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EXHIBIT NO. 103

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DOCKET NO: 20190001-EI

WITNESS: Jeffrey Swartz

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PARTY: Duke

DESCRIPTION: Late filed deposition Exhibit No. 5

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

PROFFERED BY: Office of Public Counsel

Bartow 4S Root Cause Analysis – Evaluation of Contributing Factors

- LP Turbine Back-End Loading (>15,000 lb./hr./ft.^{2})
- Blending Operations
- Hood Spray Operations
- Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches
- Configuration (e.g. Hard-Facing on Z-Notches)

Executive Summary – written last to summarize…

Brief History – Copy/Paste and Add to what Ben wrote in his summary to Jeff Swartz/Tony Salvarezza (03/29)

Briefly address the exhaustive analysis of potential contributing factors (give examples of the ones that didn't make the cut) and then lead in to the discussion of the primary 5.

<u>LP Turbine Back-End Loading (>15,000 lb./hr./ft.^{2})</u>

Talk about how this has had an effect (or not) on the unit across the different periods of operation.

<u>Blending Operations</u>

We've had bad blends during all 5 periods of operation.

<u>Hood Spray Operations</u>

We've had consistent through the 5 periods with the exception of the operating feed pressure, which began to decay over time beginning in Period 2 (which was indicative of poor atomization).

<u>Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches</u>

Based on the quality documentation received from OEM , as well as from our own measurements, we've noted a wide range of variation contact surface parallelism, or lack thereof. Observed markings and wear patters, esp. on the Z-notches that would indicate poor point-to-point contact between adjacent blades. Type 1-3 blades were designed to be parallel in the cold setting, whereas the new Type 5 design is designed with a taper such that it goes parallel in the operating condition.

<u>Blade Configuration (e.g. Hard-Facing on Z-Notches)</u>

Period 4…

Period 3…

Maybe discussion on the history of the different types of blades.

Bartow L-0 RCA Draft Working Meeting 08/24/2017

Excessive Steam Flow

- For Periods 1-5, and by a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the avoidance zone hours relative to total operating hours.
- Damage was relegated to five (5) broken mid-span snubbers on the turbine end of the machine. All turbine end L-0 blades were replaced. Some degree of fretting was observed on the contact surfaces of both turbine and generator ends of the machine.
- For Period 3, additional damage seen on the shroud Z-Lock contact surfaces relative to other Periods, was likely due to loss of dampening at the snubber, which were HVOF coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

Empirical Support for Root Cause

		Excessive Steam Flow			
Period	Operating Hours	Driving Mechanism Present	Avoidance Zone Exceedance Hours	hrs./(1k Op hrs.)	Normalized Ranking
1	21734	X	2466	0.11	1.00
2	21284		1	0.00	0.00
3	10286	X	240	0.02	0.21
4	2942		1.15	0.00	0.00
5	1561		0	0.00	0.00

- Column D – Captured operating hours above 15,000 lb/ft2-hr limit as indicated by the IP Exh pressure
- Column E – No. of operating hours above the limit divided by the period operating hours
- Column F – Normalized against the highest value.

Pressure Pulses

- Hood spray operation – from commissioning – was not programmed to the OEM specifications. Specifically, the hood sprays come on with the curtain sprays, and this is counter to the MHI design, which only specifies that sprays come on during start-up, shut-down and high temperatures in the exhaust.
- Over time, hood spray pressure decayed due to apparent valve trim contamination and upstream filter screen debris.

- Information provided by the hood spray nozzle vendor suggest that low pressures lead to poor atomization. It is further speculated that larger droplet size can lead to pressure pulses as water droplet vaporize in the exhaust flow.

Empirical Support for Root Cause

		Pressure Pulses				
Period	Operating Hours	Driving Mechanism Present	Avg. Hood Spray Pressure (psig)	Hours of Hood Spray Operation	% of Total Operating Hours	Normalized Ranking
1	21734		35.2	5098.4	23	0.68
2	21284	X	13.2	7342.7	34	1.00
3	10286	X	10.4	439.7	4	0.12
4	2942		5.5	173.8	6	0.17
5	1561	X	8.7	93.1	6	0.17

- Hours of hood spray operation are weighted – 1.00 multiplier for 50psig linearly varying to 1.75 at 5psig.
- % of Total Op Hrs is the weighted hours divided by total operating hours.
- Normalized against maximum %

Thermal Distress at L-0 Exit (dTsh/dt)

- Calculated a value of superheat at the hood spray thermocouples, calculating a rate of change of that value, and flagging those values over 20 degrees F when a CT is being blended off or on the steam turbine and the steam turbine output is greater than 50 MW.
- The limits of 20 degrees F 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.
- This process of determining blends that were outside of the condenser OEM's recommended operating practices for the spargers.

Empirical Support for Root Cause

		Thermal Distress (dTsh/dt)			
Period	Operating Hours	Driving Mechanism Present	Counts (> 20Fsh/min)	Counts/(1 k Op hrs.)	Normalized Ranking
1	21734	X	13	0.60	0.17
2	21284	X	7	0.33	0.09
3	10286	X	37	3.60	1.00
4	2942	X	3	1.02	0.28
5	1561	X	5	3.20	0.89

- Counts are defined as blends where there was a rate of change in superheat temperature greater than 20 degrees at the hood spray thermocouples.
- Continue speaking to the columns definitions…

Loss of Dampening

- For Period 3, additional damage seen on the shroud Z-Lock contact surfaces relative to other Periods, was likely due to loss of dampening at the snubber, which were HVOF coated. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

Blade Fitment (Contact Surfaces)

-

Other Mechanisms

- Operation in higher dynamic stimulus zones within the normal operating window – i.e. outside the avoidance zone – as identified by strain gauge testing in December 2014.
- List others here...

Executive Summary

Duke and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 12 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation. During a presentation given at Bartow Station on 15 March 2017, MHPS suggested the sole root cause for Period 3 (Dec 2014-Mar 2016) was "operation in the avoidance zone". While Duke Engineering would agree that operation in the "avoidance zone" is certainly a *contributing factor* to the shroud chipping experienced in Period 3, it is not the only driving mechanism that should be considered when trying to determine root cause for the Period 3 Bartow Unit 4S event, or any of the previous/subsequent events for that matter.

After months of study, 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
- Thermal Distress at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operations
- Blade Fitment (Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches
- Loss of Dampening (e.g. Hard-Facing on Mid-span Snubbers and Z-Notches)

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. The ST LP admission system was modified by MHPS with the intent for 4x1 CC operations to yield a 450MW gross output rating.

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-Notch 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.

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Empirical Support for Root Cause

Period	Operating Hours	Excessive Steam Flow: Potential Factor Present	Excessive Steam Flow: Avoidance Zone Exceedance Hours	Excessive Steam Flow: Exceedance Hours / (1k Operating Hours)	Excessive Steam Flow: 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): Potential Factor Present	Thermal Distress (dT_{SH}/dt): Counts ($\Delta T > 20$ deg_ F_{SH} / Minute)	Thermal Distress (dT_{SH}/dt): Counts / (1k Operating Hours)	Thermal Distress (dT_{SH}/dt): 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: Potential Factor Present	Pressure Pulses: Avg. Hood Spray Pressure (psig)	Pressure Pulses: Hours of Hood Spray Operation	Pressure Pulses: % of Total Operating Hours	Pressure Pulses: 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: Potential Factor 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	Operating Hours	Blade Fitment: Potential Factor Present	Blade Fitment: Normalized Ranking
1	21,734	X	1.00
2	21,284	X	1.00

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

"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 exceedence hours per 1000 hours of operation in a given period
"Normalized Ranking" -- Data normalized against the highest value in the column, "Exceedance Hours / (1k Operating Hours)"

"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 the column, "Counts / (1k Operating Hours)"

"Pressure Pulses" Notes

"Avg. Hood Spray Pressure (psig)" -- Calculated from PI Historian data
"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 the column, "% of Total Operating Hours"

"Blade Fitment" Notes

"Blade Fitment" – References the gap measurements for both the mid-span snubbers and the shroud Z-Lock contact surfaces

3	10,286	X	1.00
4	2,942	X	1.00
5	1,561	X	1.00

	Damage Assessment				
	Period 1	Period 2	Period 3	Period 4	Period 5
Operating Hours	21,734	21,284	10,286	2,942	1,561
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	0 TE / 8 GE
Comments	Not Captured	TE and GE Mid-Span Snubbers Found Intact. Minimal TE and GE Shroud Chipping Observed.	High Degree of Wear Observed on Z-Locks. Z-Lock Damage / Loss of Material on TE Blade No. 41 Rendered It "Freestanding".	One (1) TE L-0 Found with Tip Liberation at Airfoil of Trailing Edge	High Degree of Wear Observed on Z-Locks.

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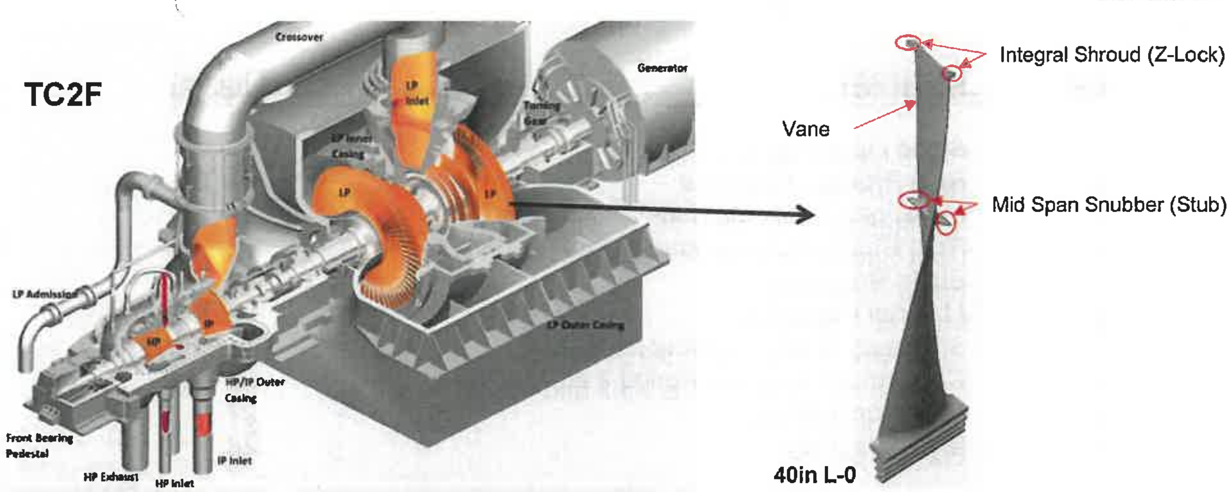

Bartow RCA Summary

Nick Porteous
Muhammad Riaz, Ph.D.

September 22nd, 2017

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Agenda

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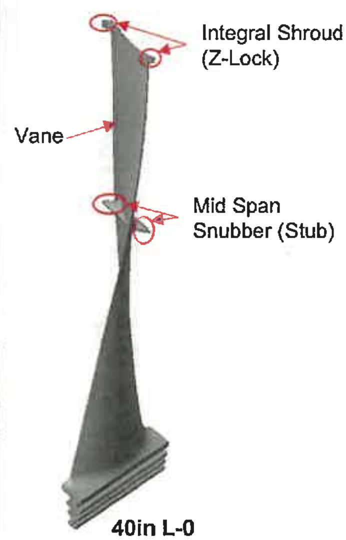
Bartow Blade Operating Summary

Period	Operating Time	Blade Type	Major Damage
Period 1	2009 - 2012	Type 1	Mid Span Snubber Only 
Period 2	2012 - 2014	Type1	No Significant Damage 
Period 3	Dec 2014 – Apr 2016	HVOF Stellite Mid Span Type 3	Shroud Only 
Period 4	Jun 2016 – Oct 2016	HVOF Stellite Mid Span + HVOF Stellite Shroud Type 3	Vane + Snubber (Note 1) 
Period 5	Dec 2016 – Feb 2017	Type 1	Mid Span Snubber Only 



Note 1 – Period 4 did not show shroud fretting fatigue / contact wear damage.

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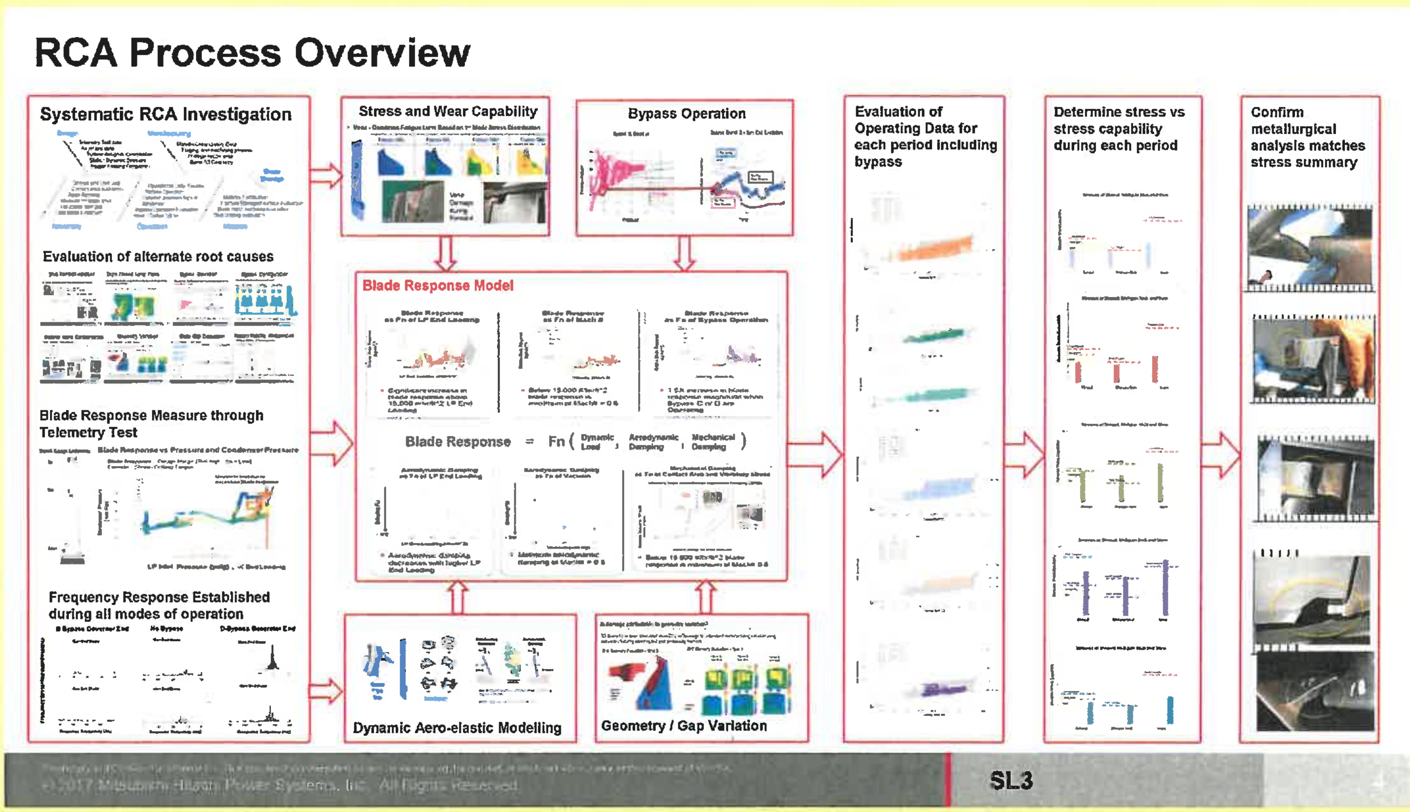

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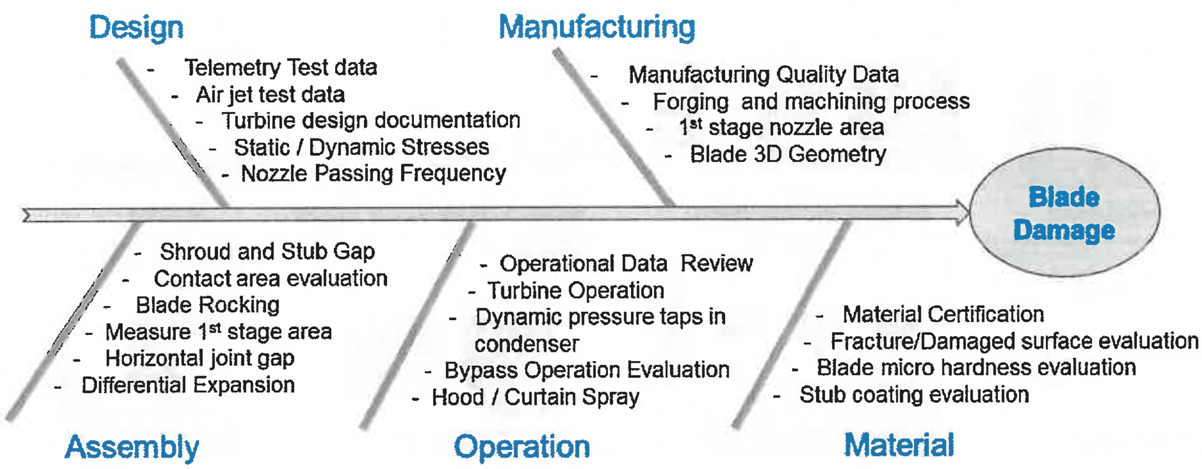
Why is Bartow's experience different from the 40in Fleet ?

- **RCA Areas of Investigation – Systematic RCA Implemented**



- LP Loading + Bypass Operation at high load were identified as the primary root causes for the Bartow 40" Blade reliability differences from the global fleet.

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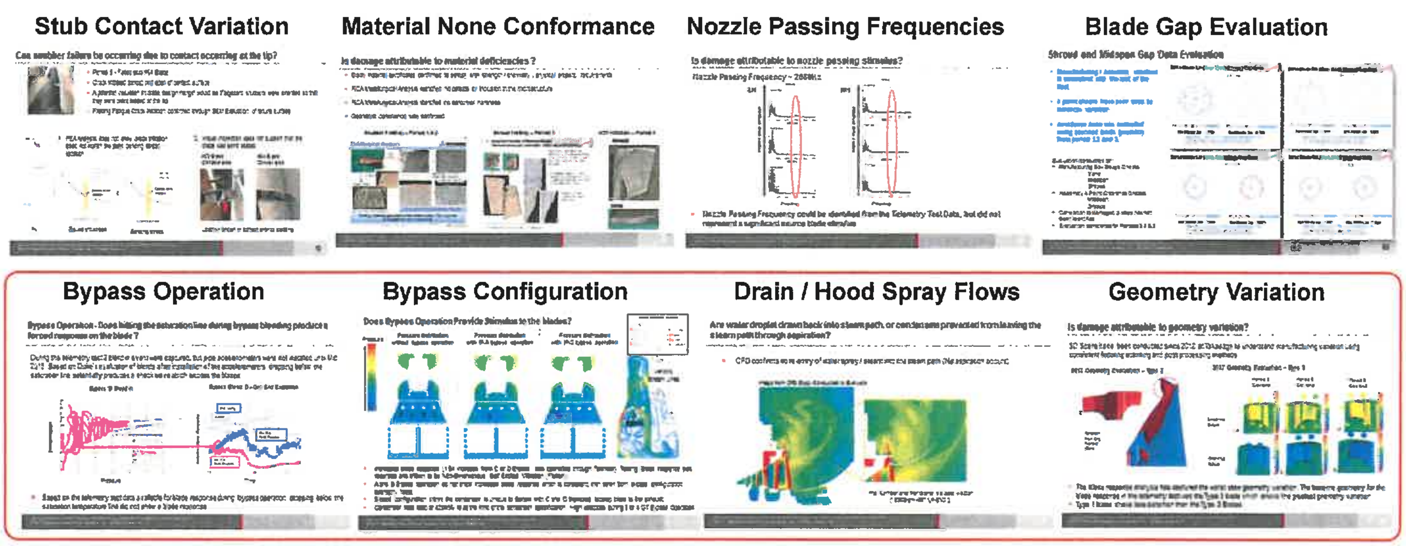
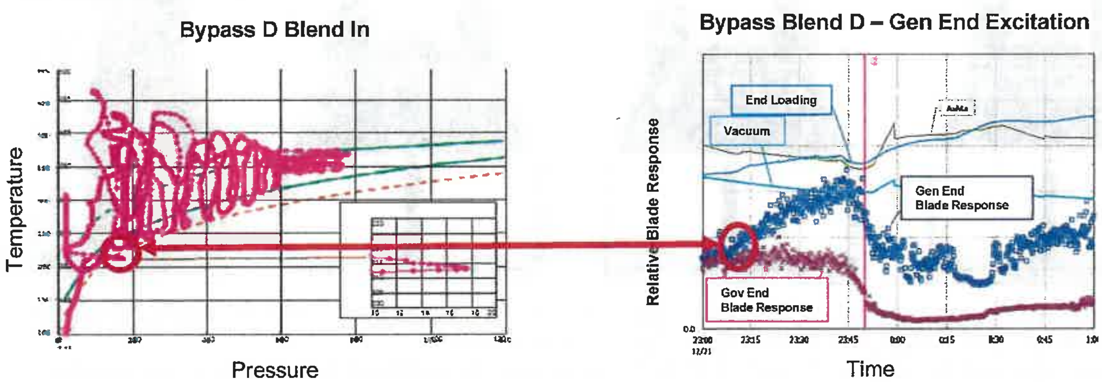
Evaluation of potential Root Causes included :



- Pressure pulses from bypass operation, drain / hood spray flows, and blade geometry variation and gaps were not found to impact on blade loading. During bypass operation increased blade response was still shown as flutter.

Bypass Operation - Does hitting the saturation line during bypass blending produce a forced response on the blade ?

During the telemetry test 2 blend in event were captured, but pipe accelerometers were not installed until Mid 2015. Based on Duke's evaluation of blends after installation of the accelerometers, dropping below the saturation line potentially produces a shock wave which excites the blades.



- Based on the telemetry test data available for blade response during bypass operation, dropping below the saturation temperature line did not show a blade response

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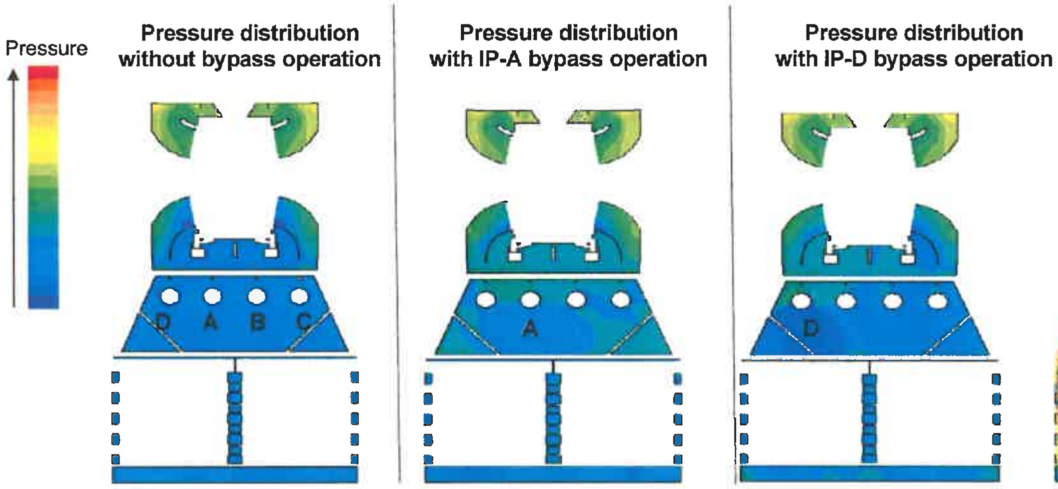
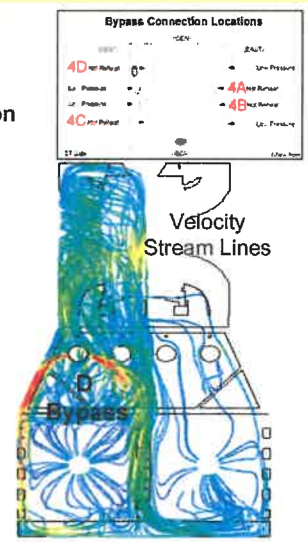
Does Bypass Operation Provide Stimulus to the blades?





- Increased blade response (1.5X Increase from C or D Bypass) was quantified through Telemetry Testing (Blade response was recorded and shown to be Non-Synchronous Self Excited Vibration (Flutter))
- A and B Bypass operation do not show increased blade response which is consistent with other 2on1 bypass configuration telemetry Tests.
- Bypass configuration within the condenser is unique to Bartow with C and D bypasses located close to the exhaust.
- Condenser heat load at 420MW is at the limit of the condenser specification. High velocities during 3 to 4 GT Bypass Operation

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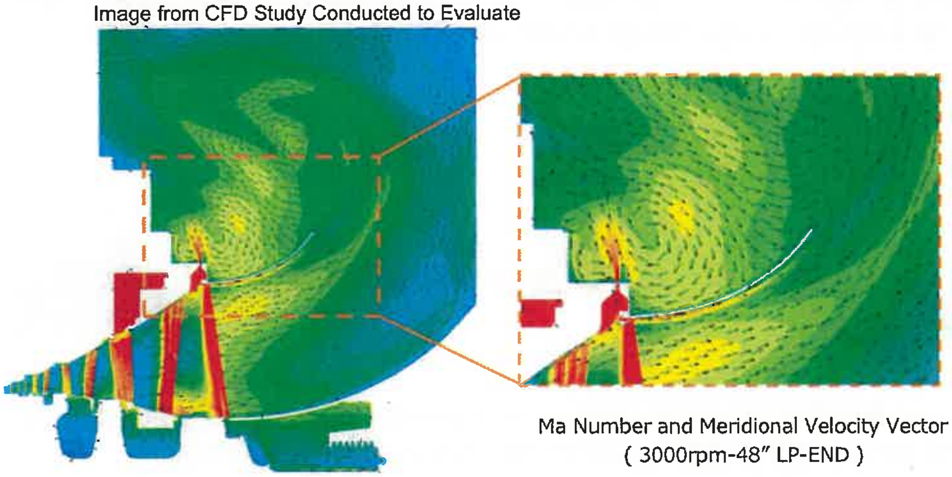
Are water droplet drawn back into steam path, or condensate prevented from leaving the steam path through aspiration?

- CFD confirms no re-entry of water spray / steam into the steam path (No aspiration occurs)

Image from CFD Study Conducted to Evaluate



Ma Number and Meridional Velocity Vector
(3000rpm-48″ LP-END)

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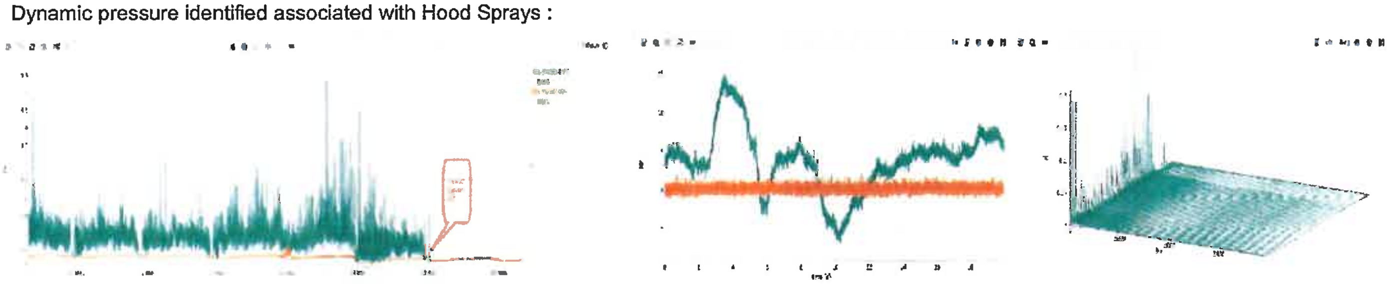
Does flashing of water droplets from hood sprays or curtain sprays within the steam path or exhaust produce a forced response on the blades?

- Telemetry Test does not show evidence of forced vibration. Blade response is self excited vibration
- Vaporization of attemperation steam droplets has not been identified as a potential source of pressure stimulus to the blades as flashing only occurs when spray water temperature is above saturation temperature (108F @ 2.4in Hg) . Larger droplet evaporate more slowly due to lower surface area to volume ratio.

Dynamic pressure identified associated with Hood Sprays :



Pressure fluctuations did not have high frequency content, and identified pressure rising from 2.5" Hg to atmospheric pressure. No corresponding blade response identified during telemetry test.

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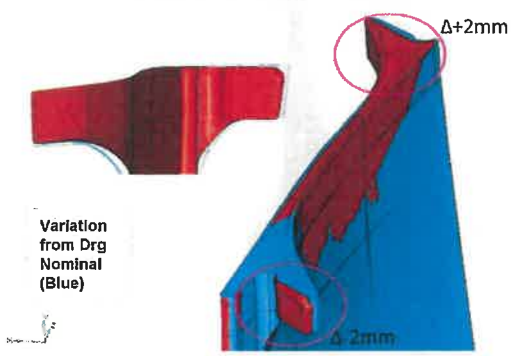
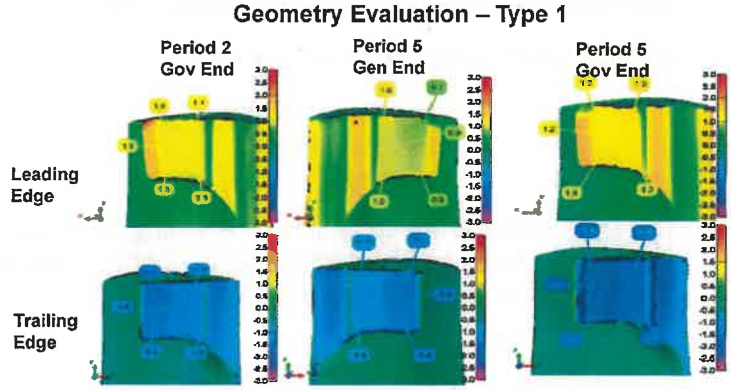
Is damage attributable to geometry variation?

- 3D Scans have been conducted since 2012 at Takasago to understand manufacturing variation using consistent fixturing scanning and post processing methods.
- 55 Rows of blade in operation with zero occurrence of midspan snubber damage. (All see same centrifugal loads)

Geometry Evaluation – Type 3



Geometry Evaluation – Type 1



- The blade response analysis has captured the worst case geometry variation. The baseline geometry for the blade response in the telemetry test was the Type 3 blade which shows the greatest geometry variation.
- Type 1 blade shows less distortion than the Type 3 Blades.

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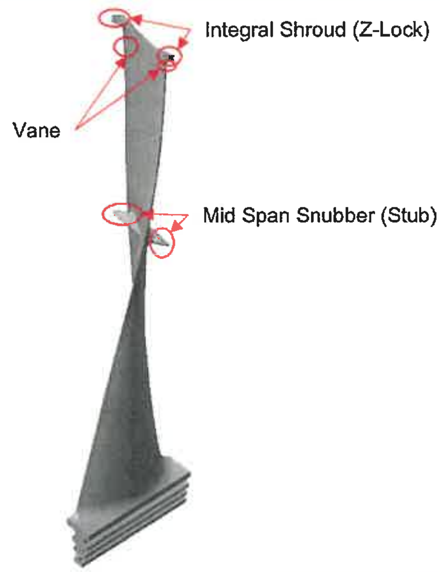
Damage Mechanism

Blade damage occurs when : Stress > Material Capability

- Stress comes from Dynamic Loads superimposed on the steady state loads (Centrifugal + Steam Bending Loads).
- Limiting stress locations for 40" L-0 Blade :

  1) Mid Span Snubber
  2) Integral Shroud
  3) Vane HCF

- Dynamic Stresses are controlled by avoiding resonant operating conditions where the blade response frequency matches frequency of the stimulus, and ensuring adequate damping.



Root Cause Analysis has identified all blade damage from Period 1 thru Period 5 has been identified as Dynamic Loads from Non-Synchronous Self Excited Vibration (Flutter)

Note : Non-synchronous 1st Mode Higher Nodal Diameters response was presented March 18th 2015 , prior to Period 3 RCA

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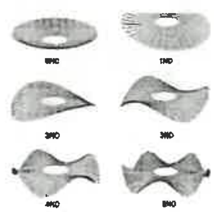
Non-Synchronous Self Excited Vibration (Flutter)

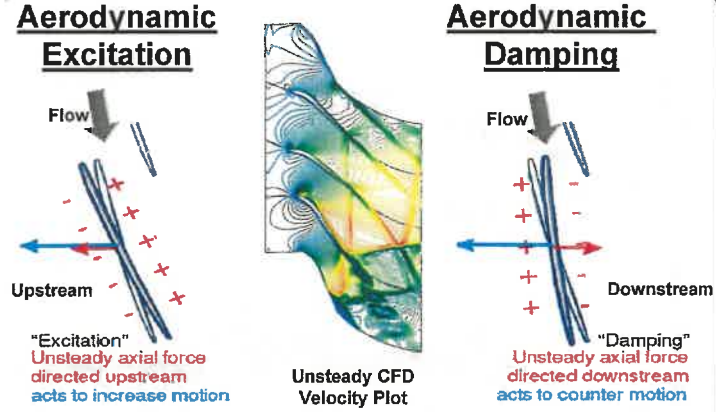
- Blade response is measured during Telemetry Testing and analytically predicted at around 16th Nodal Diameter of the first mode (approx. 200Hz).
- The Notable Non-synchronous Vibration is caused by aero-dynamic flow and observed as the Multiple Modes Response (180Hz-230Hz).

Similar to 1st Mode Shape



Nodal Diameters

- Cycles accumulate at 12,000 cycles per minute at 200 Hz



- Alternating component of pressure shown as (Red) at mid point of travel
- Motion (Blue) at midpoint of vibration cycle

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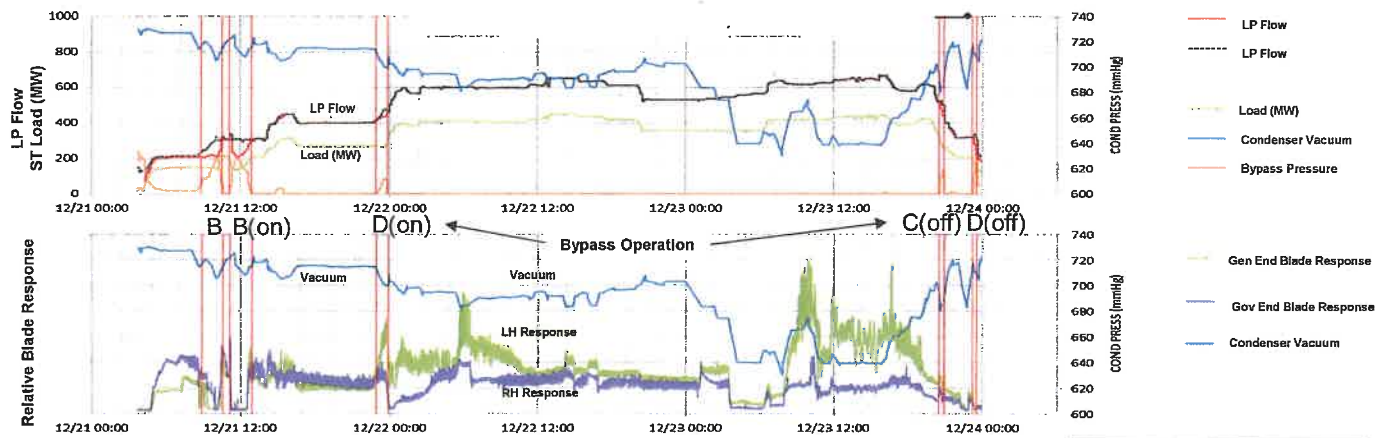
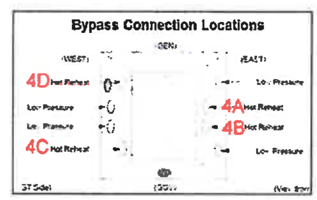
How do we know the dominant response is Non-Synchronous Self Excited Vibration?

A Telemetry Test directly measuring the blade response was conducted – Dec 21st to Dec 24th 2014



Range of Operating Conditions During Test :

- Blade Response was measured up to 455 MW and 5 in.Hg
- Bypass Operation of 2 Blend In and 2 Blend Out Events were recorded
- Mach Number Ranged from 0.4 to 0.9



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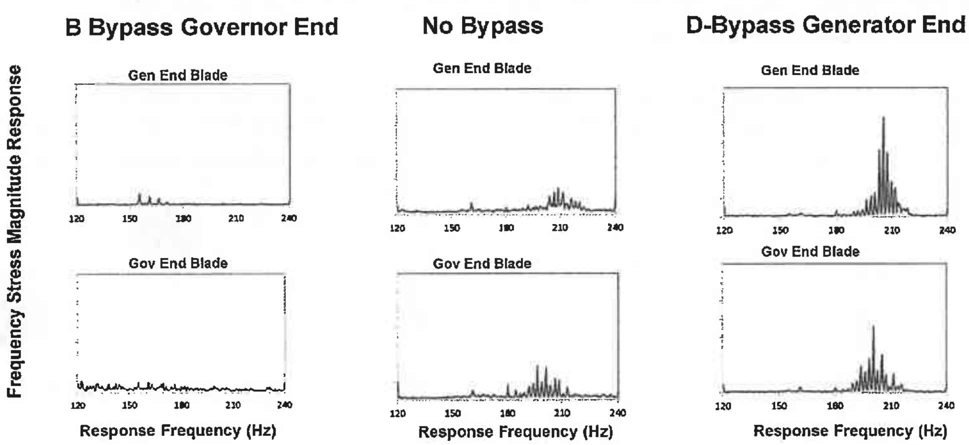
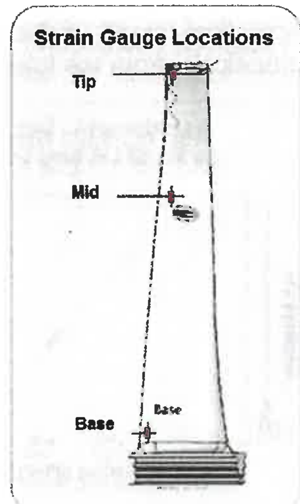
How do we know the dominant response is Non-Synchronous Self Excited Vibration?

Frequency Response from Telemetry Test :





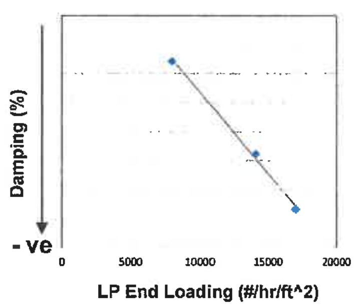
Recorded Response :

- Peeks at 120, 180, 240Hz are per Rev Responses
- Peeks between 180 to 230Hz are High Nodal Diameter responses of the First Cantilever Mode. These frequencies are associated with Non-Synchronous Self Excited Vibration

Blade Response = Fn (Dynamic Load , Aerodynamic Damping , Mechanical Damping)

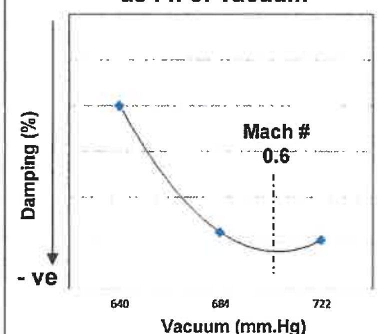
Analytical results of damping below show trends, but the magnitude of blade response is established empirically from the telemetry test conducted at the start of period 3

Aerodynamic Damping as Fn of LP End Loading



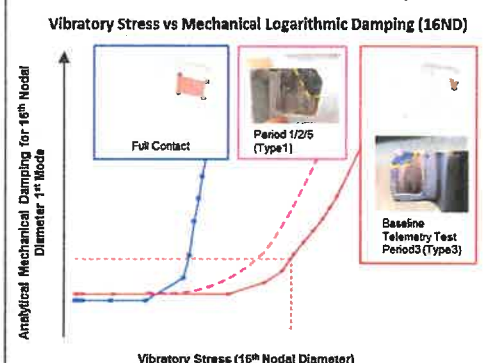
- Aerodynamic damping decreases with higher LP End Loading

Aerodynamic Damping as Fn of Vacuum



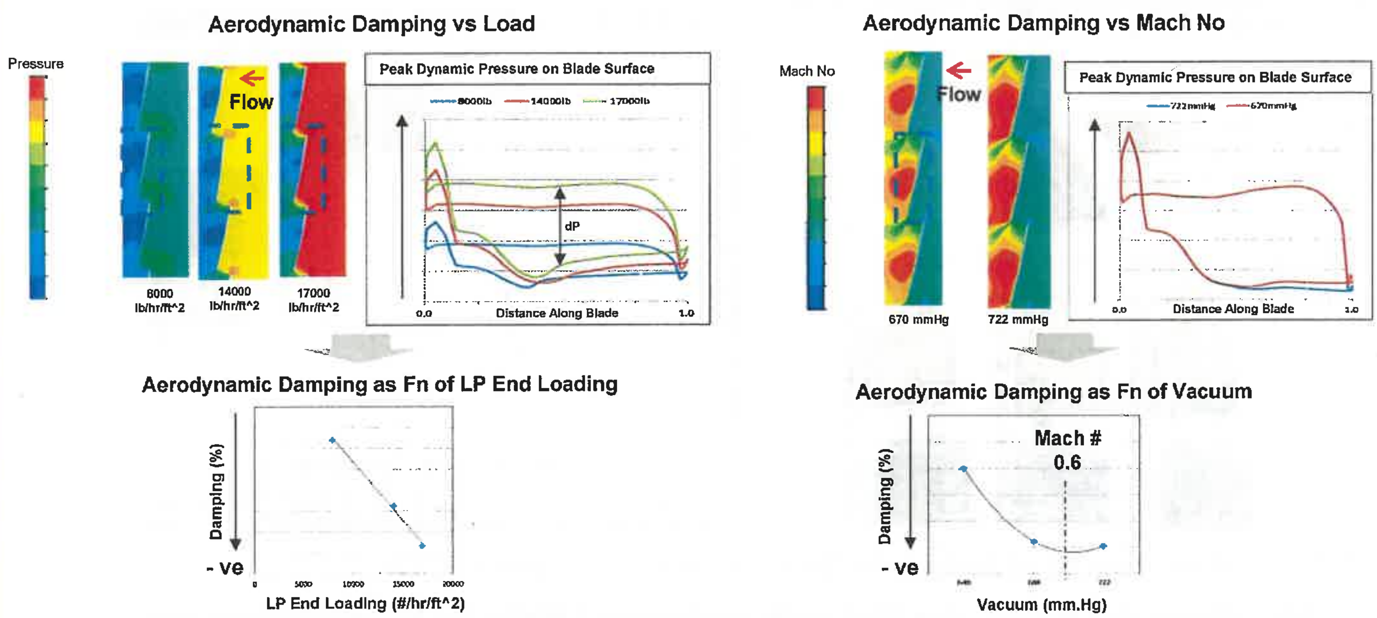
- Minimum aerodynamic damping at Mach# = 0.6

Mechanical Damping as Fn of Contact Area and Vibratory stress



- Mechanical damping decreases with smaller contact area

Aerodynamic Damping Analysis (Vibratory Stress and Logarithmic Damping)



Transient CFD was Correlated with Telemetry Test Data to understand Aerodynamic Damping

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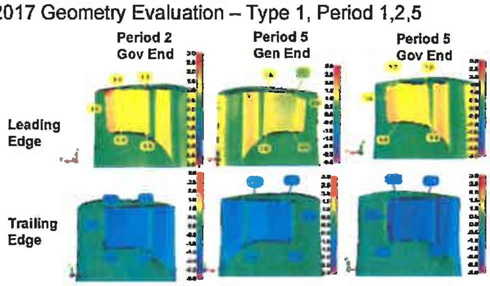
Geometry Variation - Mechanical Damping is impacted by contact faces on adjacent blades

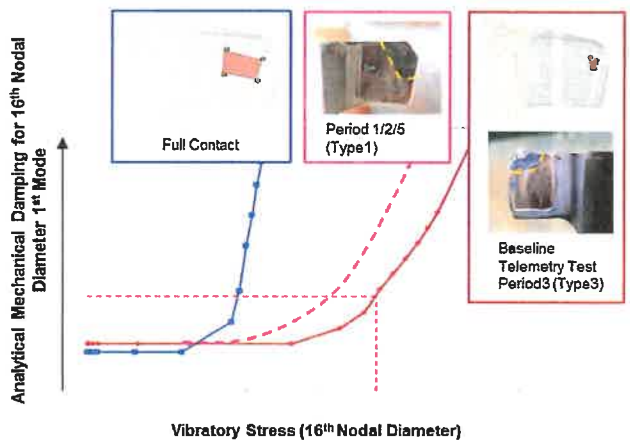
3D Scans conducted on multiple blades for Period 1,2,3 & 5 to understand manufacturing variation

2012 Geometry Evaluation – Type 3 Period 3

2017 Geometry Evaluation – Type 1, Period 1,2,5



Vibratory Stress vs Mechanical Logarithmic Damping (16ND)



Analytical damping results are intended to understand drivers for blade response, absolute blade response was established from Telemetry Test

- Type 3 Blades established the baseline blade response from the telemetry test.
- Type 3 Blades were found to have lower damping than Type 1 Blades due to smaller contact area

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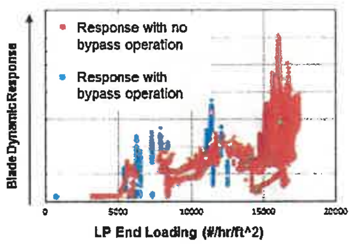
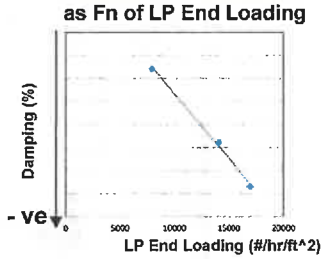
Blade Response = Fn (Dynamic Load , Aerodynamic Damping , Mechanical Damping)

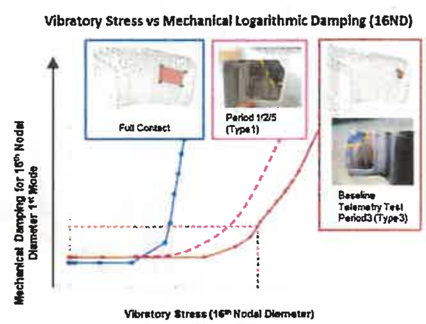
Blade Response
as Fn of LP End Loading



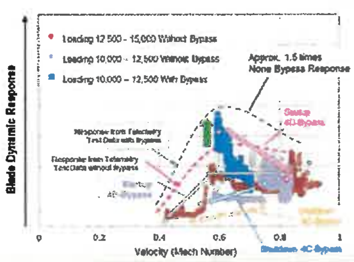
Aerodynamic Damping
as Fn of LP End Loading



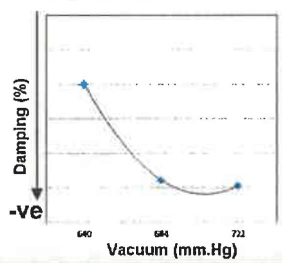
Mechanical Damping
as Fn of Contact Area and Vibratory stress



Blade Response
as Fn of Mach No. and Bypass Operation



Aerodynamic Damping
as Fn of Vacuum

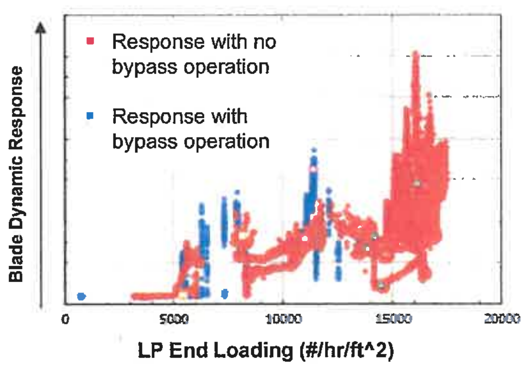


- Details in following slides

Blade Response as a Function of LP End Load

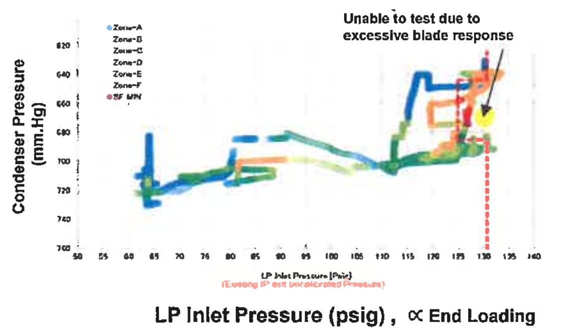
The telemetry test provided direct blade magnitude of the blade response from strain gauges

Blade Response vs LP End Loading



Blade Response vs Pressure and Condenser Pressure

Blade Response – Design Margin (Red High / Blue Low)
Example : Shroud Fretting Fatigue

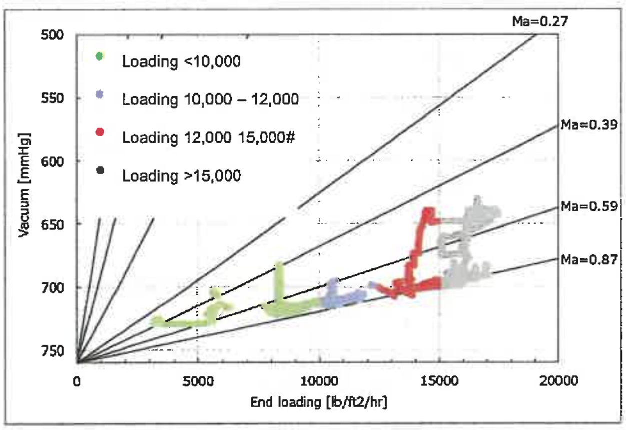


- Outside of the originally developed design space, blade response becomes sensitive to operating conditions.
  Example : At 16,500 #/hr/ft^2 there is a 10X change in blade response based on condenser pressure

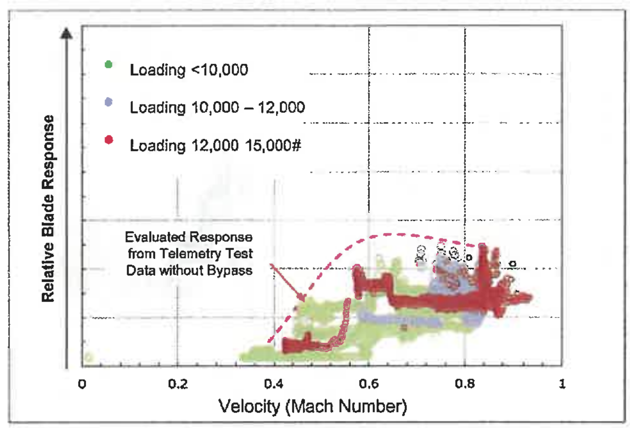
- The avoidance zone established in 2015 was developed to prevent operation in the region which measured high blade response.

Blade Response as a Function of Mach Number – without Bypass

Telemetry Test Operation without Bypass



Blade Response vs Velocity without Bypass



- Below 15,000 lb/hr/ft^2 Blade Response becomes dominated by Mach Number

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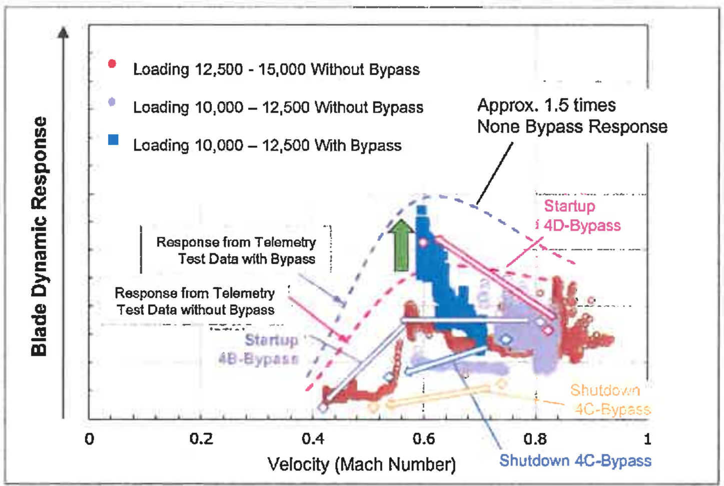
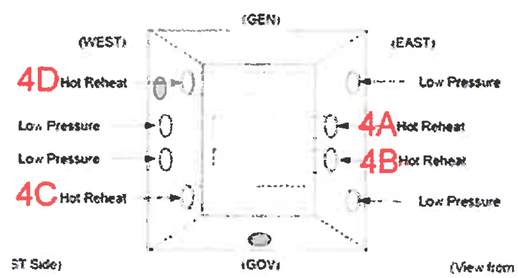
Blade Response as a Function of Bypass Operation



Bypass Connection Locations



- Bypass C Operation increases response on Governor End Blades
- Bypass D Operation increases response on Generator End Blades

- Operation with Bypass D and C Produce a 1.5X Increase in blade response on the blades closest to the bypass
- Operation with Bypass A and B did not show an increase in blade response over none Bypass Operation

- Limited Blade Response data during Bypass is available with the operation before and after Dec 2014 Telemetry Testing being assumed to have remained the same change in response.

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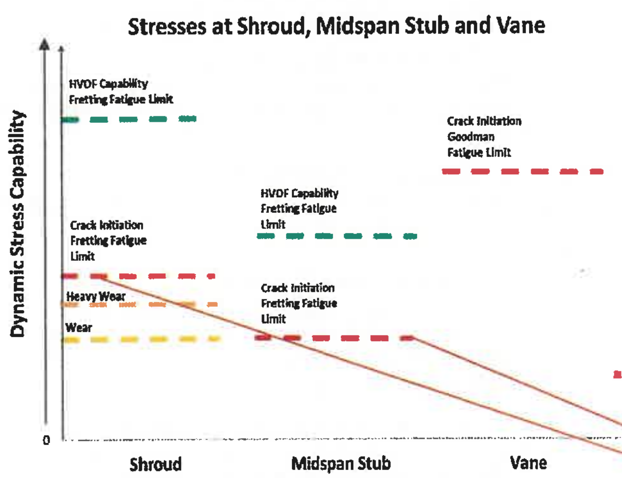
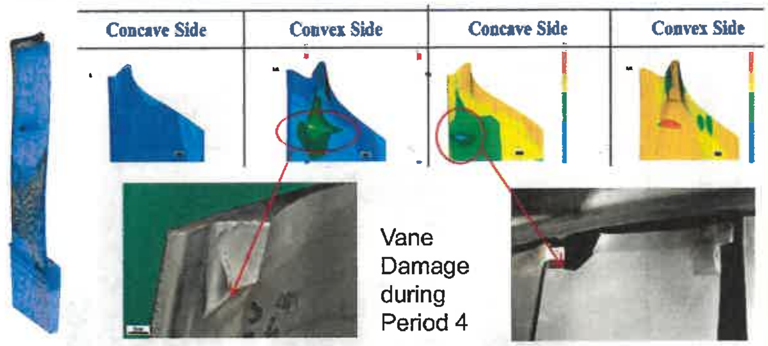
Material Capability – Material Test Data

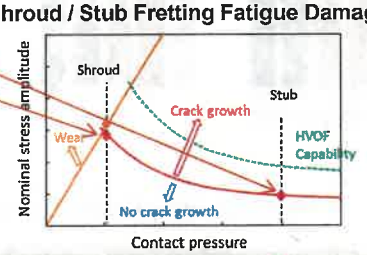


- Estimated Blade Response can be evaluated against Material Capability for Shroud, Mid Span Stub, and Vane

- Vane - Goodman Fatigue Limit Based on 1st Mode Stress Distribution

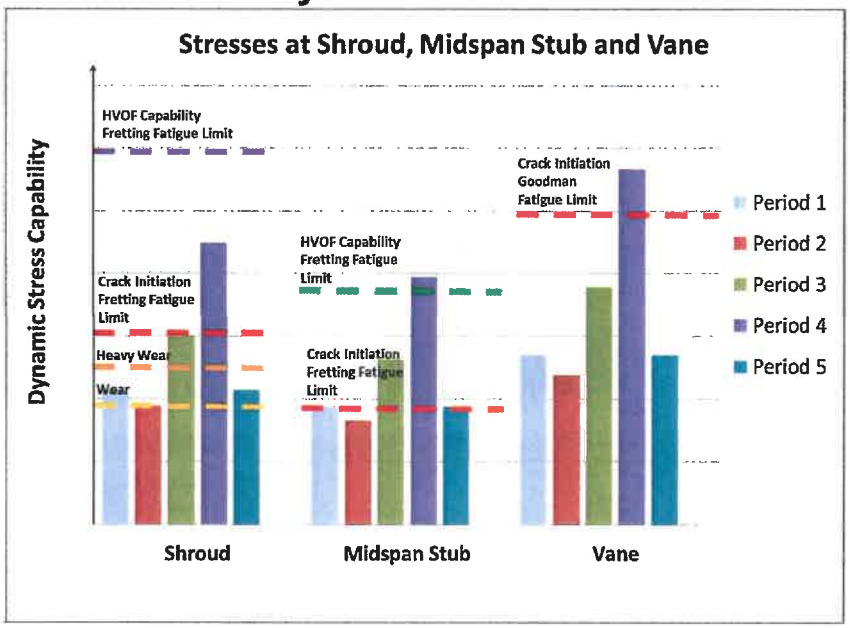


- Shroud / Stub Fretting Fatigue Damage based on fretting material testing



- Stress Amplitude relative to Contact Pressure impacts fretting capability
- Application of HVOF doubles the fretting fatigue capability

Stress Summary – Period 1 thru 5



- **Period 1 – Mid Span Stub Cracking**
  High LP Loading but increased mechanical damping from Type 1 blade over baseline telemetry test
- **Period 2 – No Major Damage**
  Reduced LP Loading over Period 1, reduced bypass operation loading over period 5, light wear observed on shroud
- **Period 3 – Shroud Cracking**
  High LP Loading identified in Telemetry Test. Mid Span Stub protected by HVOF
- **Period 4 – Vane Cracking**
  Reduced Loading. Application of HVOF reduces mechanical damping increasing amplitude of response. With HVOF protecting Shroud and Stub, the limiting location becomes the Vane
- **Period 5 – Mid Span Stub Cracking**
  Reduced Loading with longer periods of bypass operation at High Mach Number over Period 2. No HVOF Protection

- Damage observed in all 5 Periods of operation is consistent Blade Response vs Capability Model

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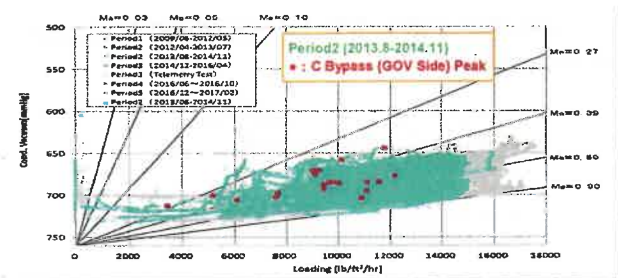
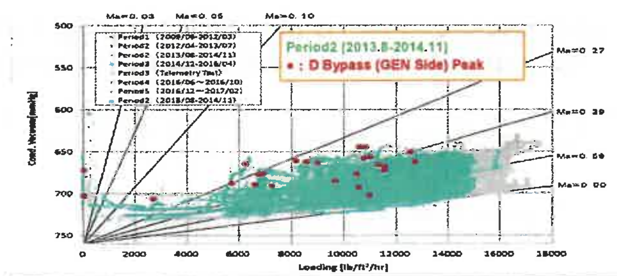
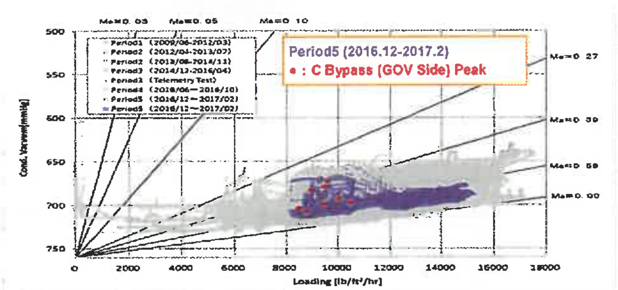
How is the different operating experience between Period 2 and Period 5 explained ?



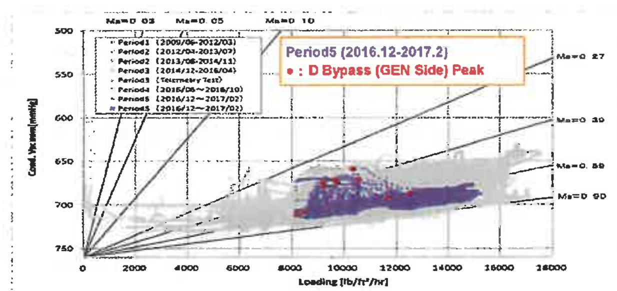
Period 2 Gov End - Type 1 Blade



Period 2 Gen End - Type 1 Blade



Period 5 Gov End - Type 1 Blade



Period 5 Gen End - Type 1 Blade

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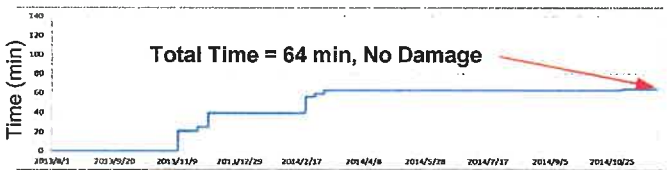
How is the different blade damage between Period 2 and Period 5 Explained ?

The following evaluation is intended to highlight difference in Period 2 to 5. It is not intended to be an absolute methodology to predict damage accumulation on the blades.

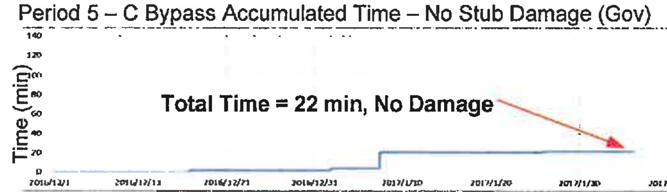
- Damage accumulates with High Load Bypass Operation of 4th GT Blending In or Out at 4C or 4D , High Mach #
- Accumulated damage below is based on time spent conducting 4th GT Bypass on C or D + Mach# > 0.55

Period 2 – C Bypass Accumulation – No Stub Damage (Gov)



Period 2 – D Bypass Accumulation – No Stub Damage (Gen)
+ Period 1 but no minute data available

Period 5 – C Bypass Accumulated Time – No Stub Damage (Gov)



Period 5 – D Bypass Accumulated Time – Stub Damage (Gen)

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RCA Summary

Period	Operating Time	Blade Type	Loading	Aerodynamic Damping	Mechanical Damping	Root Cause
Period 3	Dec 2014 – Apr 2016	HVOF Midpsan Type 3	169 hrs Operation in avoidance zone High Load Bypass Operation (4th GT)	Baseline Response	Baseline Response	Operation 169 hrs in avoidance zone Mid Span protected by HVOF resulting in no Damage from Bypass Operation
Period 4	Jun 2016 – Oct 2016	HVOF Midspan + HVOF Shroud Type 3	69 min Operation in avoidance zone High Load Bypass Operation (4th GT)	Baseline Response Assumed	HVOF reduces contact area and reduces mechanical damping	Low mechanical damping from application of HVOF increased magnitude of blade response above telemetry test levels. No Bypass Operation at high loading / Mach #
Period 5	Dec 2016 – Feb 2017	Type 1 (No HVOF)	No operation in avoidance zone. Increased time with High Load Bypass Operation (4th GT) Bypass Water Hammer Event	Baseline Response Assumed	Baseline Response Assumed	Blending GT C or D as 4th GT at high load 4on1 Configuration is creating higher blade loading than fleet experience Vibration events from the bypass are not showing a blade response. Impact of water hammer event on blade is not confirmed.

Upgraded blade to achieve 450MW available by Oct 2018

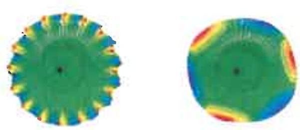
Features :

1) Updated Design Criteria – For Fretting Fatigue

Based on Development Material Testing in 2016 :

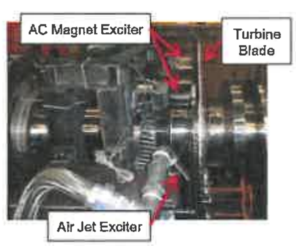
Old Design Criterial – Fretting Fatigue Limit to prevent crack initiation
New Design Criteria – Fretting Fatigue Limit to prevent crack propagation

2) Test Facility Upgraded to Excite High Nodal Diameter Modes



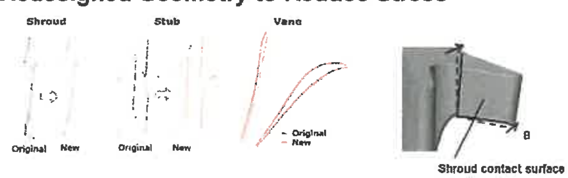
High-nodal diameter mode | Low-nodal diameter mode

Magnetic exciter allows stimulus of high nodal diameter nodes with back to back testing being conducted on old vs new design to confirm design improvements.



Blade Excitation System

3) Redesigned Geometry to Reduce Stress



Design changes planned (including Type 5 Blade Shroud Geometry Improvement to reduce blade response and induced dynamic stress by 80%. Results can be validated in upgraded test facility.

4) Telemetry Testing + BVM

Application of upgraded blade would include initial telemetry test to validate operating design space for Bartow's plant configuration and include BVM Blade Vibration Monitoring System for continuous real time monitoring of blade response.

5) Bypass Operating Guidelines

If required based on Telemetry Test results, operating guidelines for bypass can reduce blade response by minimizing operation of C and D Bypass at a Mach # > 0.55
DCS controls update strategy is in evaluation.

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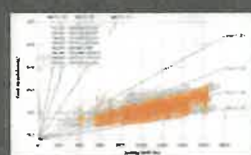
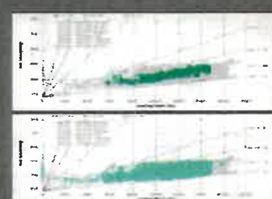
MHPS

Backup

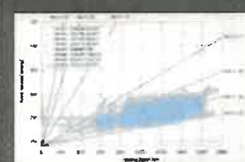
Operating Summary Period 1 thru 5



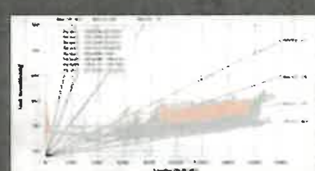
Period 1



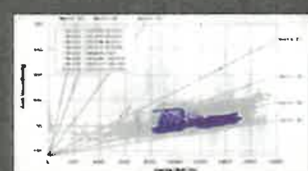
Period 2



Period 3



Period 4

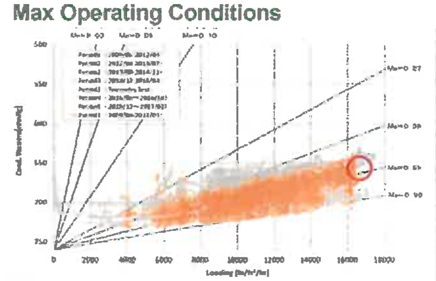


Period 5

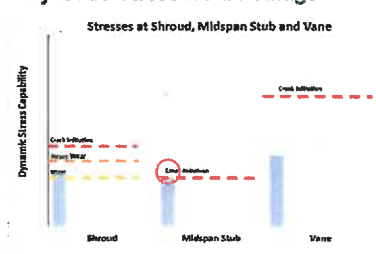
Period 1 – Stub Cracking

Operation at higher loads than Period 3, but Type 1 Blade has improved damping over Type 3 in Telemetry Test

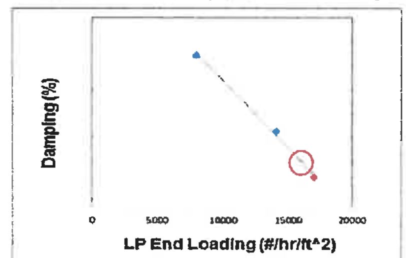
Max Operating Conditions



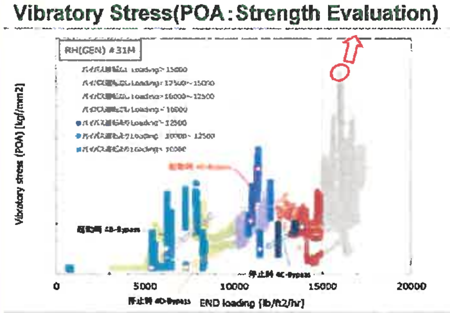
Dynamic Stress from Damage



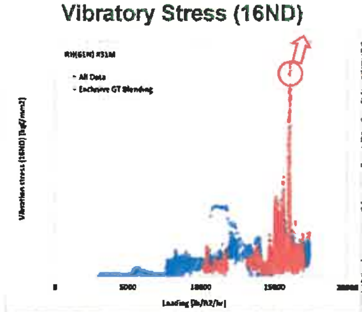
Aerodynamic Damping (3D Flutter Analysis)



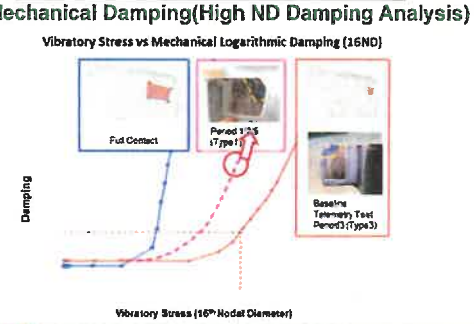
Vibratory Stress(POA:Strength Evaluation)



Vibratory Stress (16ND)



Mechanical Damping(High ND Damping Analysis)



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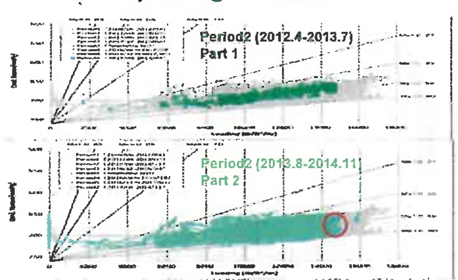
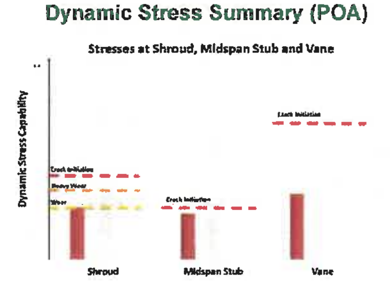
Period 2 – No Major Damage, Minor Shroud Chipping

Reduced LP Loading over Period 1, reduced bypass operation loading over period 5, light wear observed on shroud

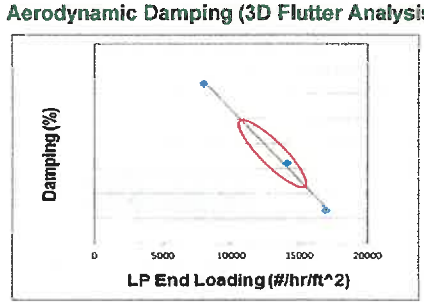
Max Operating Conditions



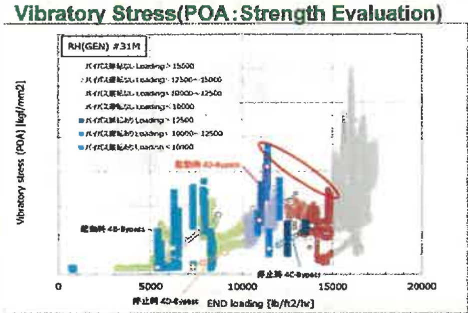
Dynamic Stress Summary (POA)



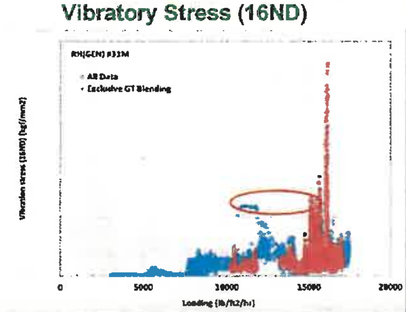
Aerodynamic Damping (3D Flutter Analysis)



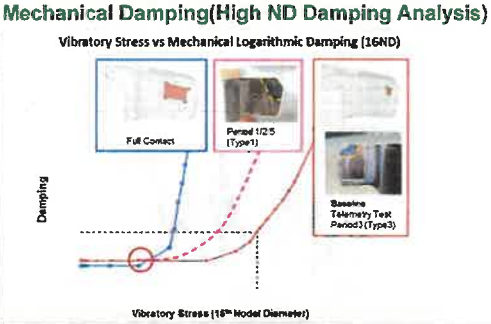
Vibratory Stress(POA:Strength Evaluation)



Vibratory Stress (16ND)



Mechanical Damping(High ND Damping Analysis)



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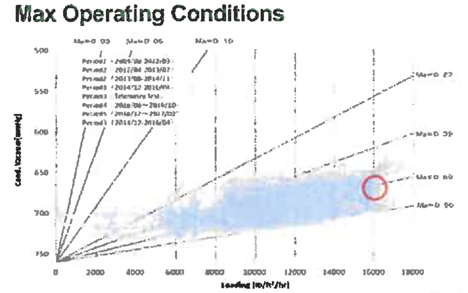
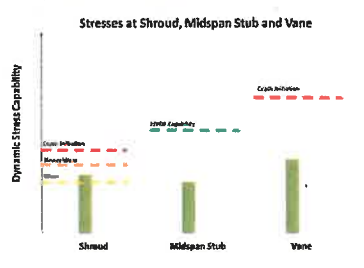
Period 3 – Shroud Cracking - Outside Avoidance Zone

Outside of avoidance zone, bypass operation becomes most limiting. With HVOF on Mid Span Stub no cracking is predicted.

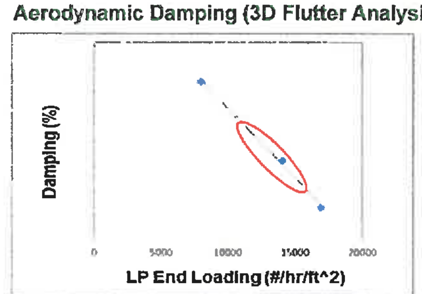
Max Operating Conditions



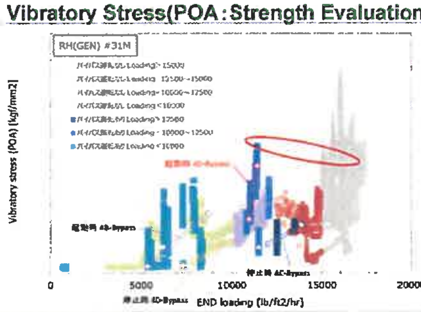
Dynamic Stress Summary (POA)



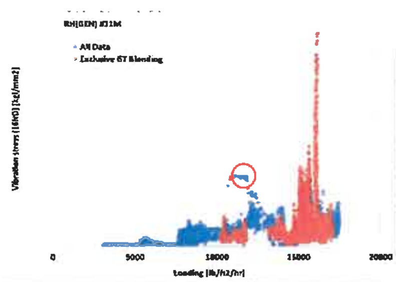
Aerodynamic Damping (3D Flutter Analysis)



Vibratory Stress(POA:Strength Evaluation)

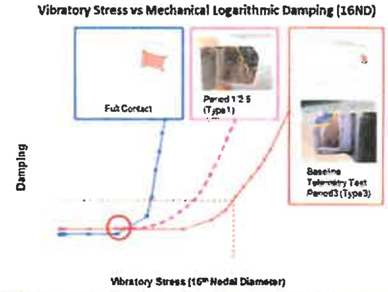


Vibratory Stress (16ND)



Mechanical Damping(High ND Damping Analysis)

Vibratory Stress vs Mechanical Logarithmic Damping (16ND)



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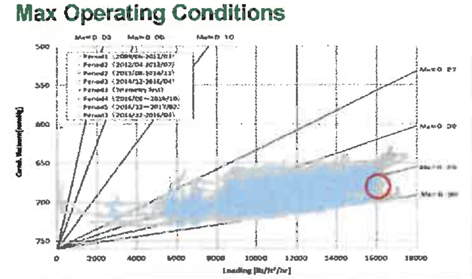
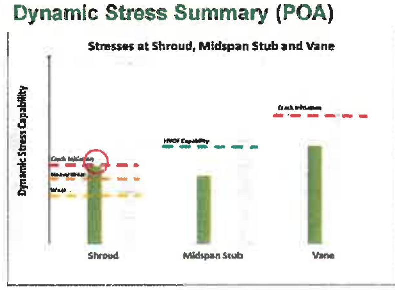
Period 3 – Shroud Cracking– Inside avoidance zone

High blade response established in Telemetry Test. Mid Span Stub protected by HVOF. Shroud become limiting location.

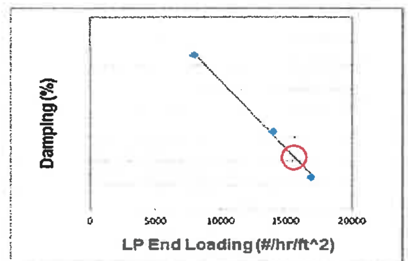
Max Operating Conditions



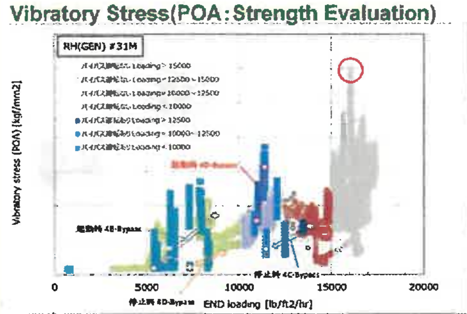
Dynamic Stress Summary (POA)



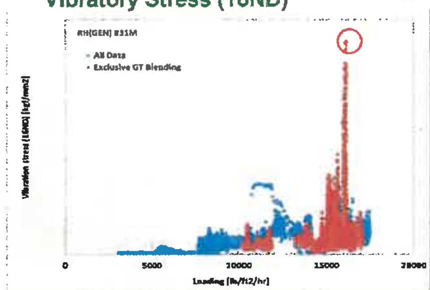
Aerodynamic Damping (3D Flutter Analysis)



Vibratory Stress(POA : Strength Evaluation)

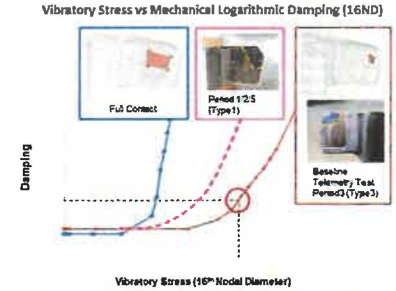


Vibratory Stress (16ND)



Mechanical Damping(High ND Damping Analysis)

Vibratory Stress vs Mechanical Logarithmic Damping (16ND)



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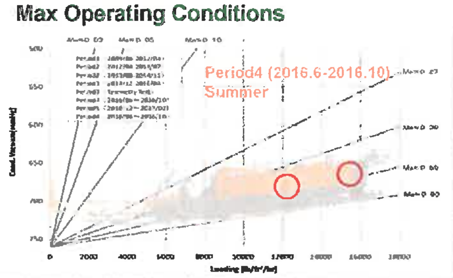
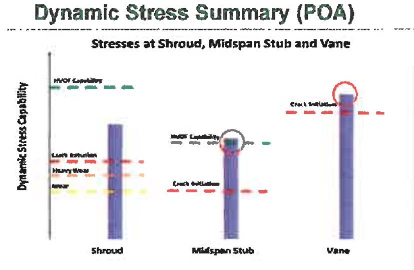
Period 4 – Vane + Stub Cracking

Reduced LP Loading. Application of HVOF reduces mechanical damping increasing amplitude of response. With HVOF protecting the Shroud and Stub, the limiting location becomes the Vane

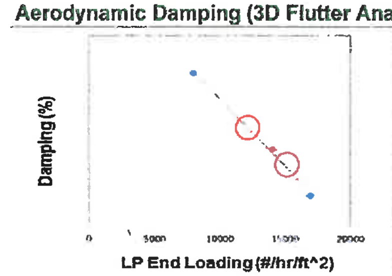
Max Operating Conditions



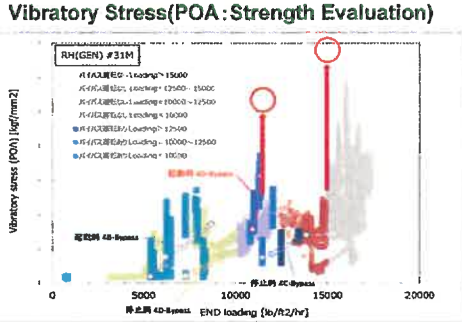
Dynamic Stress Summary (POA)



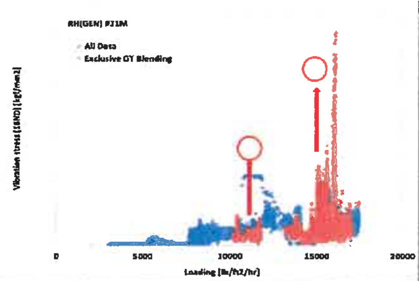
Aerodynamic Damping (3D Flutter Analysis)



Vibratory Stress(POA : Strength Evaluation)

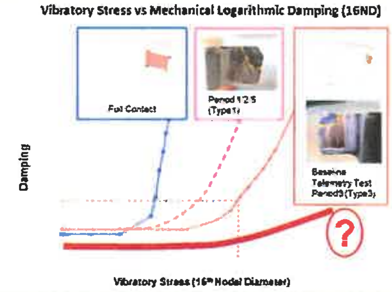


Vibratory Stress (16ND)



Mechanical Damping(High ND Damping Analysis)

Vibratory Stress vs Mechanical Logarithmic Damping (16ND)



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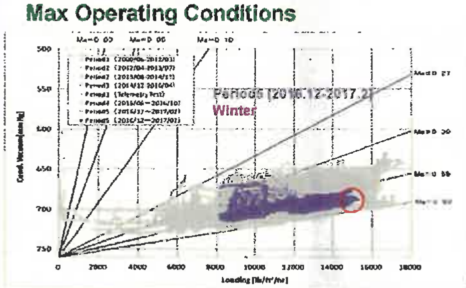
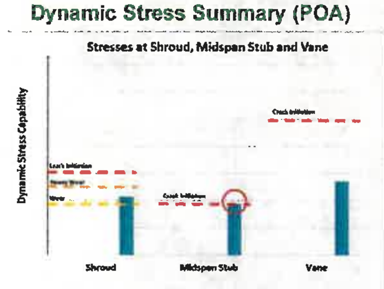
Period 5 – Stub Cracking

Reduced LP Loading over Period 2 with longer periods of bypass operation at High Mach Number. No HVOF Protection.

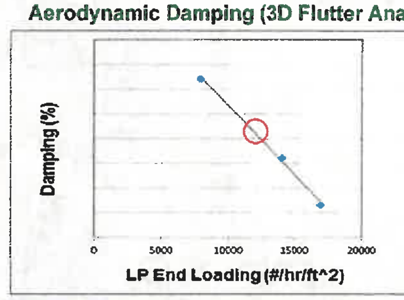
Max Operating Conditions



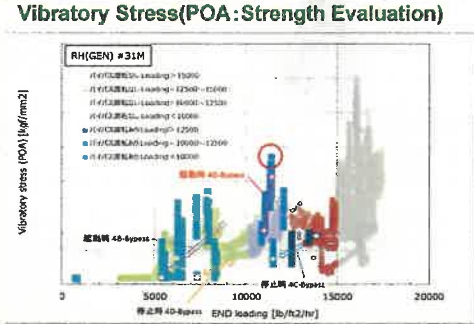
Dynamic Stress Summary (POA)



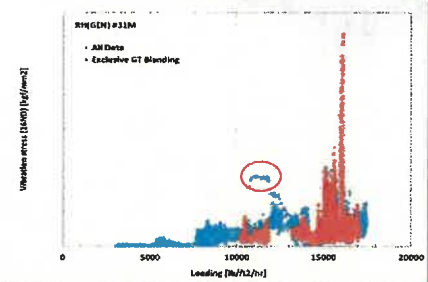
Aerodynamic Damping (3D Flutter Analysis)



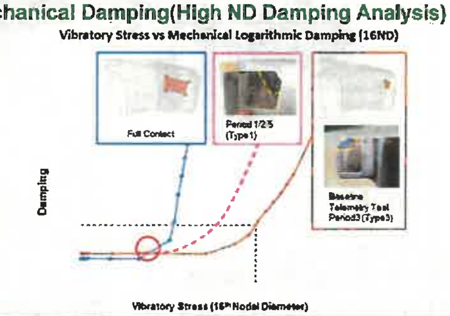
Vibratory Stress(POA:Strength Evaluation)



Vibratory Stress (16ND)



Mechanical Damping(High ND Damping Analysis)



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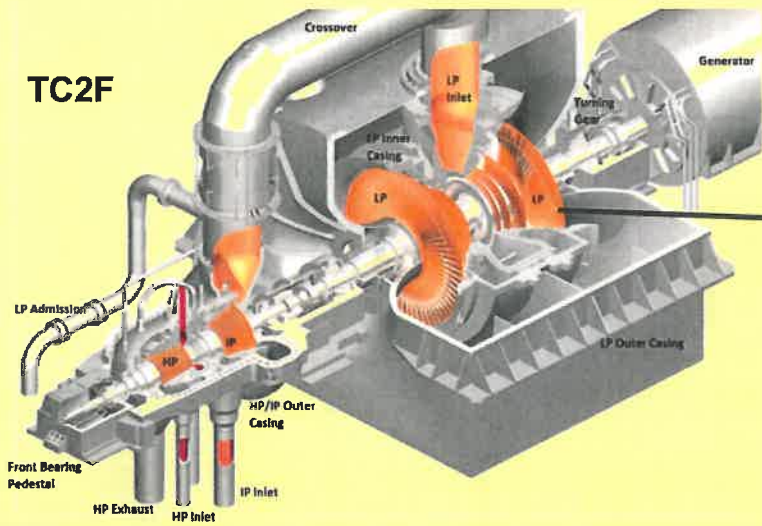

Bartow RCA - Actions

October 2nd , 2017

Nick Porteous
Muhammad Riaz, Ph.D.

SL3

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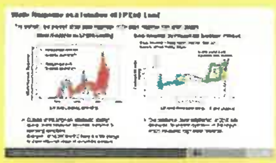
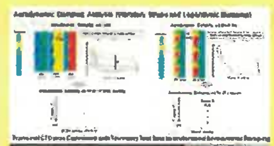
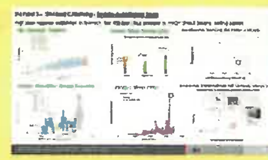
Duke - Empirical Evaluation of Root Cause

Duke identified 5 potential root causes. Items 1,3,4,5 were addressed during the 9/22/17 RCA Meeting as identified below. Item 2 is addressed in this presentation.

1) Excessive Steam Flow
Reviewed on Slides 17, 20, 39 →

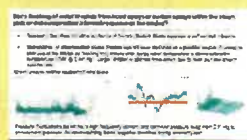






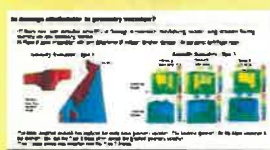
2) Thermal Distress
Summary included in this presentation

3) Pressure Pulses
Reviewed on Slide 10 →



4) Loss of Dampening
Reviewed on Slide 40 →

5) Blade Fitment
Reviewed on Slides 11, 34 →



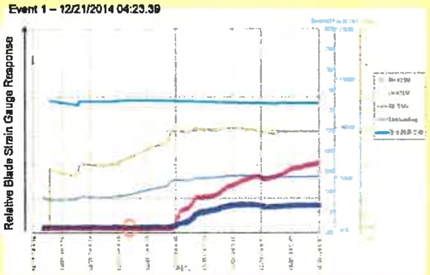
Note : Slides Referenced are from presentation : Bartow RCA Summary, Sept 22nd 2017

Thermal Distress Evaluation

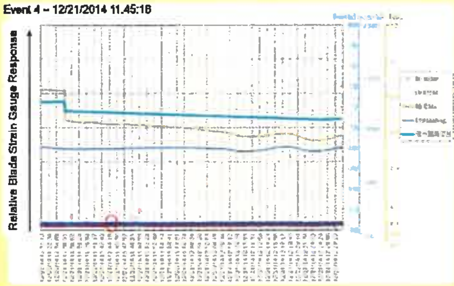
The action was taken on 9/22/17 to evaluate the telemetry test data to confirm whether high rate of change events of superheat showed any blade response.

Evaluation of the 11 thermal event during the 2014 telemetry test did not show any corresponding increase in blade response.

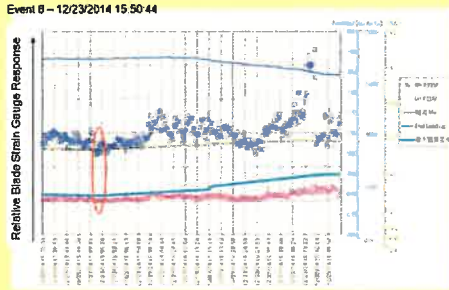
Event 1 – 12/21/2014 04:23.39



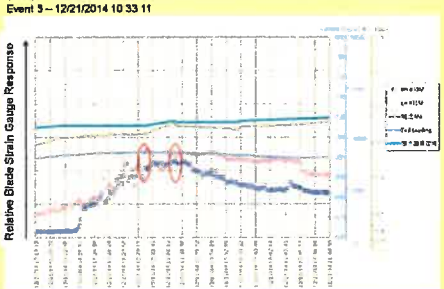
Event 4 – 12/21/2014 11.45:18



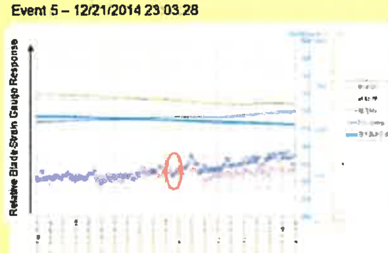
Event 6 – 12/23/2014 15:50:44



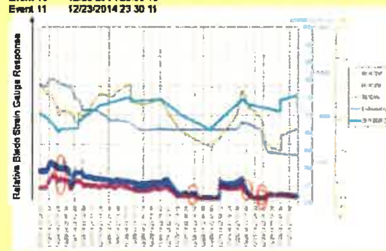
Event 2 – 12/21/2014 10:29:49
Event 3 – 12/21/2014 10:33:11



Event 5 – 12/21/2014 23:03:28



Event 7 12/23/2014 20:40:13
Event 8 12/23/2014 22:32:43
Event 9 12/23/2014 23:17:58
Event 10 12/23/2014 23:30:10
Event 11 12/23/2014 23:30:11



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RCA Summary (Updated with period 1 and 2)

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Period	Operating Time	Blade Type	Loading	Aerodynamic Damping	Mechanical Damping	Root Cause
Period 1	2009 - 2012	Type 1 (No HVOF)	>2400 hrs with high loading High Load Bypass Operation (4th GT)	Baseline Response Assumed	Baseline Response Assumed	Operation beyond design limit of 15,000#/hr/ft^2. Mechanical damping improves with contact surface wear over time reducing rate of damage.
Period 2	2012 - 2014	Type 1 (No HVOF)	~1hr with high loading High Load Bypass Operation (4th GT)	Baseline Response Assumed	Baseline Response Assumed	No significant damage observed
Period 3	Dec 2014 – Apr 2016	HVOF Midpsan Type 3	169 hrs Operation in avoidance zone High Load Bypass Operation (4th GT)	Baseline Response	Baseline Response	Operation 169 hrs in avoidance zone Mid Span protected by HVOF resulting in no Damage from Bypass Operation
Period 4	Jun 2016 – Oct 2016	HVOF Midspan + HVOF Shroud Type 3	69 min Operation in avoidance zone High Load Bypass Operation (4th GT)	Baseline Response Assumed	HVOF reduces contact area and reduces mechanical damping	Low mechanical damping from application of HVOF increased magnitude of blade response above telemetry test levels. No Bypass Operation at high loading / Mach #
Period 5	Dec 2016 – Feb 2017	Type 1 (No HVOF)	No operation in avoidance zone. Increased time with High Load Bypass Operation (4th GT) Bypass Water Hammer Event	Baseline Response Assumed	Baseline Response Assumed	Blending GT C or D as 4th GT at high load 4on1 Configuration is creating higher blade loading than fleet experience Vibration events from the bypass are not showing a blade response. Impact of water hammer event on blade is not confirmed.

Bartow Steam Turbine
RCA Review
Nov 9th 2016

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.

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RCA Team

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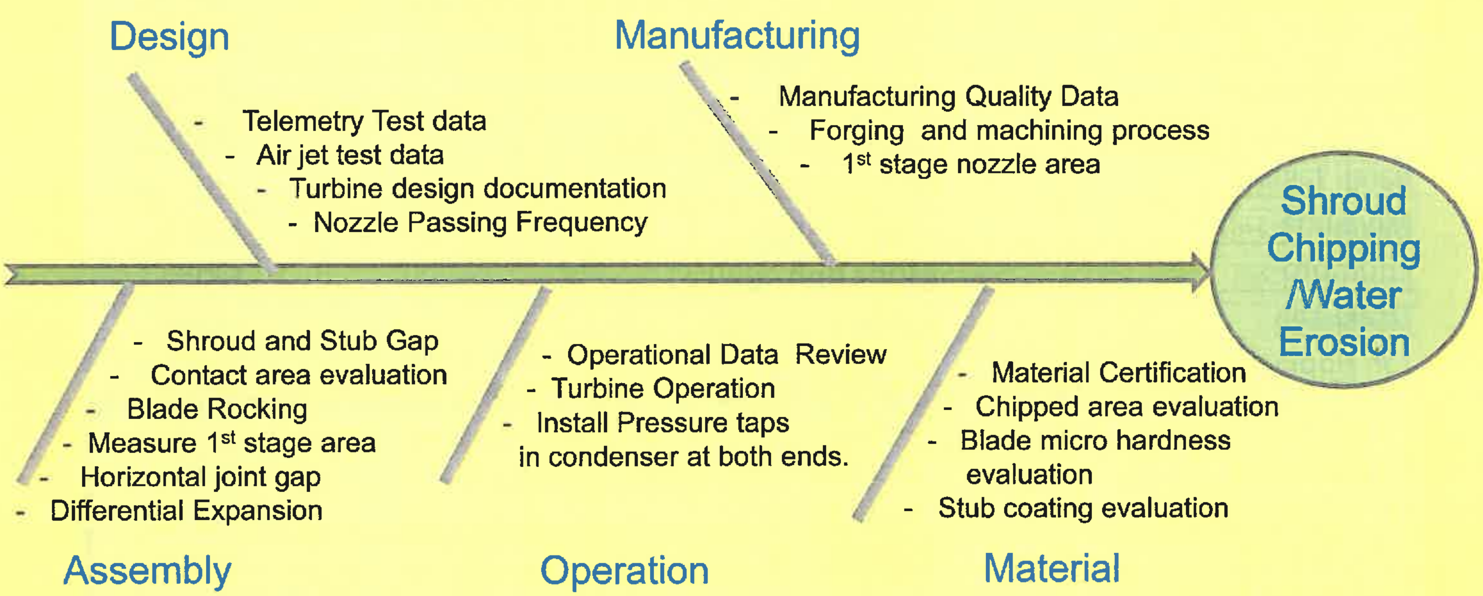
Muhammad Riaz	RCA Lead	MHPSA
Nick Porteous	MHPSA RCA Sponsor + Technical Contributor	MHPSA
Ikushima-san	MHPSA Communications Lead	MHPSA
Ryan Paulson	Inspection	MHPSA
Ruban Amirtharajah	Operating Data Review	MHPSA
Balaji Jayaraj	Metallurgist	MHPSA
Miyajima-san	Lead Analyst	MHPS
Enomoto-san	MHPS RCA Sponsor	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



Key Areas of Investigation

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Blade Shroud Chipping RCA CONFIDENTIAL

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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 CONFIDENTIAL

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

Influence

Influence
Low
Medium
High

		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)

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Blade Inspection Results

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	#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

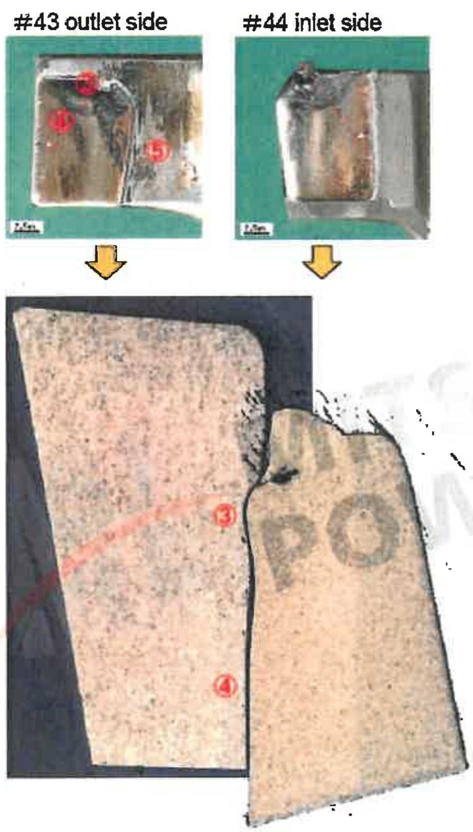
Microscopic observation was performed on the same sections in contact condition for each of outlet side of #43 blade and inlet side of #44 blade.

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

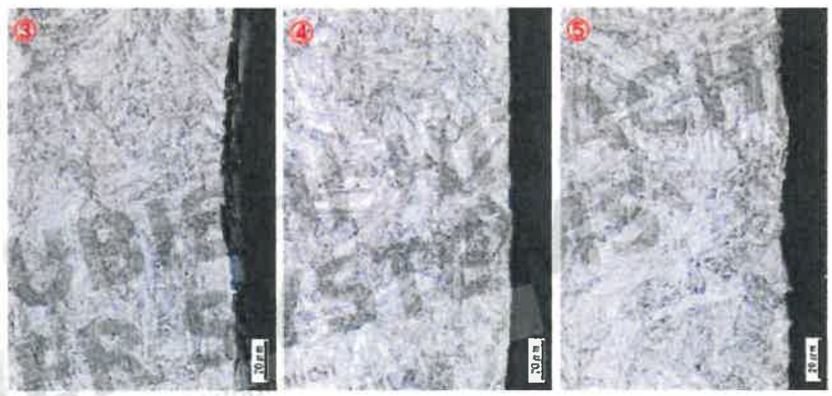
- Plasticity is found in concave part of local deformation.

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

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Metallurgical Evaluation of Blades

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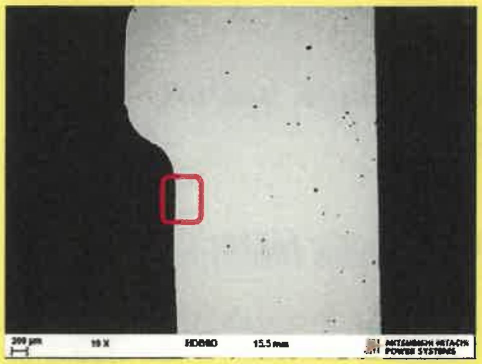

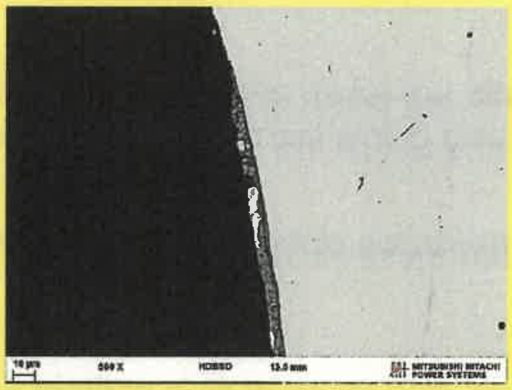

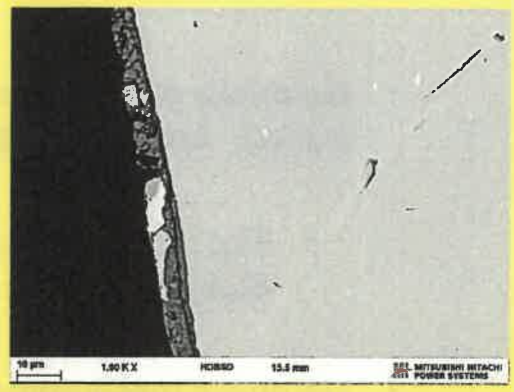

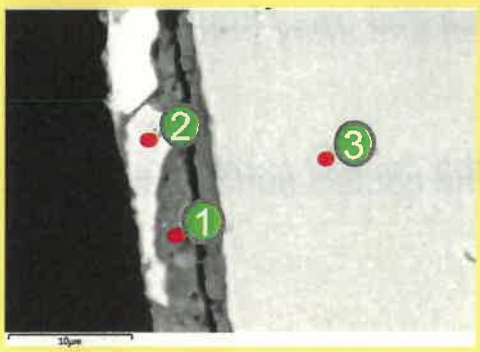

Location	Semi-Qualitative EDS analysis of elements detected (wt%)							
	O	Si	Cr	Mn	Fe	Ni	Cu	Nb
1	25.97	0.44	7.67	0.41	61.59	1.84	1.18	0.00
2	0	0.35	18.15	0.95	70.12	9.35	0.08	1.00
3	0	0.33	15.86	0.54	73.65	4.91	3.58	1.14

- 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.

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Damage Mechanism

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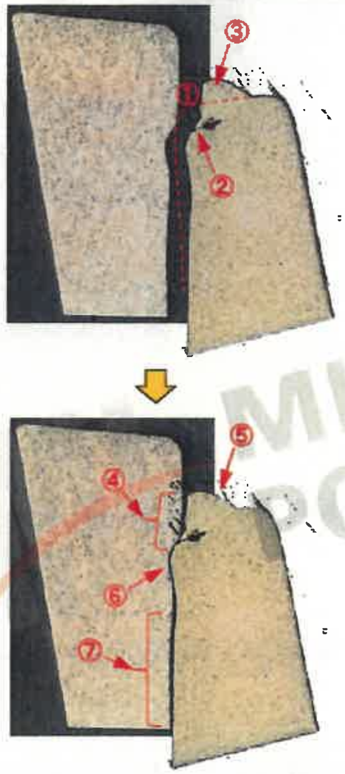
Images of initial contact conditions



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.

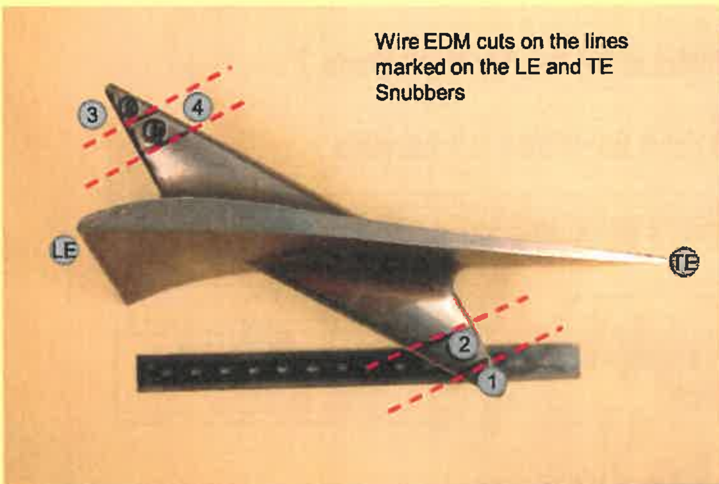
⑥ Local wear generated by high surface pressure & excessive sliding. Oxide scale developed by heat generation (black surface).

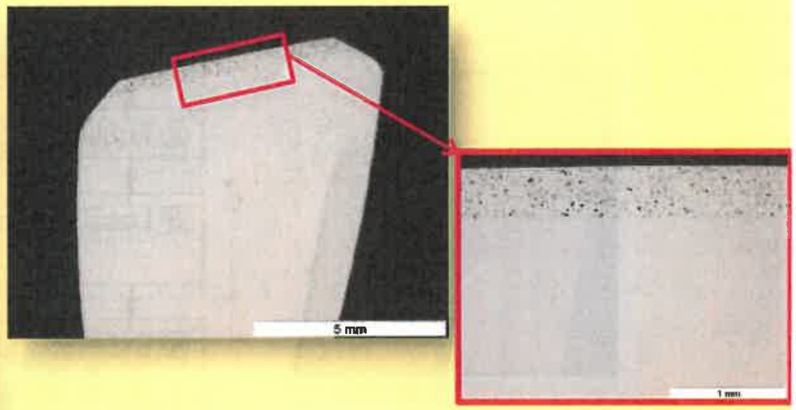
⑦ Worn by wear debris

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

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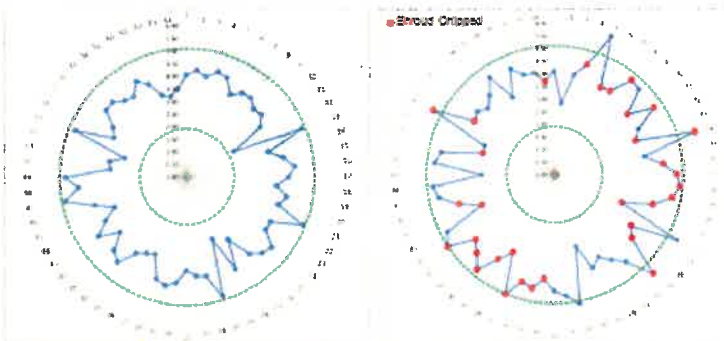
2014 Blade LH (Gov. End) Shroud Gap Data



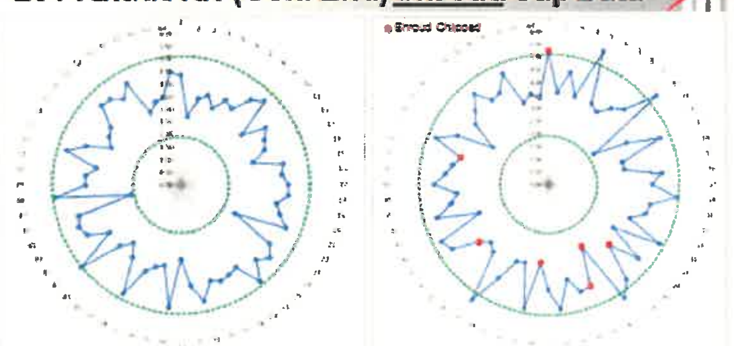
Shroud Gap Data in 2014 Assembly — Row Average Gap = 3.9mm

Shroud Gap Data in 2016 Dis-Assembly — 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

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Stub Gap Data

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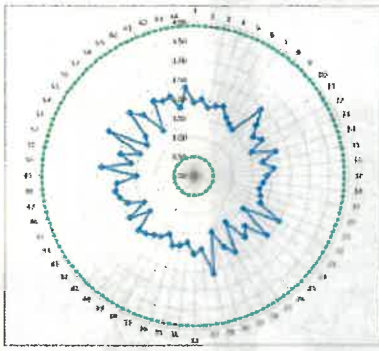
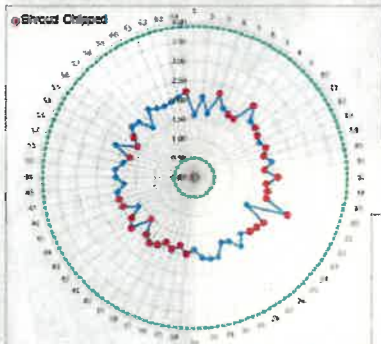
2014 Blade LH (Gov. End) Stub Gap Data



Shroud Gap Data in 2014 Assembly



Shroud Gap Data in 2016 Dis-Assemb

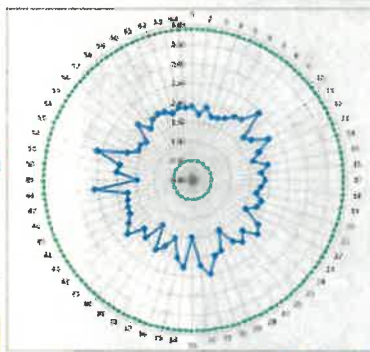
Row Average Gap = 1.9mm

Row Average Gap = 1.9mm

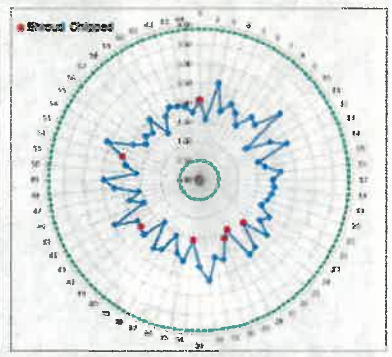
Criteria: Stub 0.5mm to 3.9mm Average, with no single blade above 4.8mm.

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.

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Manufacturing Quality Data - Box Gauge

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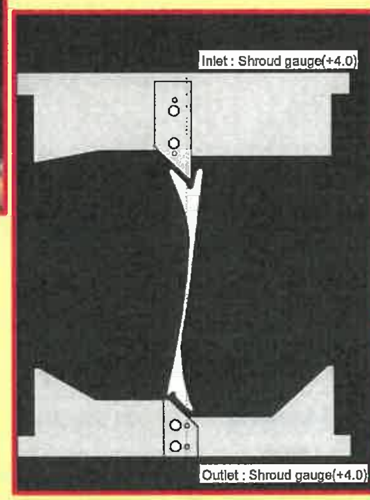
Box Gauge with 40" L0 Blade



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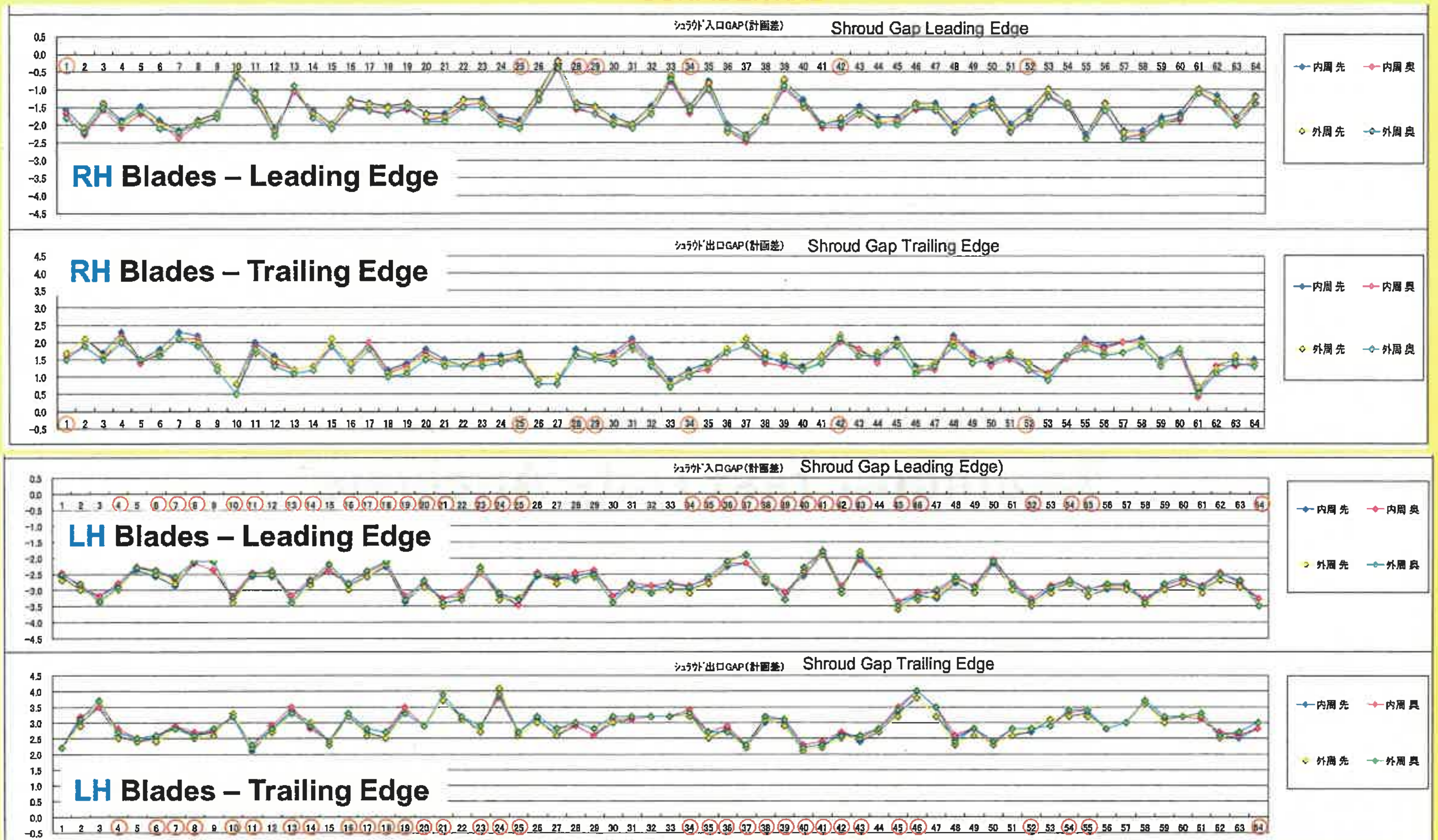
Box Gauge Measurement Results - 2014 blades



Blade manufacturing data show variation within criteria

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Telemetry Test Data Analysis

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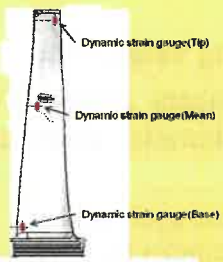
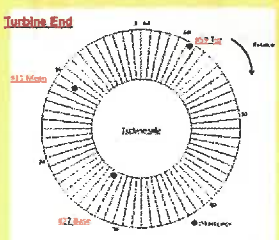
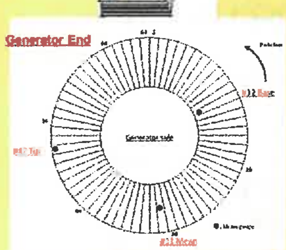
Telemetry Test Results

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



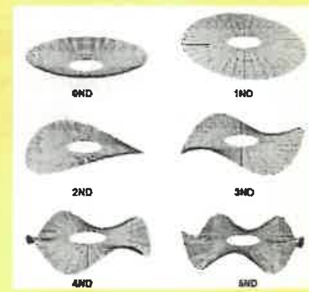




Test Results

- 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

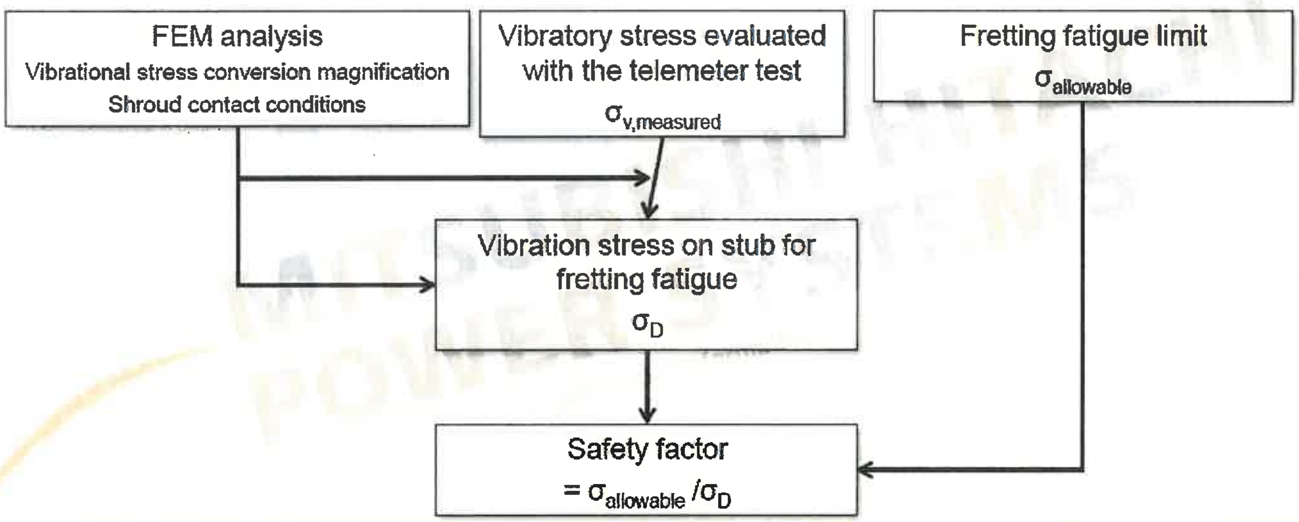


Nodal Diameters

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.



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Telemetry Test Results – Shroud Fretting

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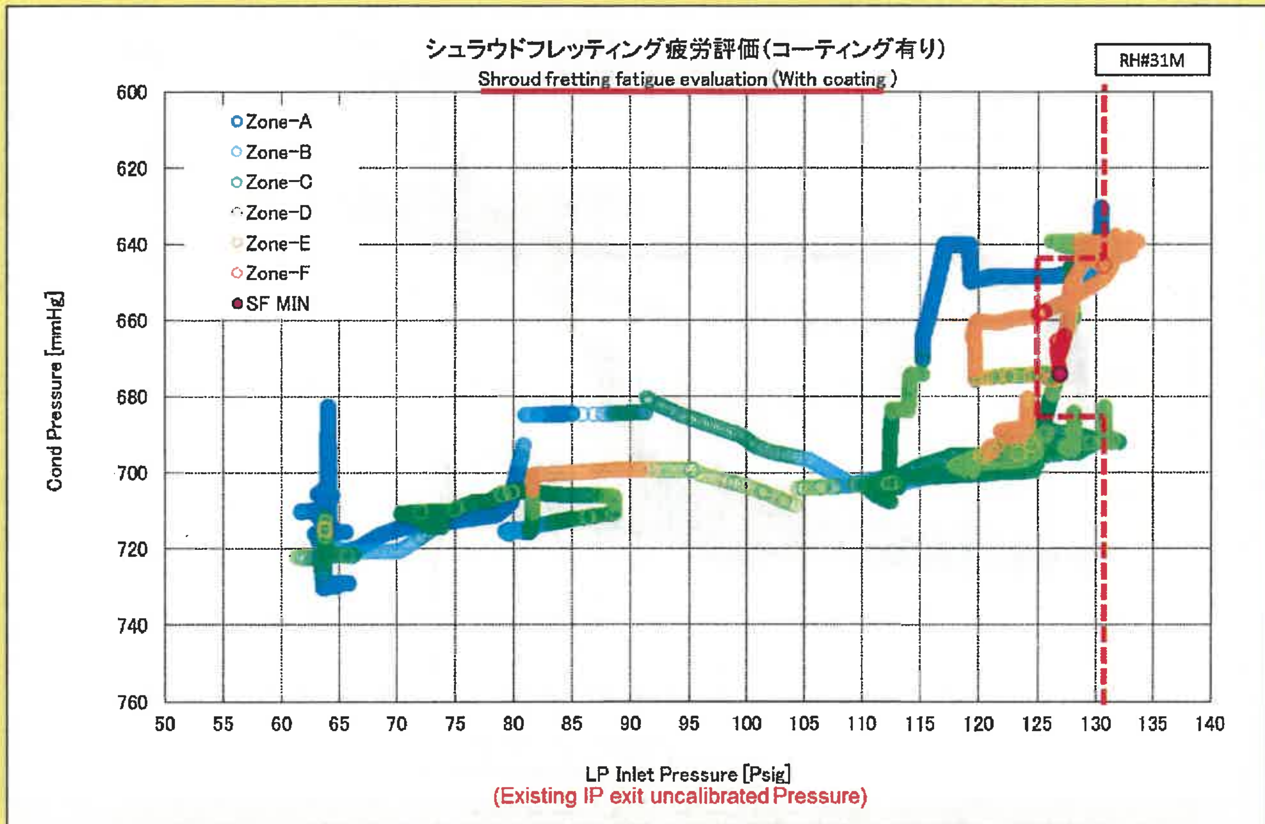
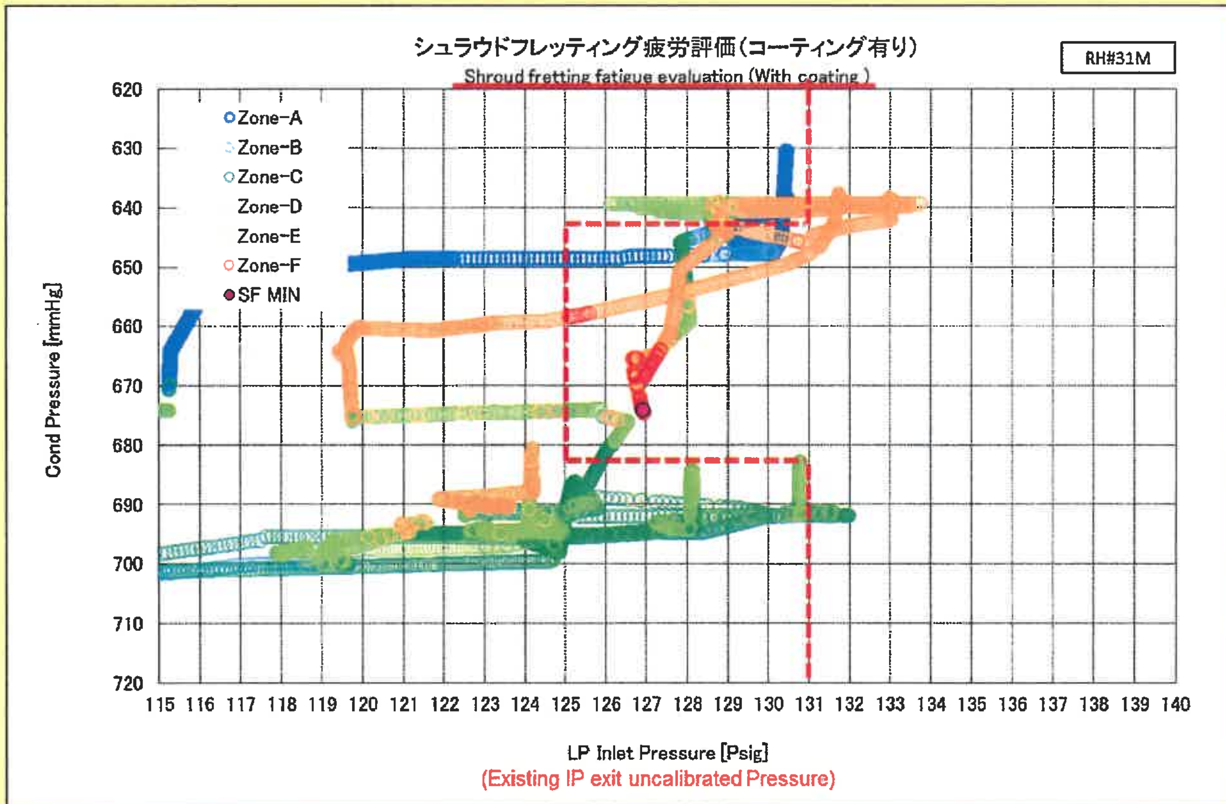


Fretting fatigue calculations for shroud with coating show acceptable margins outside avoidance zone

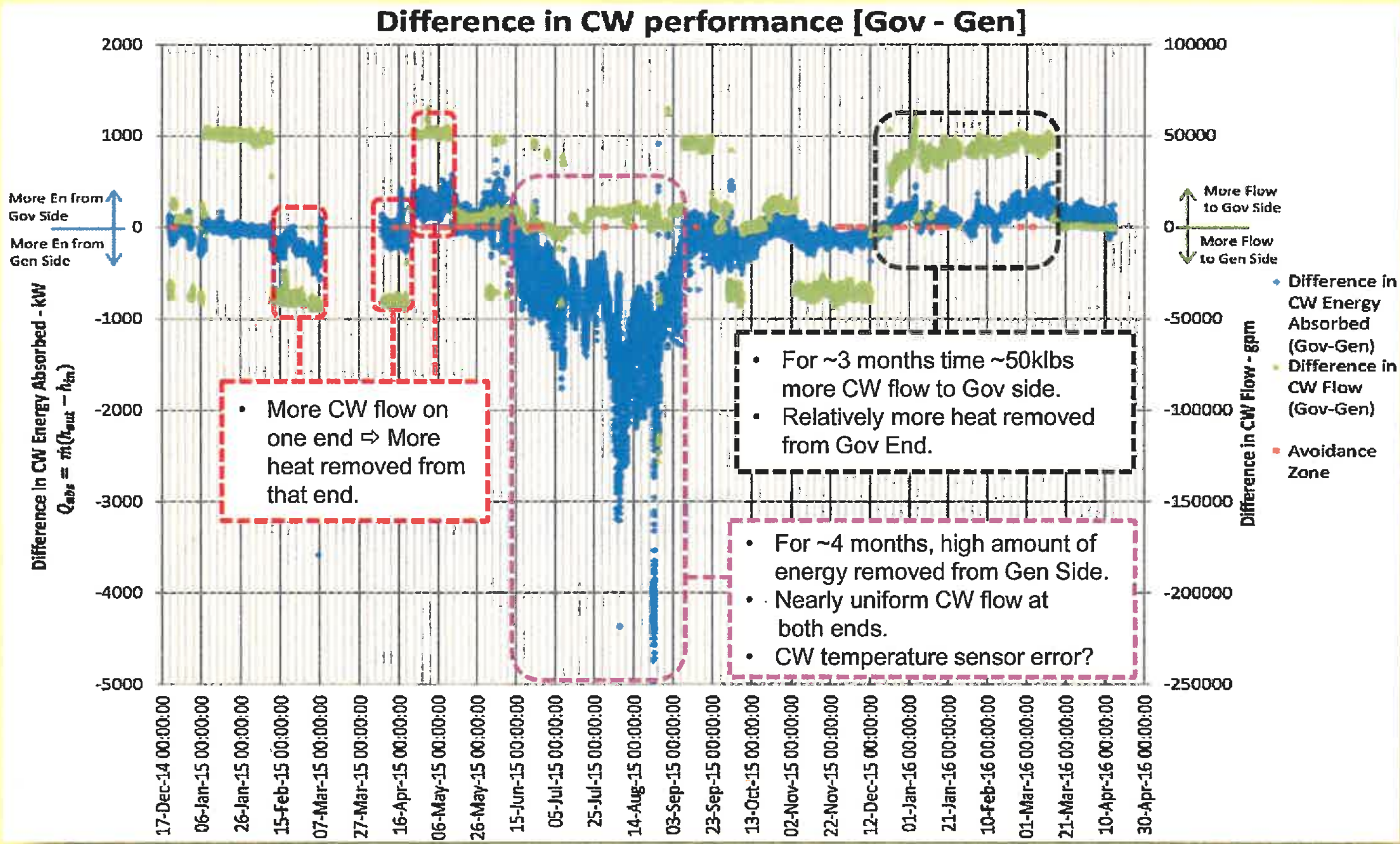
Telemetry Test Data – Shroud Fretting



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

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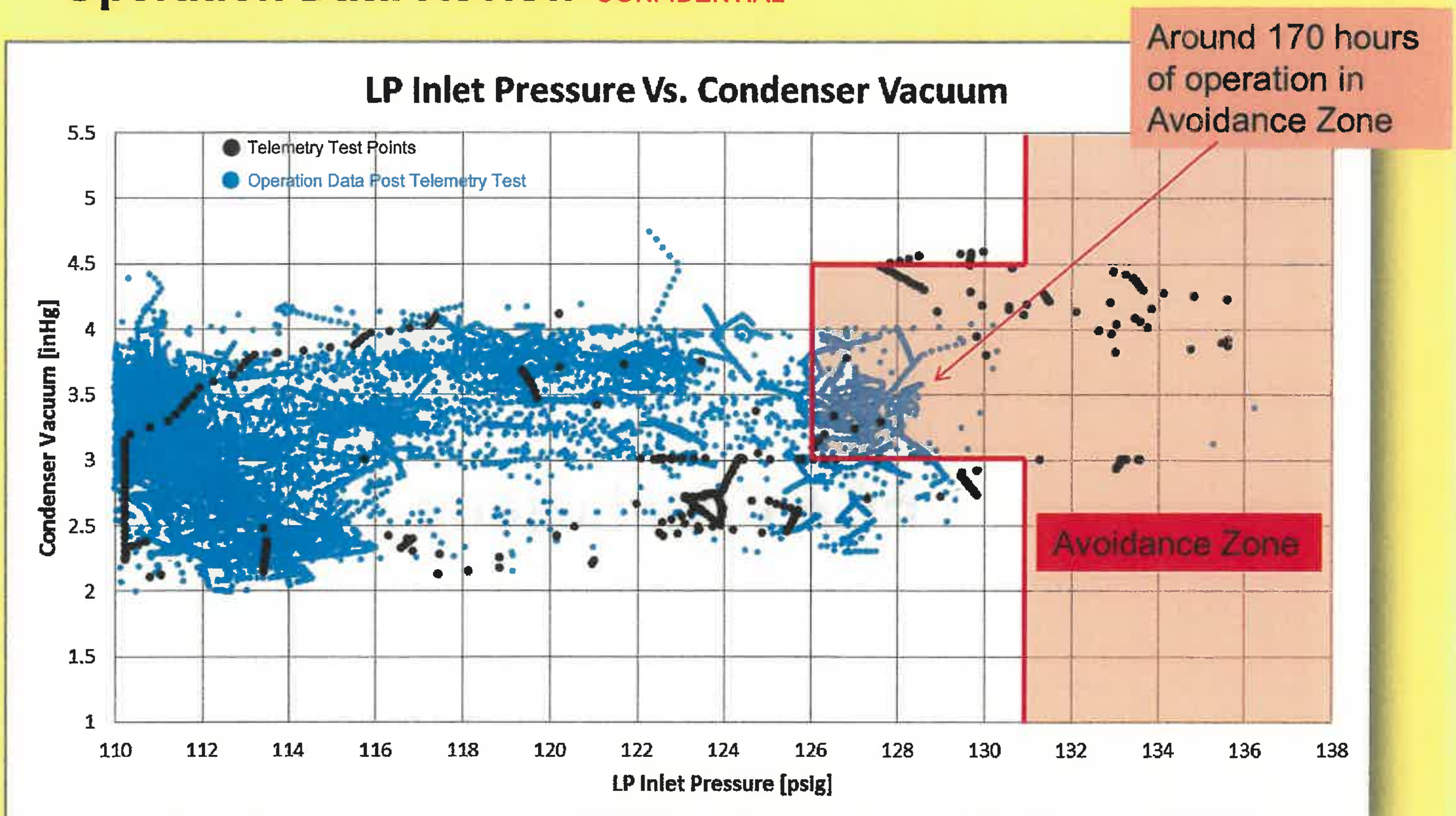
Operation Data Review CONFIDENTIAL



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

RCA Conclusions

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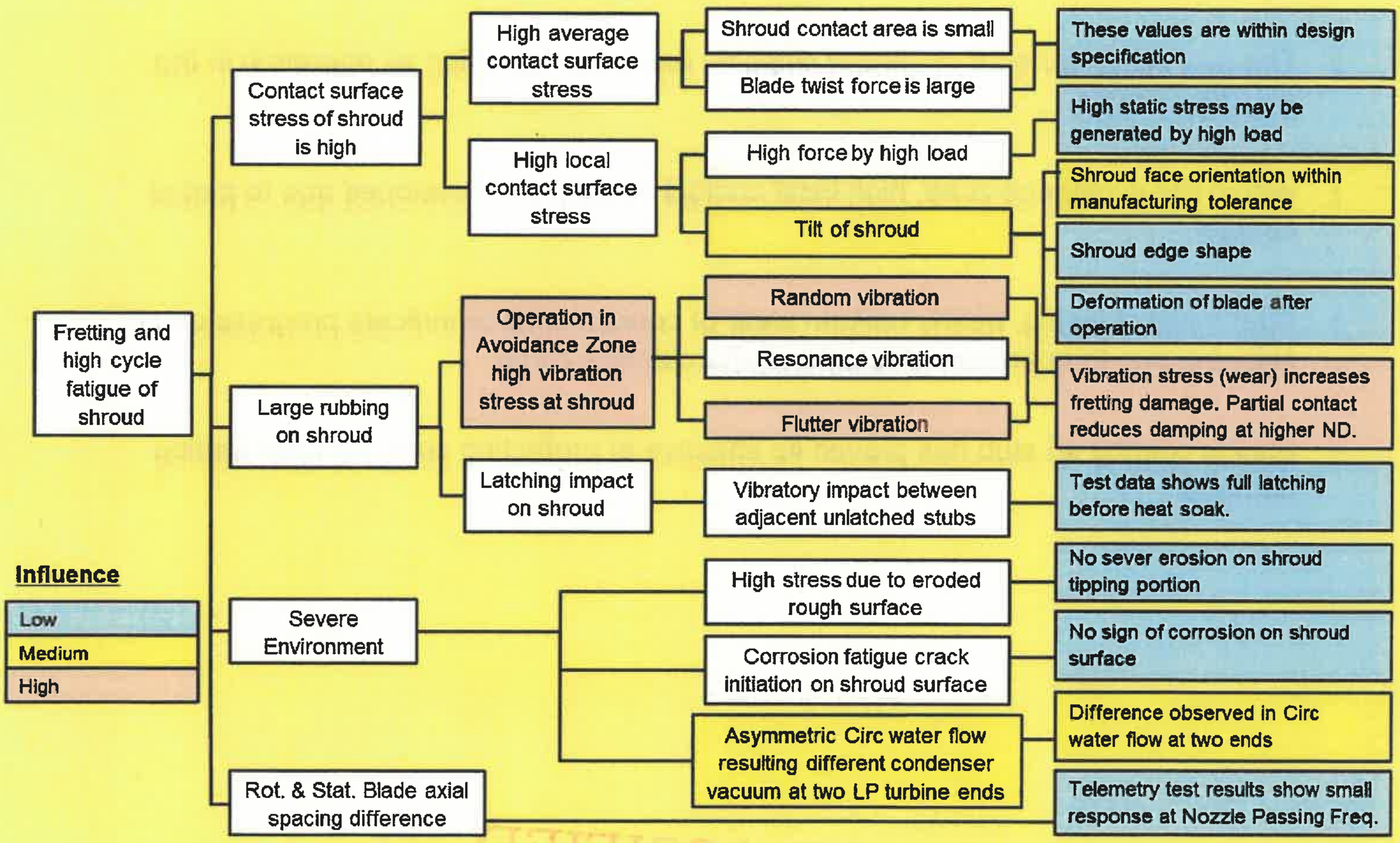
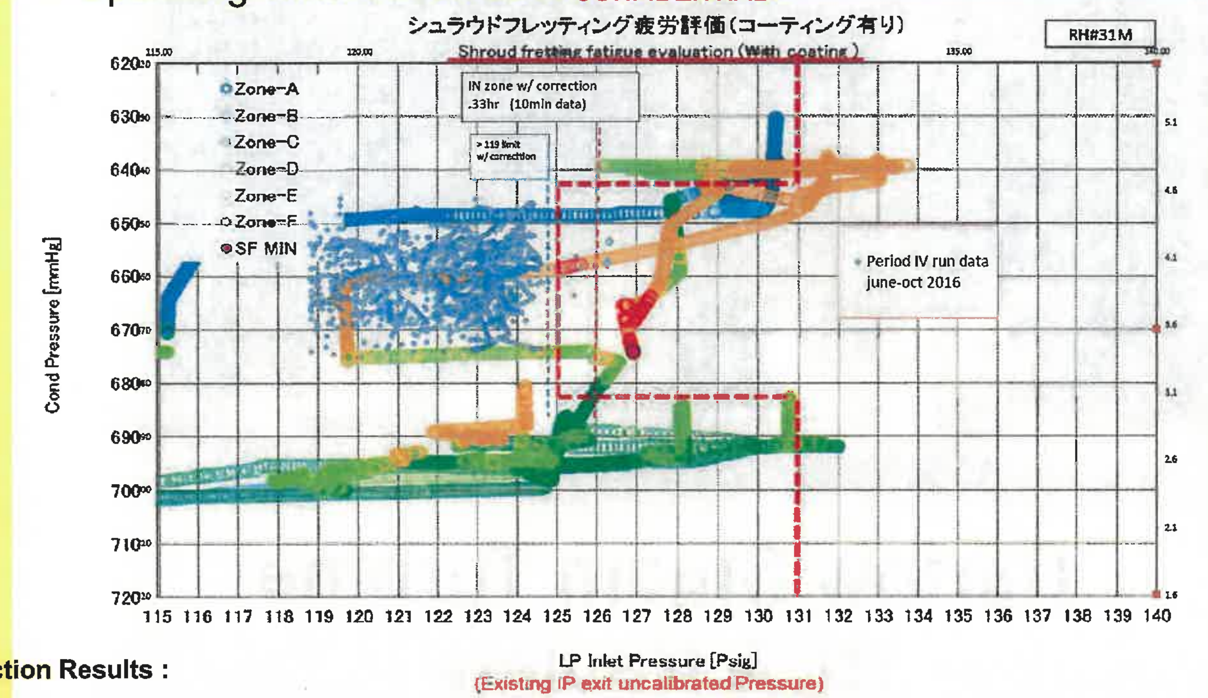
Blade Shroud Cause and Effect Diagram



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

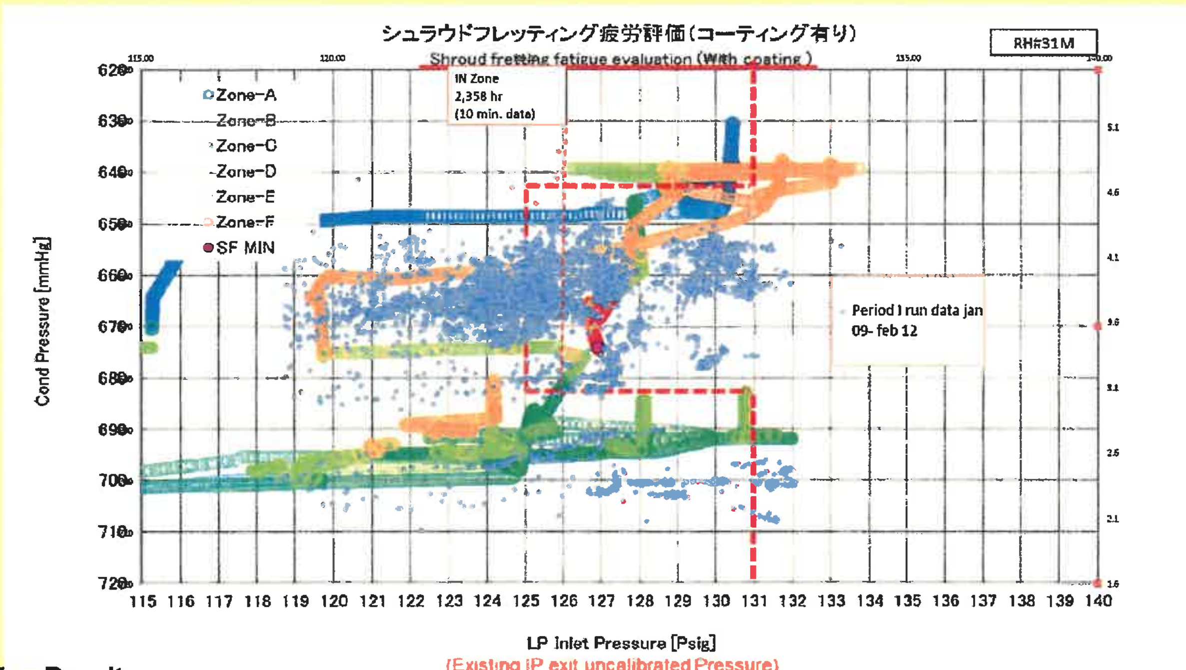
Purpose of Presentation

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.

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

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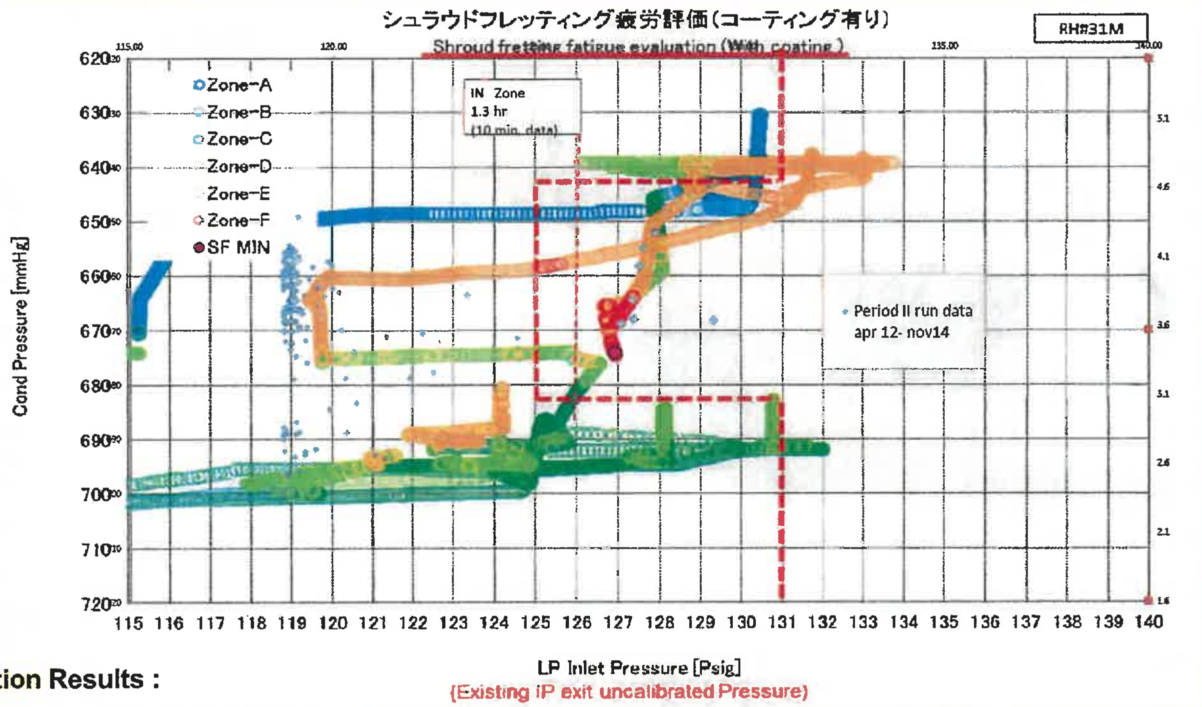
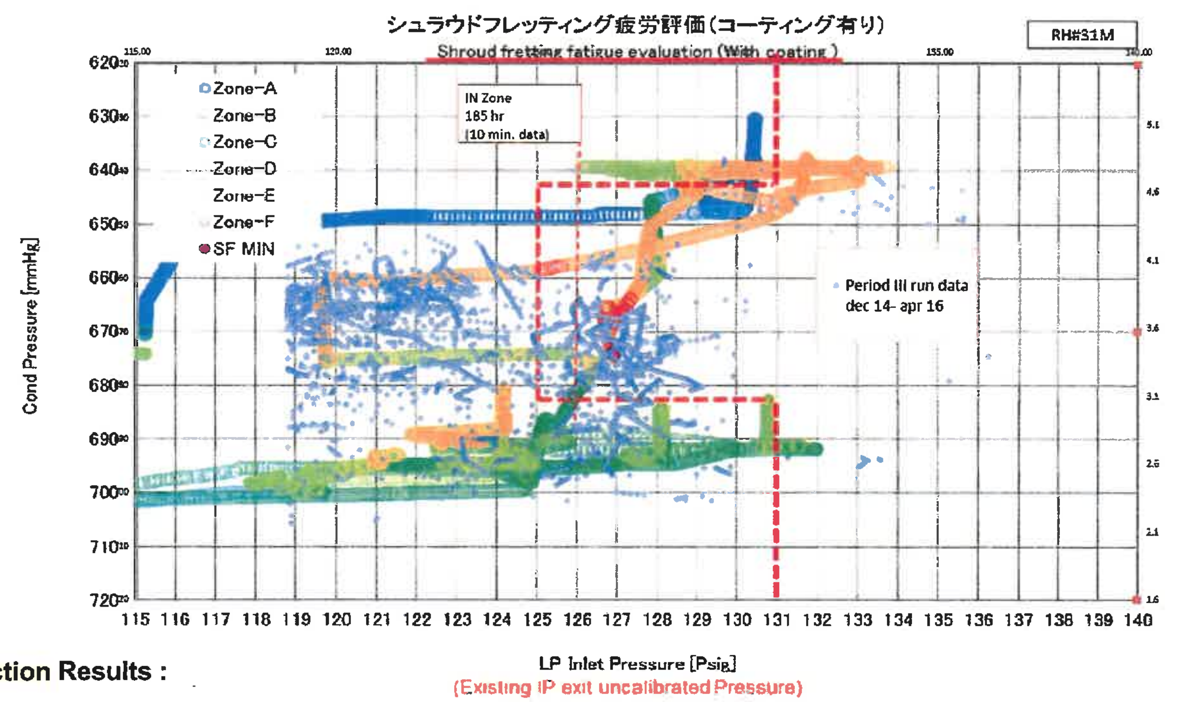


Inspection Results :

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

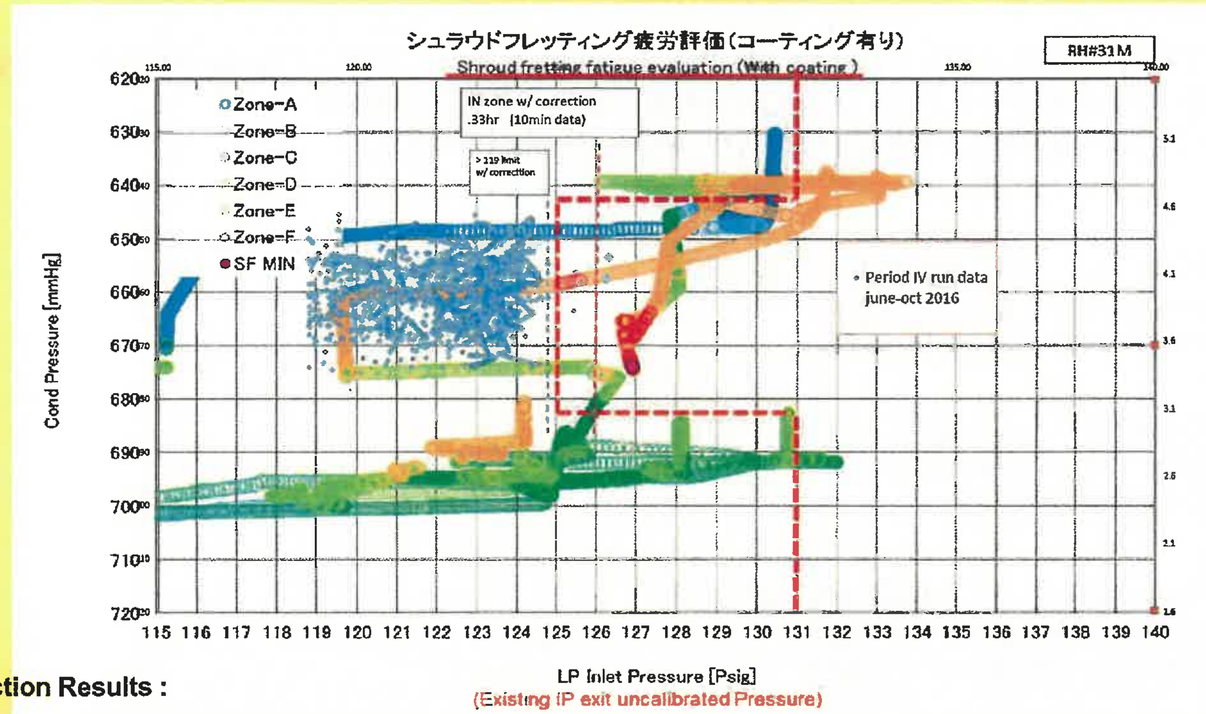
1.3) Operating Time 3 : Dec 2014 to Apr 2016



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)

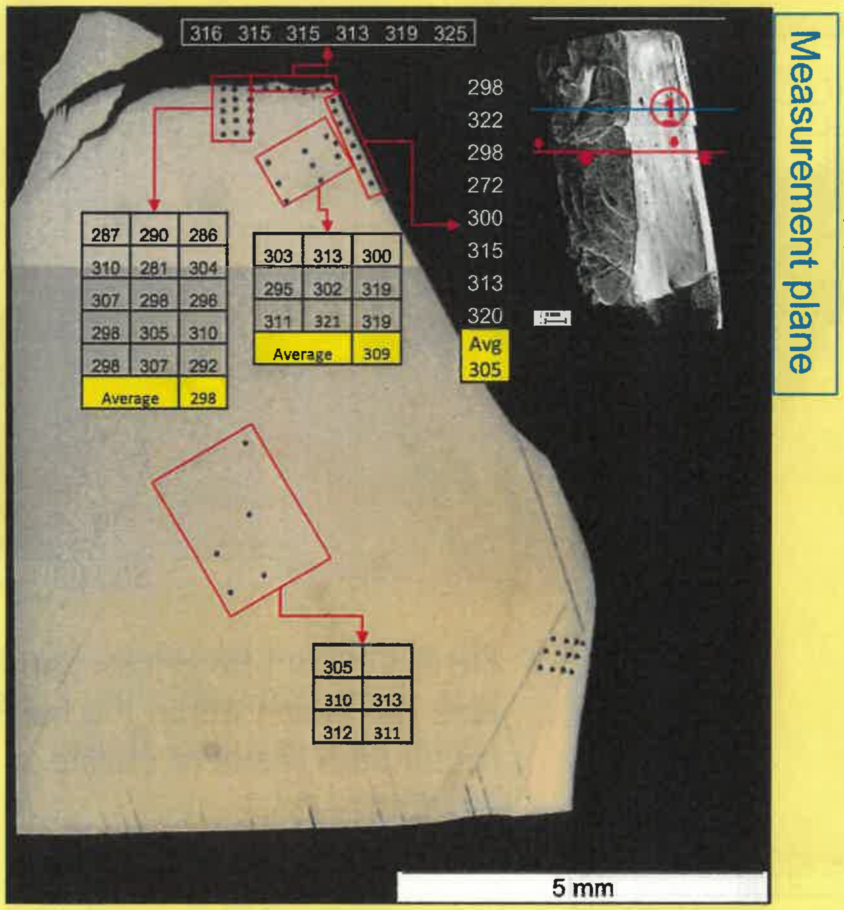
1.1) Operating Time 1 : Jan 2009 to Feb 2012
Significant operation in the avoidance zone.
Significant damage observed on the blades.

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.

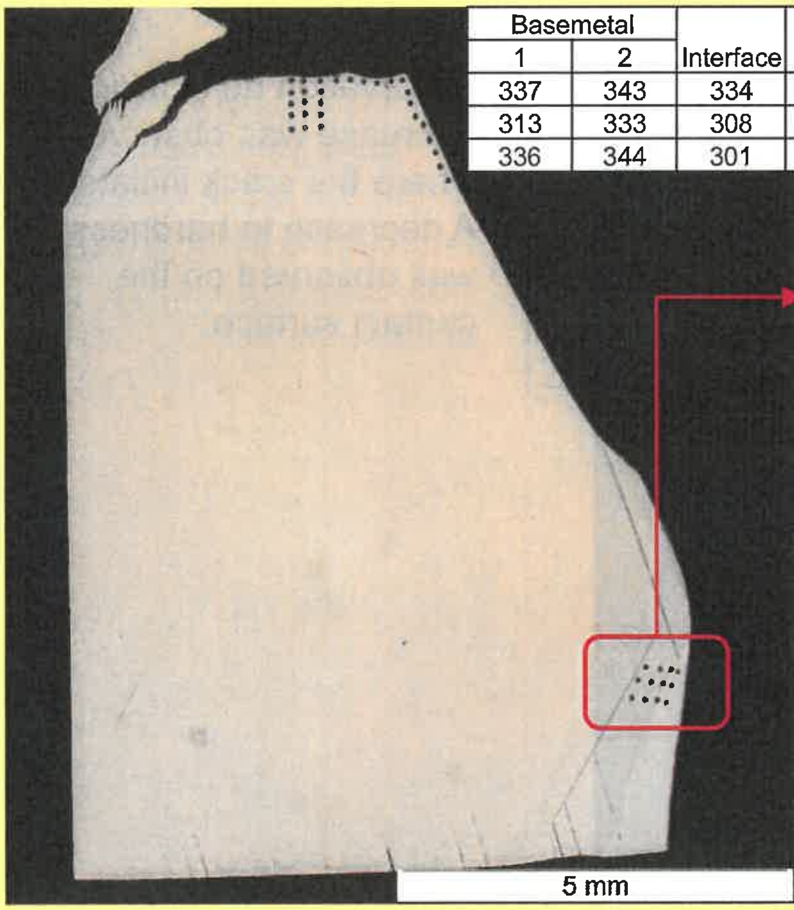
2 - Hardness Variation – Presented

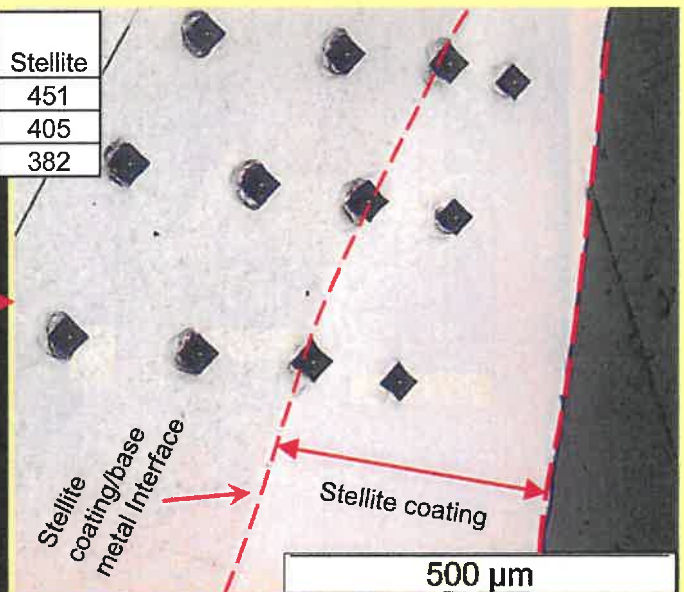


- From hardness observation no significant decrease was observed where the crack initiated.
- A decrease in hardness was observed on the contact surface.

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

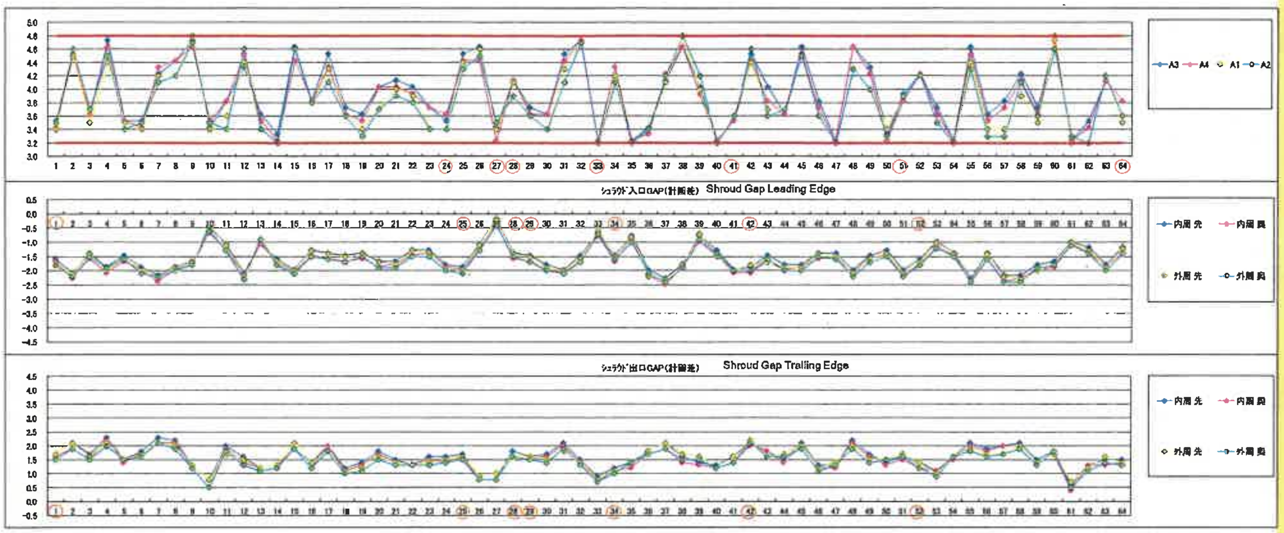




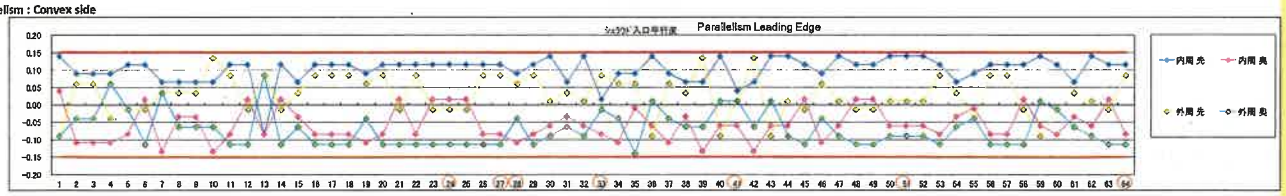
- No significant hardness variation was observed within the base metal as a result of stellite welding.

3.1) Measurement Results RH (Gen End) 2014 blades

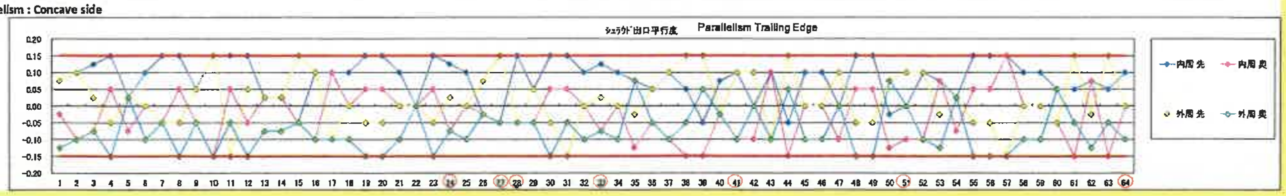
Shroud GAP ○ : Shrouds with Damage



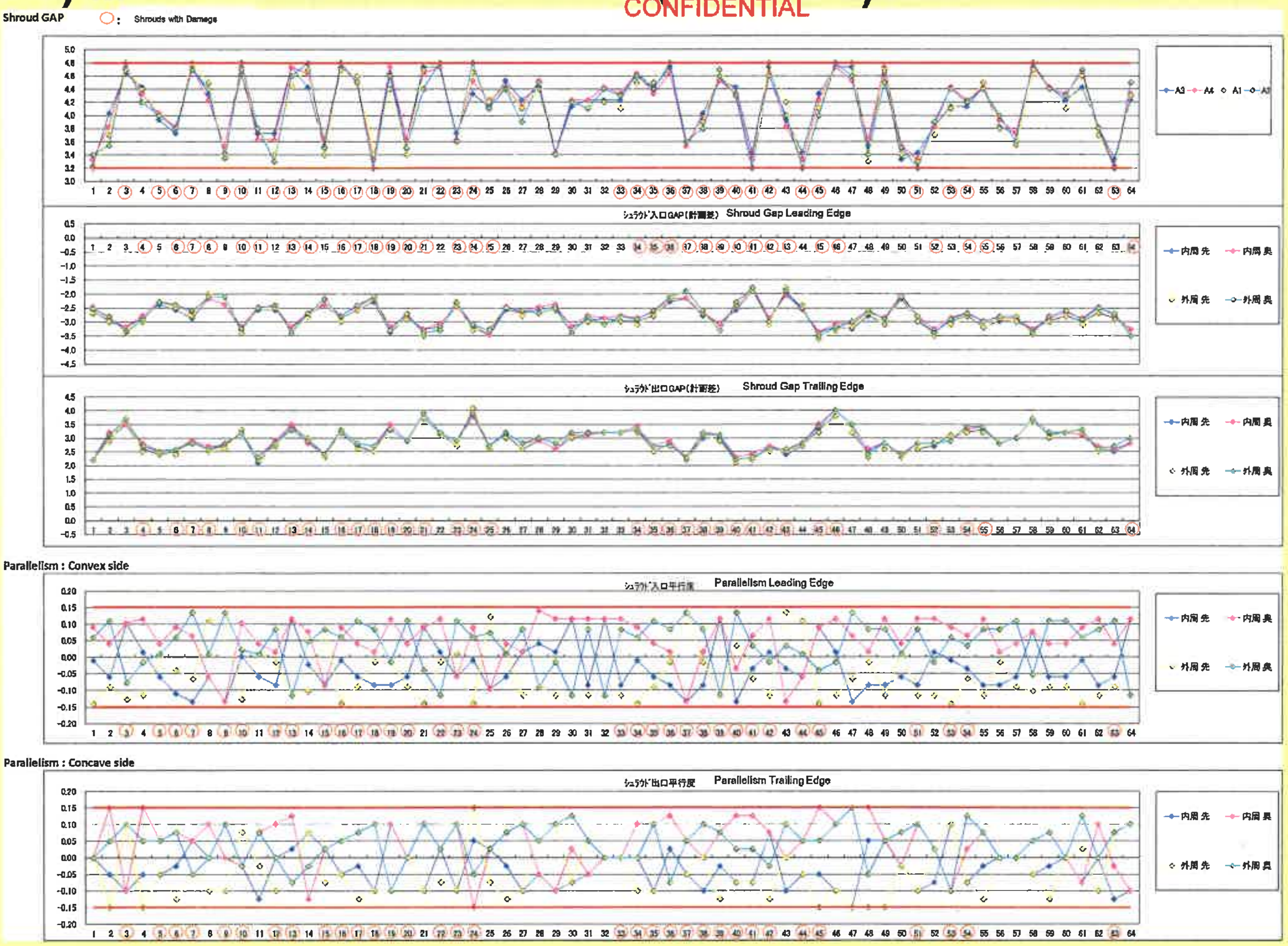
Parallelism : Convex side



Parallelism : Concave side



3.2) Measurement Results LH (Gov End) 2014 blades



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Duke Questions (From 10/26/16 Meeting)

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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

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	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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Executive Summary

Duke and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 12 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation. During a presentation given at Bartow Station on 15 March 2017, MHPS suggested the sole root cause for Period 3 (Dec 2014-Mar 2016) was "operation in the avoidance zone". While Duke Engineering would agree that operation in the avoidance zone is certainly a *contributing factor* to the shroud chipping experienced in Period 3, it is not the only contributing factor that should be considered when trying to determine root cause for the Period 3 Bartow Unit 4S event, or any of the previous/subsequent events for that matter.

After months of study, 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 Back-End Loading (>15,000 lb./hr./ft.^{2})
- Blending Operations
- Hood Spray Operations
- Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches
- Configuration (e.g. Hard-Facing on Z-Notches)

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. The ST LP admission system was modified by MHPS with the intent for 4x1 CC operations to yield a 450MW gross output rating.

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-Notch 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

LP Turbine Back-End Loading (>15,000 lb./hr./ft.^{2})

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" 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.

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.

Blending Operations

(insert text)

Hood Spray Operations

(insert text)

Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches

(insert text)

Configuration (Hard-Facing on the Z-Notches)

(insert text)

Duke Engineering's believes that MHPS's conclusions represent contributing factors in the failures; therefore, Duke is not in concurrence with the recommended RCA conclusion. MHPS and Duke have been working together, and continue to work together, to collect data and evidence to determine the drivers behind these L-0 blade failures. Data suggests that there are ***several contributing factors, none of which have been quantified conclusively to determine the root cause to any particular failure event***.

There are five periods of interest:

Period 1: Concluded in 2012 with approximatly 34 months of operation with Type 1 L-0's in service.
- Five turbine end (TE) L-0 blades were found to have broken snubbers, the L-0 blades were replaced.
- During this period the blades operated in (what MHPS would define during the transition from Period 2 into Period 3 as) the avoidance zone for 2,466 hours with no operating restrictions placed on the ST.
- No RCA was conducted as Duke worked with MHPS and was willing to have MHPS provide and eventually install what was thought to be the solution to the issue with new design blades (installed in Fall 2014).

Commented [JRS1]: I think we should add because we worked with MHPS to design and install what was thought to be the solution to the issue with new design blades installed in fall 2014.

Period 2: Concluded in 2014 with approximatly 28 months of operation with Type 1 L-0's in service. This was a planned outage to replace the L-0 blades with an Enhanced/More Robust Blade (Type 3 v1).
- The IP Exhaust Pressure operated at a limit of 118 psig during period 2.
- Blade telemetry instrumentation was also installed during the Period 2 outage to measure blade stresses and determine the limits of the avoidance zone in operation (performed by crossing the avoidance zone in operation and measuring blade stresses).
- No RCA was required.

Period 3: Concluded in the spring of 2016 with approximately 17 months of operation with Type 3 (v1) L-0's inservice. This was a forced outage as a result of several blades with broken Z-lock interfaces on both generator end (GE) and turbine end (TE) L-0's.
- After commissioning the blades operated in the avoidance zone for ~20 hrs to further refine the avoidance zone. Operations restricted output by limiting IP Exhaust pressure to 126 psig (based on strain gauge data). Blade strain gage data also shows high stress areas in operation outside the avoidance zone (no operating limitations placed around these areas by MHPS).
- MHPS Engineering added stellite hard facing to the Z-lock contact faces to the newly installed blades as a measure to prevent wear and breakage.
- The RCA is currently inconclusive from data and findings, but several contributing factors have been determined.
- *Note: At the onset of Period 3, per MHPS Engineering, short term operation – i.e. 10-20 minutes per occurance – within the avoidance zone was allowable under certain operating ranges for both condenser backpressure and IP exhaust pressure during, for example, peak power seasons in summer. Over the course of time and subsequent L-0 events, MHPS Engineering amended and restated their technical disposition to express that operation within the avoidance zone should be prohibited altogether.*

Period 4: Concluded in the fall of 2016 with approximatly 5 months of operation with Type 3 (v2) L-0's inservice. This was an forced outage as a result of several L-0 blades with broken Z-lock interfaces and missing airfoil material. Inspection of the Z-lock area showed less than desirable contact on the Z-lock surface (~10% contact vs ~60% contact). The Z-lock surface needs to properly contact to obtain the desired dampening effect during operation.

During this period the blades operated in the avoidance zone for 1.15 hours with additional operating limitations of 119 psig in IP exhaust pressure.

Several L-0 blades from Period 1, 3, and 4 were measured to compare geometry. Scans show wide range of geometry from manufacturing; it is unknown if these deviations are within design expectancy or not (MHPS has requested blades for scanning to compare – in process).

MHPS is evaluating if the additional stellite coating on the Z lock promoted a loss of dampening. Since this failure mode was significantly different than any in the past or since this period, i.e. complete loss of a Z-lock tip and air foil section, and the crack started at the blades high point for stress the design may have been compromised because of hard facing on all mating surfaces. The RCA is currently inconclusive, the application of the HVOF coating on the Z-lock surface appear to be one of the leading factors in the failure. The replacement blades going into Period 5 reverted back to the Type 1 design.

The Station also installed DCS logic to trigger alarms before operation occurs in the Avoidance zone.

Period 5: Concluded in the spring of 2017 with approximately 2 months of operation with Type 1 L-0's in service. This was a forced outage that was a result of several blades with broken Z-lock interfaces and snubbers on the Generator End (GE) L-0 blades.

During this period the blades operated in the avoidance zone for 0 hours with additional operating limitations of 111.1 psig in IP exhaust pressure.

For the first time, Duke Engineering identified blending as a possible contributing factor to the RCA. "Blending steam" is a common occurance with combined cycle applications. One example of a suspect blend transient is evidence of measured water hammer event(s) in piping networks that dump into the condenser. The shock wave developed by a suspect blend transient does enter the condenser hotwell, however the impact of these type events on the L-0 blades is analytically unknown. Work is underway to determine if blend transients can be correlated to blade telemetry data from 2014/15.

Note: "Blending In" steam involves integrating steam production from a specific CT/HRSG train into the ST. "Blending Out" steam involves bypassing steam from the ST to the condenser as a particular CT/HRSG train transfers from combined cycle to simple cycle operations (or offline).

The RCA is still underway with no conclusions developed from data and findings.

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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 mon	~28 mon	~17 mon	~5 mon	~2 mon
L-0 Blade config	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	450 MW (420 Nameplate)	420 MW per MHI	450 MW	450 MW	390 MW
Operating Restrictions	None	118 psig Limit on IP Exh	126 psig Limit on IP Exh	119 psig Limit on IP Exh	111 psig Limit on IP Exh
Blade Over speed condition	Over speed testing in MFG		Over speed tested in Japan	No over speed	No Over speed
Avoidance Zone Exceedance	2,466 hrs. (of 27,552 hrs.)	1 hr (of 22,320 hrs)	240 hrs (of 11,544 hrs)	1.15 hrs (of 3,000 hrs)	0 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	not captured		high degree of wear observed		high degree of wear observed
Key notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) & 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 was observed from removed service blades. Blade telemetry instrumentation installed ('Dec 21 - Dec 24', 2014)	Blade telemetry testing; intentionally ran in avoidance zone to set limits, ran in zone for <20 hrs). No blade cracking observed after testing when test instrumentation removed. Blade telemetry data also shows higher stress areas in operation outside the avoidance zone based on blade strain data (no operating limitations placed around these areas by MHPS), data indicates we operated in these zones ~X hrs during the period.	Blade loss of material, 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. At first, MHPS did not support this recommendation, nor did they support the idea that "loss of mass" had occurred.	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). Confirmation from the Harris met lab evaluation should help determine cracking mechanism
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. MHPS learned through Duke Engineering (intentional) that we were investigating blending and its impact to the Condenser/ST. MHPS RCA team for the first time learned what "blending in" and "blending out" meant.

Appendix B: MHPS L-0 Blade Type Matrix

	Bartow L-0 Configurations			**Citrus L-0**
	Type 1	Type 3 (v1)	Type 3 (v2)	*New*
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	Height same as Bartow
Z-Lock	No HVOF	No HVOF	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

Executive Summary

Duke and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 12 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation. During a presentation given at Bartow Station on 15 March 2017, MHPS suggested the sole root cause for Period 3 (Dec 2014-Mar 2016) was "operation in the avoidance zone". While Duke Engineering would agree that operation in the "avoidance zone" is certainly a *contributing factor* to the shroud chipping experienced in Period 3, it is not the only driving mechanism that should be considered when trying to determine root cause for the Period 3 Bartow Unit 4S event, or any of the previous/subsequent events for that matter.

After months of study, 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
- Thermal Distress at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operations
- Blade Fitment (Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches
- Loss of Dampening (e.g. Hard-Facing on Mid-span Snubbers and Z-Notches)

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. The ST LP admission system was modified by MHPS with the intent for 4x1 CC operations to yield a 450MW gross output rating.

Commented [PVC1]: For period 3 only.

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-Notch 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.

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Root Cause Contributing Factors

LP Turbine Back-End Loading (>15,000 lb./hr./ft.^{2})

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" 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.

As for Period 3, there were only approximately 240 hours of operation in the "avoidance zone", of which approximately 11 hours occurred during the instrumented blade telemetry test performed by MHPS in December 2014. Even with the greatly reduced amount of high flow hours for Period 3 as compared to Period 1 – a factor of 10 fewer hours for Period 3 – a high amount of wear and distress was seen on the z-notch contact surfaces. While the amount of z-notch wear is not quantified for Period 1 and 3, photographic evidence suggests that the amount of wear is similar. 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.

Commented [PVC2]: This is what I recall - but we need the photos to prove this otherwise we can't say it.

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.

Commented [PVC3]: However, MHPS has not done any review and released us to go to higher LP inlet pressures/flows.

Blending Operations – Thermal Distress (dT_{SH}/dt) at L-0 Exit

During the most recent root cause analysis (RCA), the team expanded its view of turbine operations to 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 CTs, 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 was developed that allows large amounts of data stored in PI to be quickly reviewed for each time Period. Blends that meet the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. The process relies on 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 over 20 degrees F when a CT is being blended off or on the steam turbine and the steam turbine output is greater than 50 MW. The limits of 20 degrees F 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 a comparison of the number of higher energy blends that occurred in each period, and it allows the team to quickly identify times to look at additional blend parameters.

Below is a quick comparison of the number blends that meet the criteria for Periods 1 thru 5.

	Number of days in Period	Number of blends meeting criteria
Period 1	1185 days	13*
Period 2	973 days	7
Period 3	482 days	31**
Period 4	127 days	3
Period 5	68 days	5

*Includes the time period during commissioning from 1/1/2009 to 6/1/2009

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

Hood Spray Operations – Pressure Pulses

The 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.

Review of MHPS-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

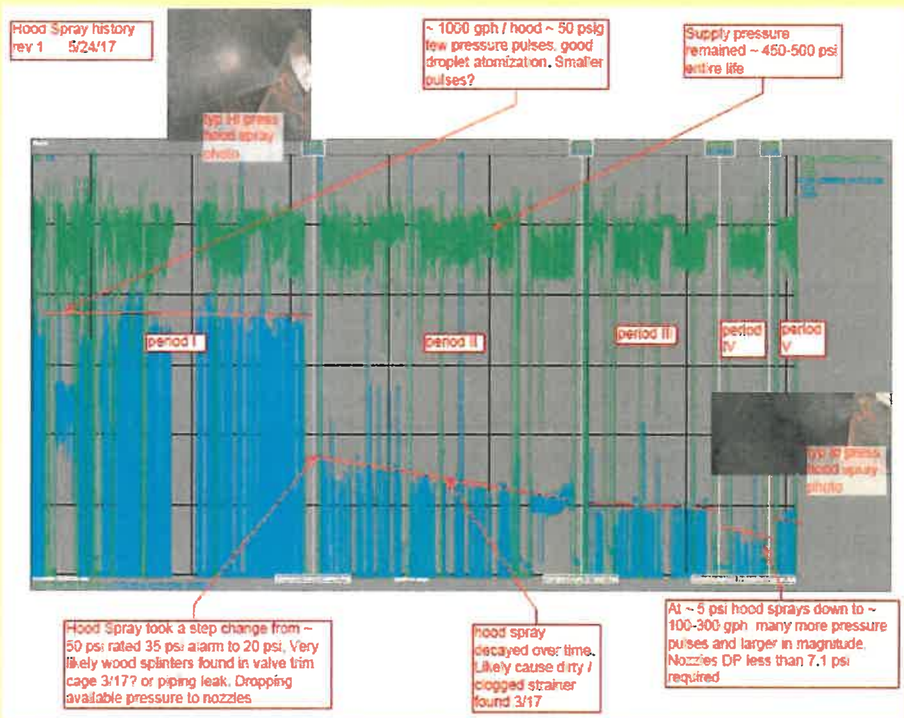
During review of the hood spray data, it became clear that additional operation besides that which is outlined above had been programmed into the DCS since unit commissioning. In addition to the above hood spray operating parameters, hood sprays were programmed to turn on anytime blending took place – similar to the way the curtain sprays are programmed. No explanation for why this was done has been found. 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 trip 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 instrument 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 valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the valve had filled with debris in prior years.

Commented [JCE4]: Which valve is this – The control valve mentioned in the above paragraph?

Commented [JCE5]: Same comment as JCE4.

The chart 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.



Curtain Spray Operations

(insert text)

Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches

(insert text)

Configuration (Hard-Facing on the Z-Notches)

(insert text)

Duke Engineering's believes that MHPS's conclusions represent contributing factors in the failures; therefore, Duke is not in concurrence with the recommended RCA conclusion. MHPS and Duke have been working together, and continue to work together, to collect data and evidence to determine the drivers behind these L-0 blade failures. Data suggests that there are ***several contributing factors, none of which have been quantified conclusively to determine the root cause to any particular failure event***.

There are five periods of interest:

Period 1: Concluded in 2012 with approximatly 34 months of operation with Type 1 L-0's in service.
Five turbine end (TE) L-0 blades were found to have broken snubbers, the L-0 blades were replaced.
During this period the blades operated in (what MHPS would define during the transition from Period 2 into Period 3 as) the avoidance zone for 2,466 hours with no operating restrictions placed on the ST.
No RCA was conducted as Duke worked with MHPS and was willing to have MHPS provide and eventually install what was thought to be the solution to the issue with new design blades (installed in Fall 2014).

Period 2: Concluded in 2014 with approximatly 28 months of operation with Type 1 L-0's in service. This was a planned outage to replace the L-0 blades with an Enhanced/More Robust Blade (Type 3 v1).
The IP Exhaust Pressure operated at a limit of 118 psig during period 2.
Blade telemetry instrumentation was also installed during the Period 2 outage to measure blade stresses and determine the limits of the avoidance zone in operation (performed by crossing the avoidance zone in operation and measuring blade stresses).
No RCA was required.

Period 3: Concluded in the spring of 2016 with approximately 17 months of operation with Type 3 (v1) L-0's inservice. This was a forced outage as a result of several blades with broken Z-lock interfaces on both generator end (GE) and turbine end (TE) L-0's.
After commissioning the blades operated in the avoidance zone for ~20 hrs to further refine the avoidance zone. Operations restricted output by limiting IP Exhaust pressure to 126 psig (based on strain gauge data). Blade strain gage data also shows high stress areas in operation outside the avoidance zone (no operating limitations placed around these areas by MHPS).
MHPS Engineering added stellite hard facing to the Z-lock contact faces to the newly installed blades as a measure to prevent wear and breakage.
The RCA is currently inconclusive from data and findings, but several contributing factors have been determined.
Note: At the onset of Period 3, per MHPS Engineering, short term operation – i.e. 10-20 minutes per occurance – within the avoidance zone was allowable under certain operating ranges for both condenser backpressure and IP exhaust pressure during, for example, peak power seasons in summer. Over the course of time and subsequent L-0 events, MHPS Engineering amended and restated their technical disposition to express that operation within the avoidance zone should be prohibited altogether.

Period 4: Concluded in the fall of 2016 with approximatly 5 months of operation with Type 3 (v2) L-0's inservice. This was an forced outage as a result of several L-0 blades with broken Z-lock interfaces and missing airfoil material. Inspection of the Z-lock area showed less than desirable contact on the Z-lock surface (~10% contact vs ~60% contact). The Z-lock surface needs to properly contact to obtain the desired dampening effect during operation.

During this period the blades operated in the avoidance zone for 1.15 hours with additional operating limitations of 119 psig in IP exhaust pressure.

Several L-0 blades from Period 1, 3, and 4 were measured to compare geometry. Scans show wide range of geometry from manufacturing; it is unknown if these deviations are within design expectancy or not (MHPS has requested blades for scanning to compare – in process).

MHPS is evaluating if the additional stellite coating on the Z lock promoted a loss of dampening. Since this failure mode was significantly different than any in the past or since this period, i.e. complete loss of a Z-lock tip and air foil section, and the crack started at the blades high point for stress the design may have been compromised because of hard facing on all mating surfaces. The RCA is currently inconclusive, the application of the HVOF coating on the Z-lock surface appear to be one of the leading factors in the failure. The replacement blades going into Period 5 reverted back to the Type 1 design.

The Station also installed DCS logic to trigger alarms before operation occurs in the Avoidance zone.

Period 5: Concluded in the spring of 2017 with approximately 2 months of operation with Type 1 L-0's in service. This was a forced outage that was a result of several blades with broken Z-lock interfaces and snubbers on the Generator End (GE) L-0 blades.

During this period the blades operated in the avoidance zone for 0 hours with additional operating limitations of 111.1 psig in IP exhaust pressure.

For the first time, Duke Engineering identified blending as a possible contributing factor to the RCA. "Blending steam" is a common occurance with combined cycle applications. One example of a suspect blend transient is evidence of measured water hammer event(s) in piping networks that dump into the condenser. The shock wave developed by a suspect blend transient does enter the condenser hotwell, however the impact of these type events on the L-0 blades is analytically unknown. Work is underway to determine if blend transients can be correlated to blade telemetry data from 2014/15.

Note: "Blending In" steam involves integrating steam production from a specific CT/HRSG train into the ST. "Blending Out" steam involves bypassing steam from the ST to the condenser as a particular CT/HRSG train transfers from combined cycle to simple cycle operations (or offline).

The RCA is still underway with no conclusions developed from data and findings.

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 mon	~28 mon	~17 mon	~5 mon	~2 mon
L-0 Blade config	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	450 MW (420 Nameplate)	420 MW per MHI	450 MW	450 MW	390 MW
Operating Restrictions	None	118 psig Limit on IP Exh	126 psig Limit on IP Exh	119 psig Limit on IP Exh	111 psig Limit on IP Exh
Blade Over speed condition	Over speed testing in MFG		Over speed tested in Japan	No over speed	No Over speed
Avoidance Zone Exceedance	2,466 hrs. (of 27,552 hrs.)	1 hr (of 22,320 hrs)	240 hrs (of 11,544 hrs)	1.15 hrs (of 3,000 hrs)	0 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	not captured		high degree of wear observed		high degree of wear observed
Key notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) & 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 was observed from removed service blades. Blade telemetry instrumentation installed ('Dec 21 - Dec 24', 2014)	Blade telemetry testing; intentionally ran in avoidance zone to set limits, ran in zone for <20 hrs). No blade cracking observed after testing when test instrumentation removed. Blade telemetry data also shows higher stress areas in operation outside the avoidance zone based on blade strain data (no operating limitations placed around these areas by MHPS), data indicates we operated in these zones ~X hrs during the period.	Blade loss of material, 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. At first, MHPS did not support this recommendation, nor did they support the idea that "loss of mass" had occurred.	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). Confirmation from the Harris met lab evaluation should help determine cracking mechanism
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. MHPS learned through Duke Engineering (intentional) that we were investigating blending and its impact to the Condenser/ST. MHPS RCA team for the first time learned what "blending in" and "blending out" meant.

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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	Height same as Bartow
Z-Lock	No HVOF	No HVOF	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

Deleted: *New*

Period	Excessive Steam Flow	Pressure Pulse from Hood Spray	Thermal Distress at L-0 Exhaust (dTempSH/dtime)	Loss of Dampening	Geometry	Other Mechanisms
1	X		X		X	
2		X	X		X	
3	X	X	X		X	
4				X	X	
5		X	X		X	

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Executive Summary

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After months of study, 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
- Thermal Distress at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operations
- Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces
- Loss of Dampening (e.g. Hard-Facing on Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces)

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.

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Commented [PVC1]: For period 3 only.

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.

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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.

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.

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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 a comparison of the number of higher energy blends that occurred in each Period, and it allows the team to quickly identify times to look at additional blend parameters.

Below is a quick comparison of the number "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	31**
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Period 5	1,561	5

*Includes the time period during commissioning from 1/1/2009 to 6/1/2009

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

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Pressure Pulses During Hood/Curtain Spray Operation(s)

The 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.

Review of MHPS-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 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. 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 trip 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 instrument issue).

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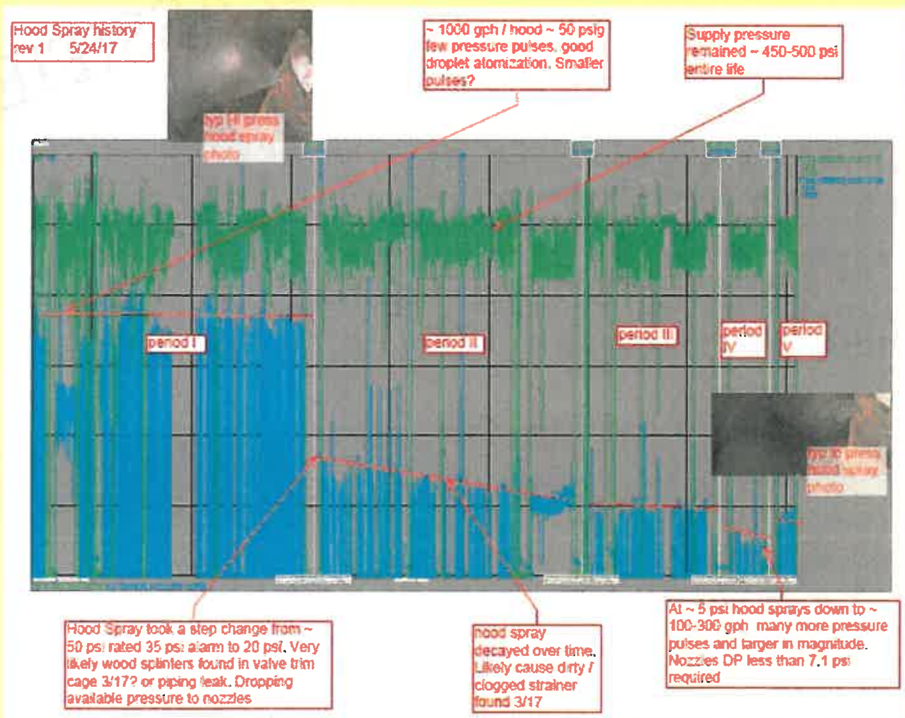

Blade Fitment – Gap Measurements for Mid-Span Snubbers and Shroud Z-Lock Contact Surfaces

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Loss of Dampening (e.g. Hard-Facing on Mid-span Snubbers and Z-Lock Contact Surfaces)

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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 mon	~28 mon	~17 mon	~5 mon	~2 mon
L-0 Blade config	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	450 MW (420 Nameplate)	420 MW per MHI	450 MW	450 MW	390 MW
Operating Restrictions	None	118 psig Limit on IP Exh	126 psig Limit on IP Exh	119 psig Limit on IP Exh	111 psig Limit on IP Exh
Blade Over speed condition	Over speed testing in MFG		Over speed tested in Japan	No over speed	No Over speed
Avoidance Zone Exceedance	2,466 hrs. (of 27,552 hrs.)	1 hr (of 22,320 hrs)	240 hrs (of 11,544 hrs)	1.15 hrs (of 3,000 hrs)	0 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	not captured		high degree of wear observed		high degree of wear observed
Key notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) & 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 was observed from removed service blades. Blade telemetry instrumentation installed ('Dec 21 - Dec 24', 2014)	Blade telemetry testing; intentionally ran in avoidance zone to set limits, ran in zone for <20 hrs). No blade cracking observed after testing when test instrumentation removed. Blade telemetry data also shows higher stress areas in operation outside the avoidance zone based on blade strain data (no operating limitations placed around these areas by MHPS), data indicates we operated in these zones ~X hrs during the period.	Blade loss of material, 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. At first, MHPS did not support this recommendation, nor did they support the idea that "loss of mass" had occurred.	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). Confirmation from the Harris met lab evaluation should help determine cracking mechanism
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. MHPS learned through Duke Engineering (intentional) that we were investigating blending and its impact to the Condenser/ST. MHPS RCA team for the first time learned what "blending in" and "blending out" meant.

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	Height same as Bartow
Z-Lock	No HVOF	No HVOF	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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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-0blade failures is that the OEM designed blades were inadequate for the operating conditions with which they were subjected.

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. Today, there is agreement between both parties that there is not just one simple root cause.

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After months of study, 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
- Thermal Distress at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operations
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening (e.g. 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 theorize 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 (e.g. redesigned blades) for the Bartow LP section 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.

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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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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. The ST LP admission system was modified by MHPS with the intent for 4x1 CC operations to yield a 450MW gross output rating.

Commented [PVC1]: For period 3 only.

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.

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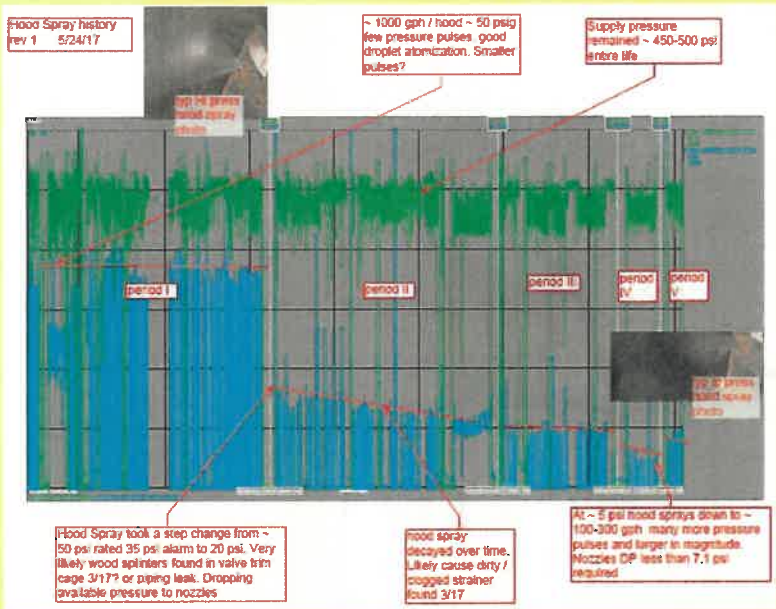

Zone Analysis – Shroud Fretting Fatigue

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 their design limit in the normal operation range of the LP turbine. The Duke RCA team defined these zones as Zone F1 thru Zone F3 (shown by the red rectangles in the figure 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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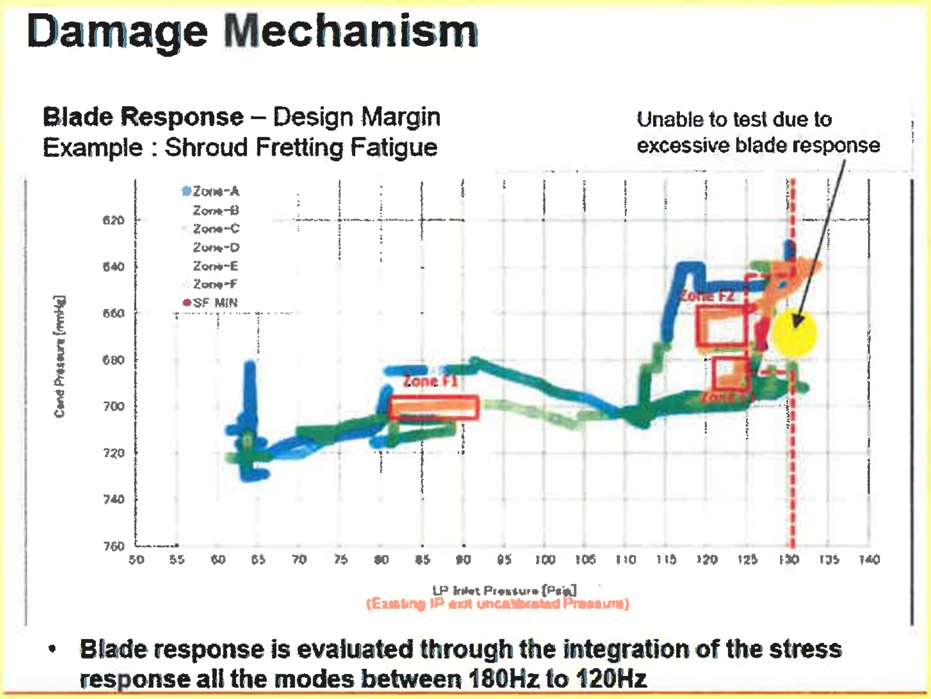

Figure X: Data presented by MHPS from a presentation dated YY/YY/YYYY

Table Y shows the breakdown of time in hours in each of the three defined F zones for each period. The total time in the 3 zones 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.

	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%

Table Y: Time in hours spent in each Zone and the total compared with operating time

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

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Figure XX. 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 XX: Photo of Z-notch from Period 5 showing wear of contact surface

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.

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Loss of Dampening (e.g. Hard-Facing on Mid-span Snubbers and 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 locating 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

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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 caused by 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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Avoidance Zone Exceedance	2,466 hrs. (of 27,552 hrs.)	1 hr (of 22,320 hrs)	240 hrs (of 11,544 hrs)	1.15 hrs (of 3,000 hrs)	0 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	not captured		high degree of wear observed		high degree of wear observed
Key notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) & 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 was observed from removed service blades. Blade telemetry instrumentation installed ('Dec 21 - Dec 24', 2014)	Blade telemetry testing; intentionally ran in avoidance zone to set limits, ran in zone for <20 hrs). No blade cracking observed after testing when test instrumentation removed. Blade telemetry data also shows higher stress areas in operation outside the avoidance zone based on blade strain data (no operating limitations placed around these areas by MHPS), data indicates we operated in these zones ~X hrs during the period.	Blade loss of material, 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. At first, MHPS did not support this recommendation, nor did they support the idea that "loss of mass" had occurred.	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). Confirmation from the Harris met lab evaluation should help determine cracking mechanism
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. MHPS learned through Duke Engineering (intentional) that we were investigating blending and its impact to the Condenser/ST. MHPS RCA team for the first time learned what "blending in" and "blending out" meant.

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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	Height same as Bartow
Z-Lock	No HVOF	No HVOF	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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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-0blade failures is that the OEM designed blades were inadequate for the operating conditions with which they were subjected.

Duke Engineering believes the root cause for Periods 1-5 involves more than driving mechanism. During a presentation given at the Duke FRHQ on 22 September 2017, MHPS 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. Today, there is agreement between both parties that there is not just one simple root cause.

After months of study, 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
- Thermal Distress at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operations
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening (e.g. 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 theorize 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 (e.g. redesigned blades) for the Bartow LP section 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. The ST LP admission system was modified by MHPS with the intent for 4x1 CC operations to yield a 450MW gross output rating.

Commented [PVC1]: For period 3 only.

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.

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 Period 1 and 3, photographic evidence suggests that the amount of wear is similar. 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.

Commented [PVC2]: This is what I recall - but we need the photos to prove this otherwise we can't say it.

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.

Commented [PVC3]: However, MHPS has not done any review and released us to go to higher LP inlet pressures/flows.

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.

Below is a quick comparison of the number "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	31**
Period 4	2,942	3
Period 5	1,561	5

*Includes the time period during commissioning from 1/1/2009 to 6/1/2009

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

Commented [JCE4]: Paul, I changed the middle column to hours (from day) to stay consistent with other charts we've created. The hours I have for Period 1 (21,734) – do they include the time frame you've included next to the first *, or are they Period 1 operating hours post-COD?

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:

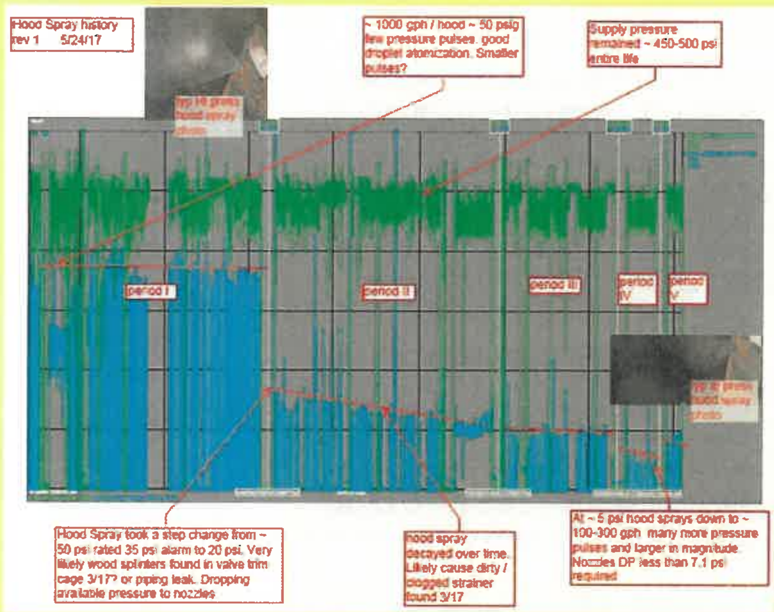
- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

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 valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the valve had filled with debris in prior years' operating.

Commented [JCE5]: Which valve is this – The control valve mentioned in the above paragraph?

The chart 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.



Zone Analysis – Shroud Fretting Fatigue

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Loss of Dampening (e.g. Hard-Facing on Mid-span Snubbers and 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 locating 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.

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. Planned design changes intend to reduce blade response and induced dynamic stress 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 mon	~28 mon	~17 mon	~5 mon	~2 mon
L-0 Blade config	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	450 MW (420 Nameplate)	420 MW per MHI	450 MW	450 MW	390 MW
Operating Restrictions	None	118 psig Limit on IP Exh	126 psig Limit on IP Exh	119 psig Limit on IP Exh	111 psig Limit on IP Exh
Blade Over speed condition	Over speed testing in MFG		Over speed tested in Japan	No over speed	No Over speed
Avoidance Zone Exceedance	2,466 hrs. (of 27,552 hrs.)	1 hr (of 22,320 hrs)	240 hrs (of 11,544 hrs)	1.15 hrs (of 3,000 hrs)	0 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	not captured		high degree of wear observed		high degree of wear observed
Key notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) & 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 was observed from removed service blades. Blade telemetry instrumentation installed ('Dec 21 - Dec 24', 2014)	Blade telemetry testing; intentionally ran in avoidance zone to set limits, ran in zone for <20 hrs). No blade cracking observed after testing when test instrumentation removed. Blade telemetry data also shows higher stress areas in operation outside the avoidance zone based on blade strain data (no operating limitations placed around these areas by MHPS), data indicates we operated in these zones ~X hrs during the period.	Blade loss of material, 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. At first, MHPS did not support this recommendation, nor did they support the idea that "loss of mass" had occurred.	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). Confirmation from the Harris met lab evaluation should help determine cracking mechanism
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Turb/Gen End	Yes	Yes	Yes	Yes
Snubber	No HVOF	Chamfer Radius & HVOF	Chamfer Radius & HVOF	Height same as Bartow
Z-Lock	No HVOF	No HVOF	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)
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Deleted: *New*

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Duke's position is as follows: The root cause of the Bartow steam turbine (ST) 40" L-0 blade failures is 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.

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. Today, there is agreement between both parties that there is not just one simple root cause.

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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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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.

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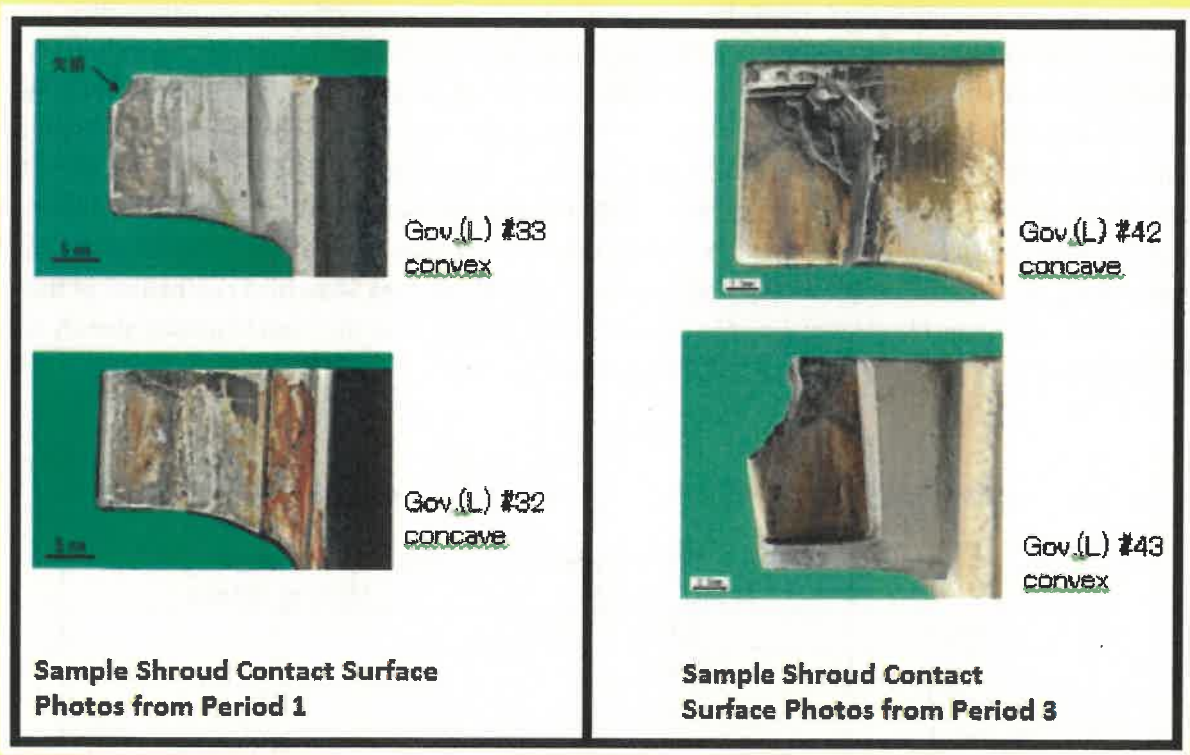
Figure 1 -- Comparative Photos of Shroud Contact Surface Wear for Periods 1 and 3



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

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 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:

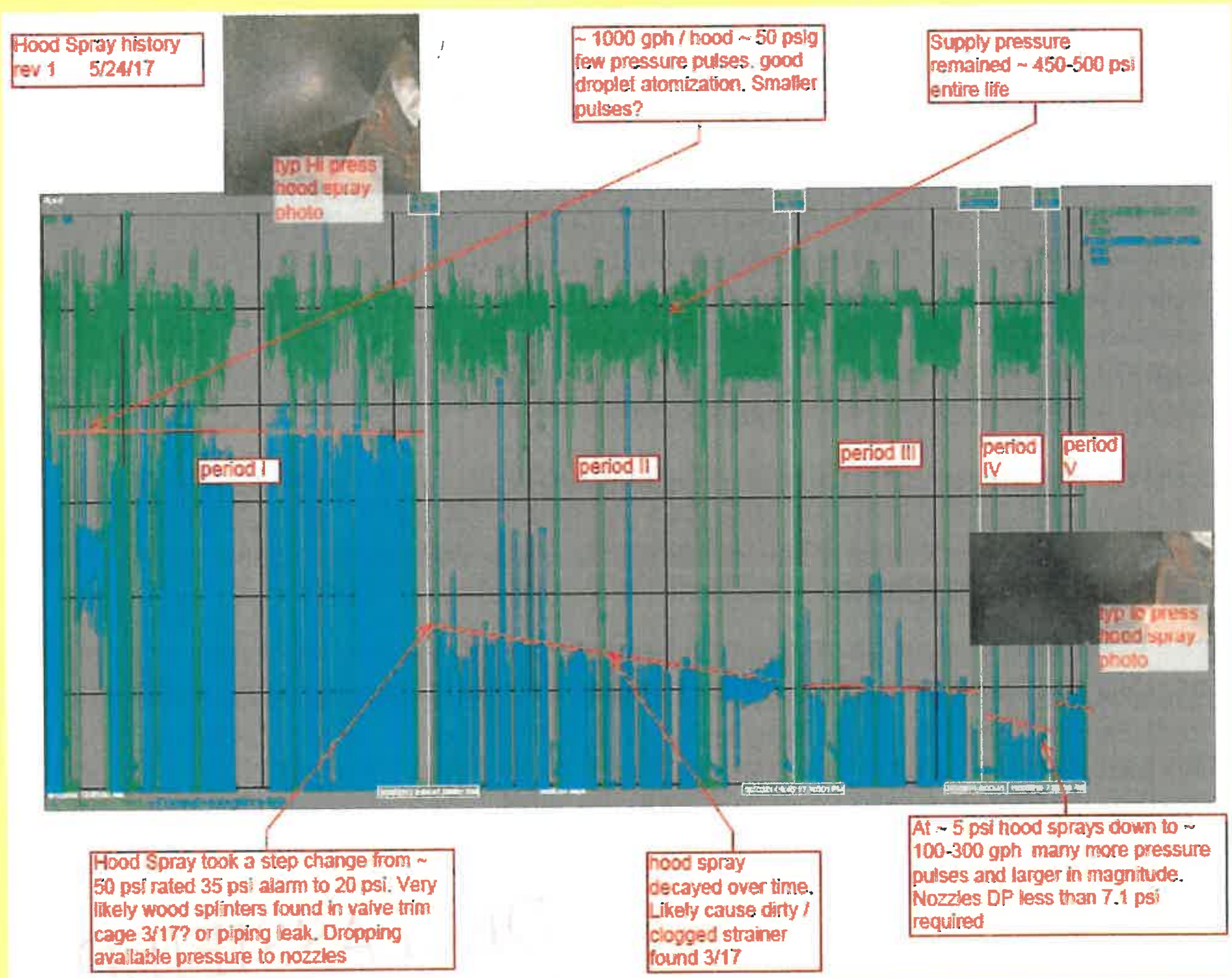
- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

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

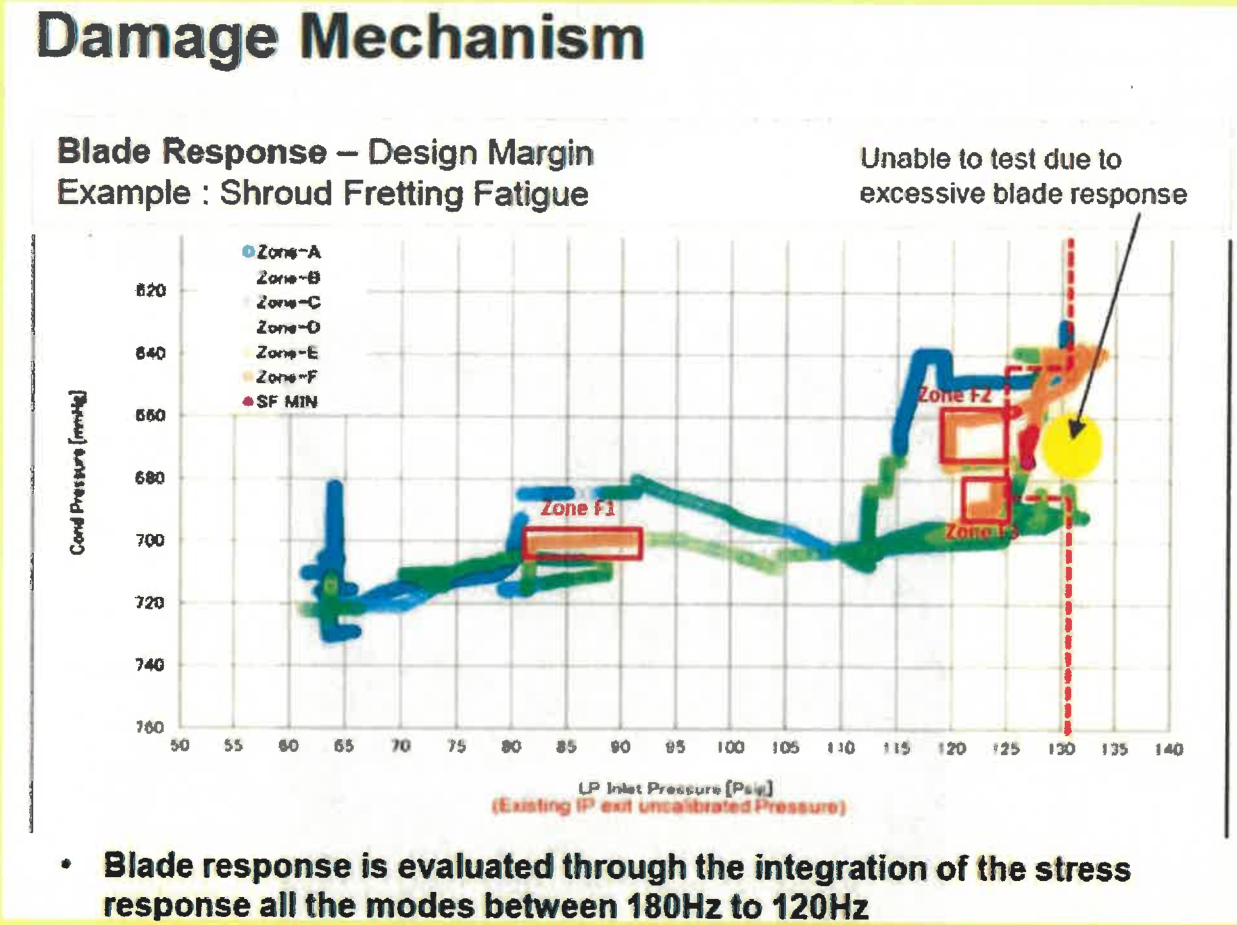


Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined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

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	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*

Executive Summary

Duke and Mitsubishi Hitachi Power Systems (MHPS) have worked both independently and together over the past 12 months to determine what has caused the Bartow Unit 4S L-0 blades to crack and break during operation. During a presentation given at Bartow Station on 15 March 2017, MHPS suggested the sole root cause for Period 3 (Dec 2014-Mar 2016) was "operation in the avoidance zone". While Duke Engineering would agree that operation in the avoidance zone is certainly a *contributing factor* to the shroud chipping experienced in Period 3, it is not the only contributing factor that should be considered when trying to determine root cause for the Period 3 Bartow Unit 4S event, or any of the previous/subsequent events for that matter.

After months of study, 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 Back-End Loading (>15,000 lb./hr./ft.^{2})
- Blending Operations
- Hood Spray Operations
- Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches
- Configuration (e.g. Hard-Facing on Z-Notches)

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. The ST LP admission system was modified by MHPS with the intent for 4x1 CC operations to yield a 450MW gross output rating.

Commented [PVC1]: For period 3 only.

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-Notch 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

LP Turbine Back-End Loading (>15,000 lb./hr./ft.[2])

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" 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.

As for Period 3, there were only approximately 240 hours of operation in the avoidance zone, of which approximately 11 hours occurred during the instrumented test by MHPS in December of 2014. Even with the greatly reduced amount of high flow hours for Period 3 as compared to Period 1 (a factor of 10 fewer hours for Period 3), a high amount of wear and distress was seen on the z-notch contact surfaces. While the amount of z-notch wear is not quantified for Period 1 and 3, photographic evidence suggests that the amount of wear is similar. It 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.

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.

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Commented [PVC3]: However, MHPS has not done any review and released us to go to higher LP inlet pressures/flows.

Blending Operations

During the most recent root cause analysis, the team expanded its view of turbine operations to 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 low pressure (LP) bypass steam flows from each of the four CTs, 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.

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A set of criteria and an automated process using Excel and PI Datalink was developed that allows large amounts of data stored in PI to be quickly reviewed for each time Period. Blends that meet the criteria were further analyzed to see how blend operations met or exceeded design criteria set by the condenser OEM. The process relies on 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 over 20 degrees F when a CT is being blended off or on the steam turbine and the steam turbine output is greater than 50 mw. The limits of 20 F 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 a comparison of the number of higher energy blends that occurred in each period, and it allows the team to quickly identify times to look at additional blend parameters.

Below is a quick comparison of the number blends that meet the criteria for Periods 1 thru 5.

	Number of days in Period	Number of blends meeting criteria
Period 1	1185 days	13*
Period 2	973 days	7
Period 3	482 days	31**
Period 4	127 days	3
Period 5	68 days	5

*Includes the time period during commissioning from 1/1/2009 to 6/1/2009

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

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Hood Spray Operations

The 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. Review of MHPS provided instructions requires use of hood sprays under the following conditions:

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- Speed greater than 600 rpm and load less than 10 mw
- Hood spray thermocouple reading greater than 160 F

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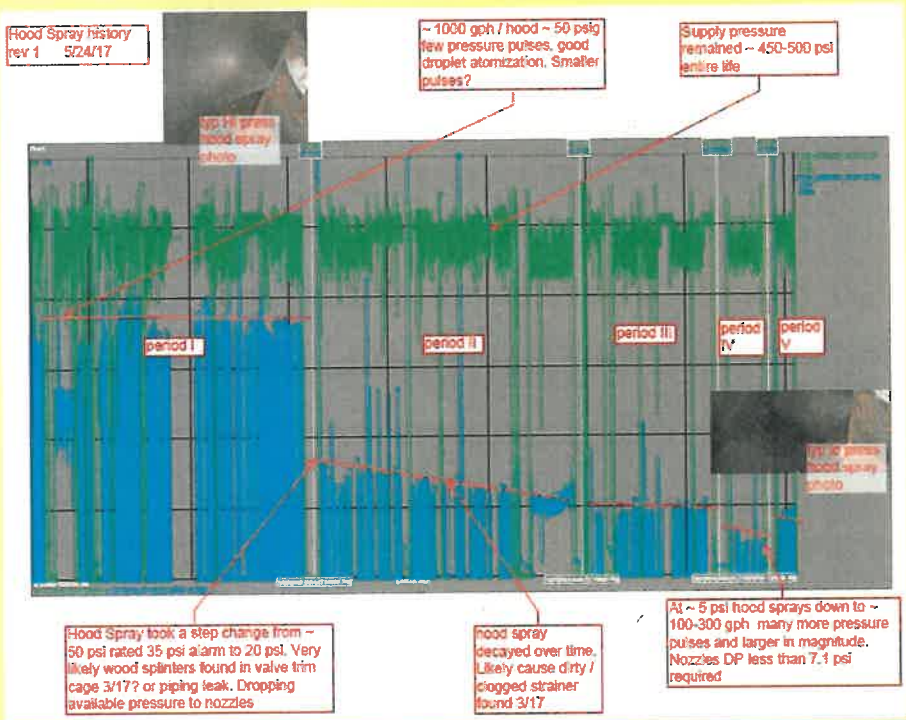
During review of the hood spray data, it became clear that additional operation besides the above had been programmed into the DCS since commissioning. In addition to the above, hood sprays were programmed to turn on anytime blending took place (similar to the way the curtain sprays are programmed). No explanation for why this was done has been found. Based on this finding, hood spray operation time is far greater than had it just been used as originally intended. A review of hood spray thermocouple data shows they rarely reach 160 F during normal operation and never over 165 F. Higher temperature are sometimes seen after a shutdown or trip when the temperature in the exhaust increases, most likely due to the hot LP casings and some windage. No temperatures over 201 F were found (one very brief reading of 1040 F was an instrument 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 valve in spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the valve had filled with debris in prior years.

The chart below shows what happened to hood spray pressure over time. The decay in water pressure at the hood spray nozzles will have 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.



Curtain Spray Operations

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Gap Measurements for Mid-Span Snubbers and Shroud Z-Notches

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Configuration (Hard-Facing on the Z-Notches)

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Duke Engineering's believes that MHPS's conclusions represent contributing factors in the failures; therefore, Duke is not in concurrence with the recommended RCA conclusion. MHPS and Duke have been working together, and continue to work together, to collect data and evidence to determine the drivers behind these L-0 blade failures. Data suggests that there are ***several contributing factors, none of which have been quantified conclusively to determine the root cause to any particular failure event***.

There are five periods of interest:

Period 1: Concluded in 2012 with approximatly 34 months of operation with Type 1 L-0's in service.
- Five turbine end (TE) L-0 blades were found to have broken snubbers, the L-0 blades were replaced.
- During this period the blades operated in (what MHPS would define during the transition from Period 2 into Period 3 as) the avoidance zone for 2,466 hours with no operating restrictions placed on the ST.
- No RCA was conducted as Duke worked with MHPS and was willing to have MHPS provide and eventually install what was thought to be the solution to the issue with new design blades (installed in Fall 2014).

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Period 2: Concluded in 2014 with approximatly 28 months of operation with Type 1 L-0's in service. This was a planned outage to replace the L-0 blades with an Enhanced/More Robust Blade (Type 3 v1).
- The IP Exhaust Pressure operated at a limit of 118 psig during period 2.
- Blade telemetry instrumentation was also installed during the Period 2 outage to measure blade stresses and determine the limits of the avoidance zone in operation (performed by crossing the avoidance zone in operation and measuring blade stresses).
- No RCA was required.

Period 3: Concluded in the spring of 2016 with approximately 17 months of operation with Type 3 (v1) L-0's inservice. This was a forced outage as a result of several blades with broken Z-lock interfaces on both generator end (GE) and turbine end (TE) L-0's.

After commissioning the blades operated in the avoidance zone for ~20 hrs to further refine the avoidance zone. Operations restricted output by limiting IP Exhaust pressure to 126 psig (based on strain gauge data). Blade strain gage data also shows high stress areas in operation outside the avoidance zone (no operating limitations placed around these areas by MHPS).

MHPS Engineering added stellite hard facing to the Z-lock contact faces to the newly installed blades as a measure to prevent wear and breakage.

The RCA is currently inconclusive from data and findings, but several contributing factors have been determined.

Note: At the onset of Period 3, per MHPS Engineering, short term operation – i.e. 10-20 minutes per occurance – within the avoidance zone was allowable under certain operating ranges for both condenser backpressure and IP exhaust pressure during, for example, peak power seasons in summer. Over the course of time and subsequent L-0 events, MHPS Engineering amended and restated their technical disposition to express that operation within the avoidance zone should be prohibited altogether.

Period 4: Concluded in the fall of 2016 with approximatly 5 months of operation with Type 3 (v2) L-0's inservice. This was an forced outage as a result of several L-0 blades with broken Z-lock interfaces and missing airfoil material. Inspection of the Z-lock area showed less than desirable contact on the Z-lock surface (~10% contact vs ~60% contact). The Z-lock surface needs to properly contact to obtain the desired dampening effect during operation.

During this period the blades operated in the avoidance zone for 1.15 hours with additional operating limitations of 119 psig in IP exhaust pressure.

Several L-0 blades from Period 1, 3, and 4 were measured to compare geometry. Scans show wide range of geometry from manufacturing; it is unknown if these deviations are within design expectancy or not (MHPS has requested blades for scanning to compare – in process).

MHPS is evaluating if the additional stellite coating on the Z lock promoted a loss of dampening. Since this failure mode was significantly different than any in the past or since this period, i.e. complete loss of a Z-lock tip and air foil section, and the crack started at the blades high point for stress the design may have been compromised because of hard facing on all mating surfaces.

The RCA is currently inconclusive, the application of the HVOF coating on the Z-lock surface appear to be one of the leading factors in the failure. The replacement blades going into Period 5 reverted back to the Type 1 design.

The Station also installed DCS logic to trigger alarms before operation occurs in the Avoidance zone.

Period 5: Concluded in the spring of 2017 with approximately 2 months of operation with Type 1 L-0's in service. This was a forced outage that was a result of several blades with broken Z-lock interfaces and snubbers on the Generator End (GE) L-0 blades.

During this period the blades operated in the avoidance zone for 0 hours with additional operating limitations of 111.1 psig in IP exhaust pressure.

For the first time, Duke Engineering identified blending as a possible contributing factor to the RCA. "Blending steam" is a common occurance with combined cycle applications. One example of a suspect blend transient is evidence of measured water hammer event(s) in piping networks that dump into the condenser. The shock wave developed by a suspect blend transient does enter the condenser hotwell, however the impact of these type events on the L-0 blades is analytically unknown. Work is underway to determine if blend transients can be correlated to blade telemetry data from 2014/15.

Note: "Blending In" steam involves integrating steam production from a specific CT/HRSG train into the ST. "Blending Out" steam involves bypassing steam from the ST to the condenser as a particular CT/HRSG train transfers from combined cycle to simple cycle operations (or offline).

The RCA is still underway with no conclusions developed from data and findings.

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 mon	~28 mon	~17 mon	~5 mon	~2 mon
L-0 Blade config	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	450 MW (420 Nameplate)	420 MW per MHI	450 MW	450 MW	390 MW
Operating Restrictions	None	118 psig Limit on IP Exh	126 psig Limit on IP Exh	119 psig Limit on IP Exh	111 psig Limit on IP Exh
Blade Over speed condition	Over speed testing in MFG		Over speed tested in Japan	No over speed	No Over speed
Avoidance Zone Exceedance	2,466 hrs. (of 27,552 hrs.)	1 hr (of 22,320 hrs)	240 hrs (of 11,544 hrs)	1.15 hrs (of 3,000 hrs)	0 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	not captured		high degree of wear observed		high degree of wear observed
Key notes from Period events	MHPSA was hired to evaluate ST design conditions (original design was for Tenaska, 3x1 heat balance) & 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 was observed from removed service blades. Blade telemetry instrumentation installed ('Dec 21 - Dec 24', 2014)	Blade telemetry testing; intentionally ran in avoidance zone to set limits, ran in zone for <20 hrs). No blade cracking observed after testing when test instrumentation removed. Blade telemetry data also shows higher stress areas in operation outside the avoidance zone based on blade strain data (no operating limitations placed around these areas by MHPS), data indicates we operated in these zones ~X hrs during the period.	Blade loss of material, 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. At first, MHPS did not support this recommendation, nor did they support the idea that "loss of mass" had occurred.	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). Confirmation from the Harris met lab evaluation should help determine cracking mechanism
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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)	*New*
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	Height same as Bartow
Z-Lock	No HVOF	No HVOF	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

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-0blade failures is that the OEM designed blades were inadequate for the operating conditions with which they were subjected.

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. Today, there is agreement between both parties that there is not just one simple root cause.

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After months of study, 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
- Thermal Distress at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operations
- Zone Analysis – Shroud Fretting Fatigue
- Loss of Dampening (e.g. 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 theorize 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 (e.g. redesigned blades) for the Bartow LP section 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.

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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 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.

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.

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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 Period 1 and 3, photographic evidence suggests that the amount of wear is similar. 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.

Commented [PVC2]: This is what I recall - but we need the photos to prove this otherwise we can't say it. Update: I think we now have sufficient photos to say this.

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.

Commented [PVC3]: However, MHPS has not done any review and released us to go to higher LP inlet pressures/flows.

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.

Below is a quick comparison of the number "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

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*Includes the time period during commissioning from 1/1/2009 to 6/1/2009

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

Commented [JCE4]: Paul, I changed the middle column to hours (from day) to stay consistent with other charts we've created. The hours I have for Period 1 (21,734) – do they include the time frame you've included next to the first *, or are they Period 1 operating hours post-COD?

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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 valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the valve had filled with debris in prior years' operating.

Commented [JCE5]: Which valve is this – The control valve mentioned in the above paragraph? Yes.

The chart 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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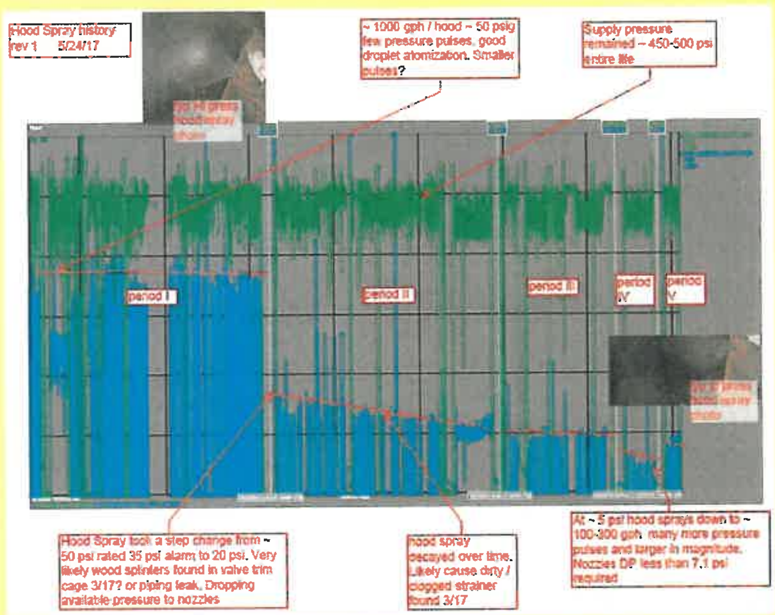

Zone Analysis – Shroud Fretting Fatigue

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 their design limit in the normal operation range of the LP turbine. The Duke RCA team defined these zones as Zone F1 thru Zone F3 (shown by the red rectangles in the figure 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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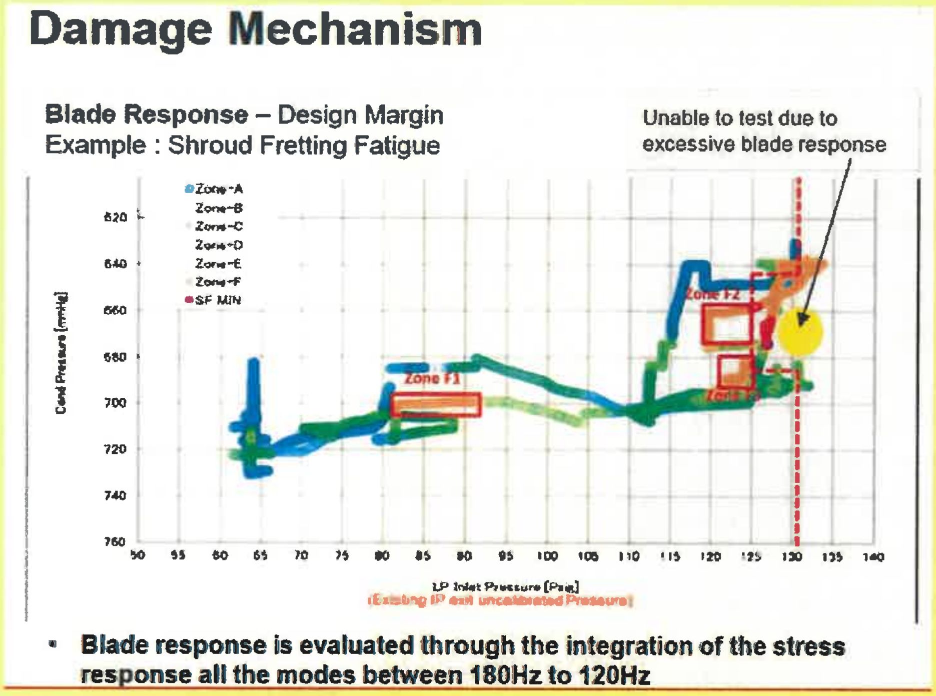

Figure X: Data presented by MHPS from a presentation dated YY/YY/YYYY

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Table Y shows the breakdown of time in hours in each of the three defined F zones for each period. The total time in the 3 zones 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.

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	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%

Table Y: Time in hours spent in each Zone and the total compared with operating time

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

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Figure XX. 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.

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Figure XX: Photo of Z-notch from Period 5 showing wear of contact surface

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.

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Loss of Dampening (e.g. Hard-Facing on Mid-span Snubbers and 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 locating 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

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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 caused by 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 mon	~28 mon	~17 mon	~5 mon	~2 mon
L-0 Blade config	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	450 MW (420 Nameplate)	420 MW per MHI	450 MW	450 MW	390 MW
Operating Restrictions	None	118 psig Limit on IP Exh	126 psig Limit on IP Exh	119 psig Limit on IP Exh	111 psig Limit on IP Exh
Blade Over speed condition	Over speed testing in MFG		Over speed tested in Japan	No over speed	No Over speed
Avoidance Zone Exceedance	2,466 hrs. (of 27,552 hrs.)	1 hr (of 22,320 hrs)	240 hrs (of 11,544 hrs)	1.15 hrs (of 3,000 hrs)	0 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
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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.

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 Period 1 and 3, photographic evidence suggests that the amount of wear is similar. 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.

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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.

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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 the time period during commissioning from 1/1/2009 to 6/1/2009

**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 valve in Spring 2017 revealed debris in the valve passageways. Review of historical records also indicate the strainer ahead of the valve had filled with debris in prior years' operating.

Figure 1, 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

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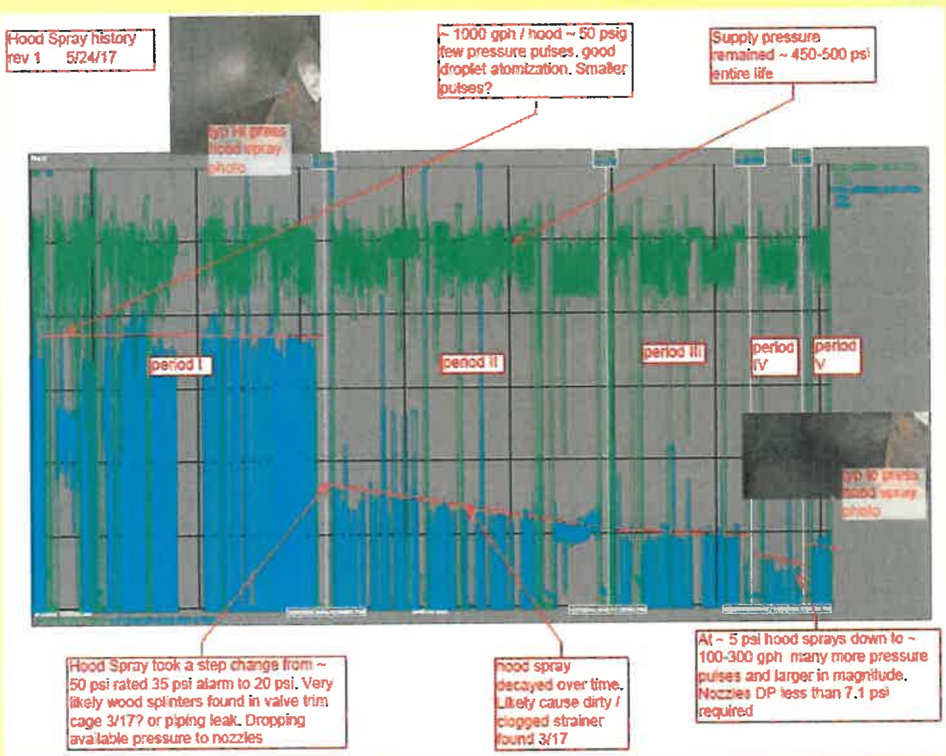
Commented [JCE5]: Which valve is this – The control valve mentioned in the above paragraph?

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 1 -- 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 2, below) and based on the PI historical data, calculated the amount of time the turbine spent in each zone for each period.

Figure 2 -- Data Presented by MHPS During a Presentation Dated 15 March 2017

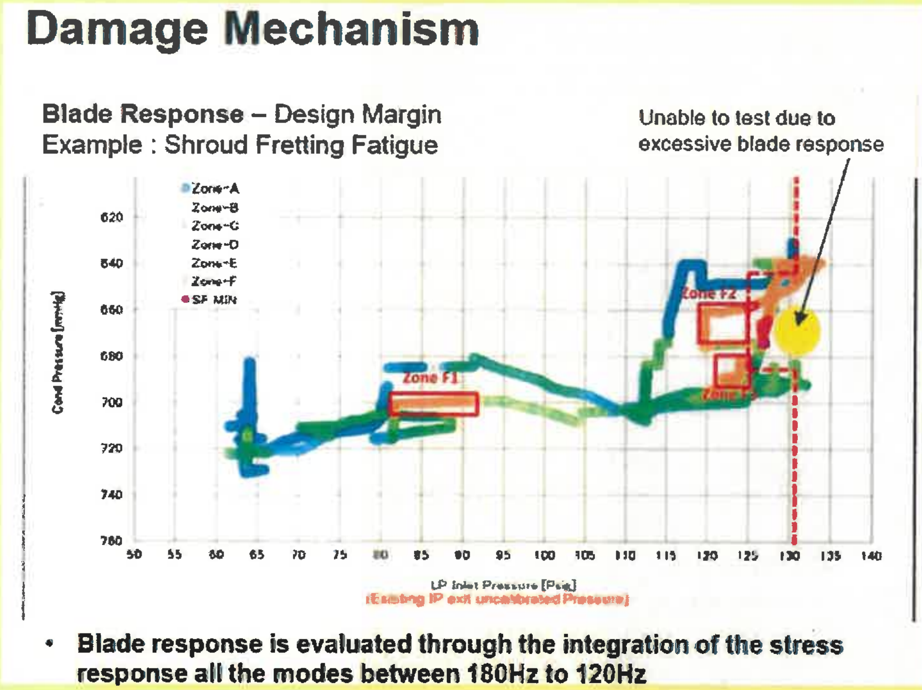


Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined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

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 mon	~28 mon	~17 mon	~5 mon	~2 mon
L-0 Blade config	Type 1	Type 1	Type 3 (v1)	Type 3 (v2)	Type 1
ST Rating	420 MW Nameplate	420 MW Nameplate	450 MW	450 MW	390 MW
Operating Restrictions	None – MHPS intent was to follow heat balances	118 psig Limit on IP Exh	126 psig Limit on IP Exh	119 psig Limit on IP Exh	111 psig Limit on IP Exh
Blade Over speed condition	Over speed testing in MFG		Over speed tested in Japan	No over speed	No Over speed
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 – mostly corner chipping, 1 z-notch with close to half missing	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 seen.	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) & 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 minor blade damage (chips at contact corners) was observed from removed service blades. Blade telemetry instrumentation installed ('Dec 21 - Dec 24', 2014)	Blade telemetry testing; intentionally ran in avoidance zone to set limits, ran in zone for <20 hrs). No blade cracking observed after testing when test instrumentation removed.	Blade loss of material, 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.

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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 (about 1 in)
Z-Lock	No HVOF	No HVOF	45° corner, 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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Executive Summary

Over the past 3 plus years, Duke Energy Florida LLC (Duke), at times working independently and at times together with Mitsubishi Hitachi Power Systems (MHPS), undertook a root cause analysis (RCA) of the cause(s) for the Unit 4S L-0 blade cracks and failures that occurred during normal station operations at Bartow Station. The intervals between failures had become shorter after each failure despite MHPS's attempts to improve the blades' performance and the station's adherence to the revised OEM operating instructions received after each successive failure.

Only after the telemetry test was completed and after the onset of Period 3, in approximately March 2015, (as a result of the telemetry test) did MHPS create an "avoidance zone" in which the station was not to operate except as needed to ramp up or down. Bartow operated in the avoidance zone only 1.15 hours in Period 4 and 0 hours in Period 5, but suffered two (2) further failures in successively shorter periods. Thus, after the fifth failure, Duke concluded that operation in MHPS' designated avoidance zone did not explain the failures and looked at whether other factors potentially were related or contributed to the failures.

Duke considered both operational and design aspects. With respect to operational factors, the Duke team used the Plant Information ("PI") data historian and operational data from each period and retroactively calculated[1] whether those factors had any correlation to the failures. Potential factors in the operational category included:

- Operations in MHPS Avoidance Zone -- Low Pressure (LP) Turbine "Excessive" Steam Flow
- Bartow Blending Operations – Potential Thermal Distress (Rate of Change in Super Heat Over Time, dT_{SH}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)

Duke Engineering concluded that there was no correlation between any one of the above-listed factors and the five (5) failure periods. Notably, Duke was only able to study each factor independently based on available data. In the absence of (1) blade telemetry, (2) duplication of the factors in various combinations, and (3) operation in varying but normal conditions, it is not possible to study how each factor relates to and interacts with any other factor, if at all.

Duke also studied design factors unique to MHPS 40" steel blades. This aspect of the RCA was largely deductive because MHPS controls design data, although MHPS did provide FEA stress and frequency analyses, material properties, and some dimensional information. The following factors were included in this portion of the study:

- Zone Analysis – Shroud Fretting Fatigue

[1] Because MHPS's operational constraint called the Avoidance Zone was not provided by MHPS until after the onset of Period 3, one could only look at hours in that zone after-the-fact for Periods 1 and 2.

- 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

With regard to the "Hard-Facing on Mid-Span Snubbers" factor, Duke was able to conclude and MHPS concurred, that this factor played a part in the blade failure in Periods 3 and 4. With respect to the Zone Analysis and Blade Fitment factor, although MHPS made no concession, it is currently re-engineering its 40" blades and making changes to the blades' geometry as discussed by MHPS Engineering in a 22 September 2017 presentation made to Duke.

Based on its observations and study, Duke has been and remains of the opinion that the root cause of the failures in the ST L-0 40" blades is the blade design/lack of blade design margin. That is to say, under expected operating conditions at Bartow's 4x1 Combined Cycle (CC) Unit, the MHPS blades are substantially more fragile than similar 40" blades both in Duke's CC fleet and elsewhere in the industry.[2]

Duke's conclusion is based on its study of the events and information that includes data supplied by MHPS, PI data from Bartow, information from similar units in Duke's fleet, and industry experience with the 40" blades. MHPS did not provide proprietary information concerning engineering and testing of the 40" blades but did provide engineering assistance and strain gauge data from a brief period of MHPS-led telemetry testing during December 2014. Duke provided all operational information requested by MHPS and met with MHPS multiple times to discuss both MHPS' findings and Duke's independent research and findings. This RCA report is Duke's product and presents its view of the root cause based on all inputs received.

For Bartow, the long-term solution is to replace the L-0 blades with blades of a different design and/or to retrofit the LP steam path and/or continue operation with pressure plate.

With either a redesign of the MHPS 40" blades or replacement with blades of a different make or an LP steam path retrofit, telemetry instrumentation and blade vibration monitoring are necessary to ensure that all potential upset conditions are resolved.

Historical Overview

Bartow is a 4x1 CC Station with a steam turbine (ST) manufactured by MHPS. The ST was purchased from Tenaska Power Equipment, LLC (Tenaska) which intended to use it for a 3x1 CC with a gross output of 420MW. The ST was never delivered to Tenaska and remained with MHPS in a warehouse in Japan until Duke purchased the unit in 2006.

Before the ST was purchased by Duke, Duke contracted with MHPS to evaluate the ST design conditions and to update heat balances for a 4x1 CC configuration. MHPS updated the heat balances for use in a 4x1 CC configuration. CC units blend steam from the combustion turbines (CT) as they start-up and/or

[2] The most commonly reported issue with the 40" L-0 blade design elsewhere is water erosion, which both Duke and MHPS agree is not a contributing factor to the Bartow failures.

shut-down with steam to the ST. These blending events, which are a common occurrence for CC units, result in brief periods of higher steam temperatures and flows into the condenser near the ST L-0 blades.

Since commissioning of the Bartow ST in 2009, there have been five (5) events involving L-0 blade failures and/or replacements as described, below.

Each 40" MHPS steel blade is twisted with a "root end" that connects it to the hub, a snubber at the mid-point or mid-span, and a shroud with airfoil tips at the top. While the ST spins up to its operating speed of 3600rpm, each blade elongates and starts to untwist. The snubbers and airfoil tips are designed to contact each other and create a stabilizing central and outer ring. If a snubber or airfoil tip fails, the blades can vibrate excessively and can cause sudden catastrophic failure. Although none of the five (5) Periods at Bartow involved a complete blade loss or catastrophic failure, two (2) involved upsets and each event affected mid-span snubbers, shroud Z-Locks, and airfoil tips.

The five (5) Periods are summarized in Table A. Each Period's start date is when the ST was put into service and each end date reflects either when the ST was taken off-line or suffered an unplanned outage. The blades for each period are described by "Type." The ST was sold and during Period 1 was operated with Type 1 blades, which at MHPS' recommendation and urging were replaced – turbine end (TE) blades only – with a re-engineered Type 1 blade at the start of Period 2. Period 2 ended with a planned shut-down, during which the TE and generator end (GE) blades were replaced with an OEM-improved design (Type 3) even though the in-service Type 1 L-0 blade condition was such that they could have run longer. The Type 3(v1) blades had hard-facing on the mid-span snubber contact surfaces and MHPS ran its brief period of telemetry testing. Damage found at the end of Period 3 resulted in a forced outage and the installation of new Type 3(v2) blades with hard-facing on the mid-span snubber, as well as hard-facing now added to the Z-Lock contact surfaces. When these Type 3(v2) blades failed at the end of Period 4, they were replaced with the original Type 1 blades for Period 5. When these Type 1 blades failed at the end of Period 5, the L-0 blades were replaced with a pressure plate.

MHPS provided OEM operating parameters in each Period as reflected in Table A under the heading "MHPS IP Exhaust Pressure Operating Limits." For Period 1, these limits were the design limits that accompanied the ST at purchase. After the damage was discovered at the end of Period 1, MHPS imposed a lower IP exhaust pressure limit. In Period 3, when the Type 3 blades were installed, MHPS raised the limit, in accordance with the original proposal by MHPS to supply blades for Period 3 that would allow operation up to 450 MW but also stay within the limits established as a result of the telemetry test. After the telemetry test, MHPS sent out a chart it called the "Avoidance Zone" and suggested that blade damage would be avoided if Duke operated as few hours as possible in the zone. The practical result of the avoidance zone limits meant that the Bartow ST unit could not achieve 450 MW as the IP exhaust pressure was, and to this day still is, limited when condenser pressure is in a range the unit normally must run in. In Period 4, with the discovery of additional damage, MHPS lowered its IP exhaust pressure limit and did so again in Period 5.

Table A: Bartow L-0 Events Summary

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	June 2009 to March 2012	April 2012 to August 2014	December 2014 to April 2016	May 2016 to Oct 2016	December 2016 to February 2017
Service Duration	~34 Months	~28 Months	~17 Months	~5 Months	~2 Months
L-0 Blade Configuration	Type 1	Type 1 (re-engineered)	Type 3 (v1)	Type 3 (v2)	Type 1
MHPS Expected ST Output	420 MW (Nameplate)	420 MW	450 MW[3]	450 MW[3]	390 MW
MHPS IP Exhaust Pressure Operating Limits	Machine controlled to HP, IP and Condenser design limits	118 psig Limit on IP Exhaust	126 psig Limit on IP Exhaust	119 psig Limit on IP Exhaust	111.5 psig Limit on IP Exhaust
Retroactive Calculation of Avoidance Zone "Exceedance" based on the MHPS Period 3 Avoidance Zone chart[4]	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	Planned outage for valve work, as well as annual L-0 inspections. At the start of this period, MHPS approved 4x1 (unfired) operations at 392 MW output, as well as 3x1 (duct fired) operation at 420 MW, supported by MHPS-provided heat balance documentation. During a plant shut down a visual inspection of the ST L-0 blades revealed damage to the turbine end blade snubbers.	Planned outage for upgrade to "heavy duty" blades, based on MHPS representation that it had improved design. 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. Planned outage for valve work, as well as an annual L-0 inspection. No blade cracking observed after testing (when the test instrumentation removed). Stellite hard-facing added to snubbers only.	Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection. Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil. Stellite hard-facing added to the blade Z-Lock.	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). L-0 blades removed and pressure plate installed; pressure plate restricted ST output to between 360-380 MW. MHPS maintains operational restrictions on ST.
Information Shared with MHPS	Duke provided all requested PI data.	Duke provided all requested PI data.	Duke provided all requested PI data.	Duke provided all requested PI data.	Duke provided all requested PI data.

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[3] Outside of operation in the MHPS Avoidance Zone

[4] For purposes of comparison, the Duke RCA team looked at hours in the Avoidance Zone even for periods in which that concept had not been introduced.

Operational Factors Potentially Impacting MHPS Blades

Low Pressure (LP) Turbine Excessive Steam Flow – "Running in the Avoidance Zone"

After the Period 3 outage was concluded and the ST was back in service, MHPS offered a view that high back-end loading on the LP turbine last stage blades must have been a significant contributing factor to the past L-0 blade damage/failures. Back-end loading is created by steam flow and operating pressure through a turbine section. Based on hindsight, MHPS Engineering claimed that at the time of the first failure (Period 1), Bartow Unit 4S exceeded the back-end loading limitation of 15,000 lb/hr-ft^2 by many hours and that the MHPS 40" L-0 fleet average for back-end loading was closer to 12,000 lb/hr-ft^2. Although MHPS had not previously imposed a back-end loading limitation, it then created what it called the "Avoidance Zone" and suggested longer run times in the avoidance zone were the root cause of the first three failures.[5]

Then and now, Duke Engineering does not agree that back-end loading above 15,000 lb/hr-ft^2 has been the failure-driving mechanism for the documented L-0 events. As Table A illustrates, Periods 2, 4 and 5 saw operating hours in the MHPS defined "Avoidance Zone" of only 1 hour, 1.15 hours and 0 hours, respectively, and still Bartow suffered damaged blades. Period 3 had only 240 hours in the avoidance zone, less than 2% of its total operating hours. Furthermore, by a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the "avoidance zone" – 2,466 out of 21,734 total hours – but despite the greatest number of hours, blade damage in this Period was limited to five (5) broken mid-span snubbers on the TE of the machine and a lesser degree of fretting on the shroud Z-Lock contact surfaces for both TE and generator end (GE) of the machine than seen in other Periods. The next highest period in the avoidance zone, Period 3, with 240 hours (out of 10,286 total hours – (11 hours of which were during approved instrumented blade telemetry tests performed by MHPS in December 2014), showed significantly greater amounts of blade damage and fretting to the Z-Lock contact surfaces on both ends of the machine than Period 1.

While the amount of Z-Lock wear cannot be quantified for Periods 1 and 3, photographs show the difference (See Figure 1 below).

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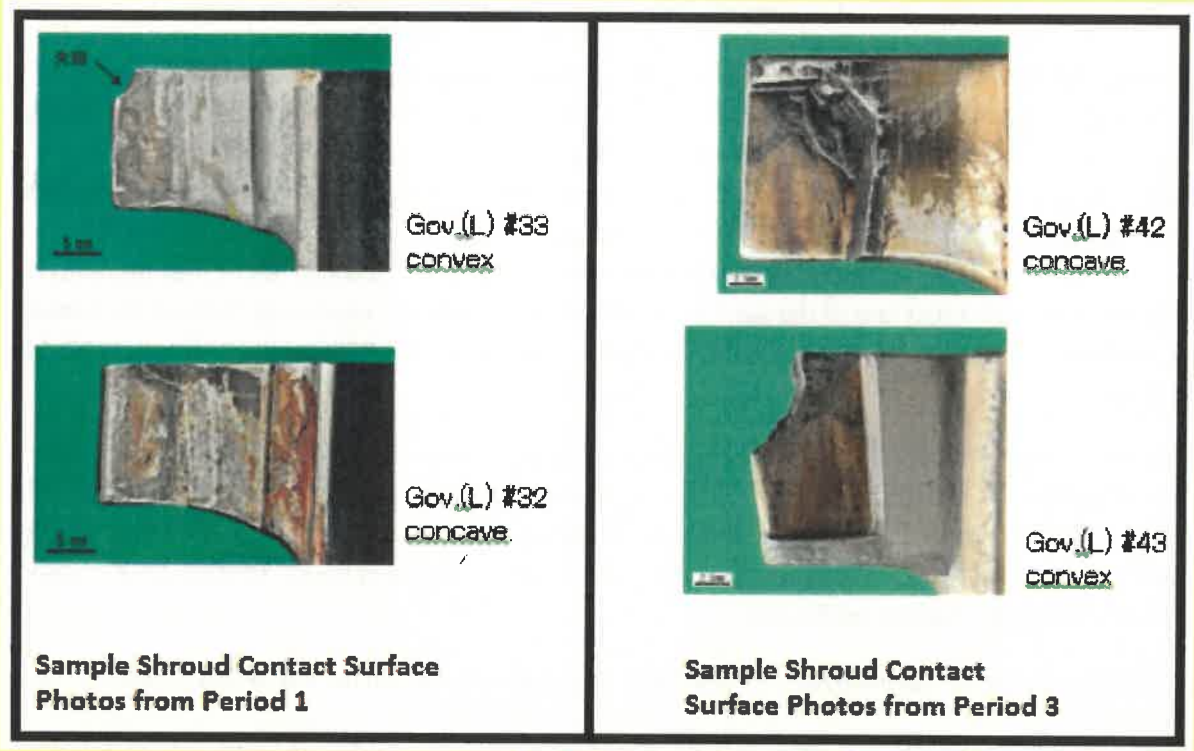
[5] MHPS Engineering extrapolated the December 2014 data to isolate operation in the Avoidance Zone as the root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil as seen during Periods 1-5. Duke Engineering does not agree that this data can be extrapolated over all five Periods, in part, because the data does not include normal operating conditions at Bartow and in part, because the information does not explain what occurred in each Period. Without telemetry over a sufficiently long period, under a sufficiently normal set of operating conditions after new blades and/or other equipment is installed, the December 2014 data yields no reliable RCA conclusions.

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



Based on comparative run times and damage, it is difficult to conclude that the L-0 blade damage in each Period or any particular Period is due to unit operation in the avoidance zone.[6]

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

After the Period 5 failure, which occurred with zero hours in the avoidance zone and with no other explanation offered by MHPS, the Duke RCA team began to consider whether other operational aspects might impact exhaust conditions of the LP. The Duke team looked for other mechanisms that might introduce forces great enough to initiate cracks in snubbers including Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF). The two (2) operational conditions that might conceivably produce forces great enough to initiate snubber cracks are blending and the use of hood sprays (especially with low out-of-spec inlet pressure). Blending is discussed first.

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) CTs, and since thermocouples positioned at the LP exhaust

[6] Even though the L-0 blades are no longer in the ST and a pressure plate has been installed, MHPS Engineering does not have enough technical data to support releasing Duke to operate the machine beyond the current IP Turbine exhaust pressure operating limits because of "potential impacts to upstream blading" – i.e. the L-1 blade sets. This suggest that MHPS is unsure what effect if any is created by its "avoidance zone" and more importantly points to a design flaw that may affect more than the L-0 blades.

just downstream of the L-0 blades (i.e. hood spray thermocouples) have experienced significant changes in temperature during a blend operation, Duke reviewed these blend operations.

Using Excel and PI Datalink, Duke Engineering determined which operational blending events might have affected the L-0 blades in order to isolate those higher risk events from the large quantity of blending operation of data for Periods 1-5. Duke identified blends with a slope change greater than 20° superheat/minute at the hood spray thermocouples and with an ST output greater than 50 MW. Duke Engineering selected the 20° F change in superheat and 50 MW minimum output as proxies for conditions when blend steam had high or low enthalpy (LCF and HCF) as reflected by high thermocouple temperature/superheat rate of change.[7] While this measure does not necessarily indicate the overall severity of any loadings on the L-0 blades, it serves as a proxy for reviewing events which could load the blades.

Operationally, blends are not defined or constrained to strict parameters because of the number of variables that can affect blends. High and low enthalpies therefore, are not functions that are typically monitored by an alarm or otherwise. This study of blends was done solely with the benefit of hindsight for this RCA. In studying blends at Bartow, the Duke team also looked at blends at other stations and found similar high and low enthalpies.

The following are the blend counts for Bartow in each Period based on the above-listed criteria:

Table B –Number of "Counts" that Meet the Blending Criteria for Periods 1-5 on Bartow Unit 4S.

	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 during strain gauge testing in December 2014

Using the same criteria as used for Bartow, blending operations at the HF Lee CC plant and for Hines Energy Power Block 2, which have 40" and 42" L-0 blades, respectively (but from different OEMs than MHPS), were used as a basis of comparison to Bartow – see Table C.

Table C – Number of "Counts" that Meet the Blending Criteria on the HF Lee CC ST

Duke Station	Date Range	Number of Operating Hours	Number of Blends (or "Counts") Meeting Criteria
HF Lee CC ST	01/01/2014 to 01/01/2016	15,045	22
Hines PB2 ST	09/01/2015 to 09/01/2017	16,123	44

[7] Although Duke could have used smaller temperature changes, selecting small changes (e.g. a three- or five- degree difference) would yield too many results, most of which could not cause a LCF or HCF effect. Likewise, at too-high a temperature delta, too many data points may have been eliminated.

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Given the comparison with Lee and Hines CC STs and the variability in blending events in the Bartow Periods, Duke was unable to draw any correlation between blending and the impacts on the MHPS blades. Bartow, Hines and Lee are similar in their blending rates and blending counts and yet, Lee's and Hines' blades have never been impacted like what has been seen at Bartow. This reinforces the Duke team's conclusion that the Bartow failures are attributable to the design or slim design margins in the MHPS 40" blades.

Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke team also studied whether hood spray operations were a possible cause of high and low energy forces on the L-0 blades because of the proximity of the sprays to the L-0 blades. The hood spray nozzles rely on pressure drop across the nozzle to create a vortex inside the nozzle that causes atomization of the water through centripetal force. Reduced pressure drop corresponds with a reduction in atomization and lower hood spray atomization may create dynamic pressures affecting the L-0 blades, as large water droplets evaporate/flash-off in the exhaust stream creating pressure pulses.

The hood spray operation is programmed into the Ovation DCS control system and is automated with no operator interaction. The condensate pump output acts as a source of water for the spray. A control valve reduces the roughly 500 psig condensate pressure to the spray design pressure of 50 psig. A review of the OEM-provided instructions directs use of hood sprays during the following two conditions:

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

Although not clear why, the Bartow hood spray data shows that the hood spray had been programmed during unit construction to operate any time blending takes place – similar to curtain sprays. Duke is not able to determine who programmed the hood spray in this way; MHPS would have had input in the control system but the architect/engineer typically designs the plant-wide control system.

In any case, because of the manner it was programmed, the hood spray operations occurred at greater rates than would have normally occurred. Two questions are raised in hood spray operations: (1) are the temperatures at the hood spray thermocouples normal or excessive and (2) is the hood spray pressure normal?

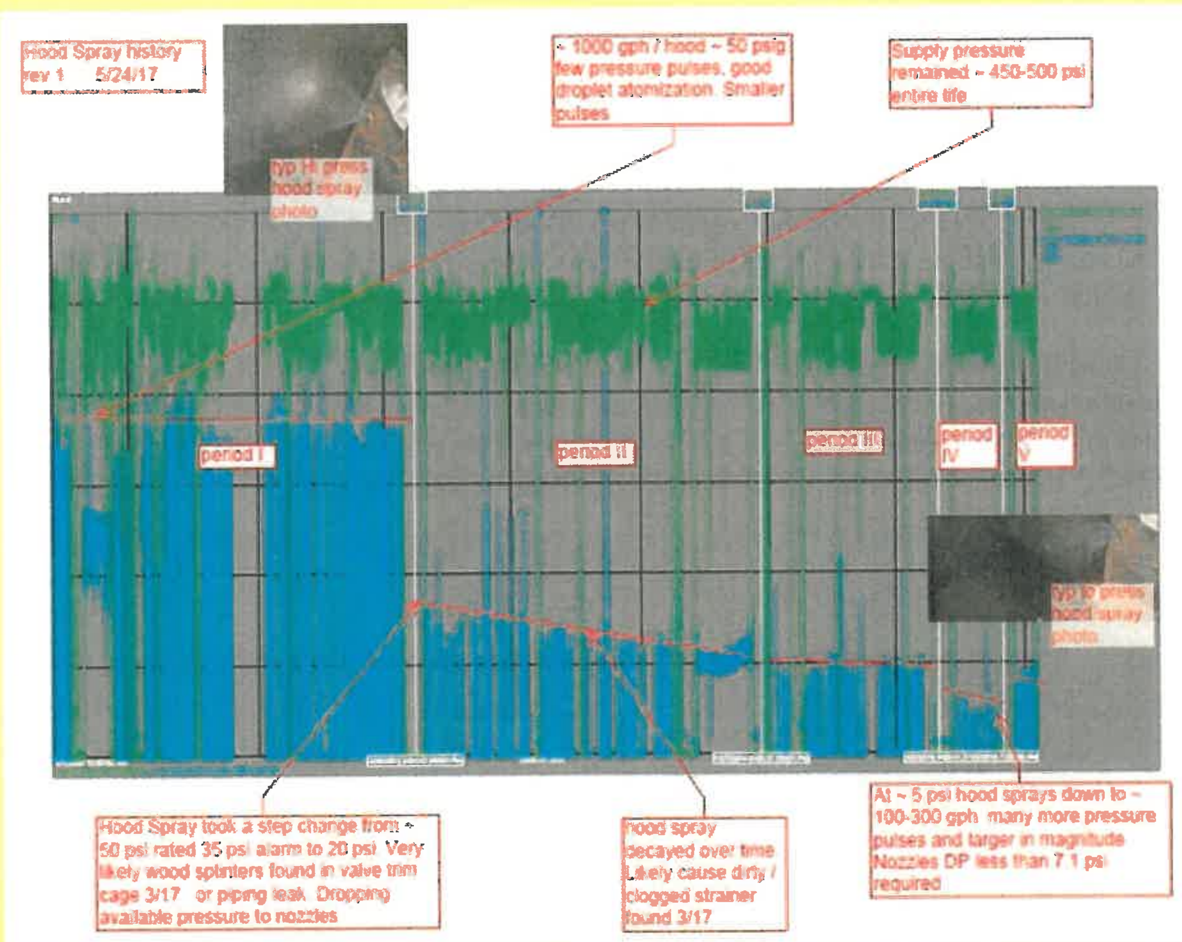
Hood spray thermocouple data shows the hood sprays rarely reached 160° F during normal operation and never exceeded 165° F. Higher temperatures are sometimes seen after a shutdown or unit trip as exhaust pressure increases, most likely due to the hot LP casings and some windage. During shutdowns and/or unit trips, there were no temperature readings above 201° F (one very brief reading of 1040° F was the result of an instrumentation issue).

Having eliminated excessive LP exhaust temperature as a concern, the team looked at hood spray pressure and found it had steadily decreased over successive Periods likely due to clogged sprays.

Figure 2 depicts the pressure decrease in the hood sprays over time. The decline in water pressure at the hood spray nozzles, likely caused by debris in the valve trim, results in reduced atomization.

At the kind of hood spray pressures shown in Figure 2, the atomization of the hood sprays would have been poor. Larger water droplets will cause pressure pulses as evaporation occurs, during times when the LP exhaust steam temperatures are elevated during blending.

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



Control of the hood sprays is automated within the plant-wide control system and not controlled by the operators. After a plant is commissioned, the hood sprays are not normally checked for accuracy and again, until there had been successive failures, there was no reason to focus on the hood spray system's functionality. Although the review that was conducted after the 5th failure revealed lower pressure which may have contributed to some additional wear of the blades, the Duke team does not believe this is the root cause of the failures as the design of the blades should have been robust enough to withstand some increased pressure pulses. Further, MHPS does not believe that any pressure pulses from the hood spray would have been strong enough to harm blades.

Zone Analysis – Shroud Fretting Fatigue

Based on data from the blade strain gauge telemetry test in December 2014, MHPS identified areas (referred to as "zones")[8] where blade response was high, but still below the OEM design limit, occurring during the normal operation range of the LP turbine (See Figure 3). These zones were neither something Duke was told about nor the result of any operational factors. They simply reflect how MHPS' 40" blades function at certain operating conditions. Notably, MHPS never issued an operational restriction associated with these zones.

As part of its RCA after the fifth and most recent failure, the Duke Engineering team reviewed the time of operation in these MHPS-identified zones in an effort to determine whether there might be some correlation between the zone time and failure. Duke Engineering was interested in this issue because of the observed excessive Z-Lock wear in Period 5 that occurred after a short operation time. Excessive wear at these contact surfaces is a sign of excessive blade movement during operation. Since there was no operation in Period 5 above the IP turbine exhaust pressure limit "avoidance zone" designated by MHPS, the only other possible reason for the wear is higher dynamic stimulus (Zone F as identified by the telemetry test).

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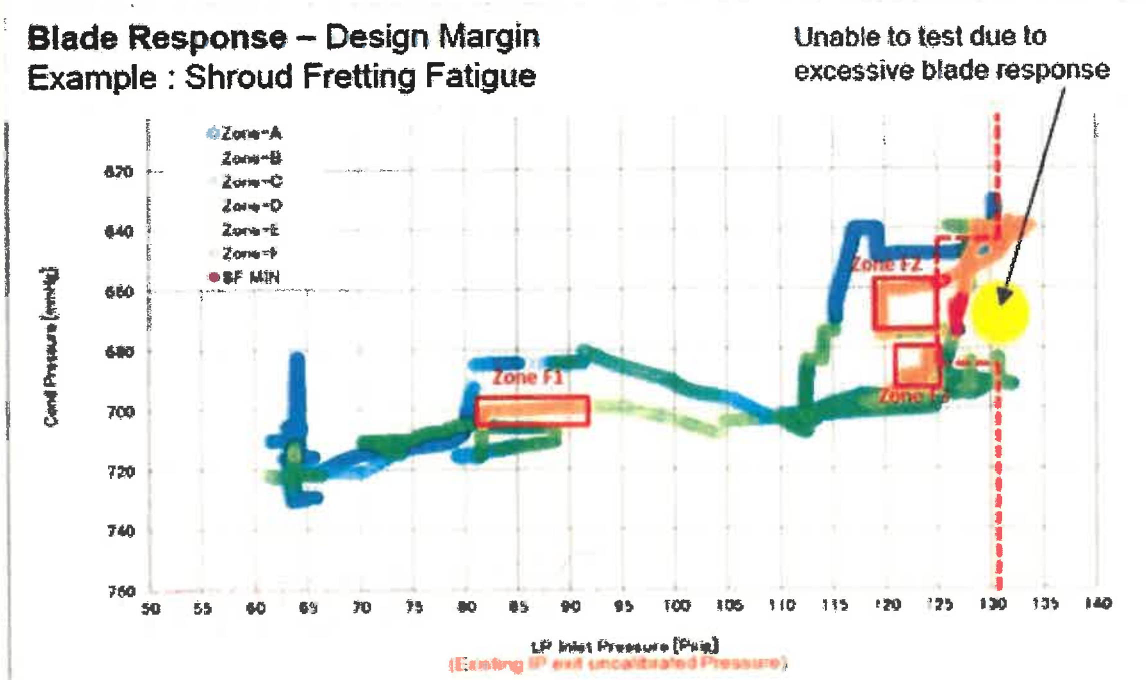
[8] These zones are not MHPS operational constraints and differ from the Avoidance Zone discussed above.

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 D shows the time in hours in each of the three (3) zones identified during the telemetry test for each Period. The total time in the three (3) zones compared with the total operating time is reflected as a percentage.

Table D – Time (in Hours) in Each Zone and Compared with Operating Time

	Time in Zone				Total Turbine	% Time in
	F1	F2	F3	Total	Operating Hours	Zone F
Period 1	901.2	466.2	9.7	1377.0	21734	6.3%
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%

Figure 4 shows the wear on one of the Period 5 Z-Locks. While varying degrees of wear are seen on the Period 5 Z-Locks, the wear is higher than what one would expect given the relatively low total turbine operating hours. Period 5's time in blend mode was consistent with those in other Periods and does not explain the amount of wear.

While the findings are not completely conclusive, there is good reason to believe that MHPS' design may be susceptible to damage when run in these zones. All Periods had hours in Zone F1 and F2. In addition, both on a percentage and absolute basis, Period 5 had a significant number of operating hours in this higher dynamic stress zone. Because each Period included run times in one or more zones and because each Period resulted in differing degrees of damage without direct correlation to the run times in those zones, it is difficult to conclude that operation within the zones is the cause of the L-0 blade failures. However, if the design margin on the blades is small, the blades may be susceptible to cracking, excessive wear, etc., when the unit either runs in or passes through these zones.

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

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

High Velocity Oxygen Fuel (HVOF) hard-facing can reduce the amount of base material fretting (wear) during operations and has many applications for blading contact surfaces in the industry. HVOF hard-facing can also change the frictional forces of the contact surface by reducing the coefficient of friction. However, as frictional forces are reduced, so are the dampening forces derived from them. A reduction in dampening, in most cases, means an increase in dynamic forces and motion.

Duke Engineering considered whether dampening loss may have been a contributing factor during Periods 3 and 4, when MHPS provided HVOC hard-faced coating on certain parts of the blades. In Period 3, only the mid-span snubbers had hard-facing. As a result, the shroud Z-Lock contact surfaces had more damage relative to other Periods, likely due to a loss of dampening at the snubbers. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

In Period 4, both the mid-span snubbers and the shroud Z-Lock contact surfaces had hard-face coating. Given that both the mid-span and shroud contact surfaces were HVOF-coated, the limiting factor then became the blade airfoil high stress location in the trailing edge, which was the observed failure at the end of Period 4. In discussions with MHPS, MHPS agreed that its attempt to harden the blade contact surfaces likely contributed to the failures in Periods 3 and 4.

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

To understand this issue, recall that at high speeds the Z-Lock and snubbers act as the mechanism by which the 40" blades are prevented from untwisting completely and moving loosely. Thus, the distance between Z-Locks and between snubbers must be precisely engineered to account for expansion and movement between the blades during operation. If the blades are too tight, (initial clearances too small) there will be too much force at the contact surface raising stresses and make breakage more likely, and if too loose (initial clearances too large), there will be too little force to provide proper dampening or allow blade vibration frequency and modes to change, potentially leading to failure.

Between Periods 3 and 4, Duke raised technical questions relative to "as left" blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. These questions were concerned with whether blade gaps at both points should be viewed together.

Because MHPS installed telemetry and conducted strain gauge testing for a short period in December 2014 at the beginning of Period 3, the Type 3(v1) L-0 blades were used to establish a baseline blade response to capture "worst case" geometry variations.

MHPS concluded that the dimensional tolerance between the Type 3(v1/v2) blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 blade (Periods 3 and 4) showed greater distortion than the Type 1 blade (Periods 1, 2 and 5).[9] With a greater geometry variation, the Type 3 blade provided less mechanical dampening (relative to the Type 1 blade) because of the smaller contact area and misalignment.

While MHPS contends that geometry variation on the Type 3 blade is not significant enough to have negatively impacted blade stress/response, MHPS also implicitely acknowledges that blade fitment/geometry is important in its current efforts to redesign the 40" blade following the fifth failure. In fact, it is is changing the geometry in response to specific Duke suggestions.

In conclusion, Duke Engineering believes that the "as-left" placement of the blades in the 3rd and 4th Periods had some impact on the failures, though again, had the blades been more robust, they may not

[9] These findings are consistent with an independent analysis of the blades by Duke using third party scanning.

have failed to the extent seen in those Periods. MHPS bears the responsibility for this cause as the replacement Services were entirely in its control.

CONCLUSION:

Based on its observations and study, Duke has been and remains of the opinion that the root cause of the failures in the ST L-0 40" blades is the blade design/lack of blade design margin. That is to say, under expected operating conditions at Bartow's 4x1 Combined Cycle (CC) Unit, the MHPS blades are substantially more fragile than similar 40" blades both in Duke's CC fleet and elsewhere in the industry.[10]

Duke's conclusion is based on its study of the failure events and both design and operational information including data supplied by MHPS, PI data from Bartow, information from similar units in Duke's fleet, and industry experience with the 40" blades. MHPS did not provide proprietary information concerning engineering and testing of the 40" blades but did provide engineering assistance and strain gauge data from a brief period of MHPS-led telemetry testing during December 2014. Duke provided all operational information requested by MHPS and met with MHPS multiple times to discuss both MHPS' findings and Duke's independent research and findings. This RCA report is Duke's product and presents its view of the root cause based on all inputs received.

[10] The most commonly reported issue with the 40" L-0 blade design elsewhere is water erosion, which both Duke and MHPS agree is not a contributing factor to the Bartow failures.

Appendix A: 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 B: Empirical Data Concerning Factors which May Have Affected L-0 Blades

Empirical Support for Root Cause

Period	Operating Hours	Excessive Steam Flow: Potential Factor 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_{su}/dt): Potential Factor Present	Counts ($\Delta T > 20$ 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	0.00
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: Potential Factor 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: Potential Factor 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	Operating Hours	Blade Fitment: Potential Factor Present	Normalized Ranking
1	21,734	X	1.00
2	21,284	X	1.00
3	10,286	X	1.00
4	2,942	X	1.00
5	1,561	X	1.00

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

"Excessive Steam Flow" Notes

"Avoidance Zone Exceedance Hours" -- Measured number of operating hours in exceedance of 15,000 $lb/hr\text{-}ft^2$ 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 the column, "Exceedance Hours / (1k Operating Hours)"

"Thermal Distress (dT_{su}/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 the column, "Counts / (1k Operating Hours)"

"Pressure Pulses" Notes

"Avg. Hood Spray Pressure (psig)" -- Calculated from PI Historian data
"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 the column, "% of Total Operating Hours"

"Blade Fitment" Notes

"Blade Fitment" -- References the gap measurements for both the mid-span snubbers and the shroud Z-Lock contact surfaces

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Executive Summary

Over the past 3 plus years, Duke Energy Florida LLC (Duke), at times working independently and at times together with Mitsubishi Hitachi Power Systems (MHPS), undertook a root cause analysis (RCA) of the cause(s) for the Unit 4S L-0 blade cracks and failures that occurred during normal station operations at Bartow Station. The intervals between failures had become shorter after each failure despite MHPS's attempts to improve the blades' performance and the station's adherence to the revised OEM operating instructions received after each successive failure.

Only after the telemetry test was completed and after the onset of Period 3, in approximately March 2015, (as a result of the telemetry test) did MHPS create an "avoidance zone" in which the station was not to operate except as needed to ramp up or down. Bartow operated in the avoidance zone only 1.15 hours in Period 4 and 0 hours in Period 5, but suffered two (2) further failures in successively shorter periods. Thus, after the fifth failure, Duke concluded that operation in MHPS' designated avoidance zone did not explain the failures and looked at whether other factors potentially were related or contributed to the failures.

Duke considered both operational and design aspects. With respect to operational factors, the Duke team used the Plant Information ("PI") data historian and operational data from each period and retroactively calculated[1] whether those factors had any correlation to the failures. Potential factors in the operational category included:

- Operations in MHPS Avoidance Zone -- Low Pressure (LP) Turbine "Excessive" Steam Flow
- Bartow Blending Operations – Potential Thermal Distress (Rate of Change in Super Heat Over Time, dT_{SH}/dt) at LP Turbine Exhaust
- Pressure Pulses During Hood/Curtain Spray Operation(s)

Duke Engineering concluded that there was no correlation between any one of the above-listed factors and the five (5) failure periods. Notably, Duke was only able to study each factor independently based on available data. In the absence of (1) blade telemetry, (2) duplication of the factors in various combinations, and (3) operation in varying but normal conditions, it is not possible to study how each factor relates to and interacts with any other factor, if at all.

Duke also studied design factors unique to MHPS 40" steel blades. This aspect of the RCA was largely deductive because MHPS controls design data, although MHPS did provide FEA stress and frequency analyses, material properties, and some dimensional information. The following factors were included in this portion of the study:

- Zone Analysis – Shroud Fretting Fatigue

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[1] Because MHPS's operational constraint called the Avoidance Zone was not provided by MHPS until after the onset of Period 3, one could only look at hours in that zone after-the-fact for Periods 1 and 2.

- 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

With regard to the "Hard-Facing on Mid-Span Snubbers" factor, Duke was able to conclude and MHPS concurred, that this factor played a part in the blade failure in Periods 3 and 4. With respect to the Zone Analysis and Blade Fitment factor, although MHPS made no concession, it is currently re-engineering its 40" blades and making changes to the blades' geometry as discussed by MHPS Engineering in a 22 September 2017 presentation made to Duke.

Based on its observations and study, Duke has been and remains of the opinion that the root cause of the failures in the ST L-0 40" blades is the blade design/lack of blade design margin. That is to say, under expected operating conditions at Bartow's 4x1 Combined Cycle (CC) Unit, the MHPS blades are substantially more fragile than similar 40" blades both in Duke's CC fleet and elsewhere in the industry.[2]

Duke's conclusion is based on its study of the events and information that includes data supplied by MHPS, PI data from Bartow, information from similar units in Duke's fleet, and industry experience with the 40" blades. MHPS did not provide proprietary information concerning engineering and testing of the 40" blades but did provide engineering assistance and strain gauge data from a brief period of MHPS-led telemetry testing during December 2014. Duke provided all operational information requested by MHPS and met with MHPS multiple times to discuss both MHPS' findings and Duke's independent research and findings. This RCA report is Duke's product and presents its view of the root cause based on all inputs received.

For Bartow, the long-term solution is to replace the L-0 blades with blades of a different design and/or to retrofit the LP steam path and/or continue operation with pressure plate.

With either a redesign of the MHPS 40" blades or replacement with blades of a different make or an LP steam path retrofit, telemetry instrumentation and blade vibration monitoring are necessary to ensure that all potential upset conditions are resolved.

Historical Overview

Bartow is a 4x1 CC Station with a steam turbine (ST) manufactured by MHPS. The ST was purchased from Tenaska Power Equipment, LLC (Tenaska) which intended to use it for a 3x1 CC with a gross output of 420MW. The ST was never delivered to Tenaska and remained with MHPS in a warehouse in Japan until Duke purchased the unit in 2006.

Before the ST was purchased by Duke, Duke contracted with MHPS to evaluate the ST design conditions and to update heat balances for a 4x1 CC configuration. MHPS updated the heat balances for use in a 4x1 CC configuration. CC units blend steam from the combustion turbines (CT) as they start-up and/or

[2] The most commonly reported issue with the 40" L-0 blade design elsewhere is water erosion, which both Duke and MHPS agree is not a contributing factor to the Bartow failures.

shut-down with steam to the ST. These blending events, which are a common occurrence for CC units, result in brief periods of higher steam temperatures and flows into the condenser near the ST L-0 blades.

Since commissioning of the Bartow ST in 2009, there have been five (5) events involving L-0 blade failures and/or replacements as described, below.

Each 40" MHPS steel blade is twisted with a "root end" that connects it to the hub, a snubber at the mid-point or mid-span, and a shroud with airfoil tips at the top. While the ST spins up to its operating speed of 3600rpm, each blade elongates and starts to untwist. The snubbers and airfoil tips are designed to contact each other and create a stabilizing central and outer ring. If a snubber or airfoil tip fails, the blades can vibrate excessively and can cause sudden catastrophic failure. Although none of the five (5) Periods at Bartow involved a complete blade loss or catastrophic failure, two (2) involved upsets and each event affected mid-span snubbers, shroud Z-Locks, and airfoil tips.

The five (5) Periods are summarized in Table A. Each Period's start date is when the ST was put into service and each end date reflects either when the ST was taken off-line or suffered an unplanned outage. The blades for each period are described by "Type." The ST was sold and during Period 1 was operated with Type 1 blades, which at MHPS' recommendation and urging were replaced – turbine end (TE) blades only – with a re-engineered Type 1 blade at the start of Period 2. Period 2 ended with a planned shut-down, during which the TE and generator end (GE) blades were replaced with an OEM-improved design (Type 3) even though the in-service Type 1 L-0 blade condition was such that they could have run longer. The Type 3(v1) blades had hard-facing on the mid-span snubber contact surfaces and MHPS ran its brief period of telemetry testing. Damage found at the end of Period 3 resulted in a forced outage and the installation of new Type 3(v2) blades with hard-facing on the mid-span snubber, as well as hard-facing now added to the Z-Lock contact surfaces. When these Type 3(v2) blades failed at the end of Period 4, they were replaced with the original Type 1 blades for Period 5. When these Type 1 blades failed at the end of Period 5, the L-0 blades were replaced with a pressure plate.

MHPS provided OEM operating parameters in each Period as reflected in Table A under the heading "MHPS IP Exhaust Pressure Operating Limits." For Period 1, these limits were the design limits that accompanied the ST at purchase. After the damage was discovered at the end of Period 1, MHPS imposed a lower IP exhaust pressure limit. In Period 3, when the Type 3 blades were installed, MHPS raised the limit, in accordance with the original proposal by MHPS to supply blades for Period 3 that would allow operation up to 450 MW but also stay within the limits established as a result of the telemetry test. After the telemetry test, MHPS sent out a chart it called the "Avoidance Zone" and suggested that blade damage would be avoided if Duke operated as few hours as possible in the zone. The practical result of the avoidance zone limits meant that the Bartow ST unit could not achieve 450 MW as the IP exhaust pressure was, and to this day still is, limited when condenser pressure is in a range the unit normally must run in. In Period 4, with the discovery of additional damage, MHPS lowered its IP exhaust pressure limit and did so again in Period 5.

Table A: Bartow L-0 Events Summary

	Period 1	Period 2	Period 3	Period 4	Period 5
Date	June 2009 to March 2012	April 2012 to August 2014	December 2014 to April 2016	May 2016 to Oct 2016	December 2016 to February 2017
Service Duration	~34 Months	~28 Months	~17 Months	~5 Months	~2 Months
L-0 Blade Configuration	Type 1	Type 1 (re-engineered)	Type 3 (v1)	Type 3 (v2)	Type 1
MHPS Expected ST Output	420 MW (Nameplate)	420 MW	450 MW[3]	450 MW[3]	390 MW
MHPS IP Exhaust Pressure Operating Limits	Machine controlled to HP, IP and Condenser design limits	118 psig Limit on IP Exhaust	126 psig Limit on IP Exhaust	119 psig Limit on IP Exhaust	111.5 psig Limit on IP Exhaust
Retroactive Calculation of Avoidance Zone "Exceedance" based on the MHPS Period 3 Avoidance Zone chart[4]	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	Planned outage for valve work, as well as annual L-0 inspections. At the start of this period, MHPS approved 4x1 (unfired) operations at 392 MW output, as well as 3x1 (duct fired) operation at 420 MW, supported by MHPS-provided heat balance documentation. During a plant shut down a visual inspection of the ST L-0 blades revealed damage to the turbine end blade snubbers.	Planned outage for upgrade to "heavy duty" blades, based on MHPS representation that it had improved design. 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. Planned outage for valve work, as well as an annual L-0 inspection. No blade cracking observed after testing (when the test instrumentation removed). Stellite hard-facing added to snubbers only.	Two (2) separate step changes (decreases) in vibration led to the Duke Engineering recommendation to remove the ST from service for inspection. Blade "loss of material" observed, as well as crack initiation in high stress area of airfoil. Stellite hard-facing added to the blade Z-Lock.	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). L-0 blades removed and pressure plate installed; pressure plate restricted ST output to between 360-380 MW. MHPS maintains operational restrictions on ST.
Information Shared with MHPS	Duke provided all requested PI data.	Duke provided all requested PI data.	Duke provided all requested PI data.	Duke provided all requested PI data.	Duke provided all requested PI data.

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[3] Outside of operation in the MHPS Avoidance Zone

[4] For purposes of comparison, the Duke RCA team looked at hours in the Avoidance Zone even for periods in which that concept had not been introduced.

Operational Factors Potentially Impacting MHPS Blades

Low Pressure (LP) Turbine Excessive Steam Flow – "Running in the Avoidance Zone"

After the Period 3 outage was concluded and the ST was back in service, MHPS offered a view that high back-end loading on the LP turbine last stage blades must have been a significant contributing factor to the past L-0 blade damage/failures. Back-end loading is created by steam flow and operating pressure through a turbine section. Based on hindsight, MHPS Engineering claimed that at the time of the first failure (Period 1), Bartow Unit 4S exceeded the back-end loading limitation of 15,000 lb/hr-ft^2 by many hours and that the MHPS 40" L-0 fleet average for back-end loading was closer to 12,000 lb/hr-ft^2. Although MHPS had not previously imposed a back-end loading limitation, it then created what it called the "Avoidance Zone" and suggested longer run times in the avoidance zone were the root cause of the first three failures.[5]

Then and now, Duke Engineering does not agree that back-end loading above 15,000 lb/hr-ft^2 has been the failure-driving mechanism for the documented L-0 events. As Table A illustrates, Periods 2, 4 and 5 saw operating hours in the MHPS defined "Avoidance Zone" of only 1 hour, 1.15 hours and 0 hours, respectively, and still Bartow suffered damaged blades. Period 3 had only 240 hours in the avoidance zone, less than 2% of its total operating hours. Furthermore, by a considerable margin, Period 1 had the greatest amount of run hours in exceedance of the "avoidance zone" – 2,466 out of 21,734 total hours – but despite the greatest number of hours, blade damage in this Period was limited to five (5) broken mid-span snubbers on the TE of the machine and a lesser degree of fretting on the shroud Z-Lock contact surfaces for both TE and generator end (GE) of the machine than seen in other Periods. The next highest period in the avoidance zone, Period 3, with 240 hours (out of 10,286 total hours – (11 hours of which were during approved instrumented blade telemetry tests performed by MHPS in December 2014), showed significantly greater amounts of blade damage and fretting to the Z-Lock contact surfaces on both ends of the machine than Period 1.

While the amount of Z-Lock wear cannot be quantified for Periods 1 and 3, photographs show the difference (See Figure 1 below).

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[5] MHPS Engineering extrapolated the December 2014 data to isolate operation in the Avoidance Zone as the root cause for blade failures at the mid-span snubber, shroud Z-Lock contact surface and/or the blade airfoil as seen during Periods 1-5. Duke Engineering does not agree that this data can be extrapolated over all five Periods, in part, because the data does not include normal operating conditions at Bartow and in part, because the information does not explain what occurred in each Period. Without telemetry over a sufficiently long period, under a sufficiently normal set of operating conditions after new blades and/or other equipment is installed, the December 2014 data yields no reliable RCA conclusions.

Figure 1 –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

Based on comparative run times and damage, it is difficult to conclude that the L-0 blade damage in each Period or any particular Period is due to unit operation in the avoidance zone.[6]

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

After the Period 5 failure, which occurred with zero hours in the avoidance zone and with no other explanation offered by MHPS, the Duke RCA team began to consider whether other operational aspects might impact exhaust conditions of the LP. The Duke team looked for other mechanisms that might introduce forces great enough to initiate cracks in snubbers including Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF). The two (2) operational conditions that might conceivably produce forces great enough to initiate snubber cracks are blending and the use of hood sprays (especially with low out-of-spec inlet pressure). Blending is discussed first.

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) CTs, and since thermocouples positioned at the LP exhaust

[6] Even though the L-0 blades are no longer in the ST and a pressure plate has been installed, MHPS Engineering does not have enough technical data to support releasing Duke to operate the machine beyond the current IP Turbine exhaust pressure operating limits because of "potential impacts to upstream blading" – i.e. the L-1 blade sets. This suggest that MHPS is unsure what effect if any is created by its "avoidance zone" and more importantly points to a design flaw that may affect more than the L-0 blades.

just downstream of the L-0 blades (i.e. hood spray thermocouples) have experienced significant changes in temperature during a blend operation, Duke reviewed these blend operations.

Using Excel and PI Datalink, Duke Engineering determined which operational blending events might have affected the L-0 blades in order to isolate those higher risk events from the large quantity of blending operation of data for Periods 1-5. Duke identified blends with a slope change greater than 20° superheat/minute at the hood spray thermocouples and with an ST output greater than 50 MW. Duke Engineering selected the 20° F change in superheat and 50 MW minimum output as proxies for conditions when blend steam had high or low enthalpy (LCF and HCF) as reflected by high thermocouple temperature/superheat rate of change.[7] While this measure does not necessarily indicate the overall severity of any loadings on the L-0 blades, it serves as a proxy for reviewing events which could load the blades.

Operationally, blends are not defined or constrained to strict parameters because of the number of variables that can affect blends. High and low enthalpies therefore, are not functions that are typically monitored by an alarm or otherwise. This study of blends was done solely with the benefit of hindsight for this RCA. In studying blends at Bartow, the Duke team also looked at blends at other stations and found similar high and low enthalpies.

The following are the blend counts for Bartow in each Period based on the above-listed criteria:

Table B –Number of "Counts" that Meet the Blending Criteria for Periods 1-5 on Bartow Unit 4S.

	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 during strain gauge testing in December 2014

Using the same criteria as used for Bartow, blending operations at the HF Lee CC plant and for Hines Energy Power Block 2, which have 40" and 42" L-0 blades, respectively (but from different OEMs than MHPS), were used as a basis of comparison to Bartow – see Table C.

Table C – Number of "Counts" that Meet the Blending Criteria on the HF Lee CC ST

Duke Station	Date Range	Number of Operating Hours	Number of Blends (or "Counts") Meeting Criteria
HF Lee CC ST	01/01/2014 to 01/01/2016	15,045	22
Hines PB2 ST	09/01/2015 to 09/01/2017	16,123	44

[7] Although Duke could have used smaller temperature changes, selecting small changes (e.g. a three- or five- degree difference) would yield too many results, most of which could not cause a LCF or HCF effect. Likewise, at too-high a temperature delta, too many data points may have been eliminated.

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Given the comparison with Lee and Hines CC STs and the variability in blending events in the Bartow Periods, Duke was unable to draw any correlation between blending and the impacts on the MHPS blades. Bartow, Hines and Lee are similar in their blending rates and blending counts and yet, Lee's and Hines' blades have never been impacted like what has been seen at Bartow. This reinforces the Duke team's conclusion that the Bartow failures are attributable to the design or slim design margins in the MHPS 40" blades.

Pressure Pulses During Hood/Curtain Spray Operation(s)

The Duke team also studied whether hood spray operations were a possible cause of high and low energy forces on the L-0 blades because of the proximity of the sprays to the L-0 blades. The hood spray nozzles rely on pressure drop across the nozzle to create a vortex inside the nozzle that causes atomization of the water through centripetal force. Reduced pressure drop corresponds with a reduction in atomization and lower hood spray atomization may create dynamic pressures affecting the L-0 blades, as large water droplets evaporate/flash-off in the exhaust stream creating pressure pulses.

The hood spray operation is programmed into the Ovation DCS control system and is automated with no operator interaction. The condensate pump output acts as a source of water for the spray. A control valve reduces the roughly 500 psig condensate pressure to the spray design pressure of 50 psig. A review of the OEM-provided instructions directs use of hood sprays during the following two conditions:

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

Although not clear why, the Bartow hood spray data shows that the hood spray had been programmed during unit construction to operate any time blending takes place – similar to curtain sprays. Duke is not able to determine who programmed the hood spray in this way; MHPS would have had input in the control system but the architect/engineer typically designs the plant-wide control system.

In any case, because of the manner it was programmed, the hood spray operations occurred at greater rates than would have normally occurred. Two questions are raised in hood spray operations: (1) are the temperatures at the hood spray thermocouples normal or excessive and (2) is the hood spray pressure normal?

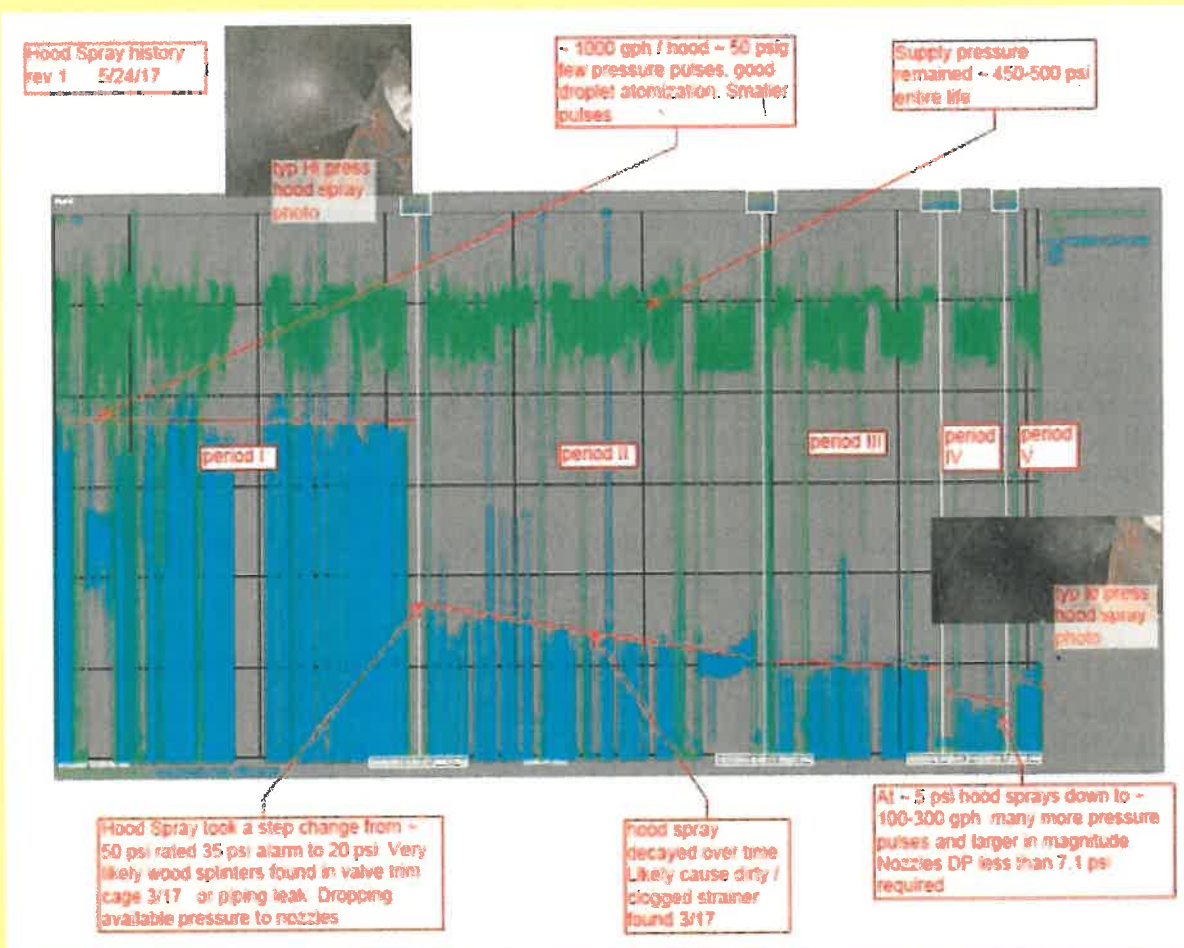
Hood spray thermocouple data shows the hood sprays rarely reached 160° F during normal operation and never exceeded 165° F. Higher temperatures are sometimes seen after a shutdown or unit trip as exhaust pressure increases, most likely due to the hot LP casings and some windage. During shutdowns and/or unit trips, there were no temperature readings above 201° F (one very brief reading of 1040° F was the result of an instrumentation issue).

Having eliminated excessive LP exhaust temperature as a concern, the team looked at hood spray pressure and found it had steadily decreased over successive Periods likely due to clogged sprays.

Figure 2 depicts the pressure decrease in the hood sprays over time. The decline in water pressure at the hood spray nozzles, likely caused by debris in the valve trim, results in reduced atomization.

At the kind of hood spray pressures shown in Figure 2, the atomization of the hood sprays would have been poor. Larger water droplets will cause pressure pulses as evaporation occurs, during times when the LP exhaust steam temperatures are elevated during blending.

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



Control of the hood sprays is automated within the plant-wide control system and not controlled by the operators. After a plant is commissioned, the hood sprays are not normally checked for accuracy and again, until there had been successive failures, there was no reason to focus on the hood spray system's functionality. Although the review that was conducted after the 5th failure revealed lower pressure which may have contributed to some additional wear of the blades, the Duke team does not believe this is the root cause of the failures as the design of the blades should have been robust enough to withstand some increased pressure pulses. Further, MHPS does not believe that any pressure pulses from the hood spray would have been strong enough to harm blades.

Zone Analysis – Shroud Fretting Fatigue

Based on data from the blade strain gauge telemetry test in December 2014, MHPS identified areas (referred to as "zones")[8] where blade response was high, but still below the OEM design limit, occurring during the normal operation range of the LP turbine (See Figure 3). These zones were neither something Duke was told about nor the result of any operational factors. They simply reflect how MHPS' 40" blades function at certain operating conditions. Notably, MHPS never issued an operational restriction associated with these zones.

As part of its RCA after the fifth and most recent failure, the Duke Engineering team reviewed the time of operation in these MHPS-identified zones in an effort to determine whether there might be some correlation between the zone time and failure. Duke Engineering was interested in this issue because of the observed excessive Z-Lock wear in Period 5 that occurred after a short operation time. Excessive wear at these contact surfaces is a sign of excessive blade movement during operation. Since there was no operation in Period 5 above the IP turbine exhaust pressure limit "avoidance zone" designated by MHPS, the only other possible reason for the wear is higher dynamic stimulus (Zone F as identified by the telemetry test).

[8] These zones are not MHPS operational constraints and differ from the Avoidance Zone discussed above.

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

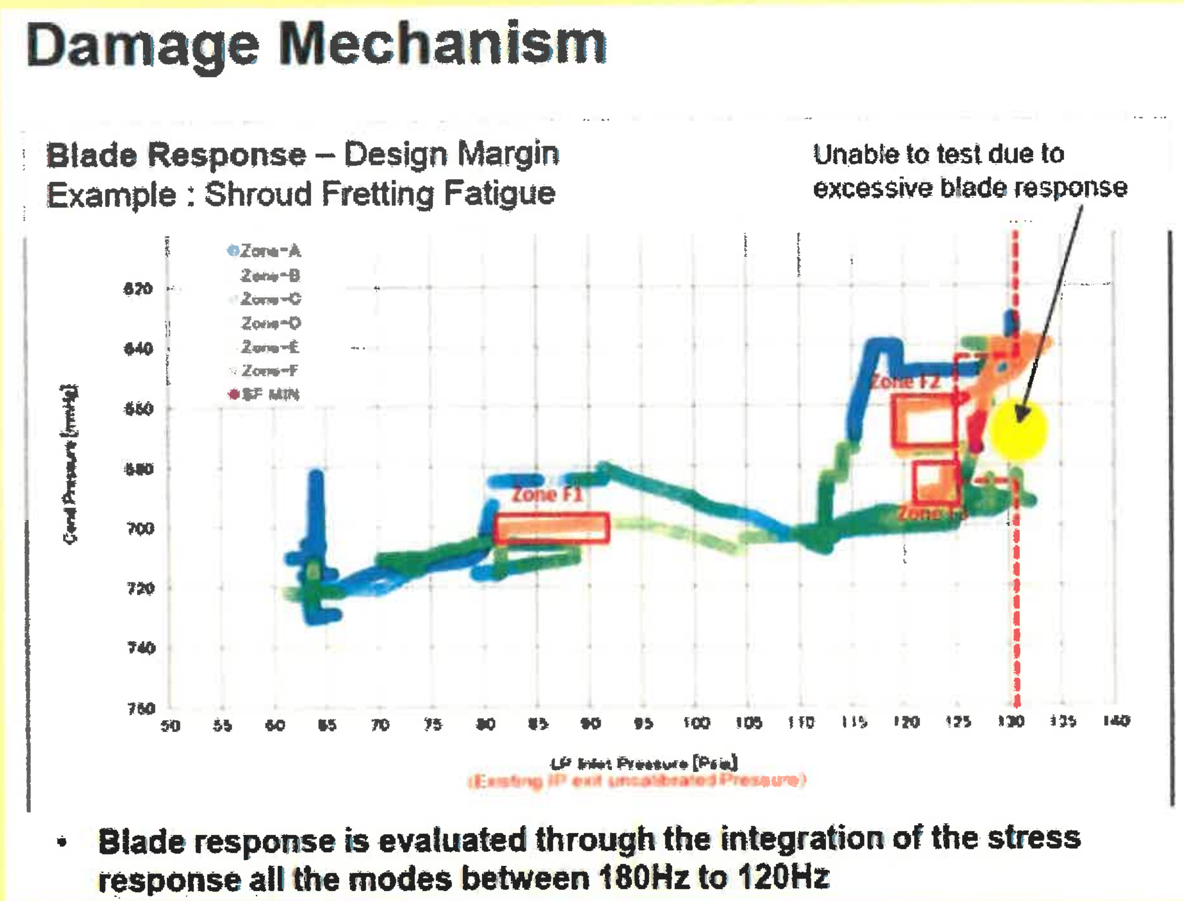


Table D shows the time in hours in each of the three (3) zones identified during the telemetry test for each Period. The total time in the three (3) zones compared with the total operating time is reflected as a percentage.

Table D – Time (in Hours) in Each Zone and Compared with Operating Time

	Time in Zone				Total Turbine	% Time in
	F1	F2	F3	Total	Operating Hours	Zone F
Period 1	901.2	466.2	9.7	1377.0	21734	6.3%
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%

Figure 4 shows the wear on one of the Period 5 Z-Locks. While varying degrees of wear are seen on the Period 5 Z-Locks, the wear is higher than what one would expect given the relatively low total turbine operating hours. Period 5's time in blend mode was consistent with those in other Periods and does not explain the amount of wear.

While the findings are not completely conclusive, there is good reason to believe that MHPS' design may be susceptible to damage when run in these zones. All Periods had hours in Zone F1 and F2. In addition, both on a percentage and absolute basis, Period 5 had a significant number of operating hours in this higher dynamic stress zone. Because each Period included run times in one or more zones and because each Period resulted in differing degrees of damage without direct correlation to the run times in those zones, it is difficult to conclude that operation within the zones is the cause of the L-0 blade failures. However, if the design margin on the blades is small, the blades may be susceptible to cracking, excessive wear, etc., when the unit either runs in or passes through these zones.

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

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

High Velocity Oxygen Fuel (HVOF) hard-facing can reduce the amount of base material fretting (wear) during operations and has many applications for blading contact surfaces in the industry. HVOF hard-facing can also change the frictional forces of the contact surface by reducing the coefficient of friction. However, as frictional forces are reduced, so are the dampening forces derived from them. A reduction in dampening, in most cases, means an increase in dynamic forces and motion.

Duke Engineering considered whether dampening loss may have been a contributing factor during Periods 3 and 4, when MHPS provided HVOC hard-faced coating on certain parts of the blades. In Period 3, only the mid-span snubbers had hard-facing. As a result, the shroud Z-Lock contact surfaces had more damage relative to other Periods, likely due to a loss of dampening at the snubbers. The Z-Lock contact surfaces were forced to provide all of the dampening for the system via additional motion.

In Period 4, both the mid-span snubbers and the shroud Z-Lock contact surfaces had hard-face coating. Given that both the mid-span and shroud contact surfaces were HVOF-coated, the limiting factor then became the blade airfoil high stress location in the trailing edge, which was the observed failure at the end of Period 4. In discussions with MHPS, MHPS agreed that its attempt to harden the blade contact surfaces likely contributed to the failures in Periods 3 and 4.

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

To understand this issue, recall that at high speeds the Z-Lock and snubbers act as the mechanism by which the 40" blades are prevented from untwisting completely and moving loosely. Thus, the distance between Z-Locks and between snubbers must be precisely engineered to account for expansion and movement between the blades during operation. If the blades are too tight, (initial clearances too small) there will be too much force at the contact surface raising stresses and make breakage more likely, and if too loose (initial clearances too large), there will be too little force to provide proper dampening or allow blade vibration frequency and modes to change, potentially leading to failure.

Between Periods 3 and 4, Duke raised technical questions relative to "as left" blade-to-blade gap measurements – both at the mid-span snubber interface and at the shroud Z-Lock contact surfaces. These questions were concerned with whether blade gaps at both points should be viewed together.

Because MHPS installed telemetry and conducted strain gauge testing for a short period in December 2014 at the beginning of Period 3, the Type 3(v1) L-0 blades were used to establish a baseline blade response to capture "worst case" geometry variations.

MHPS concluded that the dimensional tolerance between the Type 3(v1/v2) blade and the Type 1 blade may have been as great as +/- 2 mm – i.e. the Type 3 blade (Periods 3 and 4) showed greater distortion than the Type 1 blade (Periods 1, 2 and 5).[9] With a greater geometry variation, the Type 3 blade provided less mechanical dampening (relative to the Type 1 blade) because of the smaller contact area and misalignment.

While MHPS contends that geometry variation on the Type 3 blade is not significant enough to have negatively impacted blade stress/response, MHPS also implicitely acknowledges that blade fitment/geometry is important in its current efforts to redesign the 40" blade following the fifth failure. In fact, it is is changing the geometry in response to specific Duke suggestions.

In conclusion, Duke Engineering believes that the "as-left" placement of the blades in the 3rd and 4th Periods had some impact on the failures, though again, had the blades been more robust, they may not

[9] These findings are consistent with an independent analysis of the blades by Duke using third party scanning.

have failed to the extent seen in those Periods. MHPS bears the responsibility for this cause as the replacement Services were entirely in its control.

CONCLUSION:

Based on its observations and study, Duke has been and remains of the opinion that the root cause of the failures in the ST L-0 40" blades is the blade design/lack of blade design margin. That is to say, under expected operating conditions at Bartow's 4x1 Combined Cycle (CC) Unit, the MHPS blades are substantially more fragile than similar 40" blades both in Duke's CC fleet and elsewhere in the industry.[10]

Duke's conclusion is based on its study of the failure events and both design and operational information including data supplied by MHPS, PI data from Bartow, information from similar units in Duke's fleet, and industry experience with the 40" blades. MHPS did not provide proprietary information concerning engineering and testing of the 40" blades but did provide engineering assistance and strain gauge data from a brief period of MHPS-led telemetry testing during December 2014. Duke provided all operational information requested by MHPS and met with MHPS multiple times to discuss both MHPS' findings and Duke's independent research and findings. This RCA report is Duke's product and presents its view of the root cause based on all inputs received.

[10] The most commonly reported issue with the 40" L-0 blade design elsewhere is water erosion, which both Duke and MHPS agree is not a contributing factor to the Bartow failures.

Appendix A: 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 B: Empirical Data Concerning Factors which May Have Affected L-0 Blades

Empirical Support for Root Cause

Period	Operating Hours	Excessive Steam Flow: Potential Factor 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): Potential Factor 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	[illegible]
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: Potential Factor 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: Potential Factor 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	Operating Hours	Blade Fitment: Potential Factor Present	Normalized Ranking
1	21,734	X	1.00
2	21,284	X	1.00
3	10,286	X	1.00
4	2,942	X	1.00
5	1,561	X	1.00

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

"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 the column, "Exceedance Hours / (1k Operating Hours)"

"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 the column, "Counts / (1k Operating Hours)"

"Pressure Pulses" Notes

"Avg. Hood Spray Pressure (psig)" -- Calculated from PI Historian data
"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 the column, "% of Total Operating Hours"

"Blade Fitment" Notes

"Blade Fitment" -- References the gap measurements for both the mid-span snubbers and the shroud Z-Lock contact surfaces

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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.

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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.

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

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

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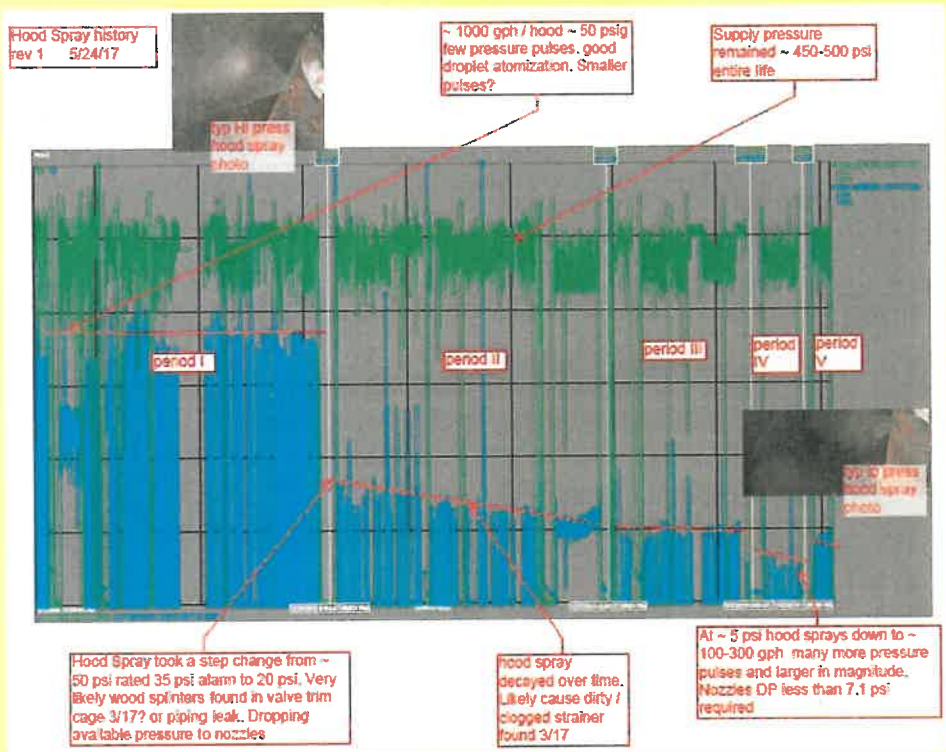
Figure 2 -- Hood Spray Pressure Degradation Over Periods 1-5



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

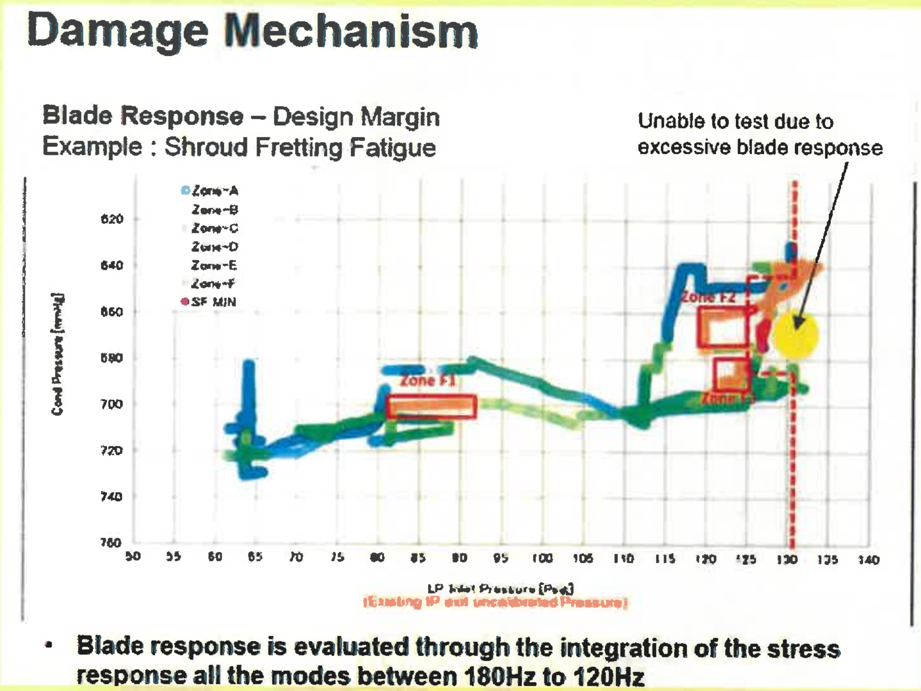

Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined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

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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

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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:

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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.

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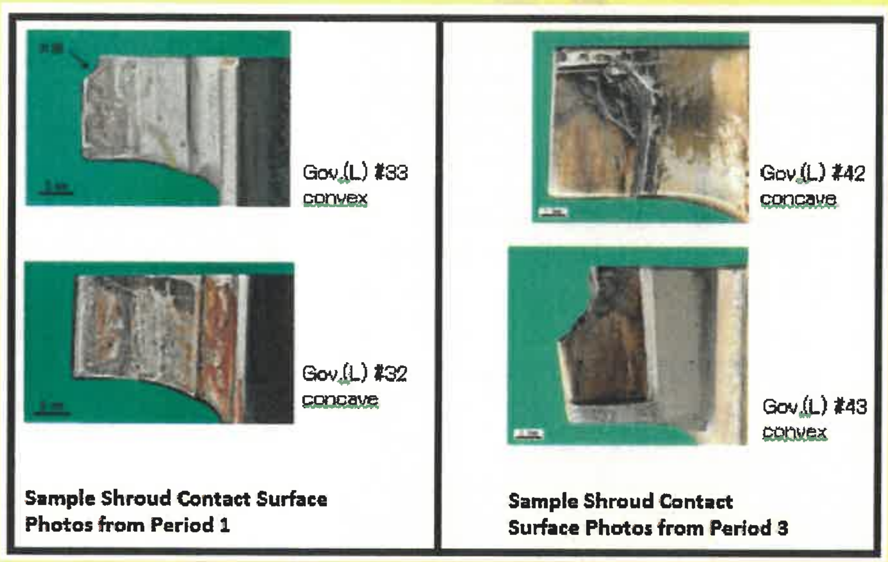
Figure 1 -- Comparative Photos of Shroud Contact Surface Wear for Periods 1 and 3



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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.

Deleted: the L-0 blades

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.

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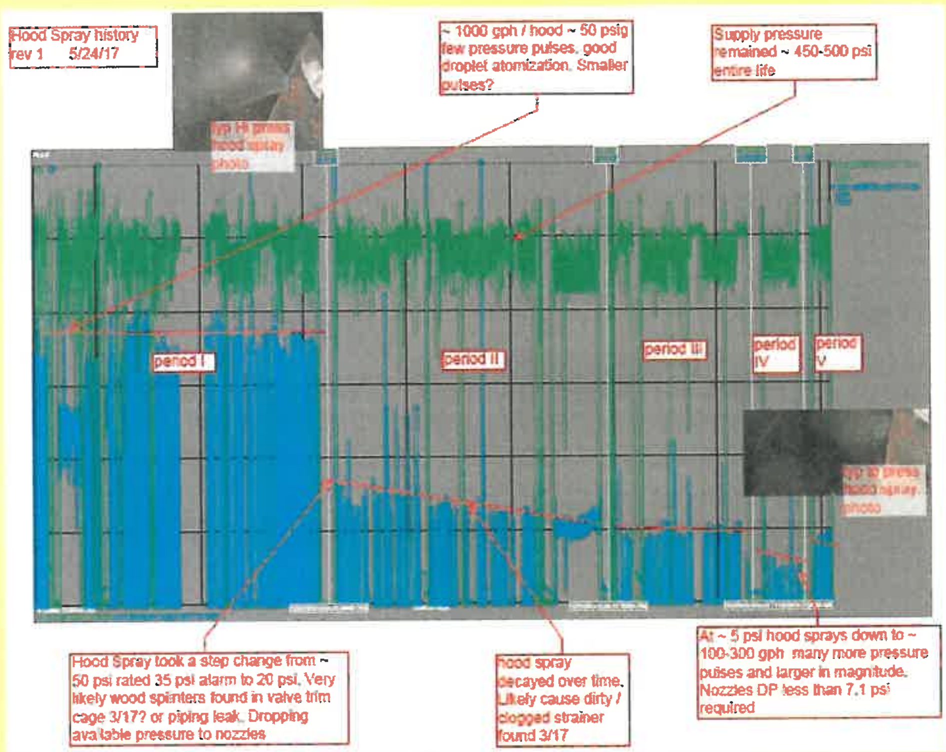
Figure 2 -- Hood Spray Pressure Degradation Over Periods 1-5



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. 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)

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

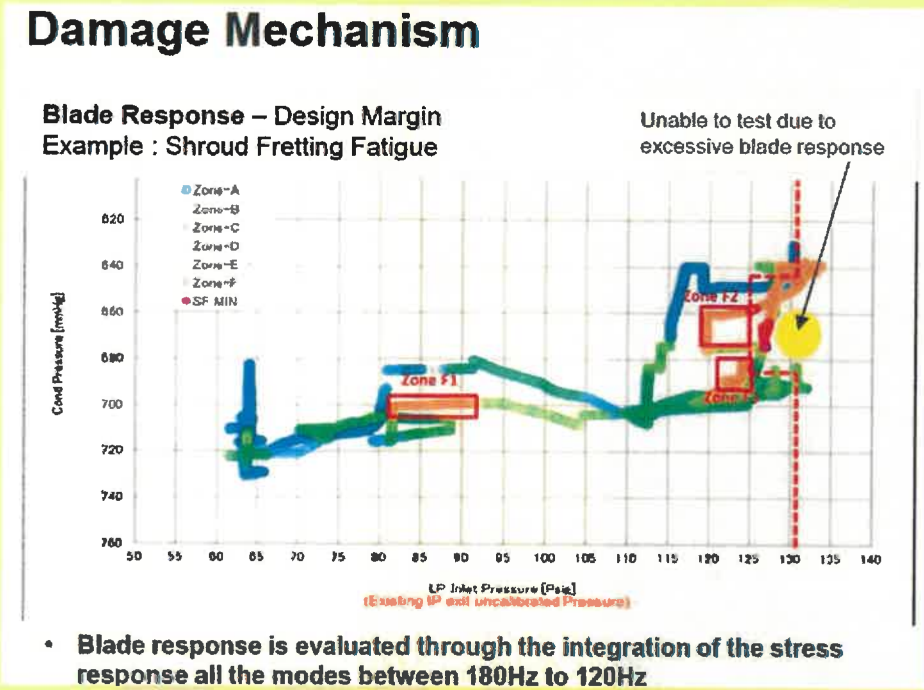

Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined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

Deleted: its share of higher

Deleted: The total of 20 hours of blend

Deleted: 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. 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.

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11 October 2017

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.

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.

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 [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??

DRAFT

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 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

Commented [MB8]: Is this right?

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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 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 simple failure driving 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 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.

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

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.

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- Hood spray thermocouple reading greater than 160 degrees F

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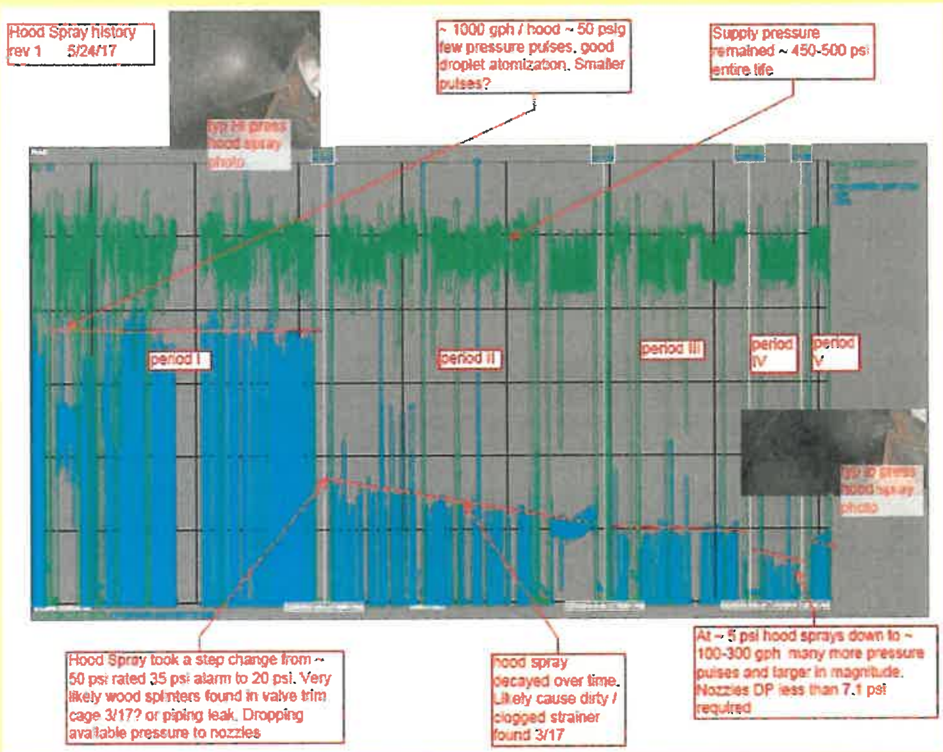

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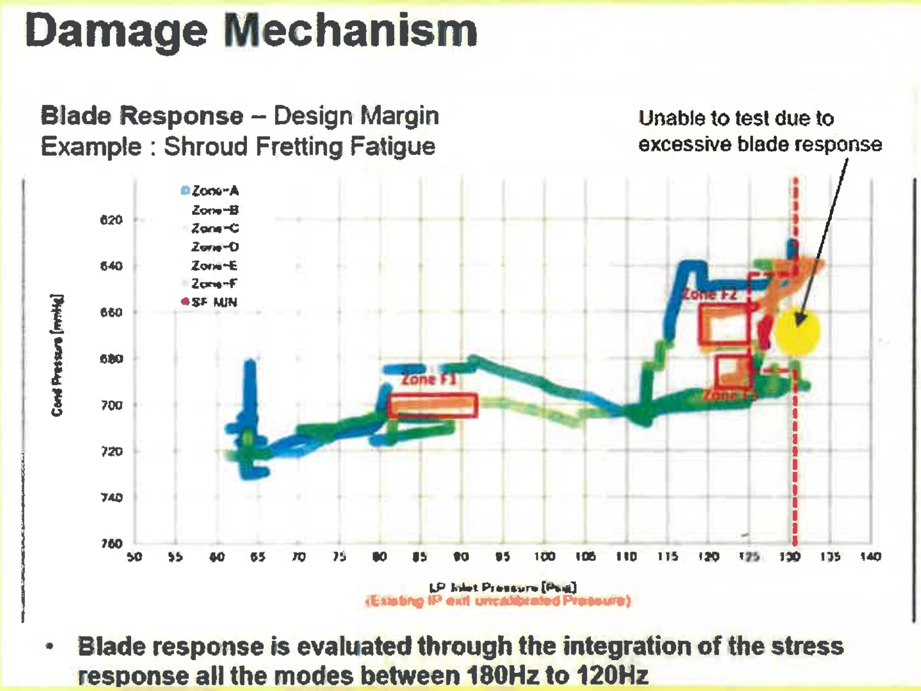
Figure 3 -- Data Presented by MHPS During a Presentation Dated 15 March 2017



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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 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

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

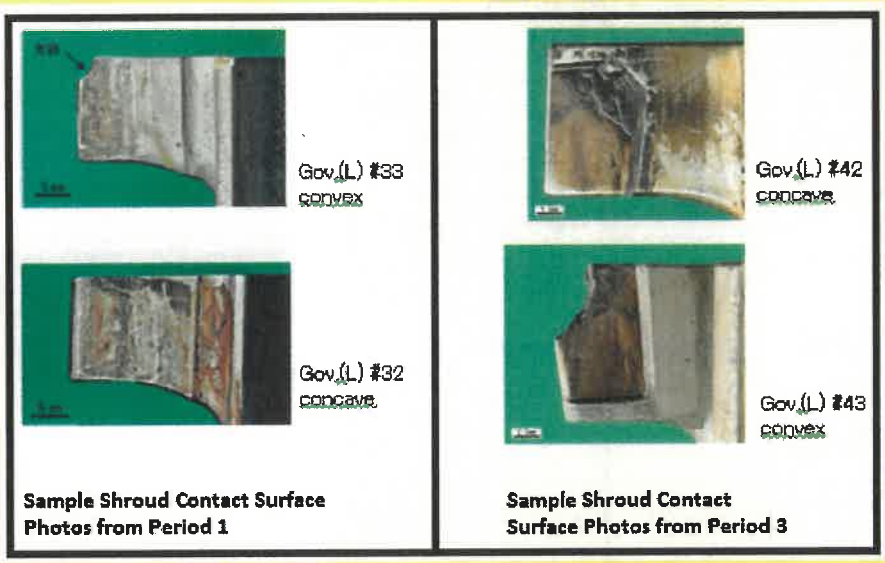
Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data evaluation – learned (and made it known to Duke) that a significant contributing factor toward the L-0 blade failures was high back-end loading on the LP turbine last stage blades. Back-end loading is a function 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



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 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.

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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:

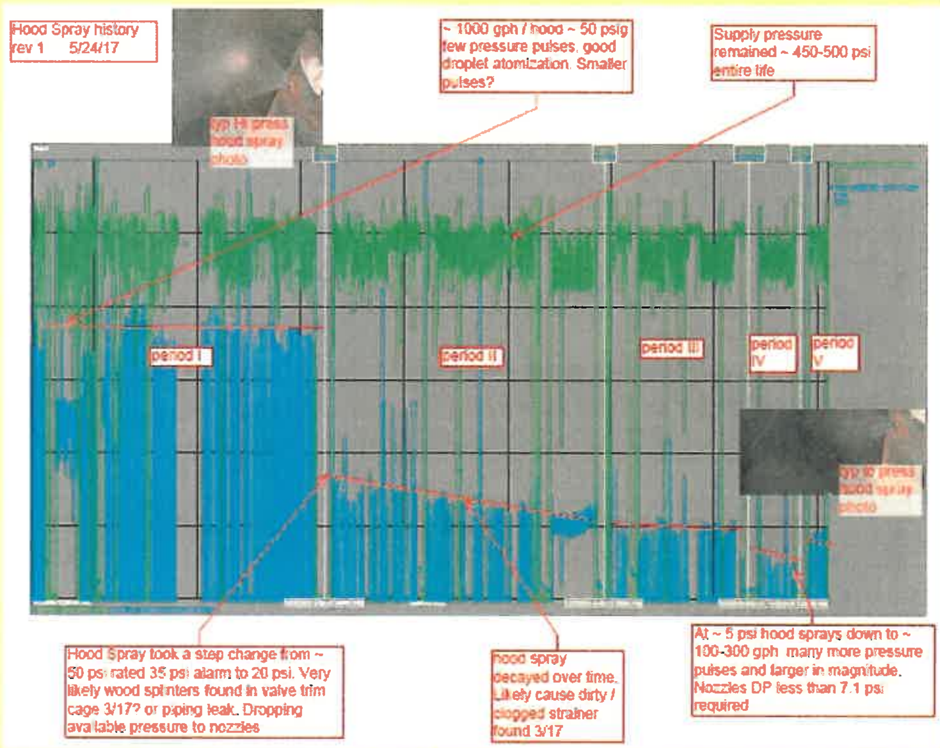
- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

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, the OEM 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, Zone F2, and 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. The OEM did not provide any restriction(s) to operation in Zone F1, Zone F2, and/or Zone F3 – only restrictions relative to "operation in the avoidance zone" identified by the area of the graph to the right of the dotted red line in Figure 3.

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

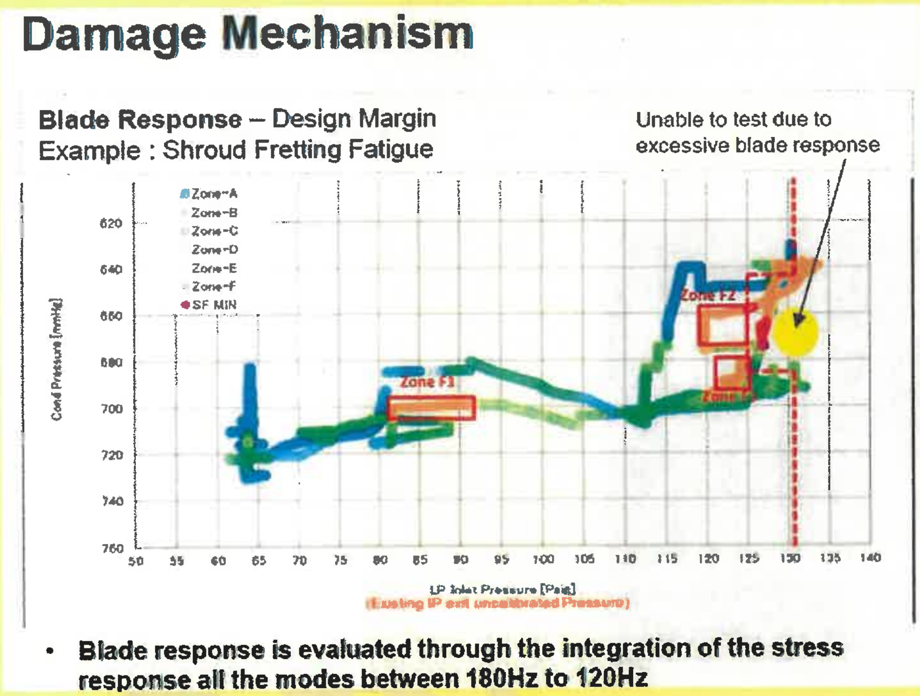

Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined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

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.

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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
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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*

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??

DRAFT

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

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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

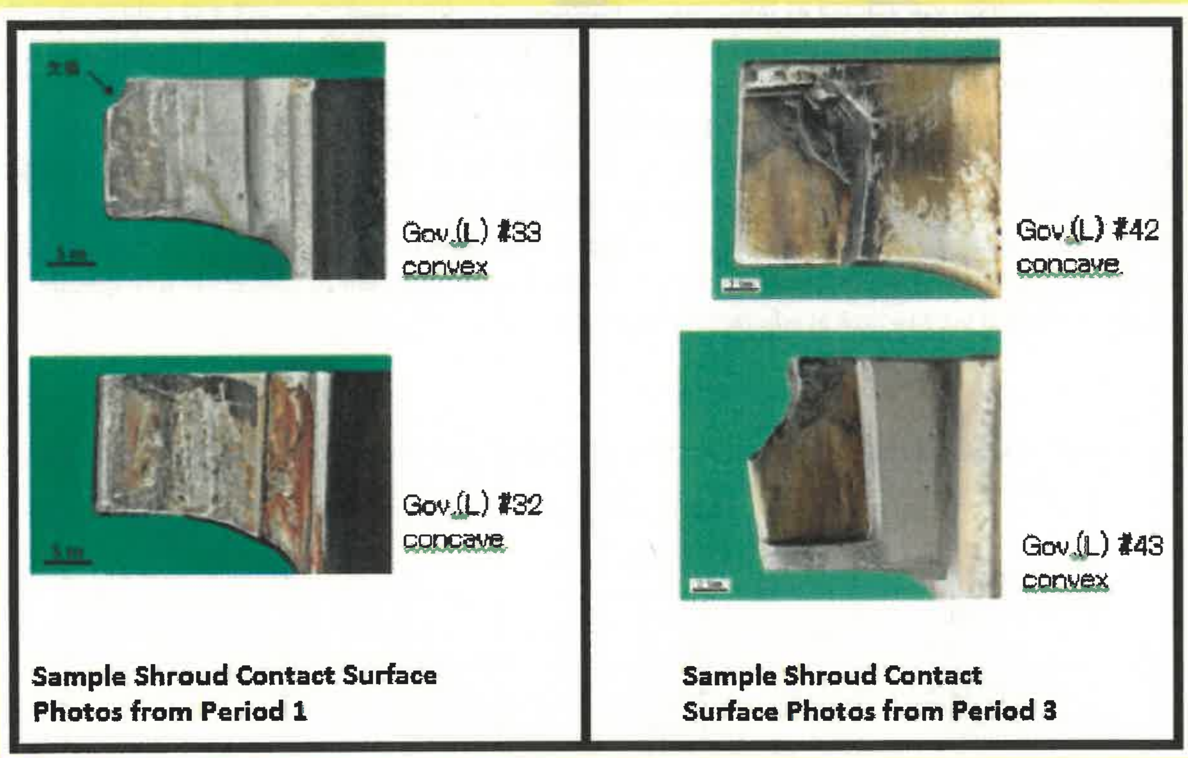
Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data evaluation – learned (and made it known to Duke) that a significant contributing factor toward the L-0 blade failures was high back-end loading on the LP turbine last stage blades. Back-end loading is a function 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



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:

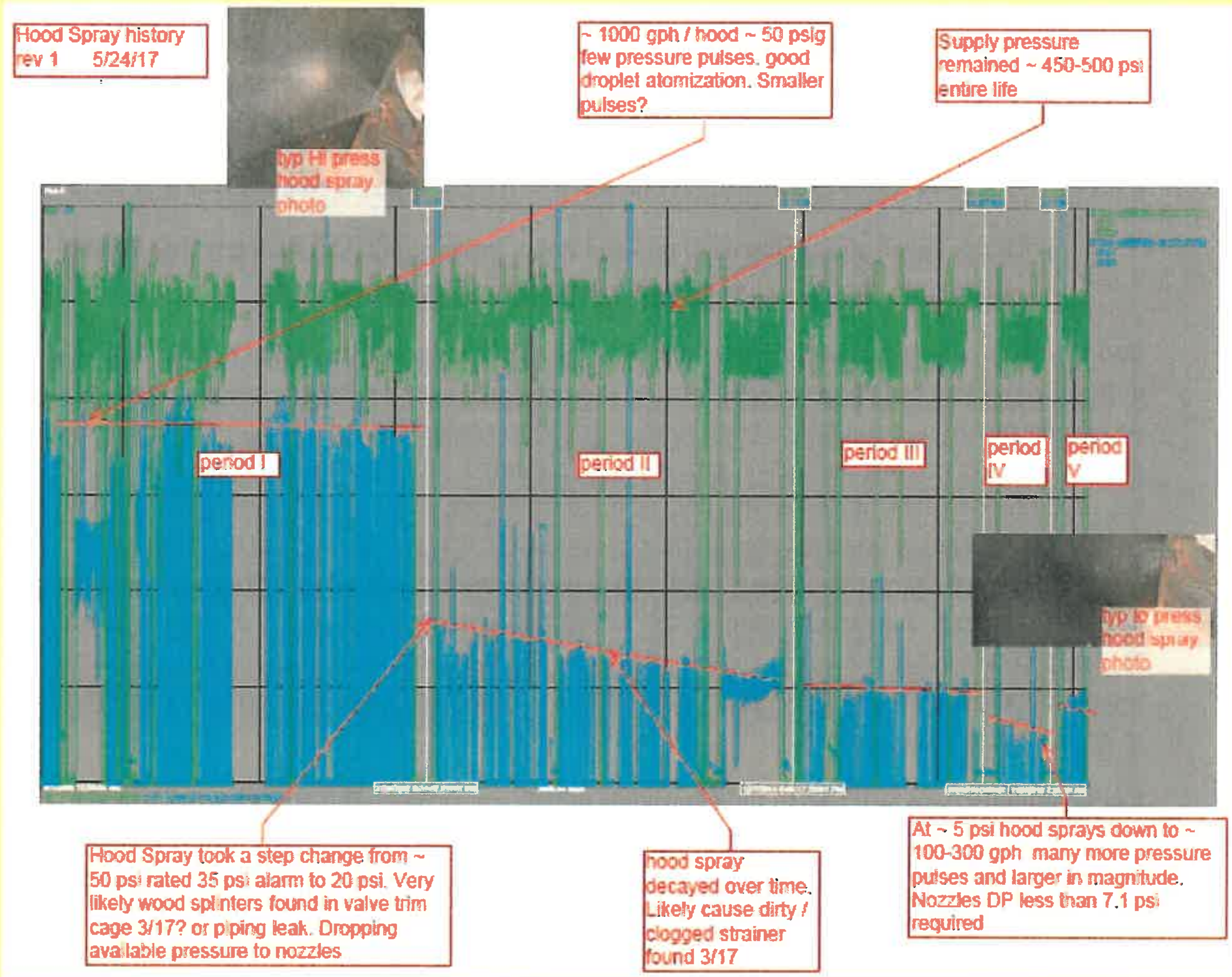
- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

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).

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 through 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

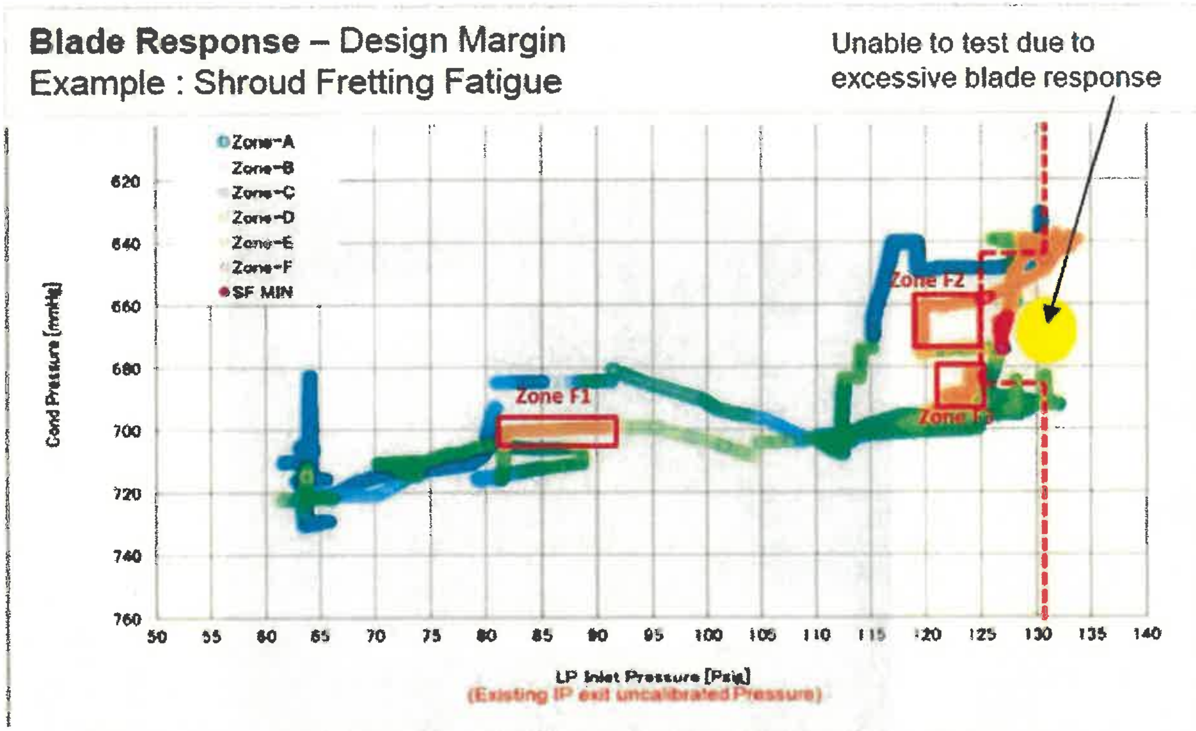


Zone Analysis – Shroud Fretting Fatigue

Based on data from the Period 3 blade strain gauge test in December 2014, the OEM 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, Zone F2, and 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. The OEM did not provide any restriction(s) to operation in Zone F1, Zone F2, and/or Zone F3 – only restrictions relative to "operation in the avoidance zone" identified by the area of the graph to the right of the dotted red line in Figure 3.

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 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.

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,

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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

	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*

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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

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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.

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Customer 10-2-17.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)
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- 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.

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Root Cause Contributing Factors

Low Pressure (LP) Turbine Excessive Steam Flow

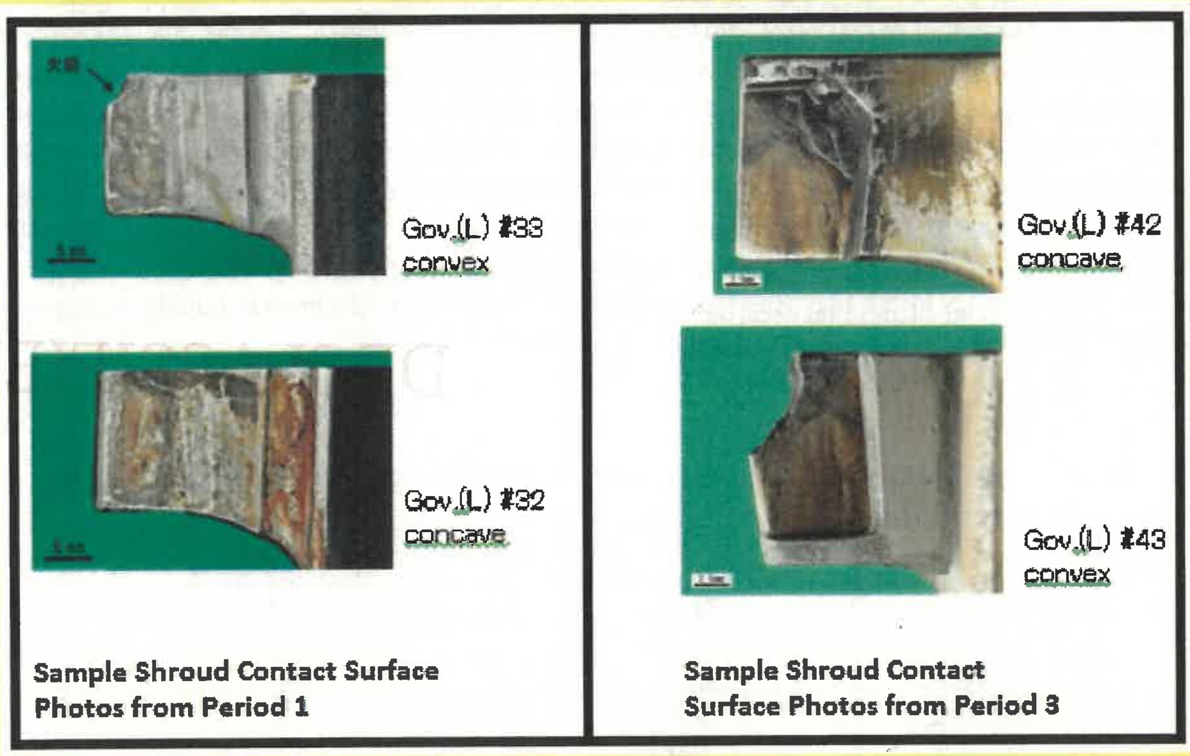
Over the course of Periods 1, 2 and leading into Period 3, MHPS Engineering – through data evaluation – learned (and made it known to Duke) that a significant contributing factor toward the L-0 blade failures was high back-end loading on the LP turbine last stage blades. Back-end loading is a function 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



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.

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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:

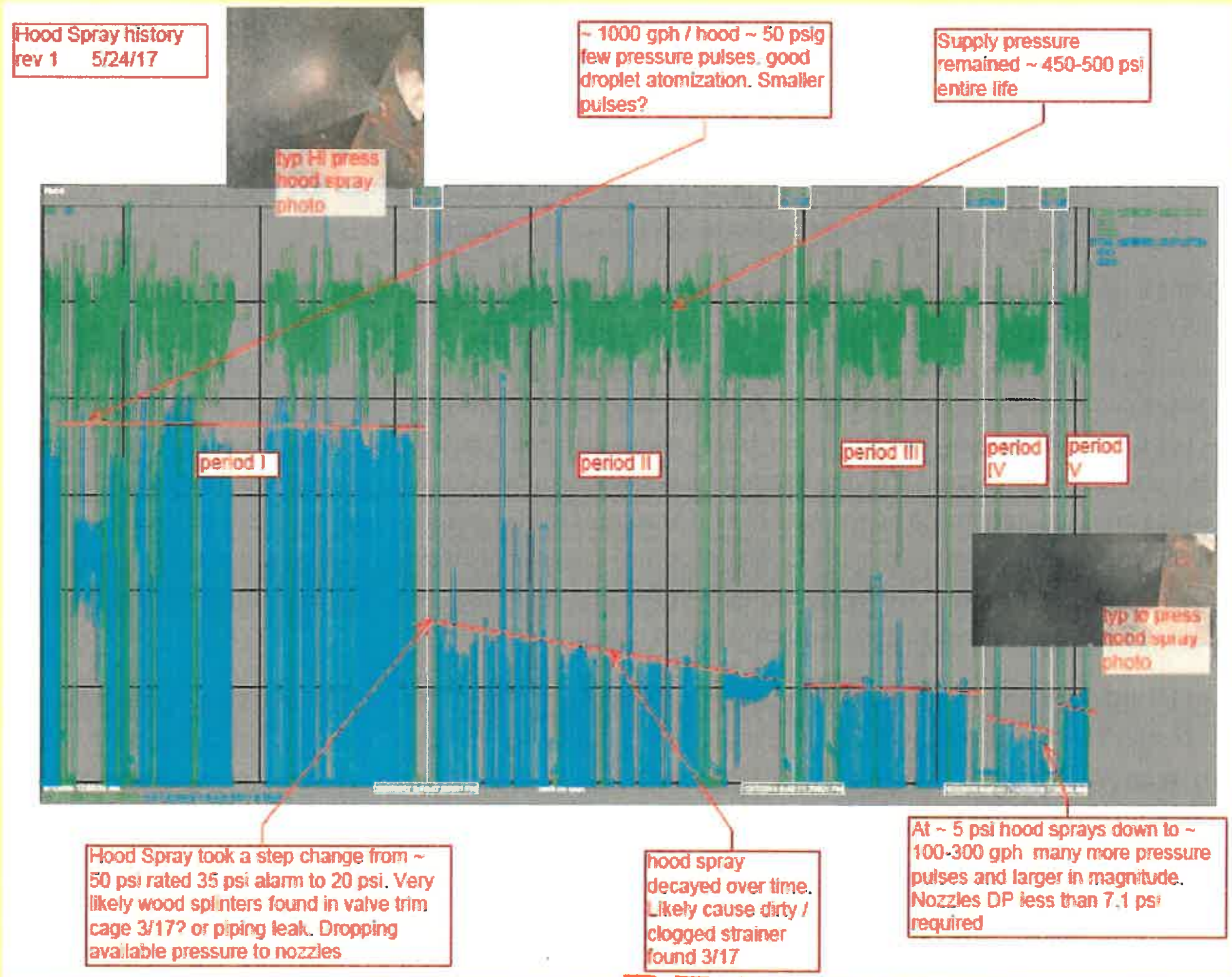
- Rotor speed greater than 600 rpm and steam turbine generator load less than 10 MW
- Hood spray thermocouple reading greater than 160 degrees F

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).

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



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Zone Analysis – Shroud Fretting Fatigue

Based on data from the Period 3 blade strain gauge test in December 2014, the OEM 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, Zone F2, and 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. The OEM did not provide any restriction(s) to operation in Zone F1, Zone F2, and/or Zone F3 – only restrictions relative to "operation in the avoidance zone" identified by the area of the graph to the right of the dotted red line in Figure 3.

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

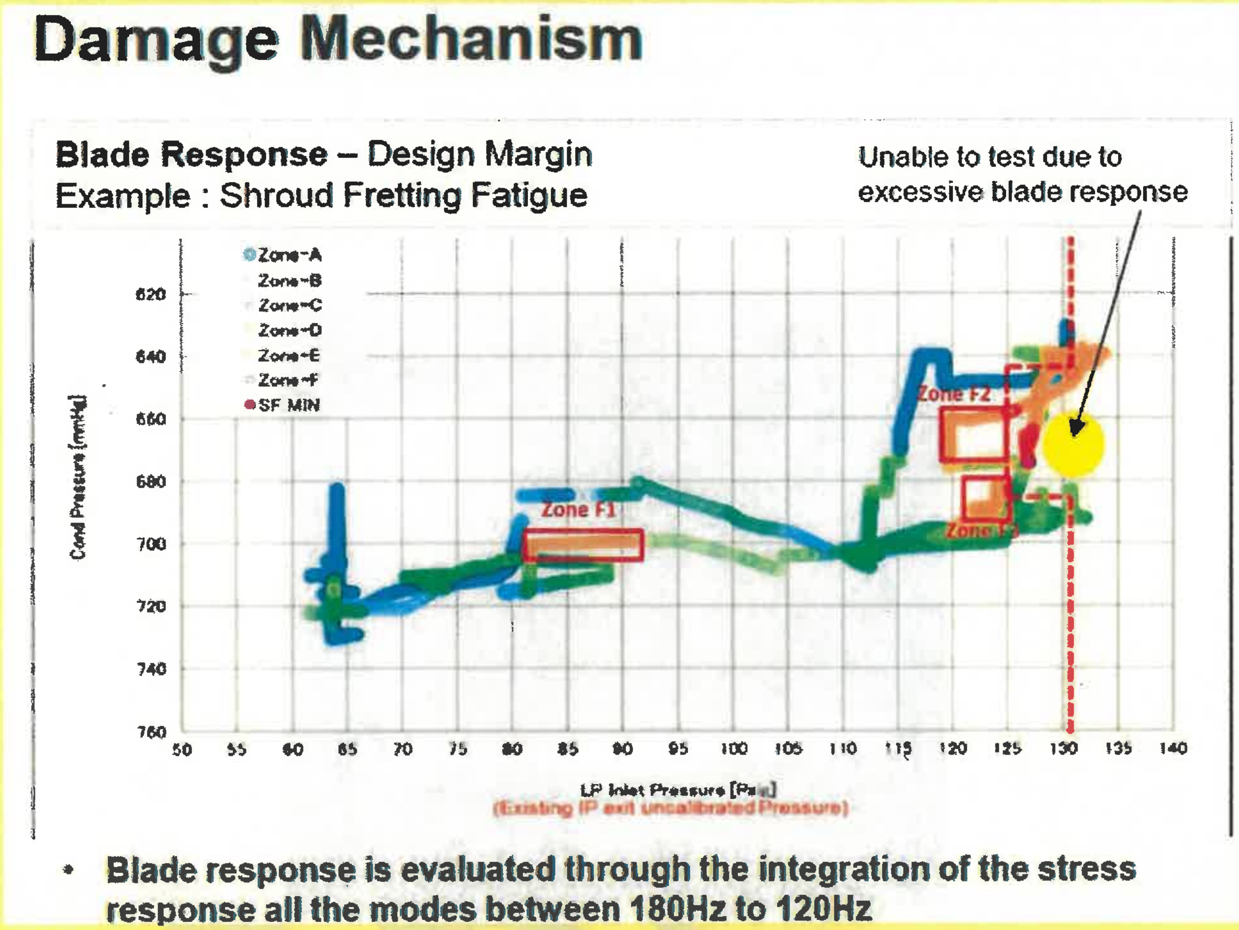

Table 2 shows the breakdown of time in hours in each of the three (3) defined Zone-F areas for each period. The total time in the three (3) Zone-F areas is compared with the total operating time as a percentage. Note that the Period 5 blades spent a high percent of time in the operating area defined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

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

	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*

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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

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

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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

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

Service Sales Manager
Mitsubishi Hitachi Power Systems Americas, Inc.
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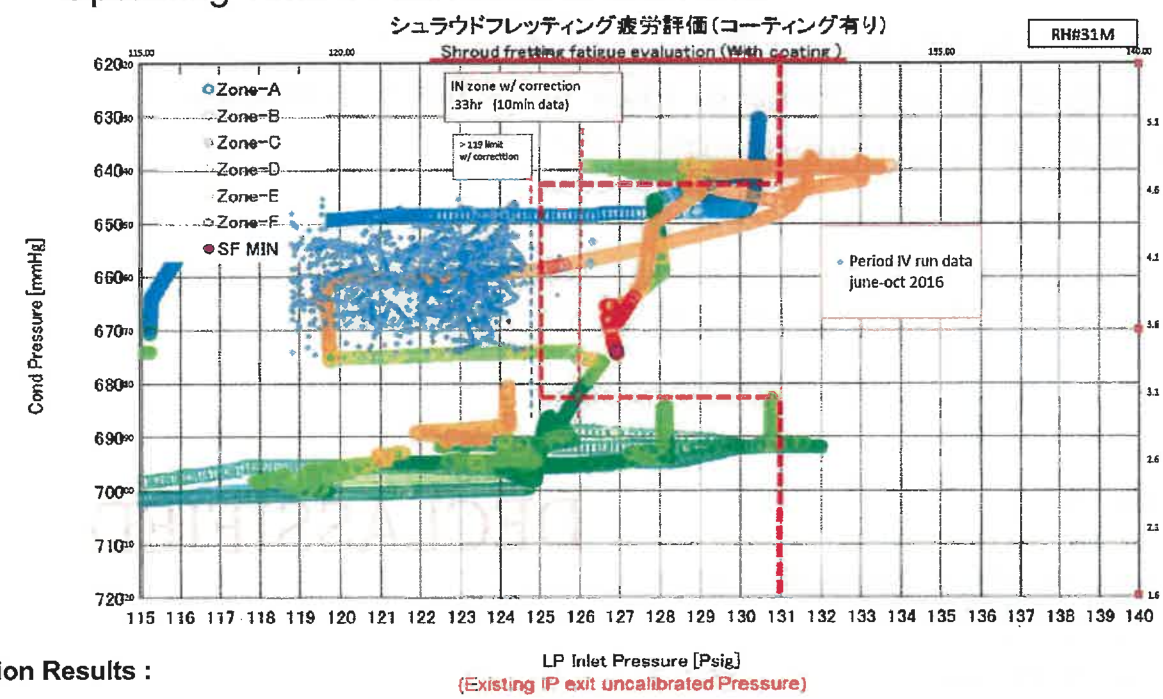
Mitsubishi Hitachi Power Systems Americas, Inc.
www.MHPowerSystems.com

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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DEF20190001BARTOW LFE5-000283

Bartow Steam Turbine

RCA Review

Nov 9th 2016

MITSUBISHI HITACHI POWER SYSTEMS

SL3

Agenda

- Goal of the Meeting

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- 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

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Blade Shroud Chipping RCA – Fish Bone

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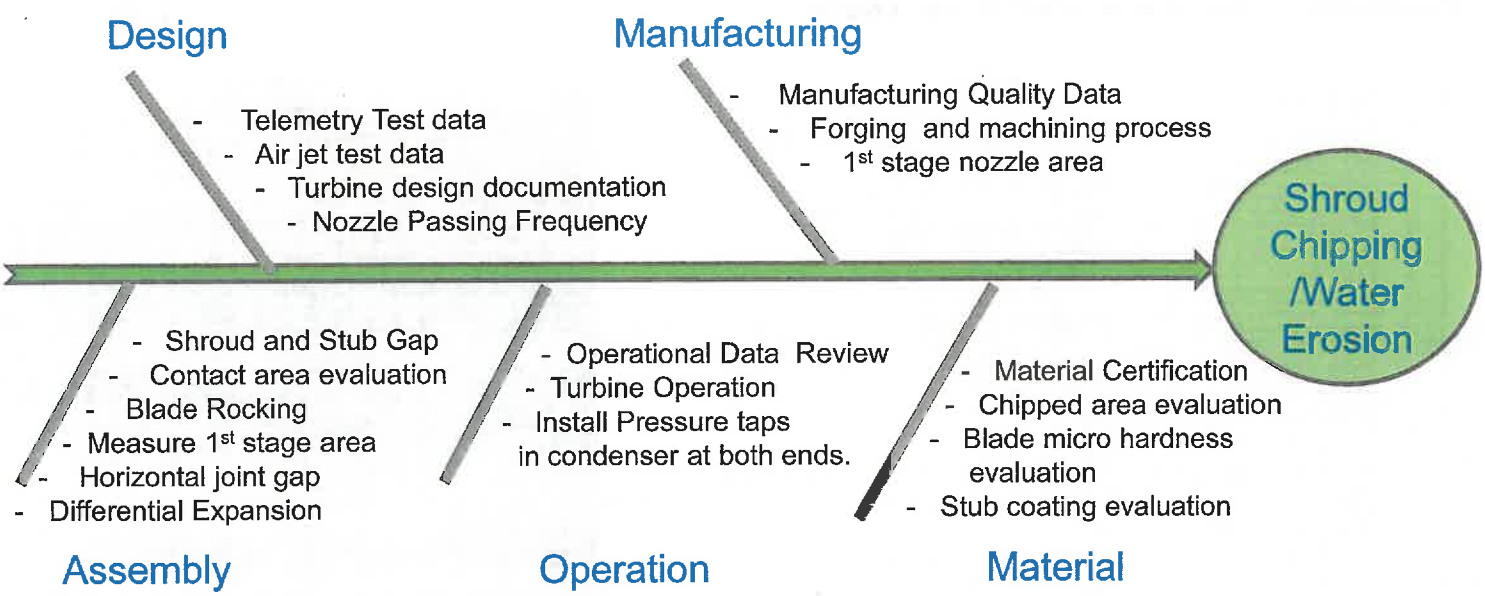

Key Areas of Investigation

Blade Shroud Chipping RCA

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

Influence

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.
Design	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.
Design	3	Re-evaluation of the Telemetry Test Data in the light of Bartow Tip Damage	Completed by team in MHPS in Japan.
Design	4	FEA Review of shroud face movement at high load compared to observed damage	FEA Analysis performed by MHPS in Japan.
Design	5	Confirm MHPS Mass Flow Calculation Method used in evaluating Telemetry Test Data	Mass flow measurements are no more used as evaluation parameter
Design	6	Telemetry Test Data Shroud Fretting Calculation sim too Snubber Calculations	Fretting evaluation completed by MHPS in Japan.
Design	7	Revisit Bartow / Tenaska design torsional margins	Torsional design calculations show acceptable design margins
Design	8	Research overall exhaust pressure limits for 40" L-0 compared to this unit	Bartow Exhaust pressures limits are standard limits
Design	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.
Manufacturing	2	Request Forging Material Test Certs for replacement blades	Material Certs show correct material used and meet design material properties and chemistry.
Manufacturing	3	Moment Weights for existing installed blades	Row of blades is balanced with acceptable unbalance residual
Manufacturing	4	Request Moment Weights Test Certs for replacement blades	Row of blades is balanced with acceptable unbalance residual
Manufacturing	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
Manufacturing	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
Manufacturing	7	Request Record of as Built Area Nozzle Check	Data not located by Japan.
Manufacturing	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.
Materiial	1	On site review of fracture surfaces and wear	Review of rotor, blades and casing on site.
Materiial	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
Materiial	3	Characterize Cracking / Chipping on Tip Wear Surface - Fretting Fatigue?	
Materiial	4	Characterize Hardness throughout tip and wear surface	
Materiial	5	Characterize microstructure throughout tip and wear surface	
Materiial	6	Evaluate Wear on Mid Span Snubber	
Materiial	7	MHPS TGO Lab Review - Establish blades to be sent	
Materiial	8	TGO Evaluation	

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Blade Shroud Chipping RCA

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

Influence

Influence
Low
Medium
High

		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

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	#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.

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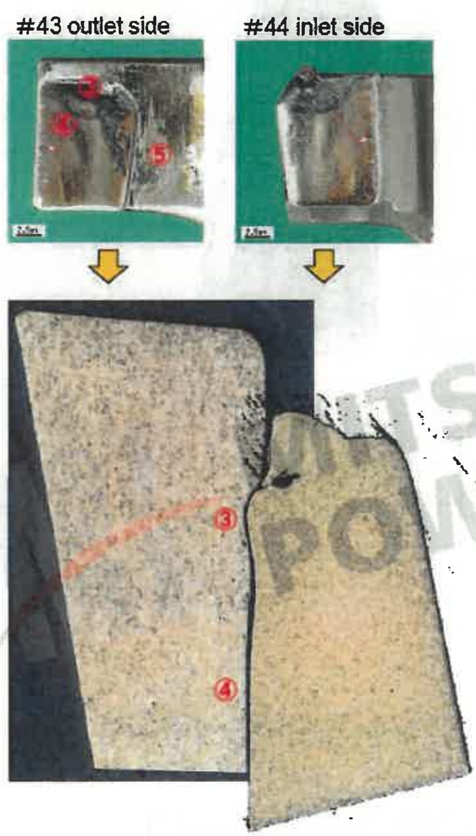
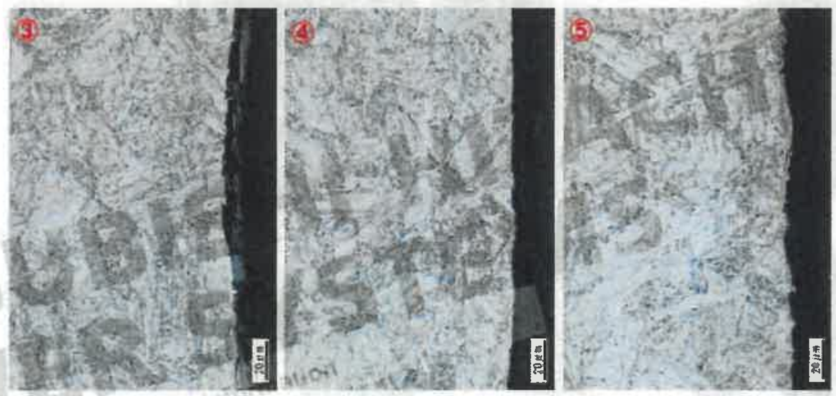
Metallurgical Evaluation of Blades



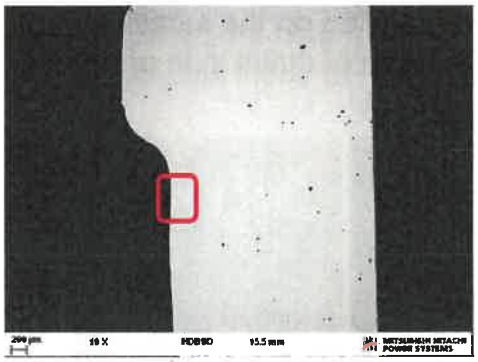
Microscopic observation was performed on the same sections in contact condition for each of outlet side of #43 blade and inlet side of #44 blade.

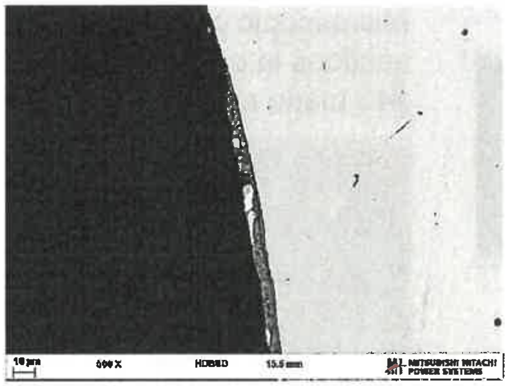


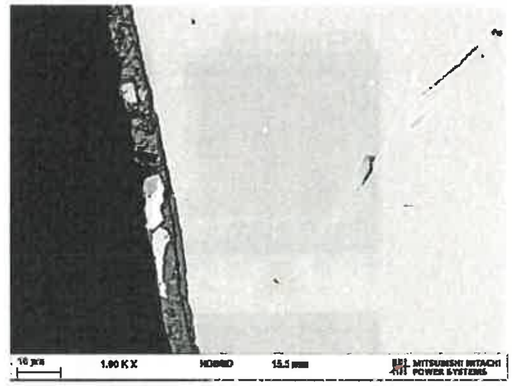
- ③: Oxide scale was found on black surface of local deformation area.
- ④: Dark brown surface of worn and thinned part is free of oxide scale and smoother than non-contact surface of ⑤.

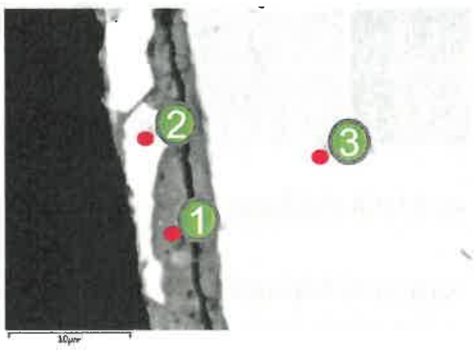
Oxide scale with local deformation observed on black surface

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

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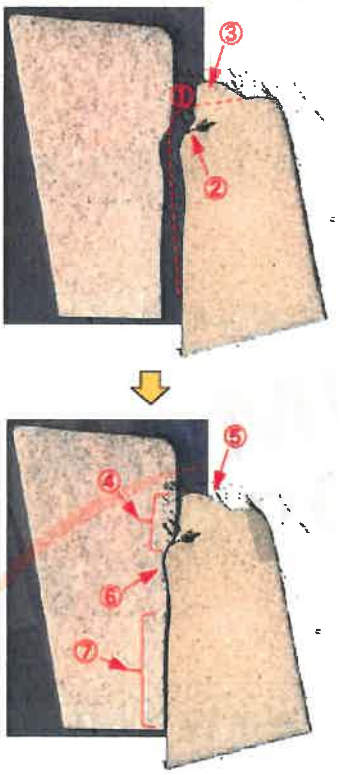
Metallurgical Evaluation of Blades - Hardness

- 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

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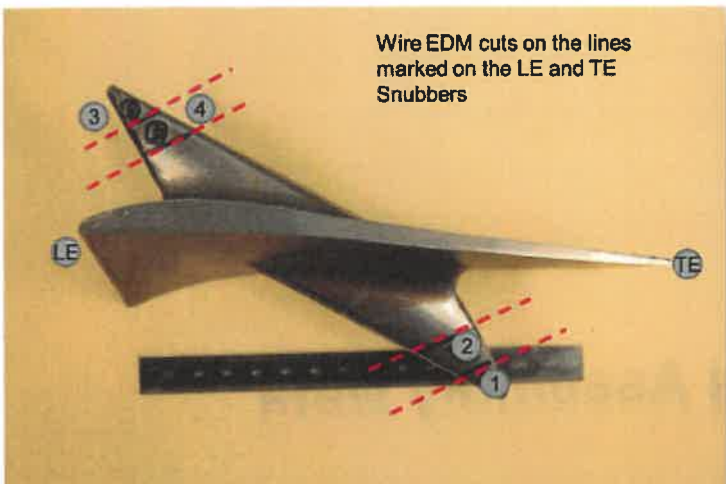
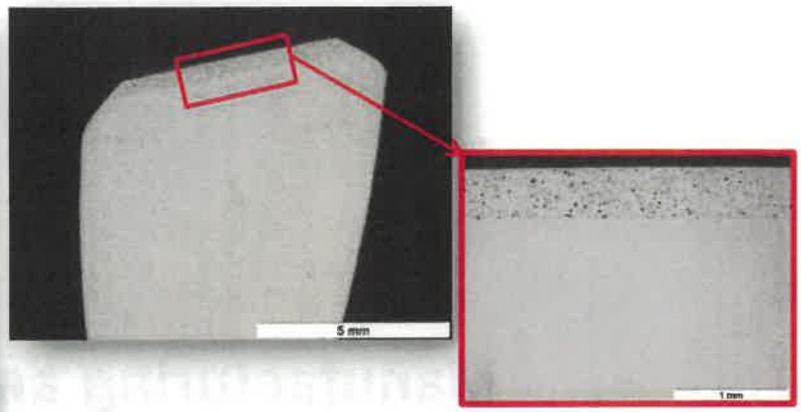
Stub Evaluation





- 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

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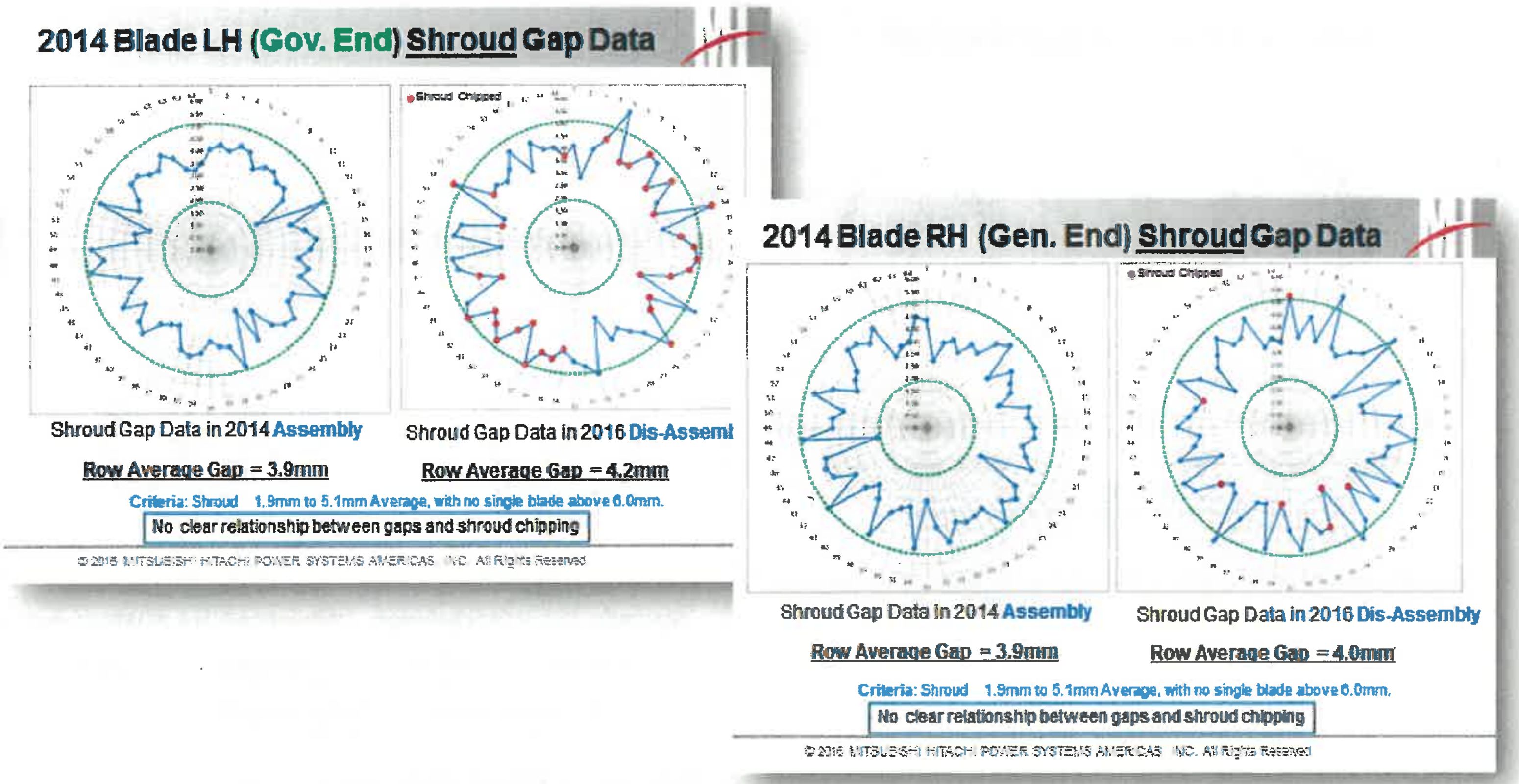

LH and RH shroud average gaps are nearly same
No clear relationship between gap and shroud chipping

Stub Gap Data

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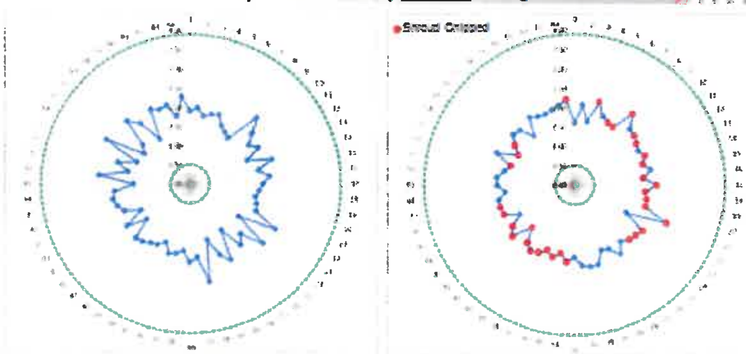
2014 Blade LH (Gov. End) Stub Gap Data



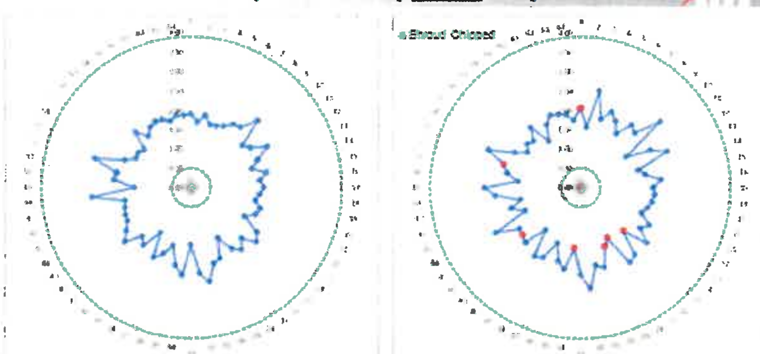
Shroud Gap Data in 2014 Assembly — Shroud Gap Data in 2016 Dis-Assemb

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.

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Manufacturing Quality Data - Box Gauge

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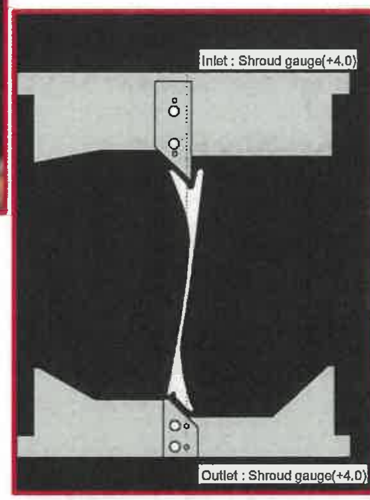
Box Gauge with 40" L0 Blade



Box Gauge Measurement Results - 2014 blades

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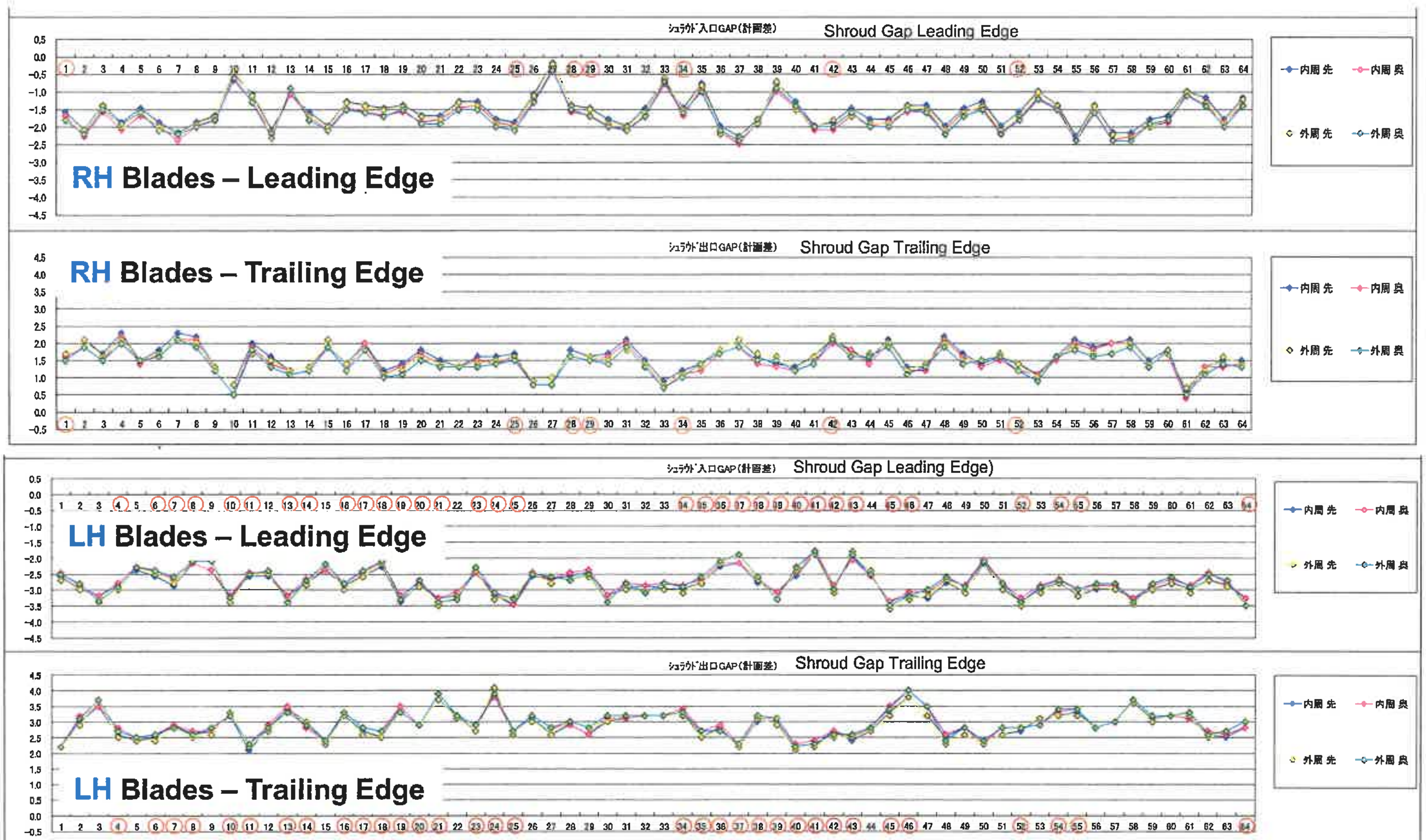

Blade manufacturing data show variation within criteria

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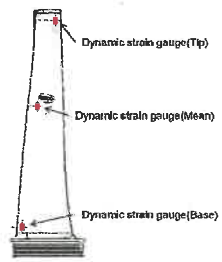
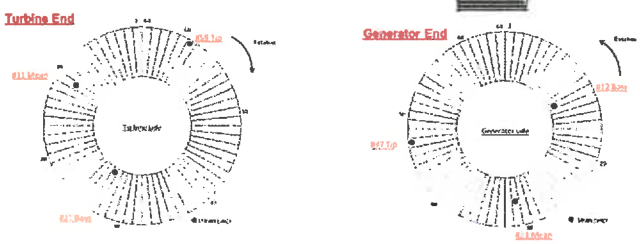
Telemetry Test Data Analysis

Telemetry Test Results

Strain Gage Locations

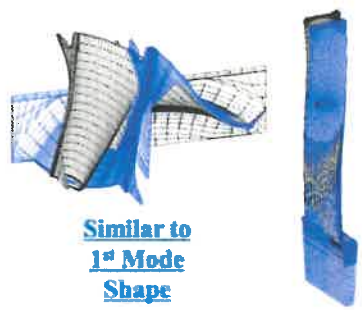
- Six strain gage were installed on LH and RH blades.
- Strain gage locations were selected
  - High Response sensitivity for vibration modes.
  - MHPS Experience



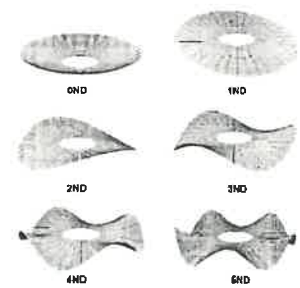


Test Results

- 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

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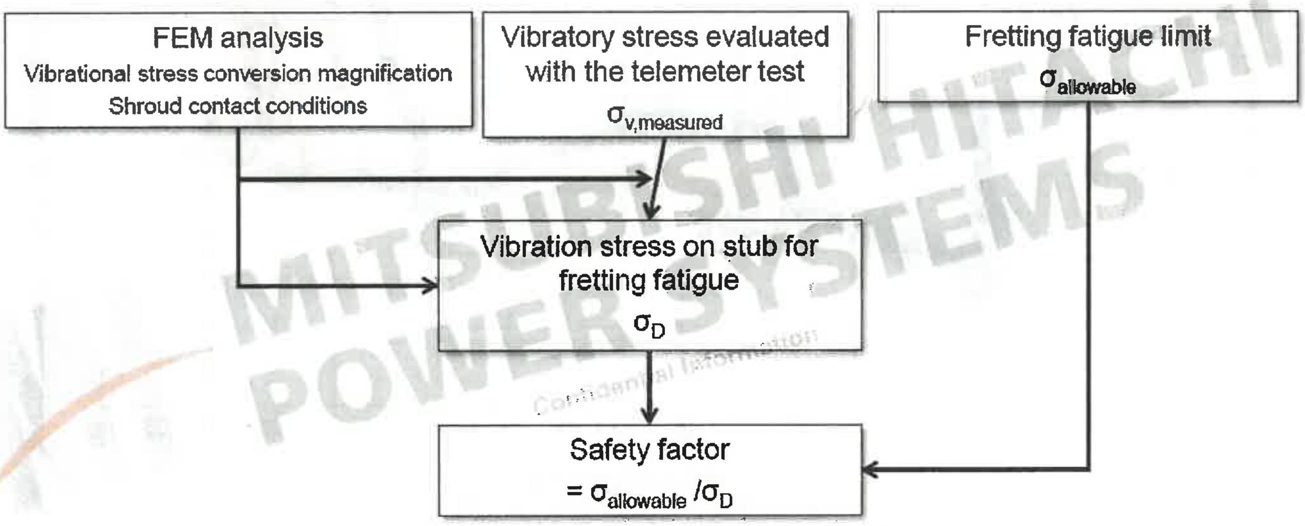
Shroud Fretting Stress Evaluation

- 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

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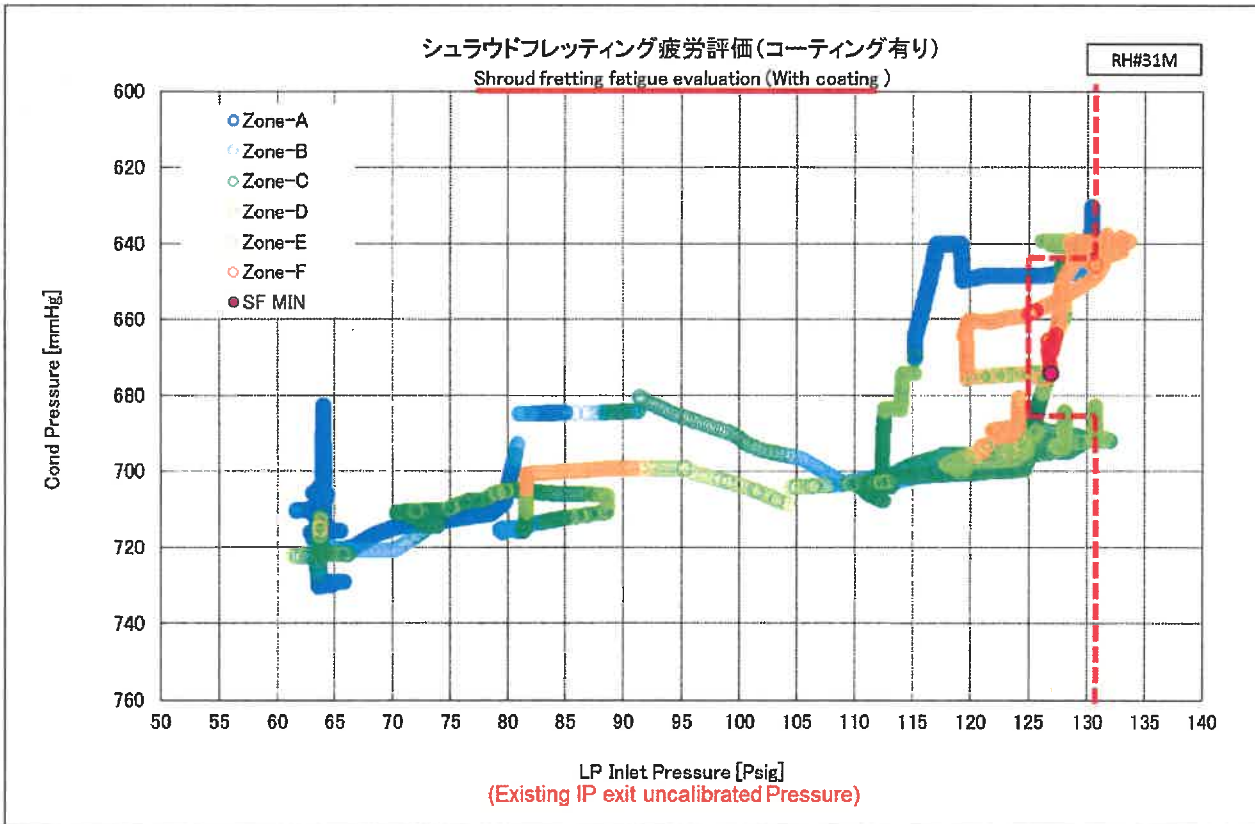

Fretting fatigue calculations for shroud with coating show acceptable margins outside avoidance zone

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Telemetry Test Data – Shroud Fretting

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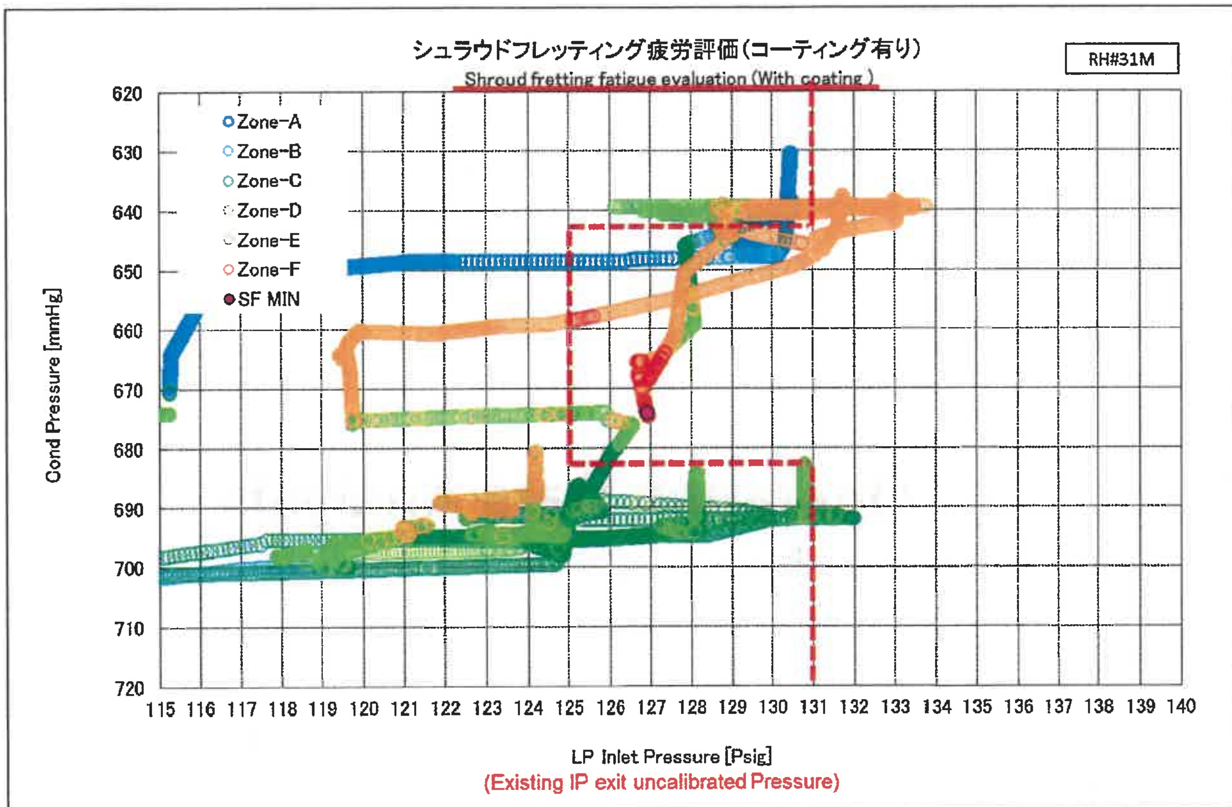

Fretting fatigue calculations for shroud with coating show acceptable margins outside avoidance zone

Operation Data Analysis

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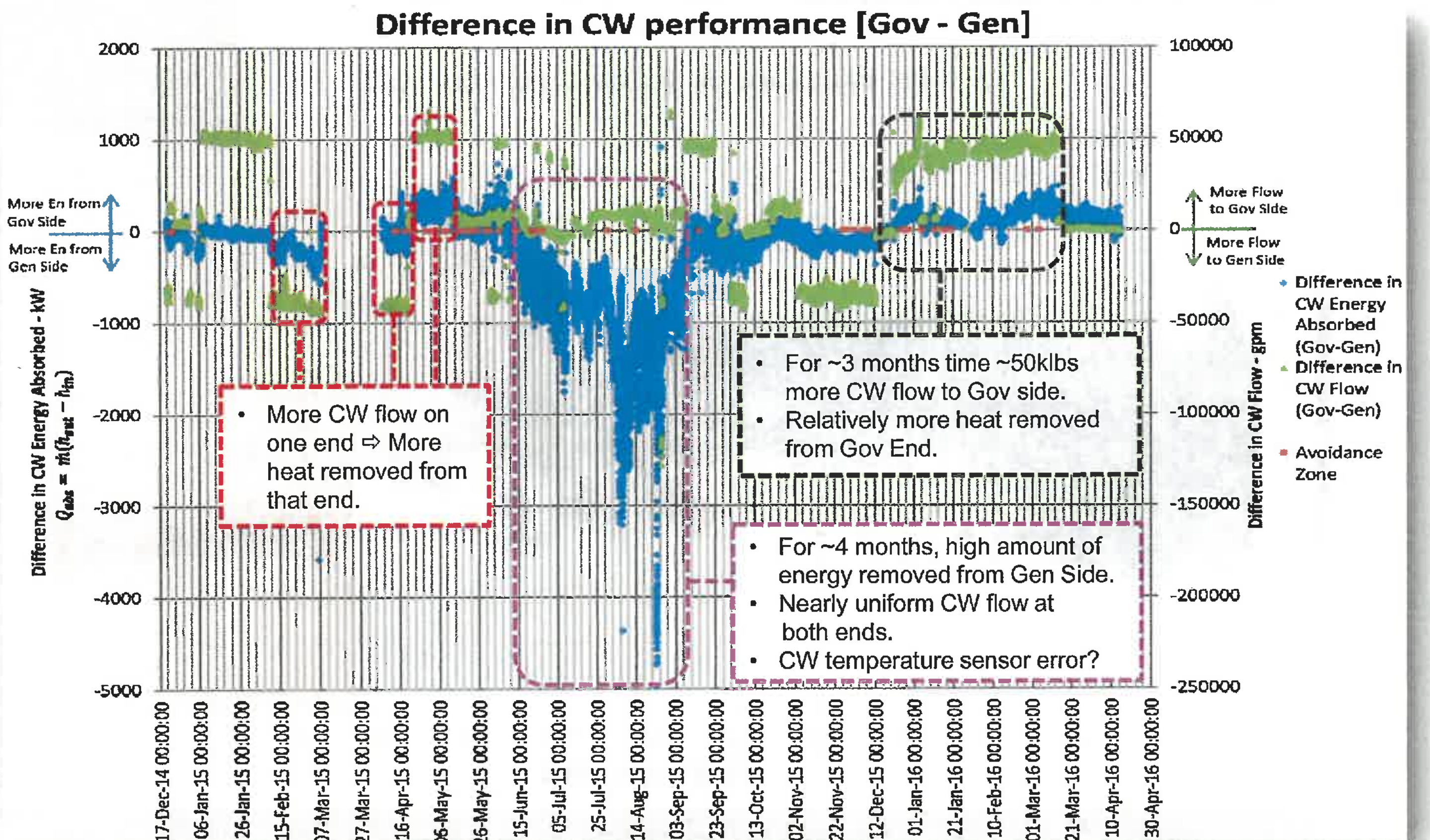
Condenser Circulating Water (CW) flow analysis



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

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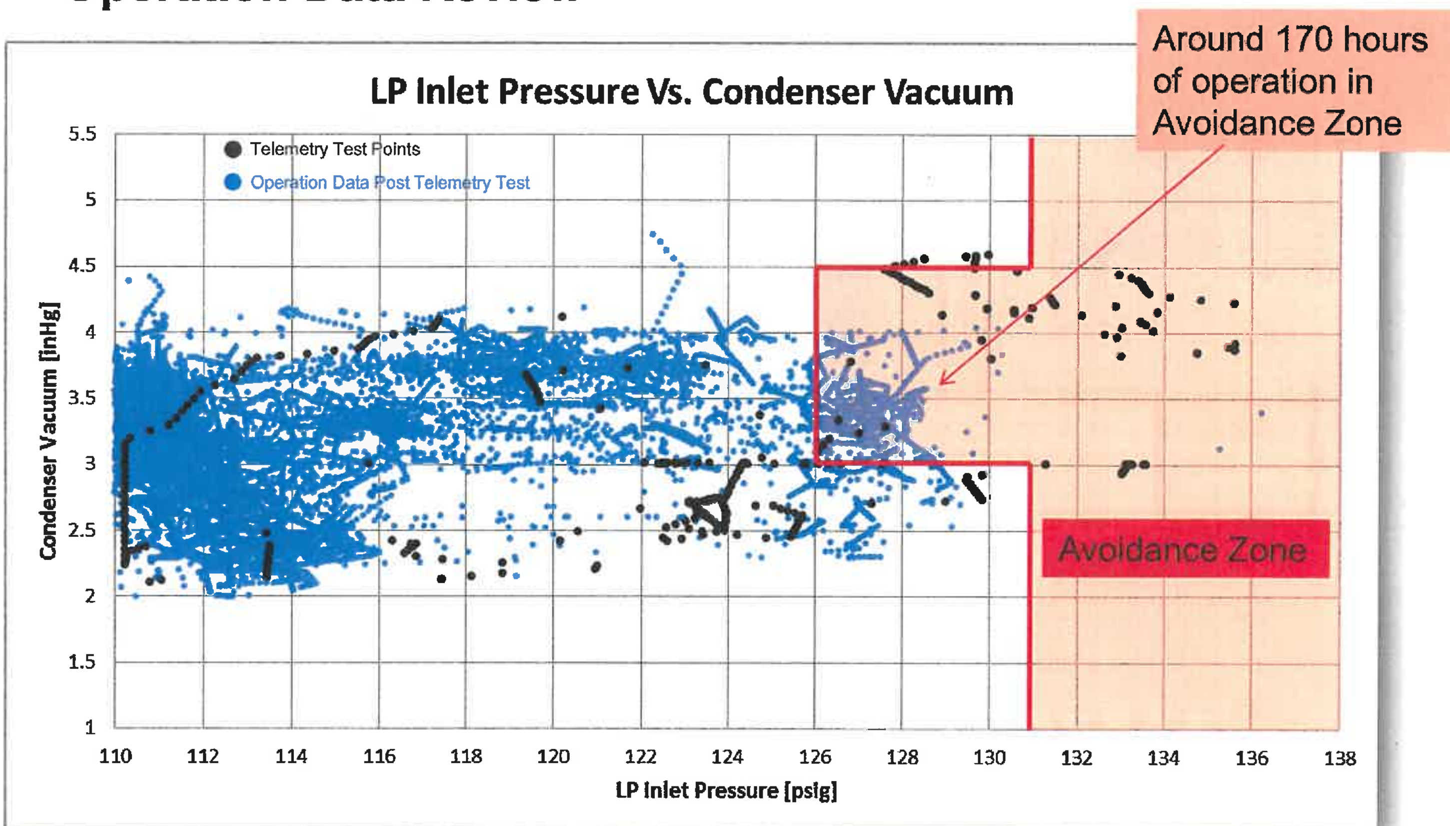

170+ hours of operation in avoidance zone with a response frequency ~200Hz = 1.2E8 Cycles

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RCA Conclusions

Blade Shroud Cause and Effect Diagram

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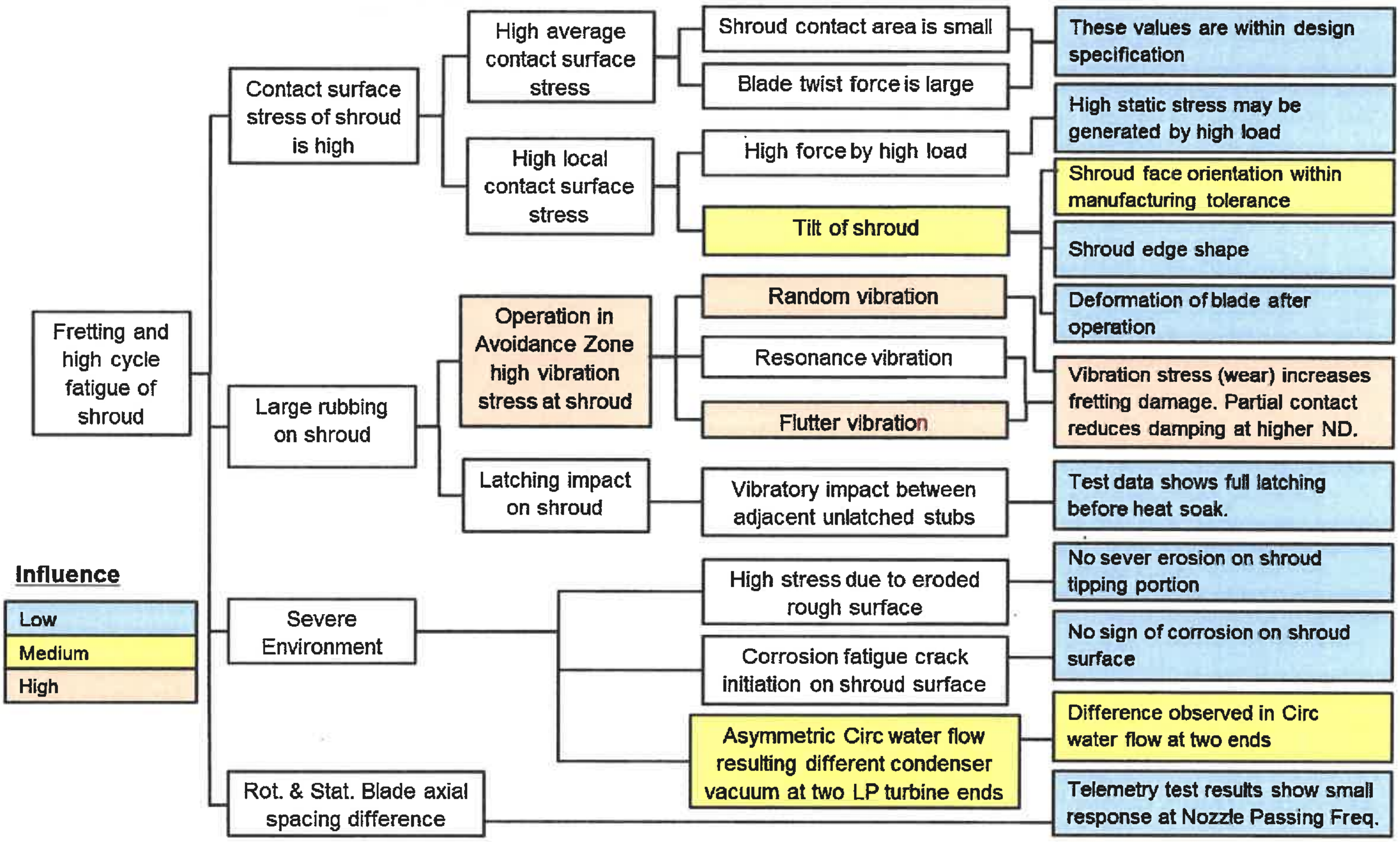

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RCA Conclusion

- 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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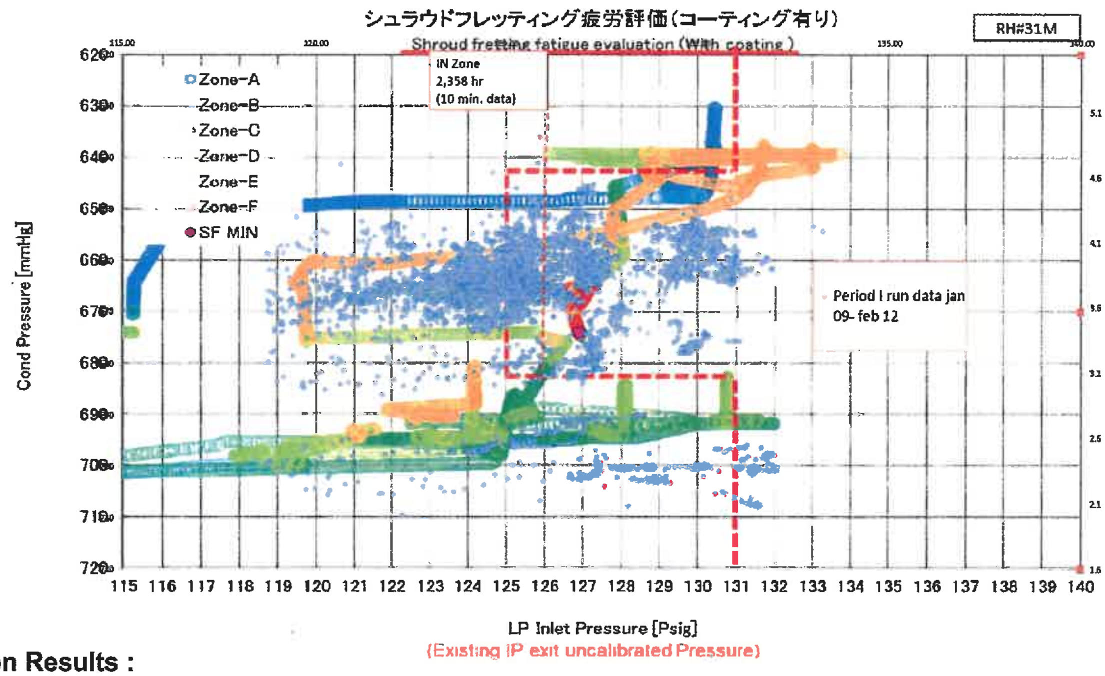
Purpose of Presentation

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.

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

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1.2) Operating Time 2 : Apr 2012 to Nov 2014

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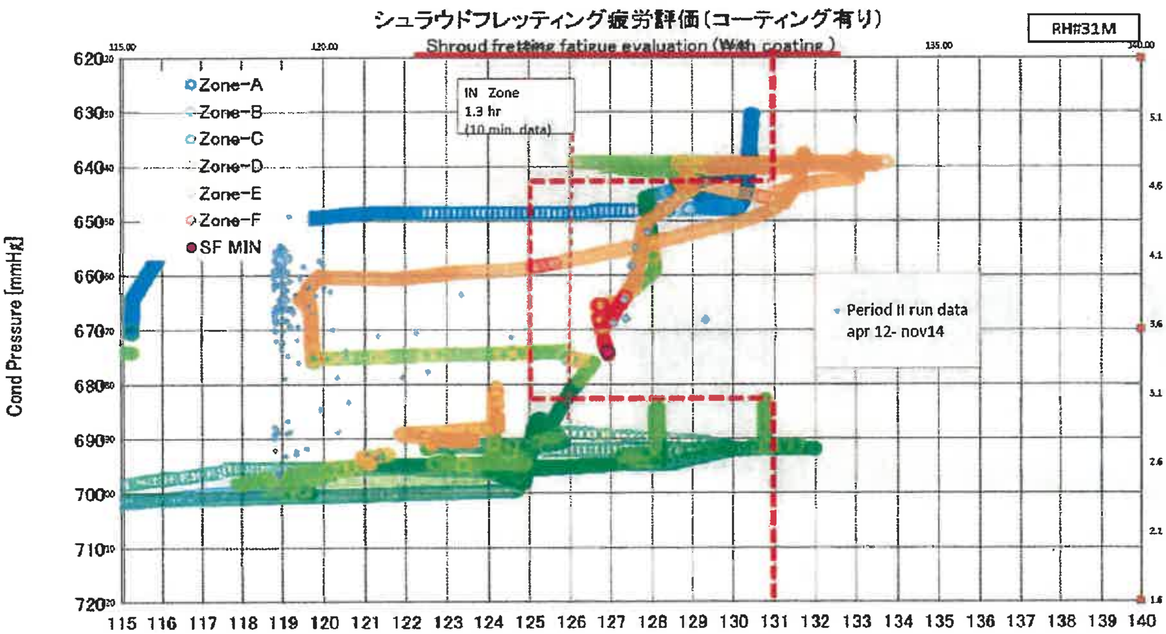
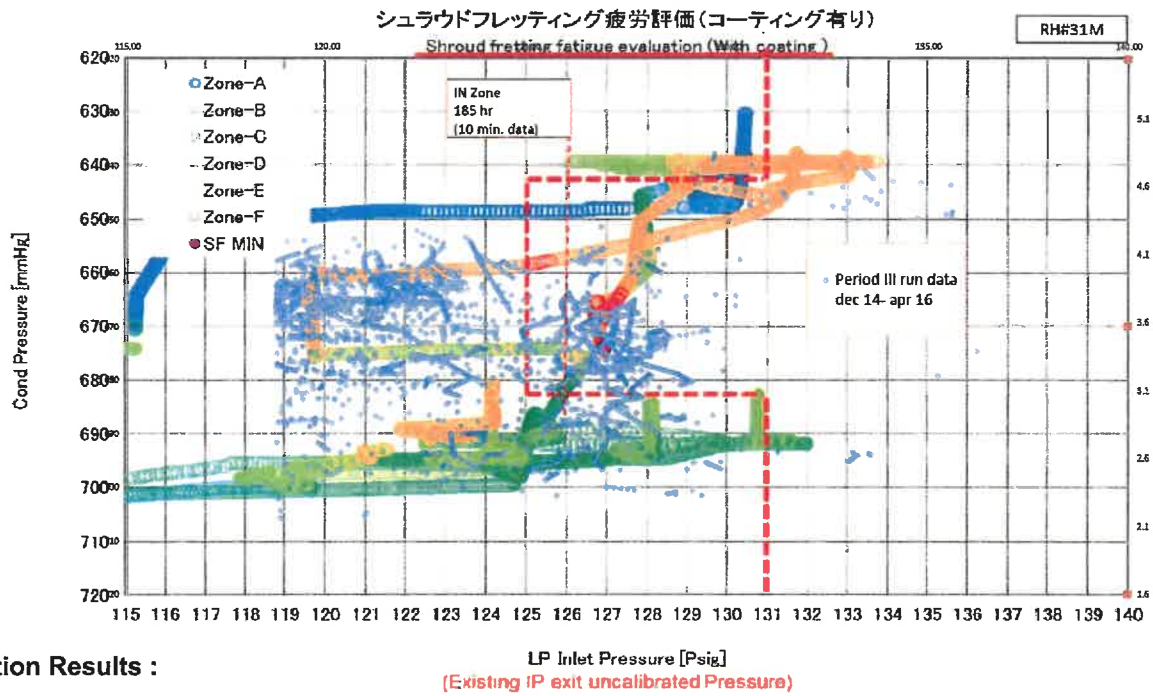


Inspection Results :

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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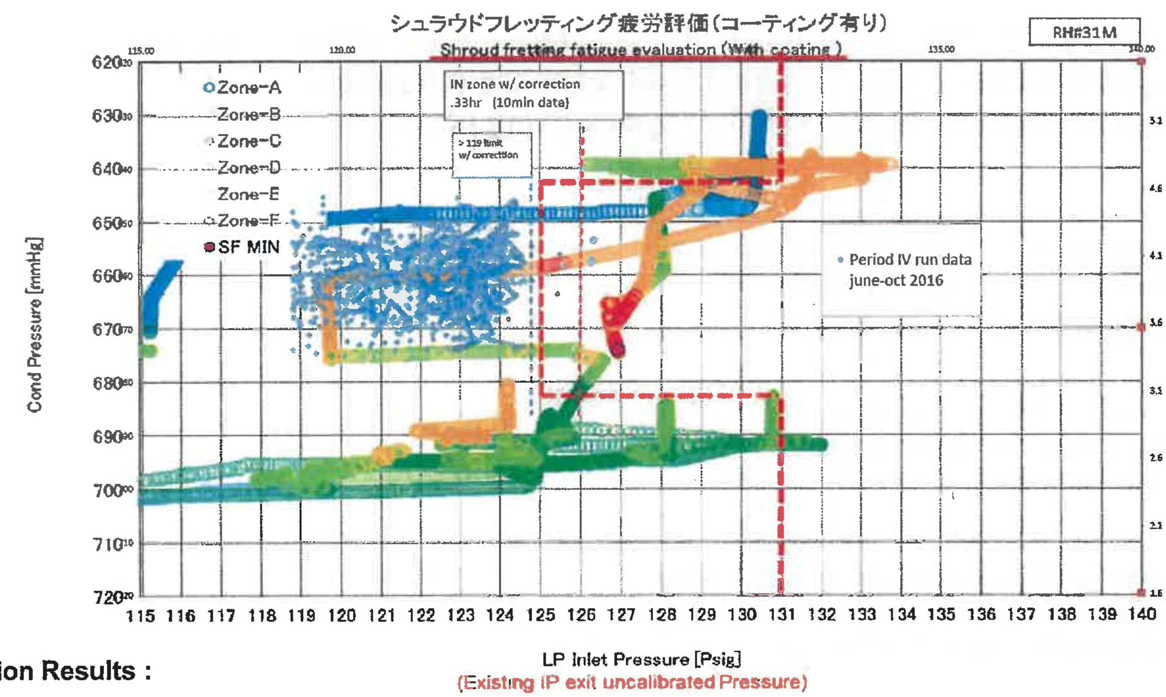
1.4) Operating Time 4 : Jun 2016 to Oct 2016



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)

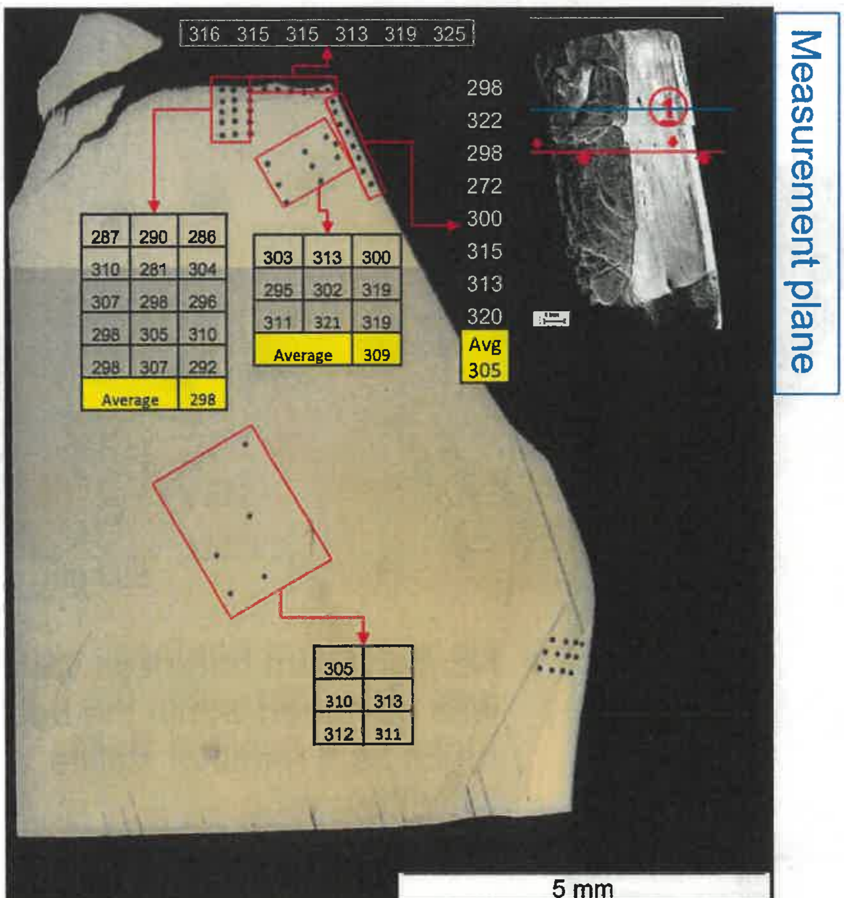
1.1) Operating Time 1 : Jan 2009 to Feb 2012
Significant operation in the avoidance zone.
Significant damage observed on the blades.

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.

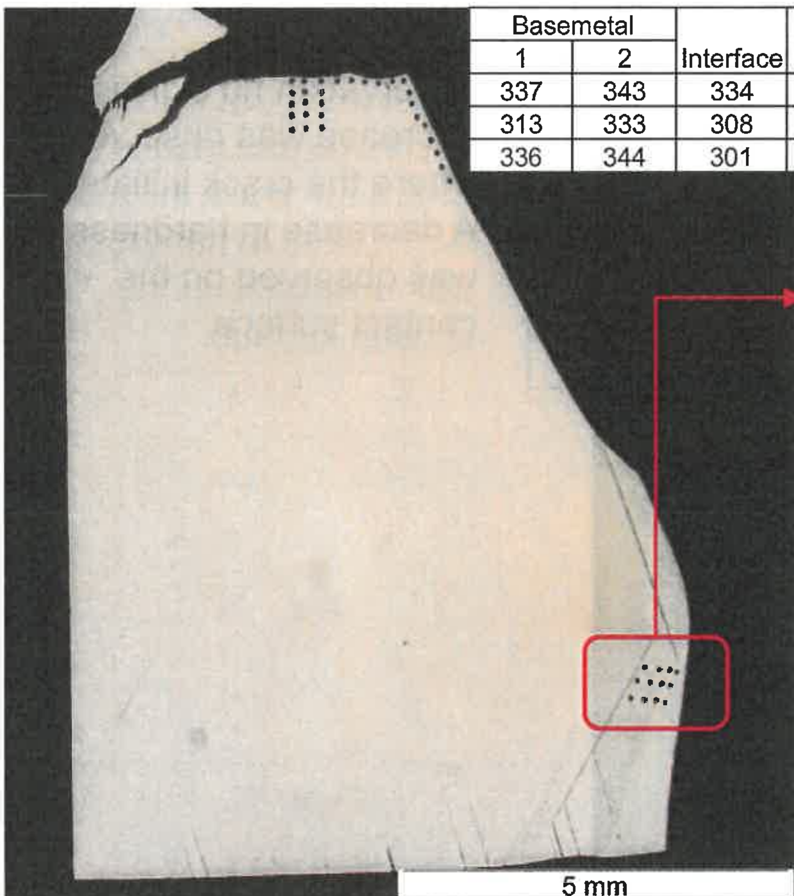
2 - Hardness Variation – Presented

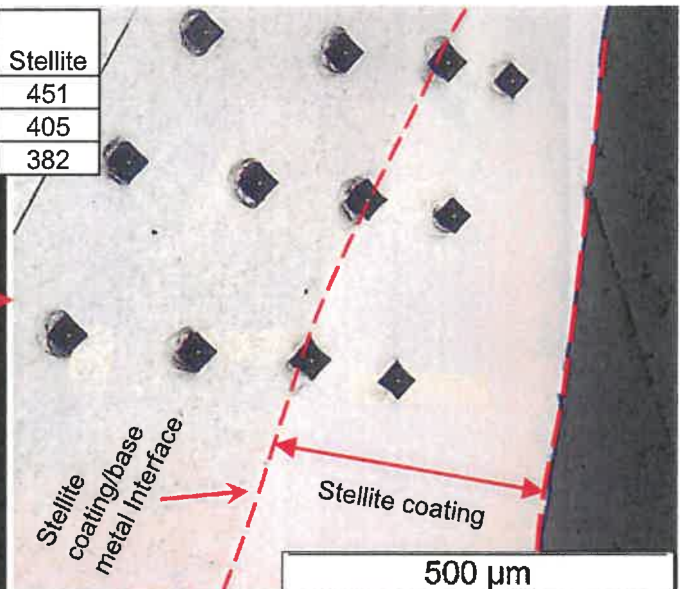


- From hardness observation no significant decrease was observed where the crack initiated.
- A decrease in hardness was observed on the contact surface.

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.

DECLASSIFIED

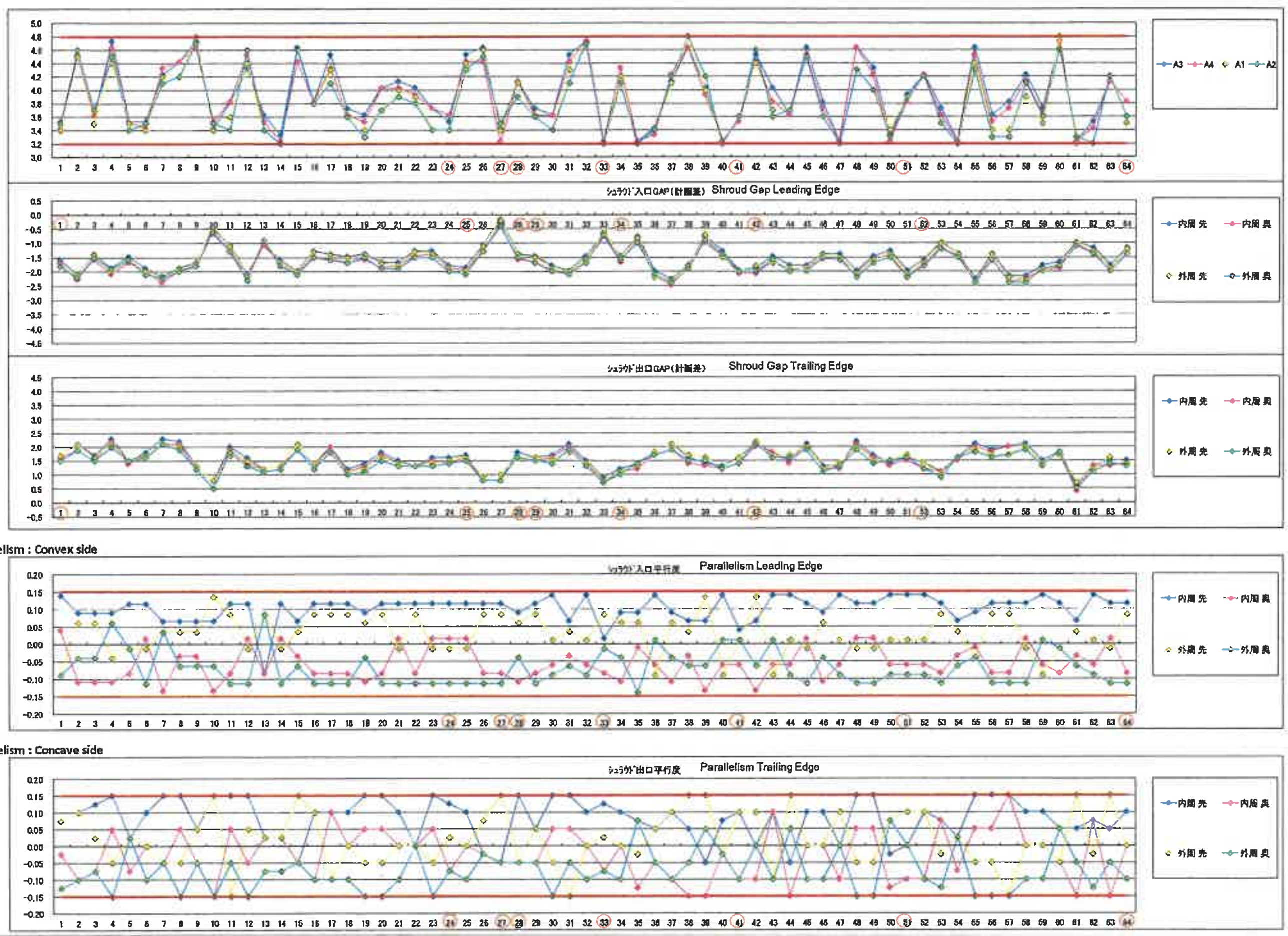
3.1) Measurement Results RH (Gen End) 2014 blades

DEF20190001BARTOW LFE5-000325

Shroud GAP ◯ : Shrouds with Damage

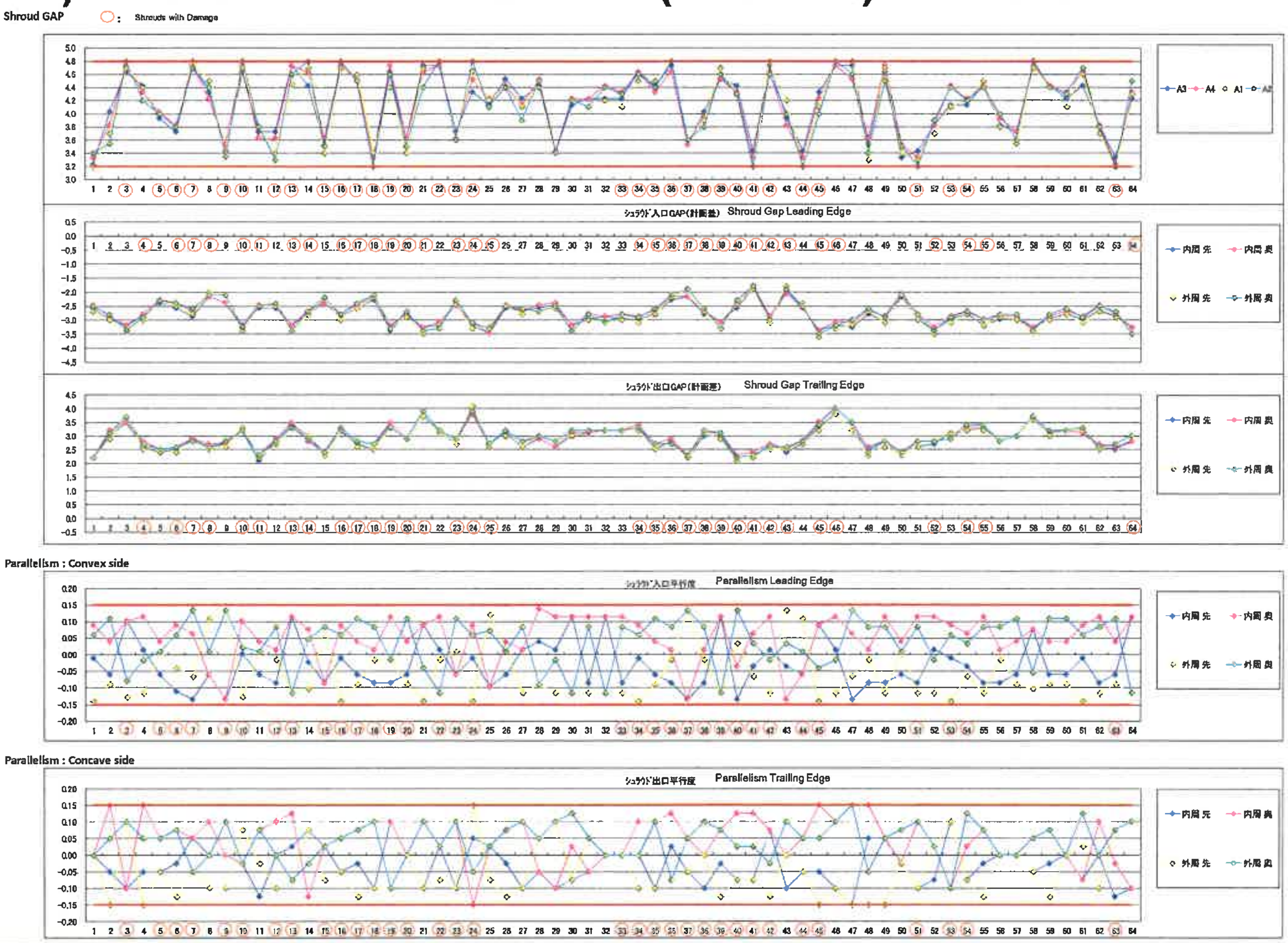
Parallelism : Convex side

Parallelism : Concave side



3.2) Measurement Results LH (Gov End) 2014 blades

Shroud GAP



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

	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