumentation installed and testing conducted in Dec 2014 at the beginning of Period 3.	During blade telemetry testing, the unit was intentionally run in avoidance zone to set limits – unit ran in zone for <20 hrs. No blade cracking observed after testing (when the test instrumentation removed).	Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil. Stellite hard facing had been added to the blade Z-Lock, and is likely a contributing factor in the failure. Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection.	Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events. Jan 2017 "loss of mass" event – blade fragment projectile traveled through the LP turbine rupture disk diaphragm. Dental mold impression of failure surfaces indicate ~10^7 striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber).
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Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	Type 5
Length	40"	40"	40"	40"
Count	64	64	64	64
Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	Different Radial Height Relative to Bartow L-0 (About 1")
Z-Lock	No HVOF	No HVOF	45° Corner with HVOF Applied	No HVOF
Blade design	Orig.	Orig.	Orig.	Attack Angle Change
Experience	3 units (2003)	12 units (2001)	1 unit, ~5 months	In commissioning (~1yr)
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

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Appendix C: Reference Materials

Mitsubishi RCA report – 9/22/2017

MHPS's evaluation is based on the data captured between Period 3 and 4 during blade telemetry testing. MHPS's evaluation is extensive and has allowed us to determine contributing factors. MHPS's intent was to draw conclusions based on actual data collected. The telemetry testing window was short not all operating conditions were witnessed during the testing (steady state and transient events); because of this the conclusions from this report may not be all encompassing of the drivers and conditions that are causing the blade failures.

Bartow RCA Customer 9-22-17.pd

Executive Summary

Duke Energy (Duke) and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 18 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation.

Duke's position is as follows: The root cause of the Bartow steam turbine (ST) 40" L-0 blade failures during Period 1-5 is driven by evidence that the OEM designed last stage blades had little or no design margins for the actual operating conditions that exist for the overall Bartow 4 x 1 Combined Cycle Unit.

Duke Engineering believes the blade failures during Periods 1-5 involve more than one driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS also indicated that there may have been more contributing factors for various Periods of failure rather than just excessive steam flow through the LP section above the MHPS design limit of 15,000 lb./hr./ft.^{2}. Excessive steam flow, or "operation in the avoidance zone", had been previously communicated by MHPS as the sole root cause back during a presentation made at Bartow Station on 15 March 2017. MPHS has since changed its position and today there is agreement between both parties that there is not just one failure mechanism.

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After months of study (and with input from MHPS) Duke Engineering believes the following to be the most significant contributing factors toward blade failure over the history of Bartow Unit 4S L-0 events:

- Low Pressure (LP) Turbine Excessive Steam Flow
- Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

Duke believes that the contributing factors presented in this paper – or during MHPS presentations – are postulations and may possibly be correct. Most of the MHPS postulations are derived from strain gauge data taken during the brief period of time that the telemetry test conducted during December 2014. That blade response data was then extrapolated by MHPS Engineering to develop potential root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil itself that were seen during Periods 1-5.

The long-term solution for the Bartow LP section is to replace the L-0 blades or to retrofit the LP steam path with a more capable/reliable design. With either scenario, blade telemetry instrumentation and blade vibration monitoring will be necessary to conclusively determine and eliminate the magnitude and impact of the identified contributing factors during various operating configurations that are integral to unrestricted 4 x 1 combined cycle operation.

This technical paper will speak briefly of the history of L-0 blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above. Any conclusions derived from Duke's efforts that are discussed in this document are based on the team's best ability to correlate data with events in operation and findings with L-0 blade inspections/failures.

Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration.

Since commissioning there have been five (5) events triggered by L-0 blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-0 blade in efforts to address the failures (see Appendix B for L-0 modifications). To date, the modifications have not resulted in improved reliability or performance of the L-0 blades in service at Bartow. The number of blade failures and problems with ST L-0 blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-0 fleet. The most common reported issue from the MHPS 40" L-0 blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-0 rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

Root Cause Contributing Factors

Low Pressure (LP) Turbine Excessive Steam Flow

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data evaluation – learned (and made it known to Duke) that a significant contributing factor toward the L-0 blade failures was high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40" L-0 fleet with several operating hours above the design limit of 15,000 lb./hr./ft.[2] (the MHPS 40" L-0 fleet average was closer to 12,000 lb./hr./ft.[2]). Duke was issued an "avoidance zone" chart with instructions from MHPS not to run to the right side of the curve – the lone exception being "brief" operation during transient conditions.

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While Duke Engineering agreed that back-end loading should be considered a significant contributing factor, one cannot definitively conclude that it has been the failure driving mechanism of all five (5) of the documented L-0 events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the "avoidance zone" of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

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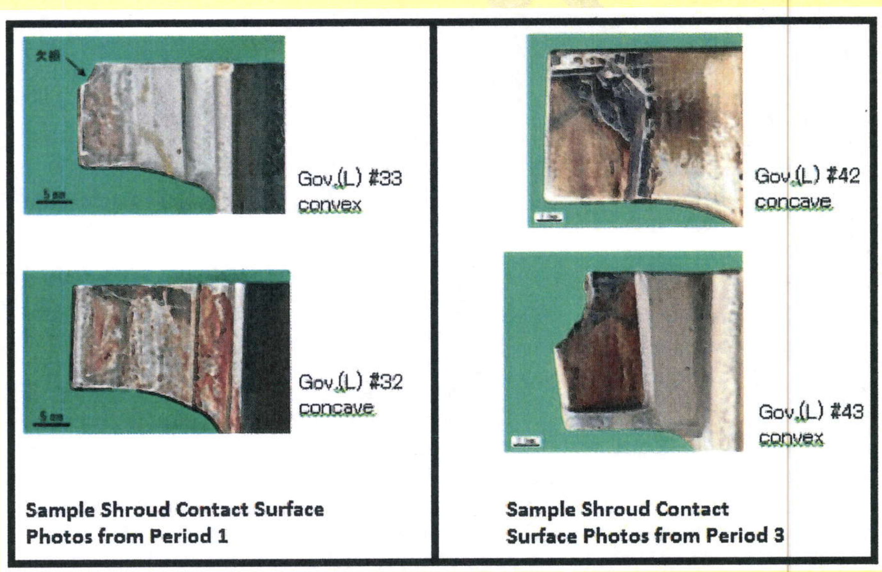
By a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the "avoidance zone" relative to total operating hours – 2,466 out of 21,734 total hours. However, blade damage was relegated to five (5) broken mid-span snubbers on the turbine end of the machine and a minimal degree of fretting on the shroud Z-Lock contact surfaces for both turbine and generator ends of the machine.

Conversely, during Period 3, there were only 240 hours (out of 10,286 total hours) of operation in the "avoidance zone", approx. 11 hours of which occurred during the instrumented blade telemetry test performed by MHPS in December 2014. Even with a significantly fewer number of "avoidance zone" hours for Period 3 relative to Period 1 – a factor of 10 fewer hours for Period 3 – there was significantly greater amounts of blade damage and fretting on both ends of the machine. While the amount of Z-Lock wear is not quantified for Periods 1 and 3, photographic evidence suggests that the amount of wear is much greater for Period 3, as shown below in Figure 1. It is therefore difficult to conclude that damage to the L-0 blades in Period 3 is solely due to unit operation above the exhaust flow limit.

Figure 1 -- Comparative Photos of Shroud Contact Surface Wear for Periods 1 and 3



With the L-0s currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern at the current LP inlet operating limits. MHPS Engineering does not have enough technical data to support releasing Duke to operate the machine beyond the current LP inlet operating limits due to concerns for impacts to upstream blading – i.e. the L-1 blade sets.

Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust

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During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to include all aspects that might impact exhaust conditions of the LP. Since the design of the condenser includes spargers, or "dump tubes", for the hot reheat (HRH) and LP bypass steam flows from each of the four combustion turbines (CT), and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

Commented [MB1]: With a robust blade the exhaust conditions shouldn't impact the part. The changing exhaust conditions is impacting the MHPS blades...leading to why we think that is the root cause.

If I am off base don't change it.

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A set of criteria and an automated process using Excel and PI Datalink were developed that allow large amounts of data (stored in the PI historian) to be quickly reviewed for each Period 1-5. Blends that met the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. This process involved extracting PI data, calculating a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values, or "counts". "Counts" are defined as the number of measureable blends where there was a slope change (+/-) in greater than (20 degrees superheat / min) at the hood spray thermocouples. The data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW. The limits of 20 degrees F (superheat) and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow for a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify specific points/periods in time to look at additional blend parameters.

Commented [MB2]: We don't really conclude anything with this section. Do we need a to add that until we install blades with telemetry testing we will not understand the total impact of this thermal energy on the blades. This was reviewed by MHPS during the previous blade telemetry test and they were not able to conclude a result. To be noted: not all blend conditions and configurations were exercised during the telemetry testing so there is not enough evidence to prove or refute this contributing factor.

Table 1 -- Quick Comparison of the Number of "Counts" that Meet the Criteria for Periods 1-5.

	Number of Operating Hours in Each Period	Number of Blends (or "Counts") Meeting Criteria
Period 1	21,734	13
Period 2	21,284	7
Period 3	10,286	37*
Period 4	2,942	3
Period 5	1,561	5

*Includes 6 blends that meet the criteria during strain gauge testing in December 2014

Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

A review of the OEM-provided instructions requires use of hood sprays during the following conditions:

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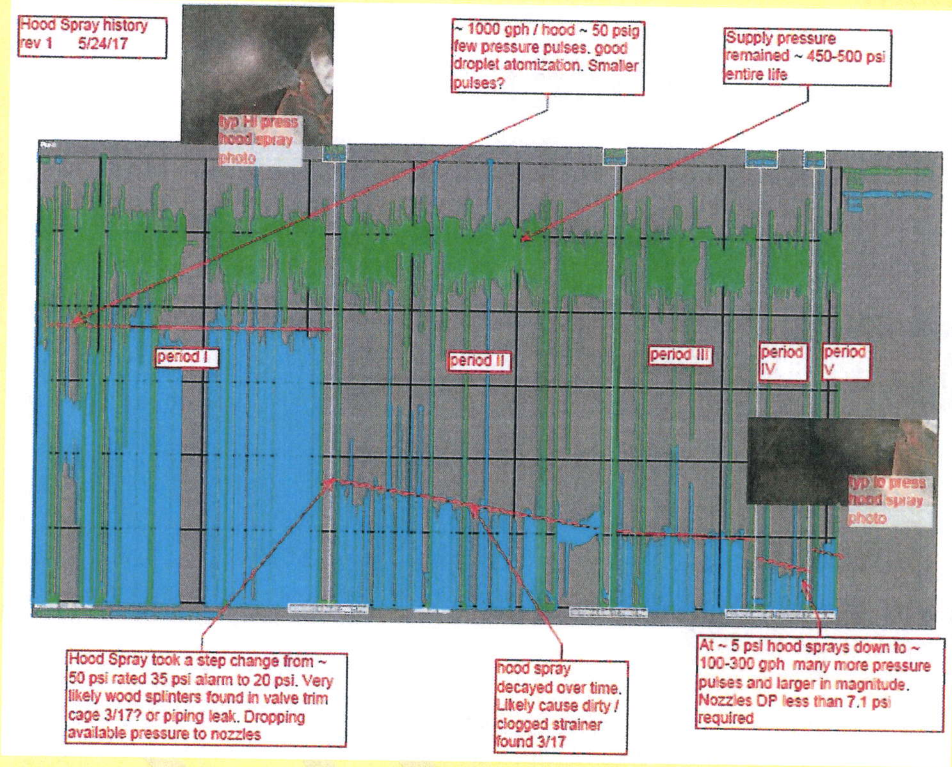
- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

During a review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found to date. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM-provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or unit trip event when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an instrumentation issue).

Careful attention was also paid to the hood spray pressure over time. This was found to steadily decrease over successive Periods. Maintenance of the hood sprays control valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the same control valve had filled with debris in prior years' operating.

Figure 2, below, demonstrates what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will yield reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization thru centripetal force. The effect of reduced atomization was verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-0 blades might see as large water droplets evaporate in the exhaust stream.

Figure 2 -- Hood Spray Pressure Degradation Over Periods 1-5



Zone Analysis – Shroud Fretting Fatigue

Based on data from the Period 3 blade strain gauge test in December 2014, MHPS identified areas (referred to as "Zones") where blade response was high, but still below the OEM design limit in the normal operation range of the LP turbine. The Duke RCA team defined these zones as Zone F1 through Zone F3 (shown by the red rectangles in Figure 3, below) and based on the PI historical data, calculated the amount of time the turbine spent in each zone for each period. MHPS did not provide any restriction of operation in Zones F1 through F3, only the exclusion zone identified by the dotted red line in Figure 3.

Commented [MB3]: Just want ot make sure it is clear to anyone reading this that we were not restricted, we just noted higher response. Also calling out the exclusion zone that MHPS created to make that clear (to people who wouldn't know what we are talkin gabout)

Figure 3 -- Data Presented by MHPS During a Presentation Dated 15 March 2017

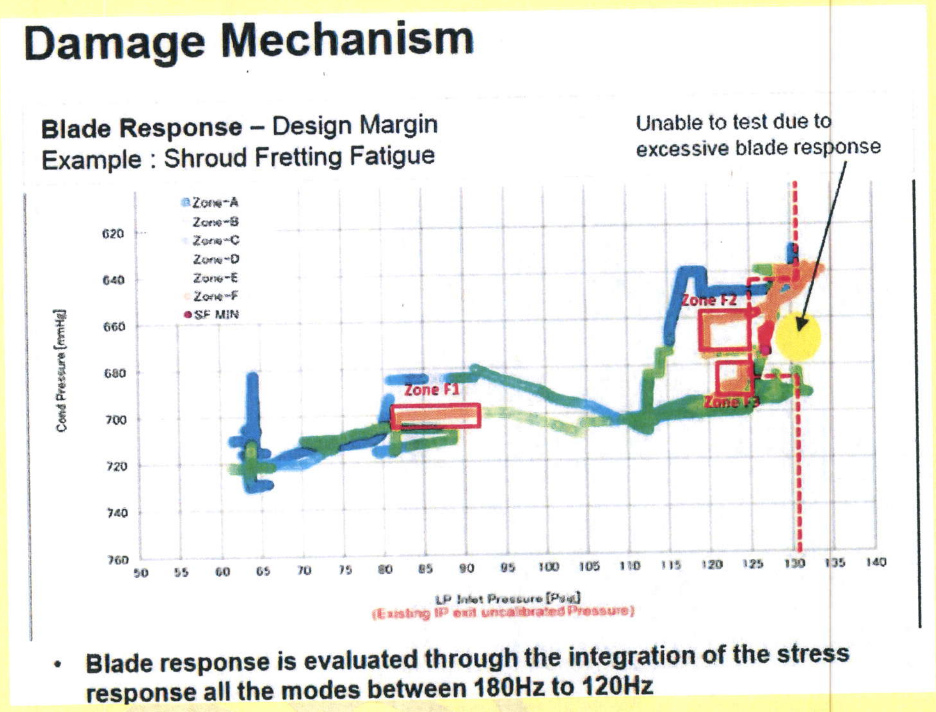


Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined as Zone F1.

Table 2 -- Time (in Hours) Spent in Each Zone and the Total Compared with Operating Time

	Time in Zone				Total Turbine	% Time
	F1	F2	F3	Total	Operating Hours	in Zone F
Period 1	901.2	257.5	23.9	1182.6	21734	5.4%
Period 2	1521.9	10.0	0.2	1532.1	21284	7.2%
Period 3	513.8	257.5	23.9	795.2	10286	7.7%
Period 4	1.3	407.8	0.0	409.1	2942	13.9%
Period 5	419.0	0.0	0.0	419.0	1561	26.8%

The main reason for conducting this analysis stems from the observed amount of wear seen on the contact surfaces for Period 5. Period 5 did not have any operation time in the exclusion zone and the amount of wear for the amount of operation time seems excessive. A photo showing the amount of wear seen is shown in Figure 4. There was a varying degree of wear seen on the Period 5 Z-notches, however, the wear is higher than what one would expect given the relatively low operating hours.

Figure 4 -- Photo of an L-0 blade Z-Lock from Period 5 Showing Contact Surface Wear

Period 5 did have high energy blends as detected by the blend energy method. However, in terms of operating hours in blend mode, Period 5 is not excessive in terms of percentage time blending as compare to time operated in Zone F1.

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Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

The loss of dampening phenomena was a contributing factor during Periods 3 and 4. HVOF hard-facing can reduce the amount of base material fretting during operation. The application of HVOF is used on many applications in the industry for blading contact surfaces. When applied the HVOF hard-facing changes the frictional forces of the contact surface reducing fretting and has an increased hardness to prevent material loss.

Commented [MB5]: Do we need this? To help quantify why dampening is reduced with hard-facing? Might need to run the wording by Paul?Harry for accuracy.

For Period 3, there was hard-facing on the mid-span snubber ONLY. Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was due to loss of dampening at the snubbers, which were HVOF-coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

For Period 4, there was hard-facing on both the mid-span snubbers and the shroud Z-Lock contact surfaces. With both the mid-span and shroud contact surfaces being HVOF-coated, the limiting stress location became the blade itself. In addition to mid-span snubber and shroud Z-Lock damage similar to what was encountered during previous Periods 1-3, one (1) of the TE L-0 blade also exhibited tip liberation at the airfoil trailing edge.

Further discussion of loss of dampening and its role as a contributing factor toward potential blade failure will continue in the next section that speaks to blade fitment.

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

During the course of the RCA investigation between Periods 3 and 4, technical questions arose relative to "as left" blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. The basis for these questions was the potential concern that if the blade gaps at both the mid-span snubber interface and the shroud Z-Lock weren't both taken into consideration together, then as the blades began to "untwist" as the machine came up in temperature and load, adjacent mid-span snubbers would achieve greater surface-to-surface contact (especially with the HVOF coating applied) before the shroud Z-Lock contact surfaces could do the same. Consequently, reduced contact surface at the shroud Z-Lock would yield reduced mechanical damping, which is a function of both contact surface area and vibratory stresses (e.g. flutter).

Per the OEM, the Type 3 L-0 blades were used to establish a baseline blade response from the telemetry and strain gauge testing that was conducted in December 2014 at the beginning of Period 3. The intent of the blade response analysis was to capture "worst case" geometry variations. The OEM concluded that the dimensional tolerance between the Type 3 blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 (Periods 3 and 4) blade shows greater distortion than the Type 1 blade (Periods 1, 2 and 5). These findings by the OEM are consistent with independent analysis of the blades by Duke via 3rd party scanning. With a greater geometry variation, the Type 3 blade provided less mechanical damping (relative to the Type 1 blade) because of the smaller contact area – a result of greater contact misalignment.

While the OEM contends that geometry variation on the Type 3 blade are not significant enough to negatively impact blade stress/response, the OEM has acknowledged blade fitment/geometry is important enough to consider in their ongoing R&D relative to a new Type 5 blade redesign. The planned design changes are intended to reduce blade response and dynamic stresses that in the past were negatively impacted by decreased contact surface area between the shroud Z-Locks.

Appendix A: Bartow L-0 Event Summary

Commented [MB6]: Is your excel summary of the better than this table or can it be in addition to this table? Key notes and other comments should be reviewed closely to make sure they don't contradict whats above. This was written before we knew a lot.

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 Months	~28 Months	~17 Months	~5 Months	~2 Months
L-0 Blade Configuration	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	420 MW (Nameplate)	420 MW	450 MW	450 MW	390 MW
Operating Restrictions	None – MHPS Intent Was to Follow Heat Balance Diagrams.	118 psig Limit on IP Exhaust	126 psig Limit on IP Exhaust	119 psig Limit on IP Exhaust	111 psig Limit on IP Exhaust
Blade Overspeed Condition	Overspeed Testing in MFG		Overspeed Tested in Japan	No Overspeed Testing	No Overspeed Testing
Avoidance Zone Exceedance	2,466 hrs. (of 21,734 hrs.)	1 hr. (of 21,284 hrs.)	240 hrs. (of 10,286 hrs.)	1.15 hrs. (of 2,942 hrs.)	0 hrs. (of 1,561 hrs.)
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-Locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE *Z-Lock and airfoils	0 TE / 8 GE
Worn Z-Locks	Moderate Amount of Surface Fretting and Galling Observed	Moderate Amount of Surface Fretting and Galling Observed	High Degree of Wear Observed	Evidence of Poor Contact Alignment Observed	High Degree of Wear (for Hours Run) Observed
Key Notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) and to continue the warranty. MHPSA was storing for Tenaska (purchased grey market, stored by OEM). ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mpph LP exhaust flow).	Not a forced outage. Outage planned to upgrade to "heavy duty" blades. Some blade damage (e.g. chipping at contact corners) was observed from removed service blades. Blade telemetry instrumentation installed and testing conducted in Dec 2014 at the beginning of Period 3.	During blade telemetry testing, the unit was intentionally run in avoidance zone to set limits – unit ran in zone for <20 hrs. No blade cracking observed after testing (when the test instrumentation removed).	Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil. Stellite hard facing had been added to the blade Z-Lock, and is likely a contributing factor in the failure. Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection.	Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events. Jan 2017 "loss of mass" event – blade fragment projectile traveled through the LP turbine rupture disk diaphragm. Dental mold impression of failure surfaces indicate ~10^7 striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber).
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Blade design	Orig.	Orig.	Orig.	*Attack Angle Change*
Experience	3 units (2003)	12 units (2001)	1 unit, ~5 months	*In commissioning (~1yr)*
Material	17-4 ph	17-4 ph	17-4 ph	*17-4 ph*

Commented [MB7]: You mentioned Type 5 above. Is the redesign blade for Bartow different than Citrus? Sounded like MHPS was "designing" something new for Bartow. If it's the citrus blade then there should have been no slide on the changes being made (in the mHPS root cause). Maybe this isn't a type 5, but the "latest Gen 40" blade??

Appendix C: Reference Materials

Mitsubishi RCA report – 9/22/2017

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Bartow RCA Customer 9-22-17.pd

11 October 2017

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This technical paper will speak briefly of the history of L-0 blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above. Any conclusions derived from Duke's efforts that are discussed in this document are based on the team's best ability to correlate data with events in operation and findings with L-0 blade inspections/failures.

Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

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Since commissioning there have been five (5) events triggered by L-0 blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-0 blade in efforts to address the failures (see Appendix B for L-0 modifications). To date, the modifications have not resulted in improved reliability or performance of the L-0 blades in service at Bartow. The number of blade failures and problems with ST L-0 blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-0 fleet. The most common reported issue from the MHPS 40" L-0 blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-0 rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

Root Cause Contributing Factors

Low Pressure (LP) Turbine Excessive Steam Flow

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data evaluation – learned (and made it known to Duke) that a significant contributing factor toward the L-0 blade failures was extremely high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40" L-0 fleet with several operating hours above the design limit of 15,000 lb./hr./ft.^{2} (the MHPS 40" L-0 fleet average was closer to 12,000 lb./hr./ft.^{2}). Duke was issued an "avoidance zone" chart with instructions from MHPS not to run to the right side of the curve – the lone exception being "brief" operation during transient conditions.

While Duke Engineering agrees that back-end loading should be considered a significant contributing factor toward the root cause, one cannot definitively conclude that it has been the failure driving mechanism of all five (5) of the documented L-0 events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the "avoidance zone" of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

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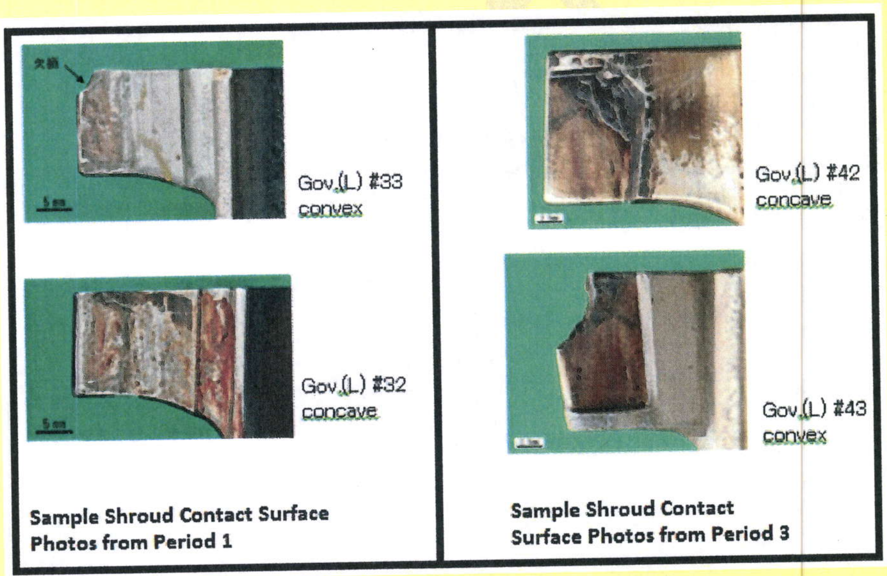
Figure 1 -- Comparative Photos of Shroud Contact Surface Wear for Periods 1 and 3



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A set of criteria and an automated process using Excel and PI Datalink were developed that allow large amounts of data (stored in the PI historian) to be quickly reviewed for each Period 1-5. Blends that met the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. This process involved extracting PI data, calculating a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values, or "counts". "Counts" are defined as the number of measureable blends where there was a slope change (+/-) in greater than (20 degrees superheat / min) at the hood spray thermocouples. The data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW. The limits of 20 degrees F (superheat) and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow for a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify specific points/periods in time to look at additional blend parameters.

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*Includes 6 blends that meet the criteria during strain gauge testing in December 2014

Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

A review of the OEM-provided instructions requires use of hood sprays during the following conditions:

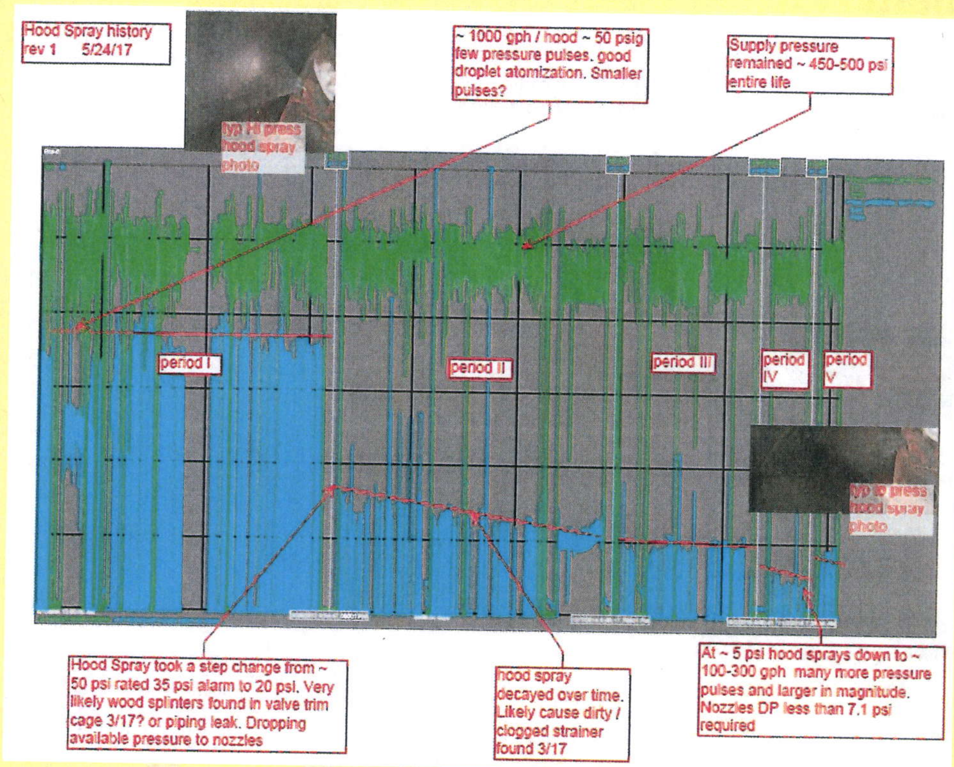
- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

During a review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found to date. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM-provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or unit trip event when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an instrumentation issue).

Careful attention was also paid to the hood spray pressure over time. This was found to steadily decrease over successive Periods. Maintenance of the hood sprays control valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the same control valve had filled with debris in prior years' operating.

Figure 2, below, demonstrates what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will yield reduced atomization as these style of nozzle rely on pressure drop to create a vortex inside the nozzle that causes atomization thru centripetal force. The effect of reduced atomization was verified during a test just prior to unit restart in April 2017. A key concern of poor atomization is the effect it might have on generating dynamic pressures which the L-0 blades might see as large water droplets evaporate in the exhaust stream.

Figure 2 -- Hood Spray Pressure Degradation Over Periods 1-5

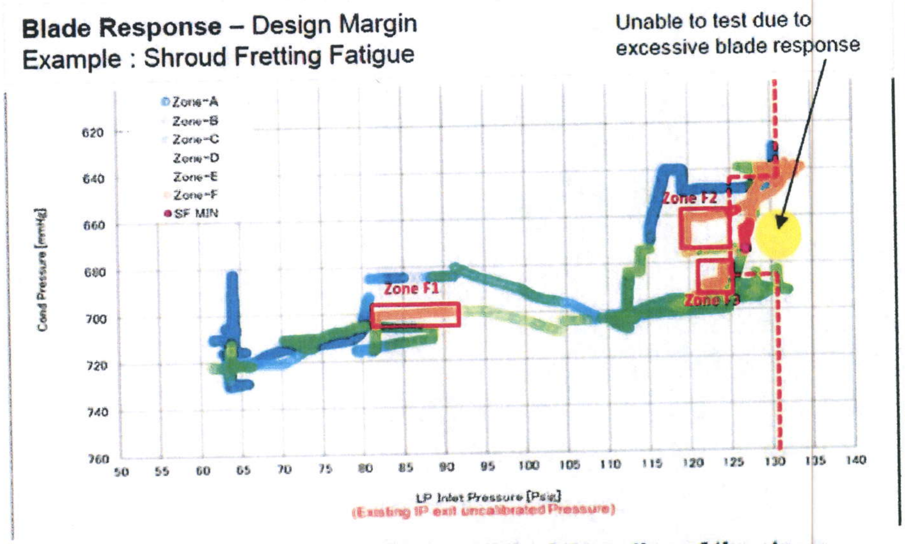


Zone Analysis – Shroud Fretting Fatigue

Based on data from the Period 3 blade strain gauge test in December 2014, MHPS identified areas (referred to as "Zones") where blade response was high, but still below the OEM design limit in the normal operation range of the LP turbine. The Duke RCA team defined these zones as Zone F1 through Zone F3 (shown by the red rectangles in Figure 3, below) and based on the PI historical data, calculated the amount of time the turbine spent in each zone for each period.

Figure 3 -- Data Presented by MHPS During a Presentation Dated 15 March 2017

Damage Mechanism



- **Blade response is evaluated through the integration of the stress response all the modes between 180Hz to 120Hz**

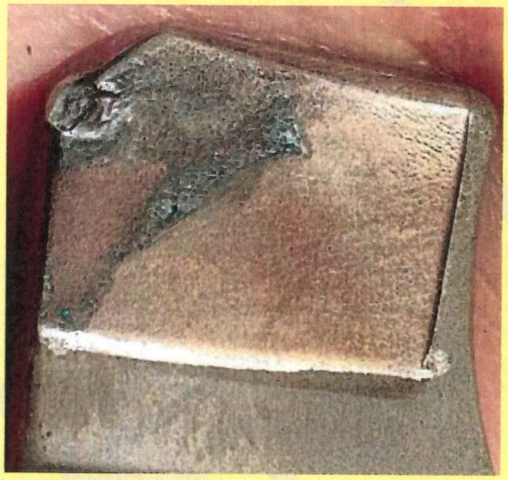
Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined as Zone F1.

Table 2 -- Time (in Hours) Spent in Each Zone and the Total Compared with Operating Time

	Time in Zone				Total Turbine	% Time
	F1	F2	F3	Total	Operating Hours	in Zone F
Period 1	901.2	257.5	23.9	1182.6	21734	5.4%
Period 2	1521.9	10.0	0.2	1532.1	21284	7.2%
Period 3	513.8	257.5	23.9	795.2	10286	7.7%
Period 4	1.3	407.8	0.0	409.1	2942	13.9%
Period 5	419.0	0.0	0.0	419.0	1561	26.8%

The main reason for conducting this analysis stems from the observed amount of wear seen on the contact surfaces for Period 5. Period 5 did not have any operation time in the exclusion zone and the amount of wear for the amount of operation time seems excessive. A photo showing the amount of wear seen is shown in Figure 4. There was a varying degree of wear seen on the Period 5 Z-notches, however, the wear is higher than what one would expect given the relatively low operating hours.

Figure 4 -- Photo of an L-0 blade Z-Lock from Period 5 Showing Contact Surface Wear



Period 5 did have its share of higher energy blends as detected by the blend energy method. However, in terms of operating hours in blend mode, Period 5 is not excessive in terms of percentage time blending. The total of 20 hours of blend time does not appear to justify the wear seen.

Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

The loss of dampening phenomena was a contributing factor during Periods 3 and 4.

For Period 3, there was hard-facing on the mid-span snubber ONLY. Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was due to loss of dampening at the snubbers, which were HVOF-coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

For Period 4, there was hard-facing on both the mid-span snubbers and the shroud Z-Lock contact surfaces. With both the mid-span and shroud contact surfaces being HVOF-coated, the limiting stress location became the blade itself. In addition to mid-span snubber and shroud Z-Lock damage similar to what was encountered during previous Periods 1-3, one (1) of the TE L-0 blade also exhibited tip liberation at the airfoil trailing edge.

Further discussion of loss of dampening and its role as a contributing factor toward potential blade failure will continue in the next section that speaks to blade fitment.

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

During the course of the RCA investigation between Periods 3 and 4, technical questions arose relative to "as left" blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. The basis for these questions was the potential concern that if the blade gaps at both the mid-span snubber interface and the shroud Z-Lock weren't both taken into consideration together, then as the blades began to "untwist" as the machine came up in temperature and load, adjacent mid-span snubbers would achieve greater surface-to-surface contact (especially with the HVOF coating applied) before the shroud Z-Lock contact surfaces could do the same. Consequently, reduced contact surface at the shroud Z-Lock would yield reduced mechanical damping, which is a function of both contact surface area and vibratory stresses (e.g. flutter).

Per the OEM, the Type 3 L-0 blades were used to establish a baseline blade response from the telemetry and strain gauge testing that was conducted in December 2014 at the beginning of Period 3. The intent of the blade response analysis was to capture "worst case" geometry variations. The OEM concluded that the dimensional tolerance between the Type 3 blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 (Periods 3 and 4) blade shows greater distortion than the Type 1 blade (Periods 1, 2 and 5). These findings by the OEM are consistent with independent analysis of the blades by Duke via 3rd party scanning. With a greater geometry variation, the Type 3 blade provided less mechanical damping (relative to the Type 1 blade) because of the smaller contact area – a result of greater contact misalignment.

While the OEM contends that geometry variation on the Type 3 blade are not significant enough to negatively impact blade stress/response, the OEM has acknowledged blade fitment/geometry is important enough to consider in their ongoing R&D relative to a Type 5 blade redesign. The planned design changes are intended to reduce blade response and dynamic stresses that in the past were negatively impacted by decreased contact surface area between the shroud Z-Locks.

Appendix A: Bartow L-0 Event Summary

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	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 Months	~28 Months	~17 Months	~5 Months	~2 Months
L-0 Blade Configuration	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	420 MW (Nameplate)	420 MW	450 MW	450 MW	390 MW
Operating Restrictions	None – MHPS Intent Was to Follow Heat Balance Diagrams.	118 psig Limit on IP Exhaust	126 psig Limit on IP Exhaust	119 psig Limit on IP Exhaust	111 psig Limit on IP Exhaust
Blade Overspeed Condition	Overspeed Testing in MFG		Overspeed Tested in Japan	No Overspeed Testing	No Overspeed Testing
Avoidance Zone Exceedance	2,466 hrs. (of 21,734 hrs.)	1 hr. (of 21,284 hrs.)	240 hrs. (of 10,286 hrs.)	1.15 hrs. (of 2,942 hrs.)	0 hrs. (of 1,561 hrs.)
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-Locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE *Z-Lock and airfoils	0 TE / 8 GE
Worn Z-Locks	Moderate Amount of Surface Fretting and Galling Observed	Moderate Amount of Surface Fretting and Galling Observed	High Degree of Wear Observed	Evidence of Poor Contact Alignment Observed	High Degree of Wear (for Hours Run) Observed
Key Notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) and to continue the warranty. MHPSA was storing for Tenaska (purchased grey market, stored by OEM). ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mpph LP exhaust flow).	Not a forced outage. Outage planned to upgrade to "heavy duty" blades. Some blade damage (e.g. chipping at contact corners) was observed from removed service blades. Blade telemetry instrumentation installed and testing conducted in Dec 2014 at the beginning of Period 3.	During blade telemetry testing, the unit was intentionally run in avoidance zone to set limits – unit ran in zone for <20 hrs. No blade cracking observed after testing (when the test instrumentation removed).	Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil. Stellite hard facing had been added to the blade Z-Lock, and is likely a contributing factor in the failure. Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection.	Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events. Jan 2017 "loss of mass" event – blade fragment projectile traveled through the LP turbine rupture disk diaphragm. Dental mold impression of failure surfaces indicate ~10^7 striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber).
Information Shared with MHPS	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.

Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			Citrus L-0
	Type 1	Type 3 (v1)	Type 3 (v2)	Type 5
Length	40"	40"	40"	40"
Count	64	64	64	64
Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	Different Radial Height Relative to Bartow L-0 (About 1")
Z-Lock	No HVOF	No HVOF	45° Corner with HVOF Applied	No HVOF
Blade design	Orig.	Orig.	Orig.	Attack Angle Change
Experience	3 units (2003)	12 units (2001)	1 unit, ~5 months	In commissioning (~1yr)
Material	17-4 ph	17-4 ph	17-4 ph	17-4 ph

Appendix C: Reference Materials

Mitsubishi RCA report – 9/22/2017

MHPS's evaluation is based on the data captured between Period 3 and 4 during blade telemetry testing. MHPS's evaluation is extensive and has allowed us to determine contributing factors. MHPS's intent was to draw conclusions based on actual data collected. The telemetry testing window was short not all operating conditions were witnessed during the testing (steady state and transient events); because of this the conclusions from this report may not be all encompassing of the drivers and conditions that are causing the blade failures.

Bartow RCA
Customer 9-22-17.pd

Duke Energy - Confidential

11 October 2017

Executive Summary

Duke Energy (Duke) and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 18 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation.

Duke's position is as follows: The root cause of the Bartow steam turbine (ST) 40" L-0 blade failures during Period 1-5 is driven by evidence that the OEM designed last stage blades had little or no design margins for the actual operating conditions that exist for the overall Bartow 4 x 1 Combined Cycle Unit.

Duke Engineering believes the blade failures during Periods 1-5 involve more than one driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS also indicated that there may have been more contributing factors for various Periods of failure rather than just excessive steam flow through the LP section above the MHPS design limit of 15,000 lb./hr./ft.^{2}. Excessive steam flow, or "operation in the avoidance zone", had been previously communicated by MHPS as the sole root cause back during a presentation made at Bartow Station on 15 March 2017. MPHS has since changed its position and today there is agreement between both parties that there is not just one failure mechanism.

After months of study (and with input from MHPS) Duke Engineering believes the following to be the most significant contributing factors toward blade failure over the history of Bartow Unit 4S L-0 events:

- Low Pressure (LP) Turbine Excessive Steam Flow
- Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

Duke believes that the contributing factors presented in this paper – or during MHPS presentations – are postulations and may possibly be correct. Most of the MHPS postulations are derived from strain gauge data taken during the brief period of time that the telemetry test conducted during December 2014. That blade response data was then extrapolated by MHPS Engineering to develop potential root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil itself that were seen during Periods 1-5.

The long-term solution for the Bartow LP section is to replace the L-0 blades or to retrofit the LP steam path with a more capable/reliable design. With either scenario, blade telemetry instrumentation and blade vibration monitoring will be necessary to conclusively determine and eliminate the magnitude and impact of the identified contributing factors during various operating configurations that are integral to unrestricted 4 x 1 combined cycle operation.

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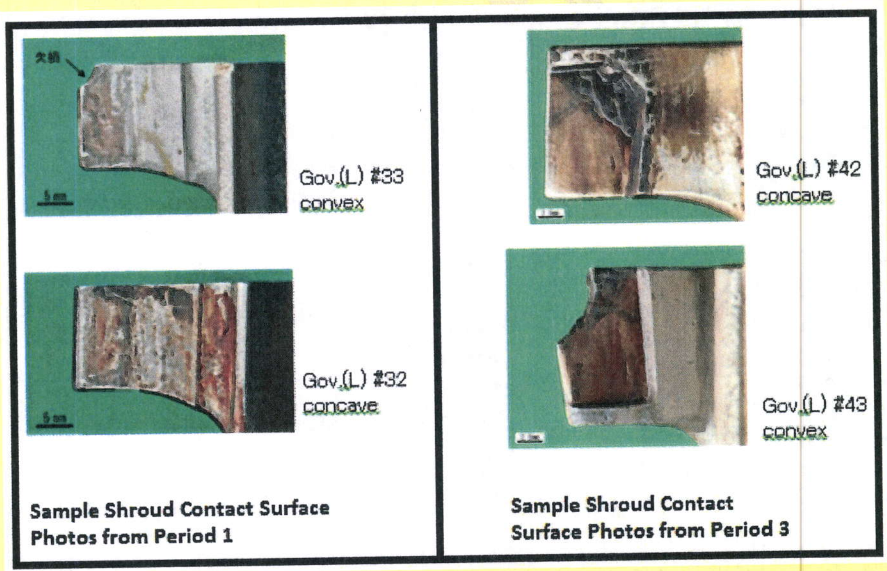

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Commented [MB1]: We don't really conclude anything with this section. Do we need a to add that until we install blades with telemetry testing we will not understand the total impact of this thermal energy on the blades. This was reviewed by MHPS during the previous blade telemetry test and they were not able to conclude a result. To be noted: not all blend conditions and configurations were exercised during the telemetry testing so there is not enough evidence to prove or refute this contributing factor.

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Figure 2 -- Hood Spray Pressure Degradation Over Periods 1-5

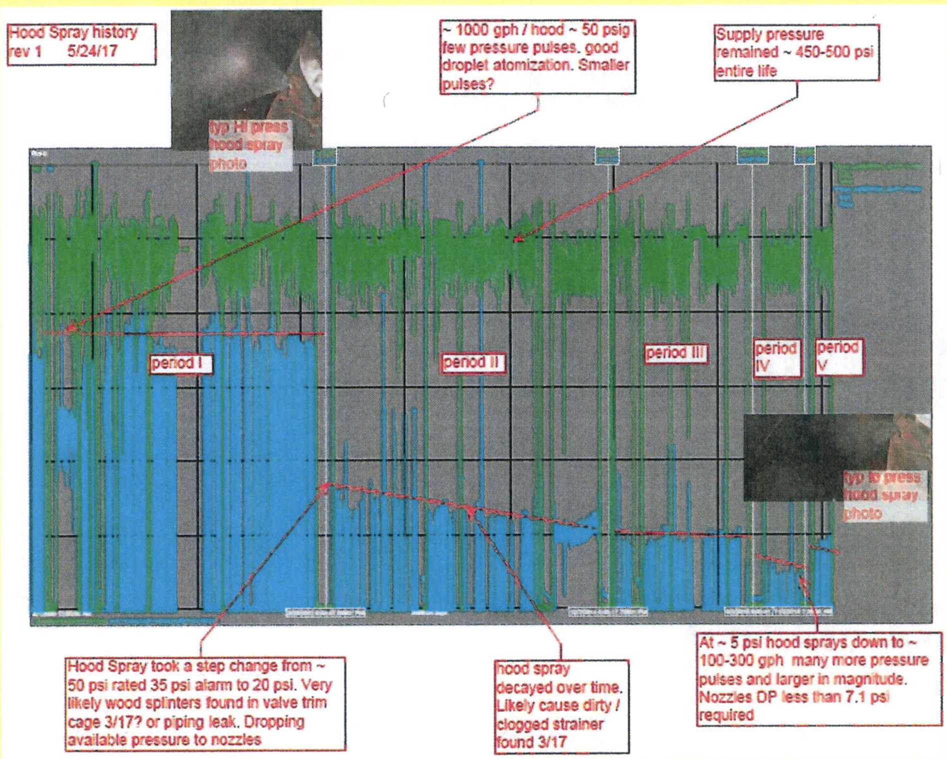

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Figure 3 -- Data Presented by MHPS During a Presentation Dated 15 March 2017

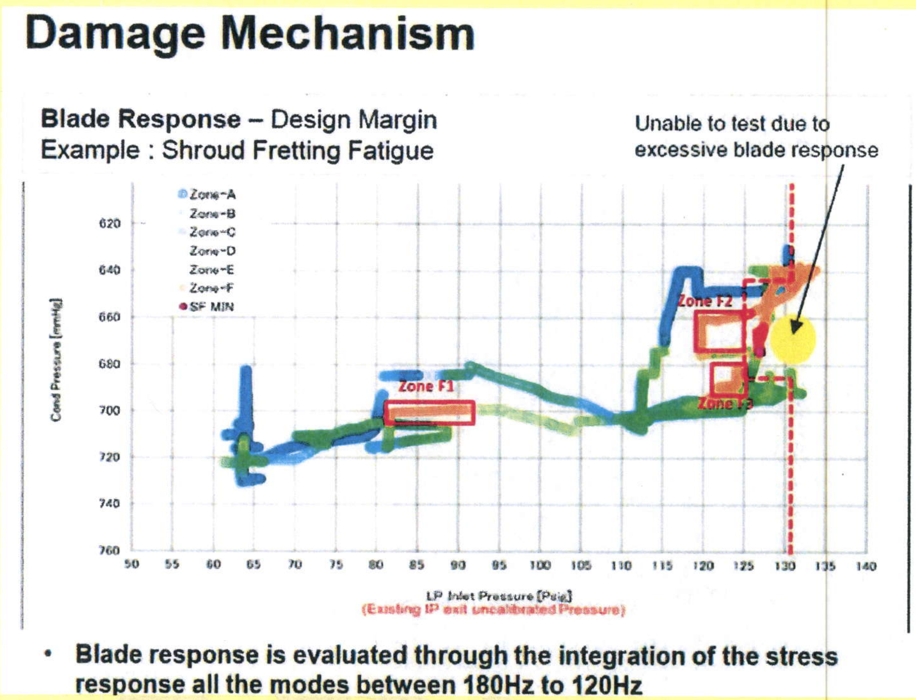

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Table 2 -- Time (in Hours) Spent in Each Zone and the Total Compared with Operating Time

	Time in Zone				Total Turbine	% Time
	F1	F2	F3	Total	Operating Hours	in Zone F
Period 1	901.2	257.5	23.9	1182.6	21734	5.4%
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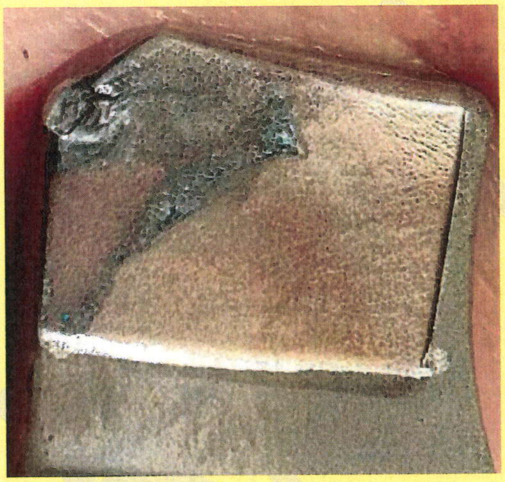
The main reason for conducting this analysis stems from the observed amount of wear seen on the contact surfaces for Period 5. Period 5 did not have any operation time in the exclusion zone and the amount of wear for the amount of operation time seems excessive. A photo showing the amount of wear seen is shown in Figure 4. There was a varying degree of wear seen on the Period 5 Z-notches, however, the wear is higher than what one would expect given the relatively low operating hours.

Figure 4 -- Photo of an L-0 blade Z-Lock from Period 5 Showing Contact Surface Wear



Period 5 did have high energy blends as detected by the blend energy method. However, in terms of operating hours in blend mode, Period 5 is not excessive in terms of percentage time blending as compared to operating hours in Zone F1.

Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

HVOF hard-facing can reduce the amount of base material fretting during operation and is used on many applications across the industry for blading contact surfaces. When applied, the HVOF hard-facing changes the frictional forces of the contact surface reducing fretting and has an increased hardness to prevent material loss.

The loss of dampening phenomena was a contributing factor during Periods 3 and 4.

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For Period 4, there was hard-facing on both the mid-span snubbers and the shroud Z-Lock contact surfaces. With both the mid-span and shroud contact surfaces being HVOF-coated, the limiting stress location became the blade itself. In addition to mid-span snubber and shroud Z-Lock damage similar to what was encountered during previous Periods 1-3, one (1) of the TE L-0 blade also exhibited tip liberation at the airfoil trailing edge.

Further discussion of loss of dampening and its role as a contributing factor toward potential blade failure will continue in the next section that speaks to blade fitment.

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

During the course of the RCA investigation between Periods 3 and 4, technical questions arose relative to "as left" blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. The basis for these questions was the potential concern that if the blade gaps at both the mid-span snubber interface and the shroud Z-Lock weren't both taken into consideration together, then as the blades began to "untwist" as the machine came up in temperature and load, adjacent mid-span snubbers would achieve greater surface-to-surface contact (especially with the HVOF coating applied) before the shroud Z-Lock contact surfaces could do the same. Consequently, reduced contact surface at the shroud Z-Lock would yield reduced mechanical damping, which is a function of both contact surface area and vibratory stresses (e.g. flutter).

Per the OEM, the Type 3 L-0 blades were used to establish a baseline blade response from the telemetry and strain gauge testing that was conducted in December 2014 at the beginning of Period 3. The intent of the blade response analysis was to capture "worst case" geometry variations. The OEM concluded that the dimensional tolerance between the Type 3 blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 (Periods 3 and 4) blade shows greater distortion than the Type 1 blade (Periods 1, 2 and 5). These findings by the OEM are consistent with independent analysis of the blades by Duke via 3rd party scanning. With a greater geometry variation, the Type 3 blade provided less mechanical damping (relative to the Type 1 blade) because of the smaller contact area – a result of greater contact misalignment.

While the OEM contends that geometry variation on the Type 3 blade are not significant enough to negatively impact blade stress/response, the OEM has acknowledged blade fitment/geometry is important enough to consider in their ongoing R&D relative to a new Type 5 blade redesign. The planned design changes are intended to reduce blade response and dynamic stresses that in the past were negatively impacted by decreased contact surface area between the shroud Z-Locks.

Appendix A: Bartow L-0 Event Summary

Commented [MB2]: Is your excel summary of the better than this table or can it be in addition to this table? Key notes and other comments should be reviewed closely to make sure they don't contradict whats above. This was written before we knew a lot.

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 Months	~28 Months	~17 Months	~5 Months	~2 Months
L-0 Blade Configuration	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	420 MW (Nameplate)	420 MW	450 MW	450 MW	390 MW
Operating Restrictions	None – MHPS Intent Was to Follow Heat Balance Diagrams.	118 psig Limit on IP Exhaust	126 psig Limit on IP Exhaust	119 psig Limit on IP Exhaust	111 psig Limit on IP Exhaust
Blade Overspeed Condition	Overspeed Testing in MFG		Overspeed Tested in Japan	No Overspeed Testing	No Overspeed Testing
Avoidance Zone Exceedance	2,466 hrs. (of 21,734 hrs.)	1 hr. (of 21,284 hrs.)	240 hrs. (of 10,286 hrs.)	1.15 hrs. (of 2,942 hrs.)	0 hrs. (of 1,561 hrs.)
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-Locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE *Z-Lock and airfoils	0 TE / 8 GE
Worn Z-Locks	Moderate Amount of Surface Fretting and Galling Observed	Moderate Amount of Surface Fretting and Galling Observed	High Degree of Wear Observed	Evidence of Poor Contact Alignment Observed	High Degree of Wear (for Hours Run) Observed
Key Notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) and to continue the warranty. MHPSA was storing for Tenaska (purchased grey market, stored by OEM). ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mpph LP exhaust flow).	Not a forced outage. Outage planned to upgrade to "heavy duty" blades. Some blade damage (e.g. chipping at contact corners) was observed from removed service blades. Blade telemetry instrumentation installed and testing conducted in Dec 2014 at the beginning of Period 3.	During blade telemetry testing, the unit was intentionally run in avoidance zone to set limits – unit ran in zone for <20 hrs. No blade cracking observed after testing (when the test instrumentation removed).	Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil. Stellite hard facing had been added to the blade Z-Lock, and is likely a contributing factor in the failure. Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection.	Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events. Jan 2017 "loss of mass" event – blade fragment projectile traveled through the LP turbine rupture disk diaphragm. Dental mold impression of failure surfaces indicate ~10^7 striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber).
Information Shared with MHPS	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.

Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			*Citrus L-0*
	Type 1	Type 3 (v1)	Type 3 (v2)	*Type 5*
Length	40"	40"	40"	*40"*
Count	64	64	64	*64*
Turb/Gen End	Yes	Yes	Yes	*Yes*
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	*Different Radial Height Relative to Bartow L-0 (About 1")*
Z-Lock	No HVOF	No HVOF	45° Corner with HVOF Applied	*No HVOF*
Blade design	Orig.	Orig.	Orig.	*Attack Angle Change*
Experience	3 units (2003)	12 units (2001)	1 unit, ~5 months	*In commissioning (~1yr)*
Material	17-4 ph	17-4 ph	17-4 ph	*17-4 ph*

Commented [MB3]: You mentioned Type 5 above. Is the redesign blade for Bartow different than Citrus? Sounded like MHPS was "designing" something new for Bartow. If it's the citrus blade then there should have been no slide on the changes being made (in the mHPS root cause). Maybe this isn't a type 5, but the "latest Gen 40" blade??

Appendix C: Reference Materials

Mitsubishi RCA report – 9/22/2017

MHPS's evaluation is based on the data captured between Period 2 and 3 during blade telemetry testing. MHPS's evaluation is extensive and has allowed us to identify and evaluate contributing factors. MHPS's intent was to draw conclusions based on actual data collected. The telemetry testing window was short not all operating conditions were witnessed during the testing (steady state and transient events); because of this the conclusions from this report may not be all encompassing of the drivers and conditions that are causing the blade failures.

Bartow RCA
Customer 9-22-17.pd

Executive Summary

Duke Energy (Duke) and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 18 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation.

Duke's position is as follows: The root cause of the Bartow steam turbine (ST) 40" L-0 blade failures during Period 1-5 is driven by evidence that the OEM designed last stage blades had little or no design margins for the actual operating conditions that exist for the overall Bartow 4 x 1 Combined Cycle Unit.

Duke Engineering believes the blade failures during Periods 1-5 involve more than one driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS also indicated that there may have been more contributing factors for various Periods of failure rather than just excessive steam flow through the LP section above the MHPS design limit of 15,000 lb./hr./ft.^{2}. Excessive steam flow, or "operation in the avoidance zone", had been previously communicated by MHPS as the sole root cause back during a presentation made at Bartow Station on 15 March 2017. MPHS has since changed its position and today there is agreement between both parties that there is not just one failure mechanism.

After months of study (and with input from MHPS) Duke Engineering believes the following to be the most significant contributing factors toward blade failure over the history of Bartow Unit 4S L-0 events:

- Low Pressure (LP) Turbine Excessive Steam Flow
- Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening – Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

Duke believes that the contributing factors presented in this paper – or during MHPS presentations – are postulations and may possibly be correct. Most of the MHPS postulations are derived from strain gauge data taken during the brief period of time that the telemetry test conducted during December 2014. That blade response data was then extrapolated by MHPS Engineering to develop potential root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil itself that were seen during Periods 1-5.

The long-term solution for the Bartow LP section is to replace the L-0 blades or to retrofit the LP steam path with a more capable/reliable design. With either scenario, blade telemetry instrumentation and blade vibration monitoring will be necessary to conclusively determine and eliminate the magnitude and impact of the identified contributing factors during various operating configurations that are integral to unrestricted 4 x 1 combined cycle operation.

This technical paper will speak briefly of the history of L-0 blade events for Bartow Unit 4S and then discuss in detail how each event was (or was not) affected by the contributing factors listed above. Any conclusions derived from Duke's efforts that are discussed in this document are based on the team's best ability to correlate data with events in operation and findings with L-0 blade inspections/failures.

Historical Perspective

Bartow is a 4x1 Combined Cycle (CC) Station with a Steam Turbine (ST) manufactured by MHPS. The ST was purchased on the "grey market" from Tenaska Power Equipment, LLC (Tenaska). Tenaska originally purchased the ST to operate in a 3x1 CC with a gross output of 420MW. The ST was never delivered and was stored in a MHPS warehouse in Japan until Duke purchased the unit.

Prior to the Bartow commissioning, MHPS was contracted by Duke to evaluate the ST design conditions and update heat balances to represent a 4x1 CC configuration.

Since commissioning there have been five (5) events triggered by L-0 blade failures (see Appendix A for event details). The types of failures include mid-span snubber failures, shroud Z-Lock failures, and airfoil tip failures. Over the course of these events, MHPS has performed several design enhancements to the 40" ST L-0 blade in efforts to address the failures (see Appendix B for L-0 modifications). To date, the modifications have not resulted in improved reliability or performance of the L-0 blades in service at Bartow. The number of blade failures and problems with ST L-0 blade performance is not typical – i.e. these issues are outliers among the Duke CC fleet, as well as in the MHPS 40" L-0 fleet. The most common reported issue from the MHPS 40" L-0 blade design is water erosion, which both Duke and MHPS agree is not a contributing factor for the Bartow failures. Presently, the ST is operating without L-0 rotating/stationary hardware and with an MHPS designed and fabricated pressure plate.

Root Cause Contributing Factors

Low Pressure (LP) Turbine Excessive Steam Flow

Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data evaluation – learned (and made it known to Duke) that a significant contributing factor toward the L-0 blade failures was high back-end loading on the LP turbine last stage blades. Back-end loading is a function affected by steam flow and operating pressure through a turbine section. MHPS Engineering indicated that Bartow Unit 4S was an outlier relative to the MHPS 40" L-0 fleet with several operating hours above the design limit of 15,000 lb./hr./ft.^{2} (the MHPS 40" L-0 fleet average was closer to 12,000 lb./hr./ft.^{2}). Duke was issued an "avoidance zone" chart with instructions from MHPS not to run to the right side of the curve – the lone exception being "brief" operation during transient conditions.

While Duke Engineering agreed that back-end loading should be considered a significant contributing factor, one cannot definitively conclude that it has been the failure driving mechanism of all five (5) of the documented L-0 events. As Appendix A illustrates, Periods 2, 4 and 5 saw operating hours in the "avoidance zone" of 1 hour, 1.15 hours and 0 hours, respectively. This indicates that back-end loading was not the cause of any of the reported blade indications/failures during those periods of operation.

By a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the "avoidance zone" relative to total operating hours – 2,466 out of 21,734 total hours. However, blade damage was relegated to five (5) broken mid-span snubbers on the turbine end of the machine and a minimal degree of fretting on the shroud Z-Lock contact surfaces for both turbine and generator ends of the machine.

Conversely, during Period 3, there were only 240 hours (out of 10,286 total hours) of operation in the "avoidance zone", approx. 11 hours of which occurred during the instrumented blade telemetry test performed by MHPS in December 2014. Even with a significantly fewer number of "avoidance zone" hours for Period 3 relative to Period 1 – a factor of 10 fewer hours for Period 3 – there was significantly greater amounts of blade damage and fretting on both ends of the machine. While the amount of Z-Lock wear is not quantified for Periods 1 and 3, photographic evidence suggests that the amount of wear is much greater for Period 3, as shown below in Figure 1. It is therefore difficult to conclude that damage to the L-0 blades in Period 3 is solely due to unit operation above the exhaust flow limit.

Figure 1 -- Comparative Photos of Shroud Contact Surface Wear for Periods 1 and 3

Sample Shroud Contact Surface Photos from Period 1

Sample Shroud Contact Surface Photos from Period 3

With the L-0s currently removed from the machine and with the pressure plate installed, MHPS Engineering has indicated that back-end loading is not currently an issue of concern at the current LP inlet operating limits. MHPS Engineering does not have enough technical data to support releasing Duke to operate the machine beyond the current LP inlet operating limits due to concerns for impacts to upstream blading – i.e. the L-1 blade sets.

Blending Operations – Thermal Distress (dT_{SH}/dt) at LP Turbine Exhaust

During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to include all aspects that might impact exhaust conditions of the LP. Since the design of the condenser includes spargers, or "dump tubes", for the hot reheat (HRH) and LP bypass steam flows from each of the four (4) combustion turbines (CT), and since it has been observed that thermocouples positioned at the exhaust of the LP turbine just downstream of the L-0 blades (hood spray thermocouples) can experience a significant change in temperature during a blend operation, it was decided by the Duke team to review this operational aspect.

A set of criteria and an automated process using Excel and PI Datalink were developed that allow large amounts of data (stored in the PI historian) to be quickly reviewed for each Period 1-5. Blends that met the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. This process involved extracting PI data, calculating a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values, or "counts". "Counts" are defined as the number of measureable blends where there was a slope change (+/-) in greater than (20 degrees superheat / min) at the hood spray thermocouples. The data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW. The limits of 20 degrees F (superheat) and 50 MW were selected as these are good indications that the blend steam had either higher, or lower, enthalpy than intended for the design of the sparging system. While this measure does not necessarily indicate the overall severity of any loadings that might be imposed upon the L-0 blades, it does allow for a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify specific points/periods in time to look at additional blend parameters.

Table 1 -- Quick Comparison of the Number of "Counts" that Meet the Criteria for Periods 1-5.

	Number of Operating Hours in Each Period	Number of Blends (or "Counts") Meeting Criteria
Period 1	21,734	13
Period 2	21,284	7
Period 3	10,286	37*
Period 4	2,942	3
Period 5	1,561	5

*Includes 6 blends that meet the criteria during strain gauge testing in December 2014

Until a long term solution other than the pressure plate is installed into the machine and the turbine is appropriately equipped with strain gauge and blade vibration monitoring hardware, Duke will not fully understand the total impact of this thermal energy on the blades. Duke Engineering believes that the brief telemetry testing period conducted in December 2014 does not – by itself – provide conclusive enough evidence to support (or refute) this contributing factor of thermal distress, as not all blend conditions and configurations were exercised during the testing period

Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke RCA team also reviewed hood spray operations because of the very close proximity of the sprays to the L-0 blades and the function they provide to protect against overpressure. Hood spray operation is programmed into the Ovation DCS control system and is basically automated with no operator interaction required. The water source is the output from the condensate pumps. A control valve reduces the roughly 500 psig condensate pressure to the design pressure for the sprays of 50 psig.

A review of the OEM-provided instructions requires use of hood sprays during the following conditions:

- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

During a review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found to date. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended per the OEM-provided instructions. A review of hood spray thermocouple data shows they rarely reach 160 degrees F during normal operation and never reach over 165 degrees F. Higher temperatures are sometimes seen after a shutdown or unit trip event when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 degrees F were found (one very brief reading of 1040 degrees F was determined to be an instrumentation issue).

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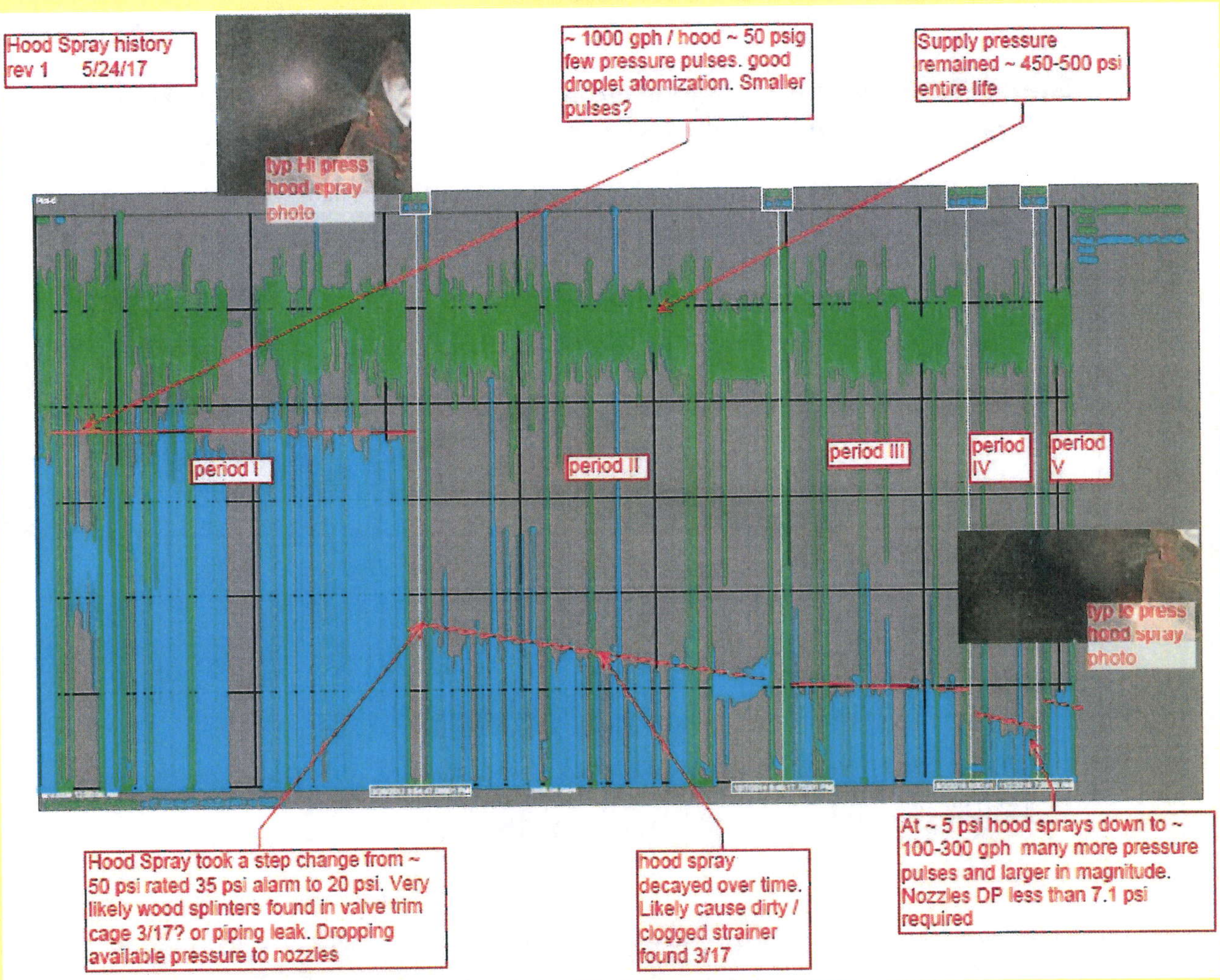

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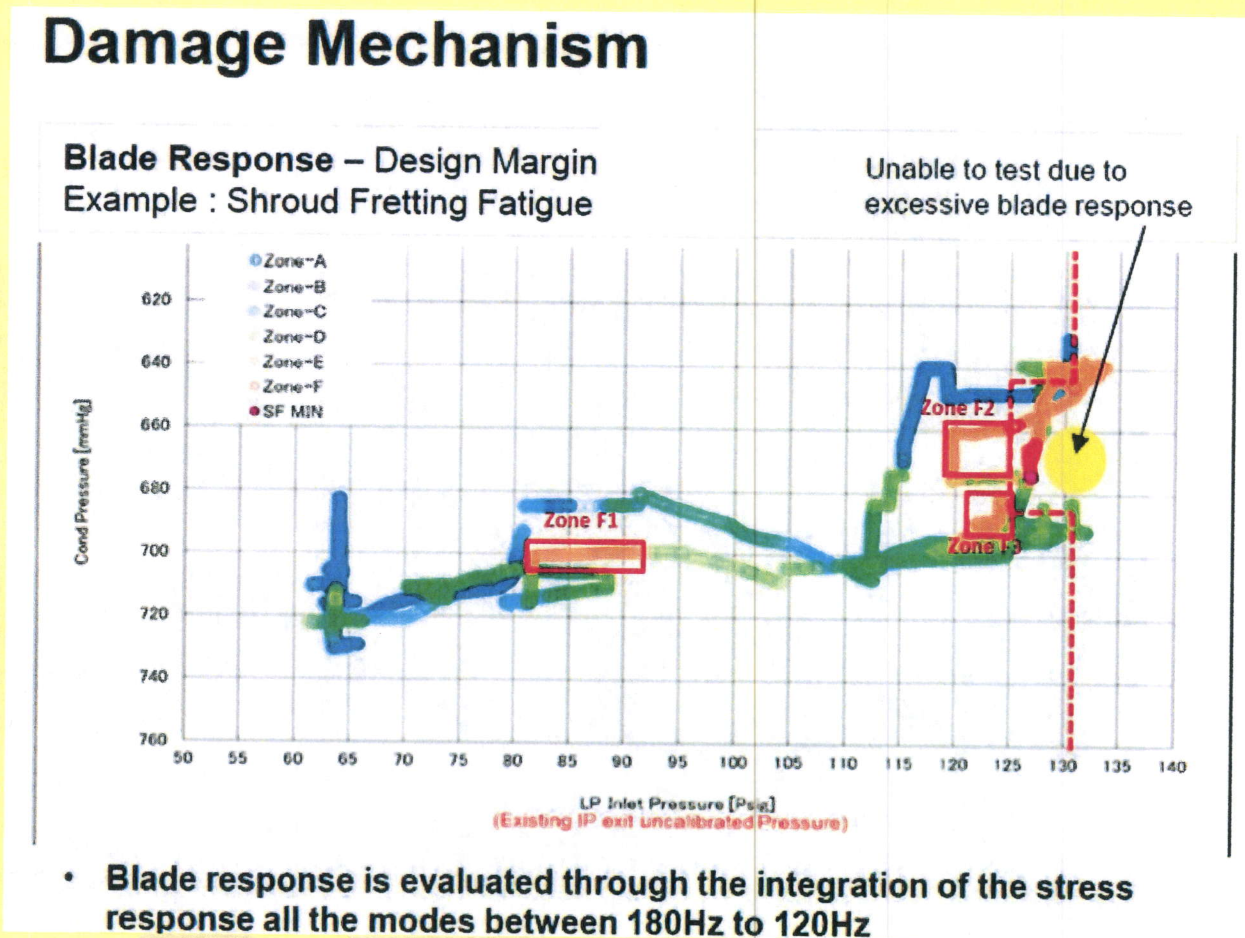

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Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

During the course of the RCA investigation between Periods 3 and 4, technical questions arose relative to "as left" blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. The basis for these questions was the potential concern that if the blade gaps at both the mid-span snubber interface and the shroud Z-Lock weren't both taken into consideration together, then as the blades began to "untwist" as the machine came up in temperature and load, adjacent mid-span snubbers would achieve greater surface-to-surface contact (especially with the HVOF coating applied) before the shroud Z-Lock contact surfaces could do the same. Consequently, reduced contact surface at the shroud Z-Lock would yield reduced mechanical damping, which is a function of both contact surface area and vibratory stresses (e.g. flutter).

Per the OEM, the Type 3 L-0 blades were used to establish a baseline blade response from the telemetry and strain gauge testing that was conducted in December 2014 at the beginning of Period 3. The intent of the blade response analysis was to capture "worst case" geometry variations. The OEM concluded that the dimensional tolerance between the Type 3 blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 (Periods 3 and 4) blade shows greater distortion than the Type 1 blade (Periods 1, 2 and 5). These findings by the OEM are consistent with independent analysis of the blades by Duke via 3rd party scanning. With a greater geometry variation, the Type 3 blade provided less mechanical damping (relative to the Type 1 blade) because of the smaller contact area – a result of greater contact misalignment.

While the OEM contends that geometry variation on the Type 3 blade are not significant enough to negatively impact blade stress/response, the OEM has acknowledged blade fitment/geometry is important enough to consider in their ongoing R&D relative to a Type 5 blade redesign. The planned design changes are intended to reduce blade response and dynamic stresses that in the past were negatively impacted by decreased contact surface area between the shroud Z-Locks.

Appendix A: Bartow L-0 Event Summary

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	2009-2012	2012-2014	2014-2016	May 2016 to Oct 2016	Dec 2016 - Feb 2017
Service Duration	~34 Months	~28 Months	~17 Months	~5 Months	~2 Months
L-0 Blade Configuration	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	420 MW (Nameplate)	420 MW	450 MW	450 MW	390 MW
Operating Restrictions	None – MHPS Intent Was to Follow Heat Balance Diagrams.	118 psig Limit on IP Exhaust	126 psig Limit on IP Exhaust	119 psig Limit on IP Exhaust	111 psig Limit on IP Exhaust
Blade Overspeed Condition	Overspeed Testing in MFG		Overspeed Tested in Japan	No Overspeed Testing	No Overspeed Testing
Avoidance Zone Exceedance	2,466 hrs. (of 21,734 hrs.)	1 hr. (of 21,284 hrs.)	240 hrs. (of 10,286 hrs.)	1.15 hrs. (of 2,942 hrs.)	0 hrs. (of 1,561 hrs.)
Broken Snubbers	5 TE / 0 GE	0 TE / 0 GE	0 TE / 0 GE	0 TE / 1 GE	0 TE / 13 GE
Broken Z-Locks	0 TE / 0 GE	0 TE / 0 GE	34 TE / 5 GE	1 TE / 2 GE *Z-Lock and airfoils	0 TE / 8 GE
Worn Z-Locks	Moderate Amount of Surface Fretting and Galling Observed	Moderate Amount of Surface Fretting and Galling Observed	High Degree of Wear Observed	Evidence of Poor Contact Alignment Observed	High Degree of Wear (for Hours Run) Observed
Key Notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) and to continue the warranty. MHPSA was storing for Tenaska (purchased grey market, stored by OEM). ST drawing modified by MHPSA and approved for 4x1 operation at 420 MW output rating (2.38 mpph LP exhaust flow).	Not a forced outage – Outage planned to upgrade to "heavy duty" blades. Some blade damage (e.g. chipping at contact corners) was observed from removed service blades. Blade telemetry instrumentation installed and testing conducted in Dec 2014 at the beginning of Period 3.	During blade telemetry testing, the unit was intentionally run in avoidance zone to set limits – unit ran in zone for <20 hrs. No blade cracking observed after testing (when the test instrumentation removed).	Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil. Stellite hard facing had been added to the blade Z-Lock, and is likely a contributing factor in the failure. Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection.	Duke Discovery: Jan/Feb 2017, first time blending considered to be a contributing factor in L-0 events. Jan 2017 "loss of mass" event – blade fragment projectile traveled through the LP turbine rupture disk diaphragm. Dental mold impression of failure surfaces indicate ~10^7 striations meaning high cycle fatigue (at 200 Hz giving over 2M cycles in 3+ hrs to fail snubber).
Information Shared with MHPS	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.	MHPS provided all PI data they requested.

Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			***Citrus L-0***
	Type 1	Type 3 (v1)	Type 3 (v2)	*Type 5*
Length	40"	40"	40"	*40"*
Count	64	64	64	*64*
Turb/Gen End	Yes	Yes	Yes	*Yes*
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	*Different Radial Height Relative to Bartow L-0 (About 1")*
Z-Lock	No HVOF	No HVOF	45° Corner with HVOF Applied	*No HVOF*
Blade design	Original	Original	Original	*Attack Angle Change*
Material	17-4 ph	17-4 ph	17-4 ph	*17-4 ph*

Appendix C: Empirical Data Supporting Root Cause

Empirical Support for Root Cause

Period	Operating Hours	Excessive Steam Flow: Driving Mechanism Present	Avoidance Zone Exceedance Hours	Exceedance Hours / (1k Operating Hours)	Normalized Ranking
1	21,734	X	2,466	0.11	1.00
2	21,284		1	0.00	0.00
3	10,286	X	240	0.02	0.21
4*	2,942		1	0.00	0.00
5	1,561		0	0.00	0.00

Period	Operating Hours	Thermal Distress (dT_{SH}/dt): Driving Mechanism Present	Counts (ΔT > 20 deg_ F_{SH} / Minute)	Counts / (1k Operating Hours)	Normalized Ranking
1	21,734	X	13	0.60	0.17
2	21,284	X	7	0.33	0.09
3	10,286	X	37	3.60	1.00
4*	2,942	X	3	1.02	0.28
5	1,561	X	5	3.20	0.89

Period	Operating Hours	Pressure Pulses: Driving Mechanism Present	Avg. Hood Spray Pressure (psig)	Hours of Hood Spray Operation	% of Total Operating Hours	Normalized Ranking
1	21,734	X	35.2	5,098	23	0.68
2	21,284	X	13.2	7,343	34	1.00
3	10,286	X	10.4	440	4	0.12
4*	2,942	X	5.5	174	6	0.17
5	1,561	X	8.7	93	6	0.17

Period	Operating Hours	Loss of Dampening: Driving Mechanism Present
1	21,734	N/A
2	21,284	N/A
3	10,286	N/A**
4*	2,942	X
5	1,561	N/A

Period 1	Jun 2009 to Mar 2012
Period 2	Apr 2012 to Aug 2014
Period 3	Dec 2014 to Apr 2016
Period 4	Jun 2016 to Oct 2016
Period 5	Dec 2016 to Feb 2017

General Notes

*** For Period 4, the first L-0 blade tip was lost on 7/6/16 at about 10:50AM -- BEFORE 1st thermal event on 7/16/16 and BEFORE operation above "avoidance zone" limit on 08/01 - 9/25/16 (55 min total).**

"Excessive Steam Flow" Notes

"Avoidance Zone Exceedance Hours" -- Measured number of operating hours in exceedance of 15,000 lb/hr-ft^2 limit as indicated by the IP exhaust pressure

"Exceedance Hours / (1k Operating Hours)" -- Number of exceedance hours per 1000 hours of operation in a given period

"Normalized Ranking" -- Data normalized against the highest value in Column F

"Thermal Distress (dT_{SH}/dt)" Notes

"Counts (DT > 20 deg_ FSH / Minute)" -- "Counts" are defined as the number of measurable blends where there was a slope change (+/-) greater than (20 degrees superheat / min) at the hood spray thermocouples -- Data was flagged only when a CT was being blended into (or out of) the steam cycle AND the ST output was greater than 50 MW

"Counts / (1k Operating Hours)" -- Number of "counts" per 1000 hours of operation in a given period

"Normalized Ranking" -- Data normalized against the highest value in Column F

"Pressure Pulses" Notes

"Avg. Hood Spray Pressure (psig)" -- Calculated from PI Historian data (??? -- Verify)

"Hours of Hood Spray Operation" -- "Hours of Hood Spray Operation" is a weighted value -- There is a 1.00 multiplier at 50 psig varying linearly to a 1.75 multiplier at 5 psig

"% of Total Operating Hours" -- The "weighted" hours of hood spray operation divided by the total number of operating hours -- converted to a percentage value

"Normalized Ranking" -- Data normalized against the highest percentage value in Column G

"Loss of Dampening" Notes

** For Period 3, there was hard-facing on the Mid-span Snubber ONLY -- Additional damage seen on the shroud Z-Lock contact surfaces (relative to other Periods) was likely due to loss of dampening at the snubbers, which were HVOF-coated -- The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion

Appendix D: Reference Materials

Mitsubishi RCA Presentation(s) – 22 September 2017 and 02 October 2017

MHPS's evaluation is based on the data captured between Period 2 and 3 during blade telemetry testing. MHPS's evaluation is extensive and has allowed us to identify and evaluate contributing factors. MHPS's intent was to draw conclusions based on actual data collected. The telemetry testing window was short, and not all operating conditions were witnessed during the testing (steady state and transient events). Because of this the conclusions from this report may not be all encompassing of the drivers and conditions that are causing the blade failures.

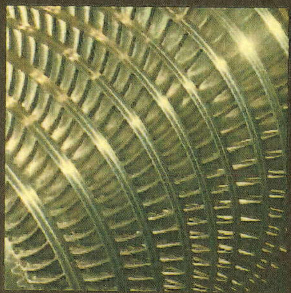
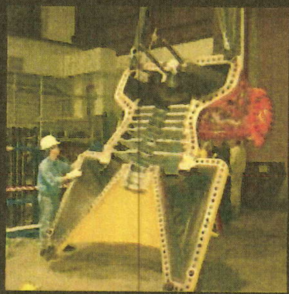
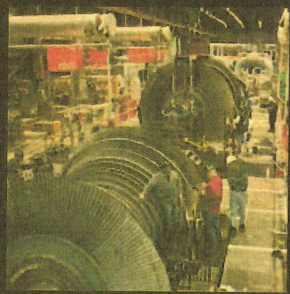
Bartow RCA
Customer 9-22-17.pd

Bartow RCA
Customer 10-2-17.pd

MITSUBISHI POWER SYSTEMS AMERICAS

Bartow Discussion

August 21st 2012

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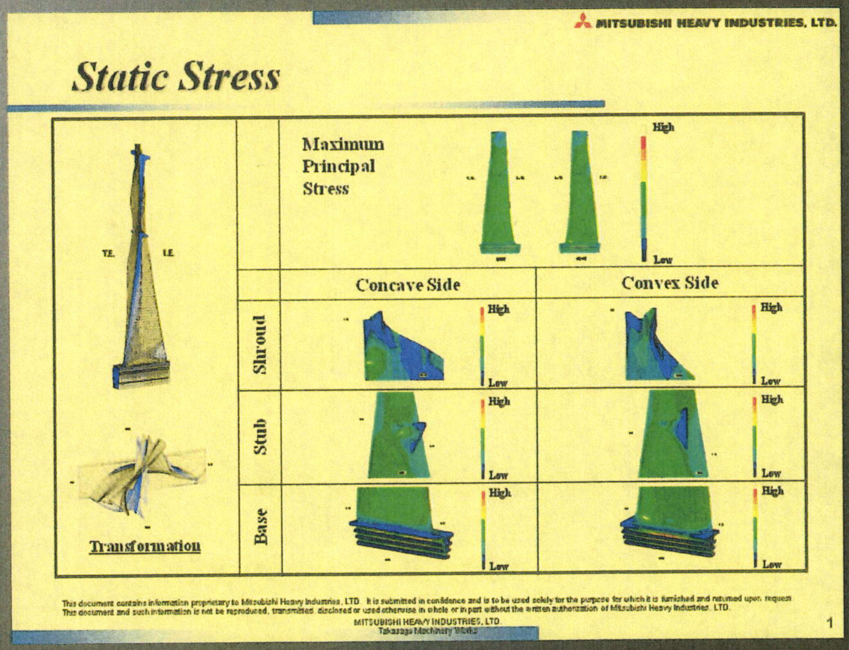
Progress Energy Questions

1. *What color is yield strength of the static plot of blade stress contours red or yellow?*

The yield stress was shown in orange. Although the local stress on the blade root exceeds the yield stress this is not problem because it is 80% of the allowable stress (as discussed with Harry Carbone in the meeting). Note that the stub does not exceed the yield stress.



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PROGRESS ENERGY QUESTIONS

2. *Do you have the normalized stresses for dynamic nominal motion of the blade for mode 1, mode 2, and mode 3?*

Request made to MHI. Expect to have by mid September.

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PROGRESS ENERGY QUESTIONS

3. *Do you have the nodal diameter tuning IE some refer to it as interference diagram?*

See next page.

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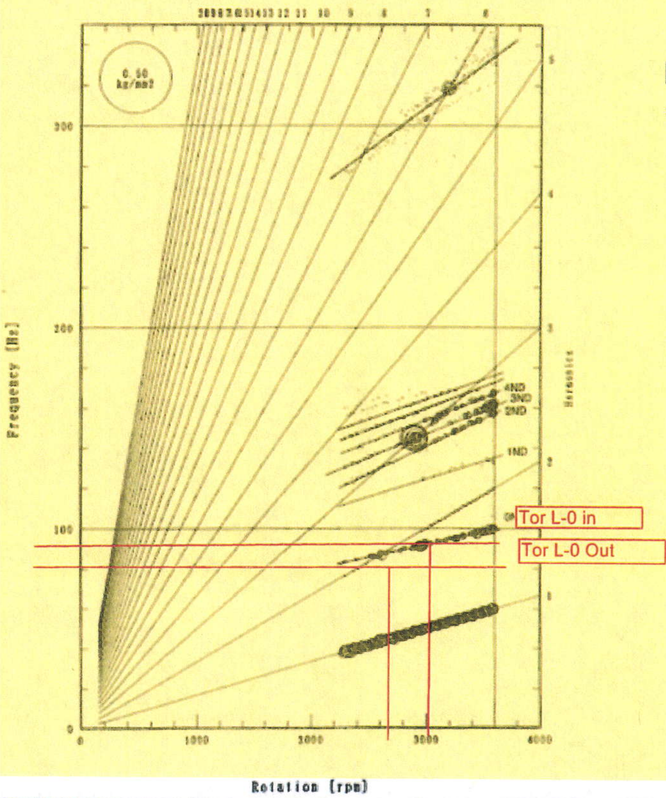
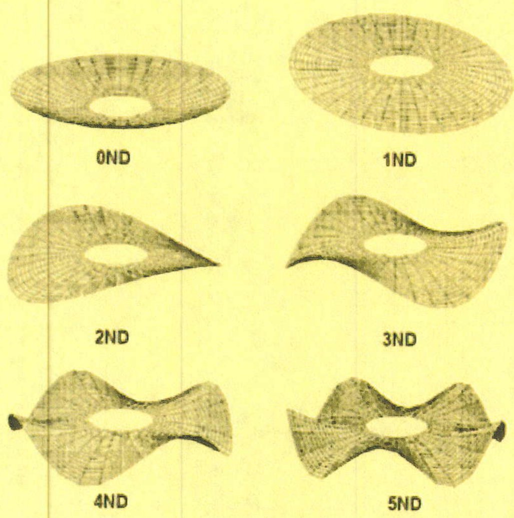
Nodal Diameter



ND (Nodal Diameter) = Harmonics
⇒ Resonance



Progress Energy Questions

4. *What f1, f2, f3 stresses or motion did you get from test data in test unit or 1 instrumented unit at 15,000 lbs/hr/ft2 rating?*

Request made to MHI. Expect to have by mid September.

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PROGRESS ENERGY QUESTIONS

5. *Did you do a cfd/fea interactive model at 15,000 lbs/hr/ft2 rating? Did the motions compare to measured in 4.?*

Request made to MHI. Expect to have by mid September.

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PROGRESS ENERGY QUESTIONS

6. *If you did this type model again at a run with 15,000/2.5*2.7= 16,200 lbs/hr/ft2 what is the predicted motion and stresses? In particular what is compressive and shear stress at damper?*

Comparison by FEM has not been done. In general, the following will be affected by loading increase: If the flow is stable, the vibration stress increases linearly with loading. Based on the operational data we have it is assumed that the flow is stable.

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PROGRESS ENERGY QUESTIONS

7. *What are the torsional mode shapes and tuning especially those that show large energy on the l-0 blading? Is there a mode shape that shows more energy at TE vs. GE on a torsional with the L-0 participation?*

See next page.

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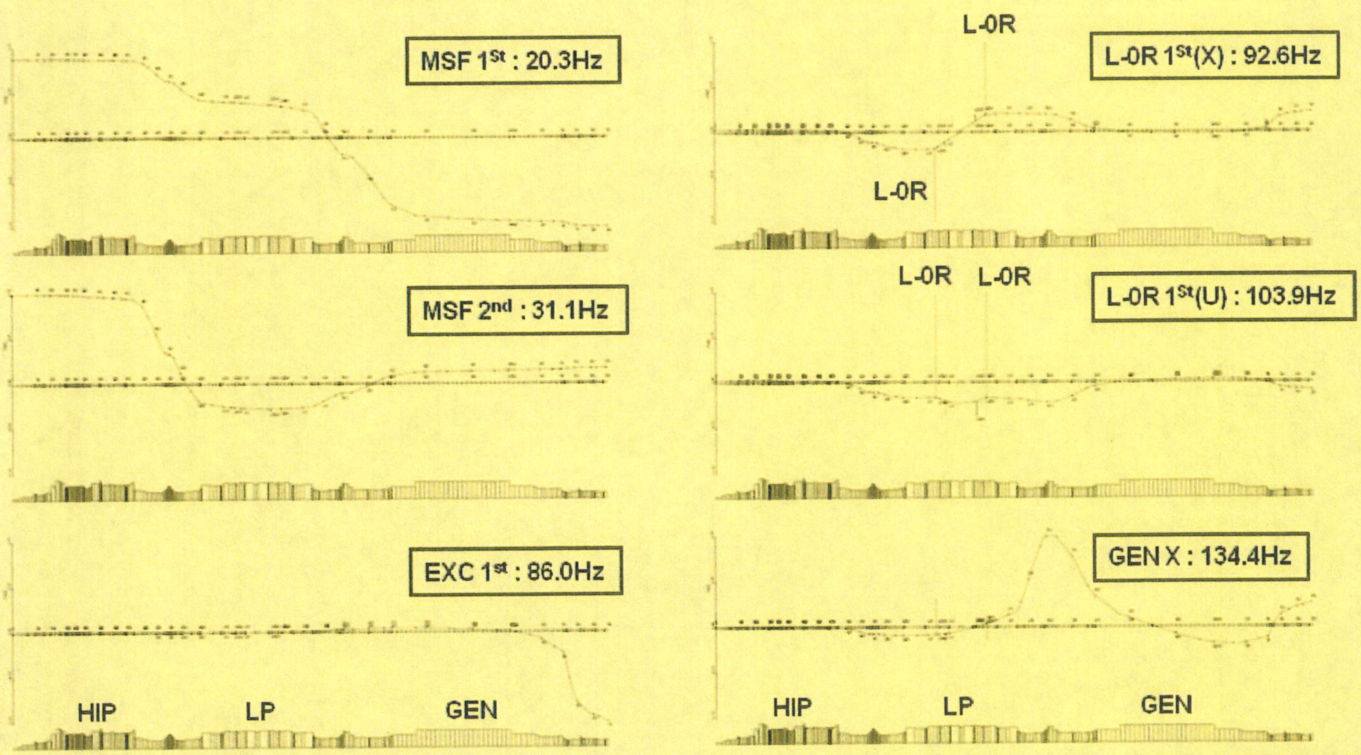
Torsional Mode Shapes



PROGRESS ENERGY QUESTIONS

8. *Could MHI model the blade stresses with mid span snubbers fractured short term operations?*

We cannot explain this occurrence with the analyses done so far. If several issues occur at the same time, such as mis-operation (low vacuum operation, short circuit, etc.), partial contact of stub, there could be a possible fracture.

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PROGRESS ENERGY QUESTIONS

9. *Has MHI considered any surface treatment such as shot peening or surface hardening to minimizing fretting fatigue?*

No surface treatment is applied to the L-0R stub because it is designed to have low contact stress and prevent fretting fatigue.

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PROGRESS ENERGY QUESTIONS

10. *MHI provide a Pressure vs. Temperature rating for the STG. Without a document that provides information on what they intend on the operating limits of the STG we will never know exactly how to operate the machine. Seems like it should be an X-Y plot or some other graph that would allow us to program the DCS to protect the machine.*

Please refer to Heat Balance for pressure vs temperature rating. For the operation limitation, please control the GT output as necessary so that LP inlet pressure (4S-PT-44304) will become less than 136 psig (Heat Balance Case 150). We cannot share the detailed setting points (X-Y plots) because we don't have the GT control logic.

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Progress Energy Questions

11. *At what RPM do midspan snubber and shroud come into contact.*

Shroud comes into contact at 1200-1500 rpm and the stub comes into contact 1200-2000rpm. We are also certain based on Rotating Vibration Test that shroud and stub come into contact by 1700 rpm.

12. *Further discussions to support their own investigation and possible means of increasing unit output.*

We will continue technical support for you. As of now it is difficult for us to propose a concrete method to increase the unit output. An engineering study is suggested.

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PROGRESS ENERGY QUESTIONS

- Other Questions

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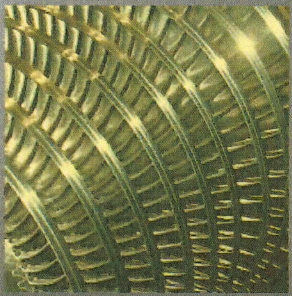
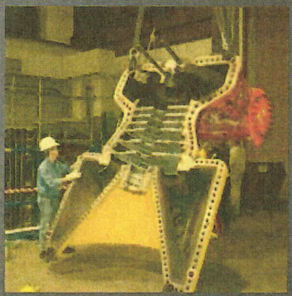
Part 2 Bartow Discussion

August 21st 2012





MITSUBISHI POWER SYSTEMS

L-0 BLADE PROPOSAL

Line	Item	Rev	Qty	Price/ea	Line Total	LT / Weeks	UM
0001	TQ-B1843-01 **Description** BLADE TS-4381E2FM L-0R 40.0IN ISB RH Customer Item:		64	$23,515.63	$1,505,000.00	77	EA
0002	TQ-B1843-05 **Description** BLADE TS-4382E2FM L-0R 40.0IN ISB LH Customer Item:		64	$23,515.63	$1,505,000.00	77	EA

Item Qty: 2

Item Total: $3,010,000.00

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PREVIOUS L-0 PROPOSAL WITH INSTALL

Hardware and Service Pricing

ST Unit	Workscope/Description	Duration	Shift	Price
Bartow ST	(1) Row LH L-0 Blades with locking hardware *	--	--	$1,530,000
Bartow ST	Field Service ST Open/Close	13 Days	2-12-7	$916,662
Bartow ST	Re-blading of Steam Turbine	5 Days	2-12-7	$237,089
Bartow ST	Subassembly work (2MSV, 2 CV, 2 ICV in shop)	16 Days	1-8-5	$88,364
Bartow ST	Standby time	2 Days / 4 Shifts		$21,007
			Total Price:	$2,793,122
			Total Price With Discount ** ($165,000):	$2,658,122

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NOTES AND ASSUMPTIONS

Additional Notes & Assumptions:

- *Includes transportation to customer site, does not include consumables for open/close
- ** A $165,000 discount will apply if all if all the services are performed by MSPSA
- Excluding taxes, additional fees, or country withholdings
- MPSA to provide power rollers
- Subassembly price is not standalone and must be purchased with other services. Transportation is not included.

MITSUBISHI POWER SYSTEMS

ENGINEERING STUDY PROPOSAL

MITSUBISHI POWER SYSTEMS

Customer Proposal

July 26, 2012

Progress Energy

Bartow Steam Turbine Engineering Study

MPSA-QTO-12557

MITSUBISHI POWER SYSTEMS

ENGINEERNIG STUDY PROPOSAL

Subject: Proposal for ST Engineering Study for the Progress Energy Bartow Unit (MPSA-QTO-12557)

Dear Mr. Mattina,

Mitsubishi Power Systems Americas (MPSA) is pleased to provide the above reference quotation to support a 2012 engineering evaluation on your Bartow unit for identification of limitations, possible upgrades, or enhancements. As the OEM, Mitsubishi Power System's steam turbine experience includes all of the expertise and technologies needed to provide optimized solutions for your unit. Costs incurred from this engineering study can be applied towards a future MPSA rotor upgrade at Bartow.

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SCOPE

Scope of Work

MPSA's Engineering Study Includes:

- Identification of operational limits/areas of improvement in the HP, IP, and LP turbines at Progress Energy's specified conditions
- Identification of modifications (such as material or design change) which will improve performance margins to allow Progress Energy to operate at its specified conditions
- Review of operating limits and recommended alarms/trips if needed
- Generate engineering report
- Recommended optimization of turbine steam cycle for maximum reliable output

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Additional Notes & Assumptions

- Study is limited to optimizing steam path and steam flows to achieve maximum reliable turbine output
- Study assumes maximum of four (4) heat balance evaluations
- Study assumes Progress Energy has access to site combined cycle models
- Progress Energy will work jointly with MPSA to optimize steam cycle with turbine-related scope items being MPSA's responsibility and combined cycle scope items being Progress Energy's responsibility
- Study does not address redesign or modification of last stage blades
- Study deliverables will include recommended steam path and steam flow changes to maximize turbine output
- Evaluation of the HRSG is beyond the scope of this study
- MPSA assumes Progress Energy will supply combined cycle models prior to the start of work.
- Study will include results showing margins and suggested changes

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PRICING

Engineering Service Price

ST Unit	Workscope Description	Price
MHI T26	Engineering Study for Additional Optimization & Reliability	$232,025

Total Price: $232,025.00

(Excluding taxes)

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DEF20190001BARTOW LFE4-000146

CONFIDENTIAL

THANK YOU

MITSUBISHI POWER SYSTEMS

From: Mazurek, James
To: Carbone, Harry M.
Cc: Porteous, Nicholas; Toms, C Wayne; English, Jacob; Huls, John N; Warren, David E; Holland, Christopher S
Subject: RE: Requested Meeting Documents
Date: Tuesday, December 6, 2016 10:13:50 AM
Attachments: image001.png
image002.gif
image003.gif
Bartow RCA Report Out Questions 11-18-16 Slide 6 Rev1.pdf

Harry,

My apologies. Here is the correct slide.

Regards,

Jim

From: Carbone, Harry M. [mailto:Harry.Carbone@duke-energy.com]
Sent: Monday, December 05, 2016 3:34 PM
To: Mazurek, James
Cc: Porteous, Nicholas; Toms, C Wayne; English, Jacob; Huls, John N; Warren, David E; Holland, Christopher S
Subject: RE: Requested Meeting Documents

Jim the slide below you just sent must be in error. The period 4 or IV blades had 3 complete loss of trailing edge z lock lugs. 1 on turbine end and 2 on Gen end. This condition drove replacement of both rows as existed damage caused both rows to be unsuitable for continued service. Total run time on blades was about 2,958 hrs - harry

From: Mazurek, James [mailto:James.Mazurek@mpshq.com]
Sent: Monday, December 05, 2016 11:19 AM
To: Carbone, Harry M.; Toms, C Wayne; English, Jacob
Cc: Porteous, Nicholas
Subject: Requested Meeting Documents

*** Exercise caution. This is an EXTERNAL email. DO NOT open attachments or click links from unknown senders or unexpected email. ***

Gentlemen,

Please find attached the PDFs that are 1) the MHPSA presentation from our 11/9 RCA report out meeting and 2) MHPSA's answers to specific questions that Duke requested answers to in that meeting.

Regards,

Jim Mazurek

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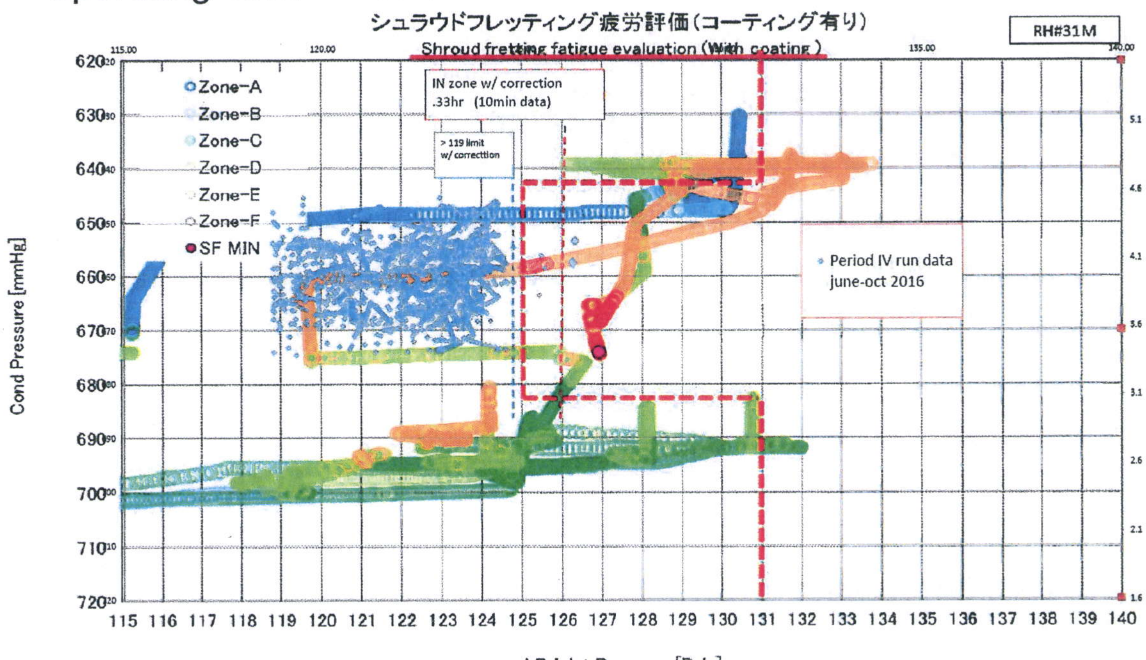
SERVICE SALES MANAGER
Mitsubishi Hitachi Power Systems Americas, Inc.
james.mazurek@mpshq.com
(407) 562-0729 (Office)
(407) 622-9053 (Cell)

Mitsubishi Hitachi Power Systems Americas, Inc.
www.MHPowerSystems.com

1.4) Operating Time 4 : Jun 2016 to Oct 2016



Inspection Results :

Location	Blades	Service	Mid Span Snubber	Shroud	Disposition
Gen End	Type 3 + HVOF++	4 Months	1 Liberation	3 Shroud Liberations	Replace Row
Gov End	Type 3 + HVOF++	4 Months	No significant damage	1 Shroud Liberation	Replace Row

From: Mazurek, James
To: Carbone, Harry M.; Toms, C Wayne; English, Jacob
Cc: Porteous, Nicholas
Subject: Requested Meeting Documents
Date: Monday, December 5, 2016 11:32:02 AM
Attachments: image001.gif
image002.gif
Bartow RCA Final Review 11-9-16 Final R2.pdf
Bartow RCA Report Out Questions 11-18-16.pdf

*** Exercise caution. This is an EXTERNAL email. DO NOT open attachments or click links from unknown senders or unexpected email. ***

Gentlemen,

Please find attached the PDFs that are 1) the MHPSA presentation from our 11/9 RCA report out meeting and 2) MHPSA's answers to specific questions that Duke requested answers to in that meeting.

Regards,

Jim Mazurek

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www.MHPowerSystems.com

DEF20190001BARTOW LFE4-000151

Bartow Steam Turbine

RCA Review

Nov 9th 2016

MITSUBISHI HITACHI POWER SYSTEMS

SL3

Agenda

- Goal of the Meeting

- RCA
  - RCA Action Items
  - Fleet History
  - Blade Metallurgical Evaluation
  - Manufacturing and Assembly Data
  - Telemetry Test Data Review
  - Operation Data Analysis
  - RCA Conclusion

Goal of the Meeting

- Review RCA evaluation of blade damage found in April 2016 and provide root cause of shroud chipping

Note : Blades were Type 3 Blades with mid-span snubber HVOF used in the telemetry test to understand the blade response and operating capability.

RCA Team

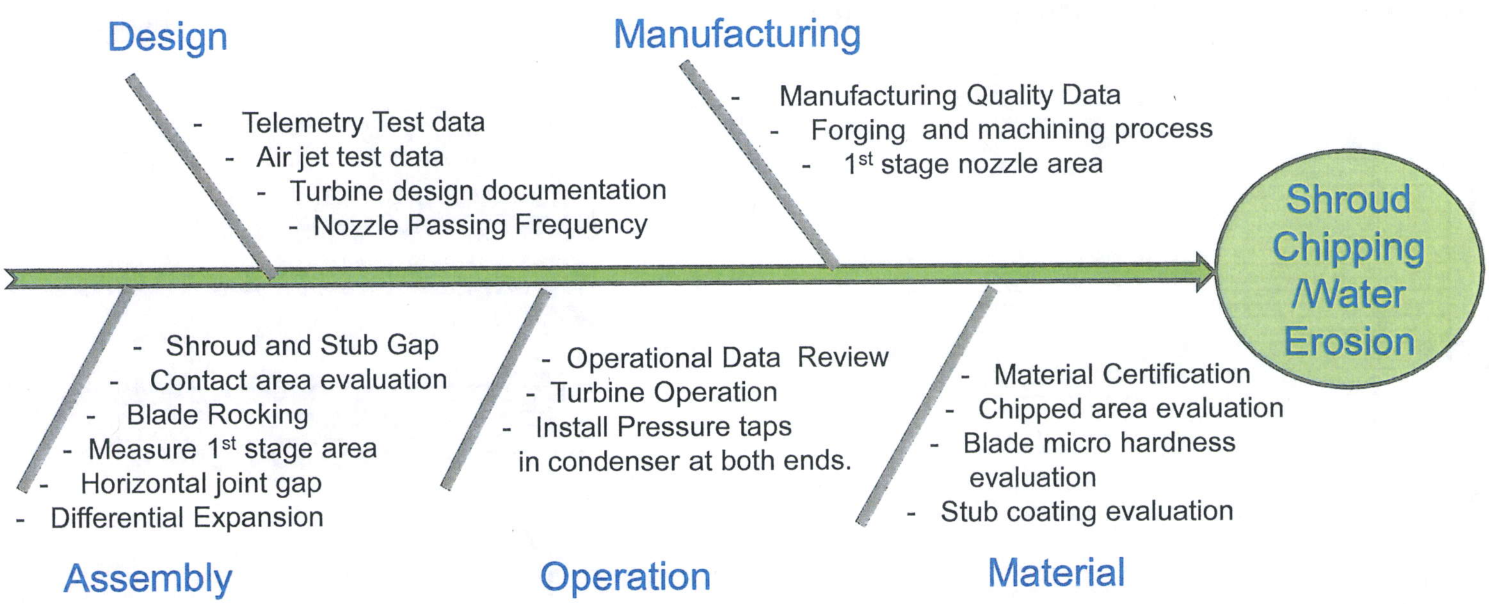
DEF20190001BARTOW LFE4-000154

Muhammad Riaz	RCA Lead	MHPSA
Nick Porteous	MHPSA RCA Sponsor + Technical Contributor	MHPSA
Ikushima-san	MHPSA Communications Lead	MHPSA
Ryan Paulson	Inspection	MHPSA
Ruban Amirtharajah	Operating Data Review	MHPSA
Balaji Jayaraj	Metallurgist	MHPSA
Miyajima-san	Lead Analyst	MHPS
Enomoto-san	MHPS RCA Sponsor	MHPS
Osaki-san	MHPS RCA Lead	MHPS
Jon Hopkins	Blades Scan	MHPSA
Jake English	Duke RCA Lead	Duke
David Brown	Operations specialist	Duke
Chris Holland	Engineering	Duke
John Burney	Engineering	Duke
Additional Resources		
Harry Carbone	Duke Technical Consutant	Duke
John Huls	Duke ST SME	Duke

RCA Team members from Duke Energy, MHPSA USA and MHPS Japan
Multiple working meetings were held to work on the RCA Actions

Blade Shroud Chipping RCA – Fish Bone

DEF20190001BARTOW LFE4-000155



Key Areas of Investigation

SL3

Blade Shroud Chipping RCA

Detailed Actions Tracked (1 of 2)
Reviews conducted with RCA Team

Influence

Influence
Low
Medium
High

		Actions	Conclusions
Design	1	Independent Review of Bartow 2015 Telemetry Test Stress Analysis and Operating Limits Provided	Telemetry Test Data review completed by team in MHPS in Japan.
	2	Confirmation of frequency margins identified in Air Test Data, comparing with original design / other air jet tests	All synchronous vibration frequencies are within design range.
	3	Re-evaluation of the Telemetry Test Data in the light of Bartow Tip Damage	Completed by team in MHPS in Japan.
	4	FEA Review of shroud face movement at high load compared to observed damage	FEA Analysis performed by MHPS in Japan.
	5	Confirm MHPS Mass Flow Calculation Method used in evaluating Telemetry Test Data	Mass flow measurements are no more used as evaluation parameter
	6	Telemetry Test Data Shroud Fretting Calculation sim too Snubber Calculations	Fretting evaluation completed by MHPS in Japan.
	7	Revisit Bartow / Tenaska design torsional margins	Torsional design calculations show acceptable design margins
	8	Research overall exhaust pressure limits for 40" L-0 compared to this unit	Bartow Exhaust pressures limits are standard limits
	9	Review Axial Rotor Position relative to asymmetry from Gen/Gov end	Rotor axial position reviewed and recommended to use as is original design.
Manufacturing	1	Request Forging Material Test Certs for existing installed blades	Material Certs show correct material used and meet design material properties and chemistry.
	2	Request Forging Material Test Certs for replacement blades	Material Certs show correct material used and meet design material properties and chemistry.
	3	Moment Weights for existing installed blades	Row of blades is balanced with acceptable unbalance residual
	4	Request Moment Weights Test Certs for replacement blades	Row of blades is balanced with acceptable unbalance residual
	5	Request Machining Manufacturing Quality Records (Including Box Gap Data + Single Blade Freq Data) New Blades	Data reviewed and blades are with in acceptable criteria
	6	Request Machining Manufacturing Quality Records (Including Box Gap Data + Single Blade Freq Data) Existing Blades	Data reviewed and blades are with in acceptable criteria
	7	Request Record of as Built Area Nozzle Check	Data not located by Japan.
	8	Field Measurements of LP 1st Stage Nozzle Area (Throat / Base Dia / Nozzle Height @ both ends)	1st stage nozzle area is within less than 0.5% on both ends.
Material	1	On site review of fracture surfaces and wear	Review of rotor, blades and casing on site.
	2	Characterize Cracking / Chipping on Tip - Fretting Fatigue?	Metallurigical Evalaution of blades performed in US and Japan included - Visual Inspection - Material Composition -Microscopic evaluation - Hardness evaluation - SEM evaluation - EPMA evaluation
	3	Characterize Cracking / Chipping on Tip Wear Surface - Fretting Fatigue?	
	4	Characterize Hardness throughout tip and wear surface	
	5	Characterize microstructure throughout tip and wear surface	
	6	Evaluate Wear on Mid Span Snubber	
	7	MHPS TGO Lab Review - Establish blades to be sent	
	8	TGO Evaluation	

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Blade Shroud Chipping RCA

Influence

Influence
Low
Medium
High

Detailed Actions Tracked (2 of 2)
Reviews conducted with RCA Team

		Actions	Conclusions
Assembly	1	On Site 4 Point Check of Snubber and Shroud (as found + as left)	Gap Data recorded and analyzed. Data within tolerance
	2	Blue / White Light Scan for sample of replacement blades	3 blades (Light/Medium/heavy) were scanned and compared with nominal model after HVOF.
	3	Geometry overlay and review	No differences identified.
	4	Blue / White Light Scan for sample of existing installed blades	7 Blades were scanned and compared with nominal model.
	5	Geometry overlay and review	No differences identified.
	6	Confirm amount of rocking on existing blades / and replacement installed blades	Small rocking was observed on few existing blades. No rocking observed on new blades.
	7	Measure HJ Gap at Diffuser	HJ gap measured at unit assembly and found to be within tolerance.
	8	Review wear profile across single tip during early damage	Wear profile checked with replica and by sectioning and reviewed under microscope.
	9	Measure shroud contact surface (L,W,Depth at 4 points)	Contact surface data collected
	10	Wear and Chipping Documented with photos and scale	Pictures taken for all contact surfaces and documented.
	11	Record water erosion at leading edge and under the shroud	Data recorded and minimum to no erosion observed.
	12	Stationary blade surface finish review	L0 Stationary blade surface finish was checked and no issue is observed.
Operation	1	Map Operating Data to LP Loading and Summarize	Operation data reviewed
	2	Install Pressure Taps / and re-evaluate exhaust flow on return to service	Additional pressure taps are installed.
	3	Operational Data Review of exhaust pressure taps on return to service	Data received and reviewed.
	4	Provide summary of LP Pressure Measurement Location and LP Admission Flow	Locations provided to Bartow
	5	Start-Up Review for Cold, Warm and Hot Starts.	Data not received from Bartow
	6	Characterization of operation from Log Book	Data not received from Bartow
	7	Operation review to determine expected moisture and sensitivity to flow and exhaust pressure changes	Asymmetric condenser circulating water flow at both ends
	8	Provide details or pictures of April 2015 Blade Inspection	Few pictures provided
	9	Provide report of Dynamic Pressure Study from ~2012 for evaluation	Summary provided- No vibration response was observed.

Team Meetings focused on methodical execution of actions and opportunity for questions / discuss of details

40" Fleet Operating Experience

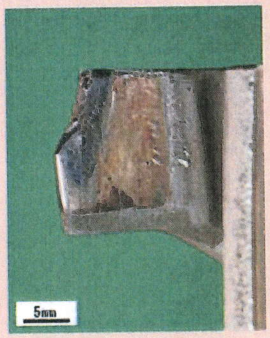
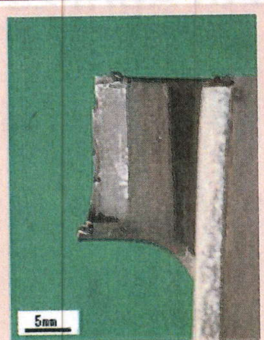
- There are 57 rows of 40" L0 blades operating in the world. 9 Single flows, 22 double flow and 1 four flow LP sections.
- There are 31 rows of type 3 blades (same blades as Bartow except no HVOF coating/ chamfer on midspan snubber). 14 double flows and 3 single flow LP sections.
- Type 3 blades have Stellite material welded under the shroud for water erosion protection.
- Oldest Type 3 blade in operation since 2008.
- Bartow steam turbine have the highest L0 Blade loading amongst the fleet.

Metallurgical Evaluation of Blades Operating from December 2014 to April 2016

Methods of Investigation :

- Visual Evaluation of Blades
- Material composition
- Microscopic evaluation
- Hardness evaluation
- SEM evaluation (Scanning Electron Microscope)
- EPMA evaluation (Electron probe micro analyzer)

Blade Inspection Results

	#39	#40	#41	#42
Contact Surface Leading Edge				
Chipped Surface				

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Blade Inspection Results

	#42 outlet #43 inlet	#43 outlet #44 inlet	#44 outlet #45 inlet	#45 outlet -----
Outlet side contact surface				
Inlet side contact surface				-----

Shroud Chipping is starting at same location for all blades

Metallurgical Evaluation of Blades

Microscopic observation was performed on the same sections in contact condition for each of outlet side of #43 blade and inlet side of #44 blade.

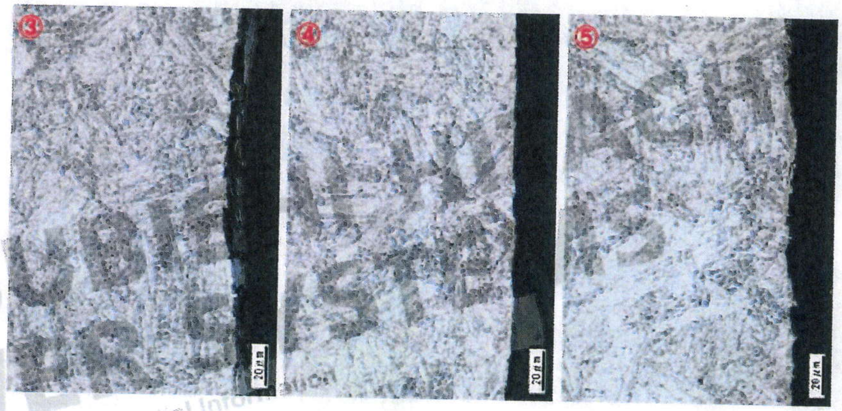
- Fine cracks, caused by fretting fatigue, are found near the end of contact part with local deformation of inlet side of #44 blade.

- Plasticity is found in concave part of local deformation.

Fretting fatigue identified as crack initiation source.

Metallurgical Evaluation of Blades

Microscopic observation was performed on the same sections in contact condition for each of outlet side of #43 blade and inlet side of #44 blade.



- ③: Oxide scale was found on black surface of local deformation area.
- ④: Dark brown surface of worn and thinned part is free of oxide scale and smoother than non-contact surface of ⑤.

Oxide scale with local deformation observed on black surface

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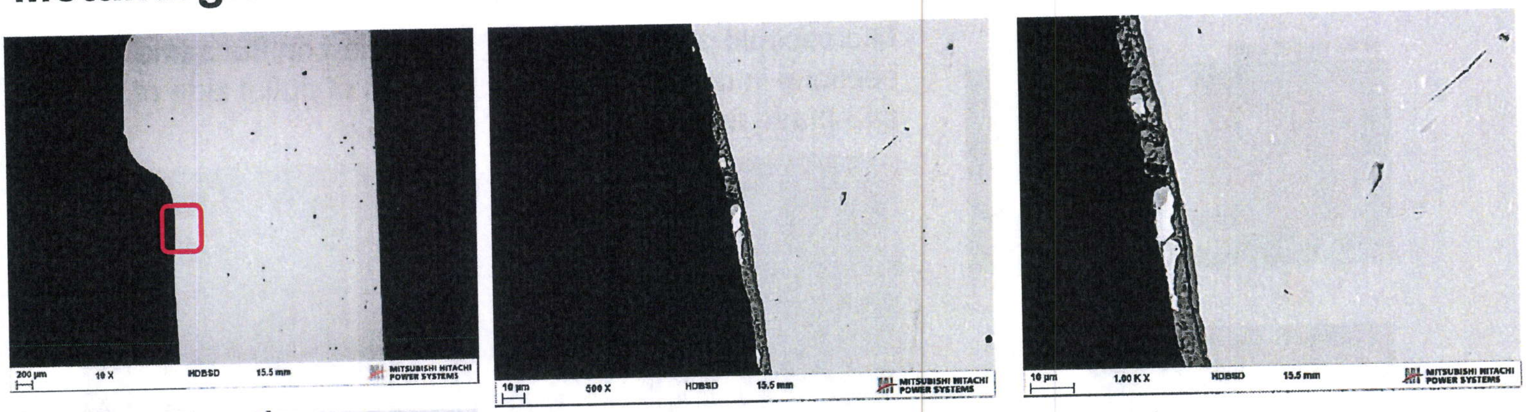
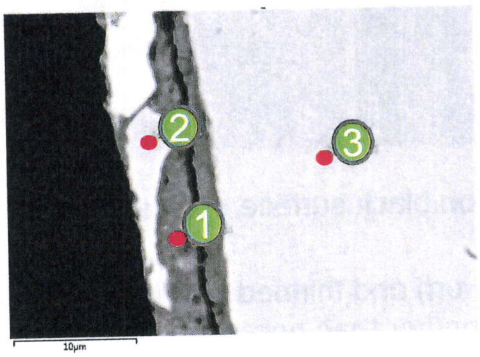
Metallurgical Evaluation of Blades





Location	Semi-Qualitative EDS analysis of elements detected (wt%)							
	O	Si	Cr	Mn	Fe	Ni	Cu	Nb
1	25.97	0.44	7.67	0.41	61.59	1.84	1.18	0.00
2	0	0.35	18.15	0.95	70.12	9.35	0.08	1.00
3	0	0.33	15.86	0.54	73.65	4.91	3.58	1.14

- Oxidation/corrosion was observed on the trailing edge contact surface of the tip shroud.
- Material removal from wear is from abrasion.

Material chemistry matched with blade original material

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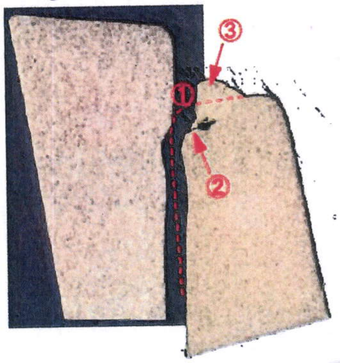
Metallurgical Evaluation of Blades - Hardness

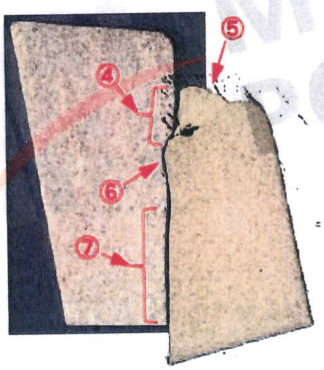
- Hardness measurements are taken at the shroud contact surface, fracture surface, base material and below the shroud on 8 blades.
  - The results show hardness close to original materials (Base Material and Stellite welding).
- Hardness measurements also taken at stub contact area and away from contact surface on base material.
  - The results also show Hardness within criteria at the contact surface and away from contact surface.

No hardening is transferred to base material due to HVOF, contact surface rubbing or welding Stellite material.

Damage Mechanism

Images of initial contact conditions





① Partial local contact at the top and tip of blade

↓

② Fretting fatigue crack generated in local area

↓

③ Local deformation is generated along with the crack

↓

④ Excessive local surface pressure (adhesion) & vibrational stress are applied.

↓

⑤ HCF crack is generated.

↓

⑥ Local wear generated by high surface pressure & excessive sliding. Oxide scale developed by heat generation (black surface).

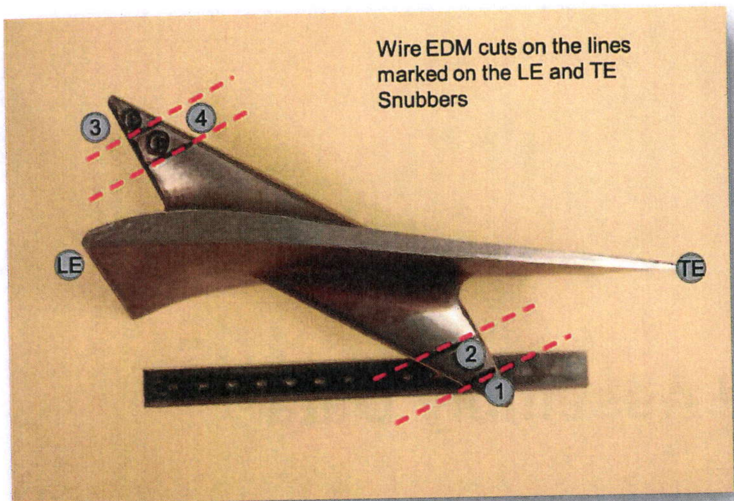
↓

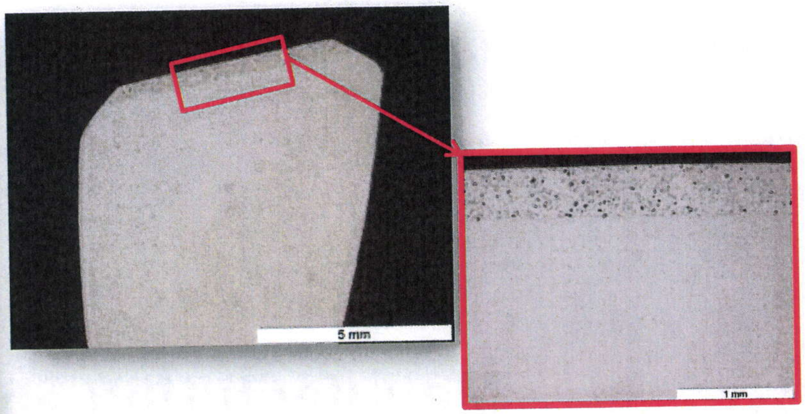
⑦ Worn by wear debris

⑧ Partial defect was caused by fretting fatigue crack which was generated and propagated in high surface pressure and sliding area (black surface).

※⑦ & ⑧ progressed at the same time

Stub Evaluation





- The contact surface coating did not show any cracks, deformation or wear.
- Uniform thickness was measured on the areas of contact between the LE and TE snubbers.

HVOF coating on the stub prevented fretting or any other surface damage

Manufacturing and Assembly Data

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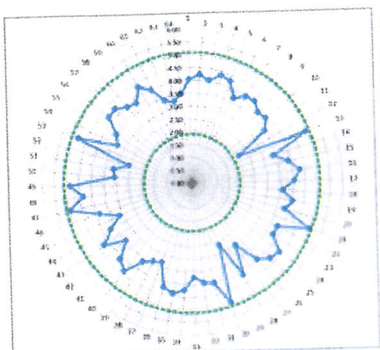
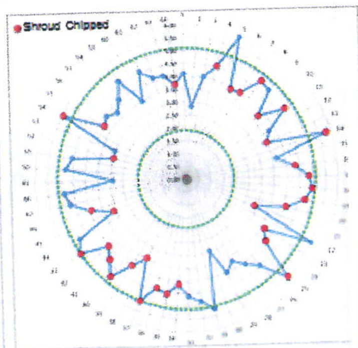
Shroud Gap Data

2014 Blade LH (Gov. End) Shroud Gap Data



Shroud Gap Data in 2014 Assembly

Row Average Gap = 3.9mm



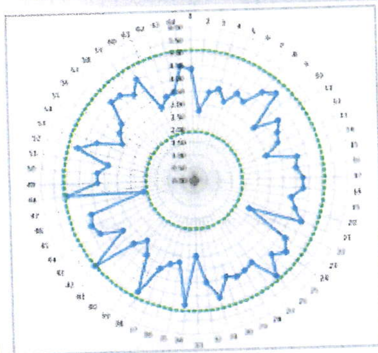
Shroud Gap Data in 2016 Dis-Asseml

Row Average Gap = 4.2mm

Criteria: Shroud 1.9mm to 5.1mm Average, with no single blade above 6.0mm.

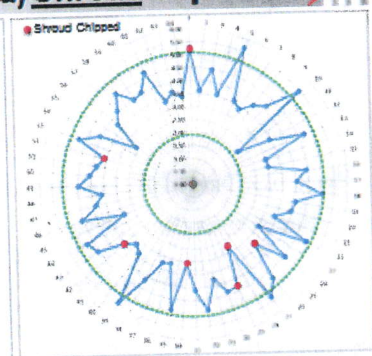
No clear relationship between gaps and shroud chipping

2014 Blade RH (Gen. End) Shroud Gap Data



Shroud Gap Data in 2014 Assembly

Row Average Gap = 3.9mm



Shroud Gap Data in 2016 Dis-Assembly

Row Average Gap = 4.0mm

Criteria: Shroud 1.9mm to 5.1mm Average, with no single blade above 6.0mm.

No clear relationship between gaps and shroud chipping

LH and RH shroud average gaps are nearly same
No clear relationship between gap and shroud chipping

Stub Gap Data

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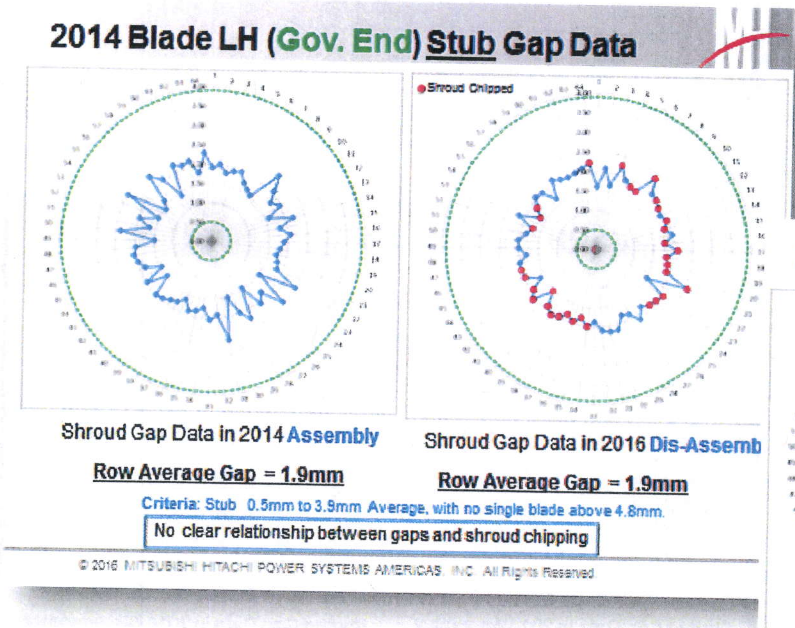
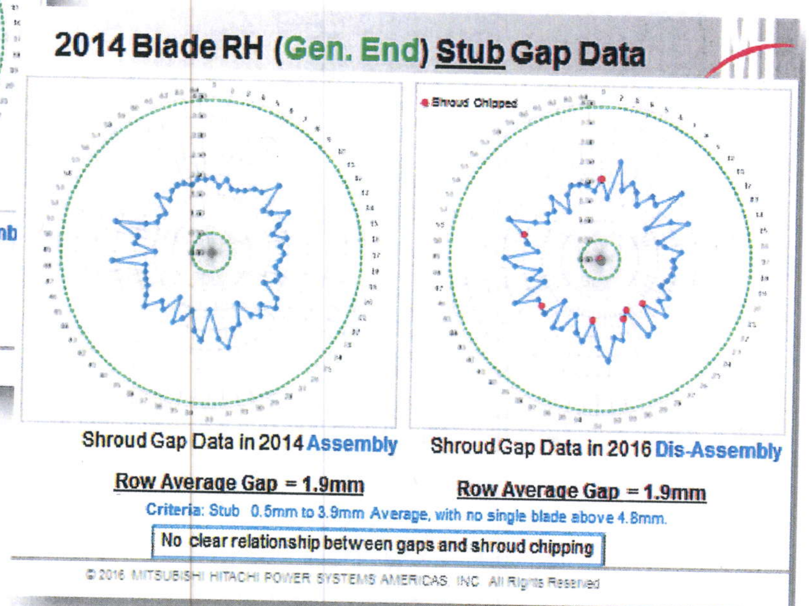
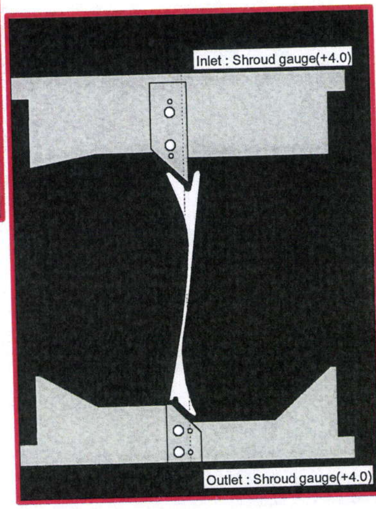




LH and RH stub average gaps are nearly same.
No clear relationship between gap and shroud chipping.

Manufacturing Quality Data - Box Gauge

Box Gauge with 40" L0 Blade



Box Gauge Measurement Results - 2014 blades

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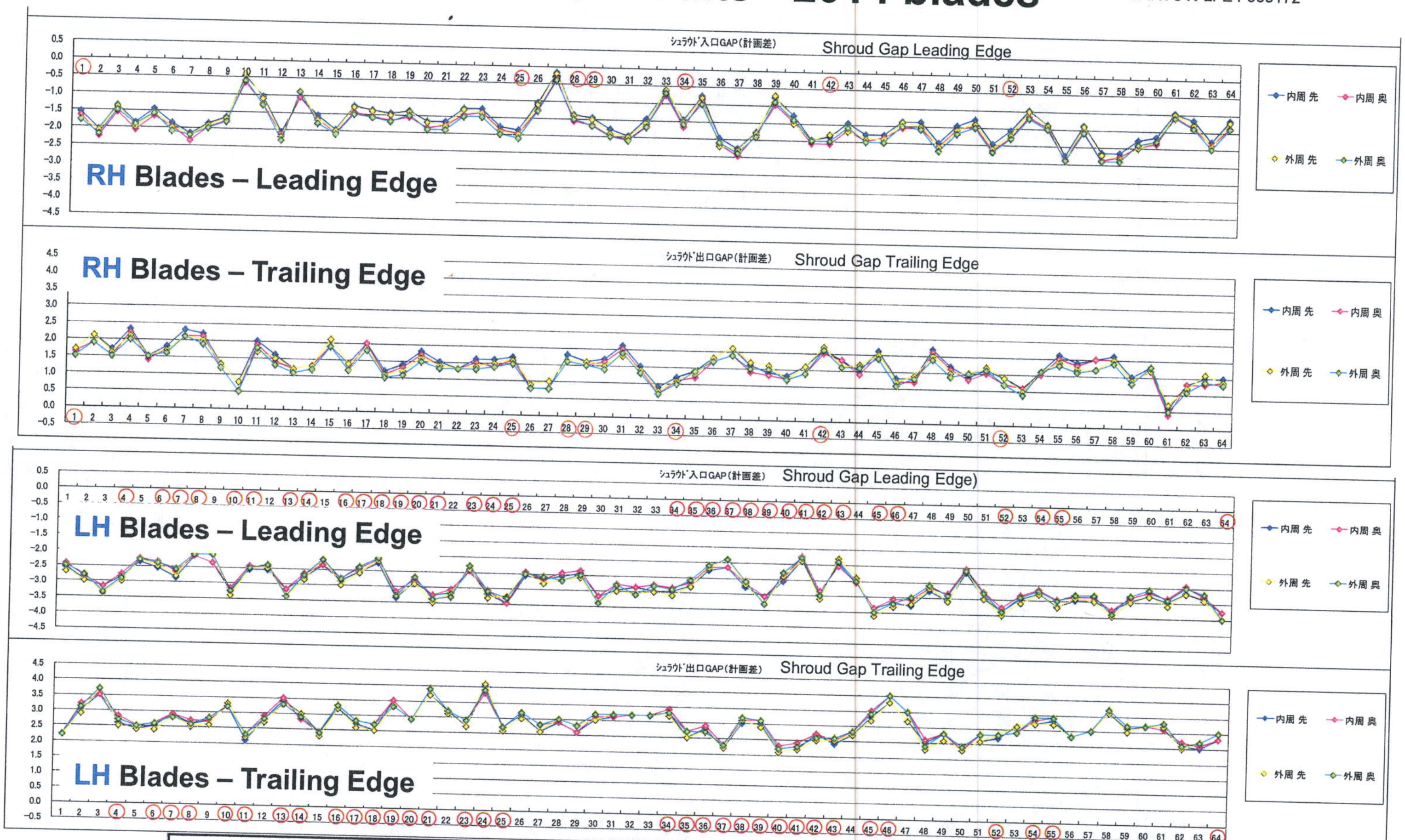

Blade manufacturing data show variation within criteria

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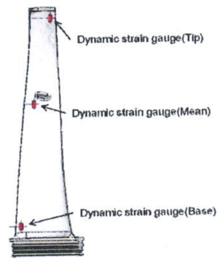
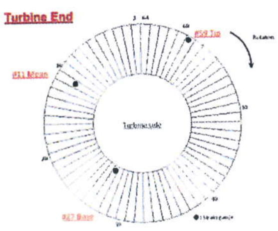
Telemetry Test Data Analysis

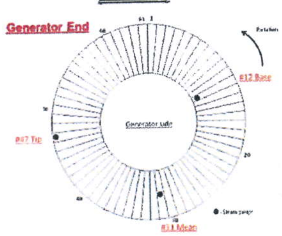
Telemetry Test Results

Strain Gage Locations

- Six strain gage were installed on LH and RH blades.
- Strain gage locations were selected
  - ➢ High Response sensitivity for vibration modes.
  - ➢ MHPS Experience

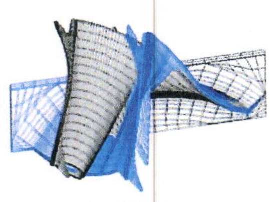




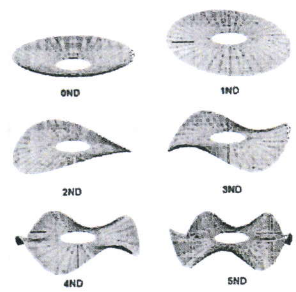


Test Results

- Analysis of Non-synchronous response show frequencies close to 200Hz region and composed of axial mode shape with higher nodal diameter.
- Fretting at stubs was evaluated with the telemeter test results.



Similar to 1st Mode Shape

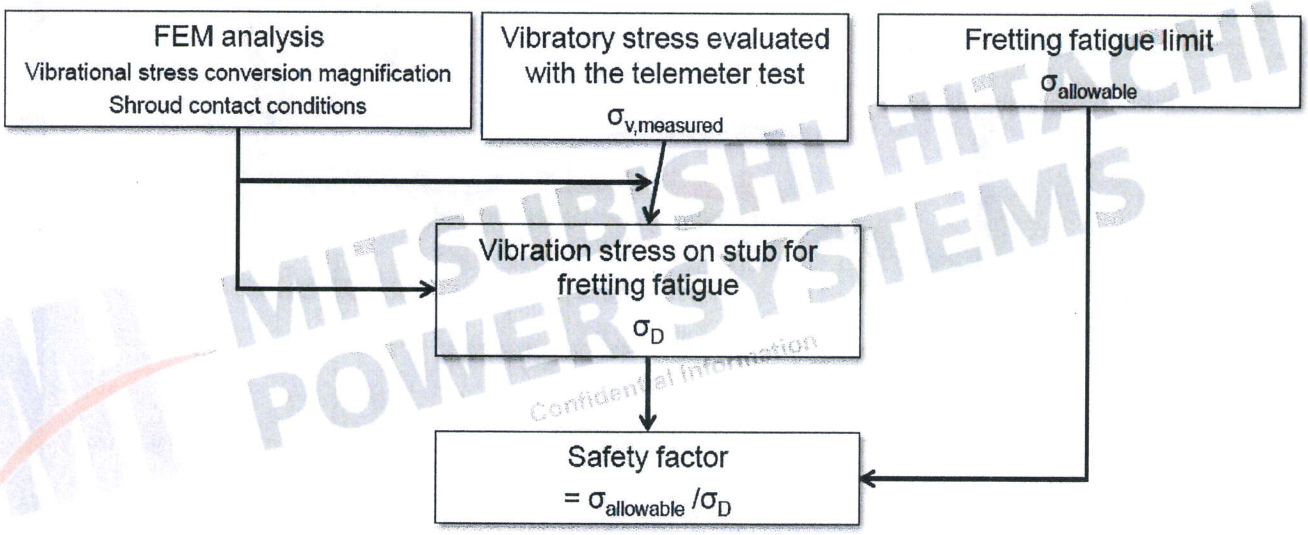


Nodal Diameters

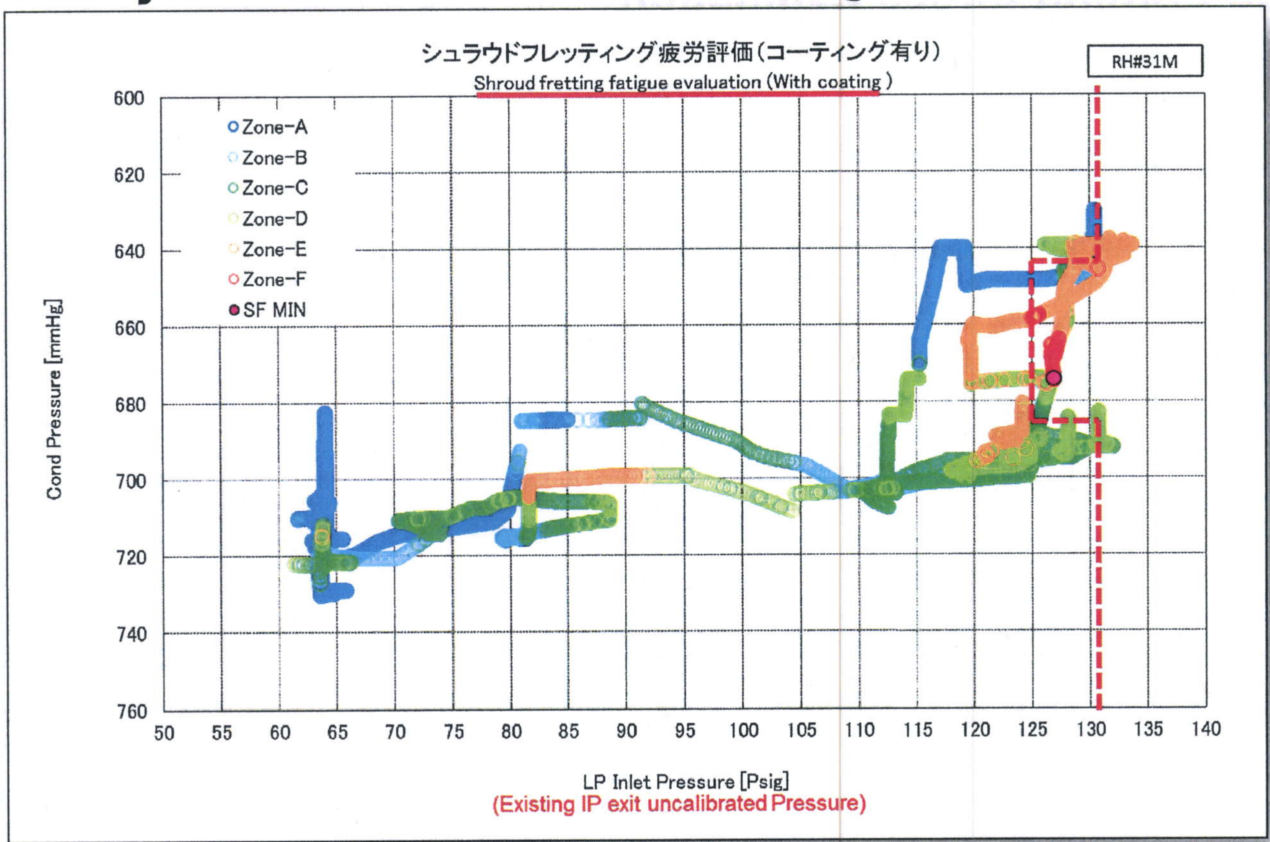
Telemetry Testing 2014 -
To understand dynamic blade response during operation

Shroud Fretting Stress Evaluation

- Evaluation method is the same as stub fretting evaluation.
- Vibrational stress is evaluated, with FEM analysis, primarily for effect of shroud contact condition (partial contact) based on actual telemeter measurement result of 2014.



Telemetry Test Results – Shroud Fretting



Fretting fatigue calculations for shroud with coating show acceptable margins outside avoidance zone

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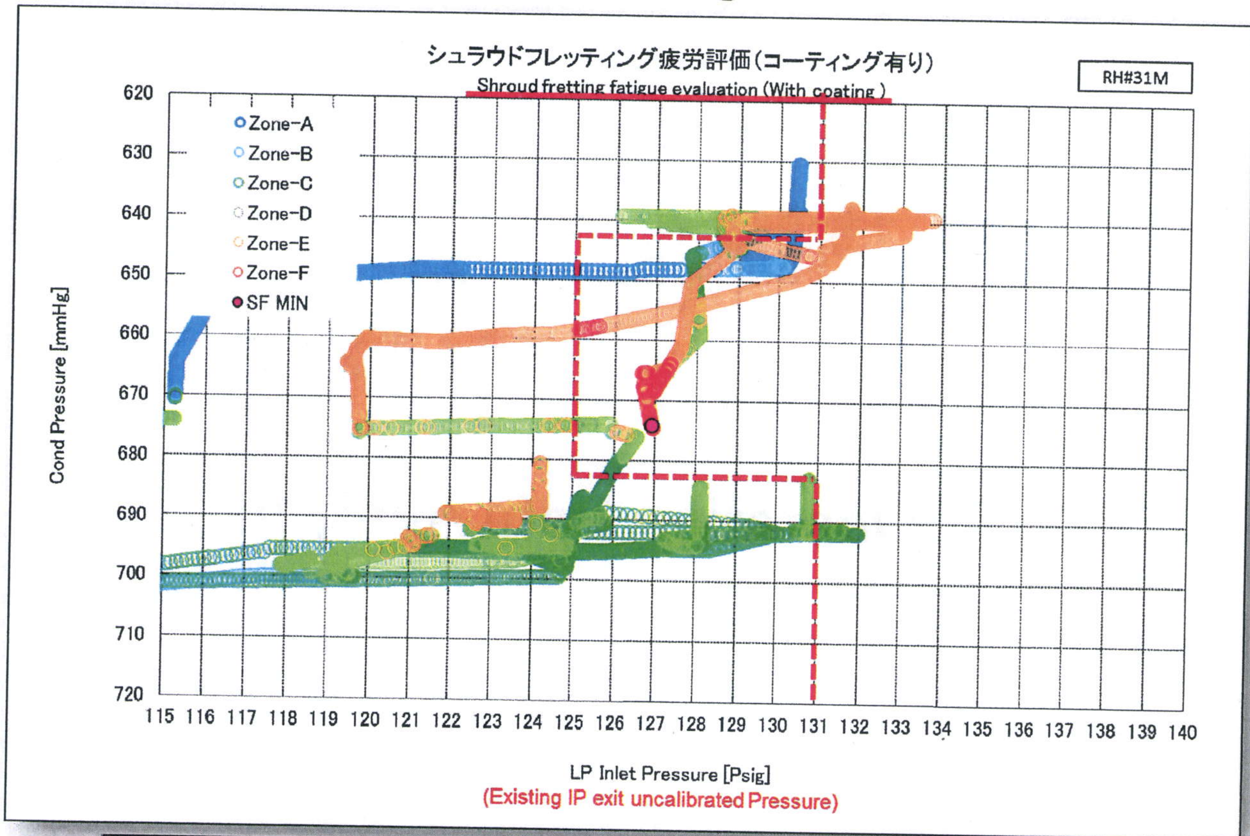
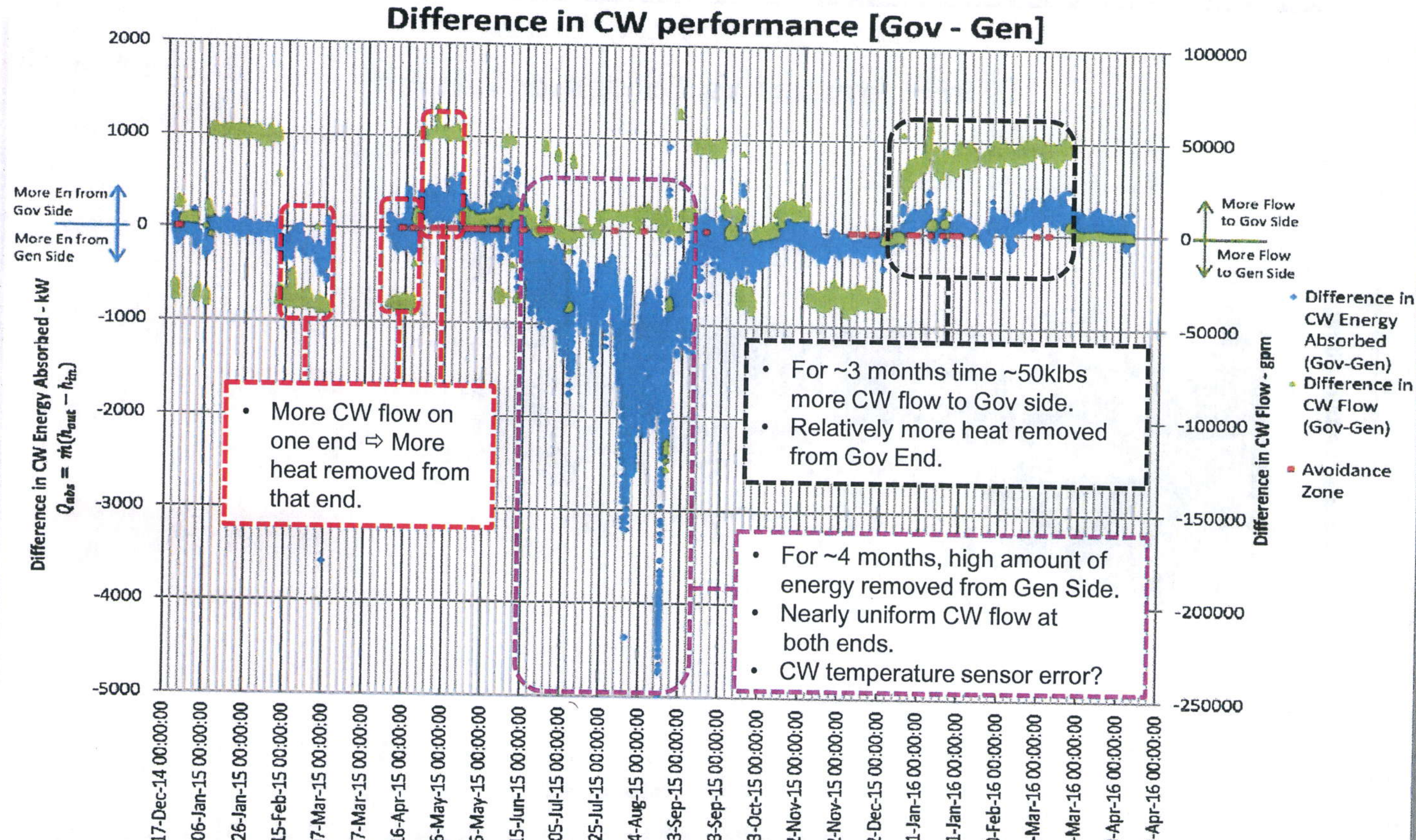
Telemetry Test Data – Shroud Fretting



Fretting fatigue calculations for shroud with coating show acceptable margins outside avoidance zone

Operation Data Analysis

Condenser Circulating Water (CW) flow analysis



Asymmetric circulating water flow may explain difference in water erosion observed
Not enough data to draw any conclusion on blade shroud damage

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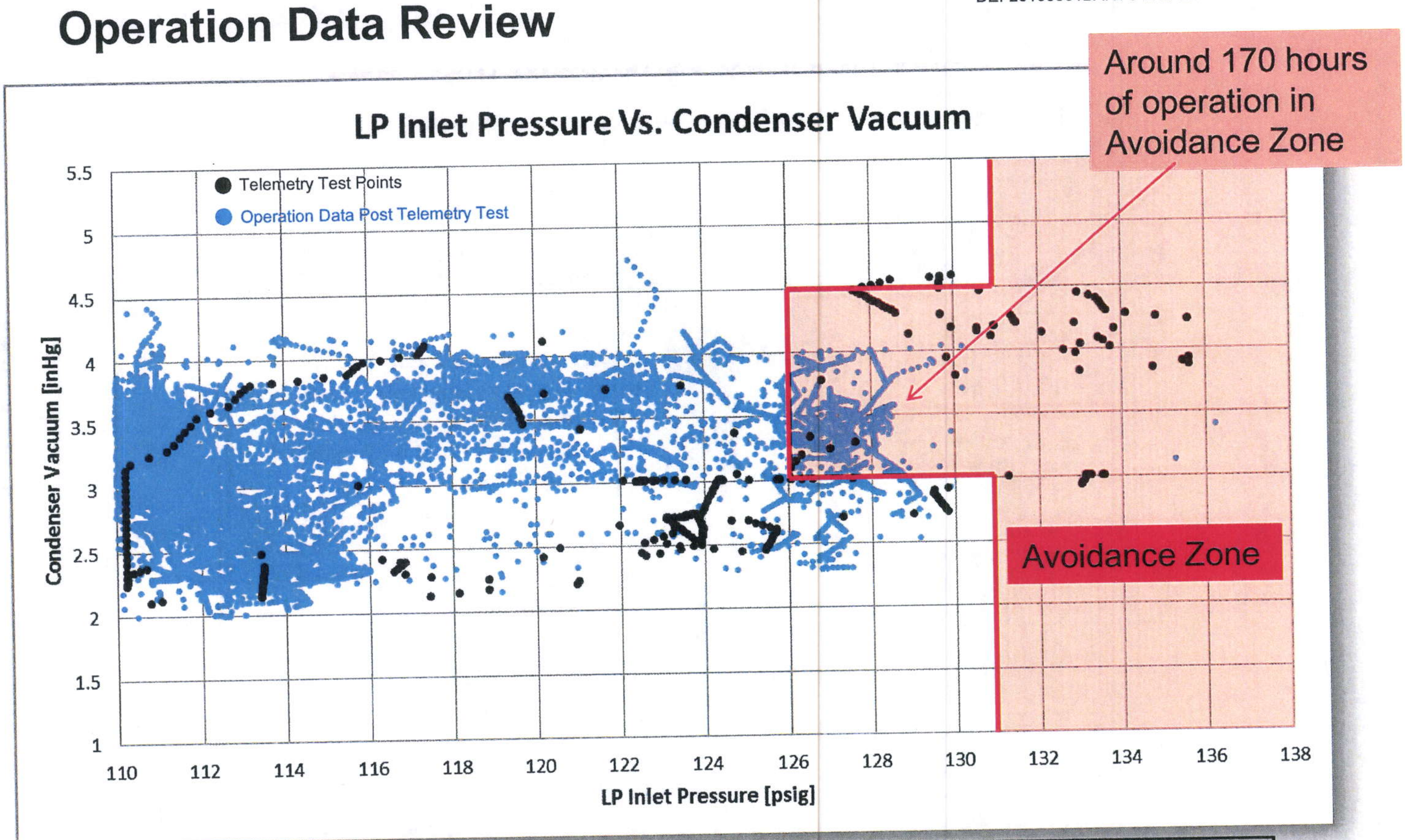
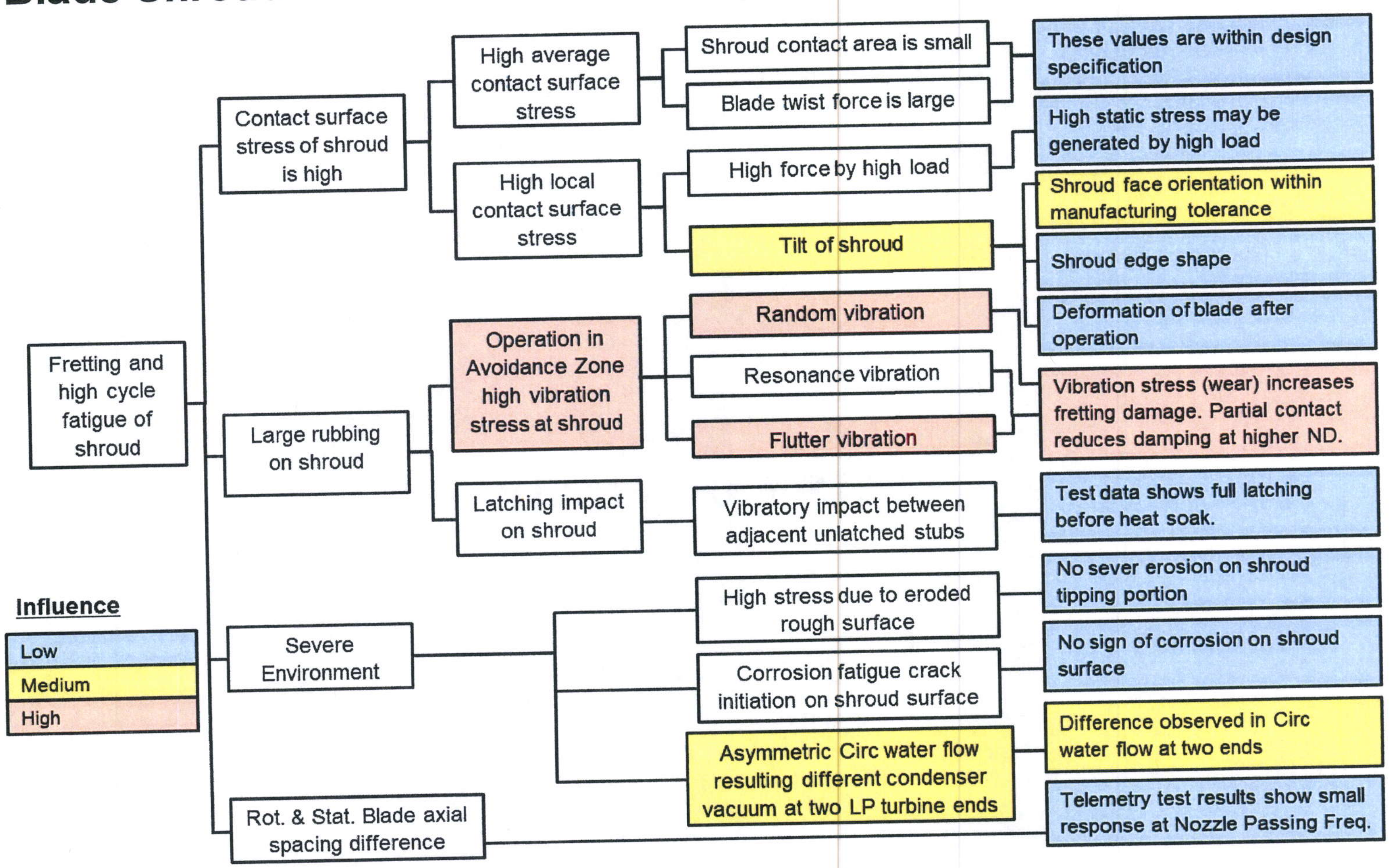
Operation Data Review



170+ hours of operation in avoidance zone with a response frequency ~200Hz = 1.2E8 Cycles

RCA Conclusions

Blade Shroud Cause and Effect Diagram



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RCA Conclusion

- The root cause for start of shroud chipping has been identified as operation in the avoidance zone.
- Within the avoidance zone, high local contact pressure is developed due to partial contact.
- After initial chipping, nearly uniform wear of contact surface indicate progression of chipping due to operation at resonance (avoidance zone).
- Stellite coating on stub has proven its effective at protecting surfaces from fretting damage.

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Bartow Steam Turbine

RCA Review

Addendum Presentation

Nov 17th 2016

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SL3

Purpose of Presentation

Provide responses to open items / questions during the Nov 9th RCA Report Out Meeting

Subjects :

1) Demonstrate that operating data from 2009 to 2014 is consistent with the RCA conclusions.
2) Provide hardness results not presented in Nov 9th .
3) Provide parallelism data not presented in Nov 9th.
4) Provide responses to prior questions from Harry Carbone.

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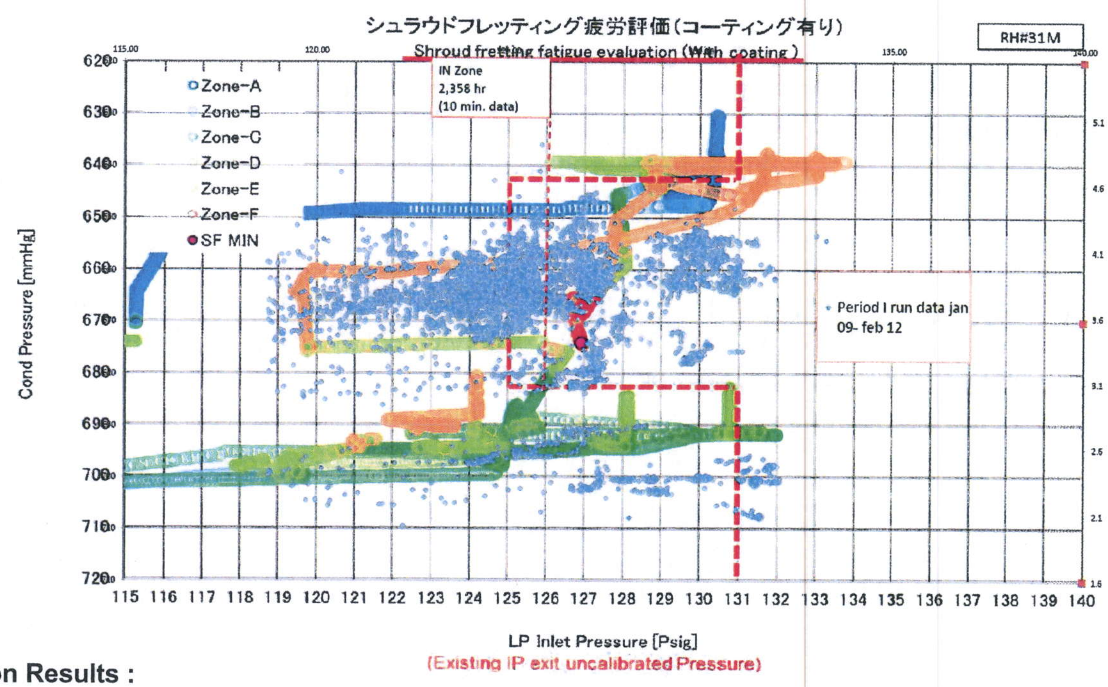
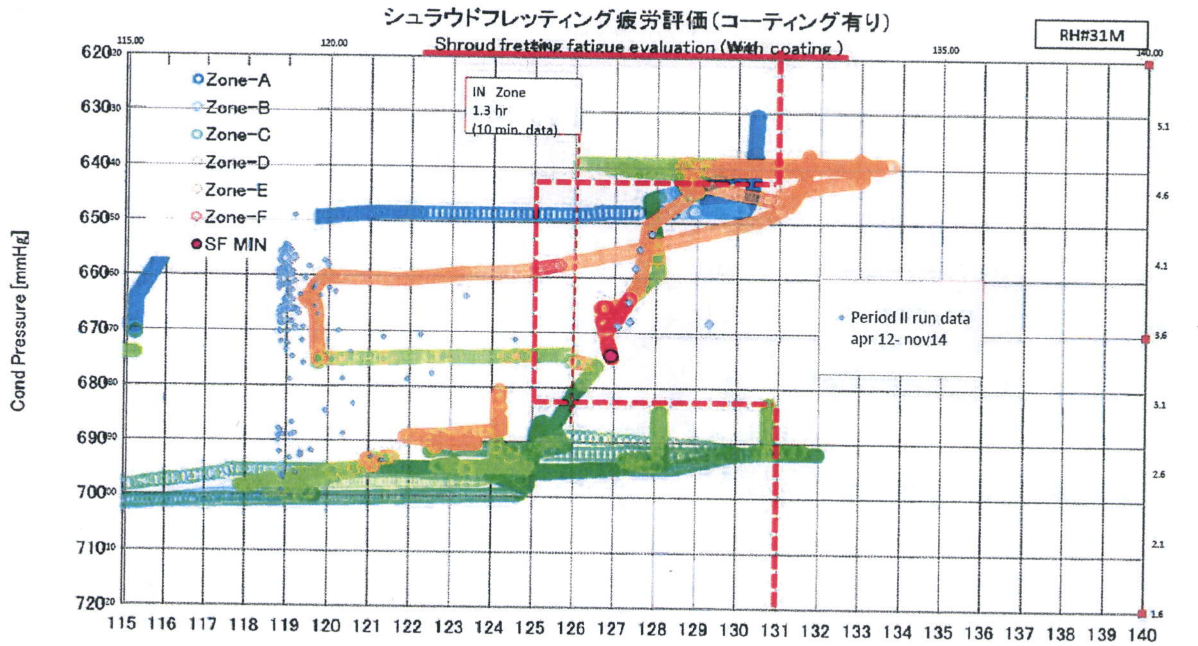
1.1) Operating Time 1 : Jan 2009 to Feb 2012



Inspection Results :

Location	Blades	Service	Mid Span Snubber	Shroud	Disposition
Gen End	Type 1	3 yrs	No significant damage	No significant damage	Continue operation until 2014 planned replacement
Gov End	Type 1	3 yrs	5 Major Chip	3 minor chips	Replace blades as continues midspan chipping could results in a free standing blade

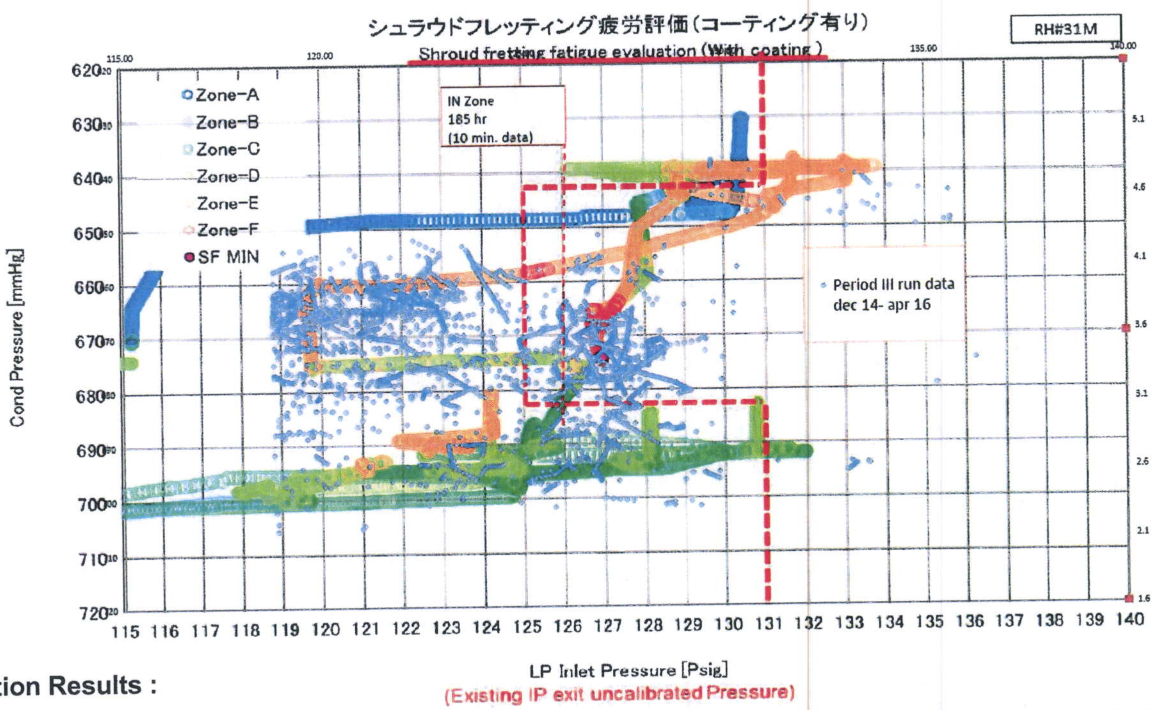
1.2) Operating Time 2 : Apr 2012 to Nov 2014



Inspection Results :

Location	Blades	Service	Mid Span Snubber	Shroud	Disposition
Gen End	Type 1	5 yrs	No significant damage	12 minor chips	Scheduled change out to blades with midspan HVOF
Gov End	Type 1	2 yrs	No significant damage	3 minor chips	Scheduled change out to blades with midspan HVOF

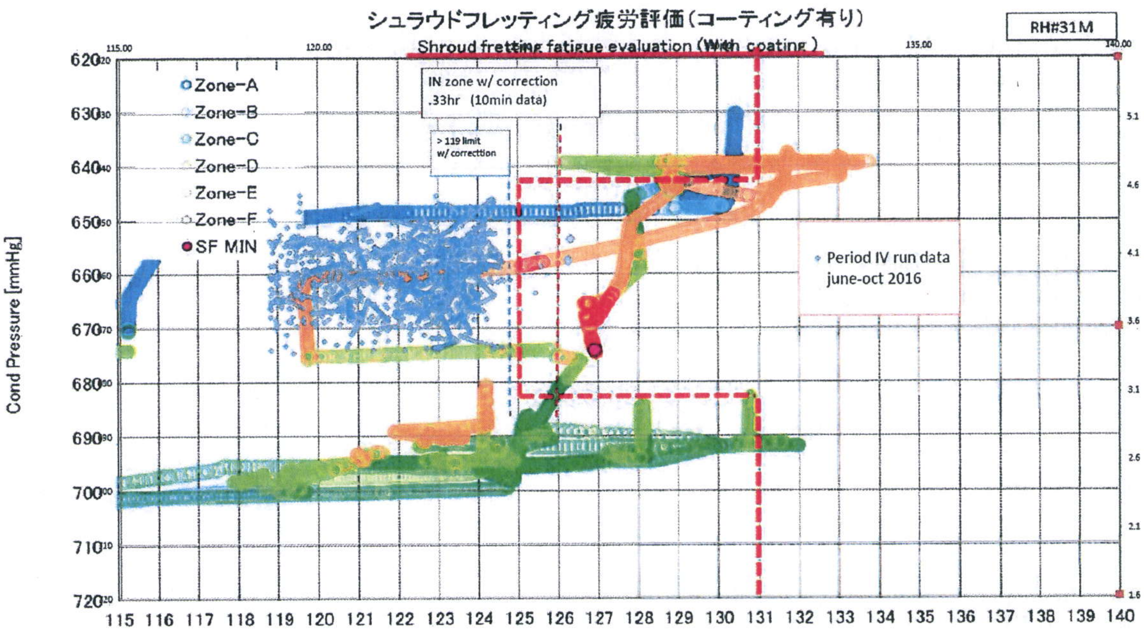
1.3) Operating Time 3 : Dec 2014 to Apr 2016



Inspection Results :

Location	Blades	Service	Mid Span Snubber	Shroud	Disposition
Gen End	Type 3 + HVOF	15 Months	No significant damage	7 minor chips	Fit for continued operation. Shroud contact on all blades.
Gov End	Type 3 + HVOF	15 Months	No significant damage	33 chips including significant damage	Replace row as free shroud contact has bee lost on 1 blade.

1.4) Operating Time 4 : Jun 2016 to Oct 2016



Inspection Results :

Location	Blades	Service	Mid Span Snubber	Shroud	Disposition
Gen End	Type 3 + HVOF++	4 Months	No significant damage	7 minor chips	Fit for continued operation. Shroud contact on all blades.
Gov End	Type 3 + HVOF++	4 Months	No significant damage	33 significant damage	Replace row as free shroud contact has bee lost on 1 blade.

Conclusions of LP Blade Loading Review

- Telemetry test results show that once in the avoidance zone, small changes in operating conditions can produce a large change blade response magnitude.
- Damage accumulates at 200Hz (720,000 cycles every hour)

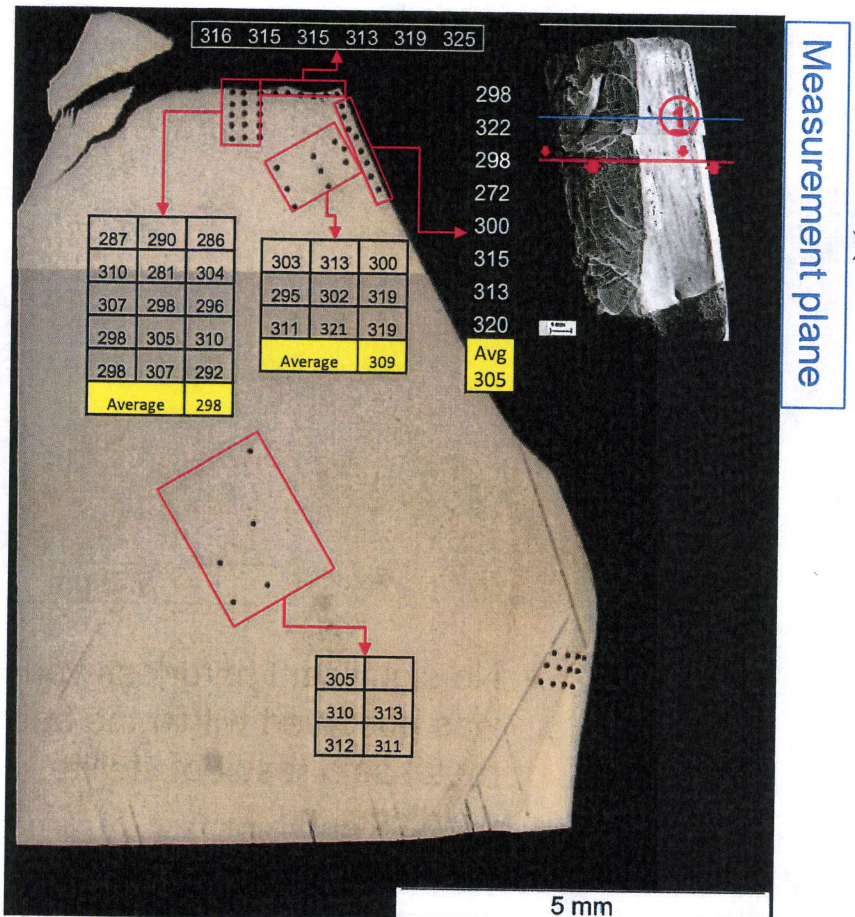
1.1) Operating Time 1 : Jan 2009 to Feb 2012
Significant operation in the avoidance zone.
Significant damage observed on the blades.

1.2) Operating Time 2 : Apr 2012 to Nov 2014
Minimal operation in the avoidance zone.
Minor chipping observed.

1.3) Operating Time 3 : Dec 2014 to Apr 2016
Significant operation in the avoidance zone.
Significant damage observed on the blades.

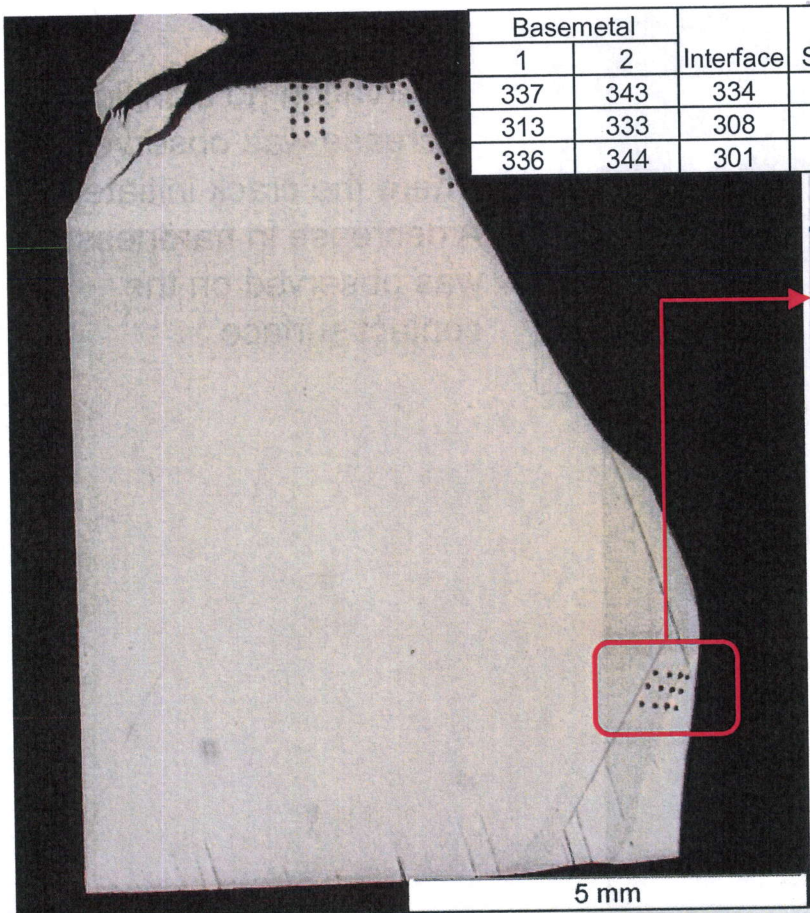
1.4) Operating Time 4 : Jun 2016 to Oct 2016
RCA evaluation has not been completed.
Operating data has not bee provided beyond, only summaries of MW and LP Pressure vs Time.

2 - Hardness Variation – Presented

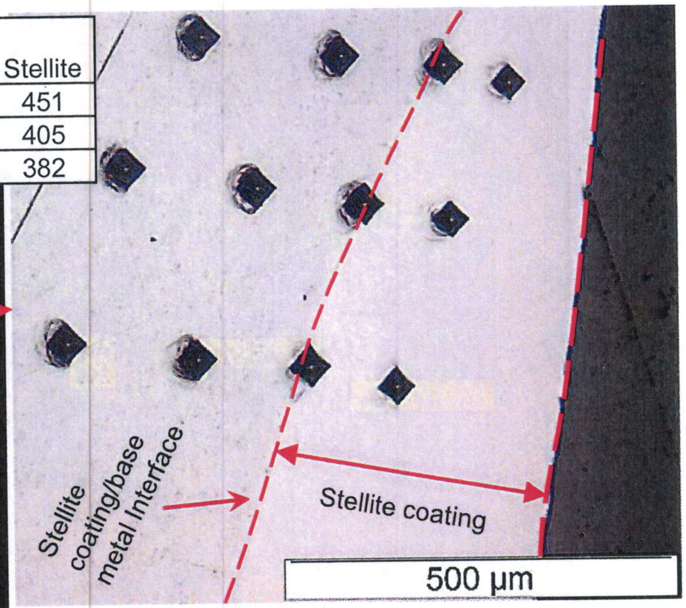


- From hardness observation no significant decrease was observed where the crack initiated.
- A decrease in hardness was observed on the contact surface.

2- Hardness Variation basemetal, Interface and Stellite Coating



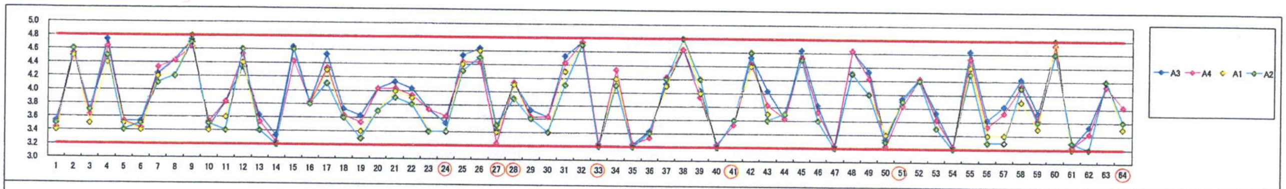
Basemetal		Interface	Stellite
1	2		
337	343	334	451
313	333	308	405
336	344	301	382

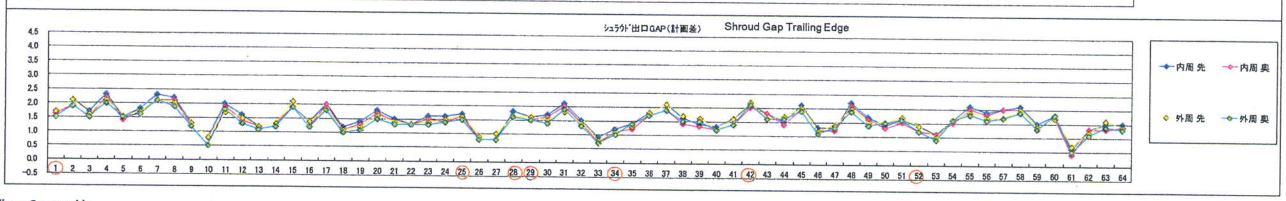


- No significant hardness variation was observed within the base metal as a result of stellite welding.

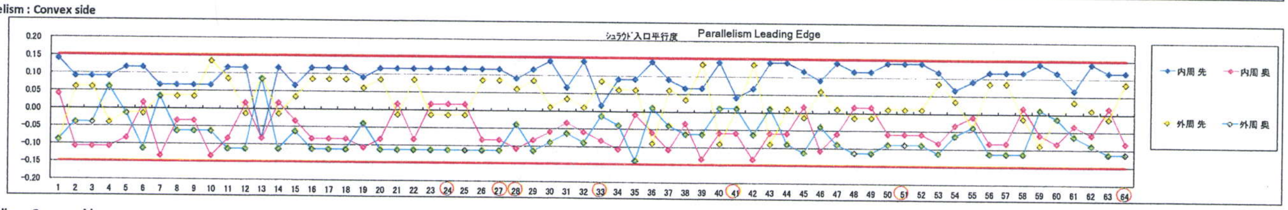
3.1) Measurement Results RH (Gen End) 2014 blades

Shroud GAP ○: Shrouds with Damage

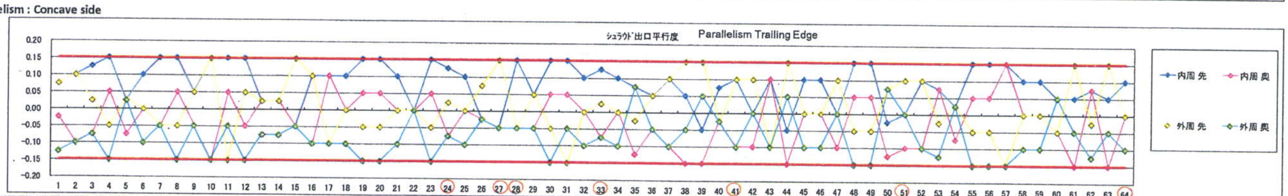




Parallelism : Convex side



Parallelism : Concave side



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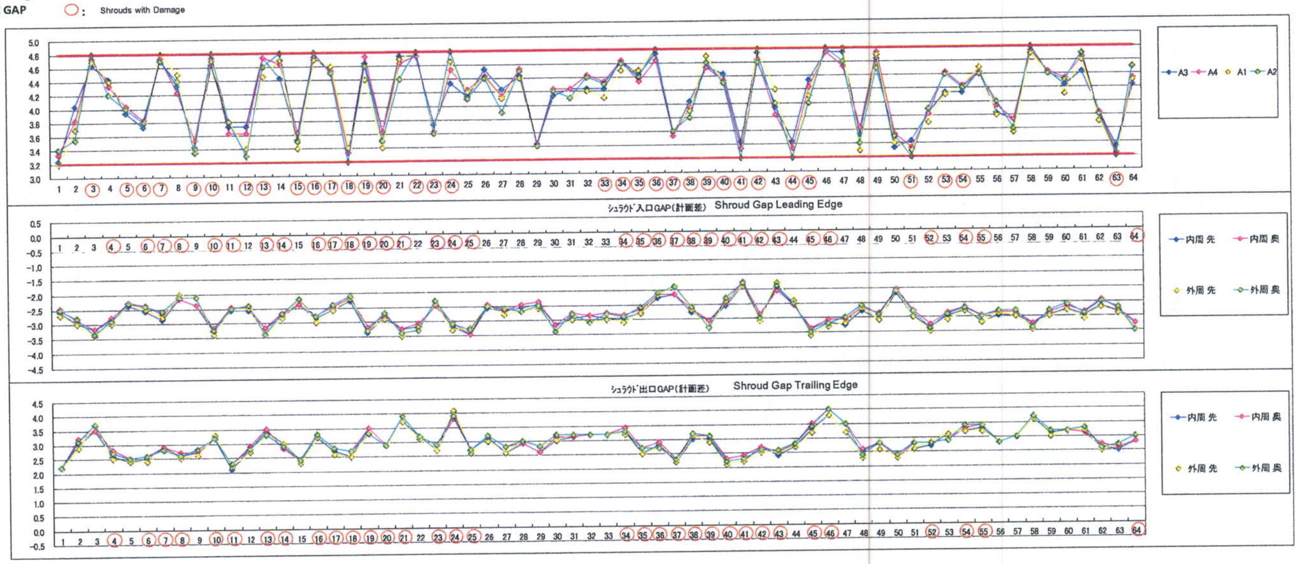
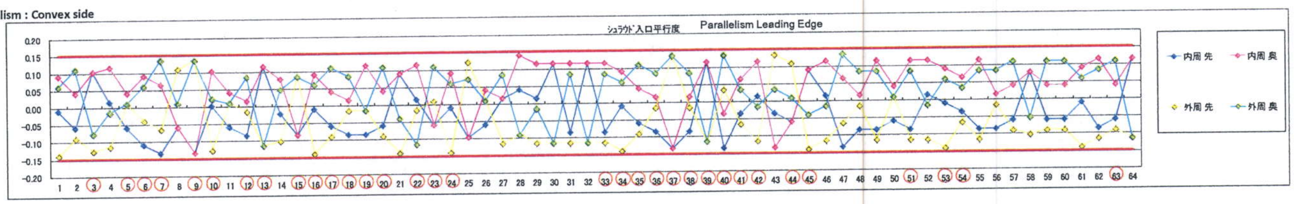
3.2) Measurement Results LH (Gov End) 2014 blades

Shroud GAP

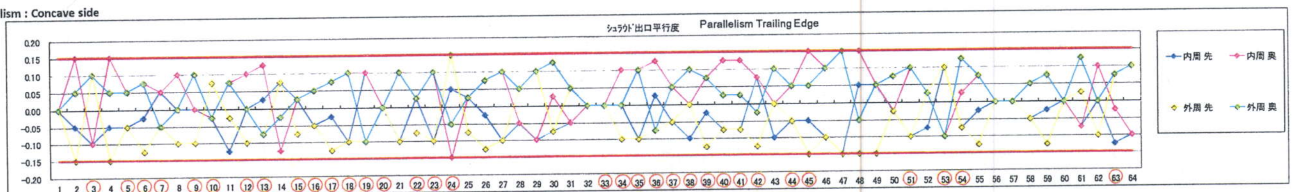
○ : Shrouds with Damage



Parallelism : Convex side



Parallelism : Concave side



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Duke Questions (From 10/26/16 Meeting):

1. Current draft of time line of blade outages
2. Updated Vibration change dates To understand the

Operating data from the operating from June 2016 to October 2016 has been requested on multiple occasions since the change in vibration was brought to the attention of MHPSA in August 2016.
To understand the operation of the unit, this information is required to provide an objective data driven assessment of the operation.

3. The mw correction factors issue

Conflicting information is being given. It is no longer clear whether during the telemetry test there was an offset MW. The operating data requested is required to understand the relationship between steam conditions and load.

4. New LP inlet pressure gage 3.7 psi zero offset error

Following the finding that the IP Exhaust Pressure Tap had not been calibrated with its water leg, the same issue has now occurred on the new LP Admission.
There is currently a lack of clarity on the calibration of the pressure taps which is critical to understanding the steam loading seen by the blades which can hopefully be addressed by review of the latest operating data.

5. Chart of blade options

An updated chart is attached.

6. Duke requested strain gage data

Results of the telemetry test have been shared during the RCA meetings. Face to face meetings were held in May 2016 specifically for the purpose of being able to openly share information which would normally not be available to share due to being business confidential information. During these reviews the nature of the none synchronous response was described identifying that the blade response is not being excited by single modes. A single stresses cannot be evaluated against a single allowable in a Goodman diagram, but a range of modes is being excited within a frequency range. The magnitude of blade response is integrated over a frequency range to determine an overall response level compared to successfully validated response levels. This is not data which can be sent directly as a file to Duke Bartow.

7. Confirm material is 17-4

Similar too material designations are provided for reference only and do not support reverse engineering of the blade design which is subject to multi-year development programs and continuous improvement by the MHPS-Japan development team.
Hardness was reviewed in detail during the face to face RCA meetings.
The RCA reports are intended to be presented in person to ensure that they are correctly interpreted due to the complex nature of the RCA investigation.

8. Supply Goodman Diagram

OEM Last Stage Blade materials are not per industry standards, with the material development being critical to achieving competitive designs. The Goodman Diagrams for MHPS developed materials is proprietary.

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Summary of Blade Types

	Base material	Brazed in Stellite Leading edge erosion strip	Spray Stellite under Z notch Leading edge	Welded Stellite Under Z notch Leading edge	Polish off shot peening after welding	Spray Stellite .3 mm on snubber contact faces	Spray Stellite .3mm on Z notch contact faces	Chamfer 1 x 0.5 mm & 2 mm radius on snubber	Corner cut on Z notch ~3mm x 3mm
Type 1	Proprietary Sim to 17-4 PH Proprietary HT	Yes	Not Applicable	No	n/a	No	No	No	No
~~Type 2~~		Note : Type 2 is a welded field modifcation provided as a temporary measure while awaiting replacemetn blades. No Type 2 Blades are operating in the fleet.							
Type 3		Yes	Not Applicable	Yes	No	No	No	No	Yes
~~Newer Type 3~~		Note : No blade type - "Newer Type 3"							
Installed 2014 (Typ3 + HVOF))		Yes	Not Applicable	Yes	No	Yes	Yes	Yes	Yes
Installed 2016 spring (Typ3 + HVOF)		Yes	Not Applicable	Yes	No	Yes	Yes	Yes	Yes
Proposed now Fall '16(Typ1)		Yes	Not Applicable	No	n/a	No	No	Yes	Yes

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