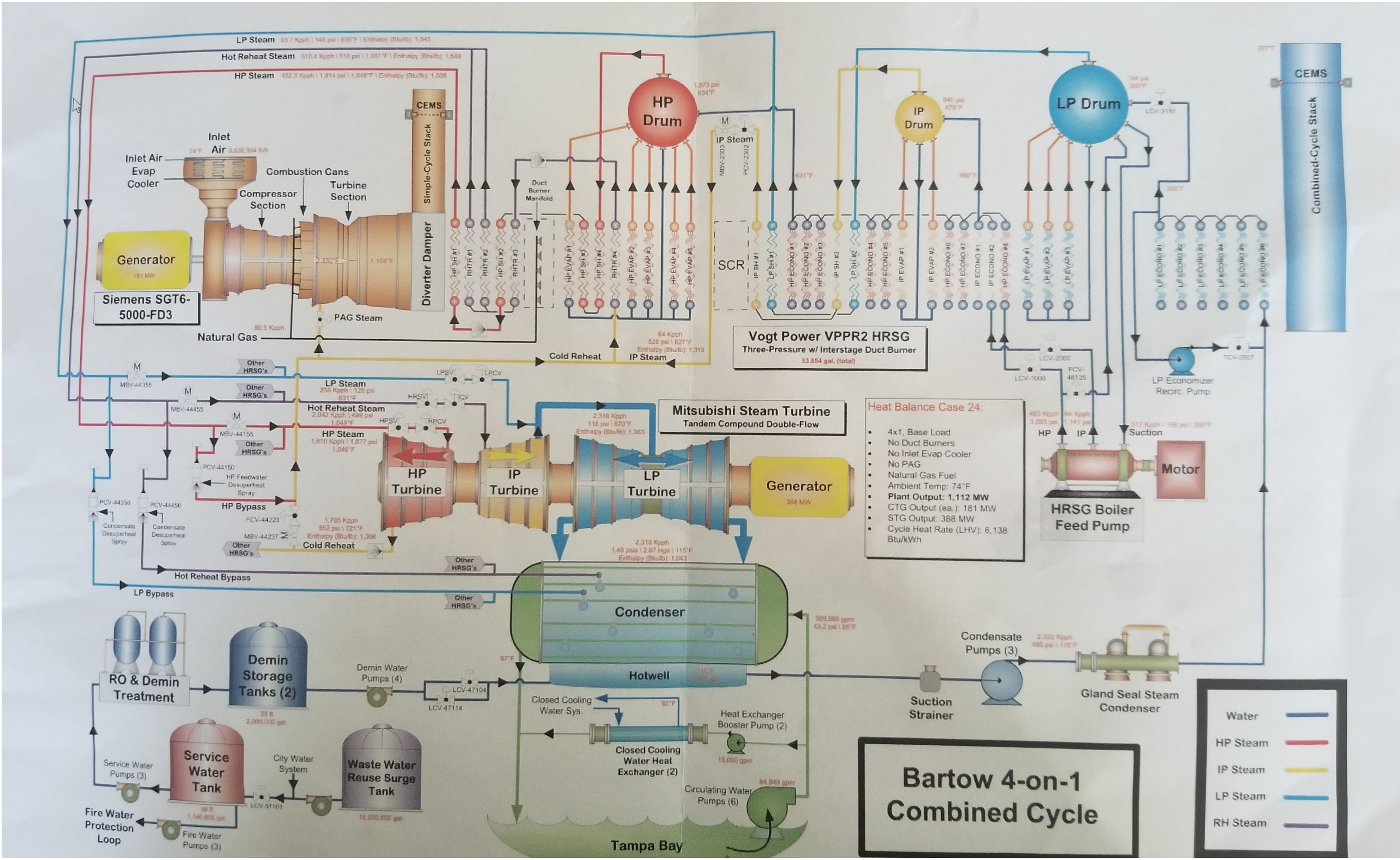
Exhibit No.	Witness	I.D. # As Filed	Exhibit Description
70	Richard A. Polich, P.E.	RAP-3	Bartow Combined Cycle Thermal Cycle. CONFIDENTIAL DN. 09202-2019, X-REF. 08773-2019
73	Richard A. Polich, P.E.	RAP-6	Bartow ST #1 LO Blade Upgrade To Achieve 450 MW, Dated September 18, 2013. CONFIDENTIAL DN. 09202-2019, X-REF. 08773-2019
74	Richard A. Polich, P.E.	RAP-7	Bartow RCA Review, Dated March 15, 2017. CONFIDENTIAL DN. 09202-2019, X-REF. 08773-2019
75	Richard A. Polich, P.E.	RAP-8	Update On 40'' Last Stage Blade, Dated 2015. CONFIDENTIAL DN. 09202-2019, X-REF. 08773-2019
80	Jeffrey Swartz	JS-2	Bartow Plant Root Cause Analysis. CONFIDENTIAL DN. 09061-2019
81	Jeffrey Swartz	JS-3	Bartow ST 40" Blade Test. CONFIDENTIAL DN. 09061-2019
82	Jeffrey Swartz	JS-4	Bartow RCA Summary. CONFIDENTIAL DN. 09061-2019



Docket No. 20190001-EI
Bartow Combined Cycle Thermal Cycle
Exhibit RAP-3
Page 1 of 1

Bartow ST#1 – L0 Blade Upgrade to Achieve 450MW

Mitsubishi Power Systems Americas, Inc.

September 18th, 2013

Agenda

MITSUBISHI POWER SYSTEMS

- Background of L-0 blades
- Analyses performed
- Root cause analysis
- Mitigation plan
- Summary
- Review of previous customer questions

Background of L-0 Blades

- Unit COD was June 2009. From the time of commissioning until Spring 2012 ST operated up to 450MW
- March 2012: five governor end L-0 blades had fretting and cracking at mid-span stub
- All governor end L-0 blades were replaced in March 2012.
- Mitsubishi estimated the cause of cracking was overloading of LP section based on 450MW which is over the design point of 420 MW.

Background of L-0 Blades

MITSUBISHI POWER SYSTEMS

- Mitsubishi recommended that the Duke ST operate at or below 420MW to ensure proper loading on the LP turbine and L-0 blades

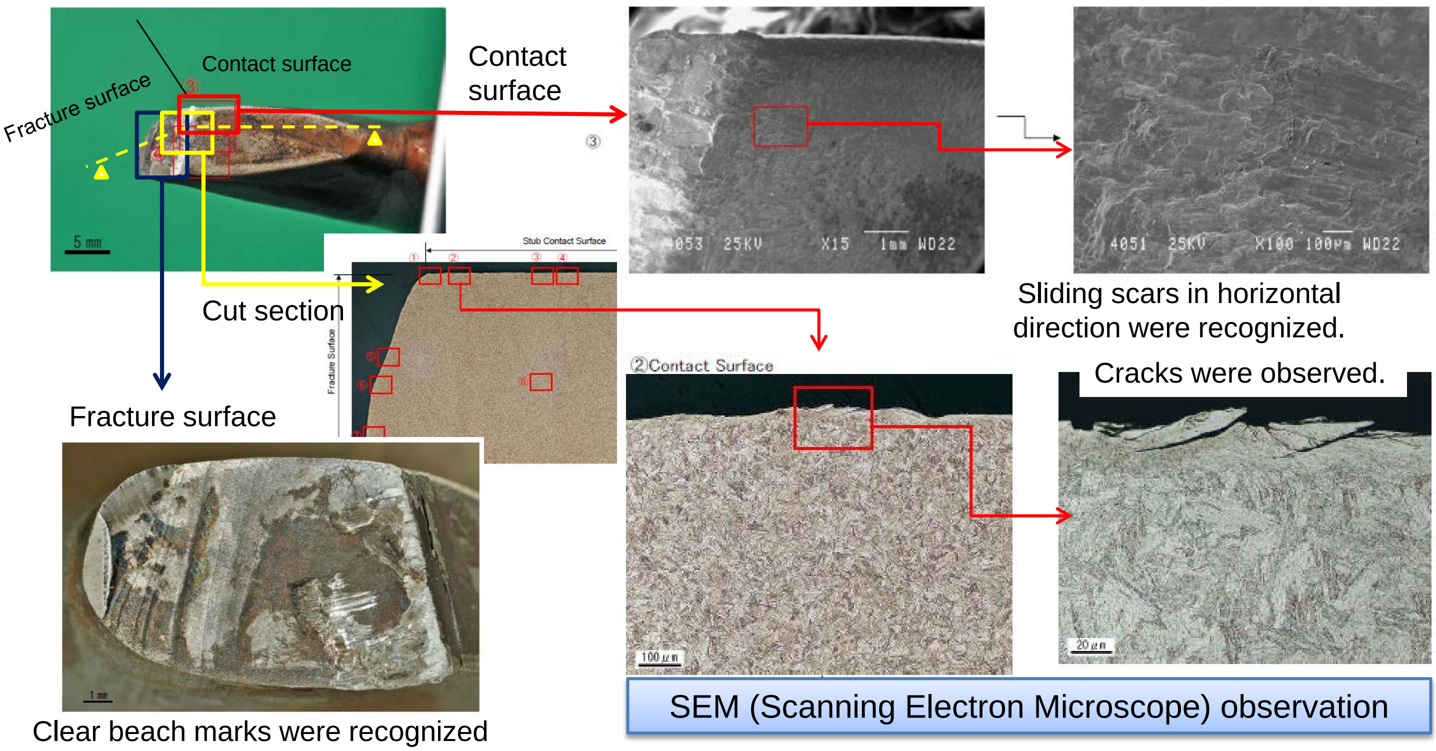
- Mitsubishi evaluated modification of L-0 blades to increase output from 420MW up to 450MW

- X-ray and mold tests were conducted by customer on the governor end L-0 blades in March 2013. Customer analysis indicates fretting wear on the contact surface of mid span stub.

Failure Blades at Site (Stub)

MITSUBISHI POWER SYSTEMS

Metallurgical Analysis



Fretting crack was generated on the contact surface. The crack was propagated by high cycle fatigue.

Analyses performed

MITSUBISHI POWER SYSTEMS

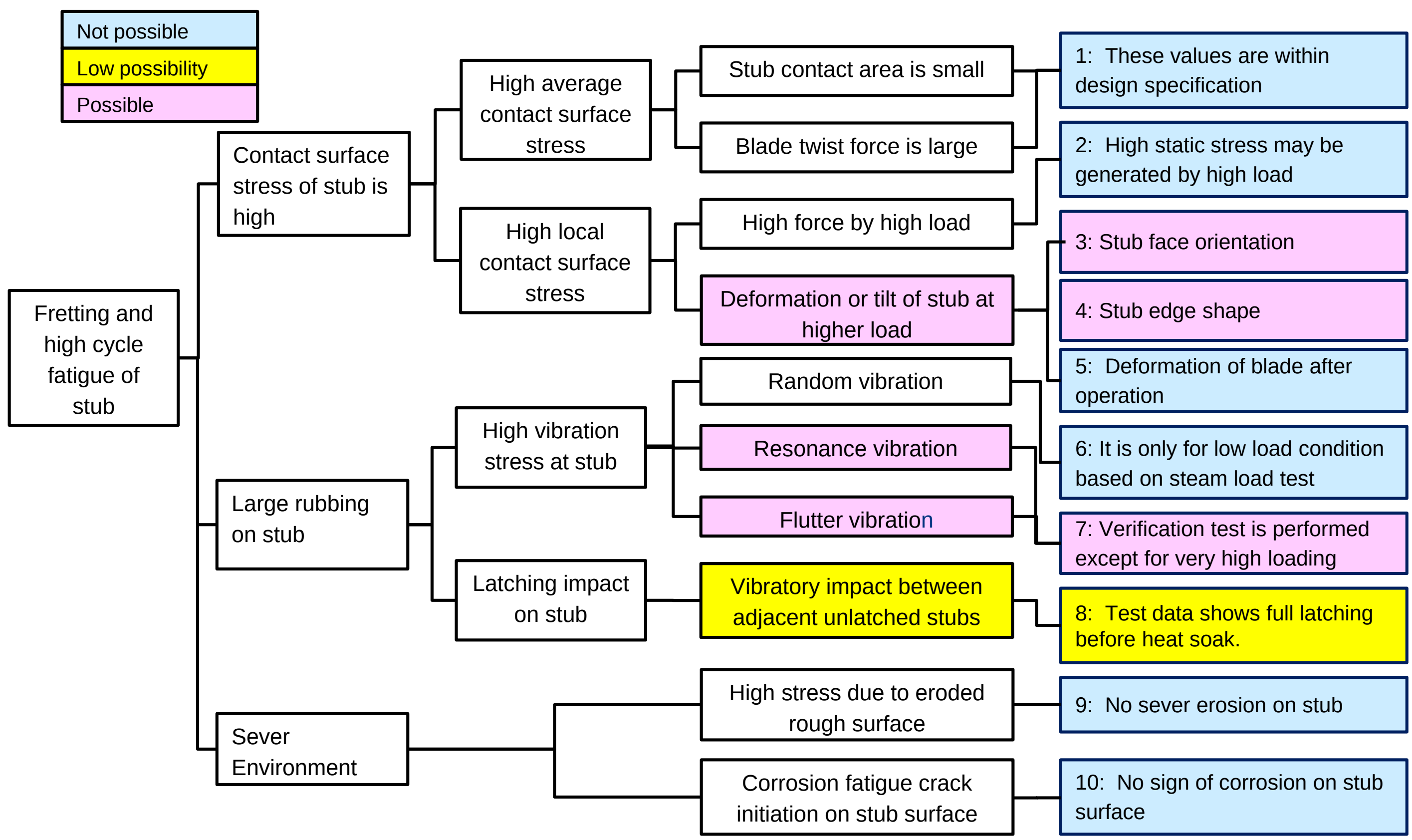
Category	Study items	Conclusion
1. Operation data analysis	Output, vacuum, vibration, steam condition data	No abnormal situation except for high loading. According to shaft vibration data, the timing of stub failue could not be estimated.
	Accumulation of operation data at each output	Total hours of 420-450MW was 2600 hours. (15%)
2. Original Manufacutring data review	Material strength	Within specification
	Blade weight	Within specification
	Natural frequency	Within specification
	Clearance control	No abnormal dimension
	Dimension control	No abnormal dimension
	Comparison with other unit	No abnoramlity
3. Blade dimension check	3D CMM for Bartow blade with design data comparison	No abnoramlity in sample blade
	3D CMM for Bartow and Another unit blade for manufacturing procedure comparison	No significant difference
4. Static stress evaluation	CFD for 450MW(17000LB/ft2/h)	Steam bending force act on the blade surface for 450MW condition was generated.
	FEA for designed dimension and Bartow blades	No abnormal stress
	FEA for influence by snubber titling	There would be high stress
	FEA for effect of shroud and snabber clearance	No significant influences on stub contact surface

Analyses performed

Category	Study items	Conclusion
5. Vibratory stress evaluation	Resonance stress for each mode with nominal, Bartow blade dimension.	No abnormal vibration stress under 17000 loading.
	Special harmonic excitation (Nozzle weak vibration)	No abnormal vibration stress under 17000 loading.
	Stability analysis for Flutter vibration	According to stress distribution of the possible vibration mode, no abnormal stresses in stub region.
6. Fretting analysis	Design blade based on fretting calculation method	No abnormal stress
	Tilting of stub	There would be high stress
7. Metallulogy analysis	#32 and #33 for SEM, micro analysis	Fretting and High cycle fatigue is estimated.
	EPMA, hardness and etc,	No corrosive envirnment no abnormal material
8. Crowning study	Stress reduction calculation	Approx. 50% reduction is expected.
	Study for shape of crowning	
9. Manufacturing study	Method of coating for actual blade	Completed
	Coating test for actual blade	Not yet
10. Coating study	Fracture limit strain test	Two test is completed with satisfactory result
	Bending fatigue strength test	Complete, Satisfactory result
	Fretting wear test	Not yet
	Fretting fatigue test	Not yet

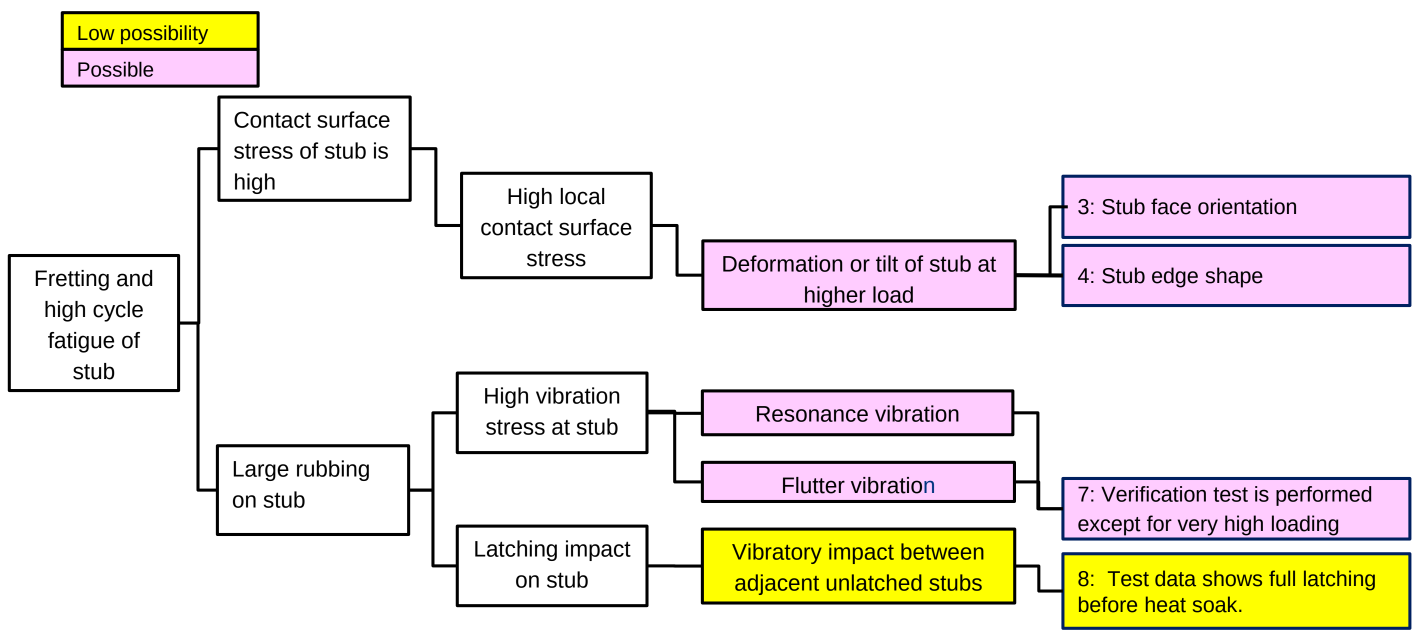
Root Cause Analysis

MITSUBISHI POWER SYSTEMS



Root Cause Analysis

MITSUBISHI POWER SYSTEMS



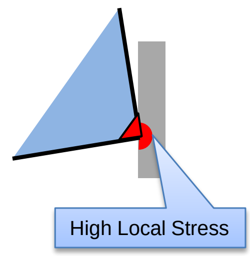
Root Cause Analysis

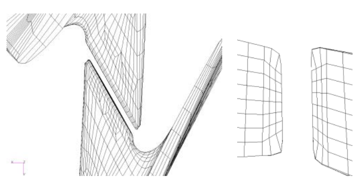
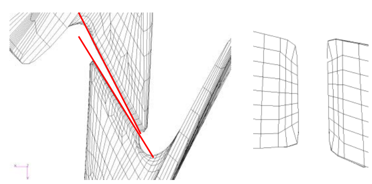
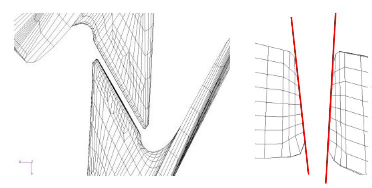
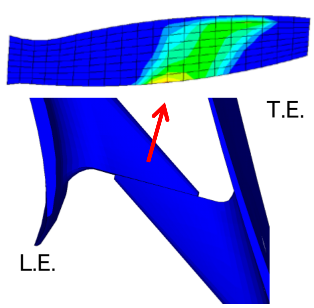
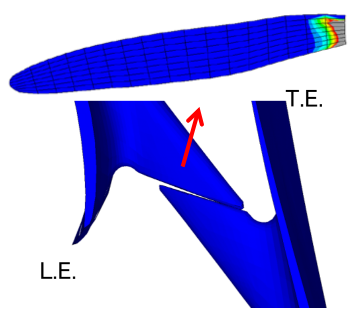
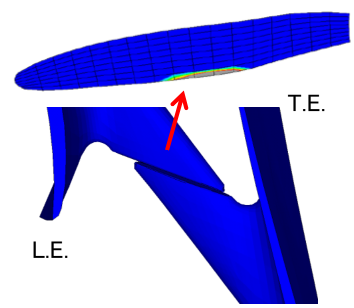
MITSUBISHI POWER SYSTEMS

Deformation or tilt of stub at higher load

- 3: Stub face orientation
- 4: Stub edge shape
- 5: Deformation of blade after operation

Local pressure increases with tilted contact surface.



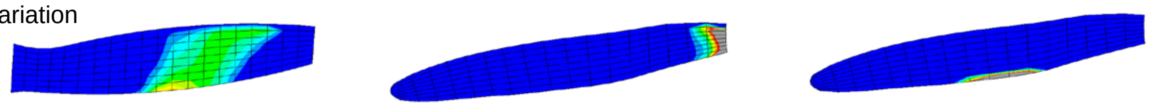
	Nominal (Design)	Tilt case-1	Tilt case-2
Analysis Model			
Contact Pressure			

Mitigation 1: Crowning

MITSUBISHI POWER SYSTEMS

- If stub surface is tilted in horizontal or vertical direction, high local stress on the stub is observed.
- Crowning is applied to the edge of stub contact to avoid the high local stress.

Contact Pressure Variation

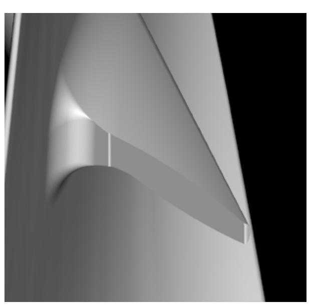


Normal Contact

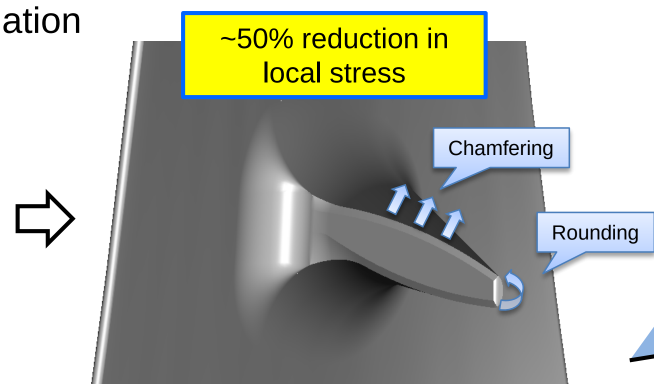
Assumed Condition (stub Tip Contact)

Assumed Condition (stub Lower Contact)

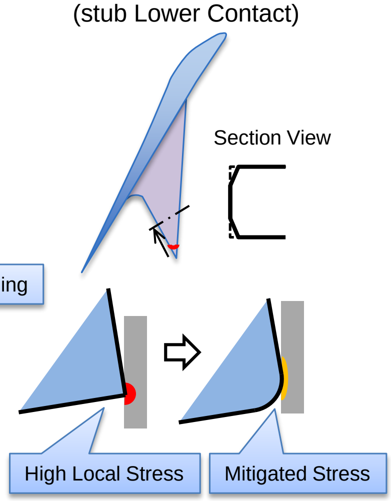
High Local Stress Mitigation



Before Crowning

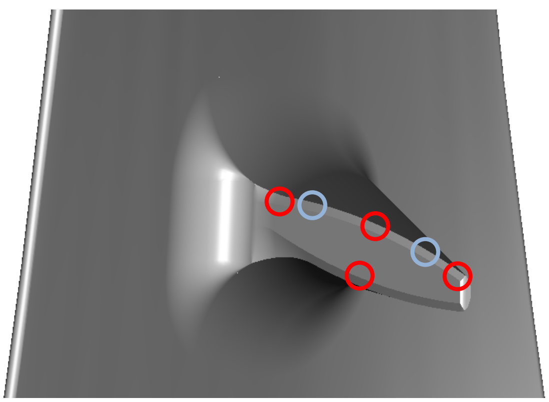


After Crowning



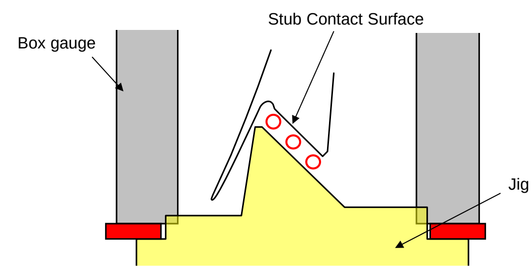
Mitigation 2: Improved Gap Control

To avoid high local stress occurrence, improved gap control will be applied to ensure contact surface parallelism.



○ : Original measurement (2 point)

○ : Improved measurement (4 point)



Dimension Diagnostics After Machining

Jig for Gap Measurement

4-point measurement will be applied to single piece and assembled row.

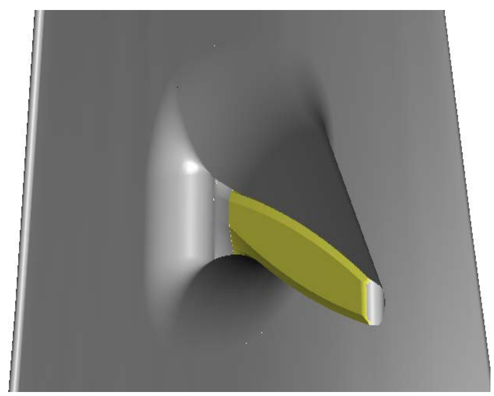
Mitigation 3: Stellite Coating

MITSUBISHI POWER SYSTEMS

- To enhance fretting durability, Stellite coating on the stub surface will be applied.
- Mitsubishi has successful experience with this coating on Titanium blade (45in).
- Verification test for 40in (17-4PH steel) will be completed by October.

Coating Specification

Base material	**Steel (17-4PH)**
Coating material	Stellite
Method	HVOF (High Velocity Oxygen Fuel)



Additional test for 17-4PH

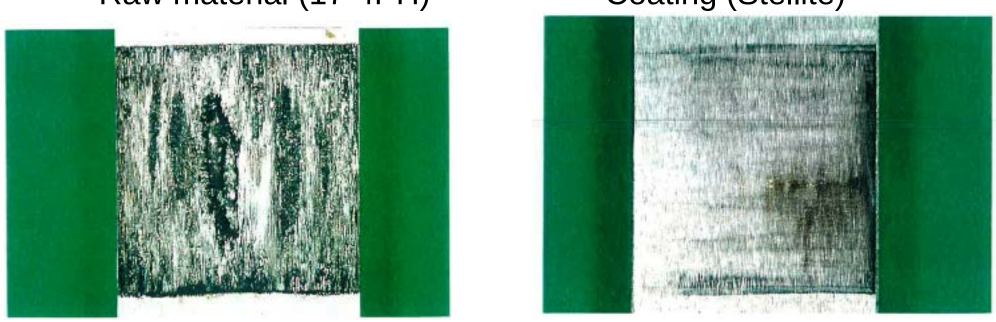
Test	Schedule
Fracture limit strain test	~ Sep. (in process)
Bending fatigue strength test	Complete
Fretting wear test	~ Oct. (in process)
Fretting fatigue test	~ Oct. (in process)
Destructive test for actual blade	~ Oct.

Mitigation 3: Stellite Coating

MITSUBISHI POWER SYSTEMS

- Wear test with large slip is conducted using coated and uncoated blade material (17-4PH).
- Wearing characteristics of coating is much better than raw material.

Raw material (17-4PH) Coating (Stellite)



6000 cycles, Pure water drop condition

Mitigation 3: Stellite Coating

MITSUBISHI POWER SYSTEMS

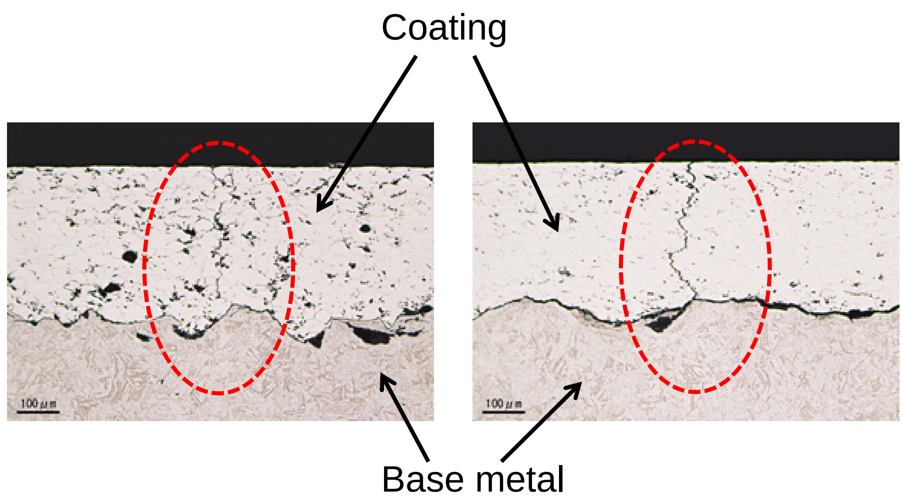
- Fretting fatigue test with micro slip representing blade vibration is conducted using coated and uncoated blade material (17-4PH).

- Fretting durability by coating is 10 times more than raw material.

Mitigation 3: Stellite Coating

MITSUBISHI POWER SYSTEMS

Bending Test Result



It is confirmed by the bending test that any crack that initiates in the coating will not propagate into base material.

Coating Experience

MITSUBISHI POWER SYSTEMS

Unit list of 45 inch ISB

	Unit Name	No. of Flow	Power (MW)	Speed(RPM)	Year in Operation
1		1		3600	Jul 2003
2		1		3600	Oct 2008
3		1		3600	Jul 2008
4		1		3600	Jun 2008
5		1		3600	Apr 2008
6		1		3600	Apr 2009
7		1		3600	Jul 2009
8		1		3600	Oct 2009
9		1		3600	Apr 2010
10		1		3600	Sep 2010

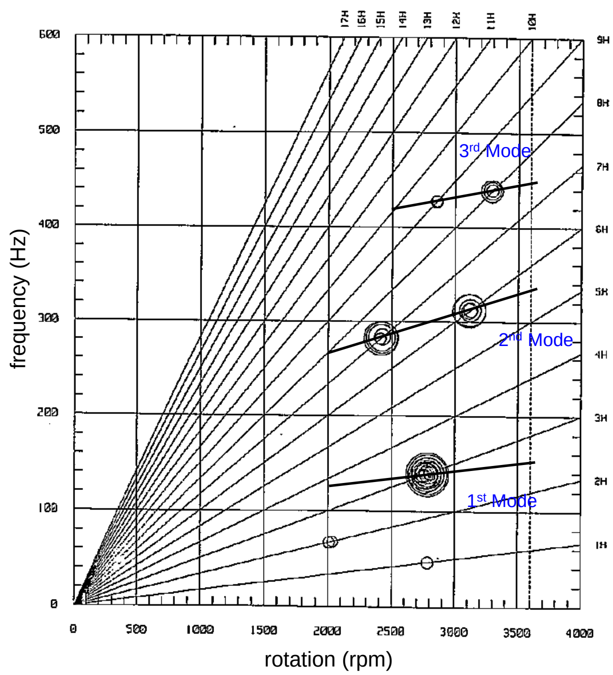
Root Cause Analysis

MITSUBISHI POWER SYSTEMS

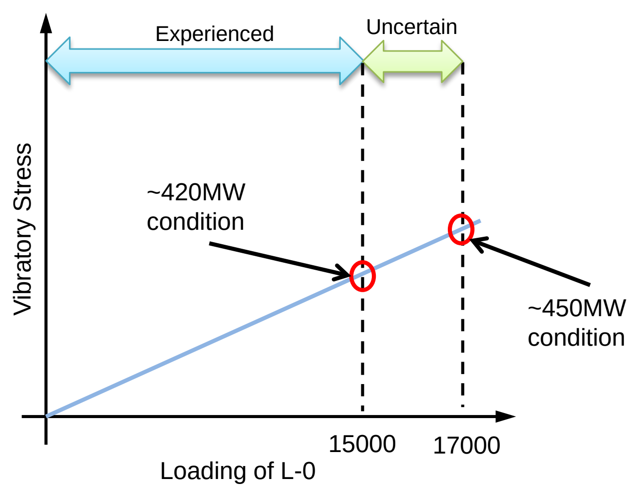
Resonance vibration

Flutter vibration

7: Verification test is performed except for high load condition



- First three modes are well tuned.
- There is no data or experience above 15000 lb/hr/ft^2



Mitigation 4: Verification Test

MITSUBISHI POWER SYSTEMS

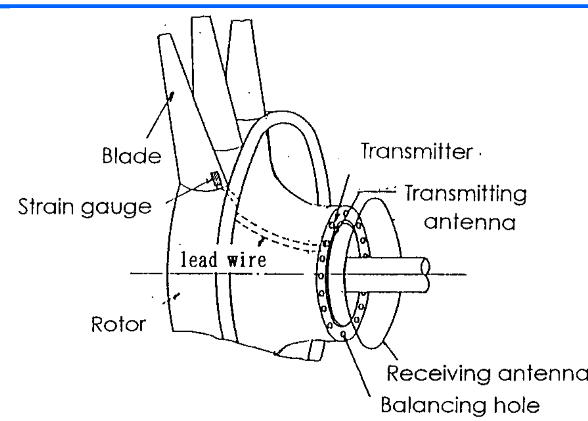
- Mitsubishi verification process requires field test above 15,000 lb/hr/ft^2.
- The reasons why this verification is necessary are following;
  - Mitsubishi's test facility does not have enough capability to test at high back end loadings.
  - Operating condition for 450MW at Bartow exceeds Mitsubishi's experience.
- Required schedule in Jan 2014 or July 2014:
  1 week for wiring on rotor
  3 days for Telemetry Test (Measurement)
  3 days for Equipment Removal
- Mitsubishi warrants the reliability of mitigation plan with verification test.

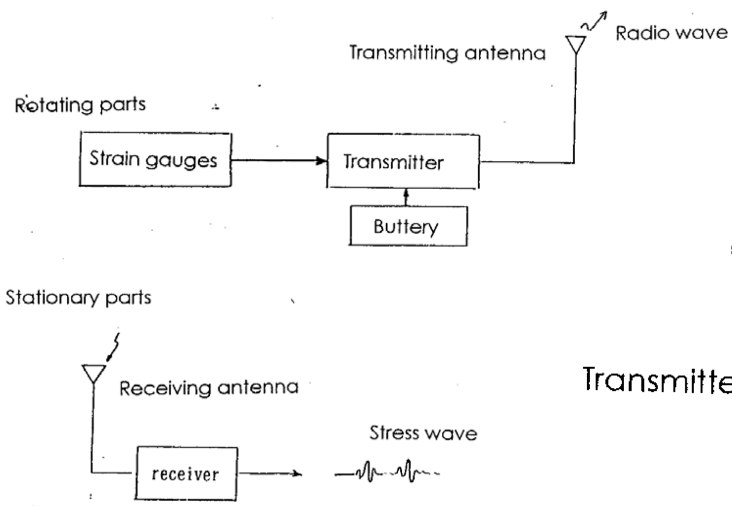
Measuring Blade Vibration

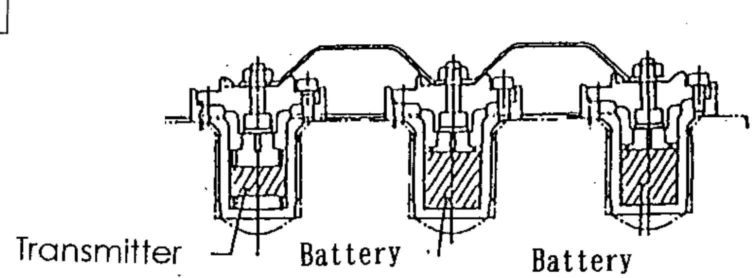
MITSUBISHI POWER SYSTEMS

- Vibratory stress of moving blades are measured by telemetry system.

- Strain gauges and transmitters are mounted on blades and rotor.







Root Cause Analysis

MITSUBISHI POWER SYSTEMS

Vibratory impact between adjacent unlatched stubs

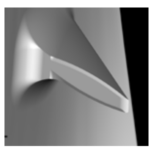
8: Test data shows full latching before heat soak.

- According to test data, stub latching is completed around 1800rpm -2000rpm.
- Vibratory impact does not occur with adjacent stubs during heat soak (2200 rpm).

Mitigation Summary

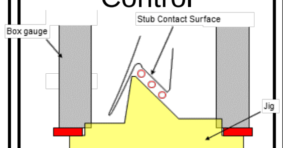
MITSUBISHI POWER SYSTEMS

Mitigation 1
Crowning



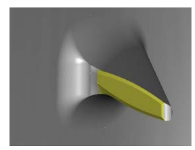
Edge of stub surface is rounded and chamfered.

Mitigation 2
Improved Gap Control



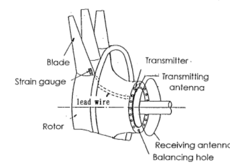
4-points measurement is performed.

Mitigation 3
Stellite coating



Stellite coating by HVOF is provided on stub surface.

Mitigation 4
Telemetry Test



Actual operation condition is measured.

- Stub Deformation and/or Tilting at higher load
- Vibratory Impact by Partial Latching
- Un-expected High Resonance Vibration
- Flutter Vibration

Mitigated High Local Stress

High Durability against Fretting

Validation

No Crack on Stub

Assuming NTP by Oct 1st 2013, this upgrade can be installed in Jan 2014.

MITSUBISHI POWER SYSTEMS

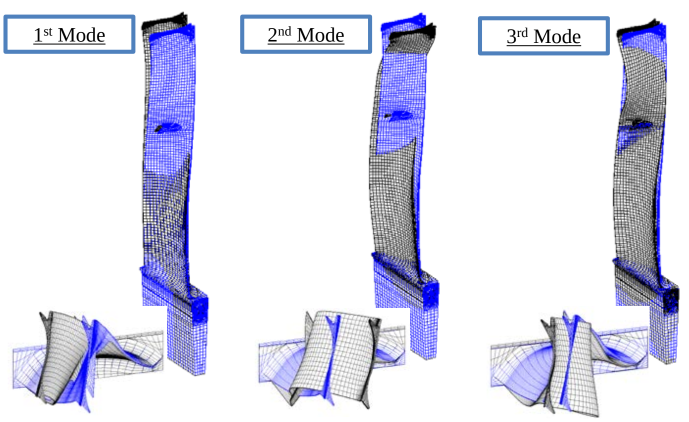
Duke Energy Questions

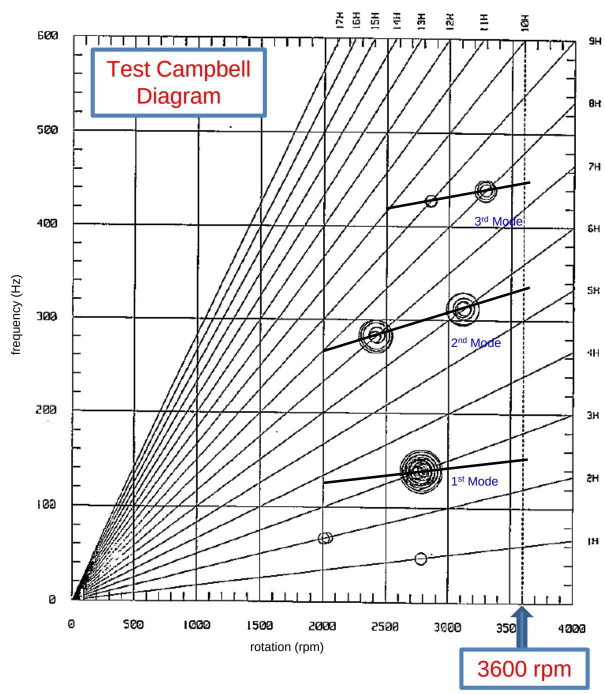
Duke Energy Questions

MITSUBISHI POWER SYSTEMS

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

At the operating speed of 3600 rpm, all the modes are detuned. Multiple vibration tests performed on the test rotor and actual rotors have confirmed this fact.





Duke Energy Questions

MITSUBISHI POWER SYSTEMS

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

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

- 40"L0 blade was tested at ~10,000 lb/hr/ft^2 last blade loading in test turbine located in Takasago factory in Japan. CFD/ FE Analysis were performed at 10,000 lb/hr/ft^2 loading.
- Comparison of test results and CFD/FEA predictions showed good correlation between the two.

Duke Energy Additional Questions

MITSUBISHI POWER SYSTEMS

Question from email from Mark Mattina email 8/24/2012

1. MPSA was to answer if newly procured blades were compliant with the MHI paper on Fretting - "Analysis of Fretting Fatigue Strength of Integral Shroud Blade for Steam Turbine (Yasutomo Kaneko et, al. October 2007).

Yes, the new blades are compliant with the methodology.
This process was developed during the design phase of 40" L0 blade but was published at a later date.

Duke Energy Additional Questions

MITSUBISHI POWER SYSTEMS

4. MPSA will review the MHI manufacture sequences with PEF as far as grinding/shot peening and furnace brazing sequences effecting dimensional tolerances.

Grinding , shot peening, Stellite shield brazing and distortion correction is performed before final gap measurement at the shroud and mid span stub . CMM on final blades is performed after gap measurement.

See next slide for manufacturing process steps sequence.

MHPS

Bartow RCA Review

3-15-17

Purpose of Meeting :

1. Demonstrate that the Period 3 Blade Failure Root Cause is not impacted by ongoing investigation into blending.

2. Show that geometry variation and design stress margin have been investigated as part of the RCA, and are not considered the root cause.

3. Address open question associated with Bartow.

MHPS RCA Conclusions

Time	Blade	Root Cause	Comments
Period 1	Type 1	Stub fretting fatigue. Operation above design limit.	Impact of bypass operation not yet understood.
Period 2	Type 1		No RCA – Shroud chipping observed
Period 3	Type 3 Blade with midspan HVOF	Shroud heavy wear. Operation in the avoidance zone.	Conclusion based on Telemetry Test results and communication of operation limits after the test. May be additional impact from bypass operation.
Period 4	Type 3 Blade with midspan and shroudr HVOF	RCA Incomplete Additional operating data required	Short term operation in avoidance zone Evaluation of bypass stimulus requires further review HVOF has potential of impacting blade damping
Period 5	Type 1 Blade	RCA Incomplete Additional operating data required Metallurgical analysis required	No operation in avoidance zone. Major water hammer event identified 3.75hrs prior to blade damage with 560g's measured on bypass piping

Note : Full operating data set is not available over 7.5 yrs.

- Bypass exhaust pipe accelerometers only available from Sept 2015
- Telemetry test data only available 12/21/14 to 12/24/14
- 100 days of operating data not captures in Pi due to data security concerns
- Data filtering limits resolution. eg. Additional 4 exhaust pressure probes were sampling on the order of hours.

Agenda

1. 40” L-0 Fleet Operating Experience
2. RCA Overview
3. Results of Metallurgical Evaluation
4. Stress Response and Damage Mechanism identified in Telemetry Test
5. Blade response during GT Blends
6. Manufacturing and Assembly Variation Review
7. Actions

Reference Information

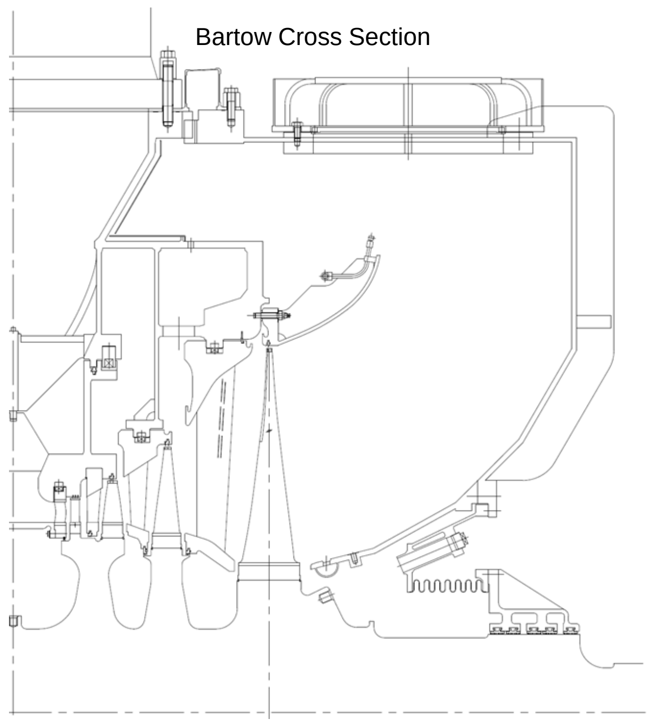
Period	Operating Time	Blade Type in Operation
Period 1	2009 - 2012	Type 1
Period 2	2012-2014	Type 1
Period 3	Dec 2014 to April 2016	HVOF Midspan Type3
Period 4	Jun 2016 to Oct 2016	HVOF Midspan + Shroud Type 3
Period 5	Dec 2016 to Feb 2017	Type 1

Blade Type	Blade Description
Type 1 Blade	Original Design
Type 3 Blade	Type 1* + Stellite Weld Inlay under shroud to prevent erosion.
Type 4 Blade	Type 1* + Stellite Shield under shroud to prevent erosion
* Chamfer added to Shroud and Radius added to Midspan	

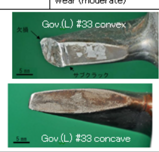
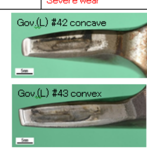
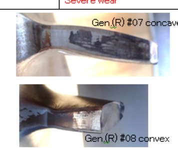
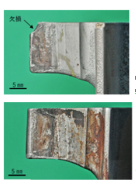
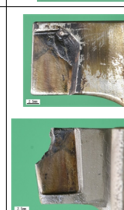
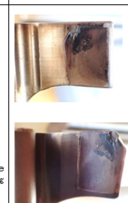
Reference Presentations

- Sept 18th, 2013 - Period 1 RC/CA
- March 18th 2015 – Results of telemetry test
- Nov 9th 2016 – Period 3 RCA results of period
- Nov17th 2016 – Responses to Period 3 RCA questions

Bartow Cross Section



Reference - Bartow Blade Operating Summary

Period	I (2009/6－2012/3)		II (2012/4－2014/8)		III (2014/12－2016/4)		IV (2016/5－2016/10)		V (2016/12－2017/2)	
Duration	Approx. 34 months		Approx. 28 months		Approx. 17 months		Approx. 5 months		Approx. 2 months	
Blades	Type 1		Type 1		Type 3 with Modified HVOF		Type 3 with Modified HVOF		Type 1	
	No HVOF		No HVOF		HVOF only stub		HVOF both stub and shroud		No HVOF	
Operation	450 MW at the maximum		Limited below 420 MW		Introduced the Avoidance Zone		←		Limited below 420 MW	
Damage	Stub	Broken(6/LH)	Stub	No Broken	Stub	No Broken	Stub	Broken (1/RH)	Stub	Broken (13/RH)
	Shroud	Chipping(5/LH), Wear (moderate)	Shroud	Chipping (3/ LH, 12/ RH) (Wear is obscure.)	Shroud	Chipping (33/LH, 7/RH) Severe wear	Shroud	Broken (1/RH)	Shroud	Chipping (1/RH) Severe wear
							Trailing edge	Broken (1/LH, 2/RH)		
Stub contact surface			–							
Shroud contact surface	 Gov.(L) #33 convex Gov.(L) #32 concave				 Gov.(L) #42 concave Gov.(L) #43 convex		 Gen.(R) #38 convex Gov.(L) #03 concave (pair of the blade broken in trailing edge)		 Gen.(R) #07 concave Gen.(R) #08 convex	
Blade trailing edge	–		–		–				–	
Comments	Trace of contact in stub is not so hard in comparison with the Period V. Shroud wear is relatively moderate in comparison with the Period III and V.		Loading was limited and stub failure did not occur, but number of chipped shrouds increased.		Severe wear of shroud occurred from the Period III. Depth of wear was 0.5-0.9mm.		Wear of shroud suppressed by HVOF, but failure of blade profile had occurred.		Trace of contact in stub is relatively hard in comparison with the Period I. Wear of shroud increases in comparison with the Period I even the state of contact surfaces are same with the period I and II.	

⇨ Shroud wear is obvious after the Period III. Blade vibration might increase.

40” L-0 Fleet Operating Experience

- 55 Rows in Global Fleet
- 25 Rows in US Fleet

- No units except Bartow with midspan snubber damage
- Minor shroud chipping observed with no corrective action required

- Bartow has not observed any excessive shroud erosion

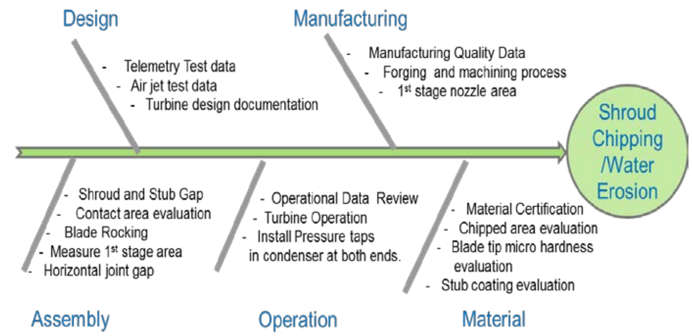
Note :– Citrus County applies a redesigned blade developed in 2015

US 40in Fleet

-	Unit Start Date	Unit Name	# Flows	Type	Fuel
TGO Fleets	Jul-03	Unit A	Single	3	CC
	Aug-03	Unit B	Single	3	CC
	Sep-03	Unit C	Single	1	CC
	Apr-03	Unit D	Double	3	CC
	Jun-03	Unit E	Double	3	CC
	Jul-03	Unit F	Double	3	CC
	Jul-03	Unit G	Double	3	CC
	Jun-09	Bartow	Double	3	CC
NGA Fleets	Dec-01	Unit H	Single	3	CC
	May-01	Unit I	Single	3	CC
	Feb-06	Unit J	Double	1	Coal
	Jul-06	Unit K	Double	3	Coal
	Sep-09	Unit L	Double	3	Coal
	Jun-08	Unit M	Double	1	CC
	Jun-11	Unit N	Double	3	Coal

Current design for existing fleet is Type 4

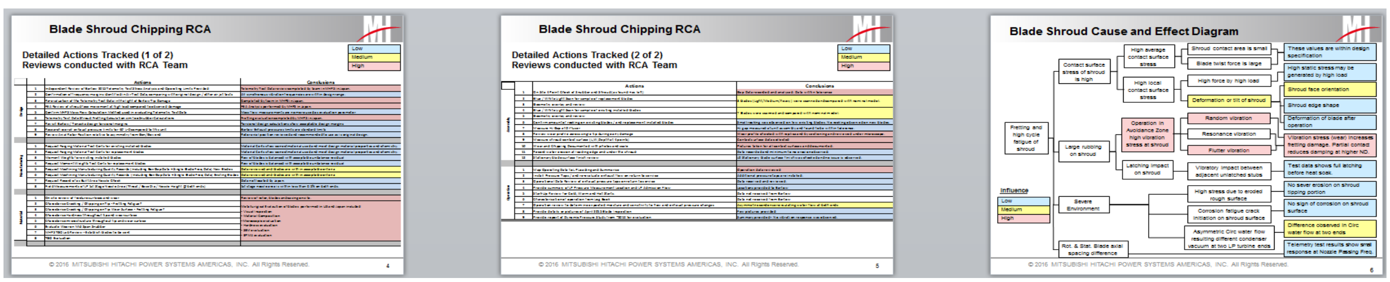
Period 3 - Blade Shroud Chipping RCA



1 Open Actions from RCA :

- Characterization of operation from log book

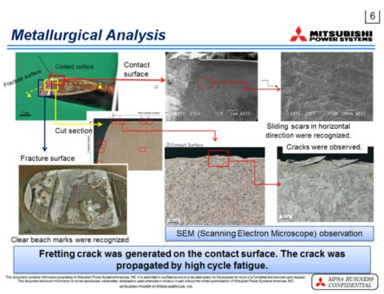
Recent operational findings on the bypass operation do not impact the root cause finding, but do impact the corrective action.



RCA working session May to June 2016. RCA presented Nov 9th, 2016

Results of Metallurgical Evaluations

Period 1 Snubber Fretting Fatigue
Presented 9/18/13

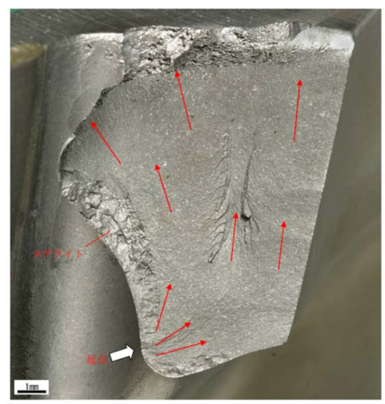


Period 3 Shroud Heavy Wear
Presented 5/26/16 and 11/9/16

Period 4 HCF Initiation and propagation

Vane Trailing Edge – HCF Initiation

Shroud– HCF Initiation



Period 5 Blades not yet received for evaluation. Visual inspection matches period 1 investigation.

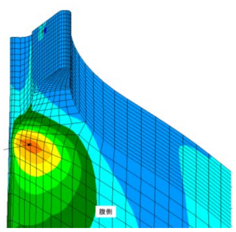
Is the damage consistent with the stress analysis? - Yes

Magnitude of blade response (High to Low)
All stresses are within design criteria and experience within operating design space.

1. Snubber Fretting
   (Protected with HVOF during Period 3 and 4)
2. Shroud Fretting
   (Protected with HVOF during Period 4)
3. Vane High Cycle Fatigue

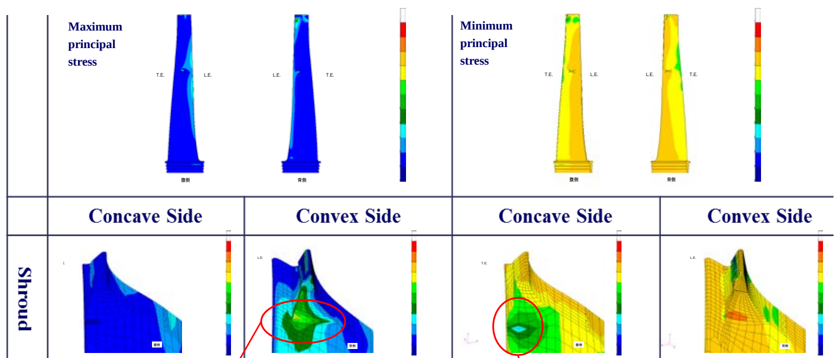
Vane Static Stress

Mitsubishi Original Design

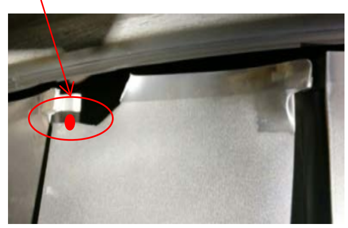


Steady State stress at trailing edge

1st Mode Stress Distribution



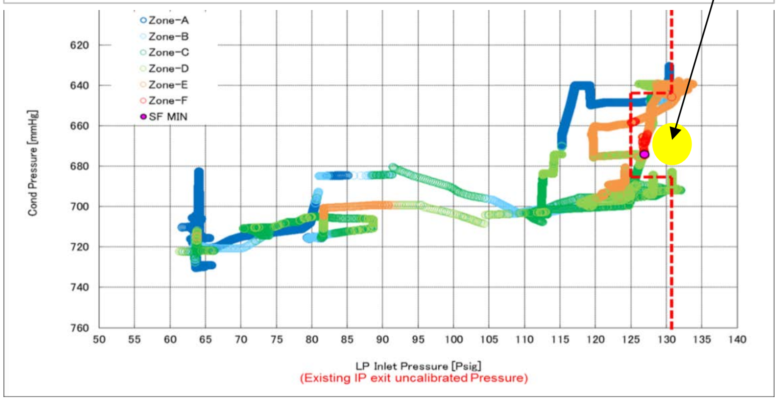
Period 4 Damage



Damage Mechanism

Blade Response – Design Margin
Example : Shroud Fretting Fatigue

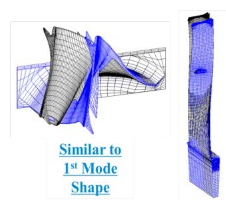
Unable to test due to excessive blade response



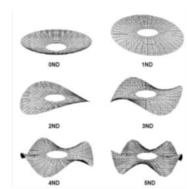
- **Blade response is evaluated through the integration of the stress response all the modes between 180Hz to 120Hz**

Snubber fretting fatigue, shroud fretting fatigue and Vane High Cycle Fatigue are all calculated from the telemetry test with avoidance zone established to address all 3 cases.

Blade response is observed 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-220Hz).

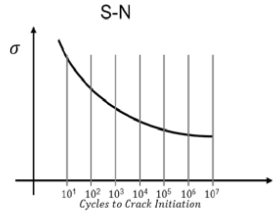


Similar to 1st Mode Shape

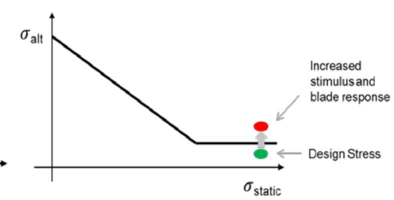


Nodal Diameters

S-N



Modified Goodman Diagram



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

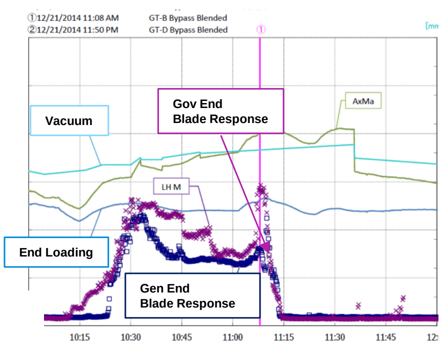
Evaluation of GT blends during 2014 telemetry test

- During the 2014 telemetry test 2 GT blends were recorded.
- The GT blends produced a 2x response in blade stress.

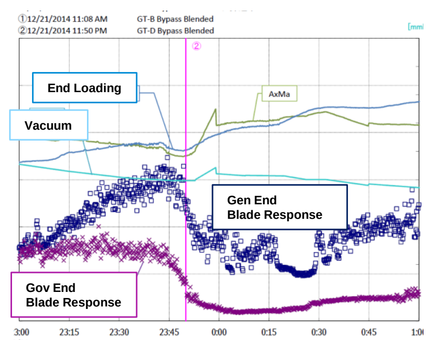
Further investigation :

- Create complete data set of available IP Bypass exhaust temps, pressures and vibration
- Characterize 'severity of blends
- CFD of condenser / exhaust flows
- Model blade response from blend stimulus
- Validate model with Telemetry Test data

Blend in "B"



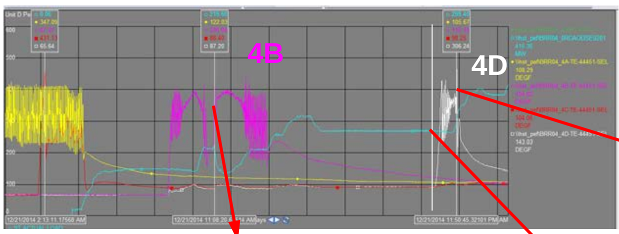
Blend in "D"

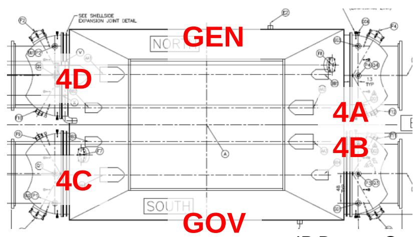


Further investigation is required to understand the impact of GT blends on blade loading

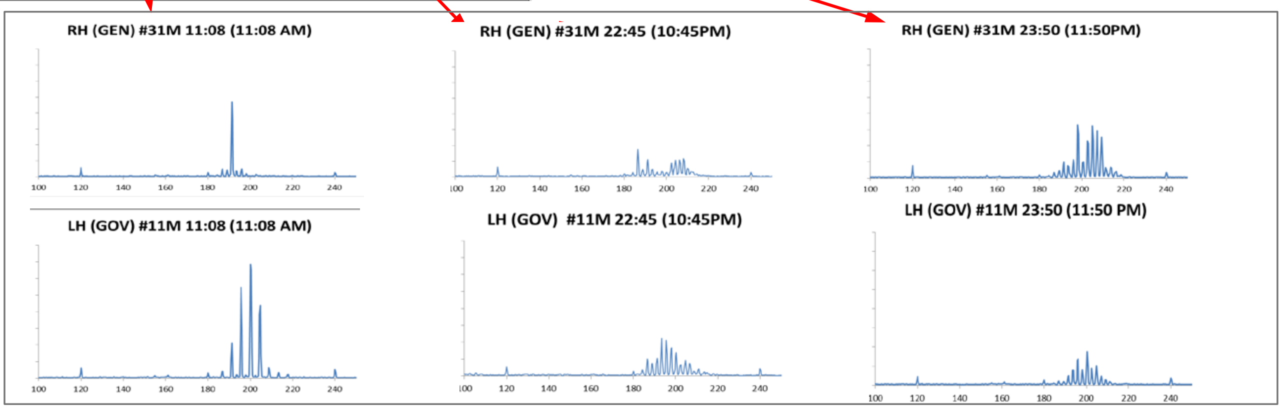
Note : Operating Data required. 874 Blend events have identified by Duke's hand evaluation.

Telemetry Test Spectrum at GT Blending





IP Bypass Configuration



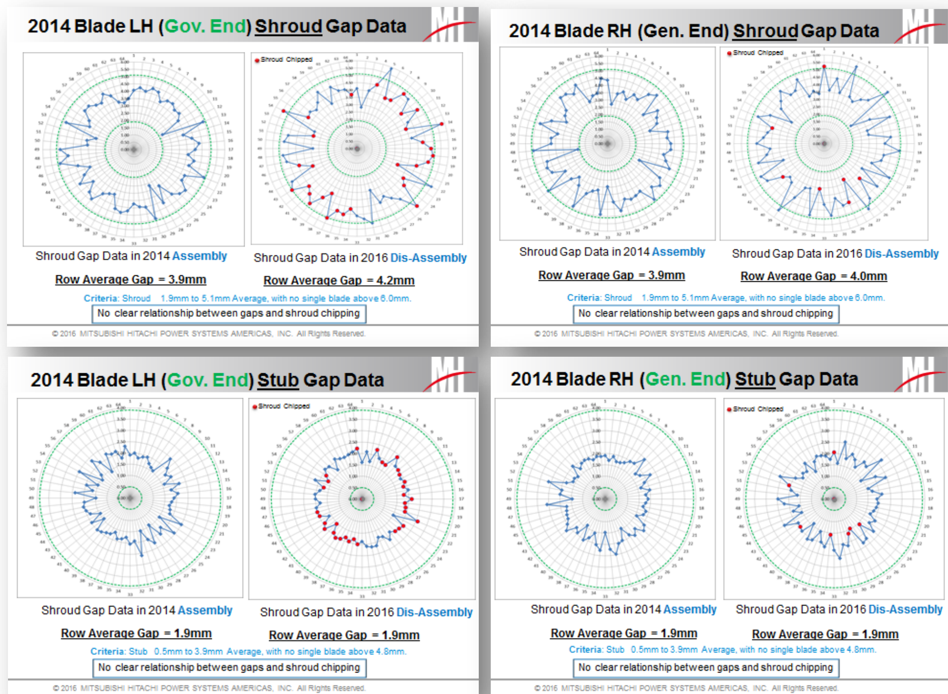
Blade response during bypass operation is also Non-synchronous 16 Nodal Diameter response around 200 Hz

Shroud and Midspan Gap Data Evaluation

- **Manufacturing / Assembly variation is consistent with the rest of the fleet.**
- **4 point checks have been used to minimize variation.**
- **Avoidance zone was evaluated using scanned blade geometry from period 1,2 and 3.**

Evaluation conducted of :

- Manufacturing Box Gauge Checks
  - Vane
  - Midspan
  - Shroud
- Assembly 4 Point Clearance Checks
  - Midspan
  - Shroud
- Correlation to damaged blades has not been identified.
- Evaluation completed for Periods 3,4,& 5.



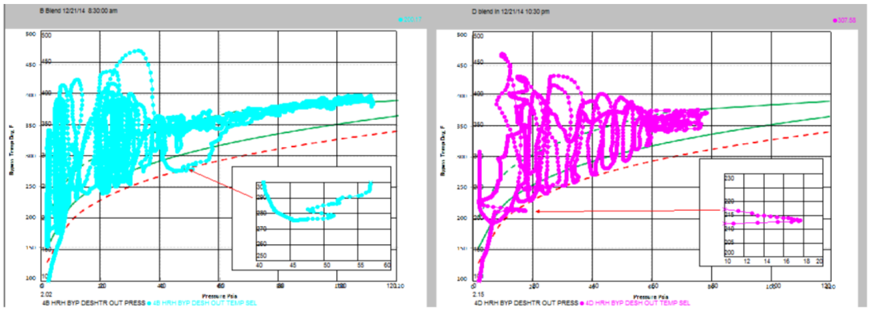
Actions

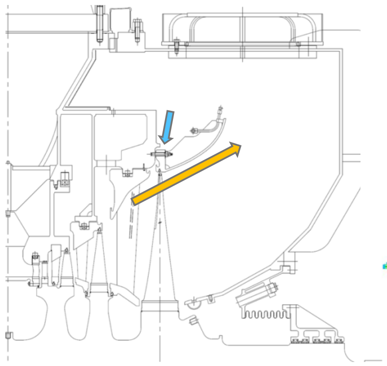
1) Investigation of bypass operation.

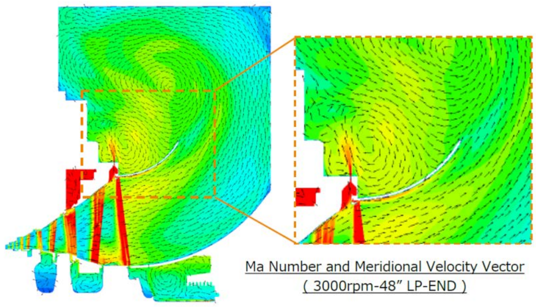
- Determination of acceptable level of temperature and pressure variation during blending. Awaiting operating data.
- Analysis of blade response to bypass blending events.
- Investigation of bypass valve and attemperation operation.

2) Aspiration

- Duke have requested evaluation of reverse flow through drain slots due to dynamic head pressure reduction from steam flow.
- Evaluation is in progress, but there is currently no analysis presented to support this is an issue. This is a standard design feature in the MHPS Fleet







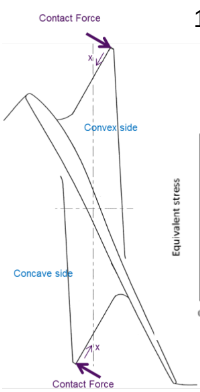
Ma Number and Meridional Velocity Vector
(3000rpm-48" LP-END)

Backup - Snubber Orientation – Evaluation of Tip Loading

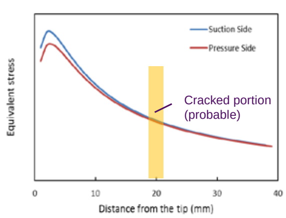
Failed stub #54 Blade.
Crack initiated at close the mid span of contact surface.

Duke raised concern that the crack initiation may be from bending stresses induced from tip contacting on the mid span snubber. Analysis was conducted to confirm that snubber cracking did not occur at the location of maximum bending stress associated with tip loading.

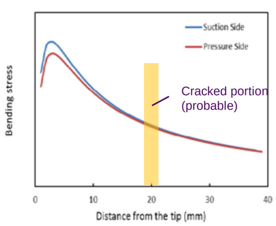
Fretting Fatigue Crack Initiation is to be confirmed through SEM review of fracture surfaces.



1. FEA Analysis does not show crack initiation does not match the peak bending stress location



Equivalent stress



Bending stress

2. Visual Inspection does not support that the blade was point loaded

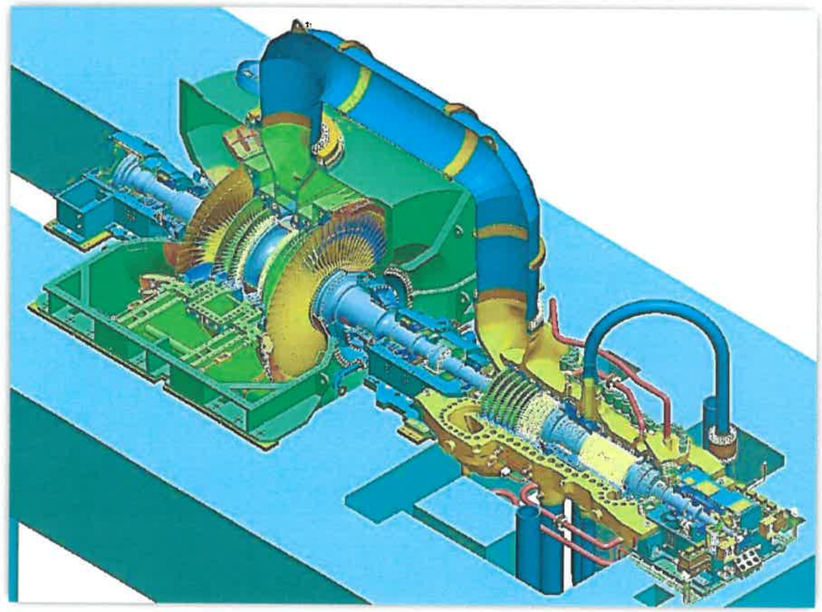
#53 Blade
Concave side

#54 Blade
Convex side

Location shown in contact prior to cracking

Update on 40" Last Stage Blade

Muhammad Riaz
Manager Steam Turbine Engineering



MITSUBISHI HITACHI POWER SYSTEMS
Mitsubishi Hitachi Power Systems Americas, Inc.

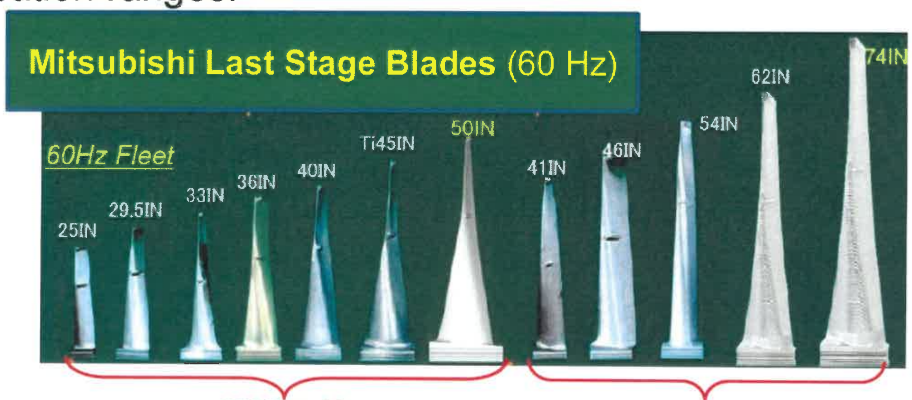
Docket No. 20190001-EI
Update on 40" Last Stage Blade, Dated 2015
Exhibit RAP-8
Page 1 of 12

Agenda

- Steam Turbine Last Stage Blades
- 40" L0 Blade Erosion
- 40" L0 Blade Shroud Chipping
- 40" L0 Mid Span Stub - update
- Vann unit Issue

Steam Turbine Last Stage Blades (L0 Blades)

- Last stage blades are one of the most important and complex part of the Steam Turbine that produces more than 10% of the total turbine output.
- Longer last stage blades are designed to enhance overall turbine efficiency and reduce cost.
- Mitsubishi being a world leader in Steam Turbines, has one of the largest collection of last stage blade designs for various application ranges.



MITSUBISHI HITACHI POWER SYSTEMS
Mitsubishi Hitachi Power Systems Americas, Inc.

Type of 40" L0 Blades

- Original Blades – **Type 1**

These are the blades with no Stellite material welded on the shrouds.

- Refurbished blades – **Type 2**

These are restored eroded blade with Stellite material welded on shrouds.

- Current offering blades – **Type 3**

These are new blades with Stellite material welded on the shroud

Stellite Shield on leading edge is standard on all 40" L0 blades

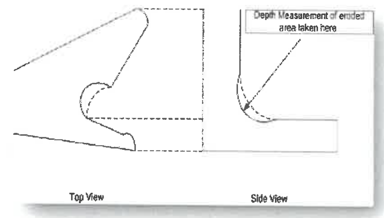
As an action from last year's Users Meeting, every plant should have received the information on the type of blade present in their turbine.

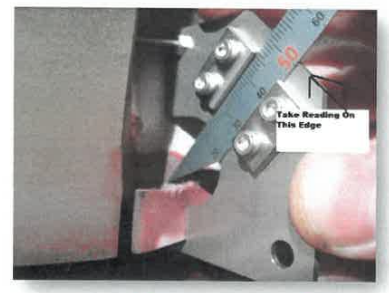
Overview of the Blade Erosion

- Erosion is a common issue for all last stage blades but a few units with 40" LSBs have observed higher erosion compared to other units.
- Many factors contribute to blade erosion such as material hardness, distance between stationary and rotating blades, moisture content in steam etc.
- Increased erosion rates can lead to material removal on the leading edge of the blade including erosion shield and shroud.
- Few units have observed shroud damage due to high erosion observed under the shroud on leading edge side.

Update on Erosion Experience

- MHPSA is working actively with individual customers to monitor erosion issue.
- New blades with Stellite material welded to the shrouds (Type 3) have been provided to customer with higher erosion rates.
- On units with higher erosion, an annual visual/ erosion depth measurement is recommended to observe erosion progression rate.
- Due to diversity in operating conditions and type of operation, it is not possible to provide one standard set of operation guidelines.
- As 40" L0 blade erosion is not a fleet wide issue, hence a MSTB for 40" L0 blade has not been issued.

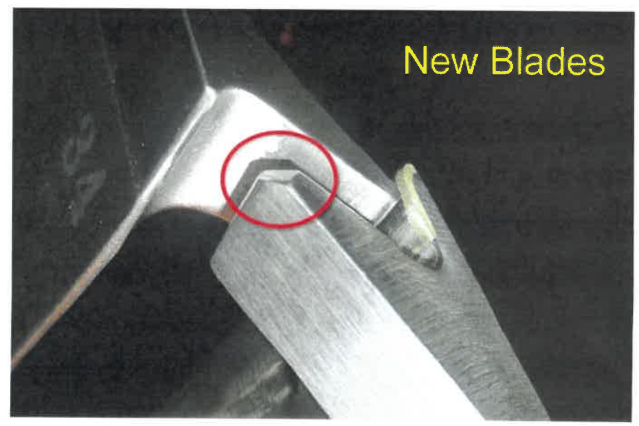




Erosion Measurement Tool

Update on Tip Chipping Experience

- On few of the units, blade shroud leading edge chipping have been observed.
- Evaluation of chipping shows no impact on structural integrity or performance of the blade.
- As a countermeasure, a chamfer is applied to reduce stress concentration caused by blade twist and contact pressure.
- This has only been applied on one unit after chipping was observed.



MITSUBISHI HITACHI POWER SYSTEMS
Mitsubishi Hitachi Power Systems Americas, Inc.

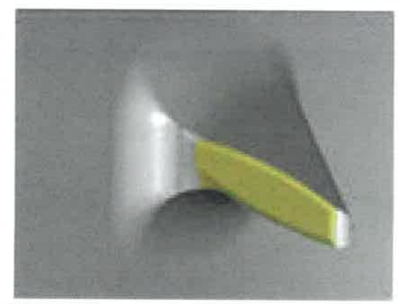
Docket No. 20190001-EI
Update on 40" Last Stage Blade, Dated 2015
Exhibit RAP-8
Page 7 of 12

Disc Two 000312

40” L0 Blade Mid Span Issue - Update

- In last year MSTUG meeting, we informed about mid-span damage on one unit.
- The cause of the damage was concluded as overloading the unit. The unit was designed for 420MW but it was operated at 450MW.
- The loading on the last stage blade for 450MW operation was well outside the Mitsubishi experience range.
- Enhanced blade with special coating at the mid span along with improved stub geometry provided to customer for high loading operation.

Damaged Stub

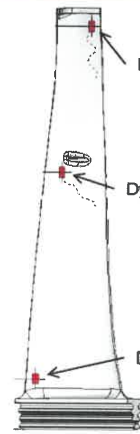


Coating at Stub

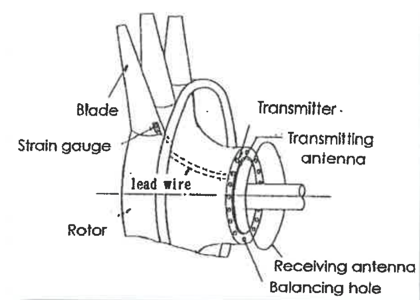
MITSUBISHI HITACHI POWER SYSTEMS
Mitsubishi Hitachi Power Systems Americas, Inc.

40" L0 Blade Mid Span Issue - Update

- To study blade response at high loading operating conditions, strain gages were applied on the blades.
- Strain gage locations were identified based on 3D finite element analysis of blades to predict blade vibration mode shapes.
- The signal from rotating blades was transmitted using telemetry system.
- A test space was established by changing turbine output and condenser pressure.
- A successful test was completed with the close collaboration of turbine operations team and Mitsubishi test team.



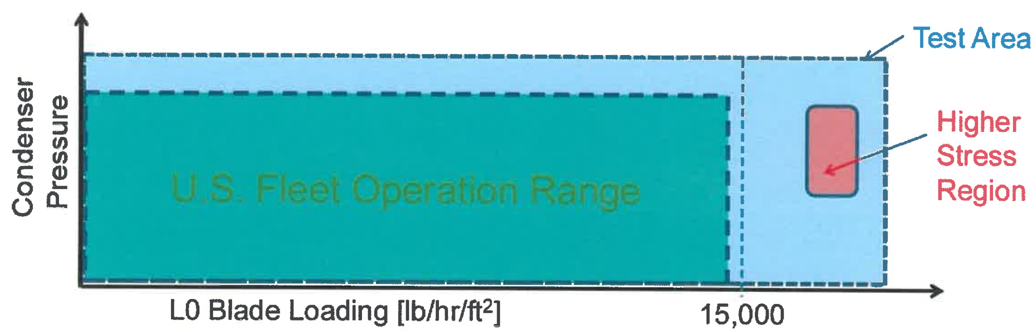
Telemetry Test



MITSUBISHI HITACHI POWER SYSTEMS
Mitsubishi Hitachi Power Systems Americas, Inc.

40" L0 Blade Mid Span Issue - Update

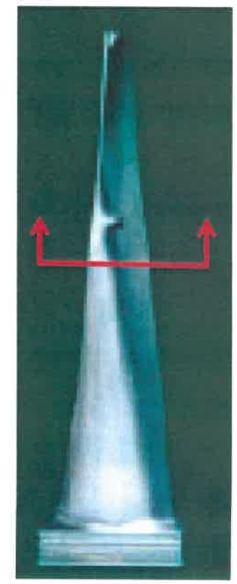
- Blade response data was collected at low load and high load zones to study entire operation space of the 40" L0 blade.



- Based on test results, guidelines based on exhaust pressure and blade loading was provided to customer for operation up to 450MW.

Summary of Vann unit issue

- An incidence of a blade damage occurred on PowerSouth's Vann unit.
- First incidence of such kind in the 15 years operational history of the 40" L0 blades.
- This incident is <u>not</u> related with erosion issue observed on few units.
- One blade was found broken off just below the Stellite shield on the leading edge.
- Mitsubishi along with PowerSouth team launched a RCA to understand the root cause.
- More details will be shared in the Vann unit presentation.



Docket No. 20190001-EI
Update on 40" Last Stage Blade, Dated 2015
Exhibit RAP-8
Page 11 of 12

Questions?

Thank You for Attending!!!

REPLACEMENT POWER COSTS
FOR BCC 40 MW DERATE

Line	Year	Month	Replacement Power Costs	Replacement MWh
	(a)	(b)	©	(d)
1	2017	4	$166,279	12,080
2	2017	5	$218,202	16,320
3	2017	6	$161,352	14,440
4	2017	7	$259,475	19,560
5	2017	8	$190,655	18,400
6	2017	9	$336,487	18,840
7	2017	10	$238,338	21,040
8	2017	11	$198,637	20,400
9	2017	12	$236,112	20,960
10	2018	1	$301,026	12,080
11	2018	2	$103,196	16,960
12	2018	3	$319,840	24,880
13	2018	4	$209,139	18,360
14	2018	5	$195,795	14,200
15	2018	6	$154,945	13,440
16	2018	7	$235,202	23,240
17	2018	8	$162,273	15,880
18	2018	9	$209,104	20,480
19	2018	10	$262,358	22,520
20	2018	11	$223,721	15,680
21	2018	12	$168,450	15,560
22	2019	1	$119,348	15,920
23	2019	2	$71,018	10,080
24	2019	3	$122,114	17,600
25	2019	4	$183,359	18,080
26	2019	5	$174,136	18,280
27	2019	6	$189,686	17,240
28	2019	7	$143,261	15,200
29	2019	8	$186,630	16,080
			Annual Totals	
30		2017	$2,005,536	162,040
31		2018	$2,545,049	213,280
32		2019	$1,189,552	128,480
33		2017 Outage	$11,100,000	
34		**Total**	**$16,840,136**	**503,800**

Duke Energy Florida
Docket No. 20190001-EI
Witness: Swartz
Exhibit No.: JS-2

February 6, 2018

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:

---

[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.

- 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

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.

[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.

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 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.

Duke Energy Florida
Docket No. 20190001-EI
Witness: Swartz
Exhibit No.: JS-2

February 6, 2018

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.

---

[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.

February 6, 2018

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 $lb/hr\text{-}ft^2$ by many hours and that the MHPS 40" L-0 fleet average for back-end loading was closer to 12,000 $lb/hr\text{-}ft^2$. 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]

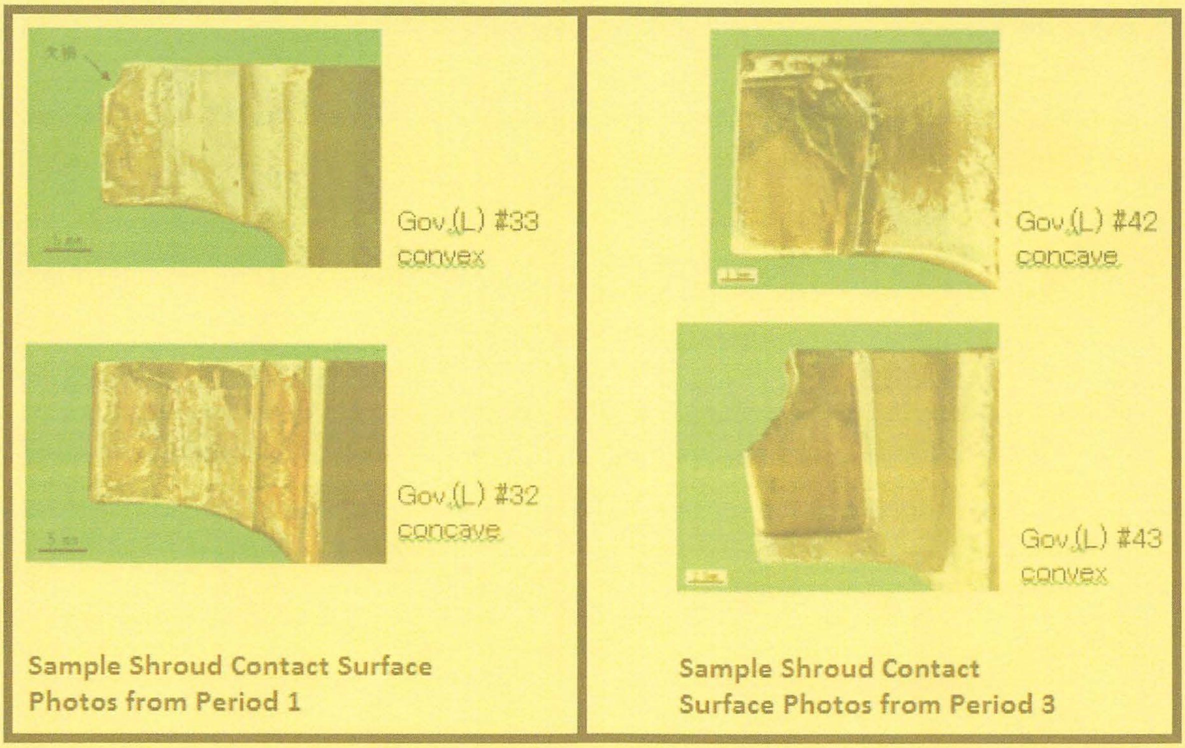
Then and now, Duke Engineering does not agree that back-end loading above 15,000 $lb/hr\text{-}ft^2$ has been the failure-driving mechanism for the documented L-0 events. As Table A illustrates, Periods 2, 4 and 5 saw operating hours in the MHPS defined "Avoidance Zone" of only 1 hour, 1.15 hours and 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).

---

[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.

[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.

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 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

[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.

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

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?

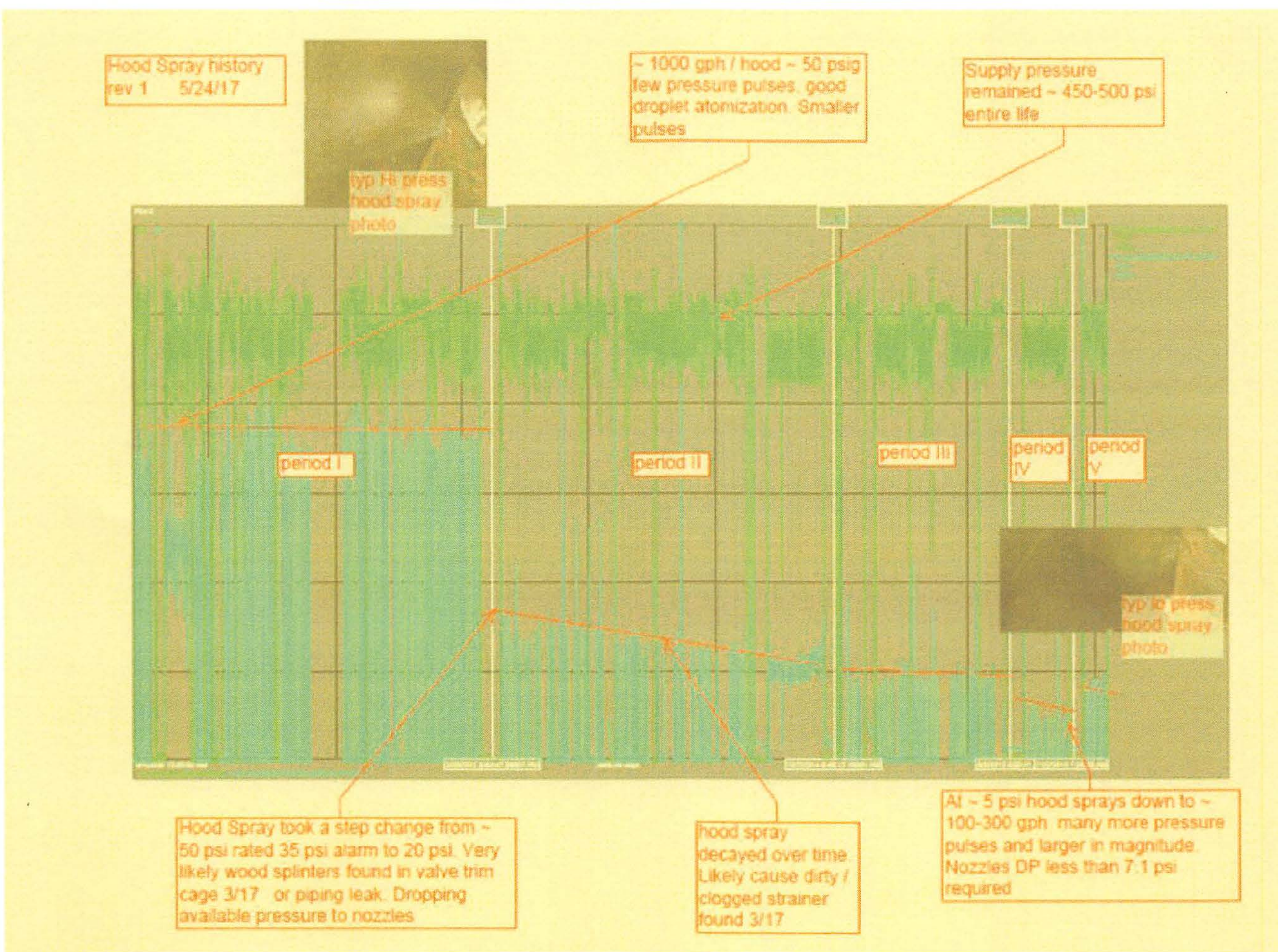
Hood spray thermocouple data shows the hood sprays rarely reached 160° F during normal operation and never exceeded 165° F. Higher temperatures are sometimes seen after a shutdown or unit trip as exhaust pressure increases, most likely due to the hot LP casings and some windage. During shutdowns and/or 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.

Duke Energy Florida
Docket No. 20190001-EI
Witness: Swartz
Exhibit No.: JS-2

February 6, 2018

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

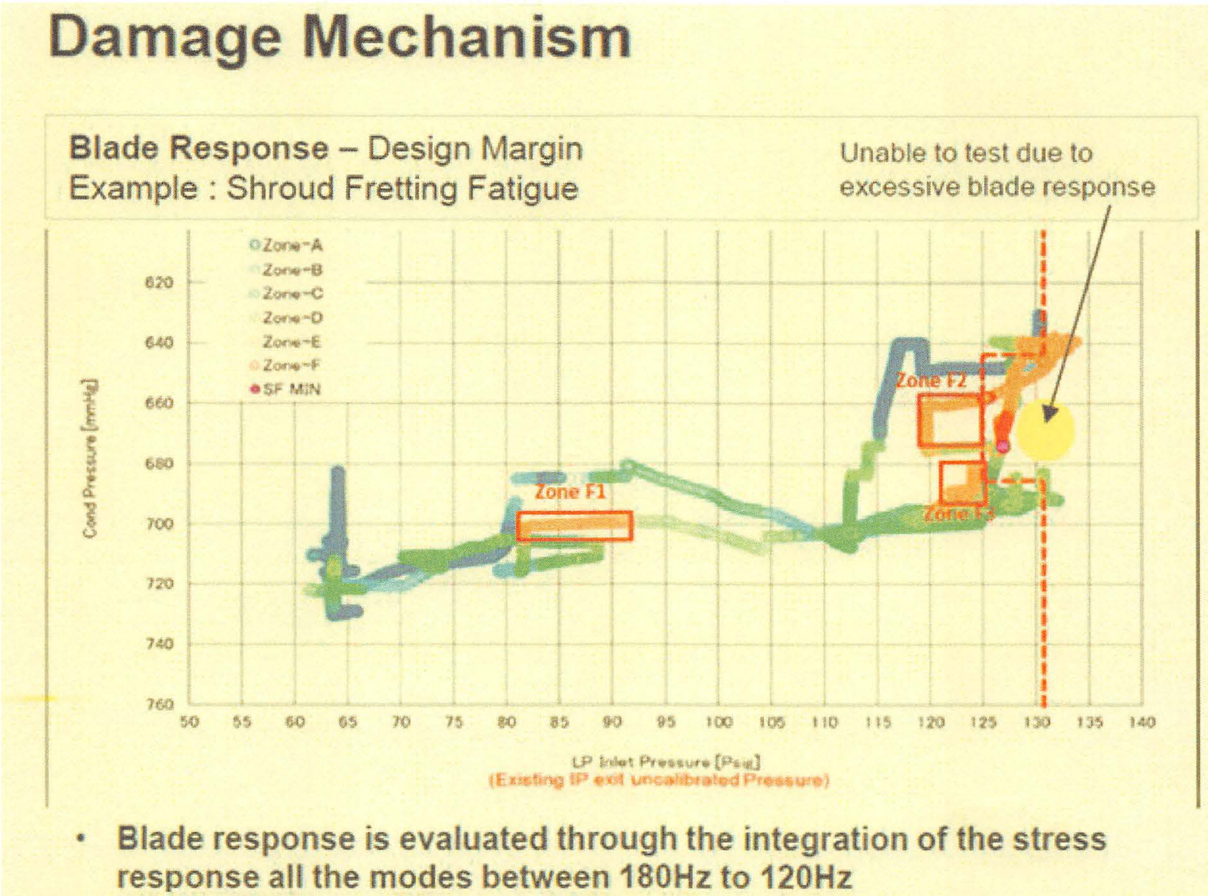


Table D shows the time in hours in each of the three (3) zones identified during the telemetry test for each Period. The total time in the three (3) zones compared with the total operating time is reflected as a percentage.

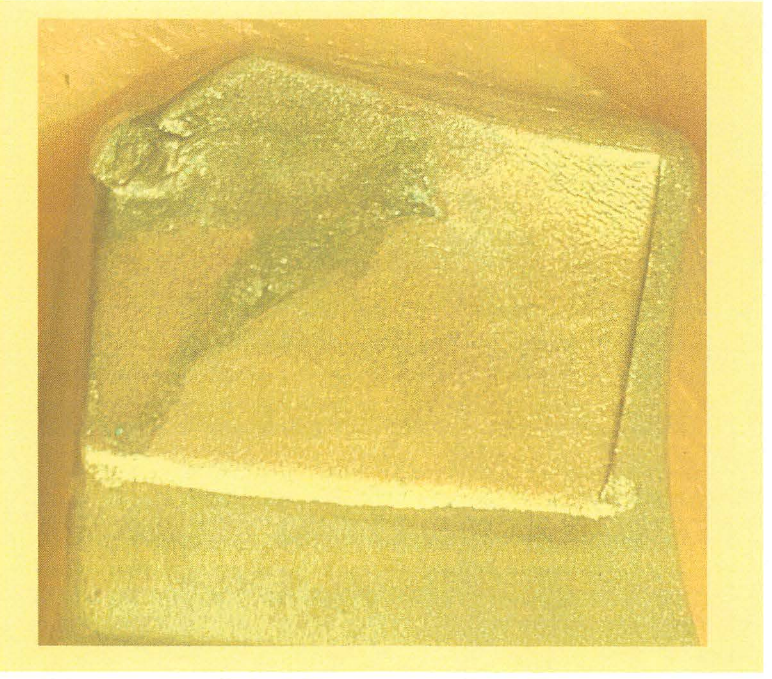
Table D – Time (in Hours) in Each Zone and Compared with Operating Time

	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 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]

---

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

[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.

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.

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 ($\Delta T > 20$ 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	0.09
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	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

CONFIDENTIAL

MHPS

Mitsubishi Hitachi Power Systems

Duke Energy Bartow ST 40" Upgrade Blade Test in Takasago Validation Rigor at MHPS

Muhammad Riaz

Manager Steam Turbine Engineering

MHPS Americas

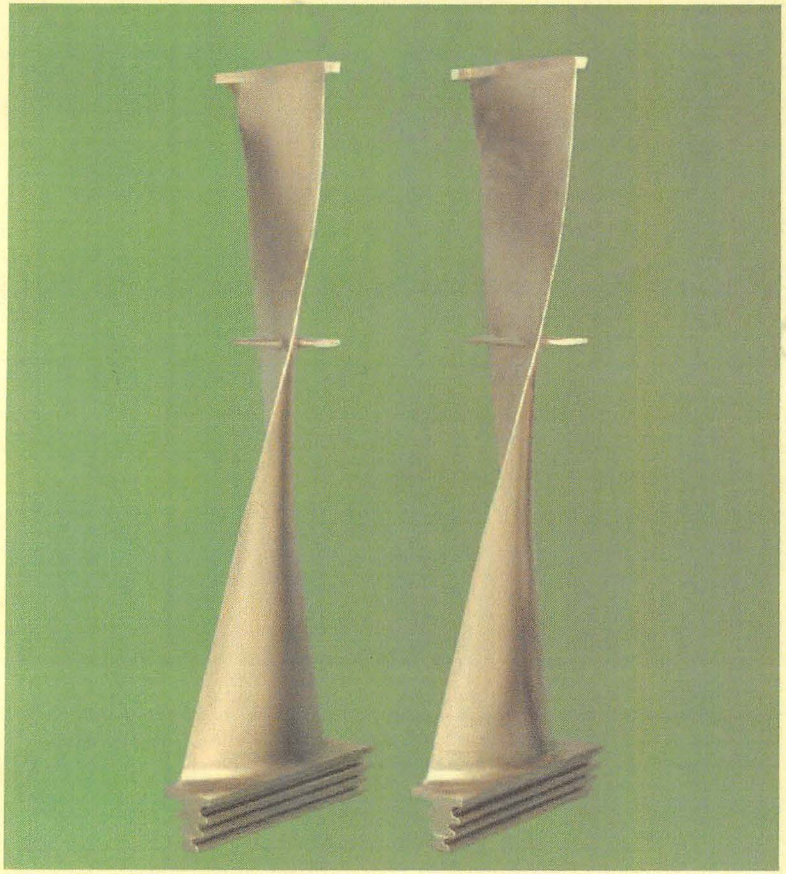
Introduction

- The Steam Turbine applied at Duke Bartow was originally designed for 420MW as tandem compound unit with a double flow LP section, while the 4 on 1 fired configuration produces steam for 450MW.
- The original blade loading limit of the 40" L-0 blade did not allow the unit to produce 450MW resulting in blade modifications and testing.
- In the following 3 years, multiple forced outages were experienced due to last stage blade damage caused by high load stimulus and high energy blending in the 4 on 1 Configuration which was not fully understood until conducting an extensive collaborative RCA.

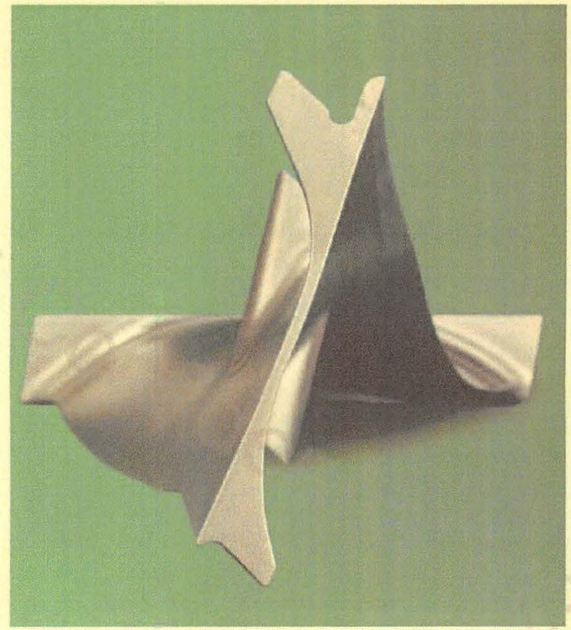
- Once the root cause was understood MHPS developed an upgraded 40" L-0 blade specifically to operate the conditions present at Bartow. **(Note : this is not required across the fleet)**
- To achieve confidence in the capability / reliability of the new blade, extensive testing was conducted.
- The upgrade blade was tested in Takasago factory and a team of Duke experts joined to witness the design validation testing.

- This presentation shows the extent of testing conducted to ensure component reliability

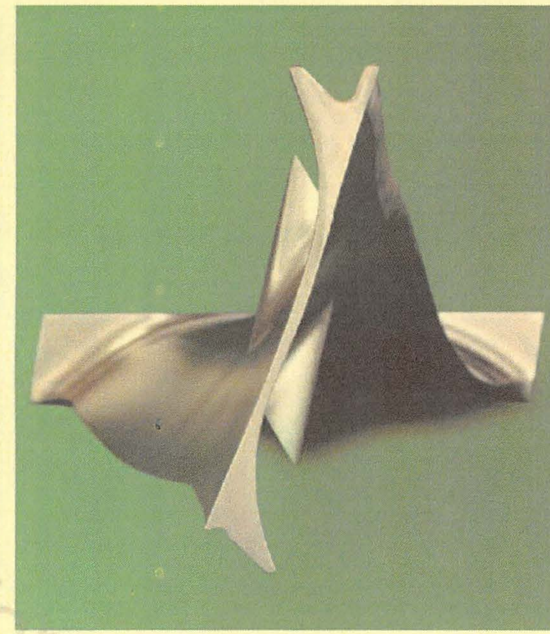
40" L-0 upgrade blade for high loading



Upgraded 40" 40" Old



Upgraded 40"



40" Old

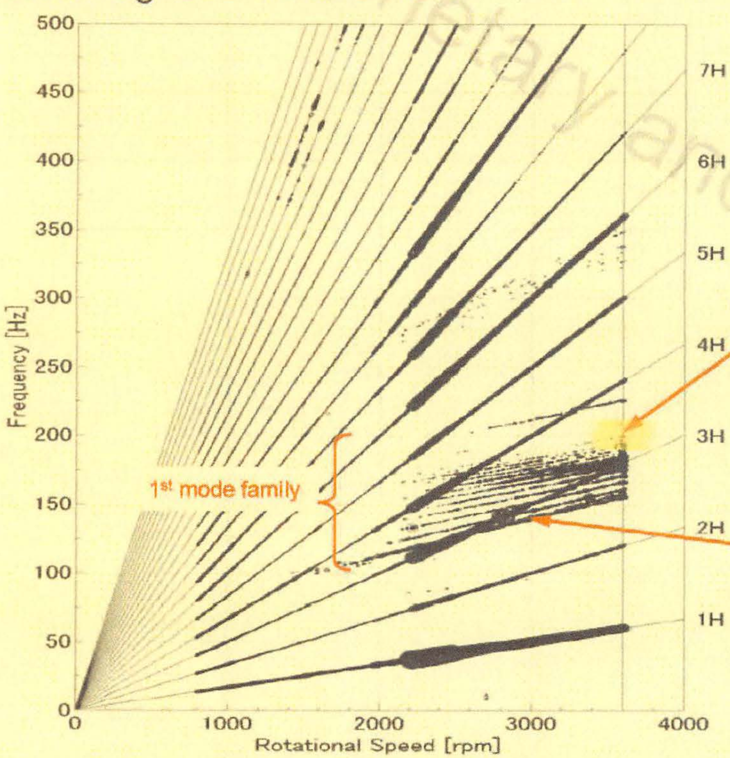
Verification Testing Plan

Following verification tests are planned for upgraded 40" L-0 blade.

- Factory Verification Testing
  - Harmonic resonance frequency of the upgraded 40" L-0 blade will be measured by air excitation.
  - Mechanical damping of high nodal diameter will be measured by electromagnetic excitation. Measured mechanical damping will certify reliability for non synchronous vibration.
  - BVM (Blade Vibration Monitoring) data will be calibrated using telemetry strain gauge data during shop testing.
- Field Validation Testing
  - Vibratory amplitude during actual operation will be measured by BVM including Bypass Operation.
- Long-Term Monitoring
  - Continuous long-term monitoring long-term BVM.

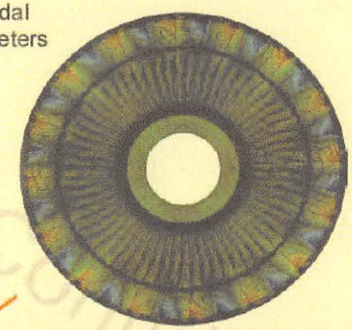
Outline of Factory Verification Testing

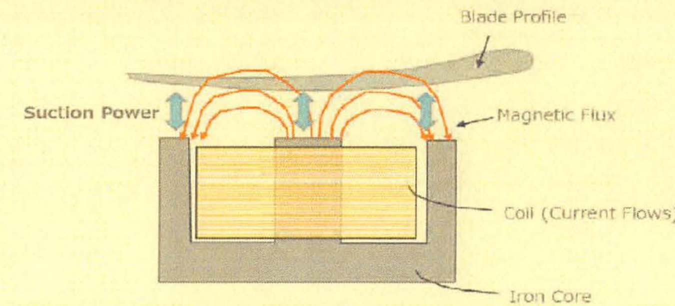
To certify reliability of Upgraded 40" L-0 Blade, the blade frequency (harmonic resonance frequency) were measured by the air jet test and the mechanical damping of the high nodal diameter was measured by the electromagnetic vibration test.



Sample Campbell Diagram

16Nodal Diameters

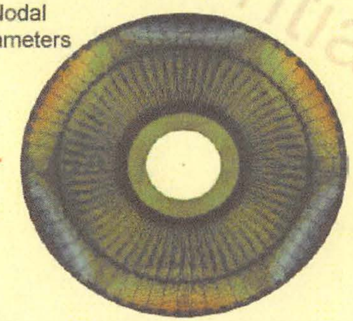


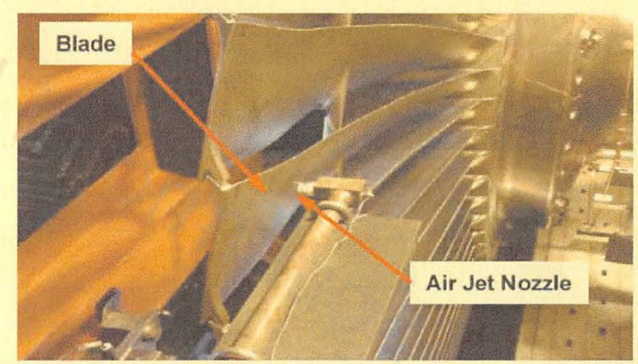


Vibrator (AC) suctions blade by Magnetic Filed

The electromagnetic exciter can excite any high nodal diameter mode at the rated rotational speed.

3 Nodal Diameters





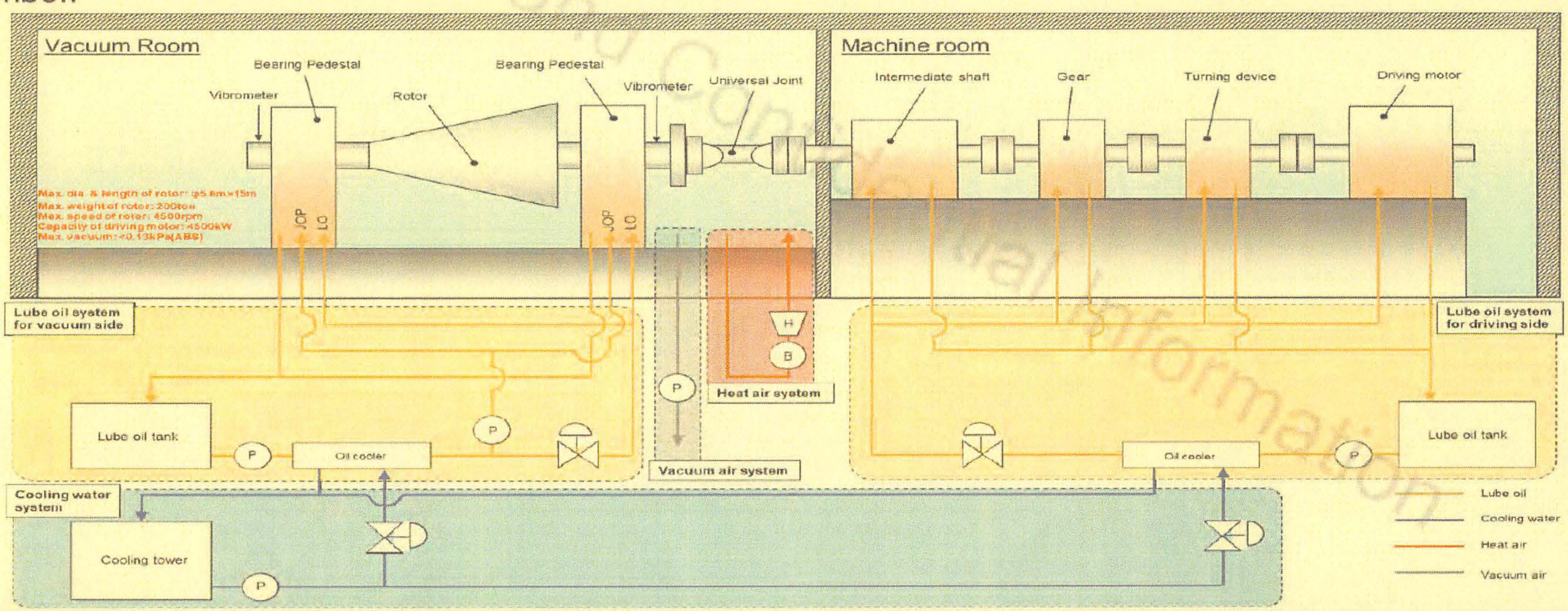
The blade frequencies and responses of harmonic resonance are measured by Air jet test

Test Facility

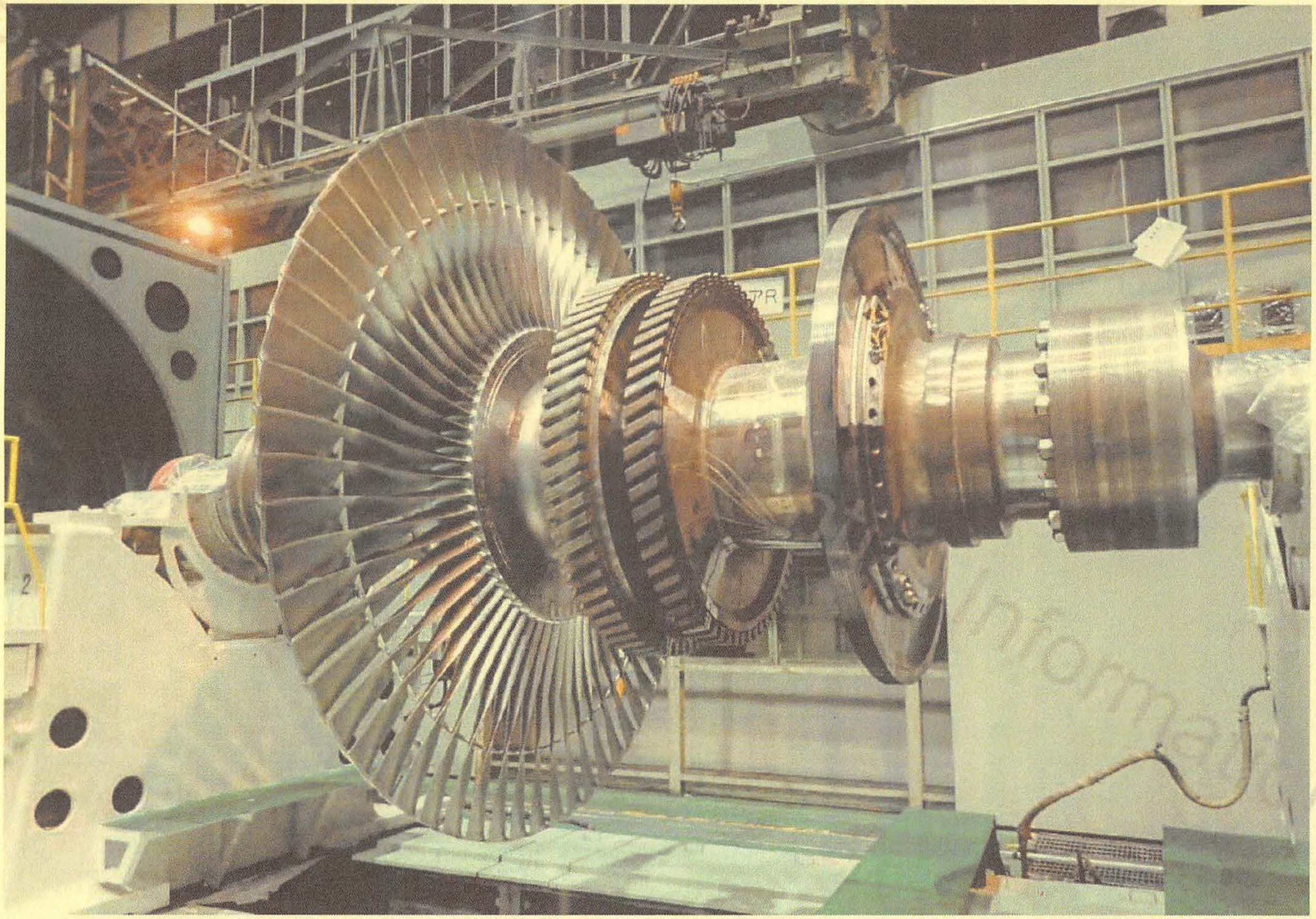
Verification test was carried out at HSB (High Speed Balance) test facility in Takasago factory.

The test rotor was installed in a vacuum chamber to avoid high blade temperature by windage heating, and was rotated by a drive motor.

All measurement equipment for the air jet test and the electromagnetic test were installed inside the vacuum chamber.

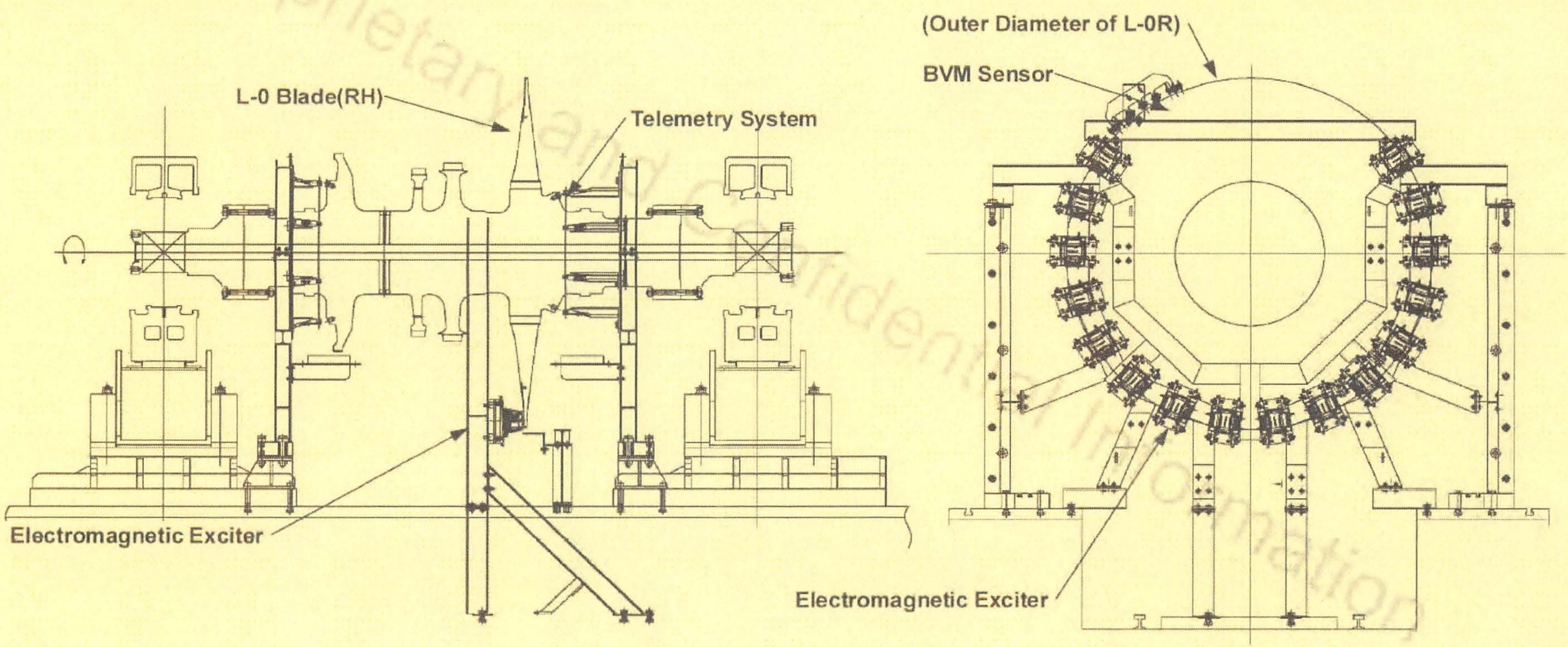


Test Rotor with Production Blades

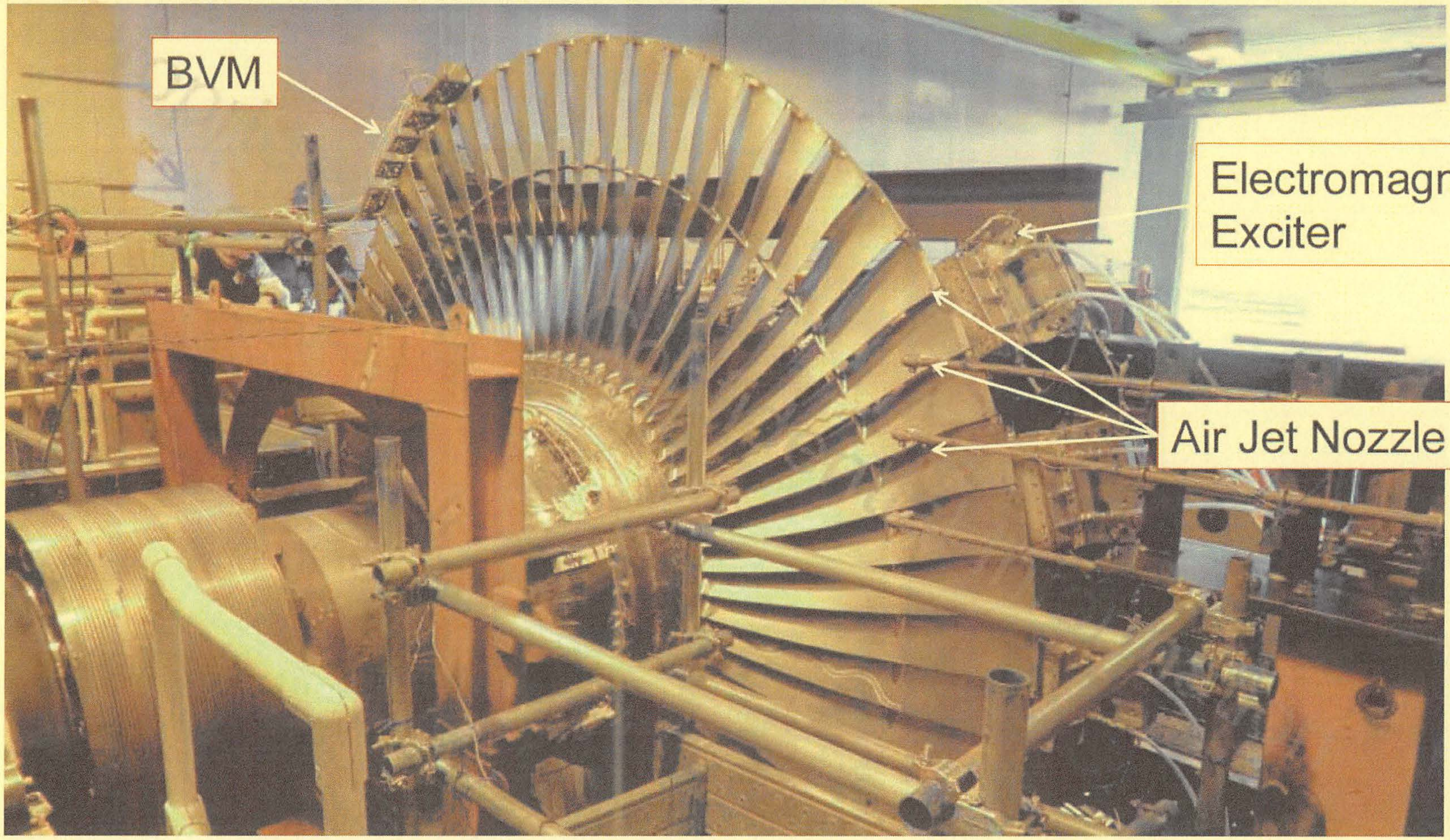


Verification Test Procedure

Air jet nozzles, electromagnetic exciters, telemetry system and BVM sensors for verification test was installed as shown below.



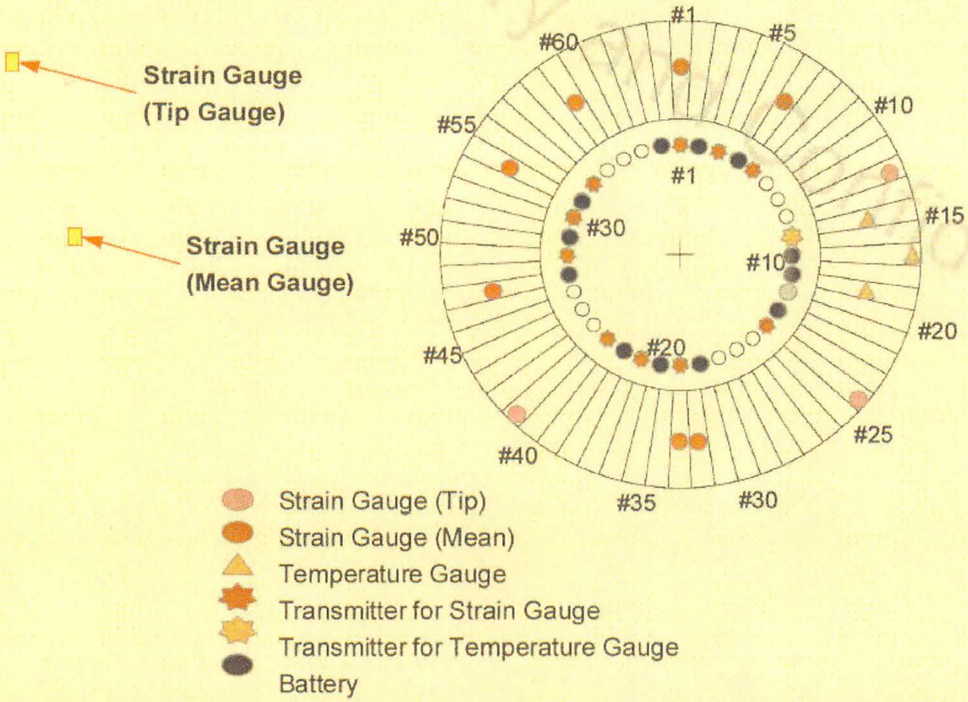
Installed Rotor in the Vacuum Chamber

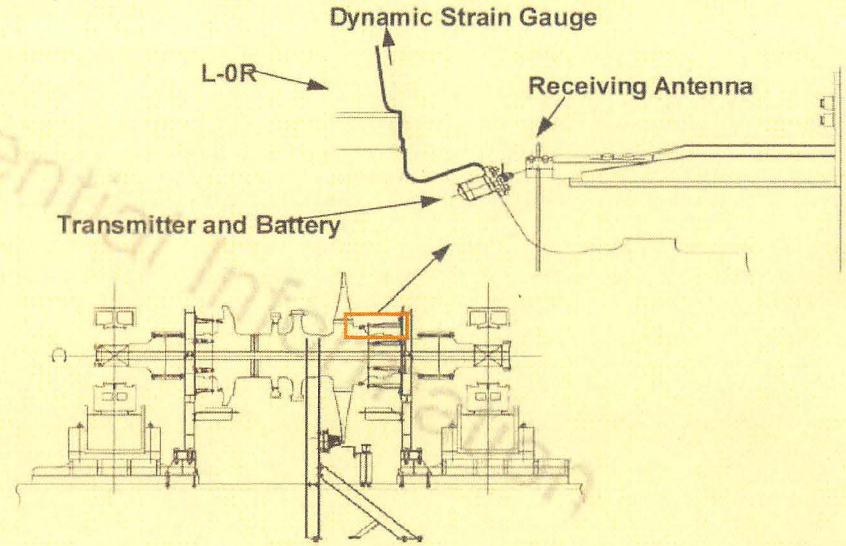


Telemetry Measurement

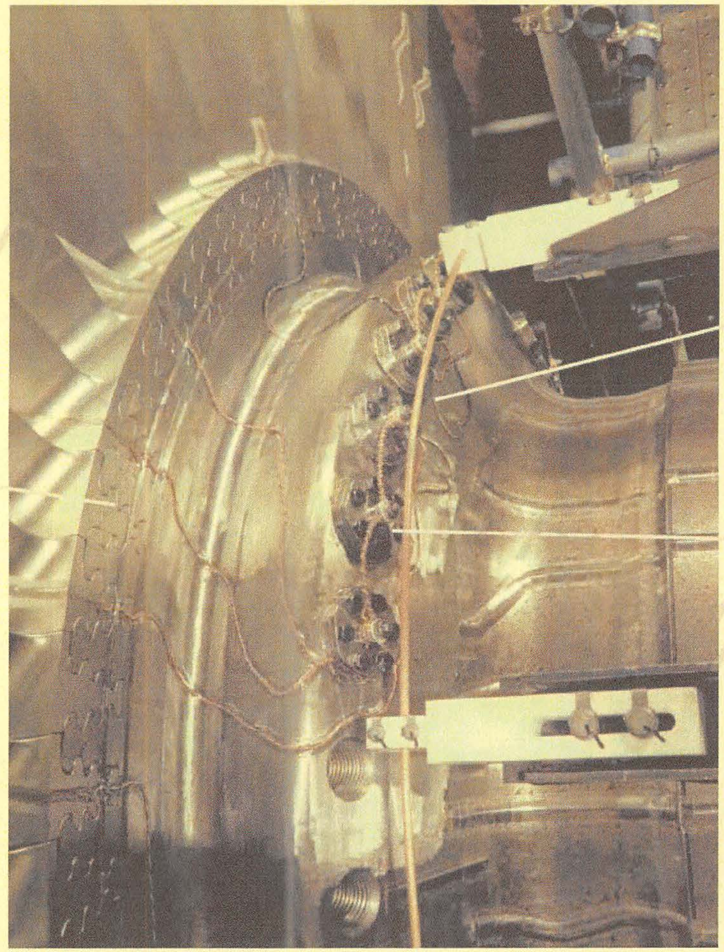
The blade vibration stress was measured by the dynamic strain gauge attached to the tip and the mean of blade surface.

The electric signals of the blade vibration stresses were sent from transmitters which were mounted in the balancing holes of the rotor to the receiving antenna which was set beside the rotor.





Telemetry System



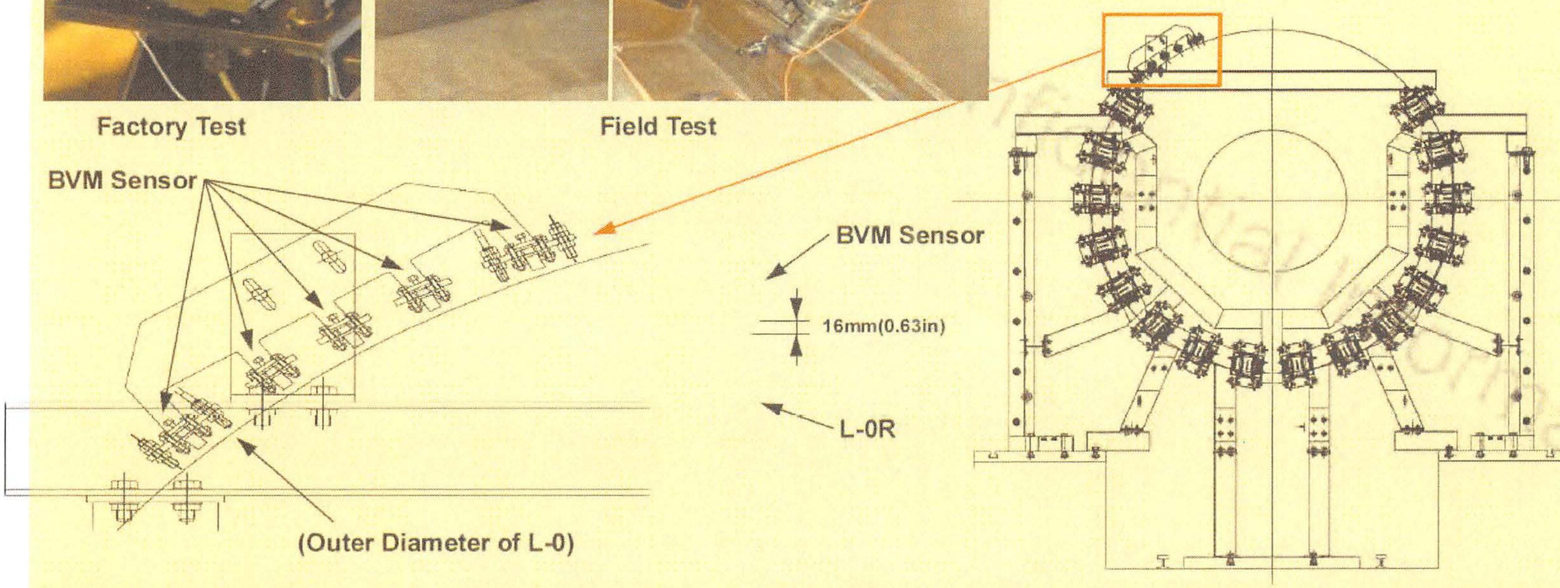
Blade Vibration Monitoring (BVM) Measurement

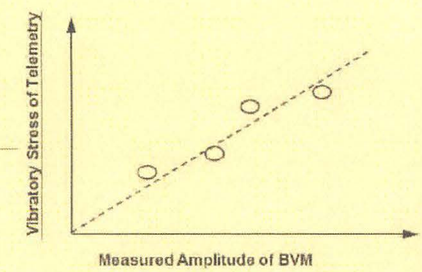
The blade vibration amplitude was measured by the BVM sensors set close to the tips of the blades.

The specification of BVM system (specification of sensor, specification of analyzing system etc.) is the same as field verification testing.

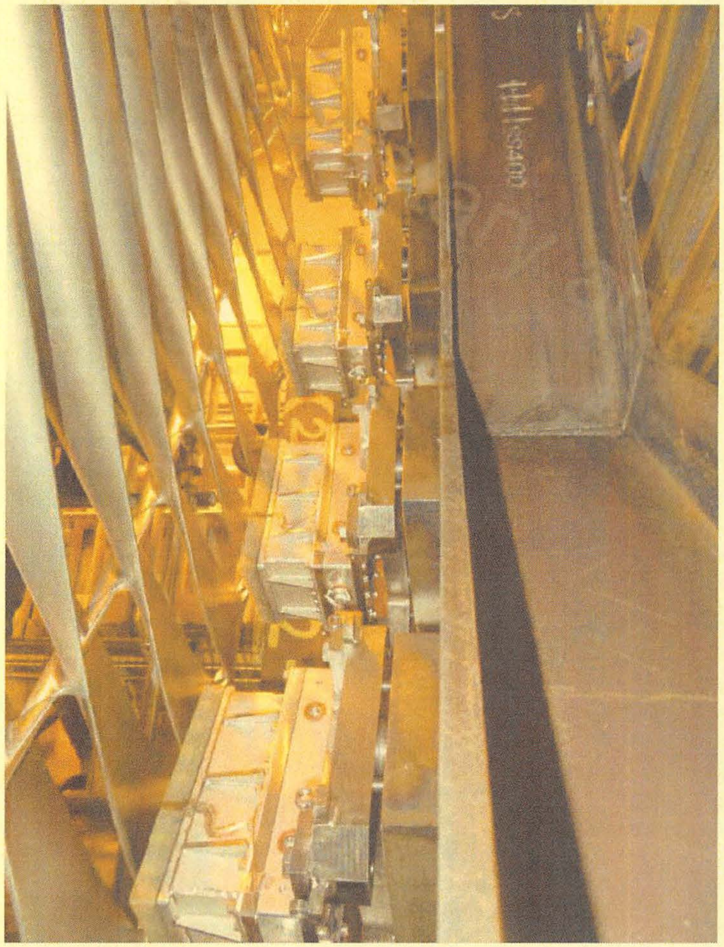
Factory Test

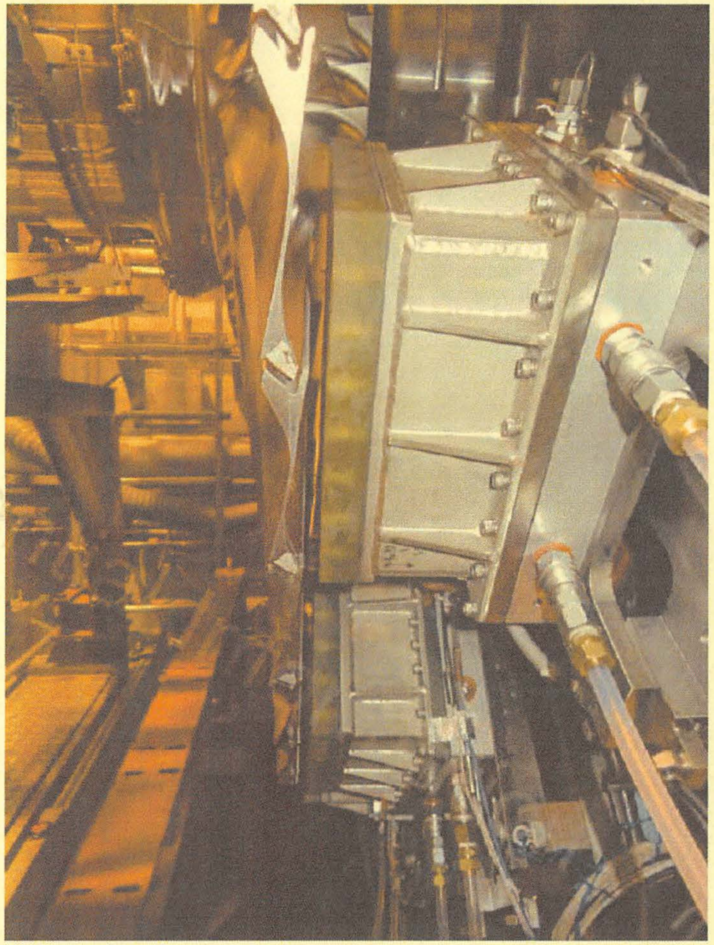
Field Test





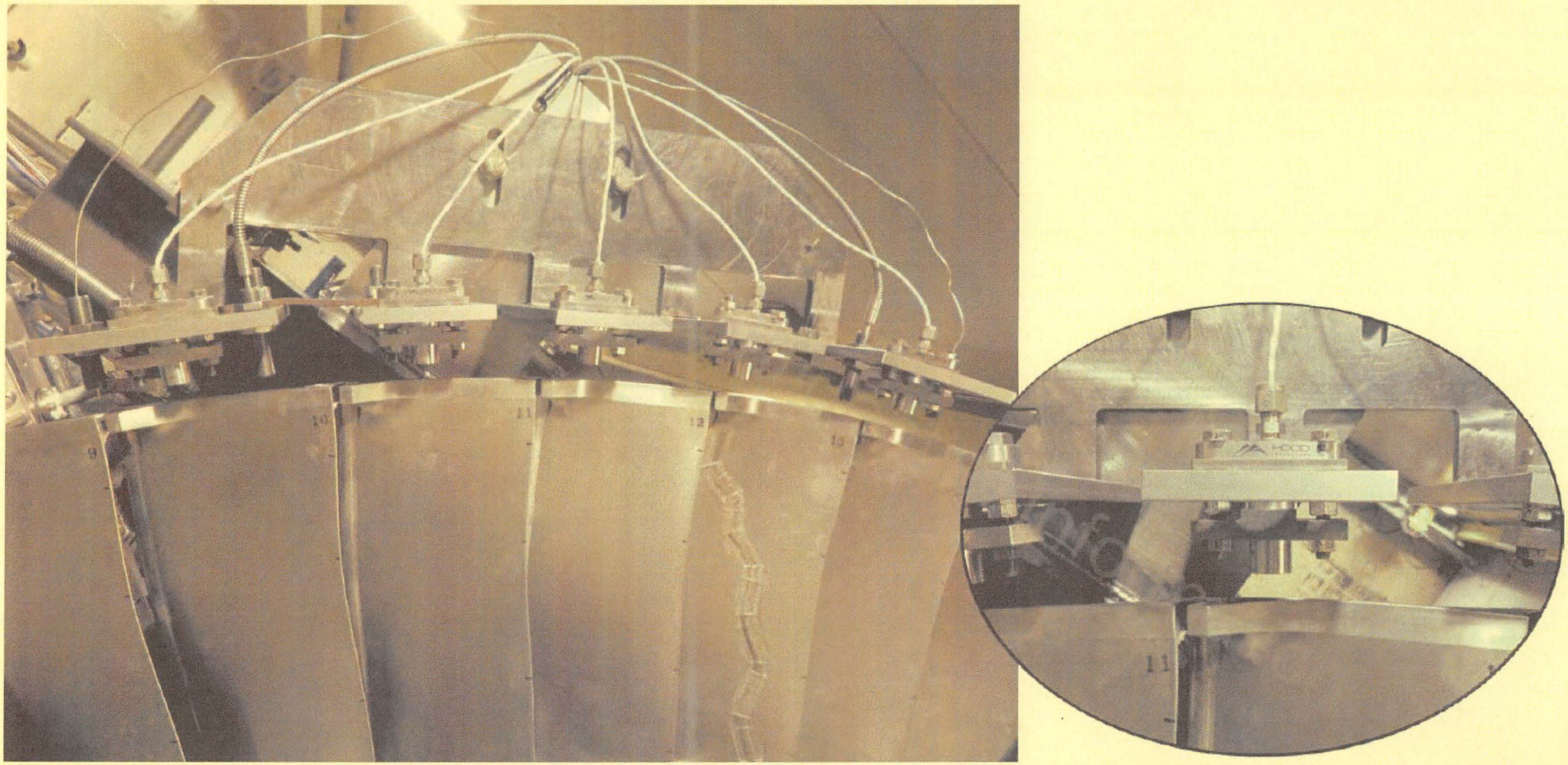
Electromagnetic Exciter





CONFIDENTIAL

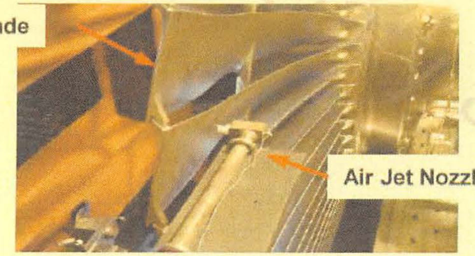
BVM Sensor

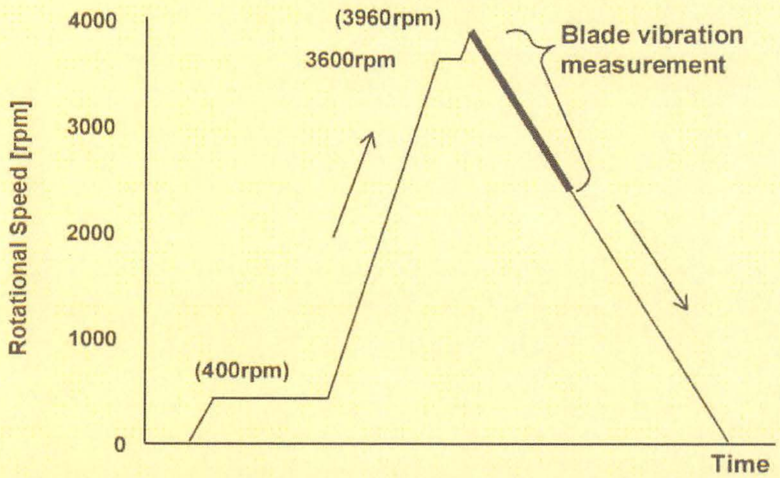


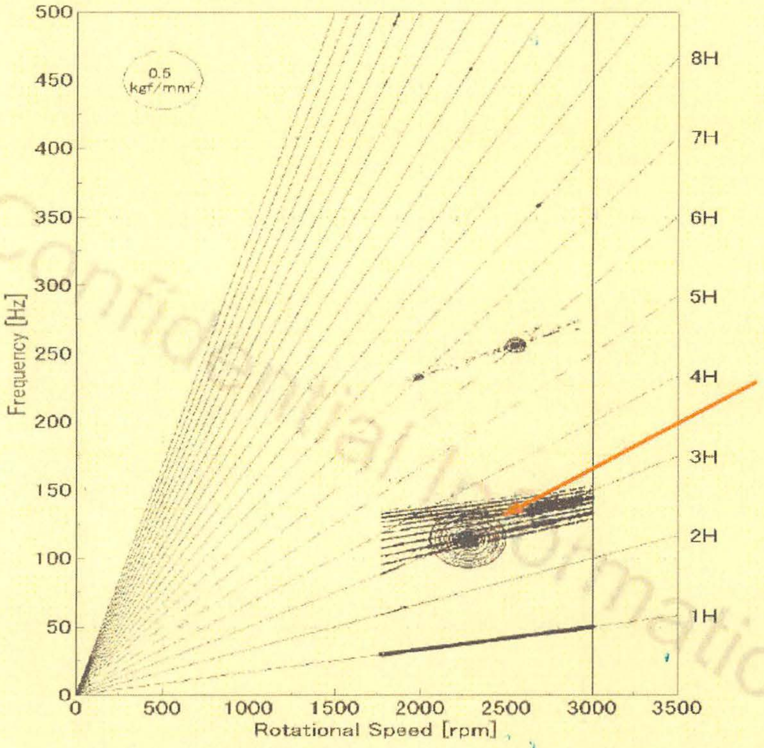
Air Jet Test Procedure

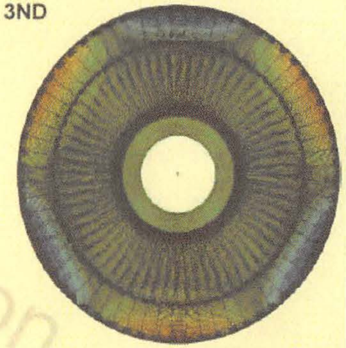
Resonance points of each mode was confirmed by air excitation while decreasing the rotational speed.

Rotational speed of shroud and stub contact was confirmed by the change in the blade vibration characteristic.









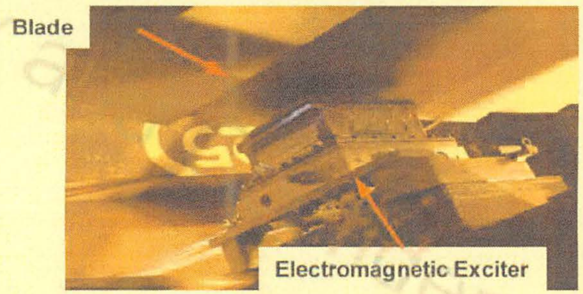
Example of Measurement Result of Air Jet Testing

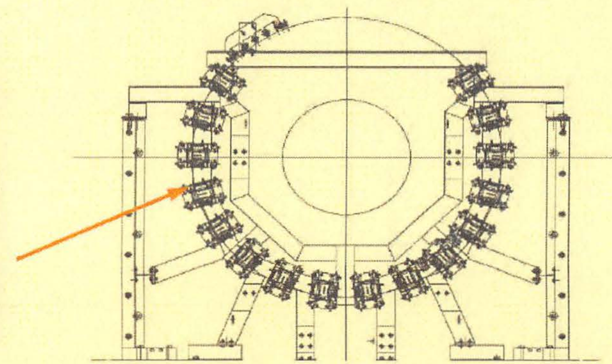
Electromagnetic Test Procedure

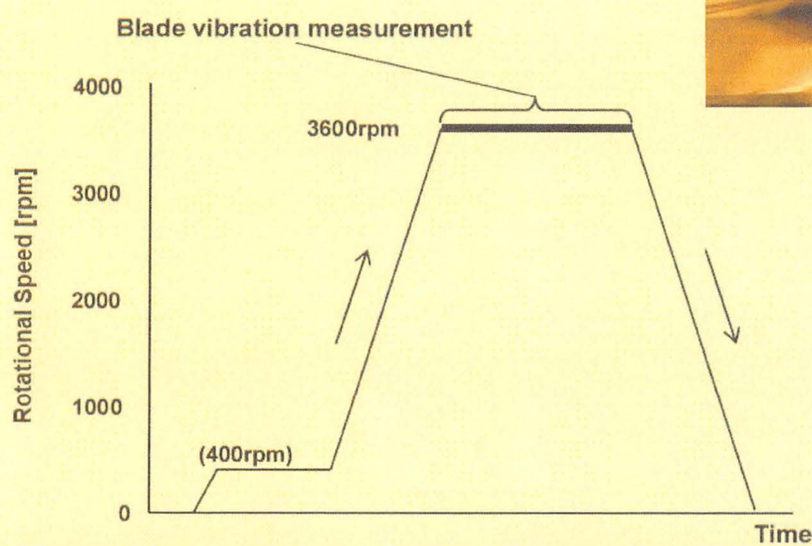
The magnitude response of high nodal diameters was confirmed by the electromagnetic test.

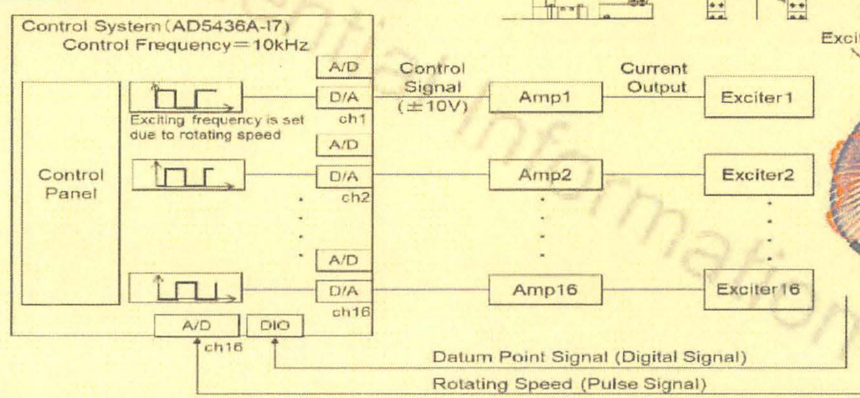
The exciting frequency, phase and power of each electromagnetic exciter were controlled.

In the electromagnetic test, the exciting frequency was swept around the natural frequency of the high nodal diameter while keeping the rotational speed at the rated speed.

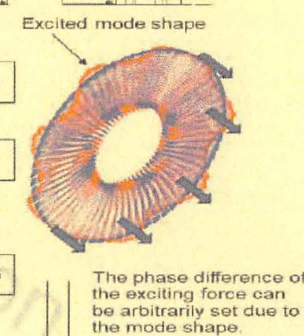








Electromagnetic Exciter Control System



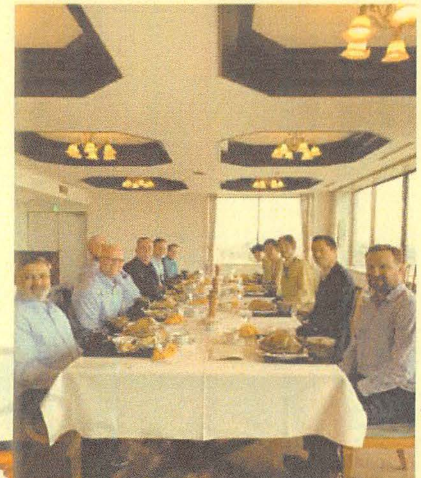
Test Control Room

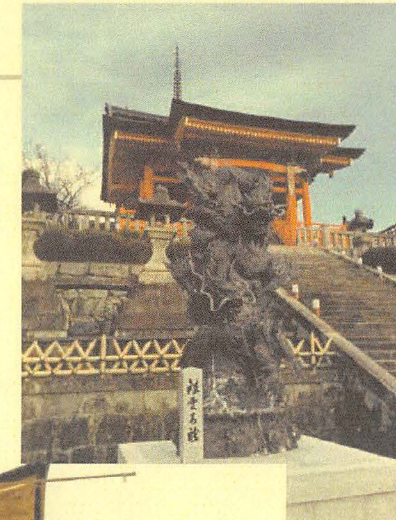
Summary and Test Results

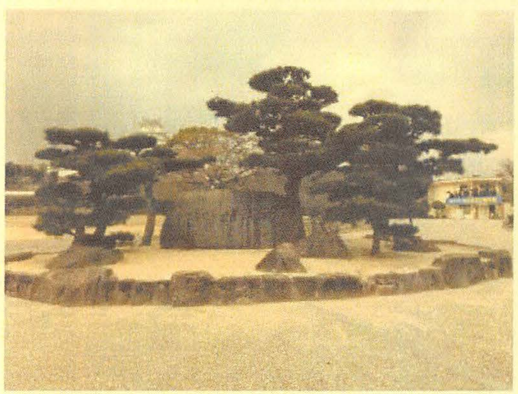
- Campbell diagram showed sufficient margins for all vibration modes
- Higher level of mechanical damping observed during the test validated the calculations
- In-house testing proved that the upgrade blade can operate at higher blade loading that is enough to produce desired output for Bartow station
- New blades will be installed in the steam turbine in Nov 2019 along with Blade Vibration Monitoring

Duke Team at MHPS Factory in Takasago

Sightseeing Pics







MHPS

Mitsubishi Hitachi Power Systems

Thank You

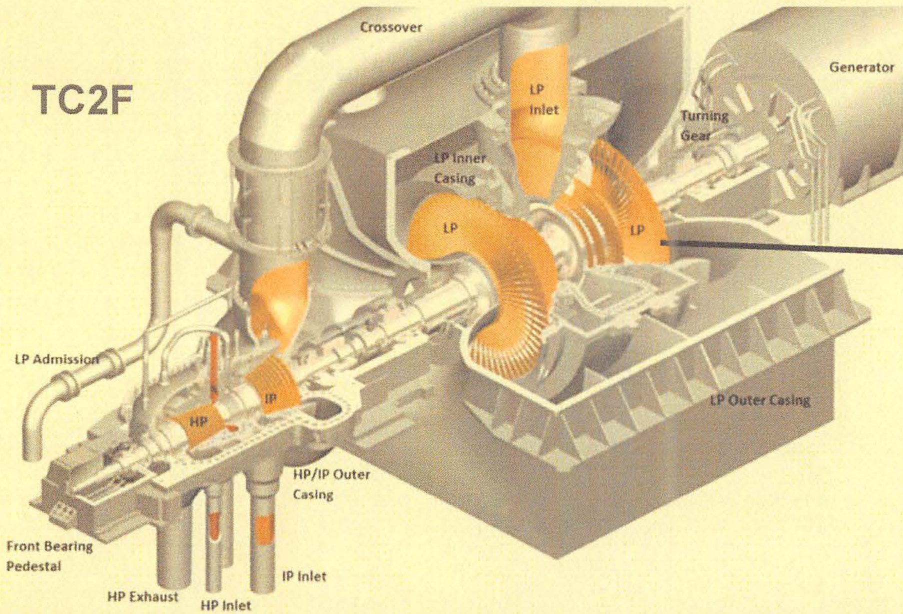
MHPS

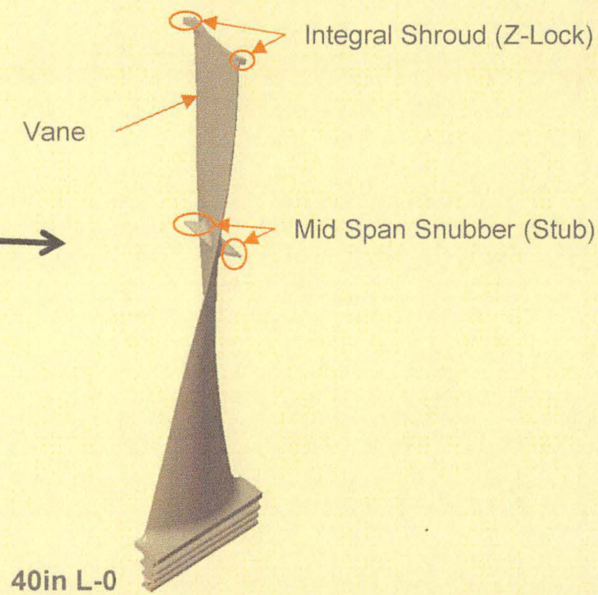
Mitsubishi Hitachi Power Systems

Power for a Brighter Future

MHPS

TC2F





Bartow RCA Summary

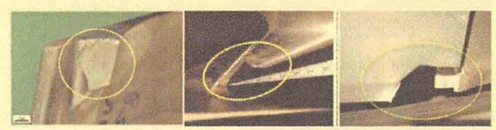
Nick Porteous
Muhammad Riaz, Ph.D.

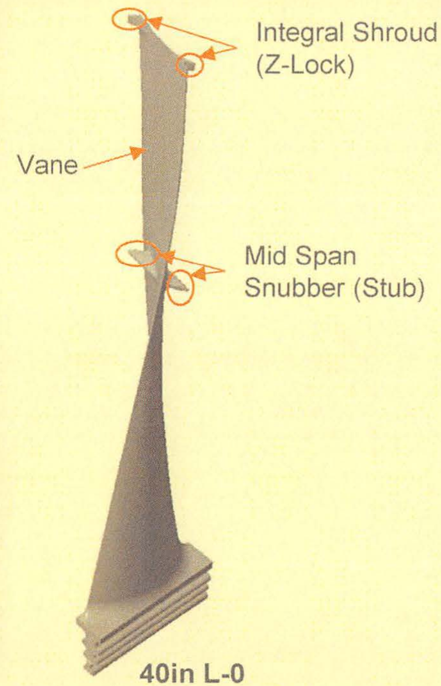
September 22nd, 2017

Agenda

Ref	Subject		Slide(s)
1.	Blade Operating Summary	-	3
2.	RCA Process Overview	-	4 - 6
3.	Investigation into alternate root causes	-	7 – 11
4.	Root Cause Damage Mechanism	-	12 – 15
5.	Blade Response	-	16 - 22
6.	Material Capability	-	23
7.	Summary of Max Operational Stress	-	24
8.	Comparison between Period 2 and Period 5	-	25 – 26
9.	RCA Conclusions	-	27
10.	Blade Upgrade	-	28

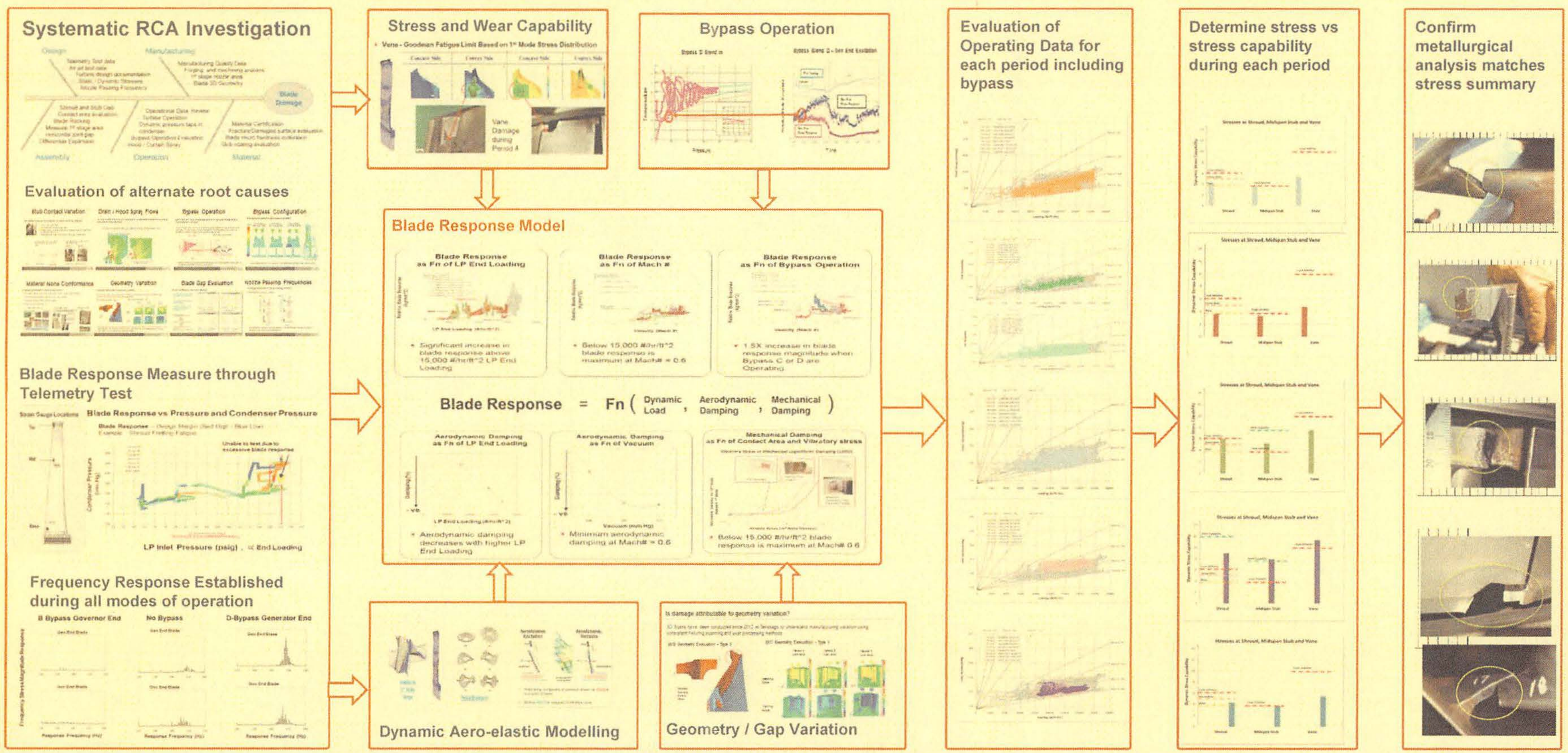
Bartow Blade Operating Summary

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 



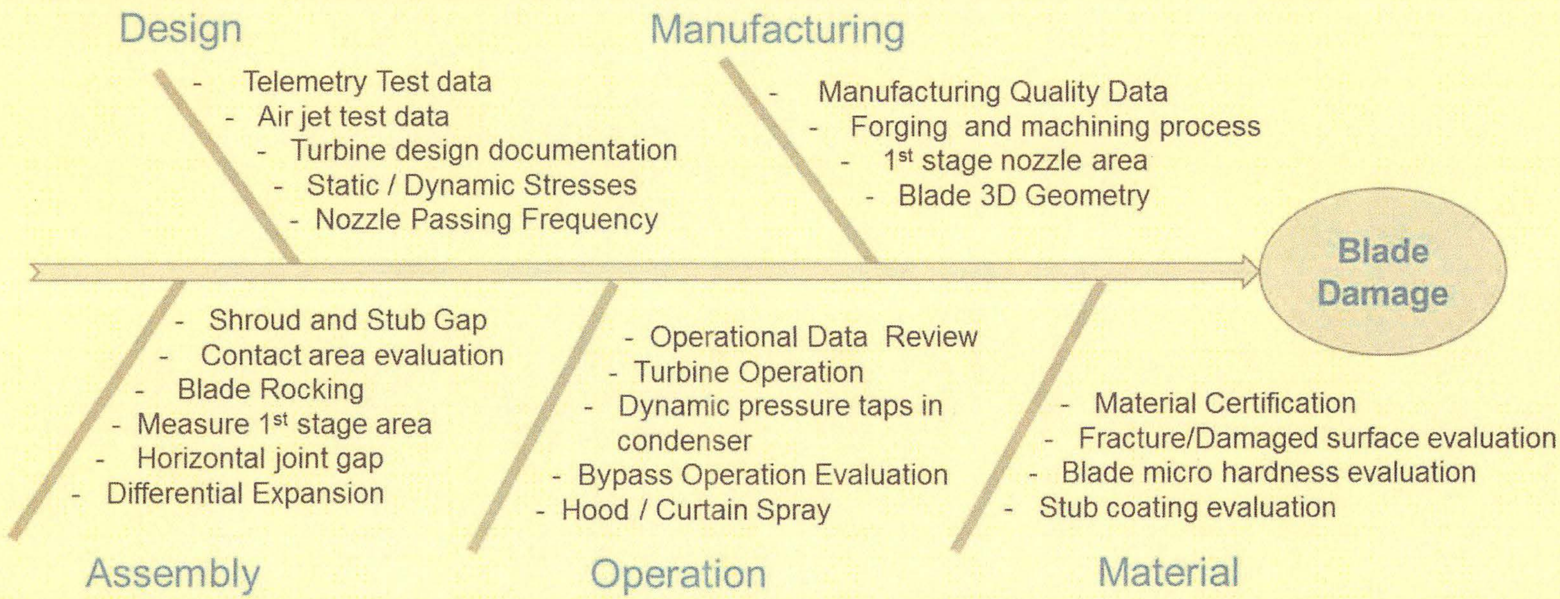
Note 1 – Period 4 did not show shroud fretting fatigue / contact wear damage.

RCA Process Overview



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

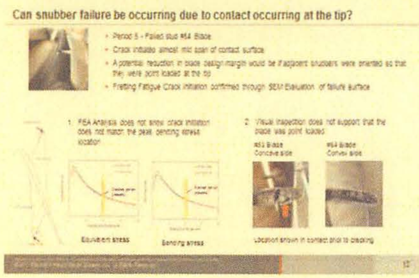
- **RCA Areas of Investigation – Systematic RCA Implemented**



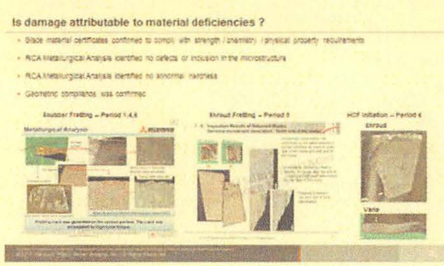
- LP Loading + Bypass Operation at high load were identified as the primary root causes for the Bartow 40" Blade reliability differences from the global fleet.

Evaluation of potential Root Causes included :

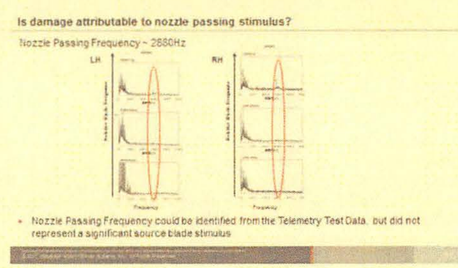
Stub Contact Variation



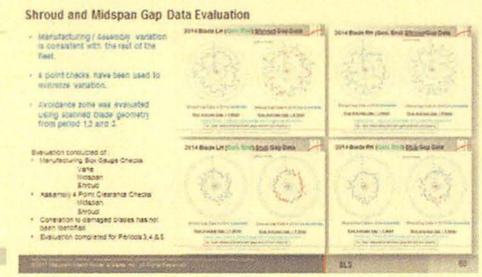
Material None Conformance



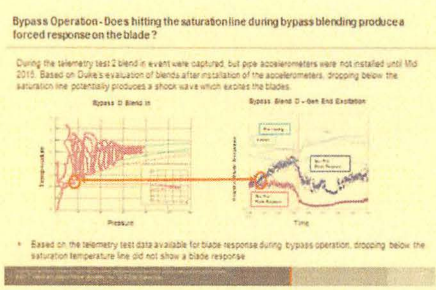
Nozzle Passing Frequencies



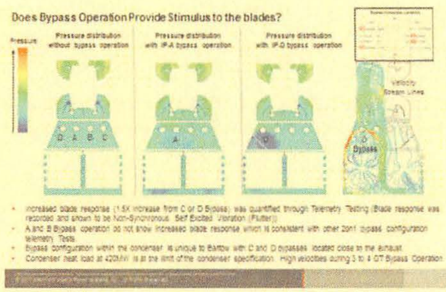
Blade Gap Evaluation



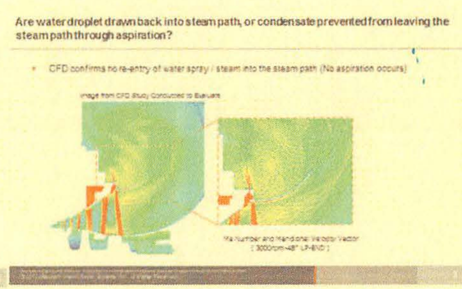
Bypass Operation



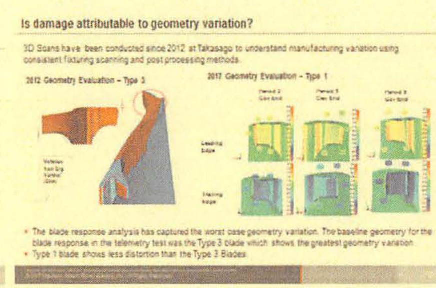
Bypass Configuration



Drain / Hood Spray Flows



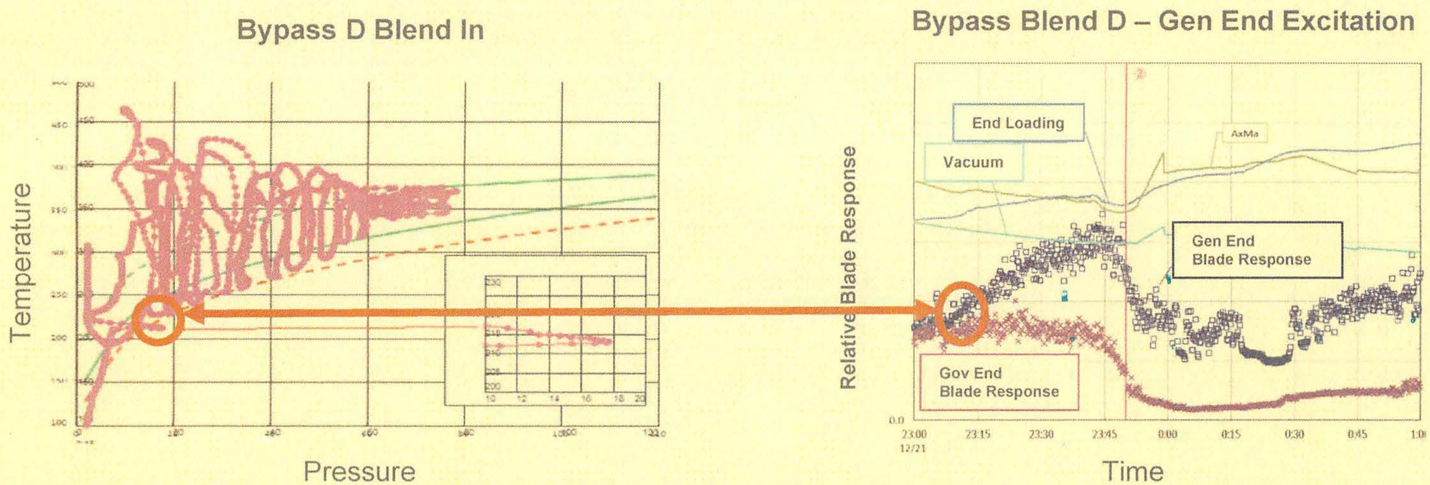
Geometry Variation



- 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.

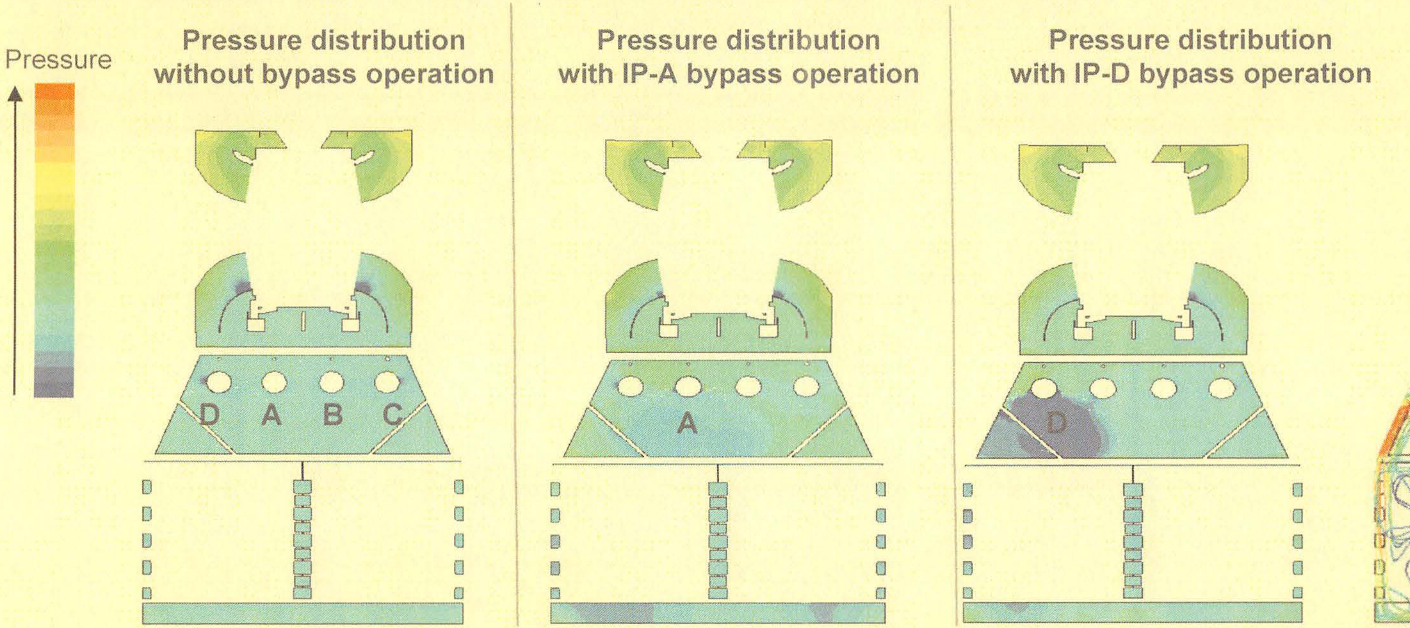
Bypass Operation - Does hitting the saturation line during bypass blending produce a forced response on the blade ?

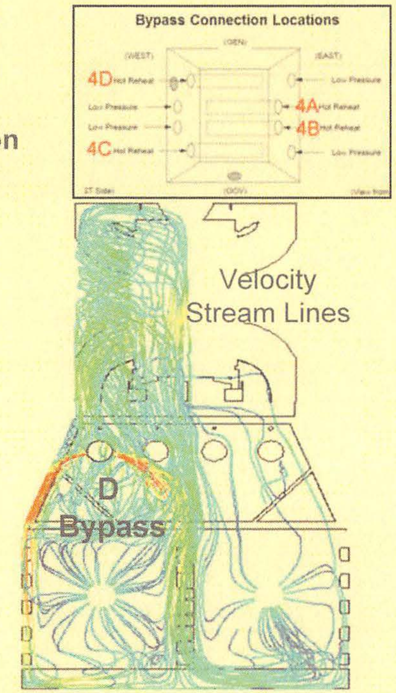
During the telemetry test 2 blend in event were captured, but pipe accelerometers were not installed until Mid 2015. Based on Duke's evaluation of blends after installation of the accelerometers, dropping below the saturation line potentially produces a shock wave which excites the blades.



- 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

Does Bypass Operation Provide Stimulus to the blades?



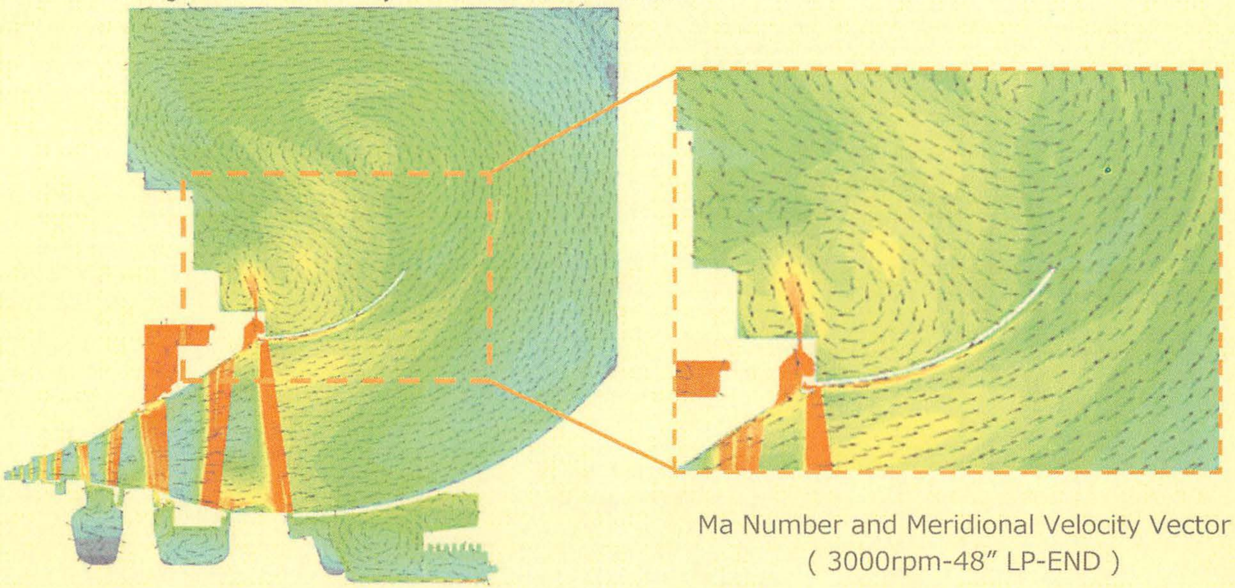


- Increased blade response (1.5X Increase from C or D Bypass) was quantified through Telemetry Testing (Blade response was recorded and shown to be Non-Synchronous Self Excited Vibration (Flutter))
- A and B Bypass operation do not show increased blade response which is consistent with other 2on1 bypass 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

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

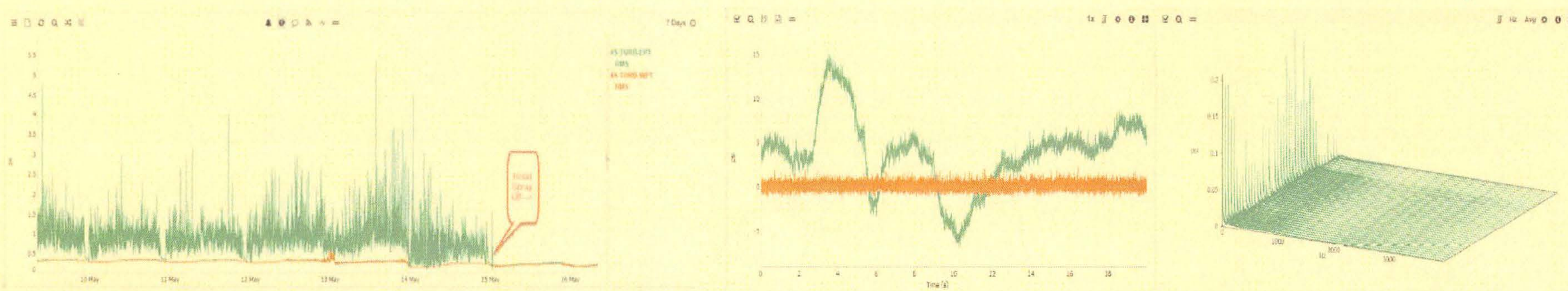


Ma Number and Meridional Velocity Vector
(3000rpm-48″ LP-END)

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 :

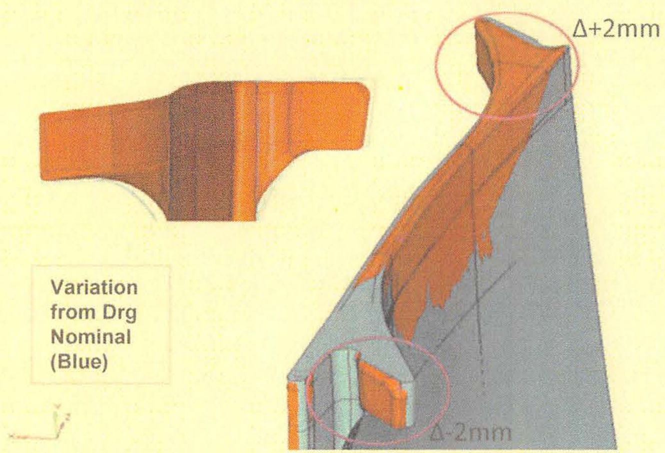


Pressure fluctuations did not have high frequency content, and identified pressure rising from 2.5" Hg to atmospheric pressure. No corresponding blade response identified during telemetry test.

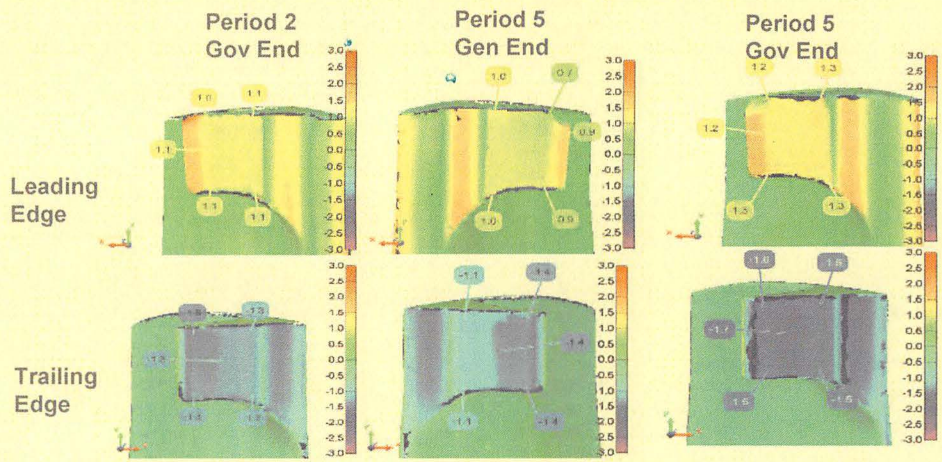
Is damage attributable to geometry variation?

- 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

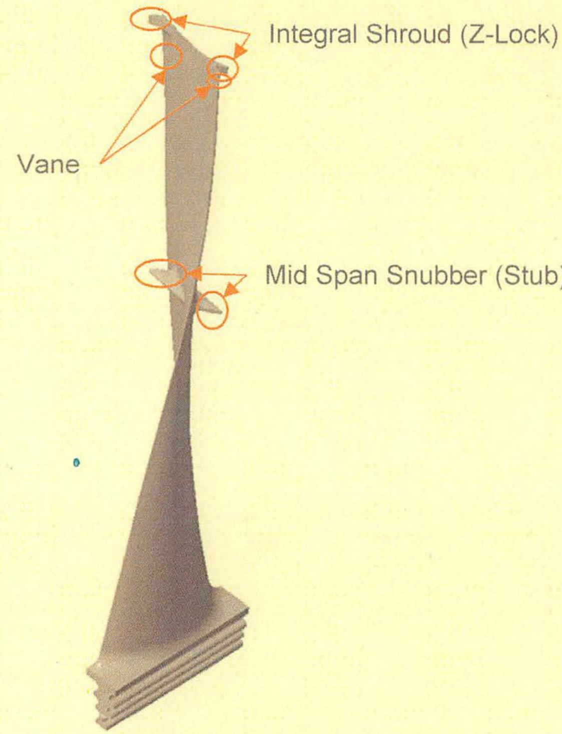


- The blade response analysis has captured the worst case geometry variation. The baseline geometry for the blade response in the telemetry test was the Type 3 blade which shows the greatest geometry variation.
- Type 1 blade shows less distortion than the Type 3 Blades.

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.

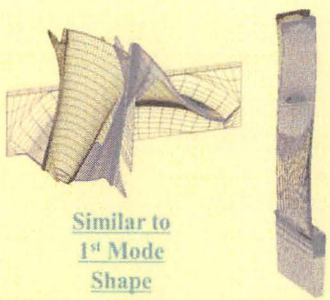


Root Cause Analysis has identified all blade damage from Period 1 thru Period 5 has been identified as Dynamic Loads from Non-Synchronous Self Excited Vibration (Flutter)

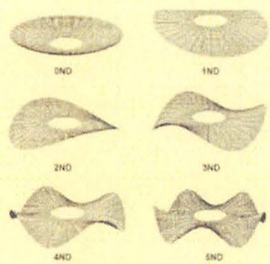
Note : Non-synchronous 1st Mode Higher Nodal Diameters response was presented March 18th 2015 , prior to Period 3 RCA

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).

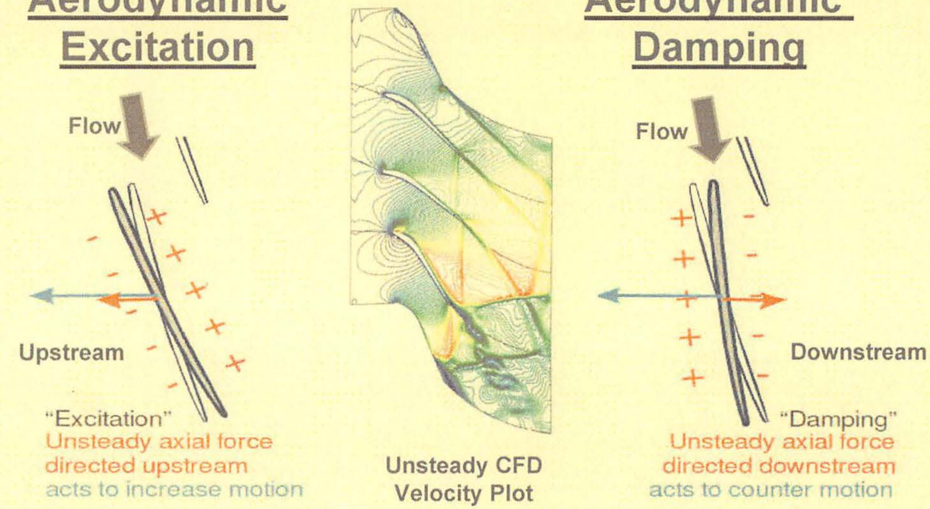


Similar to 1st Mode Shape



Nodal Diameters

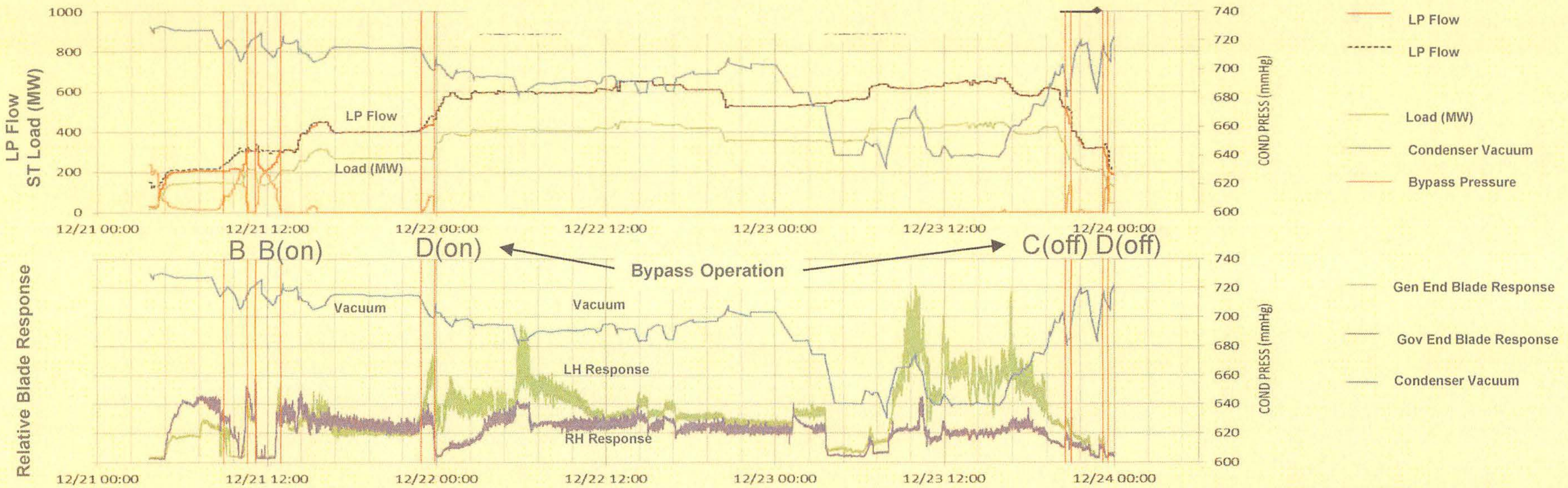
- Cycles accumulate at 12,000 cycles per minute at 200 Hz



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

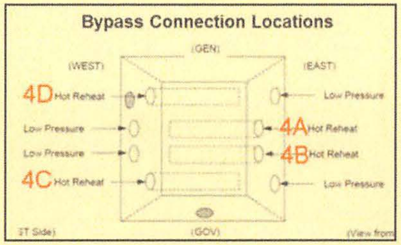
How do we know the dominant response is Non-Synchronous Self Excited Vibration?

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



Range of Operating Conditions During Test :

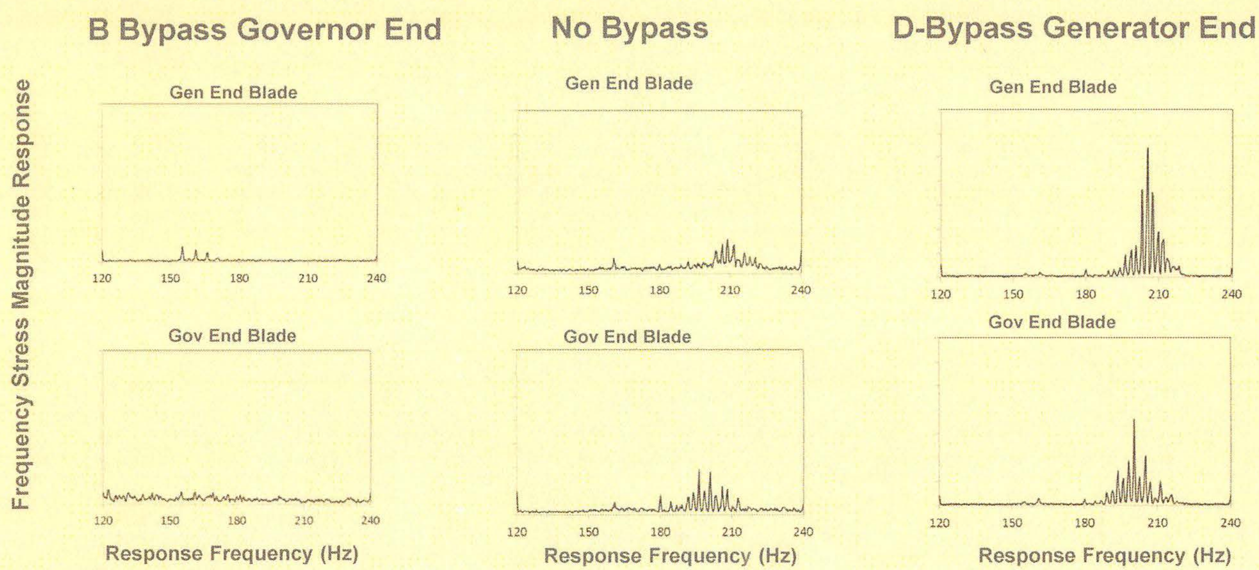
- Blade Response was measured up to 455 MW and 5 in.Hg
- Bypass Operation of 2 Blend In and 2 Blend Out Events were recorded
- Mach Number Ranged from 0.4 to 0.9

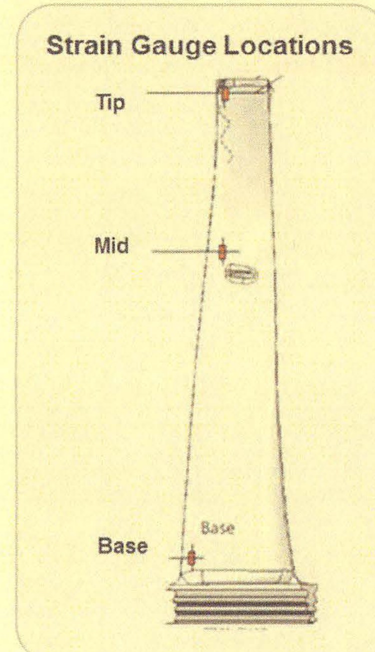


CONFIDENTIAL

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

Frequency Response from Telemetry Test :





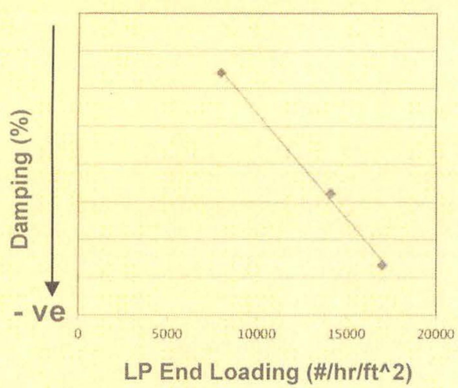
Recorded Response :

- 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)

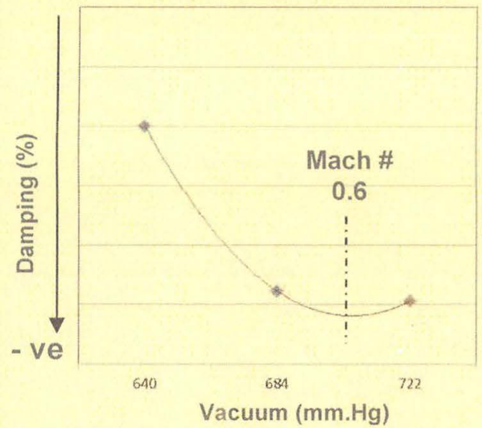
Analytical results of damping below show trends, but the magnitude of blade response is established empirically from the telemetry test conducted at the start of period 3

Aerodynamic Damping as Fn of LP End Loading



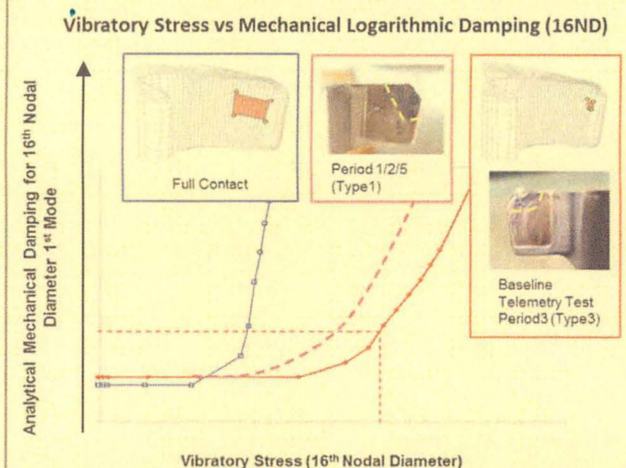
- Aerodynamic damping decreases with higher LP End Loading

Aerodynamic Damping as Fn of Vacuum



- Minimum aerodynamic damping at Mach# = 0.6

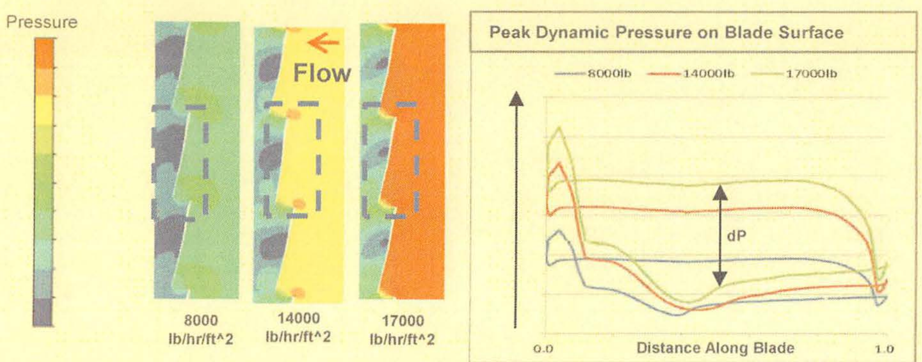
Mechanical Damping as Fn of Contact Area and Vibratory stress



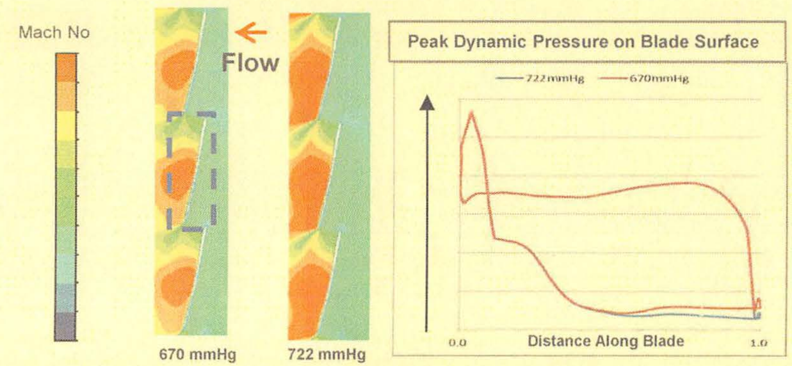
- Mechanical damping decreases with smaller contact area

Aerodynamic Damping Analysis (Vibratory Stress and Logarithmic Damping)

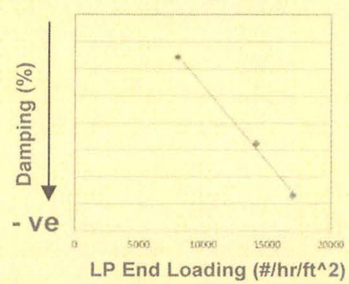
Aerodynamic Damping vs Load



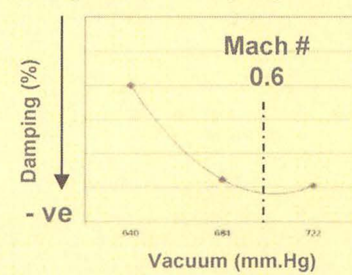
Aerodynamic Damping vs Mach No



Aerodynamic Damping as Fn of LP End Loading



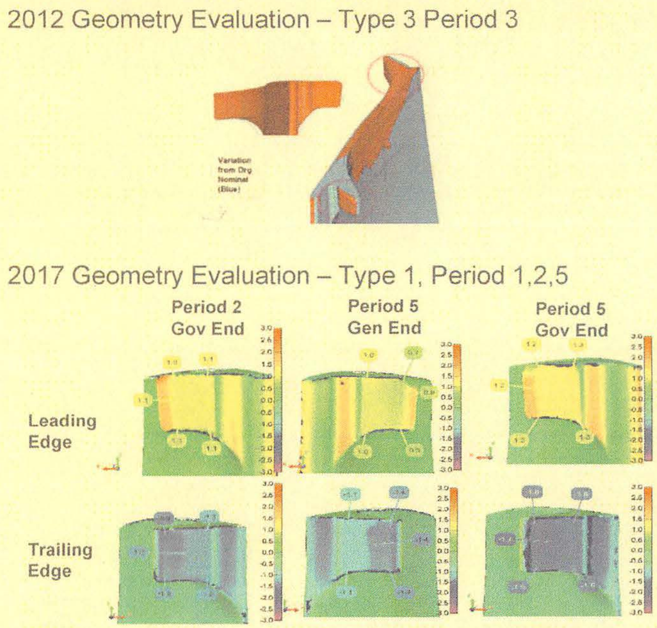
Aerodynamic Damping as Fn of Vacuum

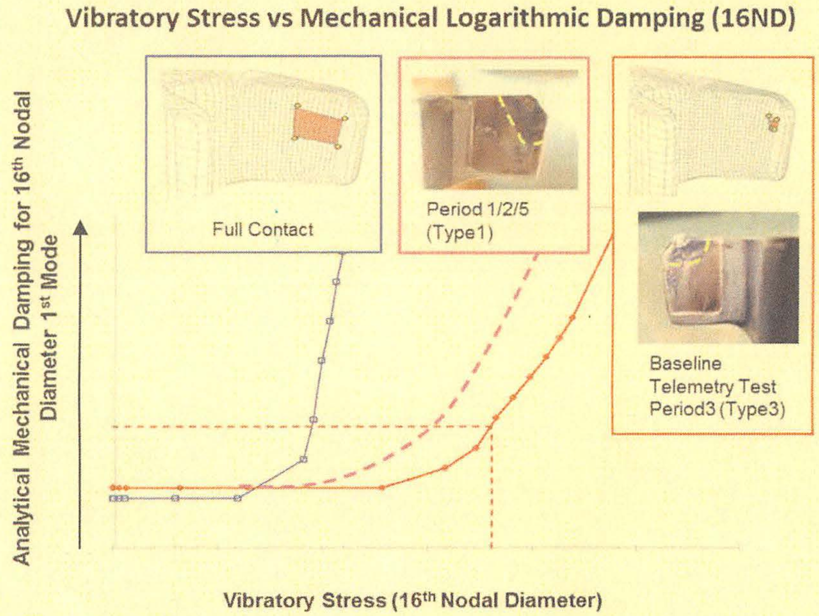


Transient CFD was Correlated with Telemetry Test Data to understand Aerodynamic Damping

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



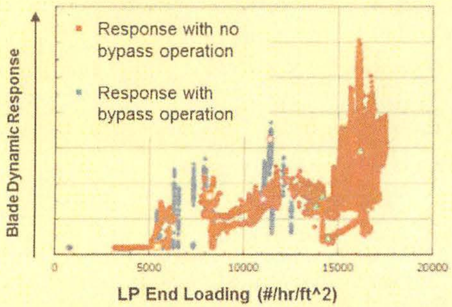


Analytical damping results are intended to understand drivers for blade response, absolute blade response was established from Telemetry Test

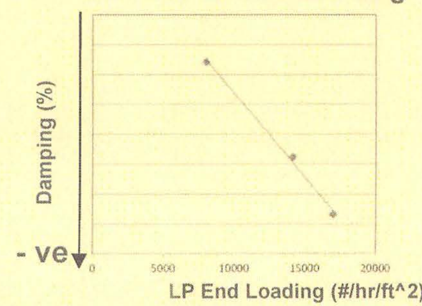
- Type 3 Blades established the baseline blade response from the telemetry test.
- Type 3 Blades were found to have lower damping than Type 1 Blades due to smaller contact area

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

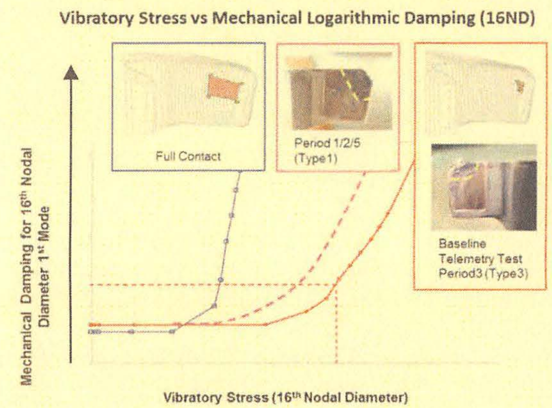
Blade Response as Fn of LP End Loading



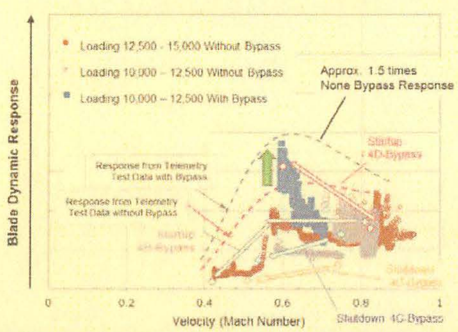
Aerodynamic Damping as Fn of LP End Loading



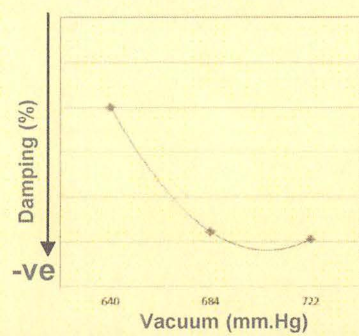
Mechanical Damping as Fn of Contact Area and Vibratory stress



Blade Response as Fn of Mach No. and Bypass Operation



Aerodynamic Damping as Fn of Vacuum

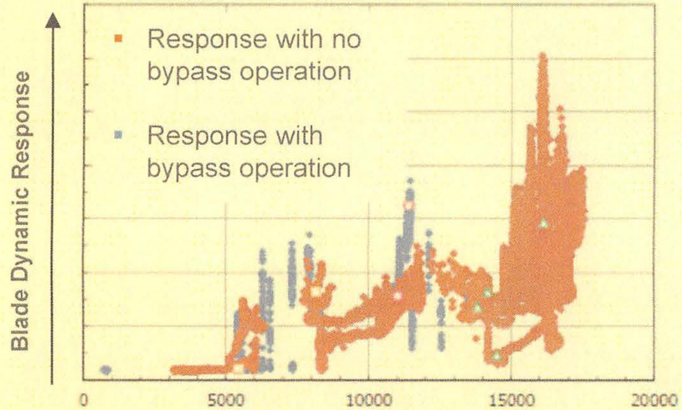


- **Details in following slides**

Blade Response as a Function of LP End Load

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

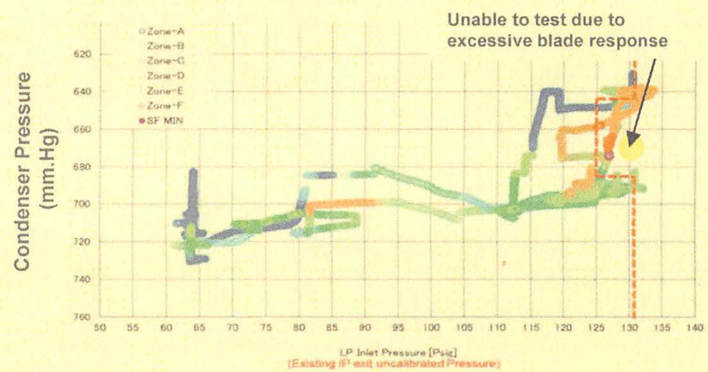
Blade Response vs LP End Loading



LP End Loading (#/hr/ft^2)

Blade Response vs Pressure and Condenser Pressure

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

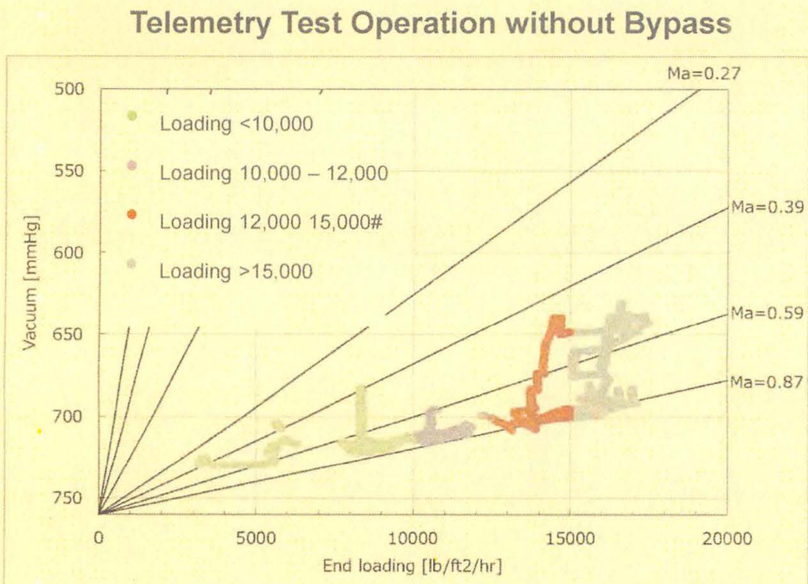


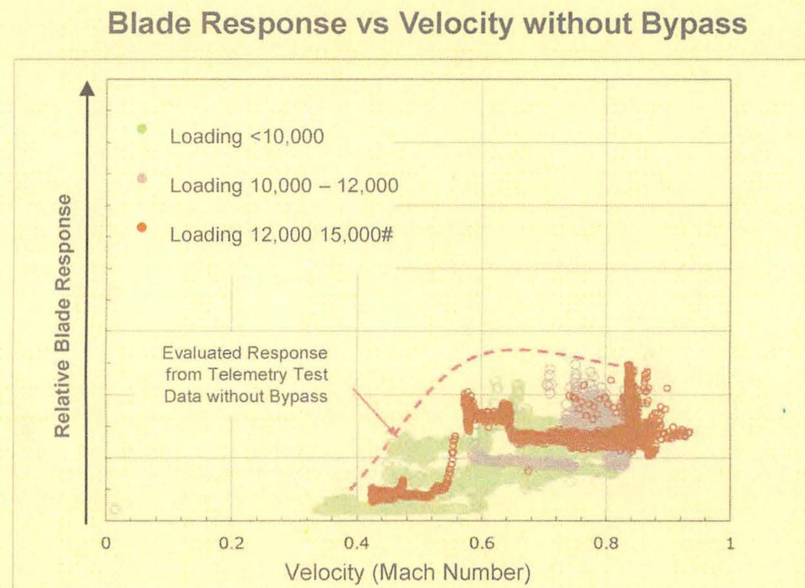
LP Inlet Pressure (psig) , ∝ End Loading

- 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.

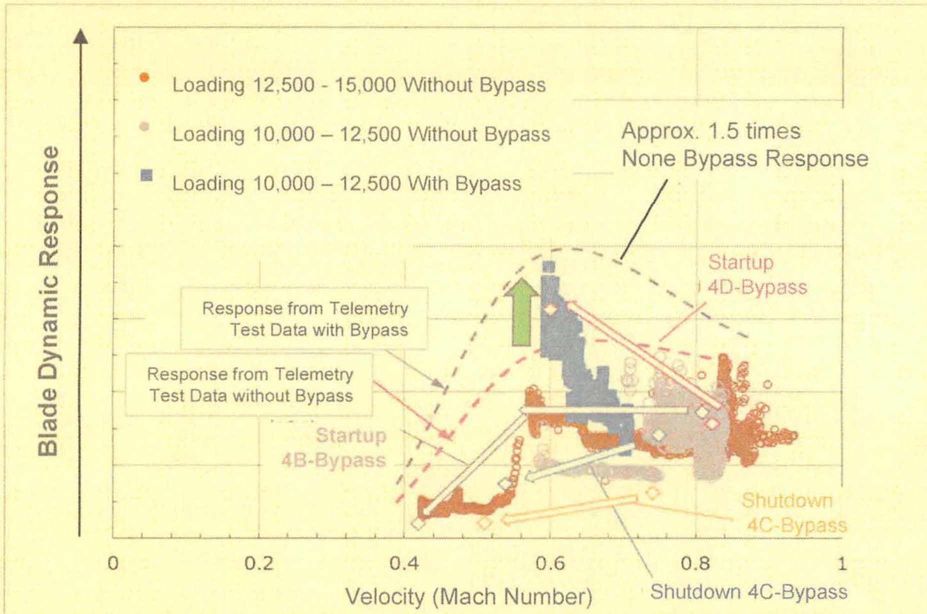
Blade Response as a Function of Mach Number – without Bypass



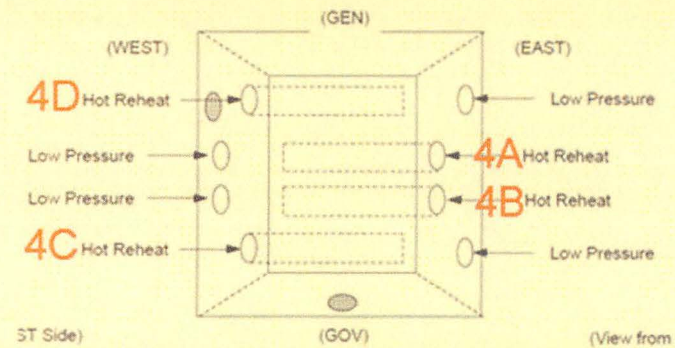


- Below 15,000 lb/hr/ft^2 Blade Response becomes dominated by Mach Number

Blade Response as a Function of Bypass Operation



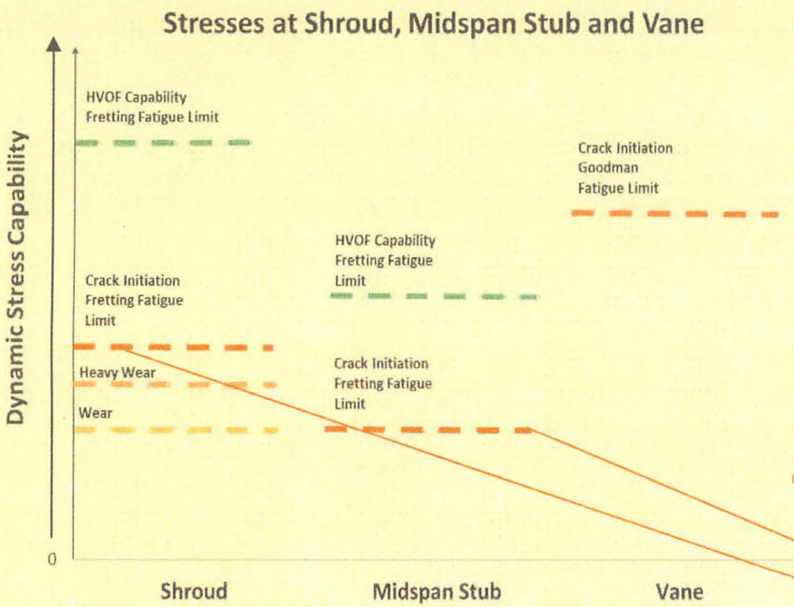
Bypass Connection Locations



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

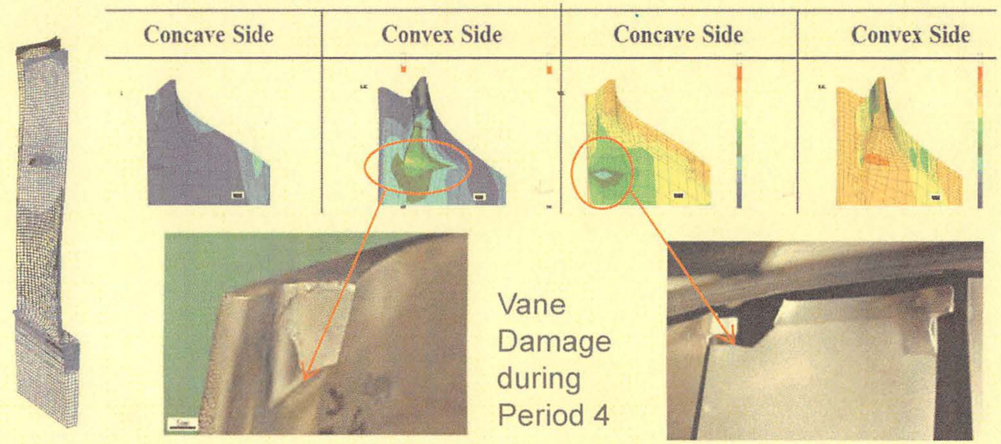
- Operation with Bypass D and C Produce a 1.5X Increase in blade response on the blades closest to the bypass
- Operation with Bypass A and B did not show an increase in blade response over none Bypass Operation
- Limited Blade Response data during Bypass is available with the operation before and after Dec 2014 Telemetry Testing being assumed to have remained the same change in response.

Material Capability – Material Test Data

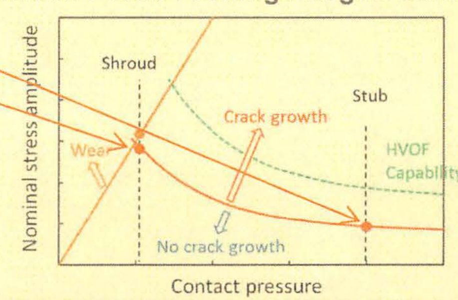


- Estimated Blade Response can be evaluated against Material Capability for Shroud, Mid Span Stub, and Vane

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



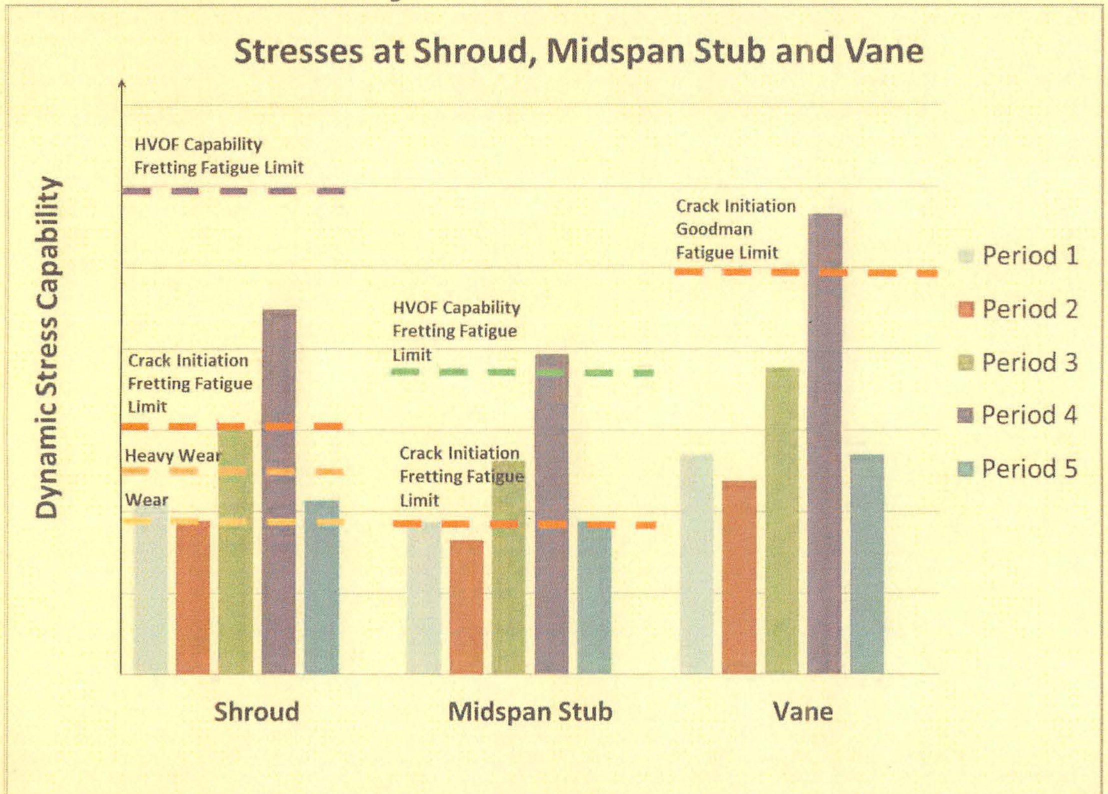
- Shroud / Stub Fretting Fatigue Damage based on fretting material testing



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

CONFIDENTIAL

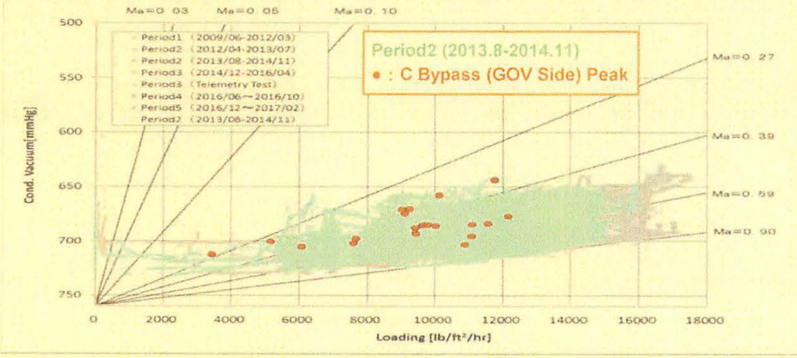
Stress Summary – Period 1 thru 5



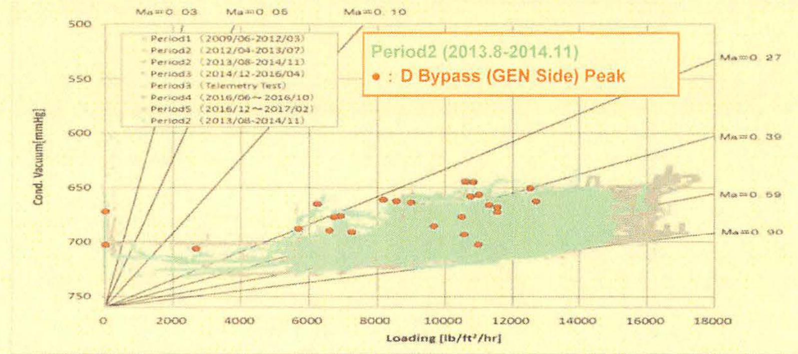
- **Period 1 – Mid Span Stub Cracking**
  High LP Loading but increased mechanical damping from Type 1 blade over baseline telemetry test
- **Period 2 – No Major Damage**
  Reduced LP Loading over Period 1, reduced bypass operation loading over period 5, light wear observed on shroud
- **Period 3 – Shroud 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

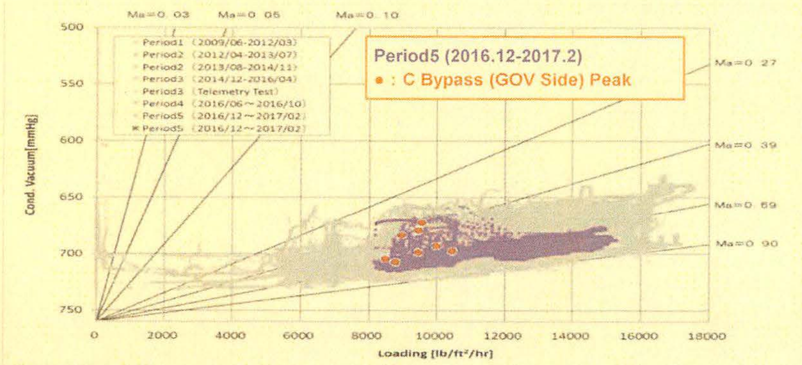
How is the different operating experience between Period 2 and Period 5 explained ?



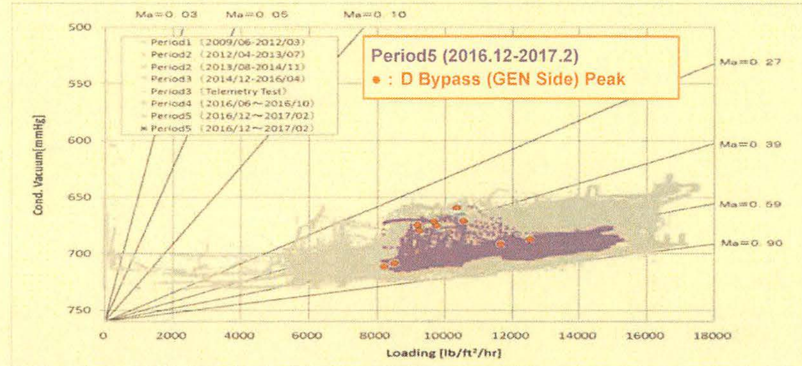
Period 2 Gov End - Type 1 Blade



Period 2 Gen End - Type 1 Blade



Period 5 Gov End - Type 1 Blade



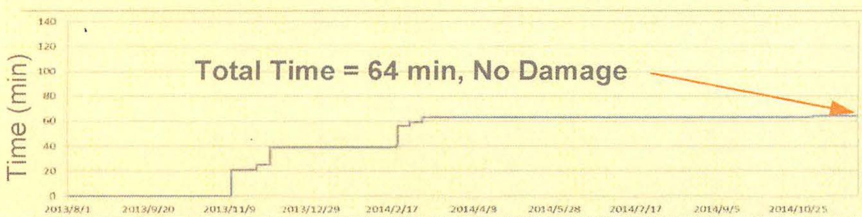
Period 5 Gen End - Type 1 Blade

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

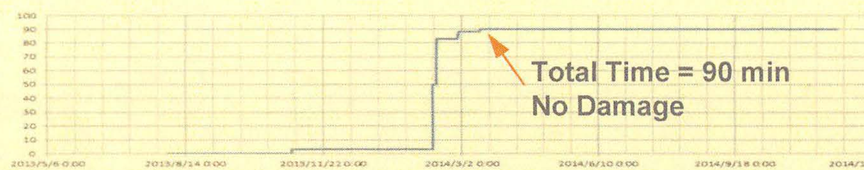
The following evaluation is intended to highlight difference in Period 2 to 5. It is not intended to be an absolute methodology to predict damage accumulation on the blades.

- 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

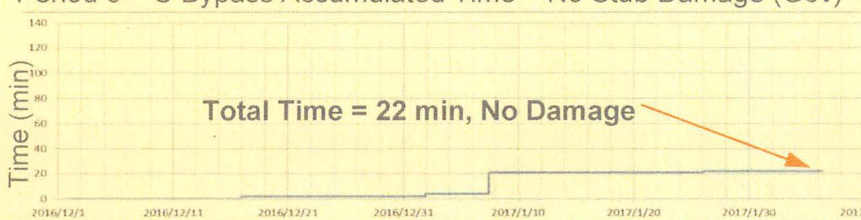
Period 2 – C Bypass Accumulation – No Stub Damage (Gov)



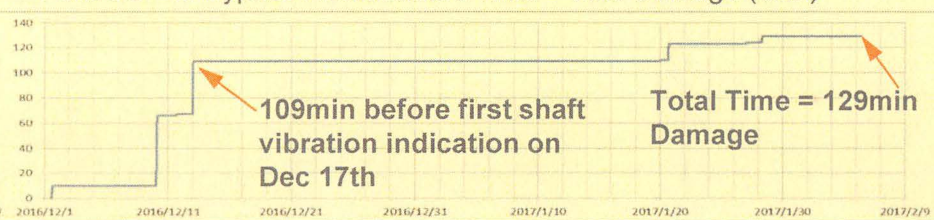
Period 2 – D Bypass Accumulation – No Stub Damage (Gen)
+ Period 1 but no minute data available



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



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



RCA Summary

Period	Operating Time	Blade Type	Loading	Aerodynamic Damping	Mechanical Damping	Root Cause
Period 3	Dec 2014 – Apr 2016	HVOF Midpspan 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

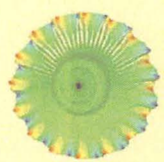
Features :

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

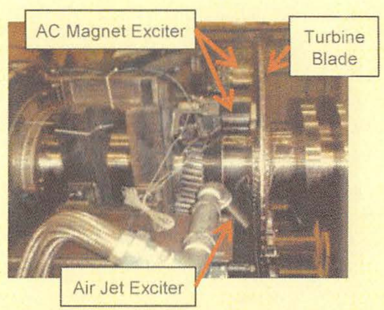
2) Test Facility Upgraded to Excite High Nodal Diameter Modes



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

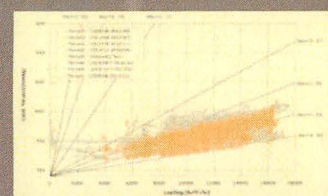
If required based on Telemetry Test results, operating guidelines for bypass can reduce blade response by minimizing operation of C and D Bypass at a Mach # > 0.55
DCS controls update strategy is in evaluation.

CONFIDENTIAL

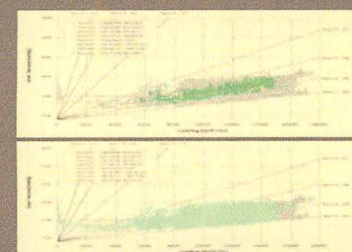
MHPS

Backup

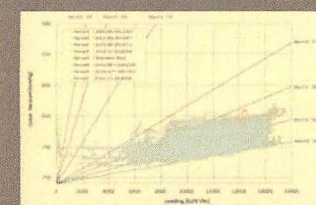
Operating Summary Period 1 thru 5



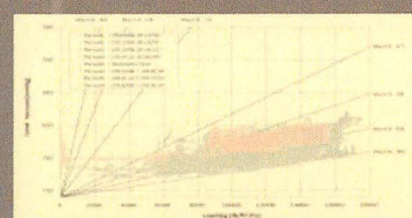
Period 1



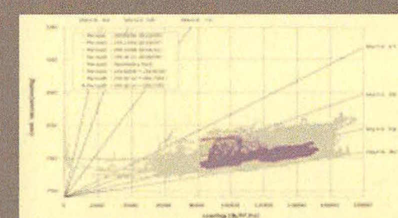
Period 2



Period 3



Period 4

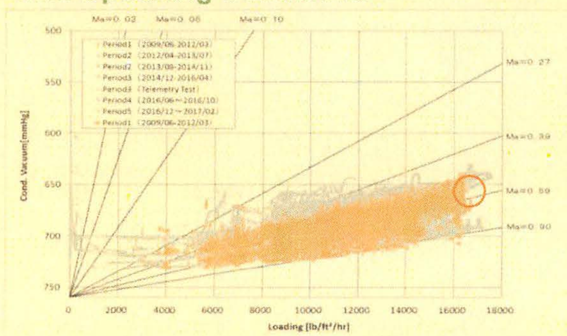


Period 5

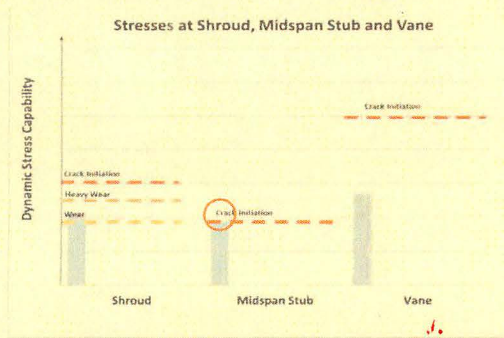
Period 1 – Stub Cracking

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

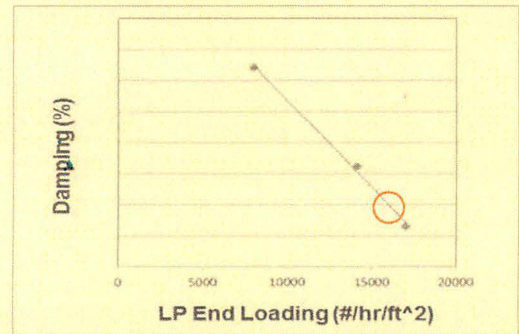
Max Operating Conditions



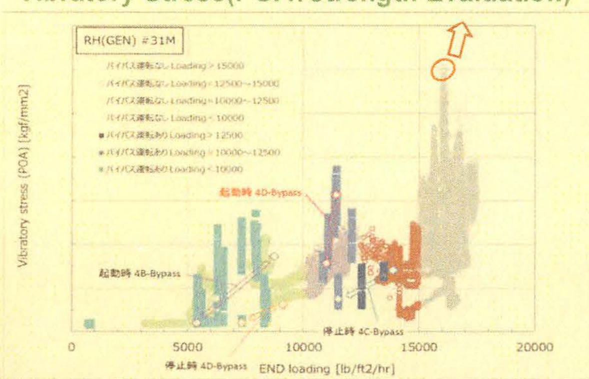
Dynamic Stress from Damage



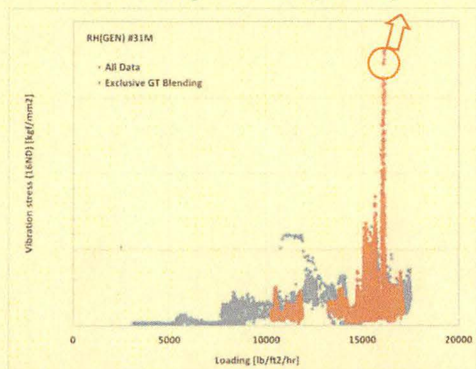
Aerodynamic Damping (3D Flutter Analysis)



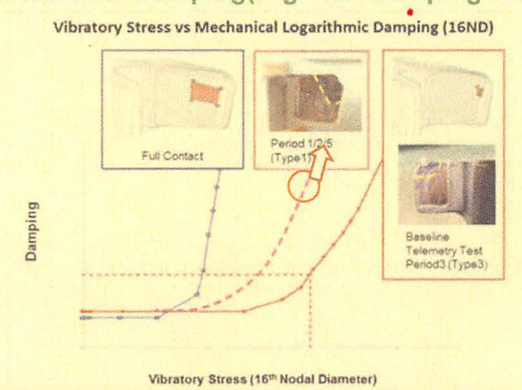
Vibratory Stress(POA：Strength Evaluation)



Vibratory Stress (16ND)



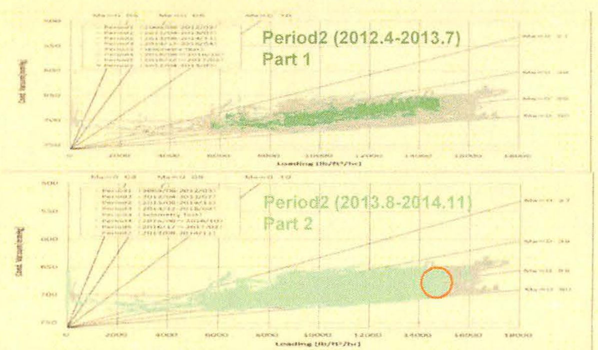
Mechanical Damping(High ND Damping Analysis)



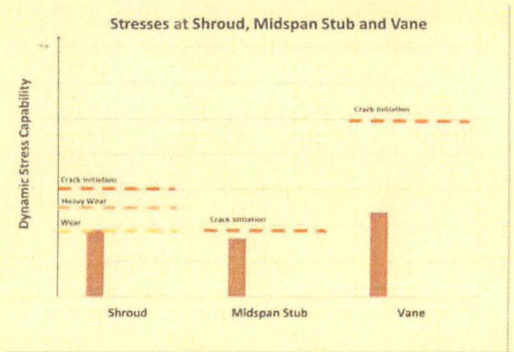
Period 2 – No Major Damage, Minor Shroud Chipping

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

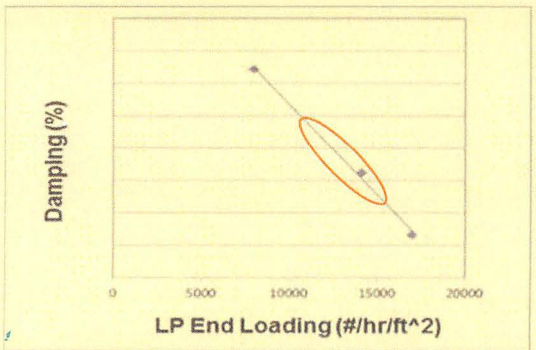
Max Operating Conditions



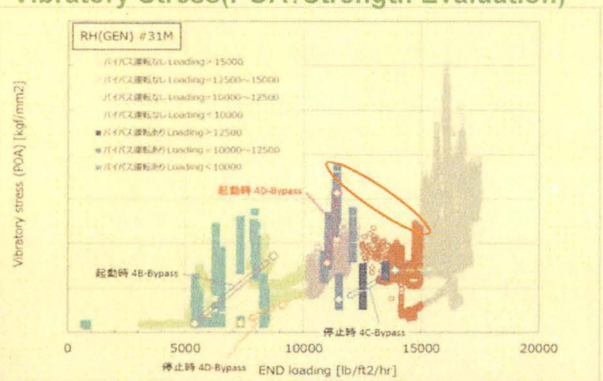
Dynamic Stress Summary (POA)



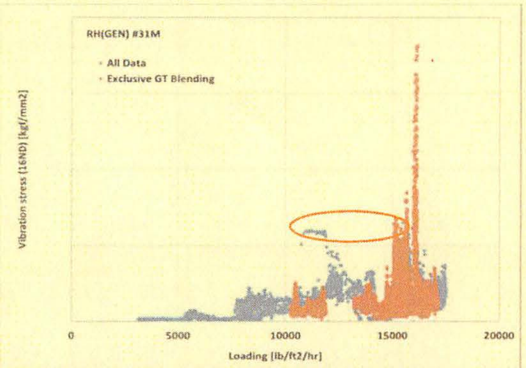
Aerodynamic Damping (3D Flutter Analysis)



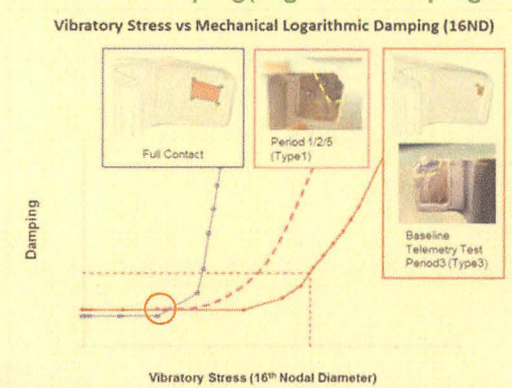
Vibratory Stress(POA: Strength Evaluation)



Vibratory Stress (16ND)



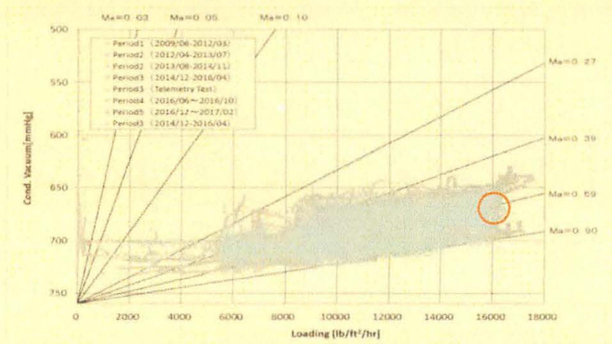
Mechanical Damping(High ND Damping Analysis)



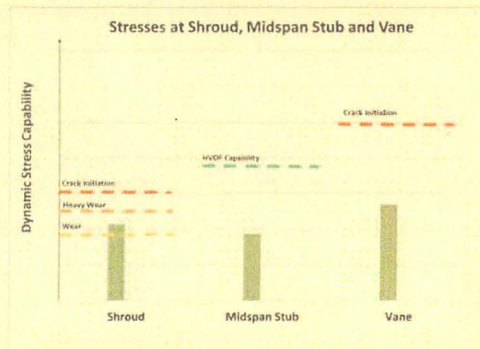
Period 3 – Shroud Cracking - Outside Avoidance Zone

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

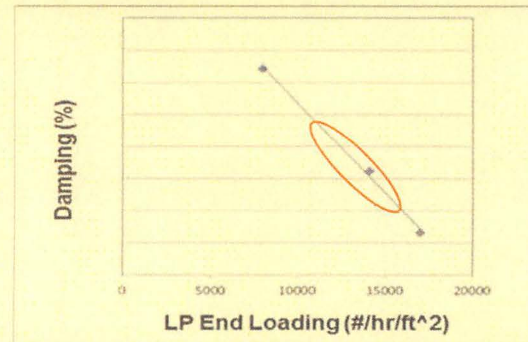
Max Operating Conditions



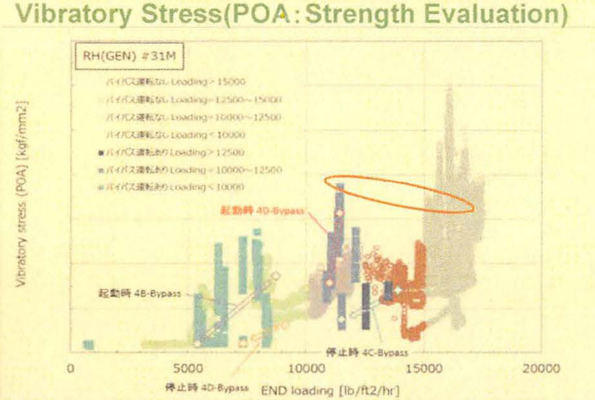
Dynamic Stress Summary (POA)



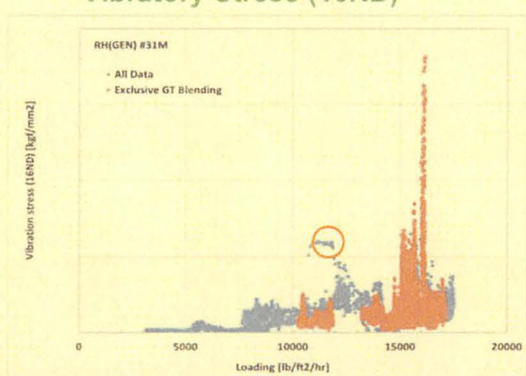
Aerodynamic Damping (3D Flutter Analysis)



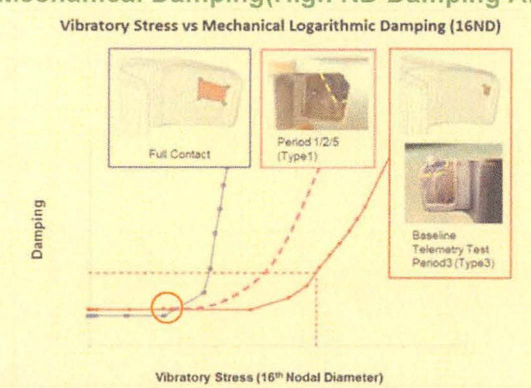
Vibratory Stress(POA: Strength Evaluation)



Vibratory Stress (16ND)



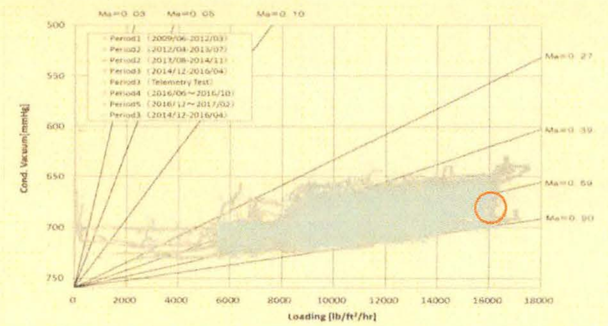
Mechanical Damping(High ND Damping Analysis)



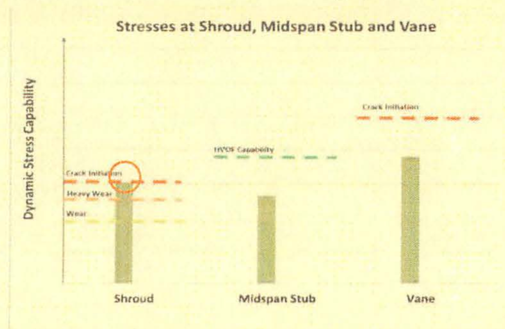
Period 3 – Shroud Cracking– Inside avoidance zone

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

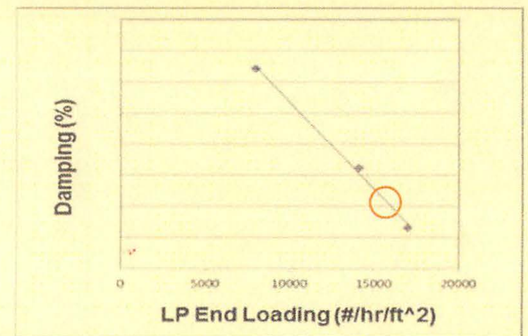
Max Operating Conditions



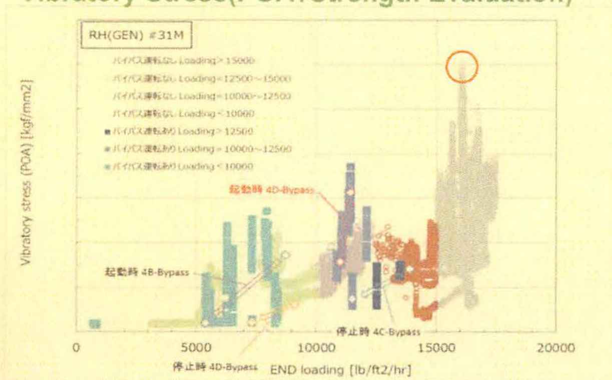
Dynamic Stress Summary (POA)



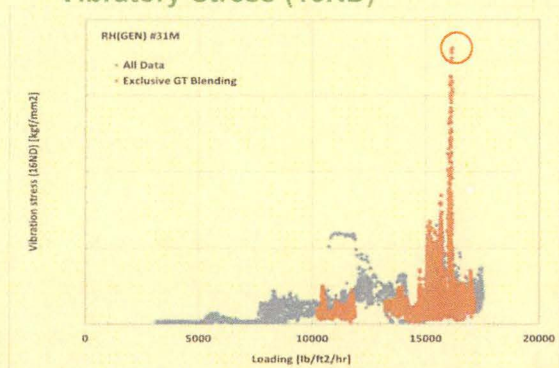
Aerodynamic Damping (3D Flutter Analysis)



Vibratory Stress(POA：Strength Evaluation)

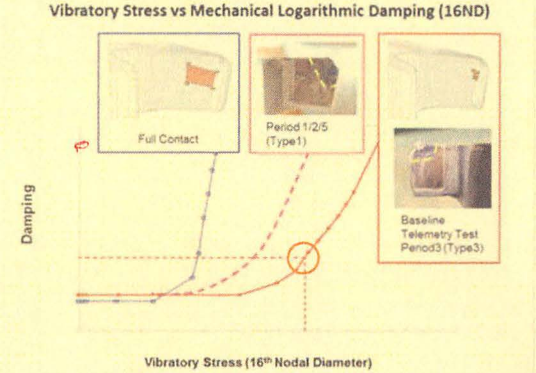


Vibratory Stress (16ND)



Mechanical Damping(High ND Damping Analysis)

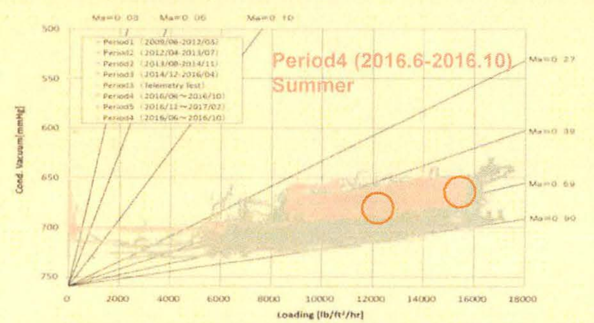
Vibratory Stress vs Mechanical Logarithmic Damping (16ND)



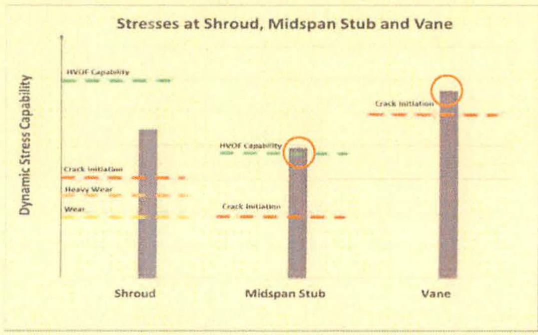
Period 4 – Vane + Stub Cracking

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

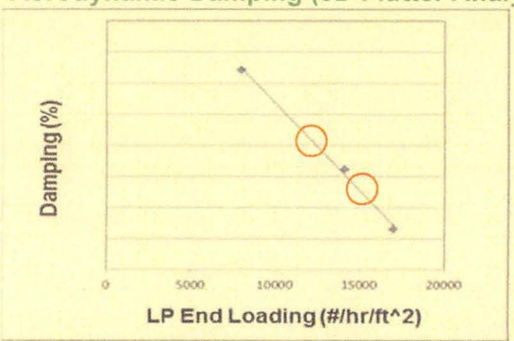
Max Operating Conditions



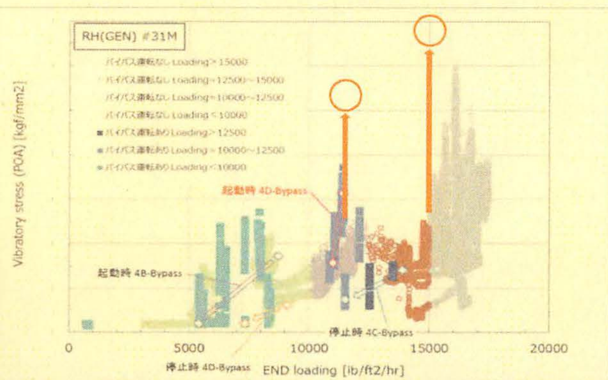
Dynamic Stress Summary (POA)



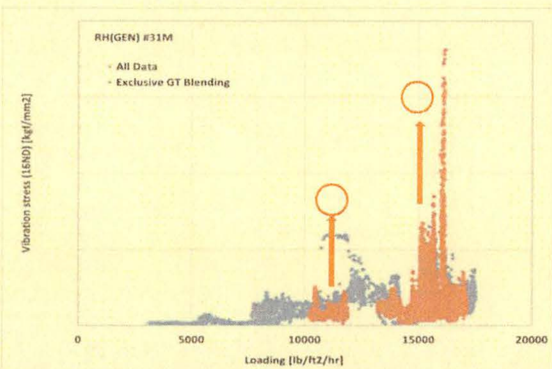
Aerodynamic Damping (3D Flutter Analysis)



Vibratory Stress(POA：Strength Evaluation)

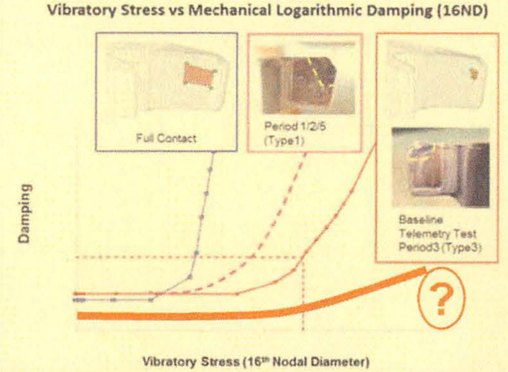


Vibratory Stress (16ND)



Mechanical Damping(High ND Damping Analysis)

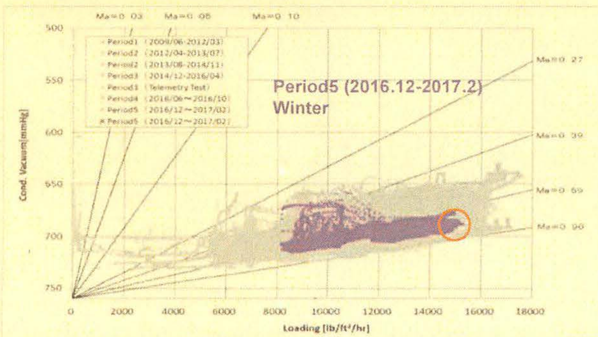
Vibratory Stress vs Mechanical Logarithmic Damping (16ND)



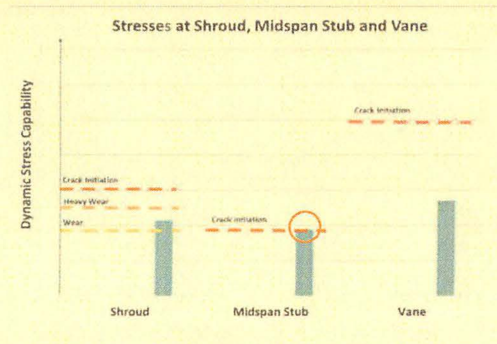
Period 5 – Stub Cracking

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

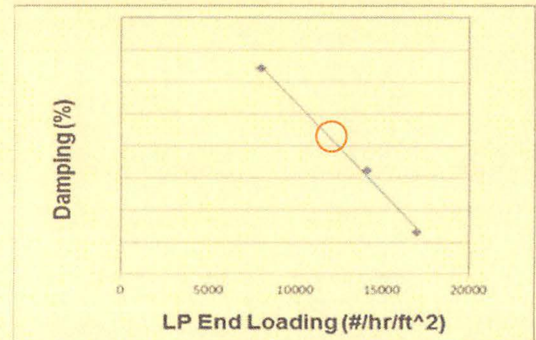
Max Operating Conditions



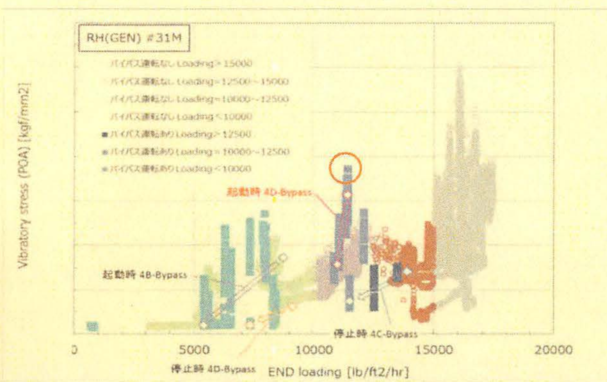
Dynamic Stress Summary (POA)



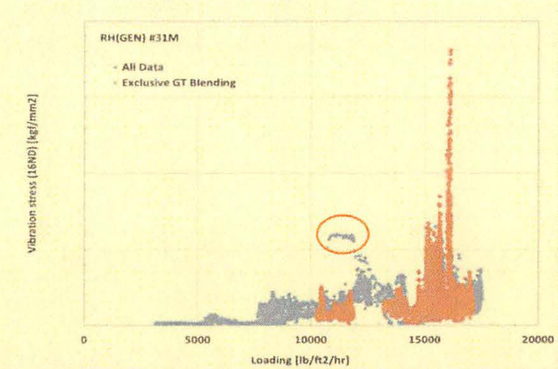
Aerodynamic Damping (3D Flutter Analysis)



Vibratory Stress(POA：Strength Evaluation)



Vibratory Stress (16ND)



Mechanical Damping(High ND Damping Analysis)

Vibratory Stress vs Mechanical Logarithmic Damping (16ND)