FLORIDA PUBLIC SERVICE COMMISSION
OFFICE OF COMMISSION CLERK

DOCUMENT NUMBER ASSIGNMENT*

FILED DATE: 1/13/2020

DOCKET NO.: 20200001-EI

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DOCUMENT NO.: 00223-2020

DOCUMENT DESCRIPTION:

Duke Energy (Bernier) - (CONFIDENTIAL) Exh A [to notice of intent to request confidential classification], information contained in 8/29/19 and 8/30/19, late-filed exhibits to deposition of Messrs. Swartz, Toms, and Salvarezza.

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LFE 6

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

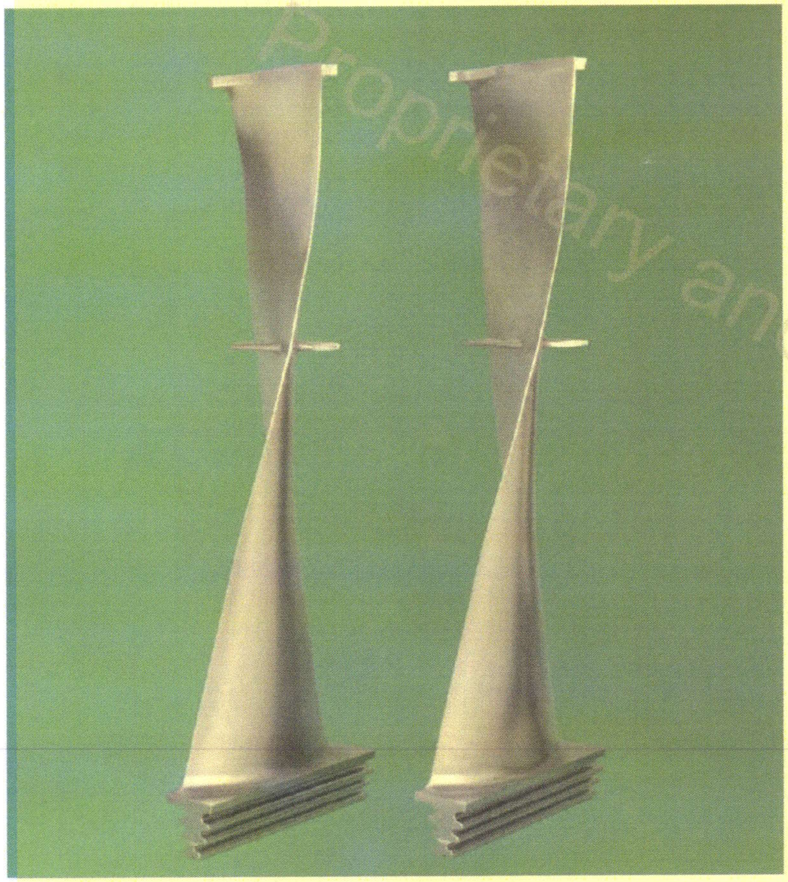
Introduction

- 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.

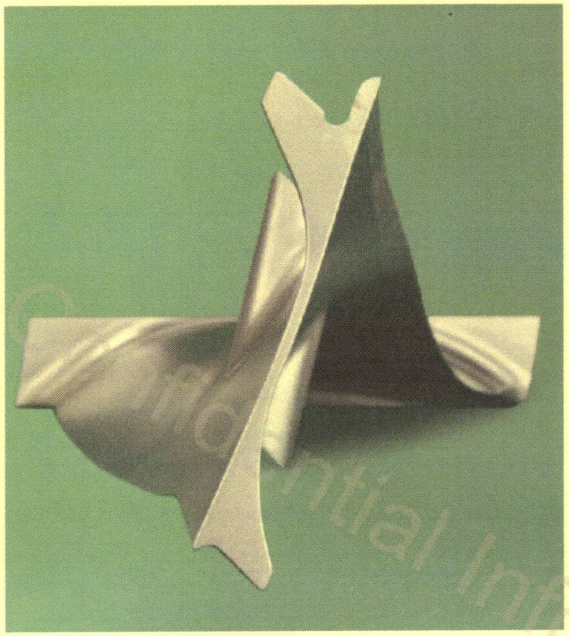
- Once the root cause was understood MHPS developed an upgraded 40" L-0 blade specifically to operate the conditions present at Bartow. **(Note : this is not required across the fleet)**
- To achieve confidence in the capability / reliability of the new blade, extensive testing was conducted.
- The upgrade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

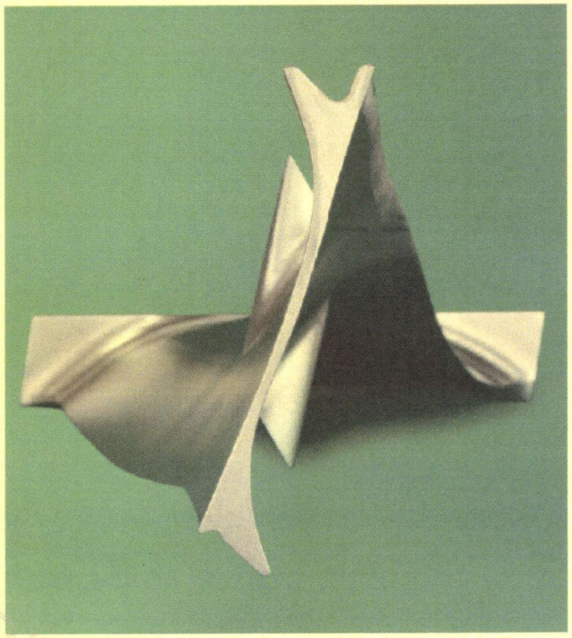
40” L-0 upgrade blade for high loading



Upgraded 40” 40” Old



Upgraded 40”



40” Old

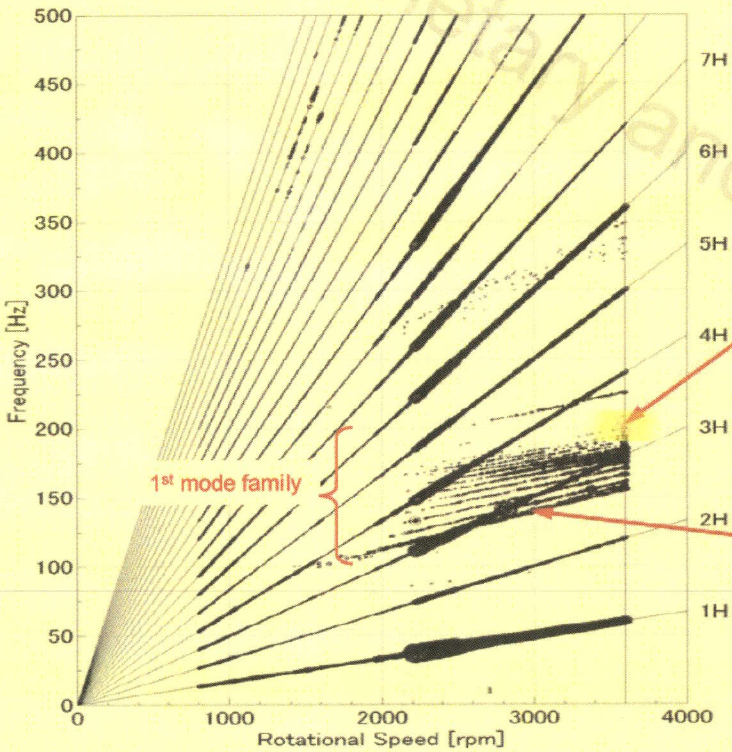
Verification Testing Plan

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

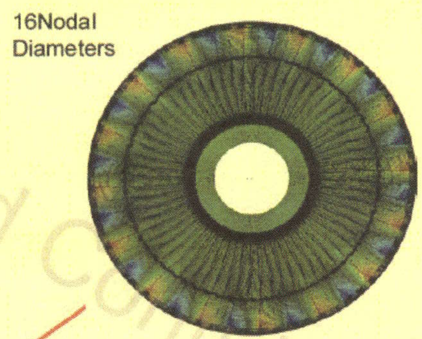
- Factory Verification Testing
  - Harmonic resonance frequency of the upgraded 40" L-0 blade will be measured by air excitation.
  - Mechanical damping of high nodal diameter will be measured by electromagnetic excitation. Measured mechanical damping will certify reliability for non synchronous vibration.
  - 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.

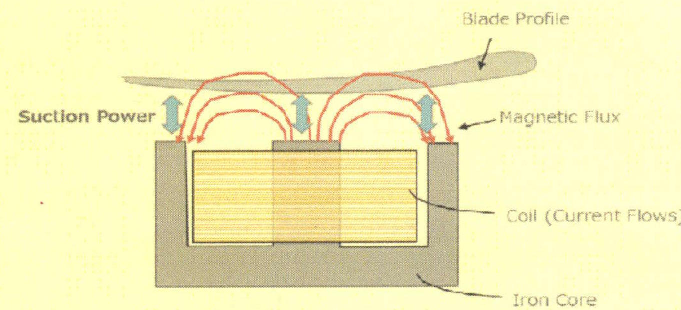
Outline of Factory Verification Testing

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.



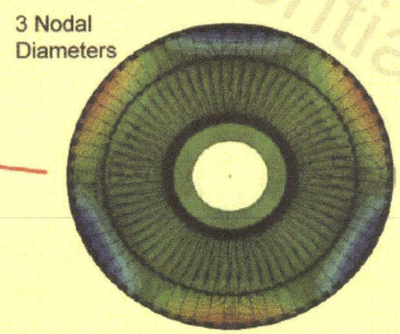
Sample Campbell Diagram

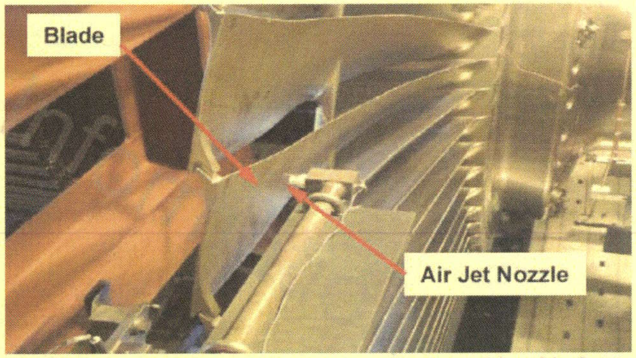




Vibrator (AC) suctions blade by Magnetic Filed

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





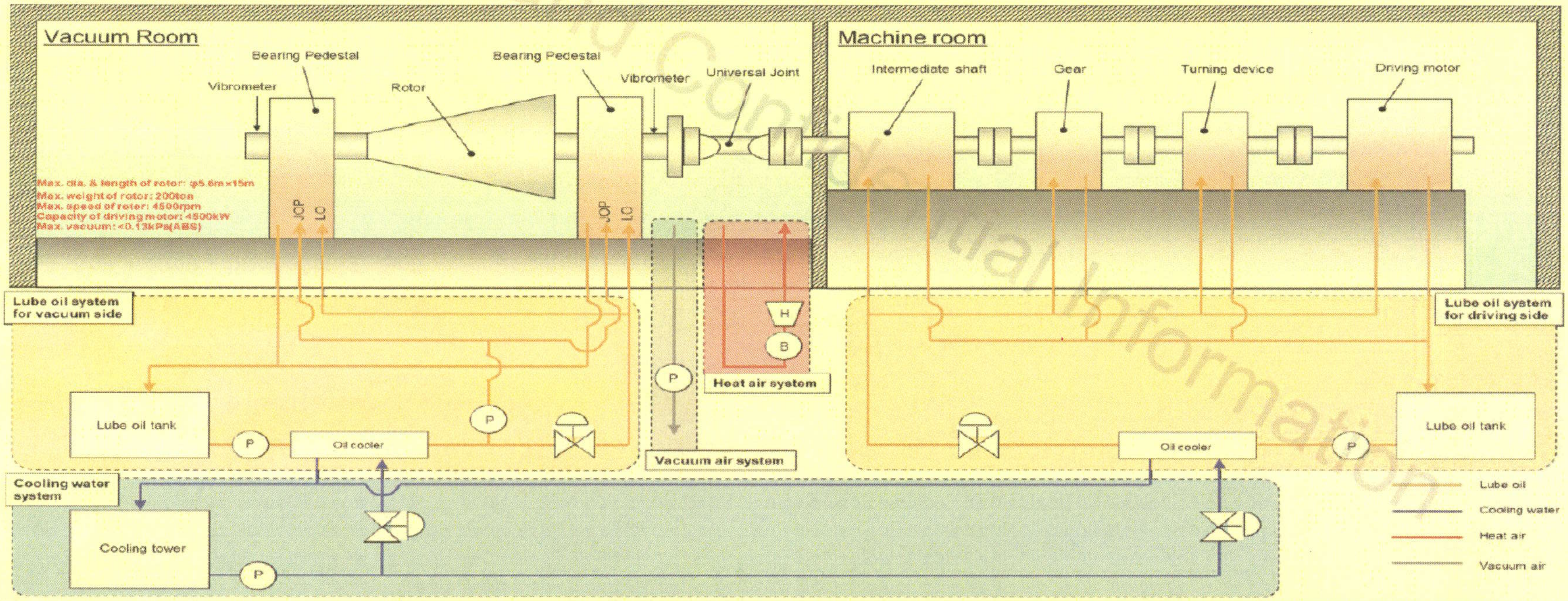
The blade frequencies and responses of harmonic resonance are measured by Air jet test

Test Facility

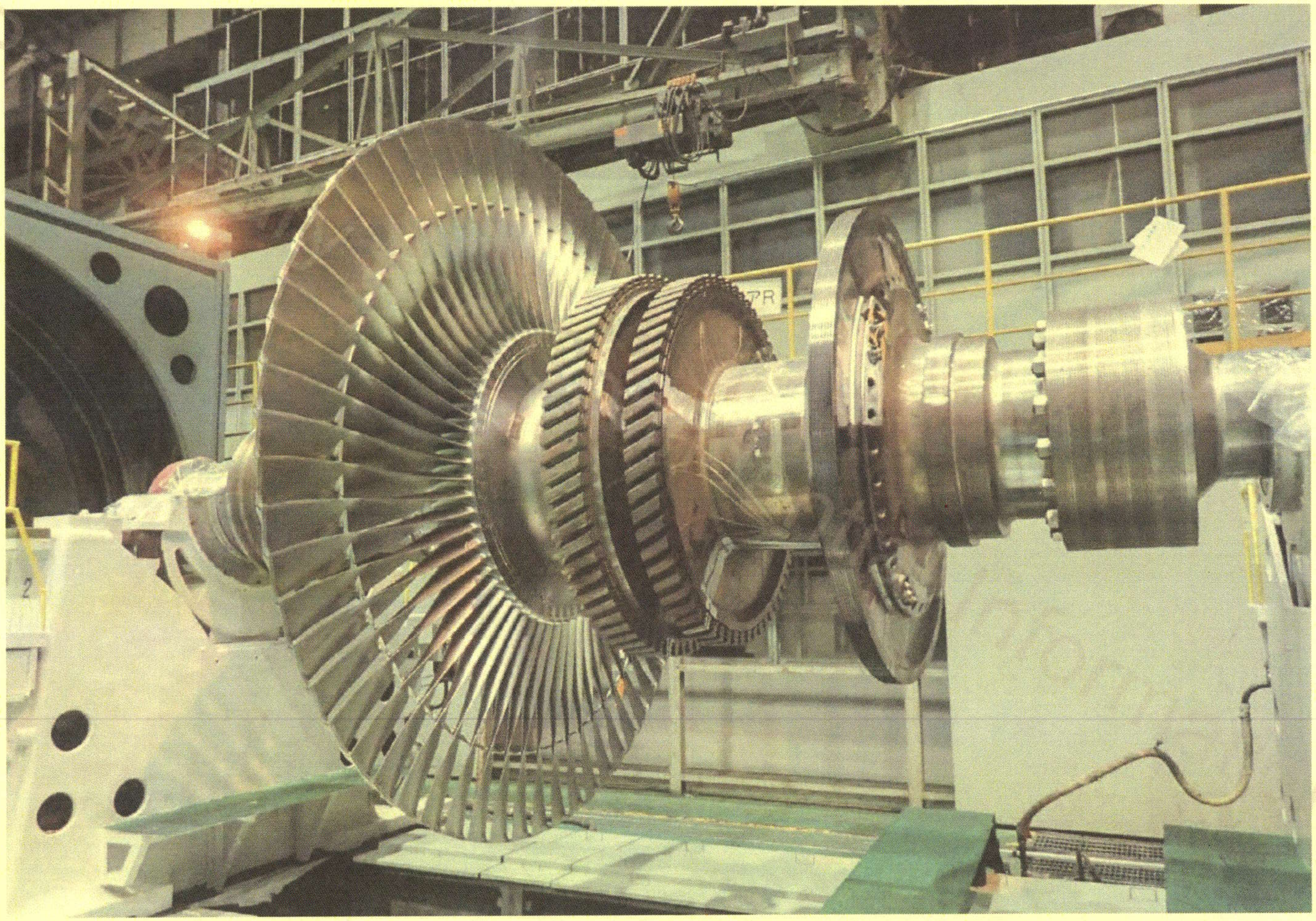
Verification test was carried out at HSB (High Speed Balance) test facility in Takasago factory.

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.

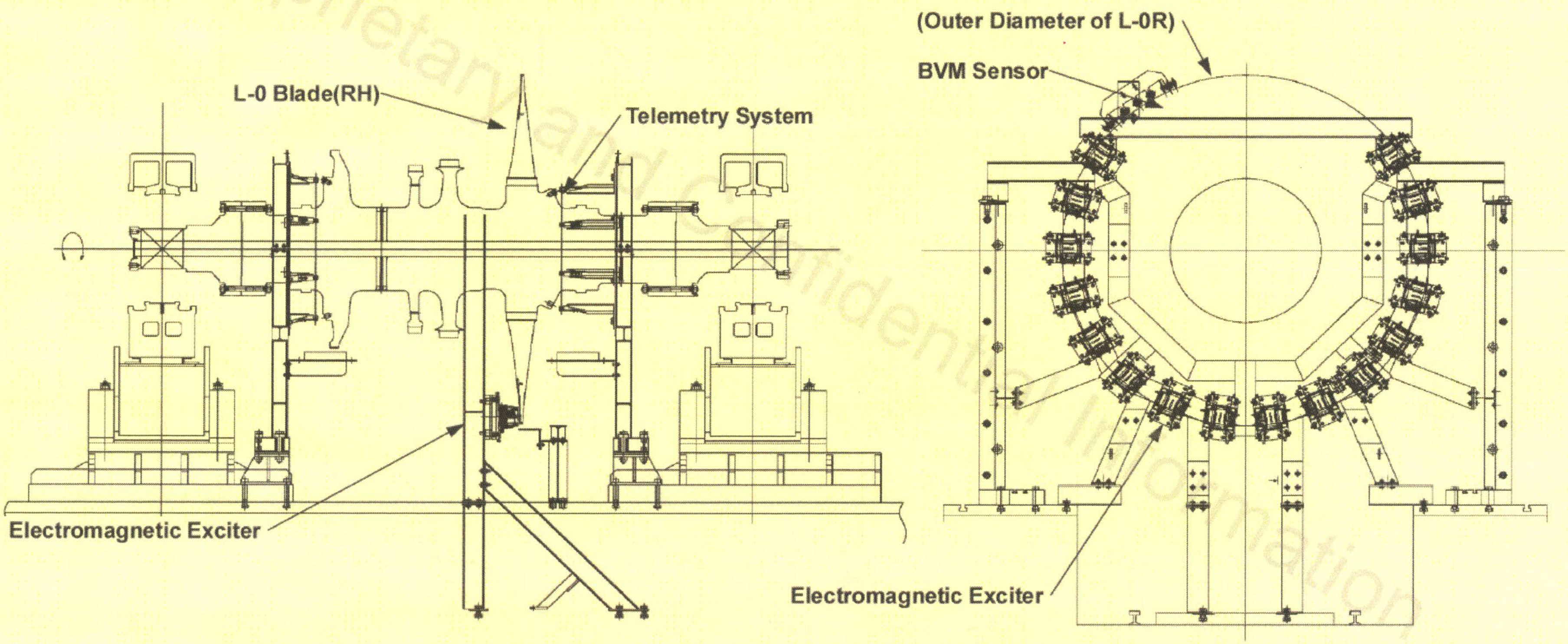


Test Rotor with Production Blades

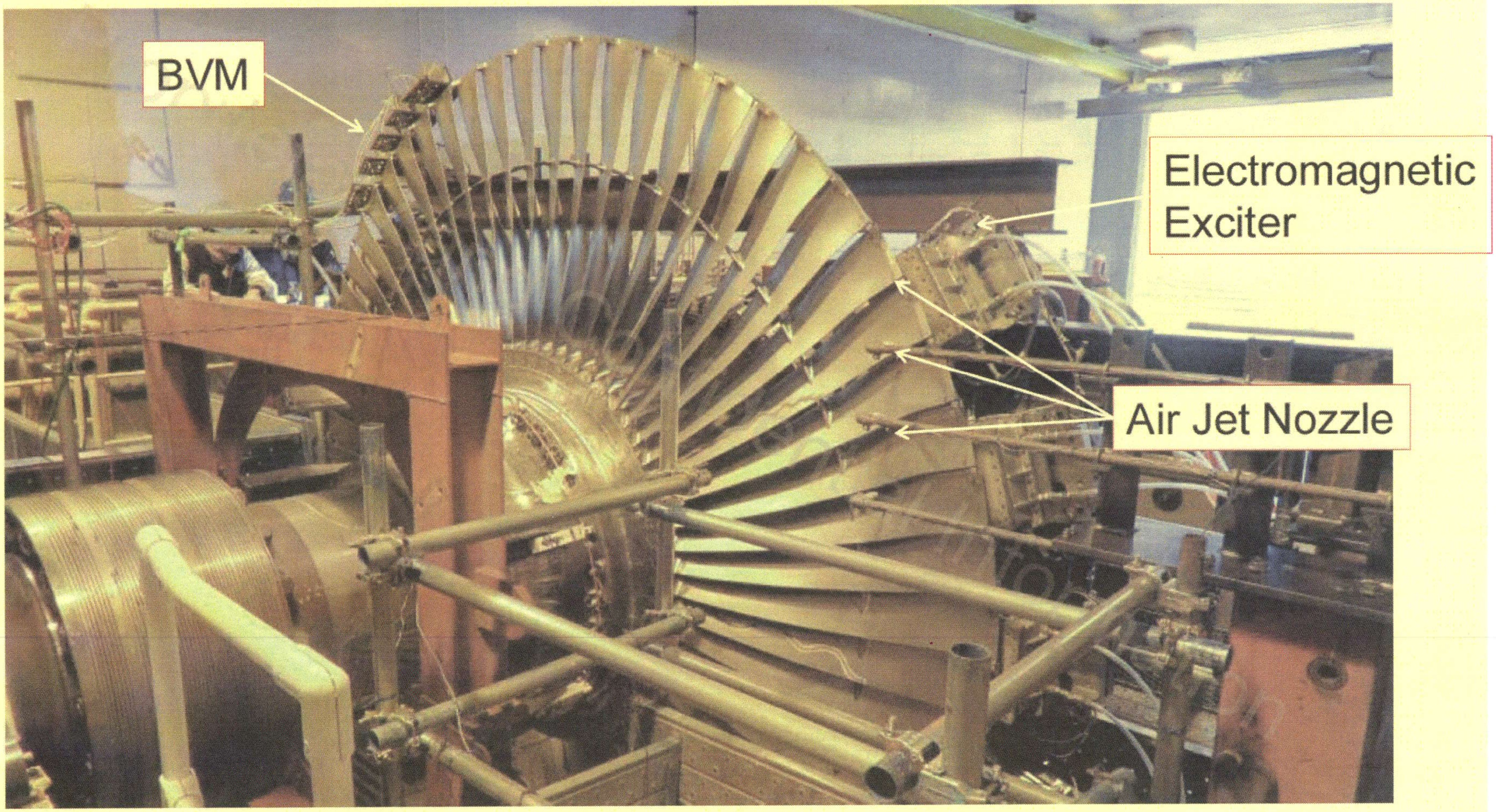


Verification Test Procedure

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



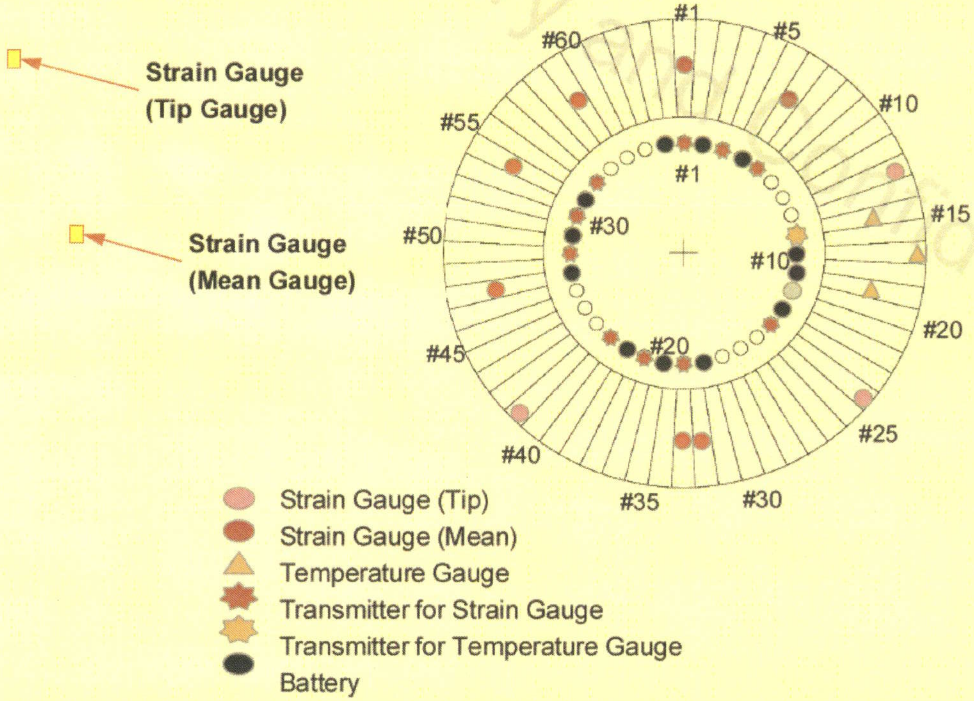
Installed Rotor in the Vacuum Chamber

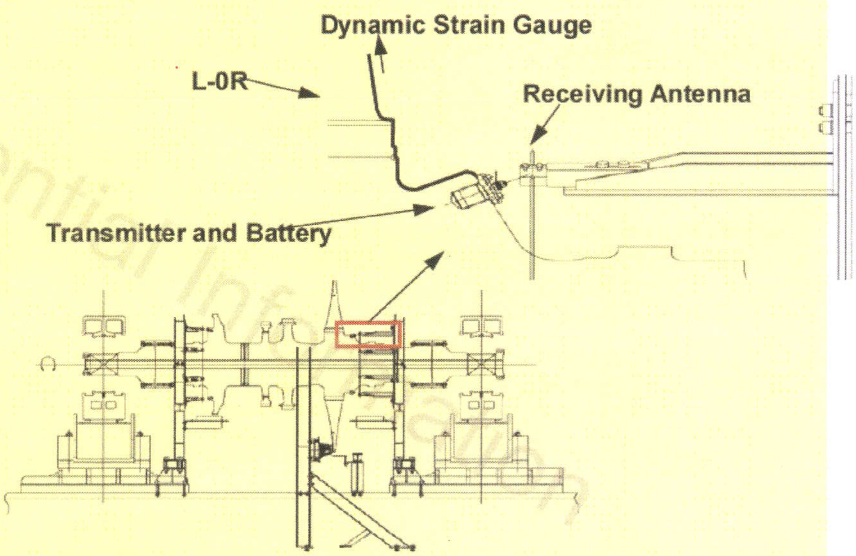


Telemetry Measurement

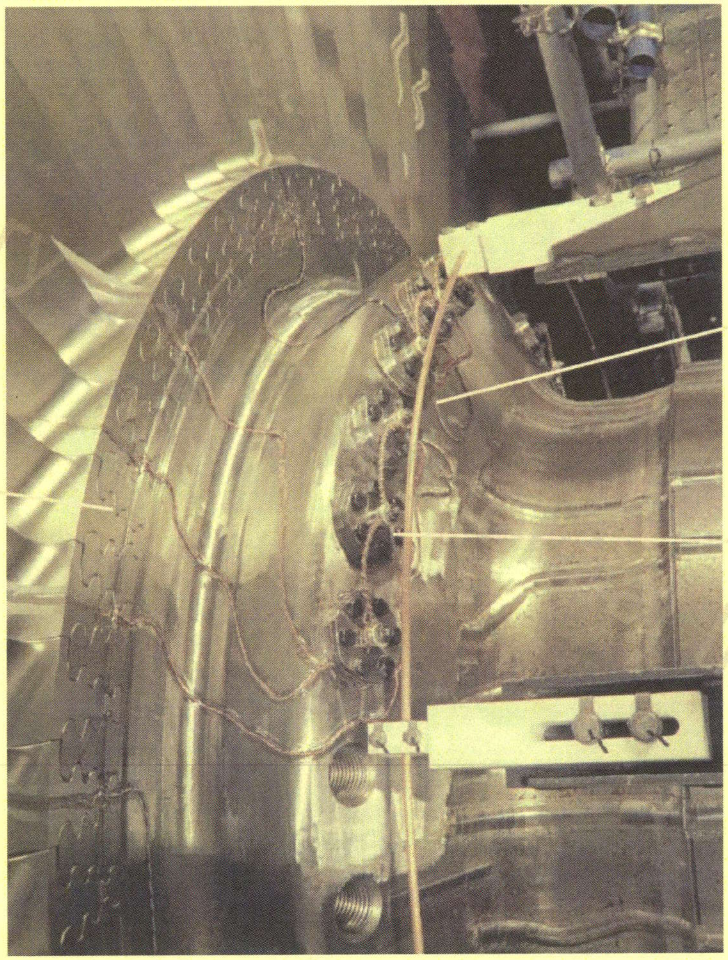
The blade vibration stress was measured by the dynamic strain gauge attached to the tip and the mean of blade surface.

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

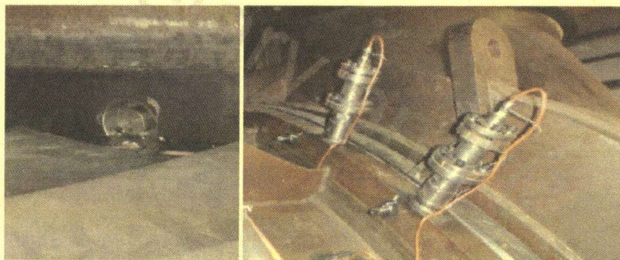


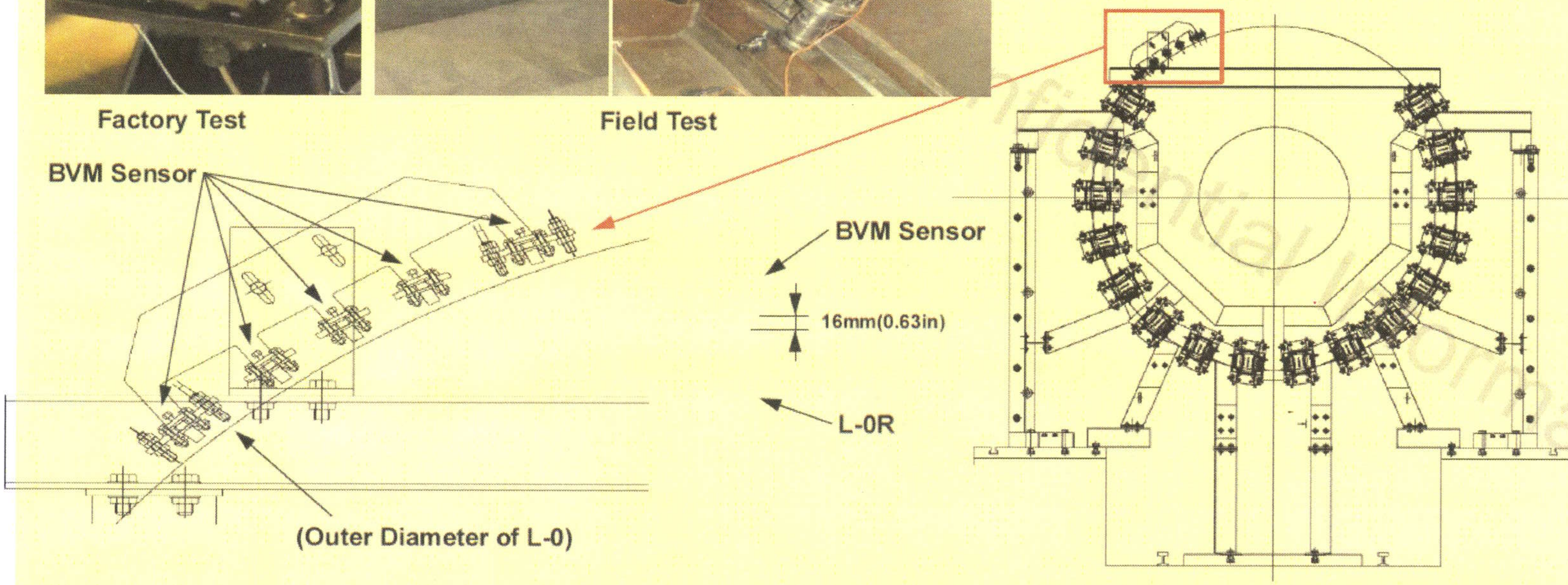
Blade Vibration Monitoring (BVM) Measurement

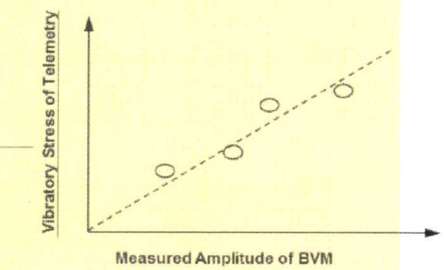
The blade vibration amplitude was measured by the BVM sensors set close to the tips of the blades.

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


Factory Test


Field Test





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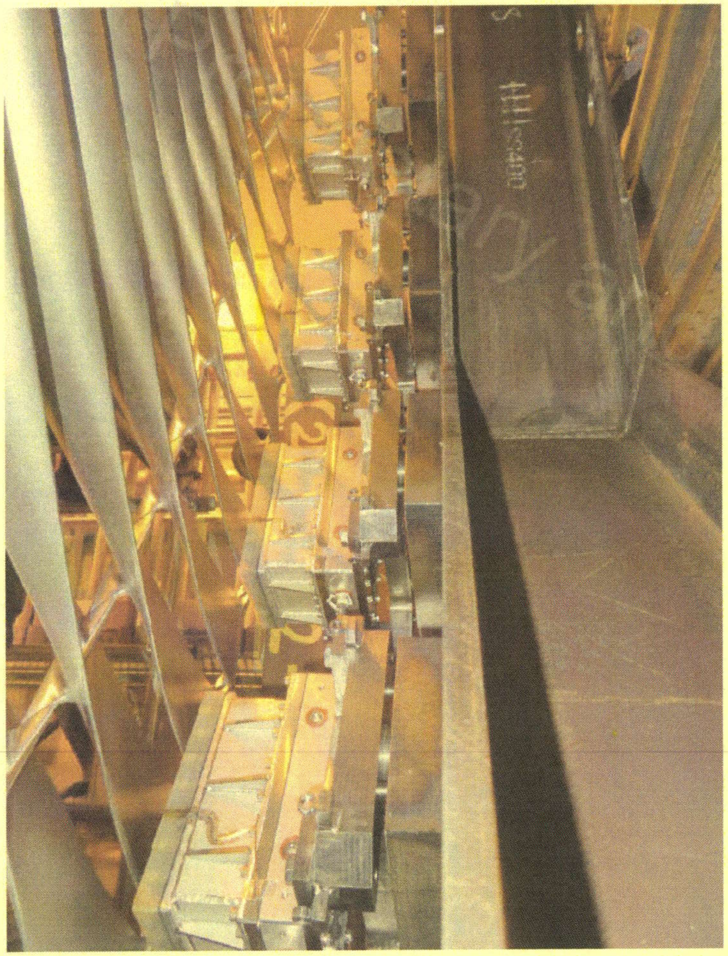
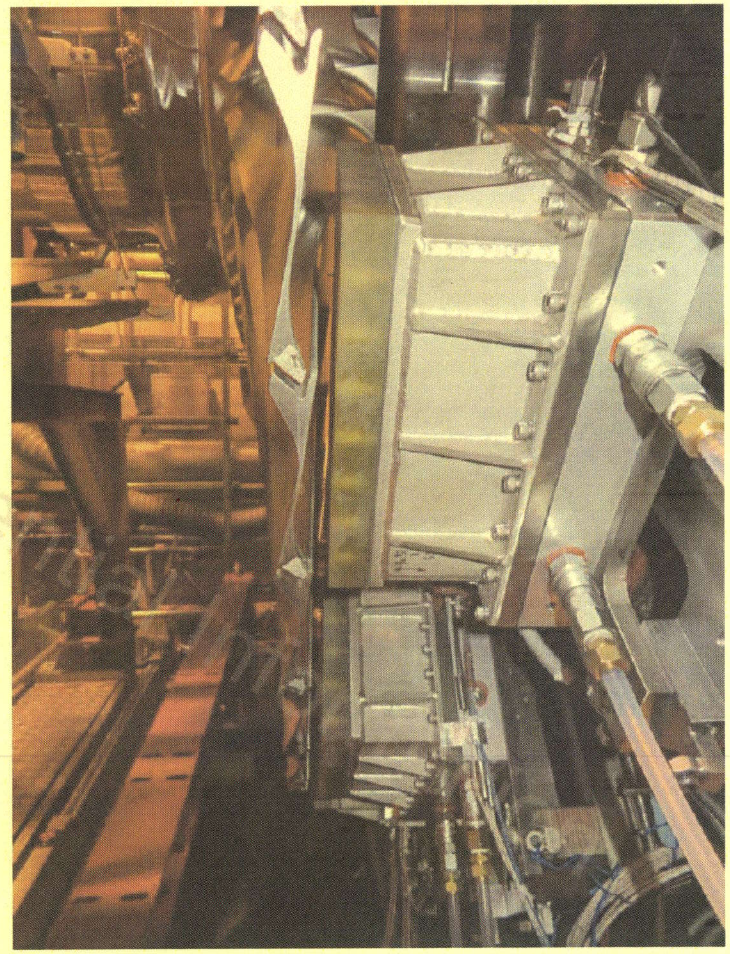
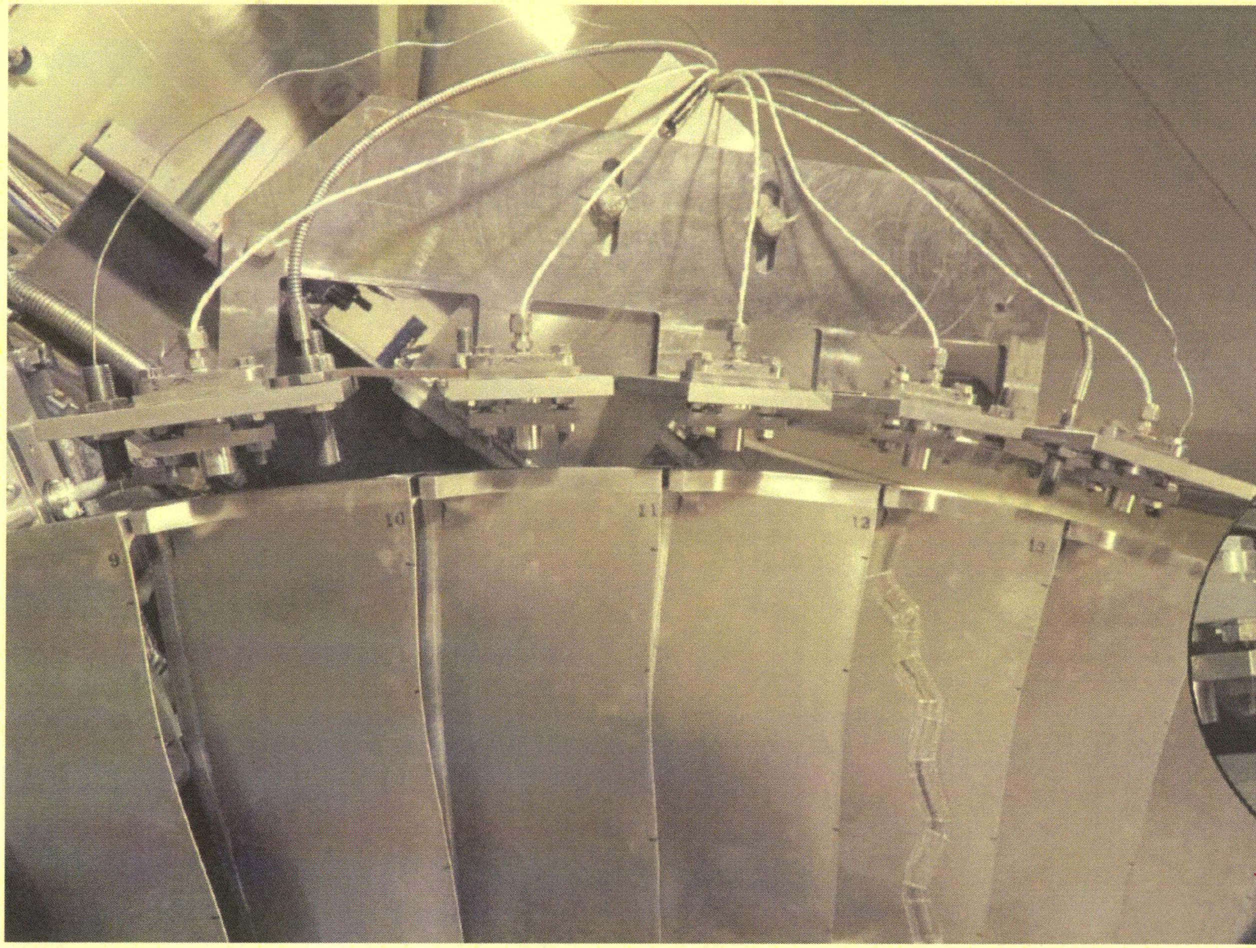
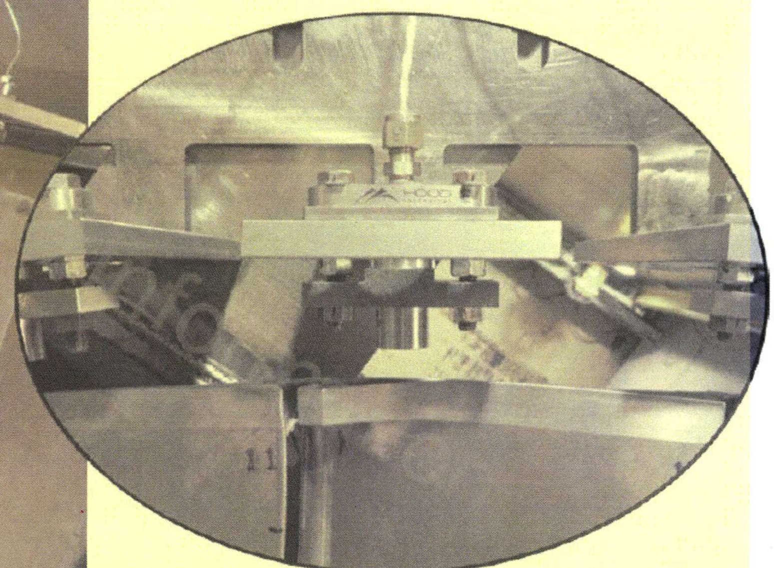
Electromagnetic Exciter





BVM Sensor

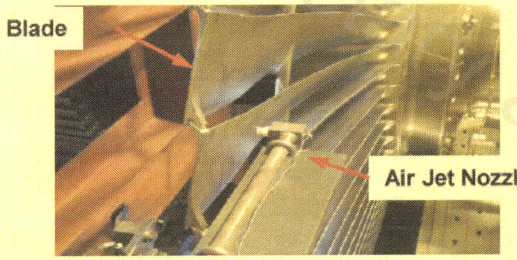


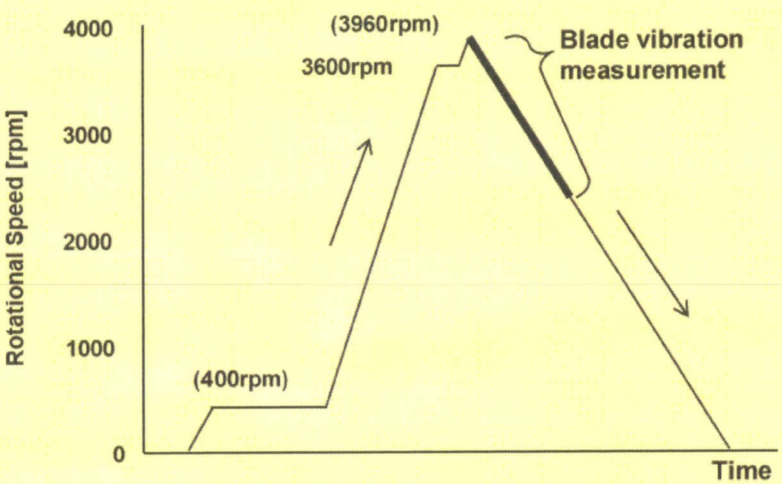


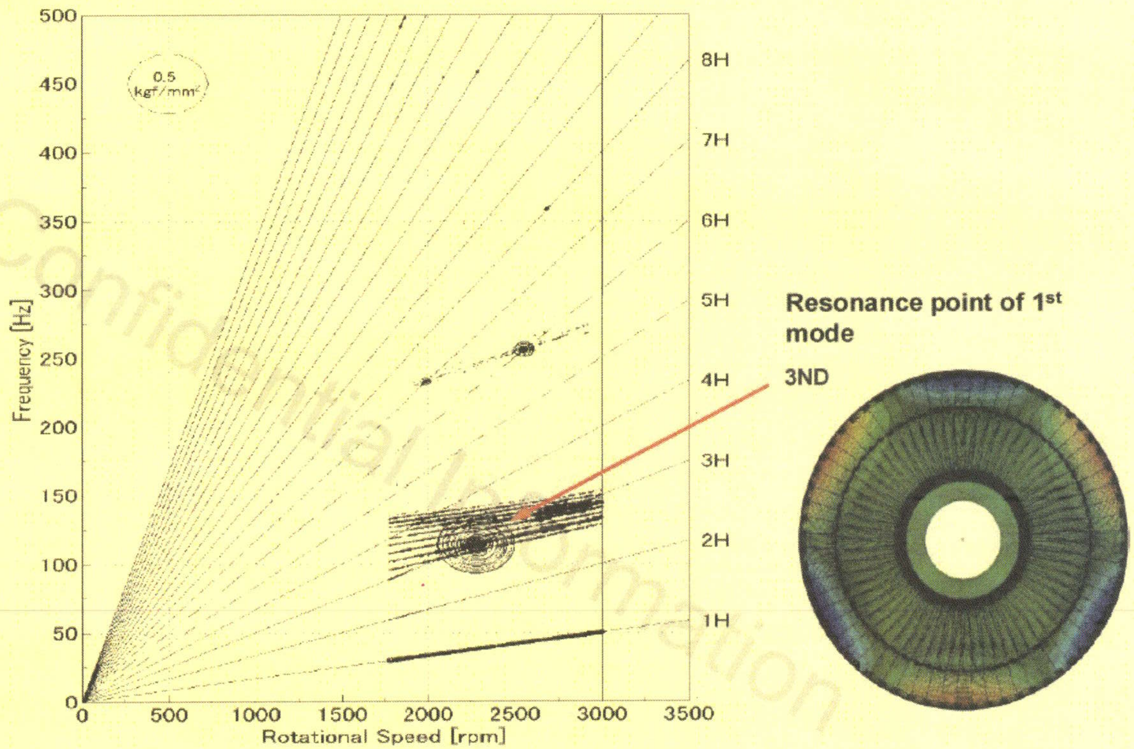
Air Jet Test Procedure

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.







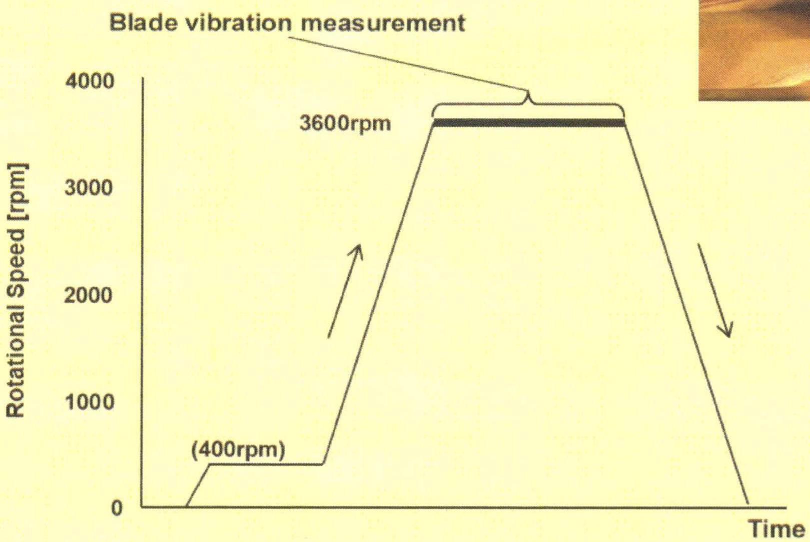
Example of Measurement Result of Air Jet Testing

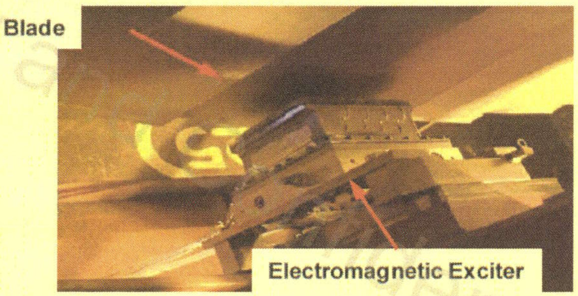
Electromagnetic Test Procedure

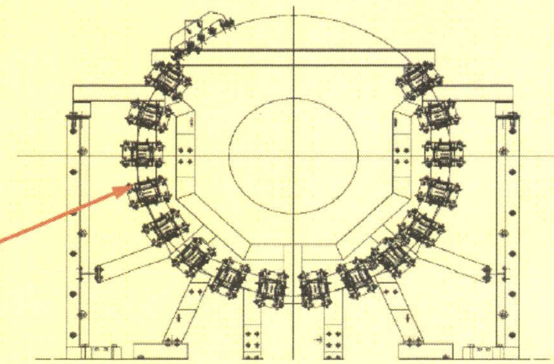
The magnitude response of high nodal diameters was confirmed by the electromagnetic test.

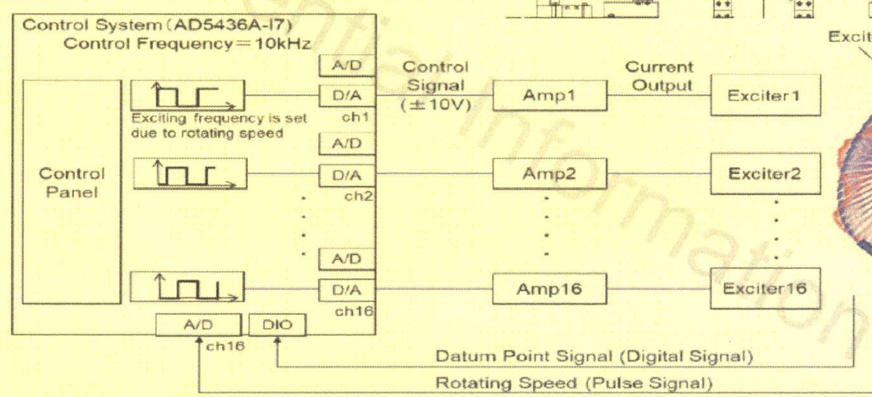
The exciting frequency, phase and power of each electromagnetic exciter were controlled.

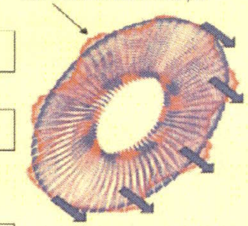
In the electromagnetic test, the exciting frequency was swept around the natural frequency of the high nodal diameter while keeping the rotational speed at the rated speed.





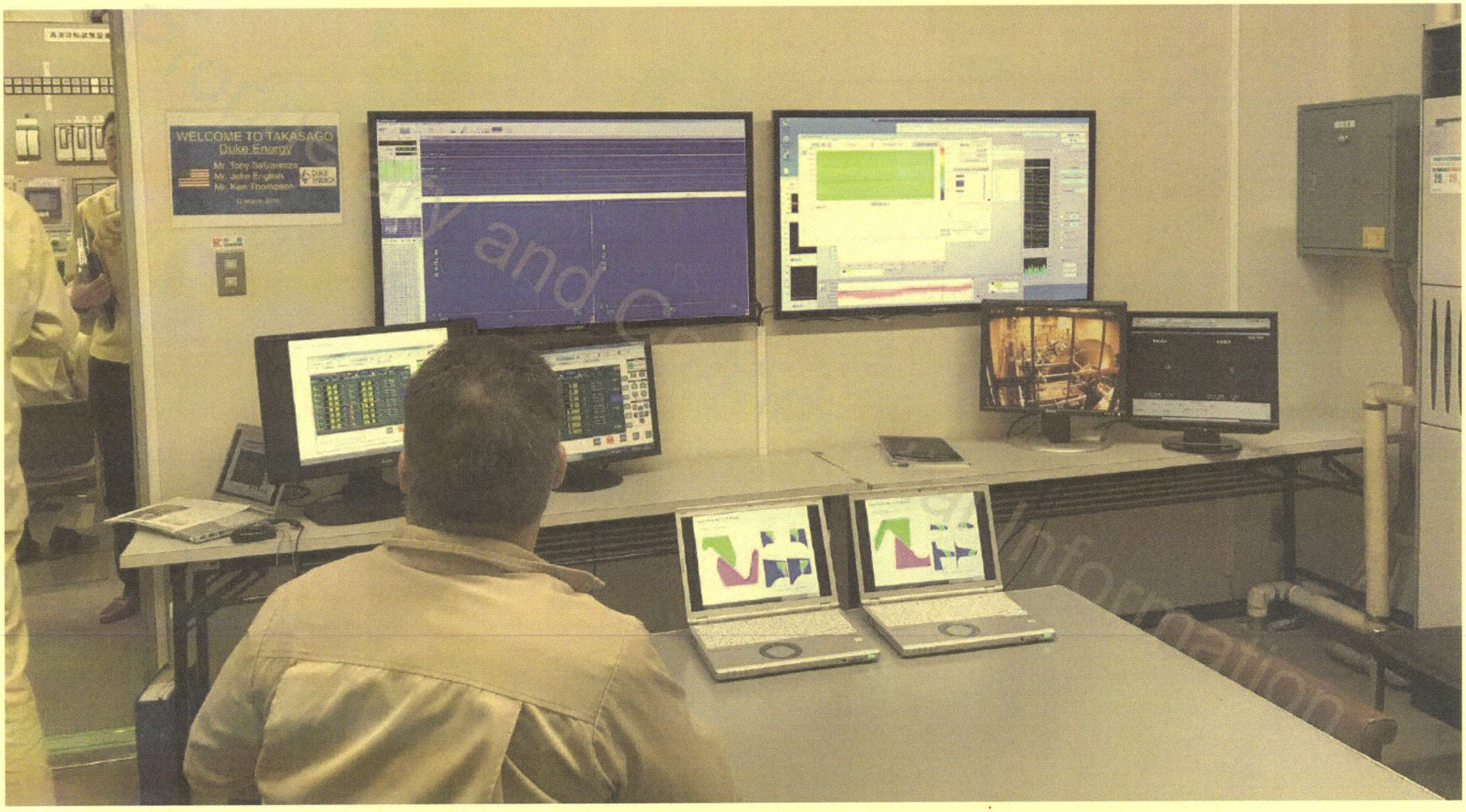






Electromagnetic Exciter Control System

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

Thank You

MHPS

Mitsubishi Hitachi Power Systems

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LFE 7

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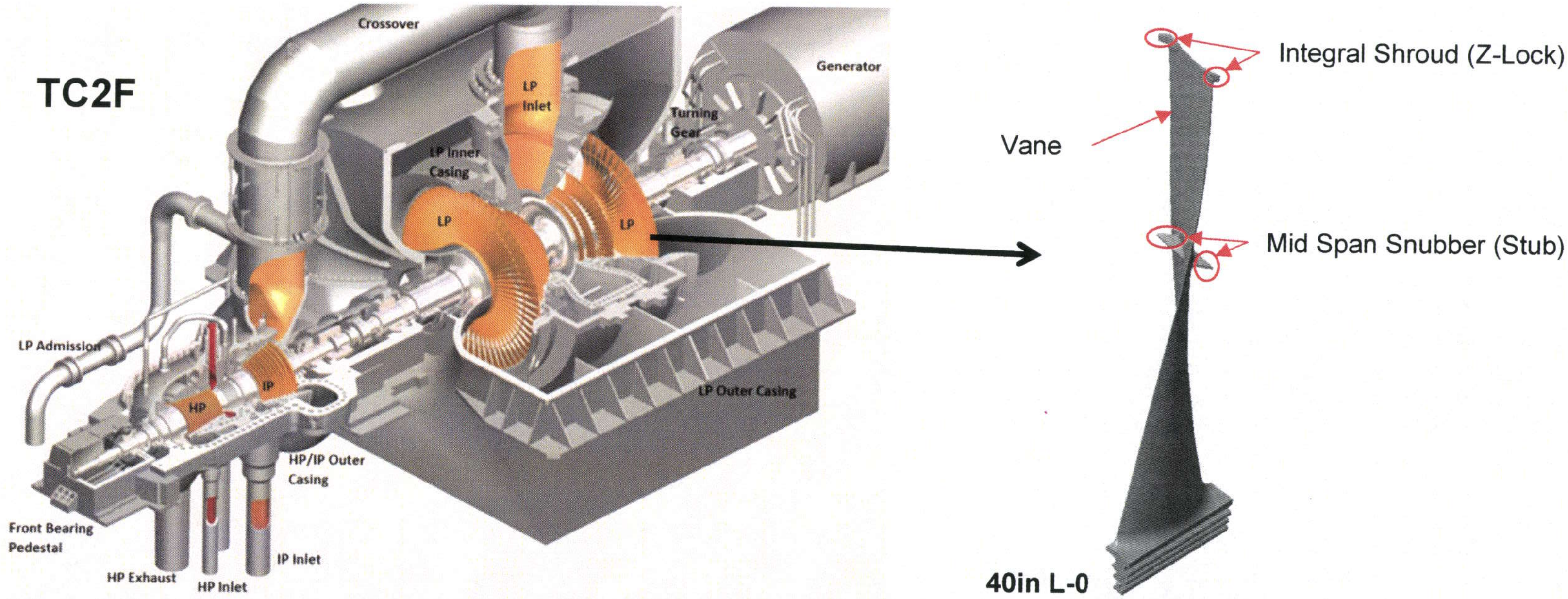
TC2F



Bartow RCA Summary

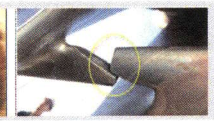
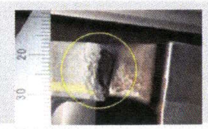
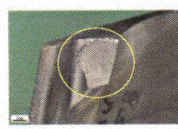
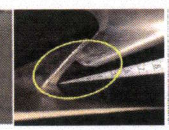
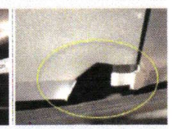
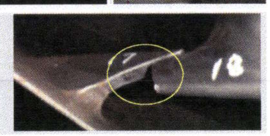
Nick Porteous
Muhammad Riaz, Ph.D.

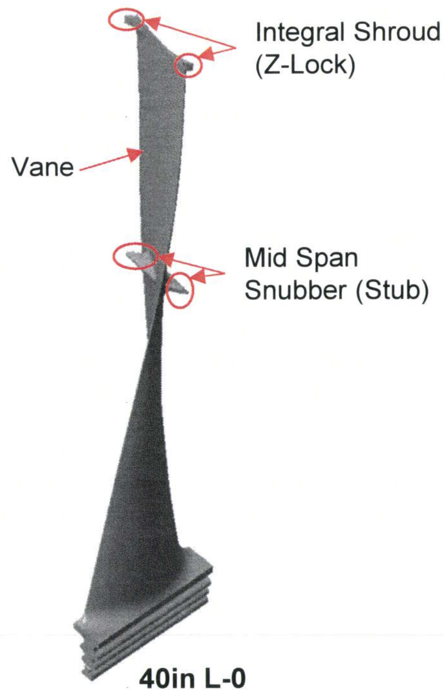
September 22nd, 2017

SL3

Agenda

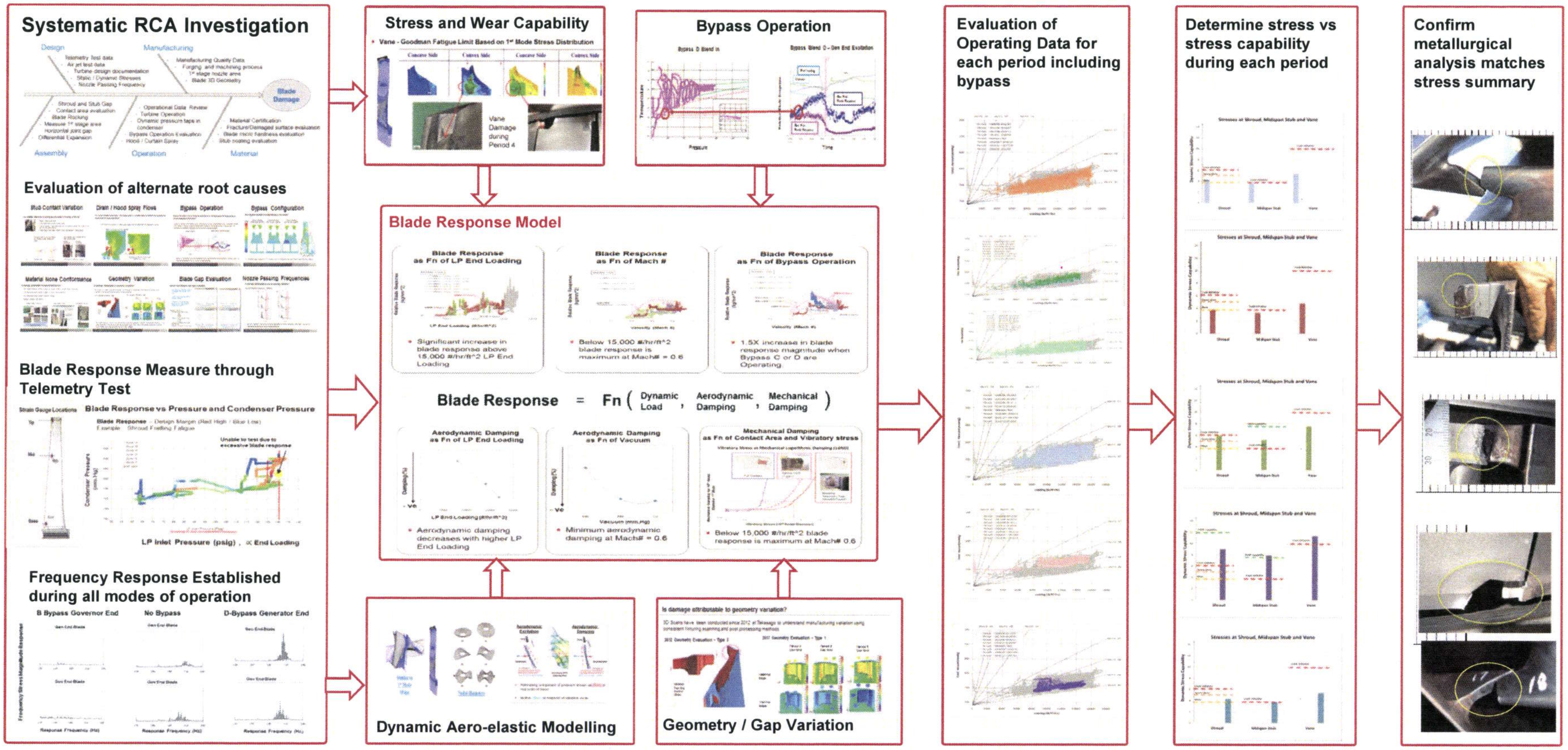
Bartow Blade Operating Summary

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



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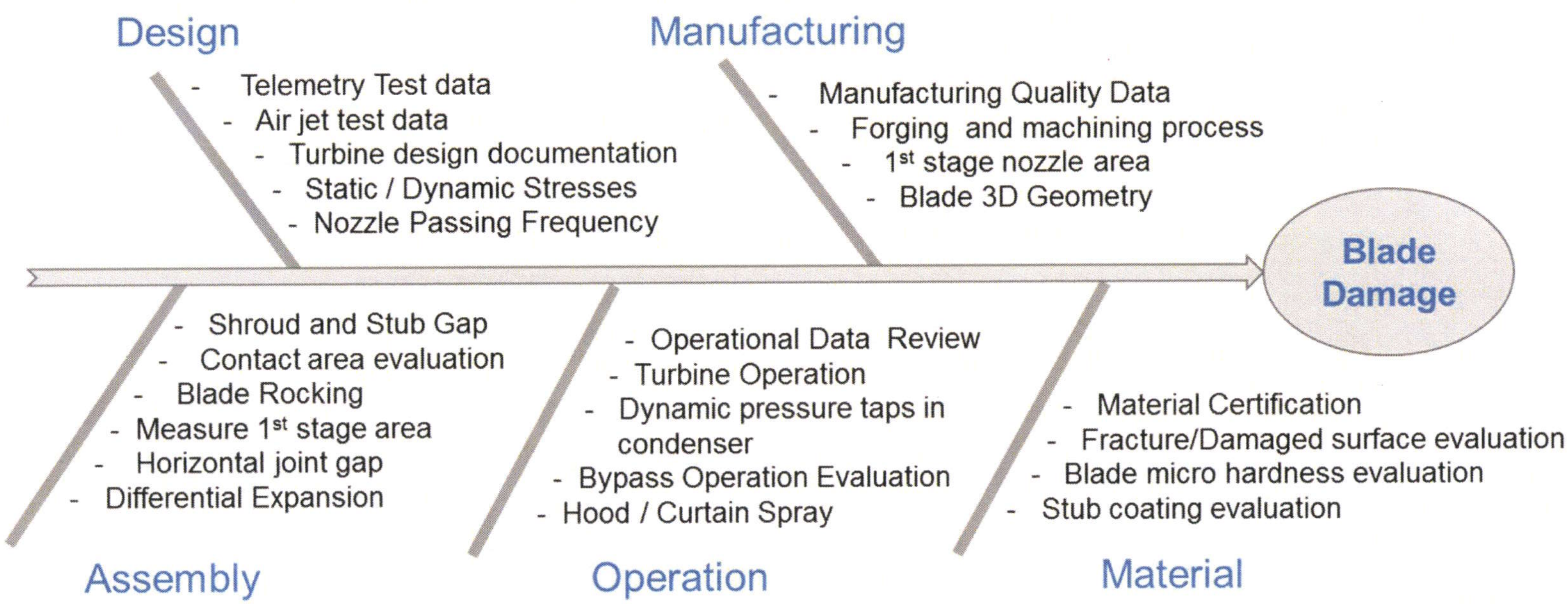
Why is Bartow's experience different from the 40in Fleet ?

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

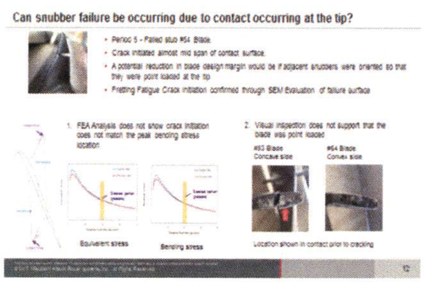


- LP Loading + Bypass Operation at high load were identified as the primary root causes for the Bartow 40" Blade reliability differences from the global fleet.

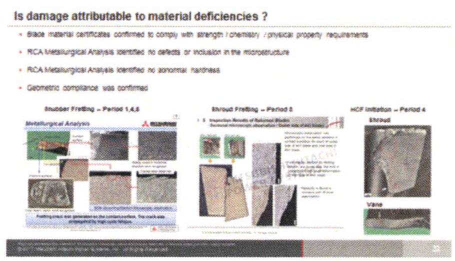
SL3

Evaluation of potential Root Causes included :

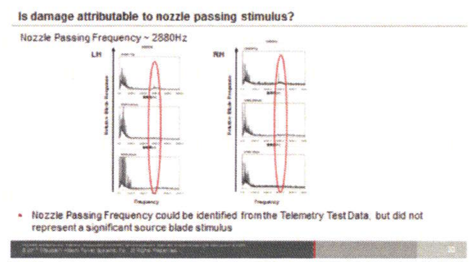
Stub Contact Variation



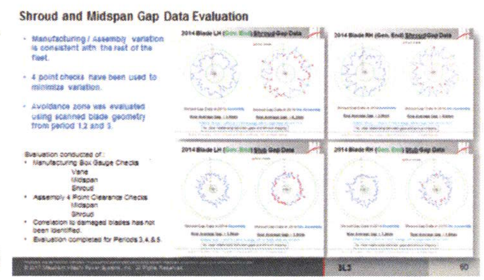
Material None Conformance



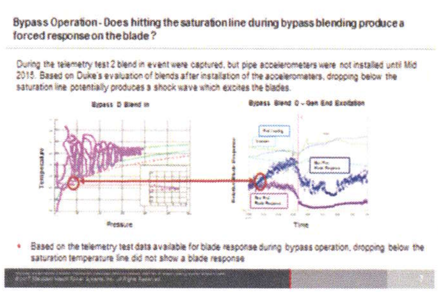
Nozzle Passing Frequencies



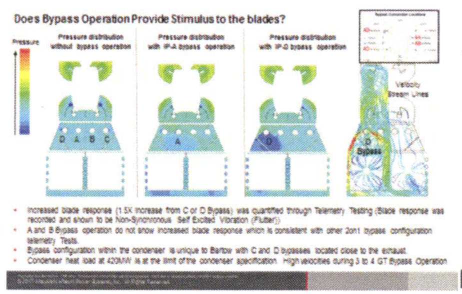
Blade Gap Evaluation



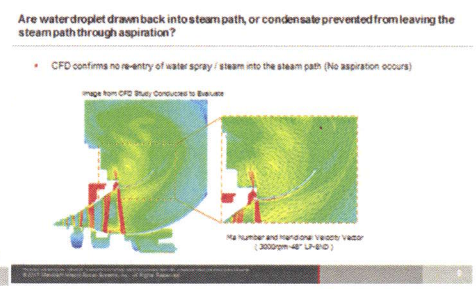
Bypass Operation



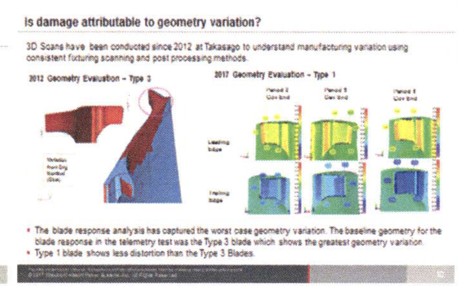
Bypass Configuration



Drain / Hood Spray Flows



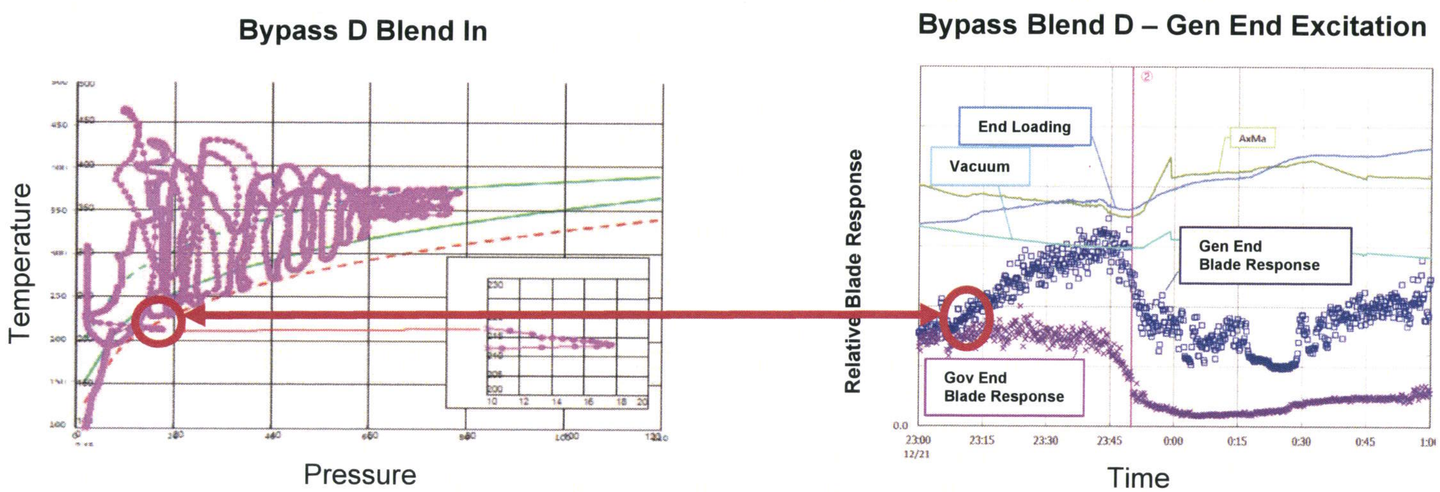
Geometry Variation



- 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.

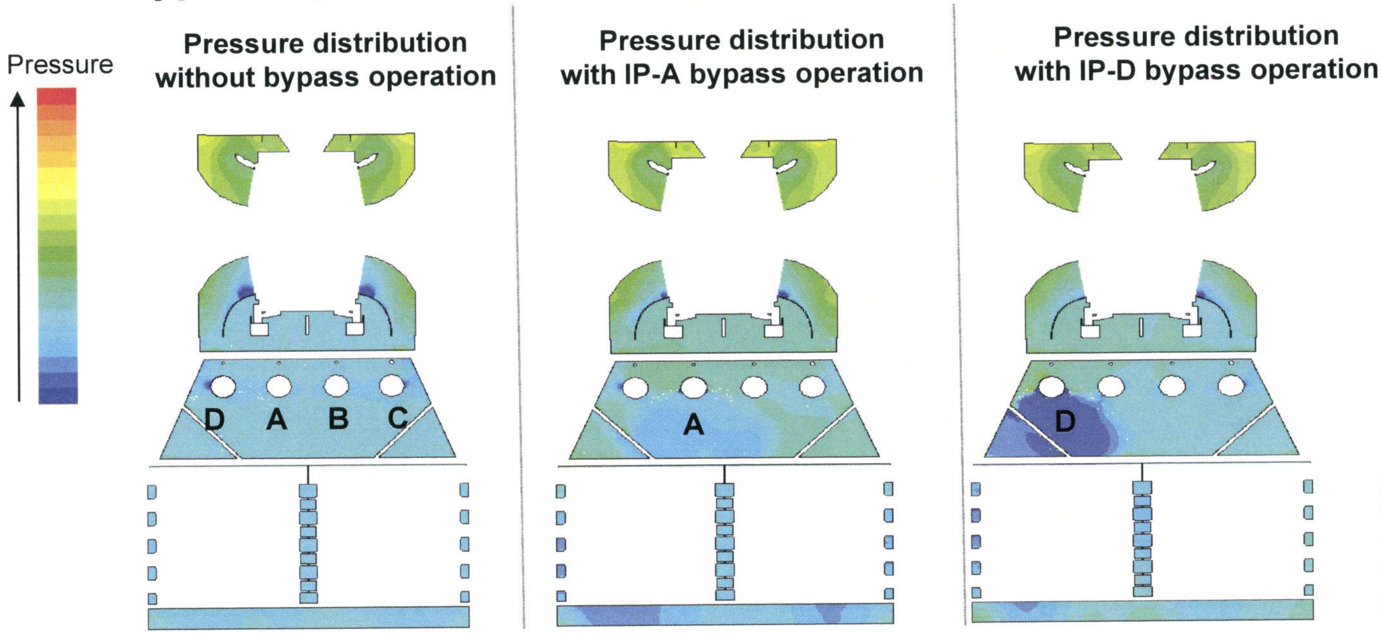
Bypass Operation - Does hitting the saturation line during bypass blending produce a forced response on the blade ?

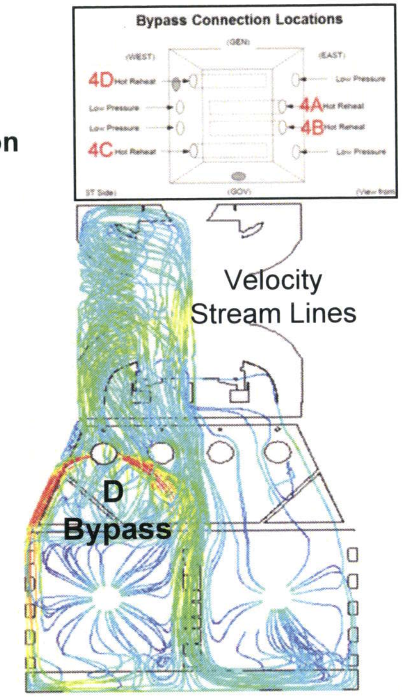
During the telemetry test 2 blend in event were captured, but pipe accelerometers were not installed until Mid 2015. Based on Duke's evaluation of blends after installation of the accelerometers, dropping below the saturation line potentially produces a shock wave which excites the blades.



- 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?



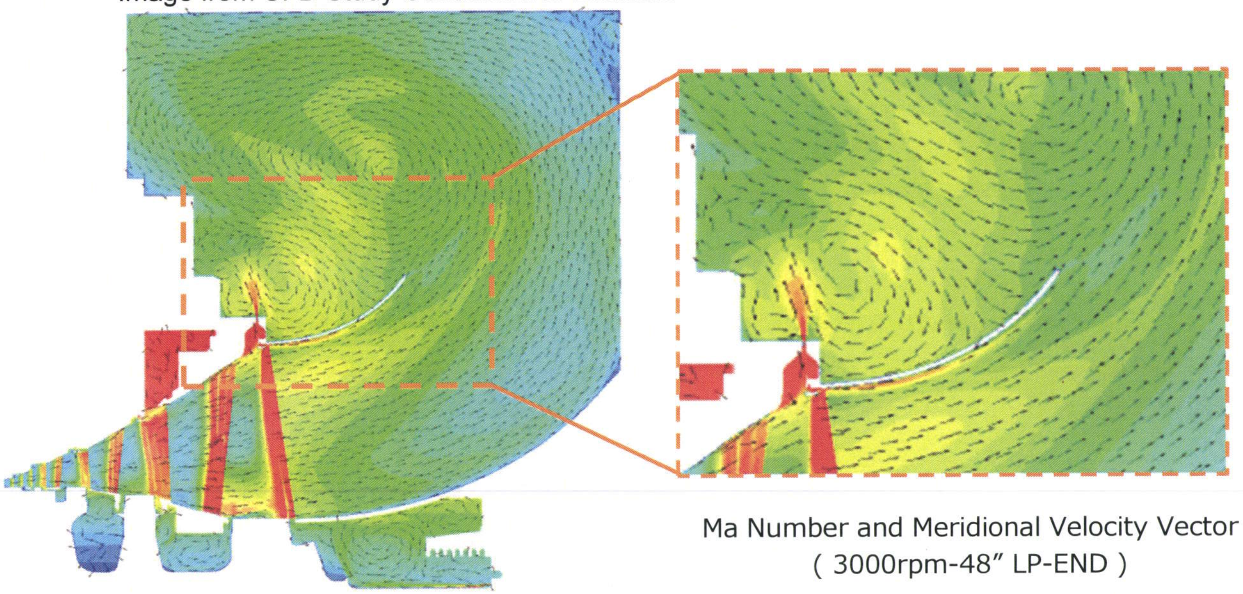


- Increased blade response (1.5X Increase from C or D Bypass) was quantified through Telemetry Testing (Blade response was recorded and shown to be Non-Synchronous Self Excited Vibration (Flutter))
- A and B Bypass operation do not show increased blade response which is consistent with other 2on1 bypass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

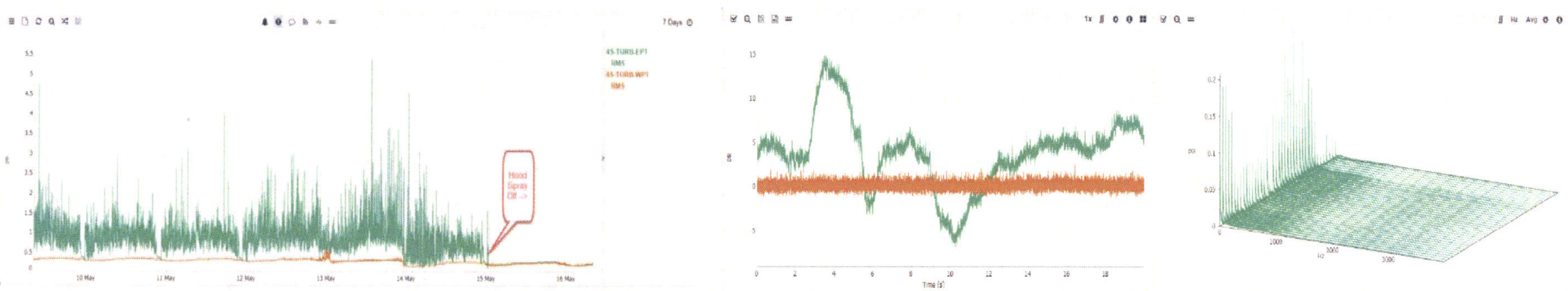


Ma Number and Meridional Velocity Vector
(3000rpm-48″ LP-END)

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.

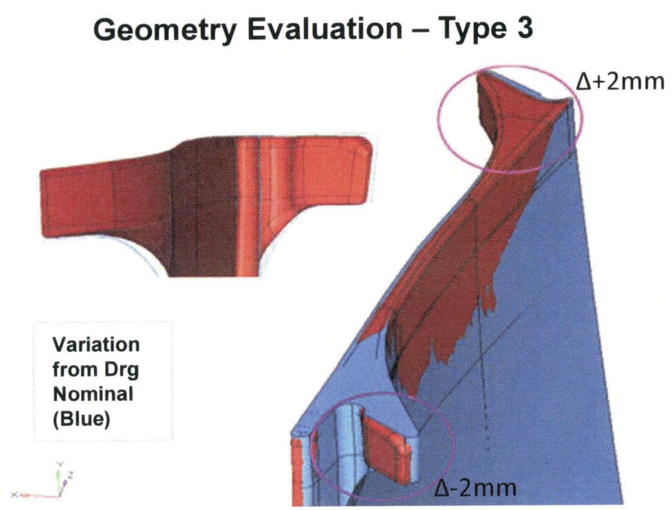
Dynamic pressure identified associated with Hood Sprays :

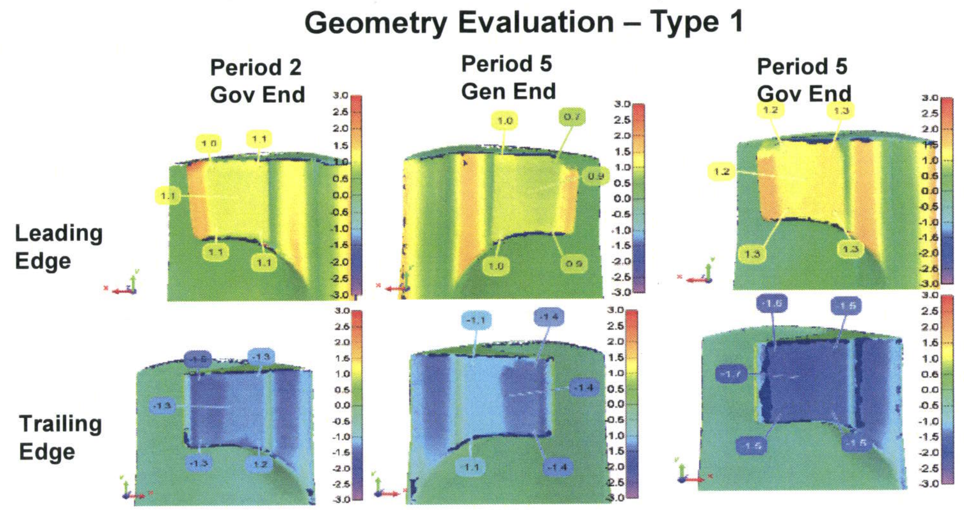


Pressure fluctuations did not have high frequency content, and identified pressure rising from 2.5” Hg to atmospheric pressure. No corresponding blade response identified during telemetry test.

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)





- 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.

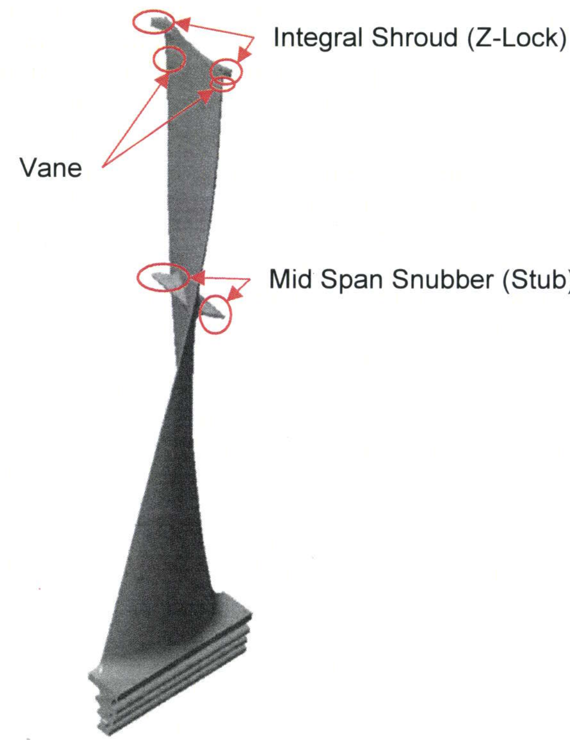
Damage Mechanism

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.



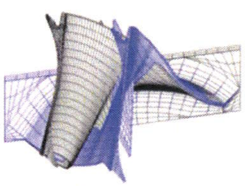
Root Cause Analysis has identified all blade damage from Period 1 thru Period 5 has been identified as Dynamic Loads from Non-Synchronous Self Excited Vibration (Flutter)

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

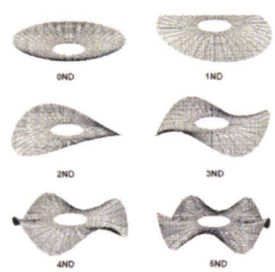
Non-Synchronous Self Excited Vibration (Flutter)

- 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).

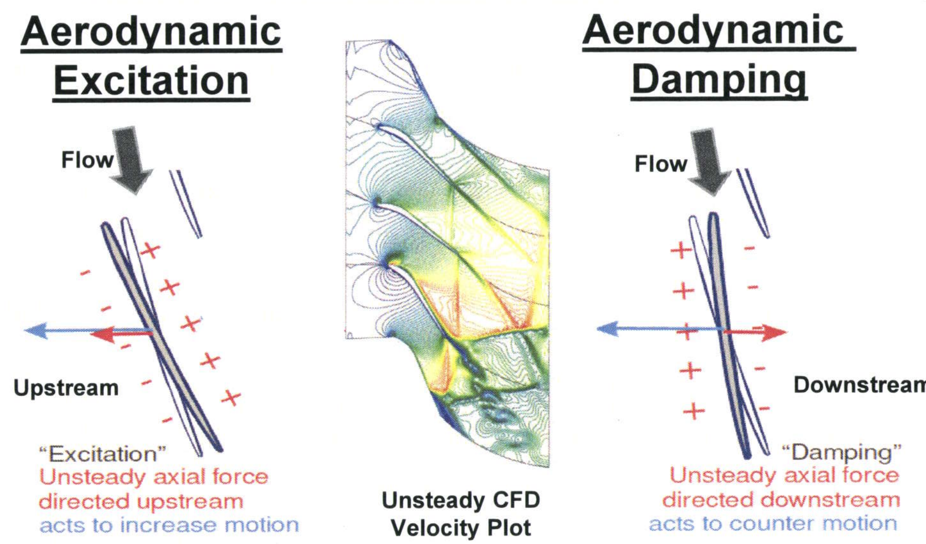


Similar to 1st Mode Shape



Nodal Diameters

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

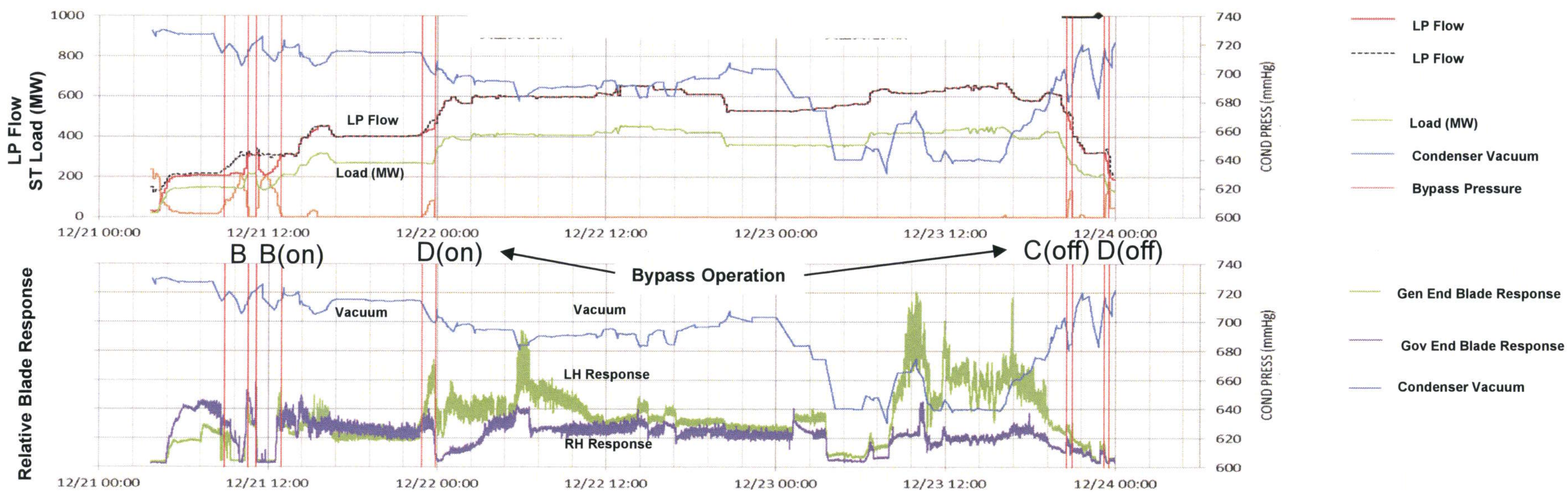


- Alternating component of pressure shown as (Red) at mid point of travel

- Motion (Blue) at midpoint of vibration cycle

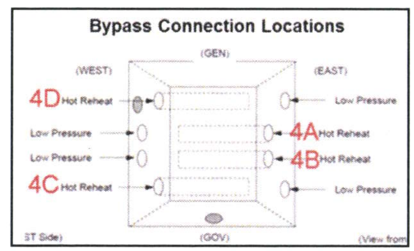
How do we know the dominant response is Non-Synchronous Self Excited Vibration?

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



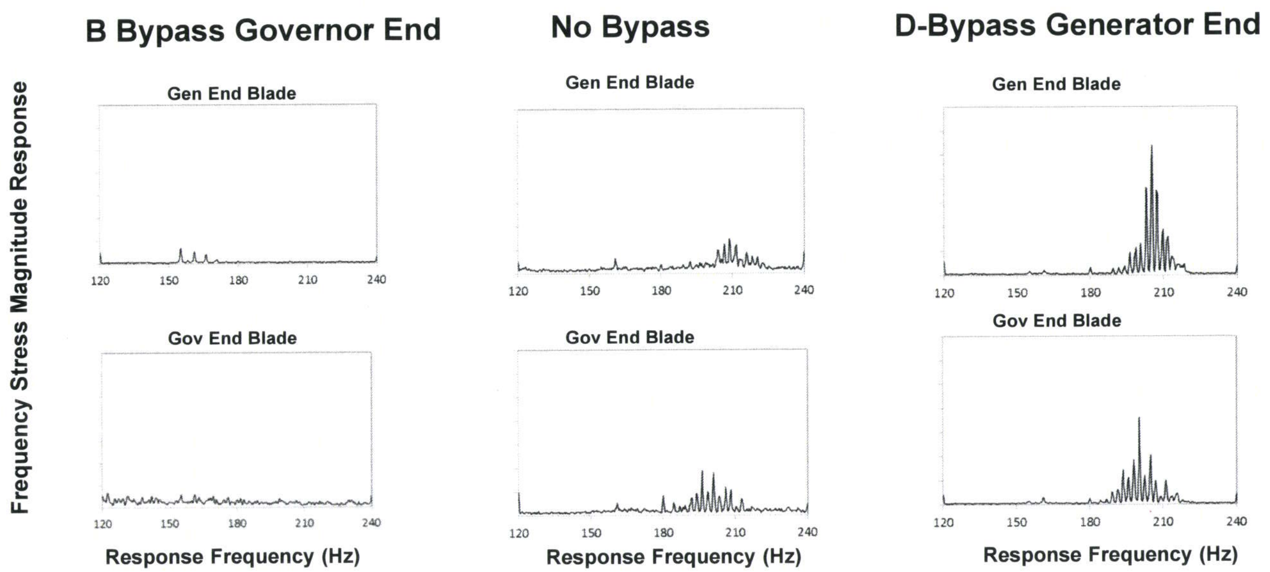
Range of Operating Conditions During Test :

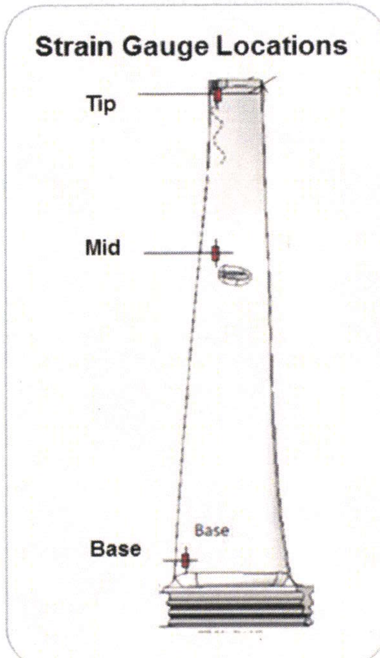
- Blade Response was measured up to 455 MW and 5 in.Hg
- Bypass Operation of 2 Blend In and 2 Blend Out Events were recorded
- Mach Number Ranged from 0.4 to 0.9



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

Frequency Response from Telemetry Test :





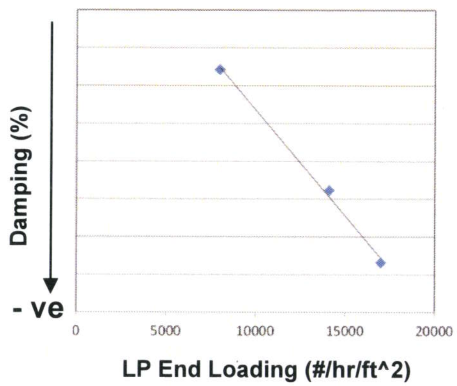
Recorded Response :

- 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)

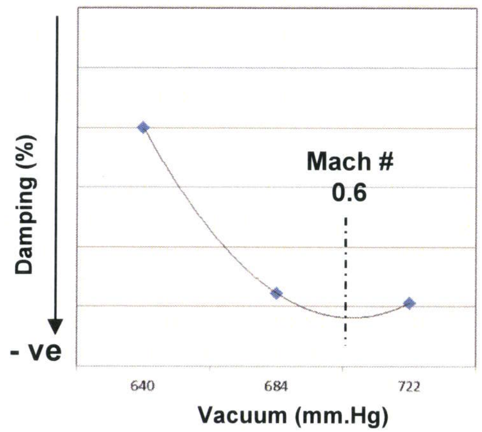
Analytical results of damping below show trends, but the magnitude of blade response is established empirically from the telemetry test conducted at the start of period 3

Aerodynamic Damping as Fn of LP End Loading



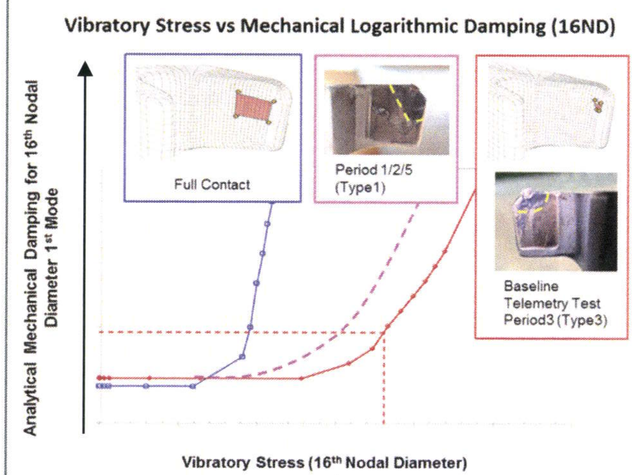
- Aerodynamic damping decreases with higher LP End Loading

Aerodynamic Damping as Fn of Vacuum



- Minimum aerodynamic damping at Mach# = 0.6

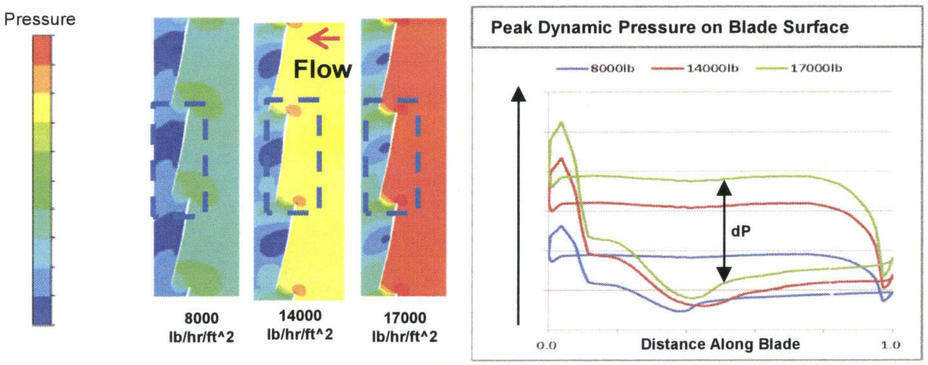
Mechanical Damping as Fn of Contact Area and Vibratory stress



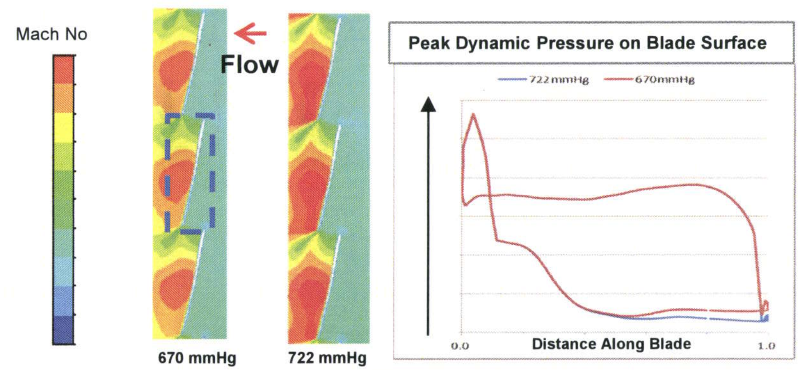
- Mechanical damping decreases with smaller contact area

Aerodynamic Damping Analysis (Vibratory Stress and Logarithmic Damping)

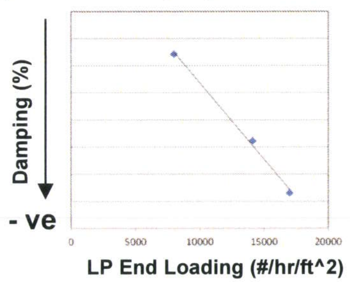
Aerodynamic Damping vs Load



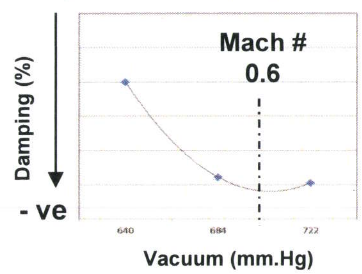
Aerodynamic Damping vs Mach No



Aerodynamic Damping as Fn of LP End Loading



Aerodynamic Damping as Fn of Vacuum

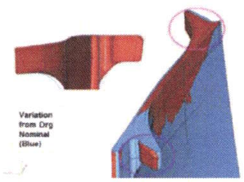


Transient CFD was Correlated with Telemetry Test Data to understand Aerodynamic Damping

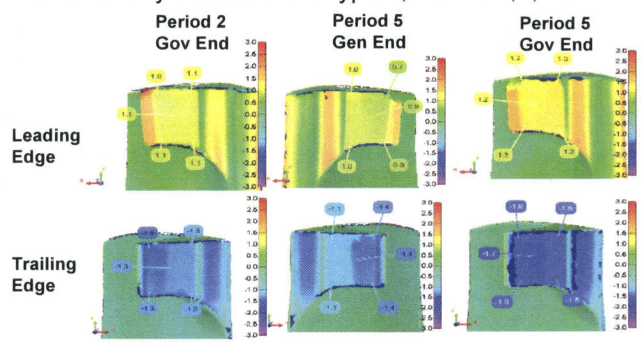
Geometry Variation - Mechanical Damping is impacted by contact faces on adjacent blades

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

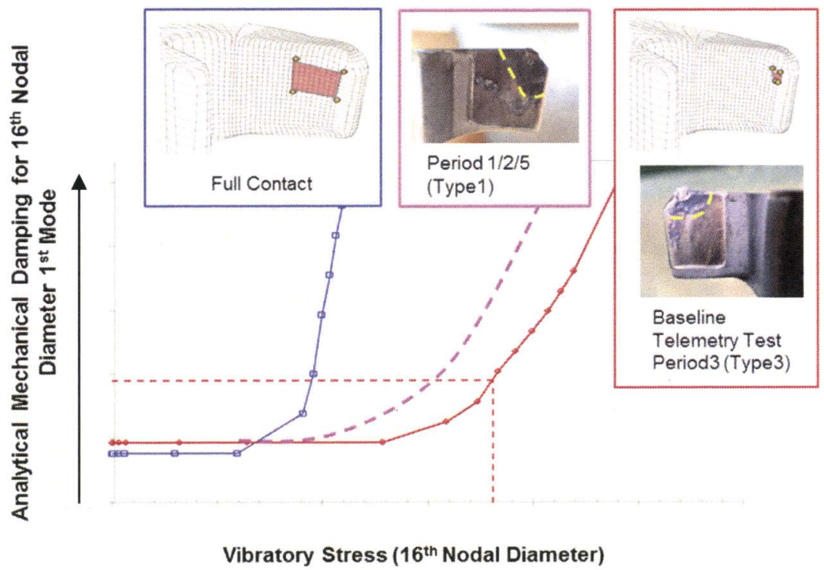
2012 Geometry Evaluation – Type 3 Period 3



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



Vibratory Stress vs Mechanical Logarithmic Damping (16ND)

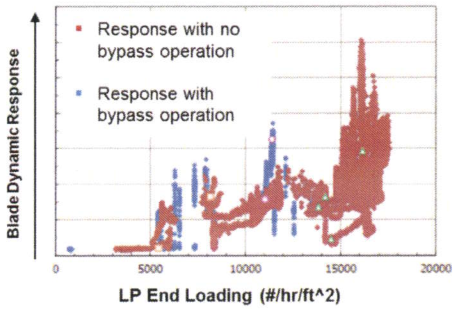


Analytical damping results are intended to understand drivers for blade response, absolute blade response was established from Telemetry Test

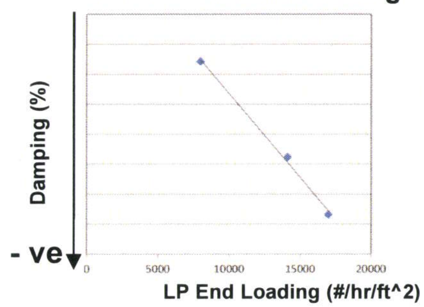
- Type 3 Blades established the baseline blade response from the telemetry test.
- Type 3 Blades were found to have lower damping than Type 1 Blades due to smaller contact area

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

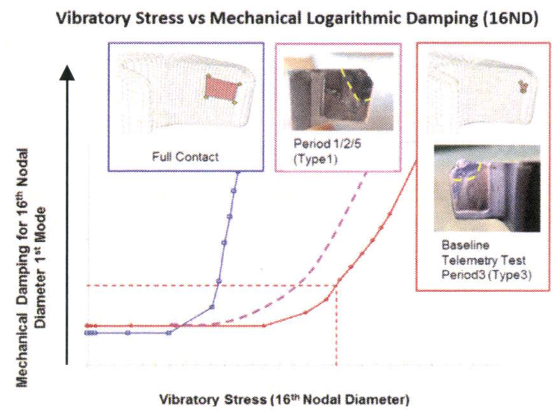
Blade Response as Fn of LP End Loading



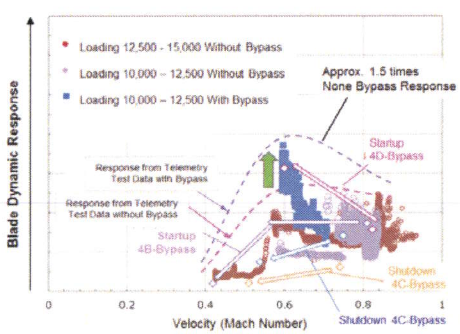
Aerodynamic Damping as Fn of LP End Loading



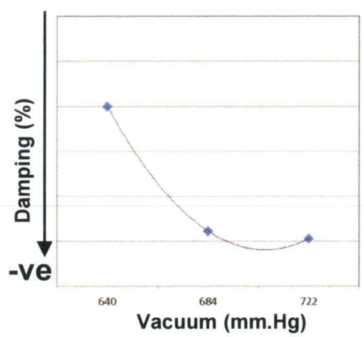
Mechanical Damping as Fn of Contact Area and Vibratory stress



Blade Response as Fn of Mach No. and Bypass Operation



Aerodynamic Damping as Fn of Vacuum

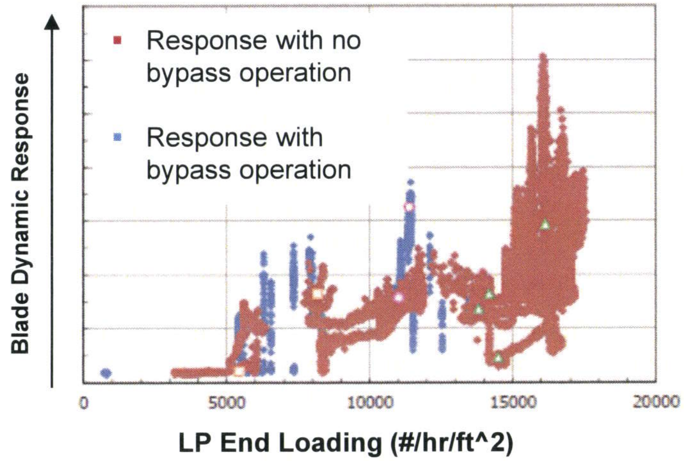


- **Details in following slides**

Blade Response as a Function of LP End Load

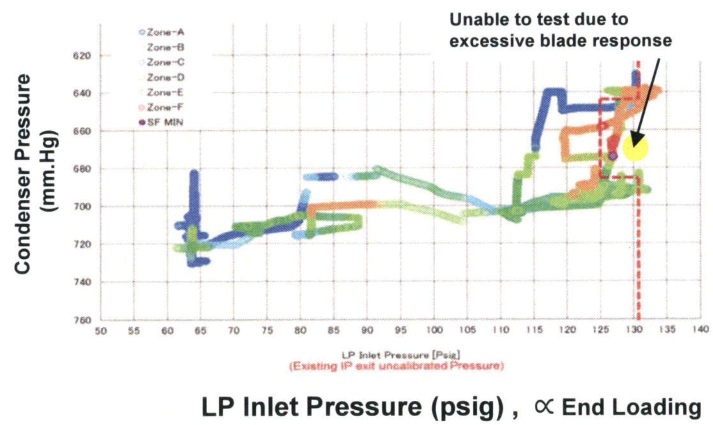
The telemetry test provided direct blade magnitude of the blade response from strain gauges

Blade Response vs LP End Loading



Blade Response vs Pressure and Condenser Pressure

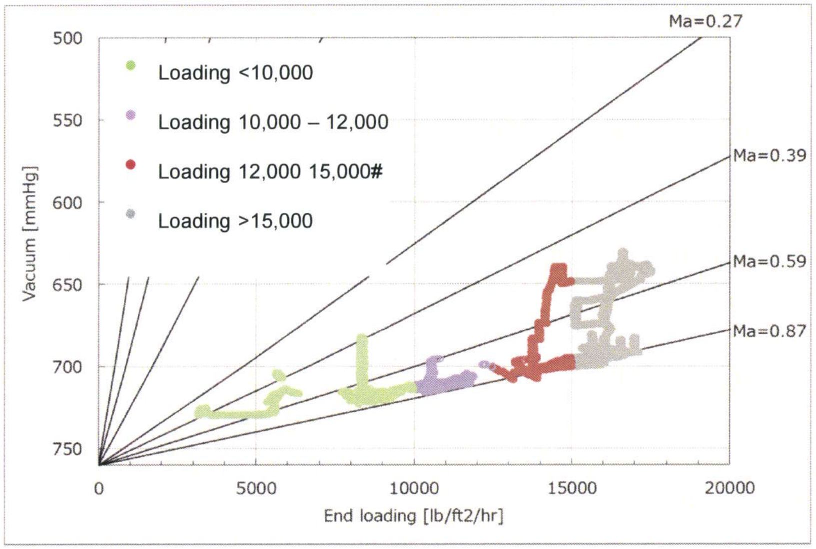
Blade Response – Design Margin (Red High / Blue Low)
Example : Shroud Fretting Fatigue

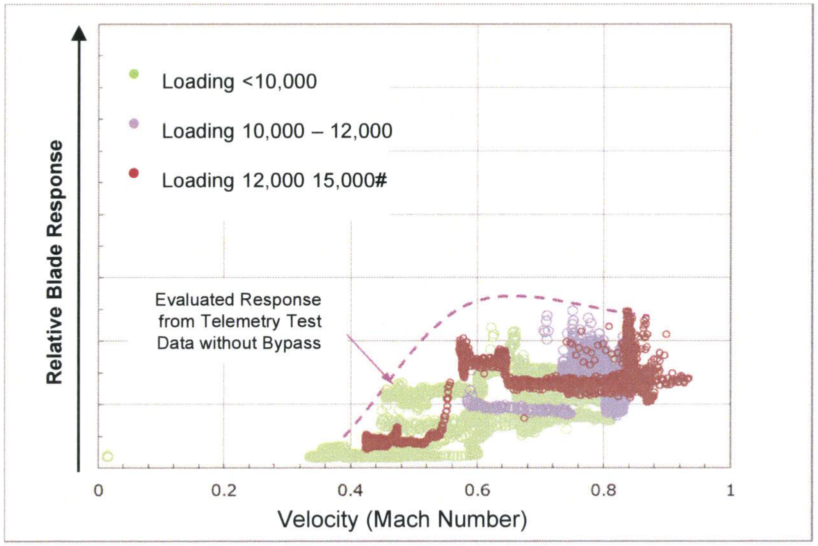


- Outside of the originally developed design space, blade response becomes sensitive to operating conditions.
  Example : At 16,500 #/hr/ft^2 there is a 10X change in blade response based on condenser pressure

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

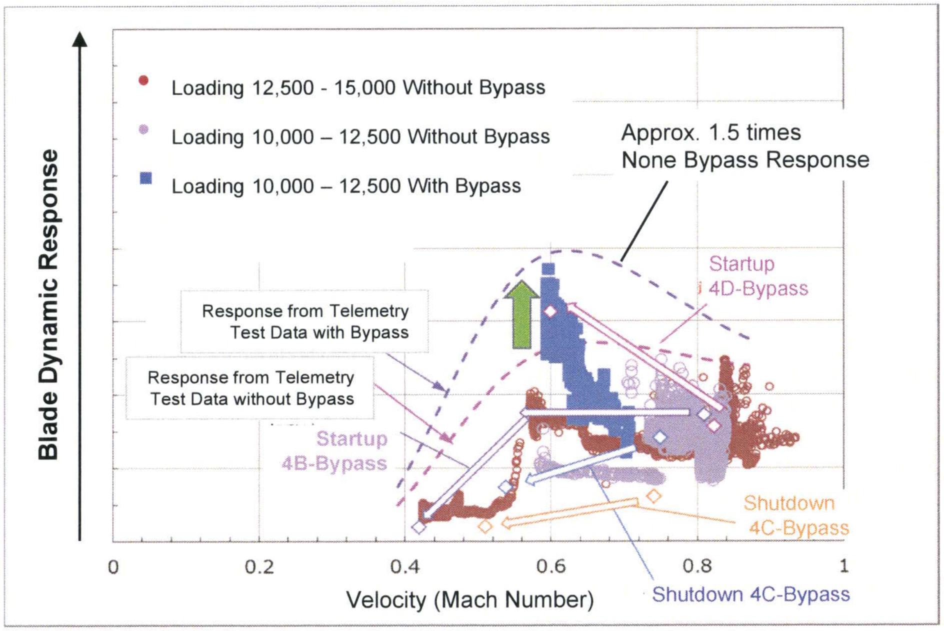
Blade Response as a Function of Mach Number – without Bypass



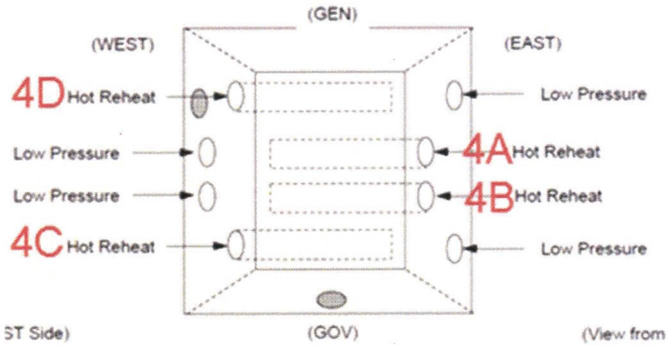


- Below 15,000 lb/hr/ft^2 Blade Response becomes dominated by Mach Number

Blade Response as a Function of Bypass Operation



Bypass Connection Locations

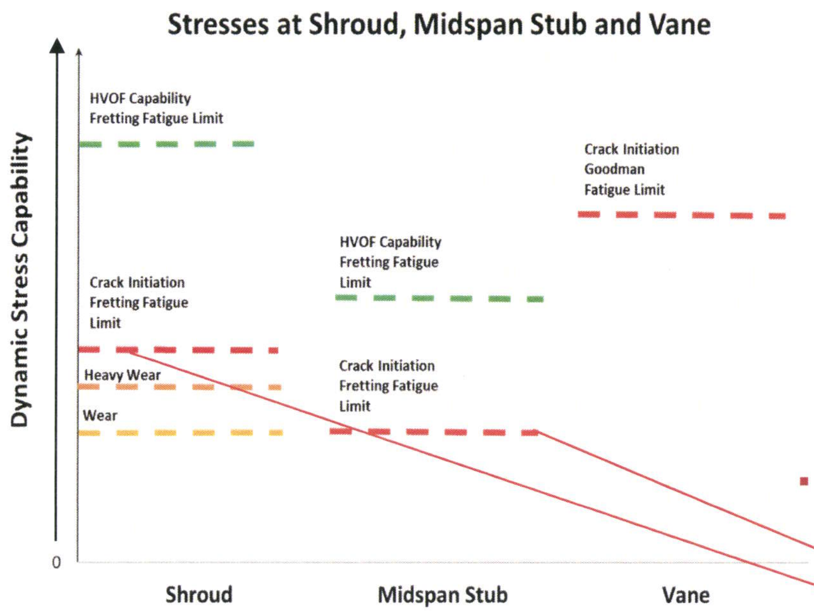


- Bypass C Operation increases response on Governor End Blades
- Bypass D Operation increases response on Generator End Blades

- 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

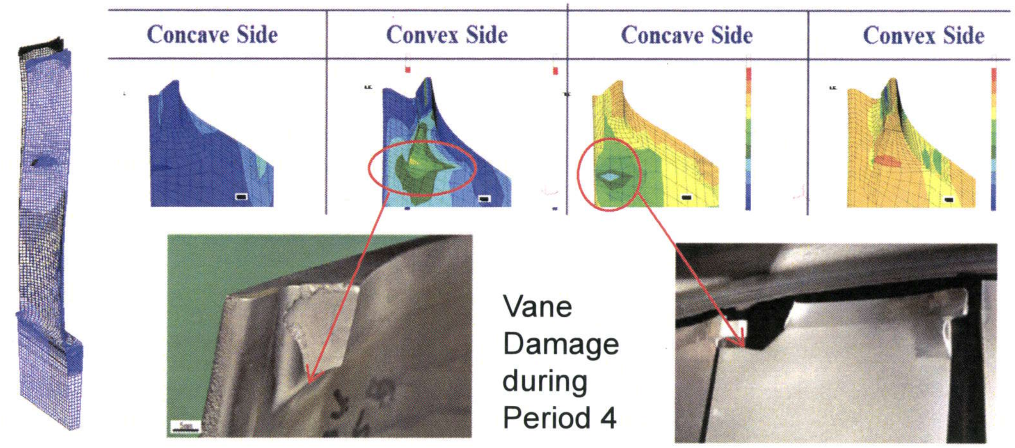
- Limited Blade Response data during Bypass is available with the operation before and after Dec 2014 Telemetry Testing being assumed to have remained the same change in response.

Material Capability – Material Test Data

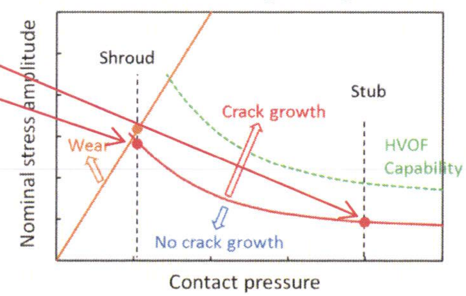


- Estimated Blade Response can be evaluated against Material Capability for Shroud, Mid Span Stub, and Vane

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

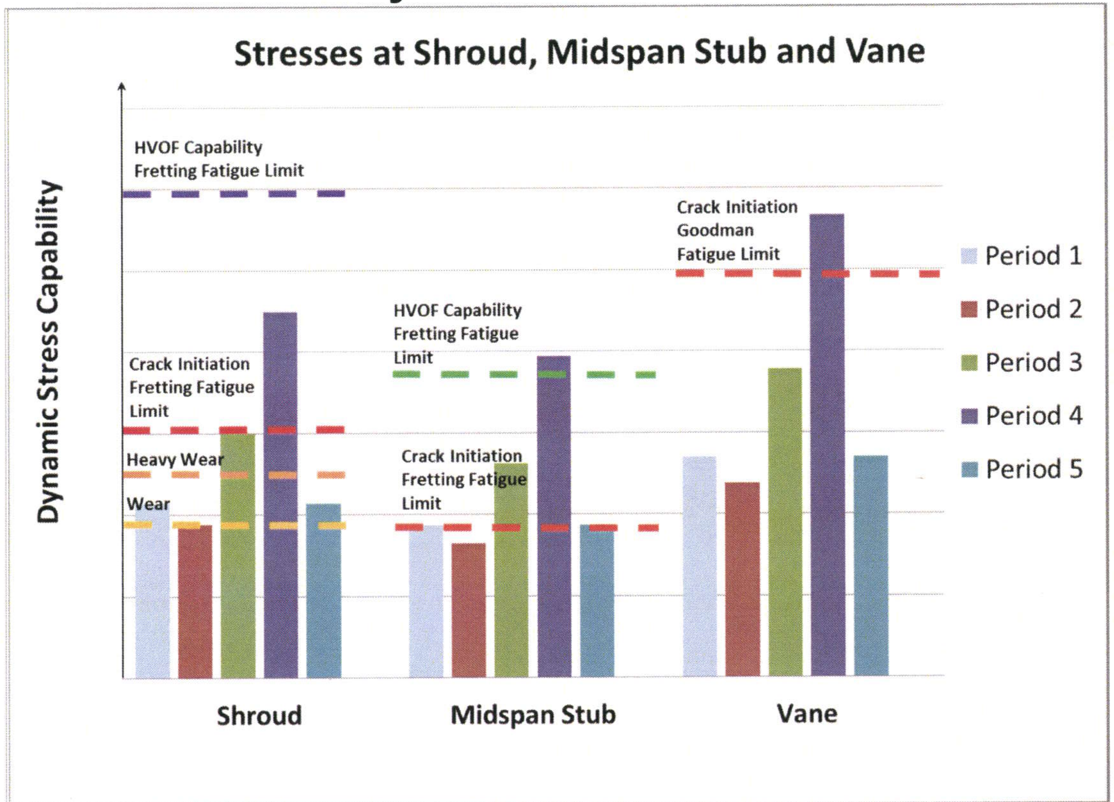


- Shroud / Stub Fretting Fatigue Damage based on fretting material testing



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

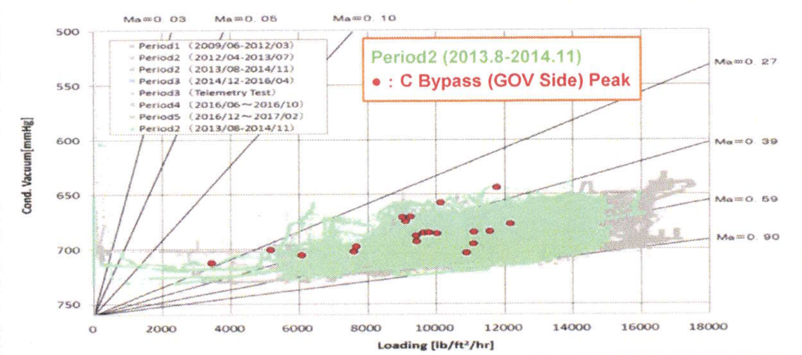
Stress Summary – Period 1 thru 5



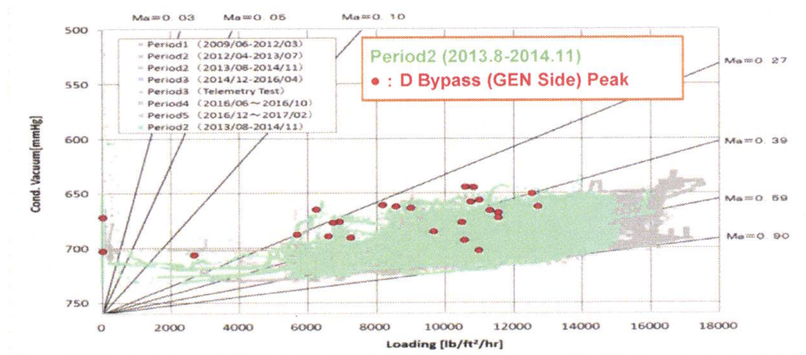
- **Period 1 – Mid Span Stub Cracking**
  High LP Loading but increased mechanical damping from Type 1 blade over baseline telemetry test
- **Period 2 – No Major Damage**
  Reduced LP Loading over Period 1, reduced bypass operation loading over period 5, light wear observed on shroud
- **Period 3 – Shroud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

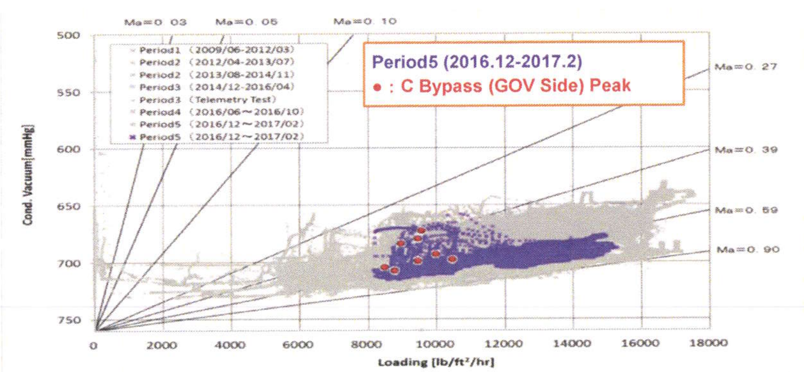
How is the different operating experience between Period 2 and Period 5 explained ?



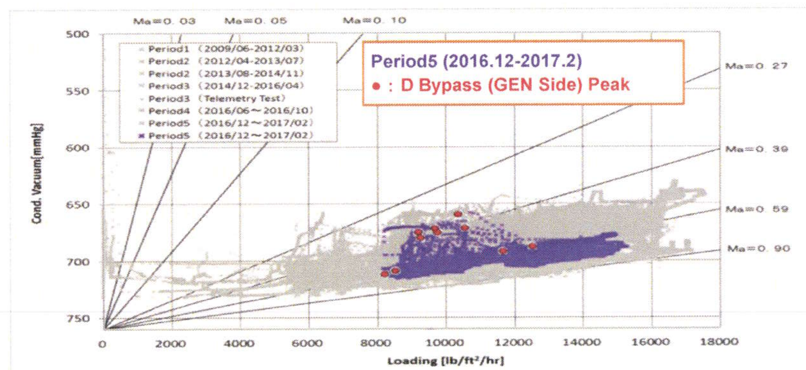
Period 2 Gov End - Type 1 Blade



Period 2 Gen End - Type 1 Blade



Period 5 Gov End - Type 1 Blade



Period 5 Gen End - Type 1 Blade

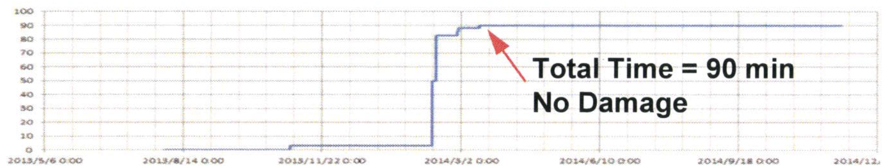
How is the different blade damage between Period 2 and Period 5 Explained ?

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

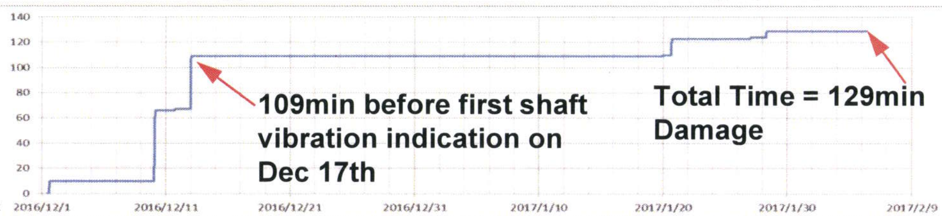
Period 2 – C Bypass Accumulation – No Stub Damage (Gov)

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

Upgraded blade to achieve 450MW available by Oct 2018

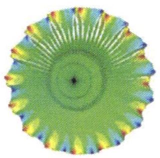
Features :

1) Updated Design Criteria – For Fretting Fatigue

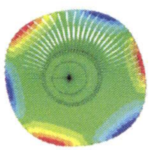
Based on Development Material Testing in 2016 :

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

2) Test Facility Upgraded to Excite High Nodal Diameter Modes

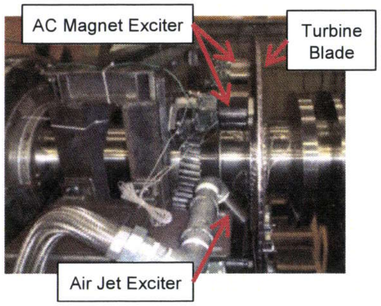


High-nodal diameter mode



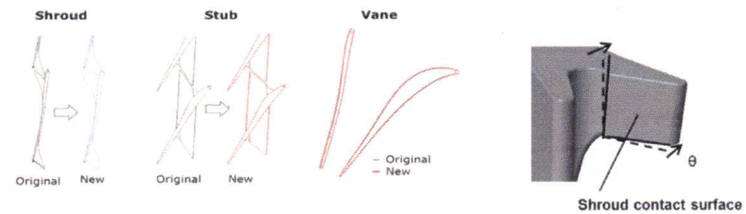
Low-nodal diameter mode

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



Blade Excitation System

3) Redesigned Geometry to Reduce Stress



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

4) Telemetry Testing + BVM

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

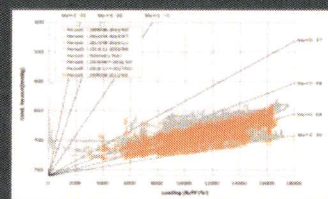
5) Bypass Operating Guidelines

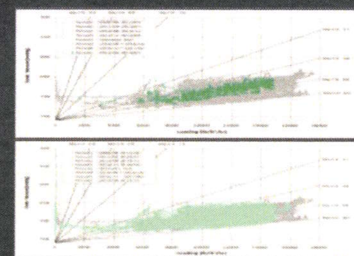
If required based on Telemetry Test results, operating guidelines for bypass can reduce blade response by minimizing operation of C and D Bypass at a Mach # > 0.55
DCS controls update strategy is in evaluation.

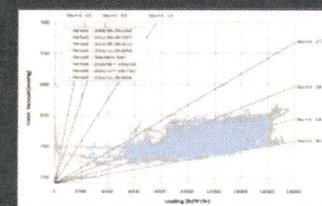
MHPS

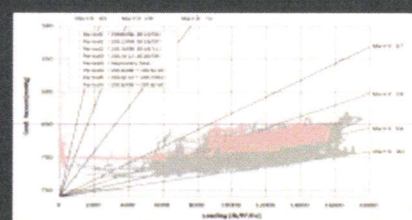
Backup

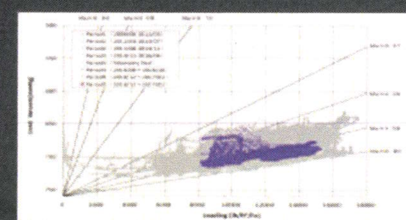
Operating Summary Period 1 thru 5


Period 1


Period 2


Period 3


Period 4

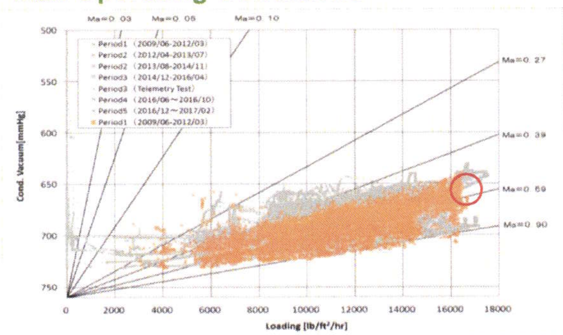

Period 5

SL3

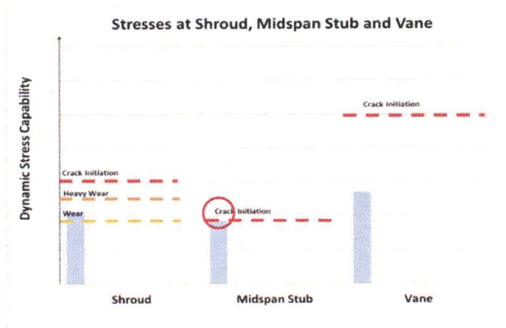
Period 1 – Stub Cracking

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

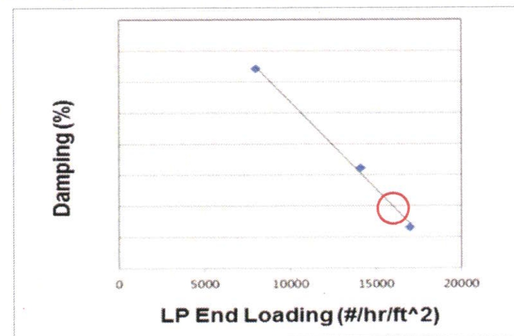
Max Operating Conditions



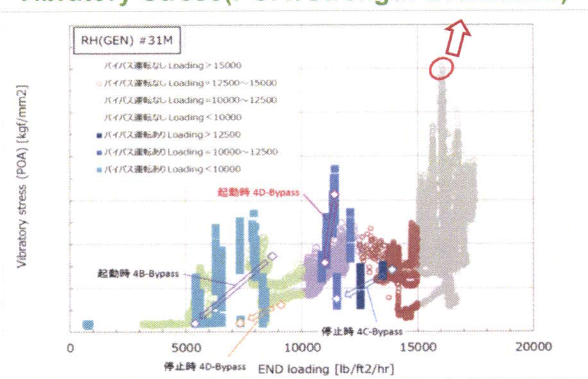
Dynamic Stress from Damage



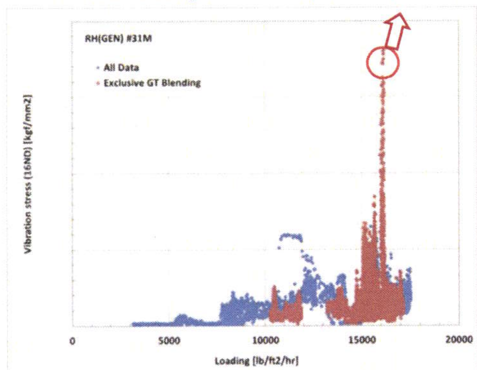
Aerodynamic Damping (3D Flutter Analysis)



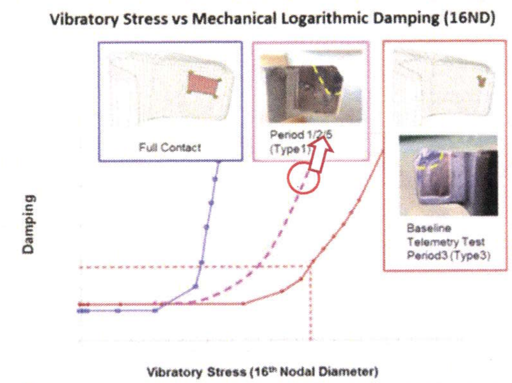
Vibratory Stress(POA:Strength Evaluation)



Vibratory Stress (16ND)



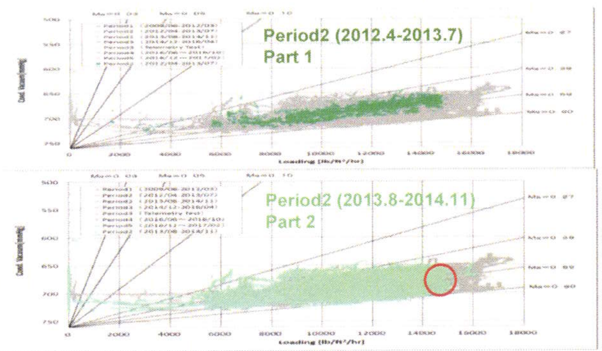
Mechanical Damping(High ND Damping Analysis)



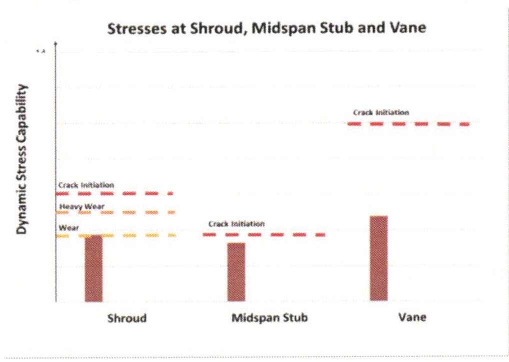
Period 2 – No Major Damage, Minor Shroud Chipping

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

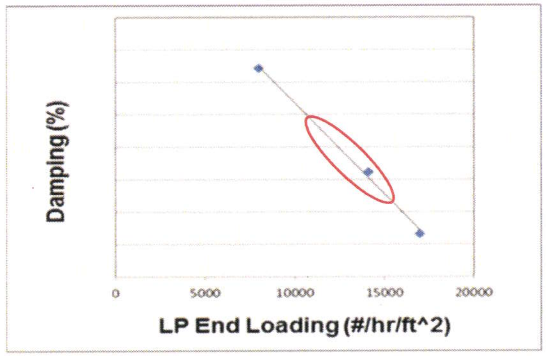
Max Operating Conditions



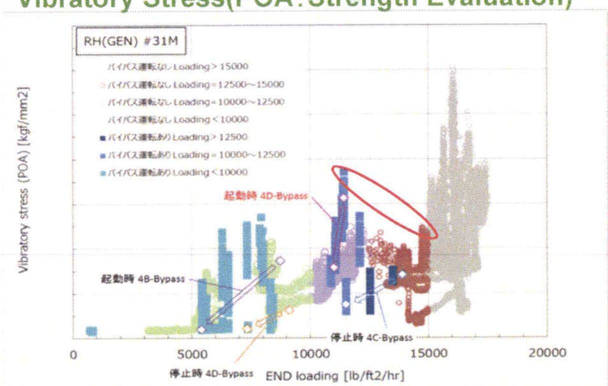
Dynamic Stress Summary (POA)



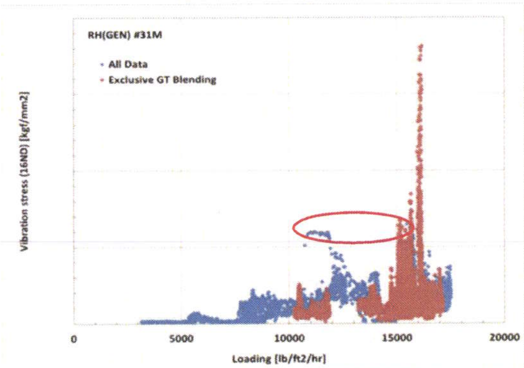
Aerodynamic Damping (3D Flutter Analysis)



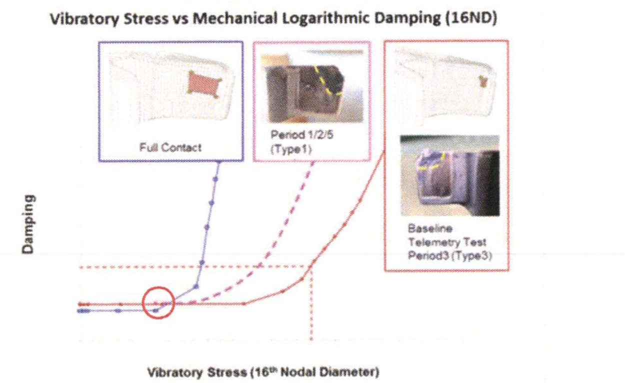
Vibratory Stress(POA：Strength Evaluation)



Vibratory Stress (16ND)



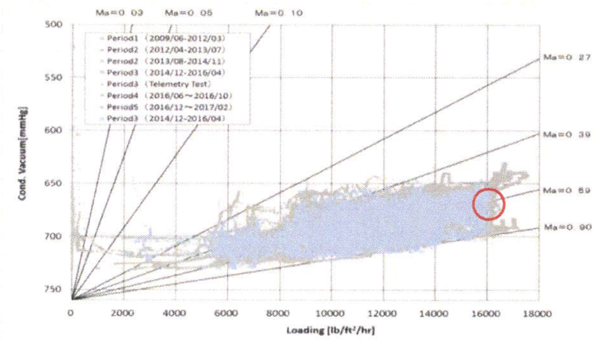
Mechanical Damping(High ND Damping Analysis)



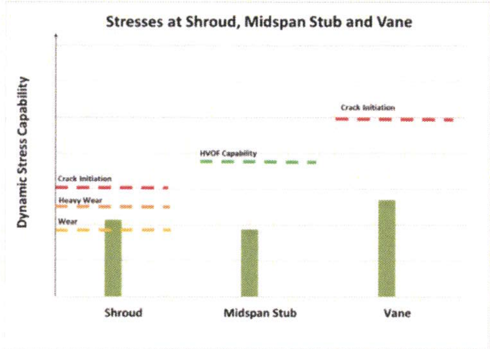
Period 3 – Shroud Cracking - Outside Avoidance Zone

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

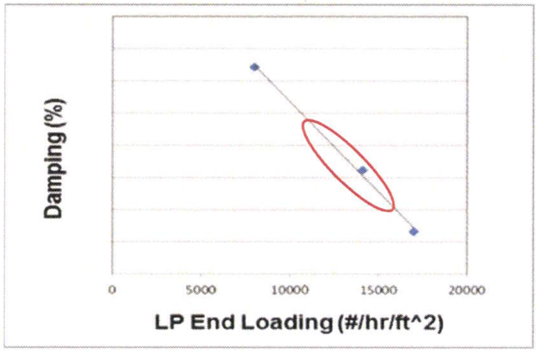
Max Operating Conditions



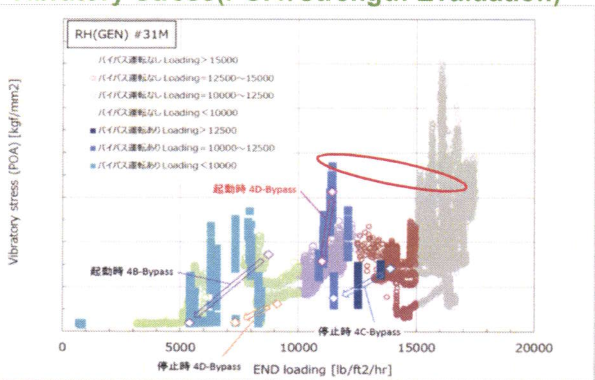
Dynamic Stress Summary (POA)



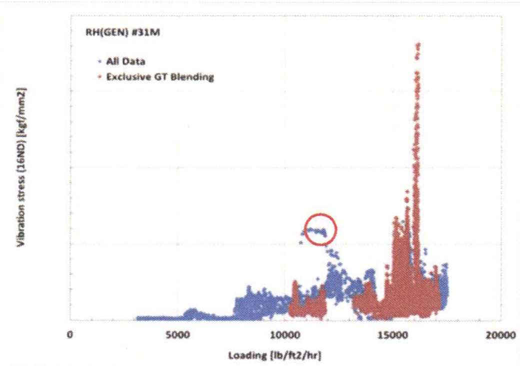
Aerodynamic Damping (3D Flutter Analysis)



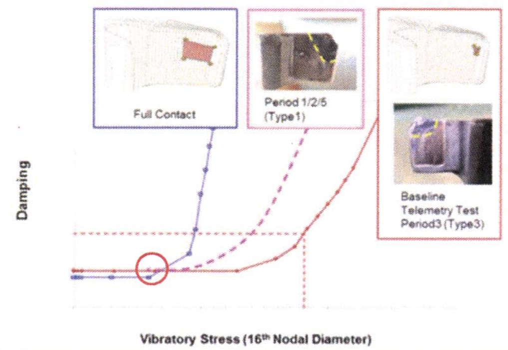
Vibratory Stress(POA: Strength Evaluation)



Vibratory Stress (16ND)



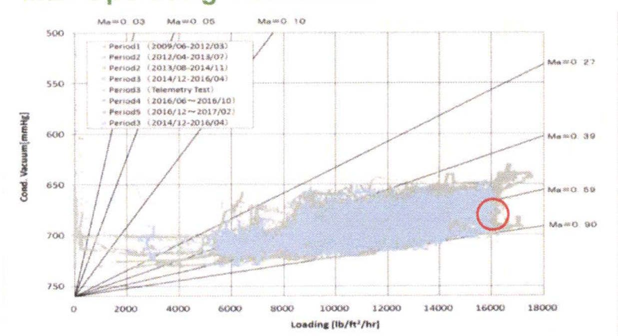
Mechanical Damping(High ND Damping Analysis)



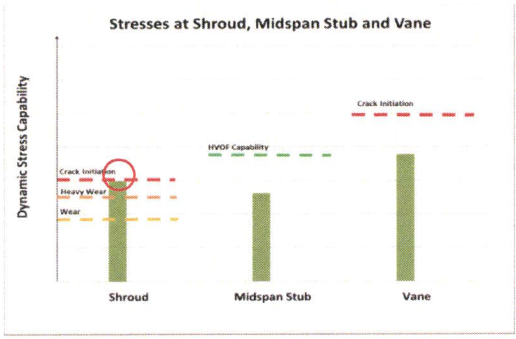
Period 3 – Shroud Cracking– Inside avoidance zone

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

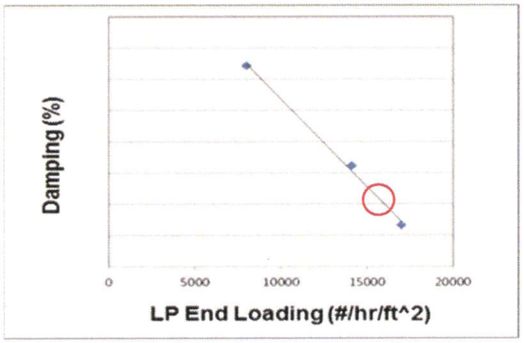
Max Operating Conditions



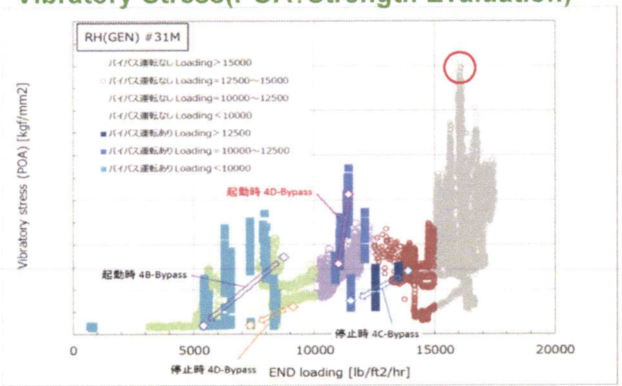
Dynamic Stress Summary (POA)



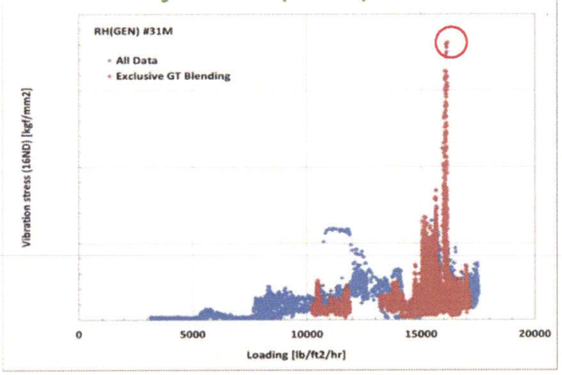
Aerodynamic Damping (3D Flutter Analysis)



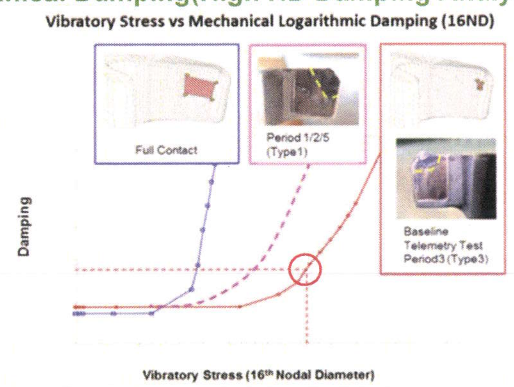
Vibratory Stress(POA：Strength Evaluation)



Vibratory Stress (16ND)



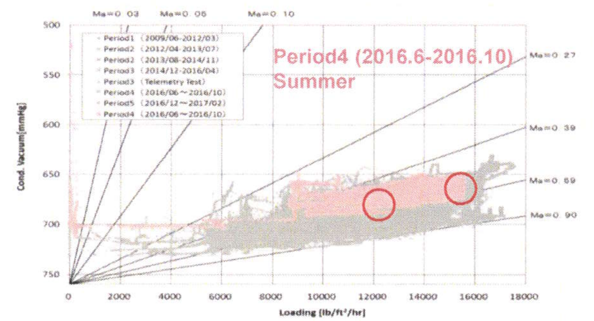
Mechanical Damping(High ND Damping Analysis)



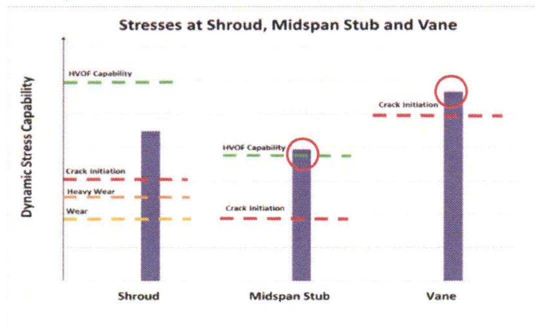
Period 4 – Vane + Stub Cracking

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

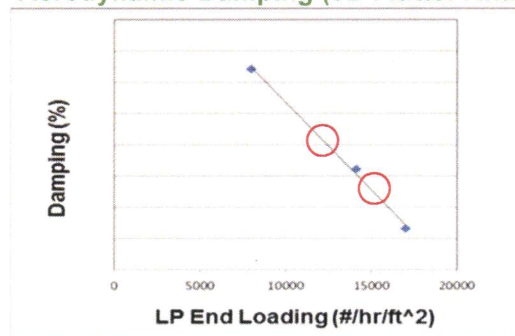
Max Operating Conditions



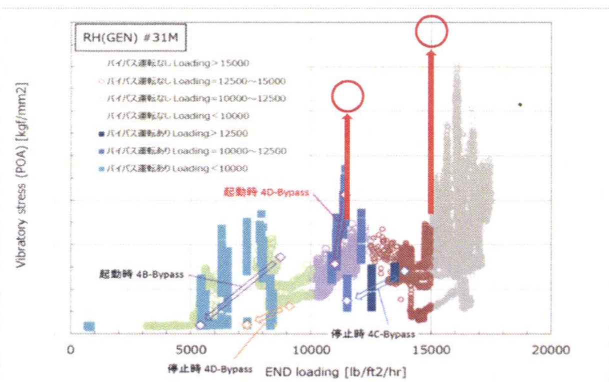
Dynamic Stress Summary (POA)



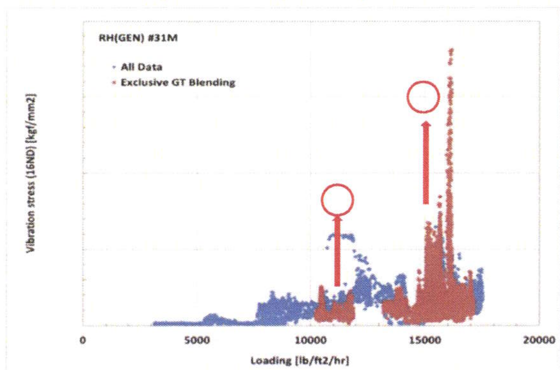
Aerodynamic Damping (3D Flutter Analysis)



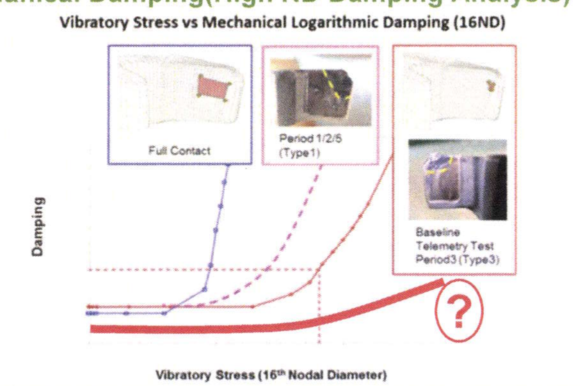
Vibratory Stress(POA: Strength Evaluation)



Vibratory Stress (16ND)



Mechanical Damping(High ND Damping Analysis)



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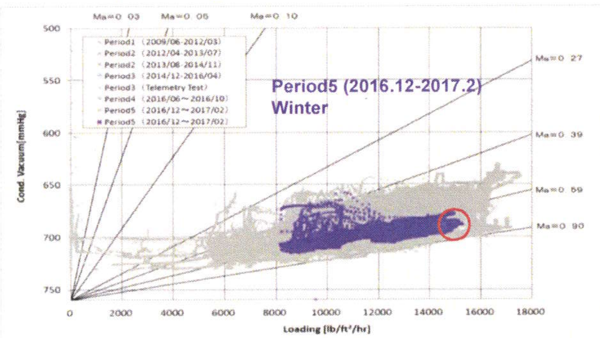
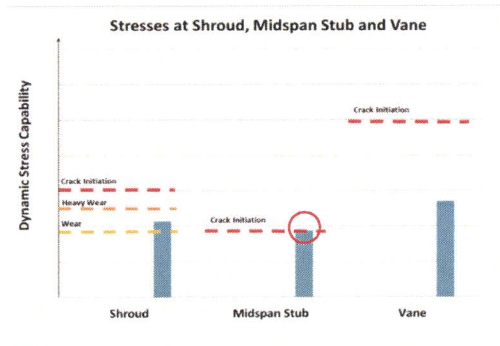
Period 5 – Stub Cracking

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

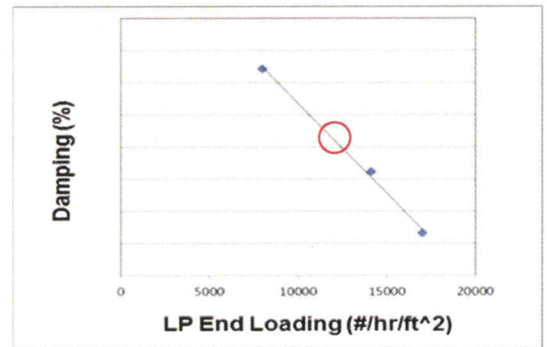
Max Operating Conditions



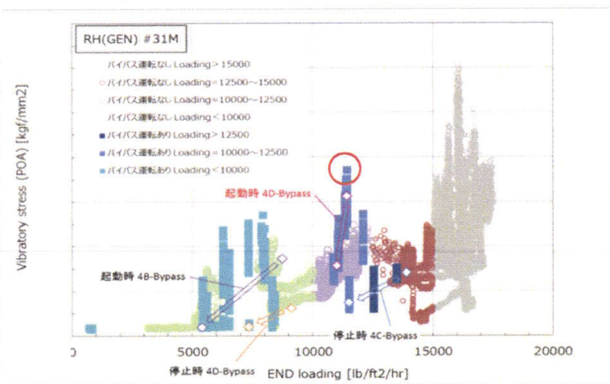
Dynamic Stress Summary (POA)



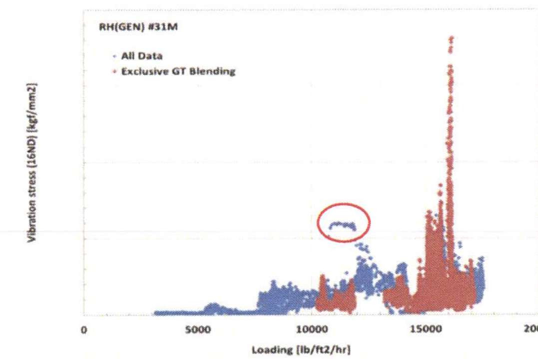
Aerodynamic Damping (3D Flutter Analysis)



Vibratory Stress(POA：Strength Evaluation)

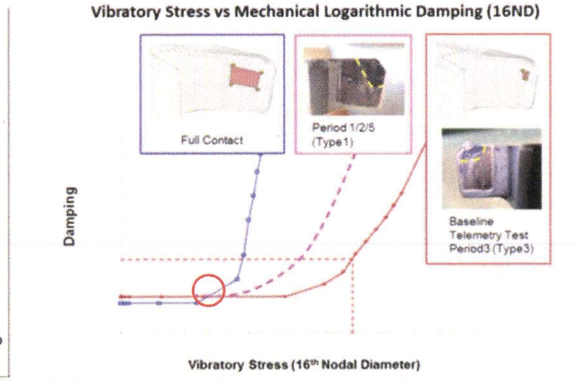


Vibratory Stress (16ND)



Mechanical Damping(High ND Damping Analysis)

Vibratory Stress vs Mechanical Logarithmic Damping (16ND)



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