TurboExpander Wheel Damage Analysis
A Case Study

Jim Cencula	GE O&G
Randy Wu	GE O&G
James Ho	GE O&G
Murari Singh	SafeTSol / GE O&G
Brian Cahoon	CalEnergy
Ernie Higgins	CalEnergy

Introduction

- **Damage analysis of a turbo-expander wheel in a geothermal application will be discussed.**
- **Presentation includes**
  - **background,**
  - **description of damage,**
  - **damage analysis,**
  - **conclusions and**
  - **finally discussion of remedial actions to achieve longer life for the wheel**

Background

- **Two high backpressure radial inflow energy-recovery Turbo Expanders are used. These are located upstream of condensing steam turbines in a geothermal plant in Southern California.**

- **The source of steam is geothermal brine, which has approximately 25% solid material. The brine is flashed at about 450 deg. F and the steam with sub-micron droplets is taken from the top of the spreador, into a transfer pipe to a scrubber.**

- **The turboexpander producing 10+ MW has been in operation since early 2000.**

- **This unit had a difficult operational history.**

Some early remedial actions

- Wheel material was upgraded to Ti-64 grade 29 with high Ruthmanium content,
- Impeller root radius was Laser shock peened,
- Tungsten-carbide coating added to flow path surfaces,

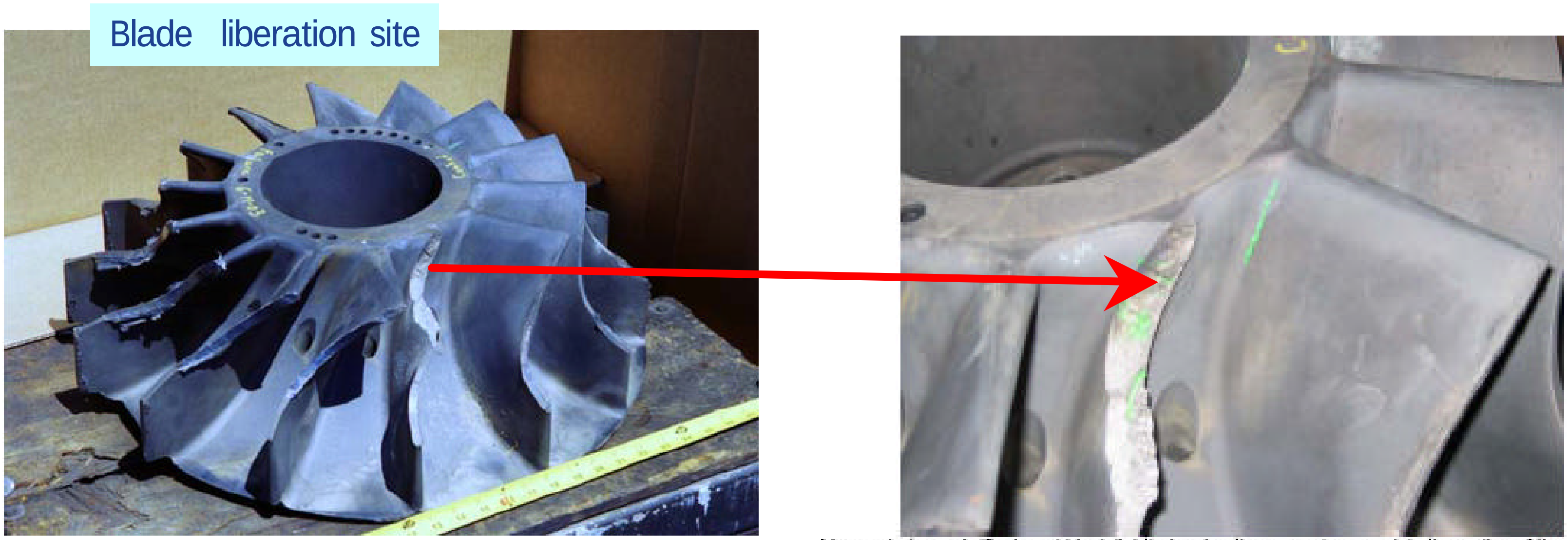
AND

- process changes were made.

Description of Damage

- The crack initiation was determined to be started on impeller blades although all resonance frequencies were cleared near synchronous speed. This has been checked by Campbell diagram based on test data. The estimated stress level was within acceptable limit per Goodman diagram of the material.

- Cracks were initiated from the blade root and sidewalls. Surface cracking was caused by SCC in the Ti-alloy.



Macro photograph (flash and black light) showing the secondary crack in the radius of the adjacent blade to the primary fracture. IMG 4273.JPG

Damage Analysis

Damage Analysis

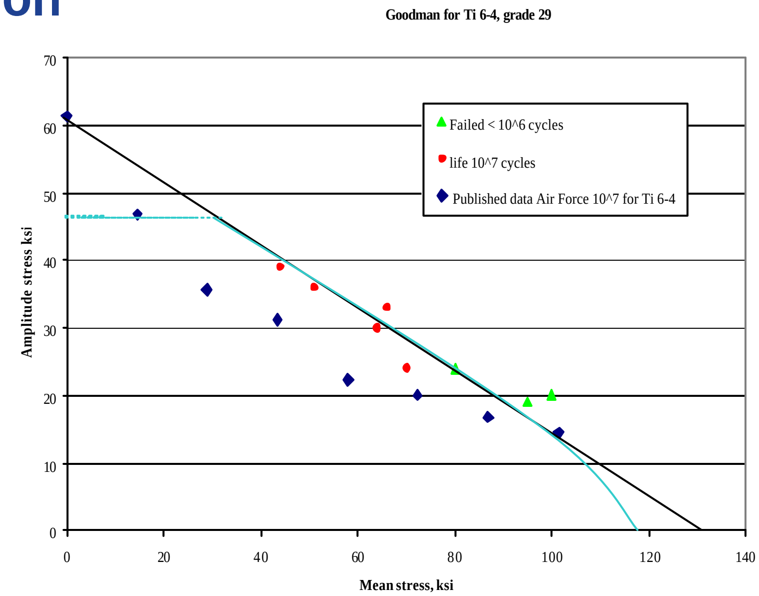
- Material property test from damaged wheel
  - Mechanical properties
  - Fatigue properties
  - Chemistry
- Inspection of the fracture generated surface
  - Environmental effect for crack initiation and/or crack growth
  - SEM testing for initiation site
  - SEM testing for estimating number of cycles

Damage Analysis (cont'd)

- Analytical solutions
  - FE “modal analysis”
  - Forced response analysis
- Probabilistic life estimation
- Dynamic pressure measurement

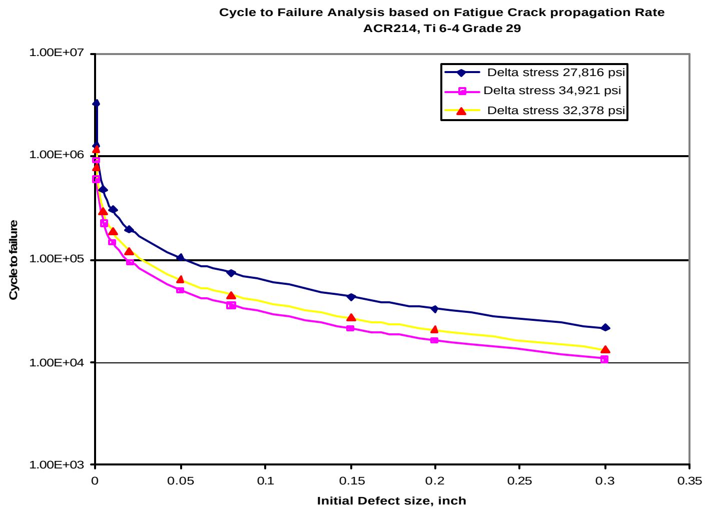
Test on the material of the damaged wheel

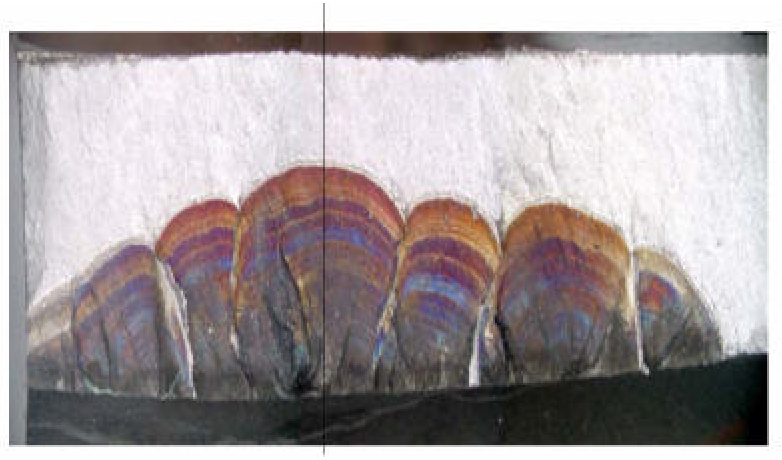
- Material tests show no influence of environment
- Tensile tests & % elongation in the specified range
- Goodman diagram created from fatigue test data meets expectation



Test on the material of the damaged wheel

- **Fatigue crack growth rate SEM test data matched to empirical data/ striations**

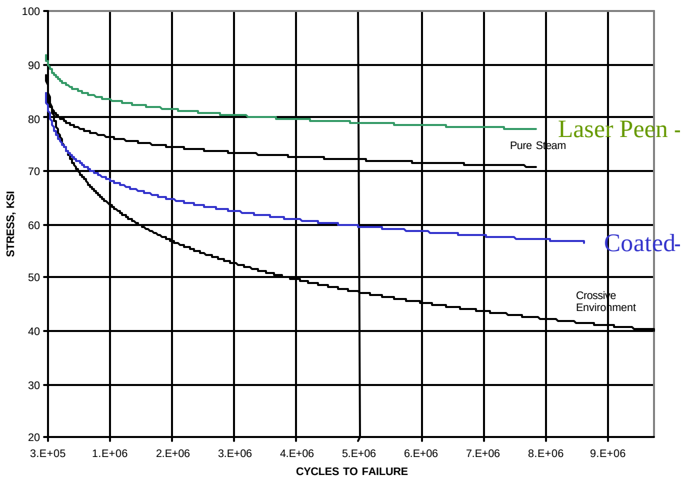




Relative fatigue strength due to different surface treatment

Macro photograph (flash and black light) showing the secondary crack in the radius of the adjacent blade to the primary fracture. IMG 4273.JPG

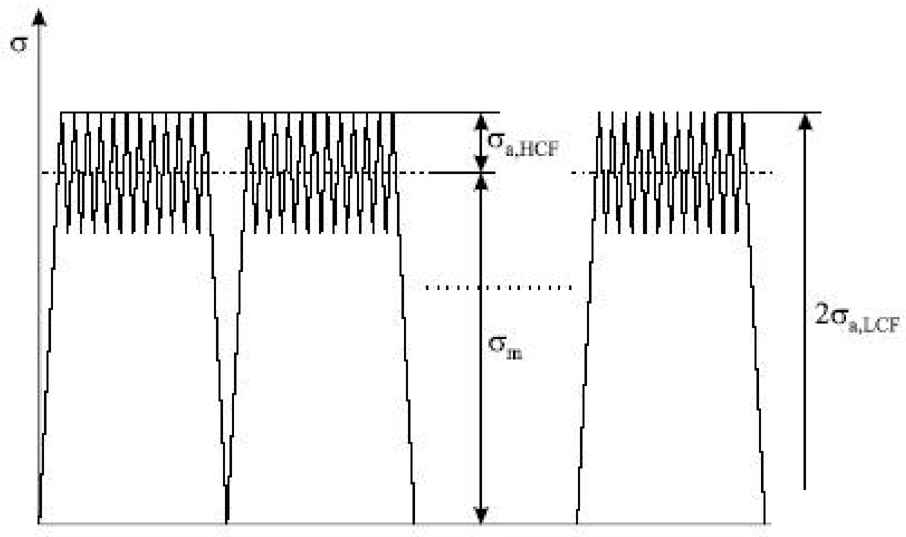
- Physical inspection of non-failed blades showed coating cracks

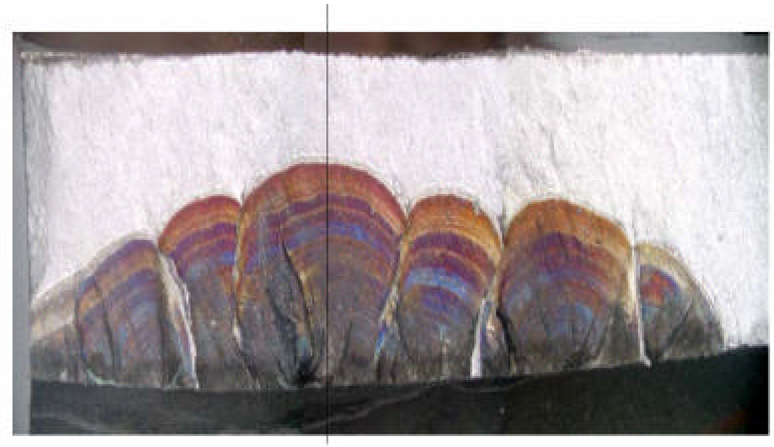


Ti 64 Fatigue Capability

- Laser shock peening of root radius is a significant benefit for improving fatigue strength
- Tungsten Coating- significant benefit to environmental protection BUT has much lower HCF capability than Titanium substrate

Inspection of the fracture generated surface



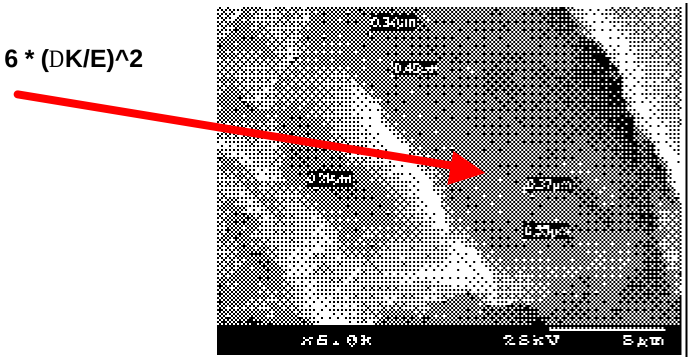


Startup, normal operation, and shut down cycles stress profiles on blades

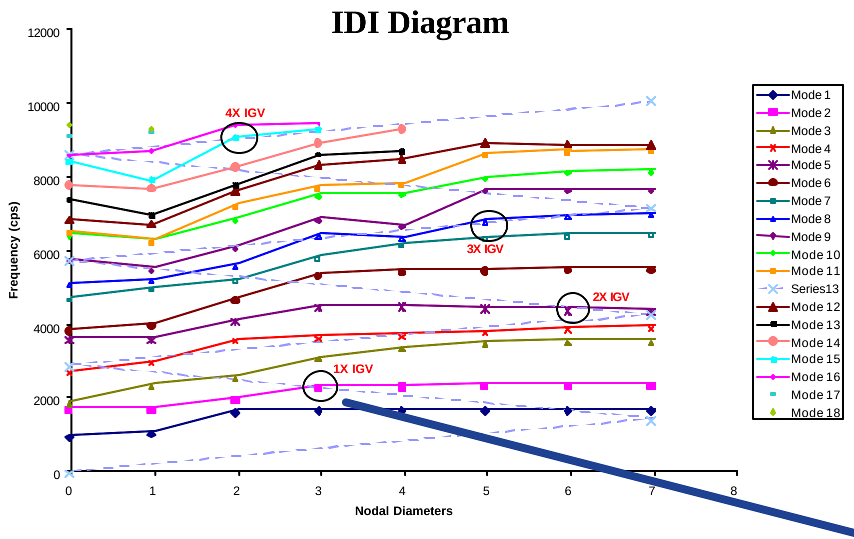
Two issues LCF and HCF
- **LCF can initiate crack**
- **HCF propagate the crack**

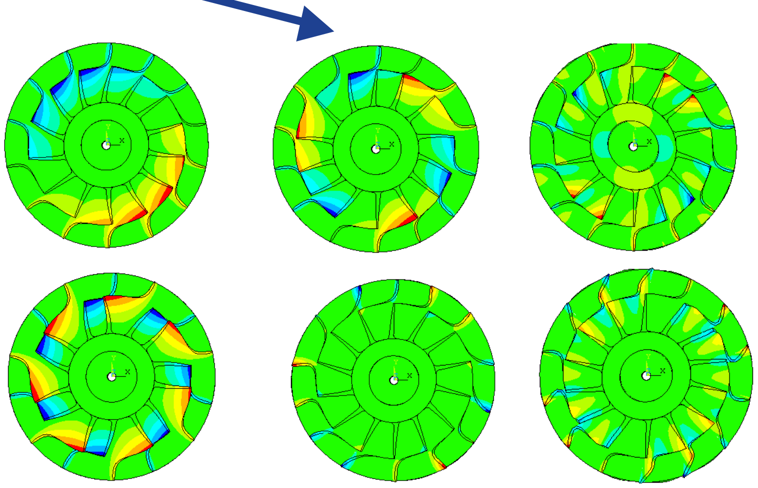
Striation Spacing, um	Location, mm	D K	D stress, psi
0.28	4	22365	32378
0.57	7	31910	34921
0.62	12	33280	27816

Striation Spacing ~ 6 * (DK/E)^2



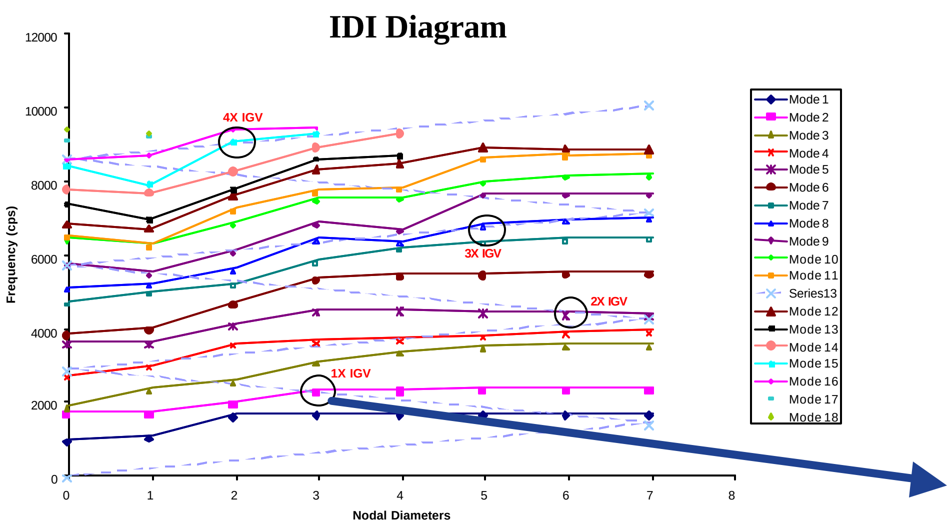
Modal Analysis

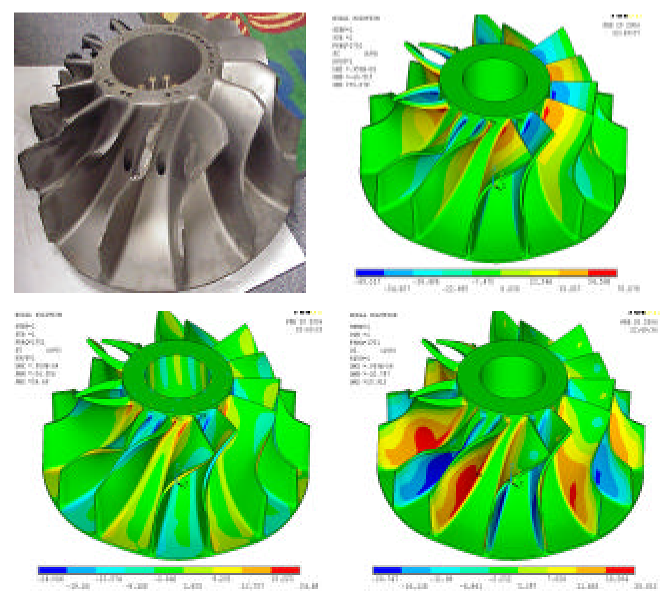




Alternating Stress Estimation

Forced Response Analyss





Alternating Stress Estimation

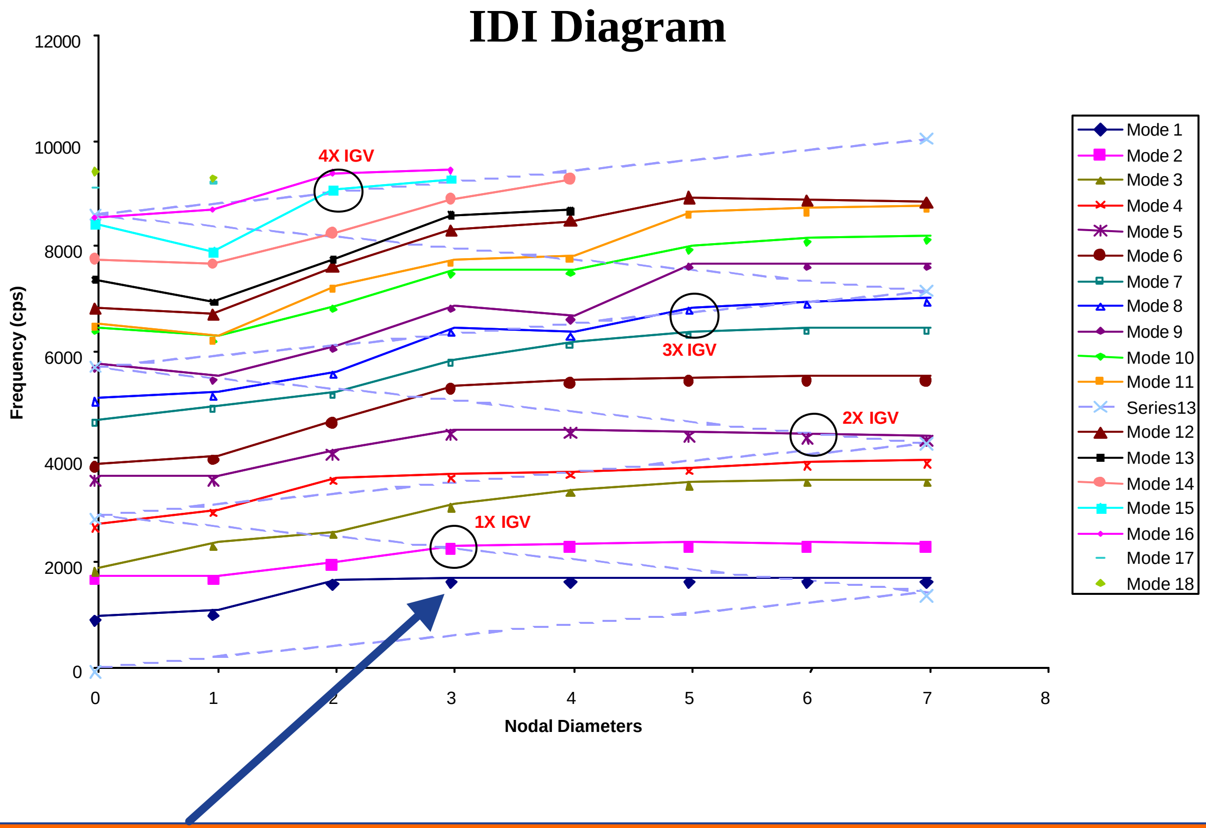
Up to 4XIGV excitation was considered for forced response analysis.

List of estimated response due to various harmonics IGV

Order of Excitation	Alternating Stress, psi
1xIGV	7515
2xIGV	2625
3xIGV	1436
4xIGV	1756

- **Which mode is causing this reduced life of wheel?**
- **Modal Analysis completed and variation examined to modes in the operating range…..**
- **Transient (start ramp) modes needed further examination to see which mode shape matched to fracture pattern**

Mode can be excited during start up



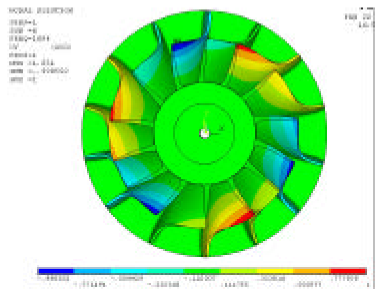
There is a 3XND mode that can be excited by 1XIGV during start up

Is this 3xND mode more significant than the ones examined earlier?

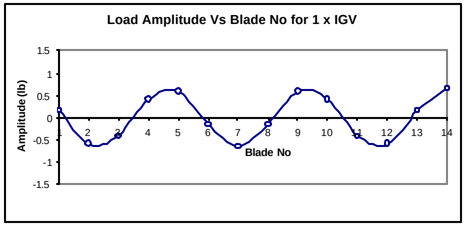
Harmonic Analysis was performed with the following load data

Nodal Diameter: 3
Natural Frequency: 1694 Hz
Speed: 9240 RPM.
Excitation force frequency range: 1644-1744 Hz

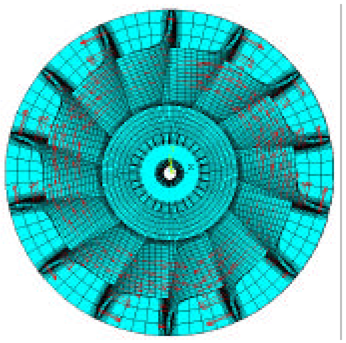
1st 3ND Mode



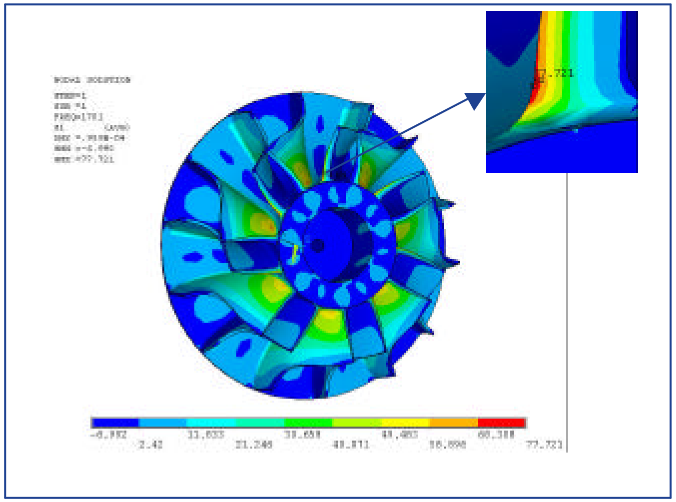
Load Amplitude Vs Blade No



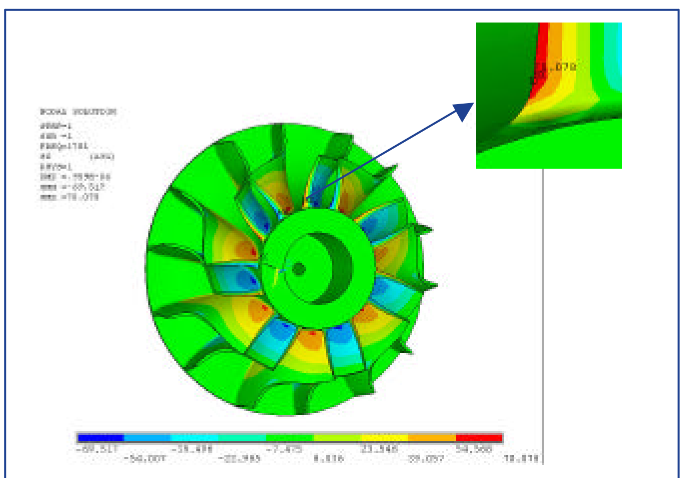
Loads applied on all the blades



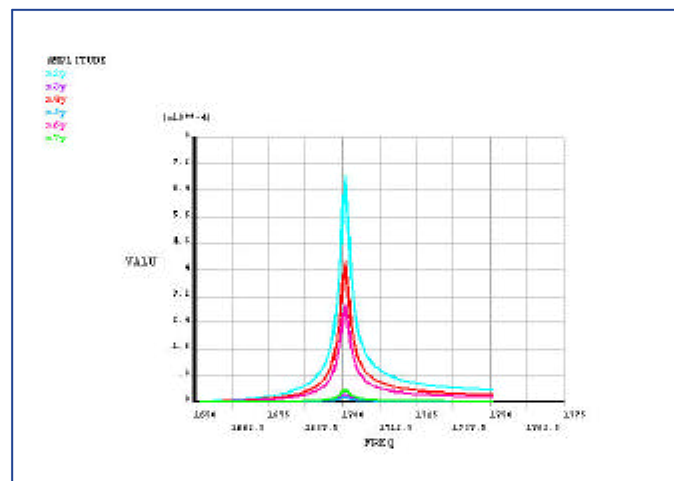
Loads were generated using distributed load amplitude per ND and a multiple of the unit HP



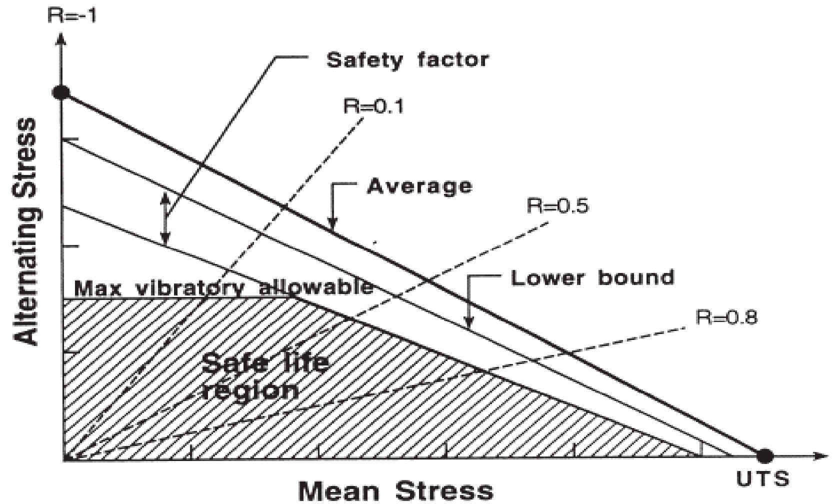
Peak/ ALT stress amplitudes were examined from Forced Response analysis to the fatigue seen in blade….
No one mode had alternating stress within 10X of that from SEM results.



Displacement Vs Frequency of excitation

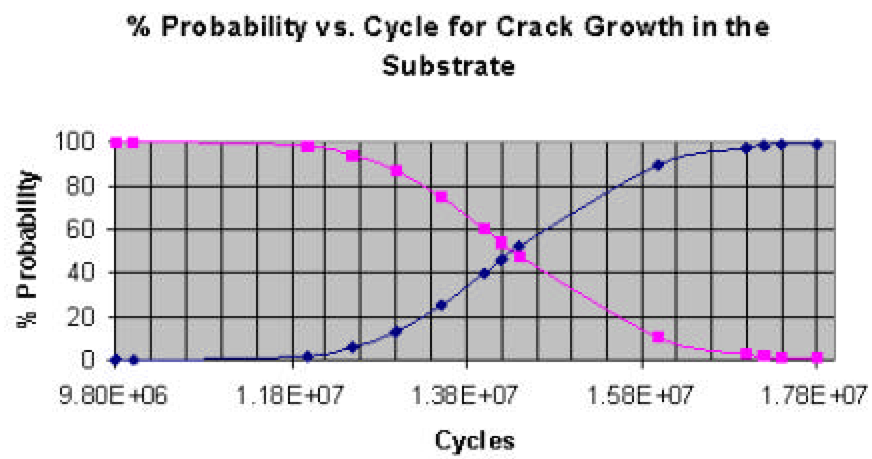


Probabilistic estimate of number of crack growth cycle

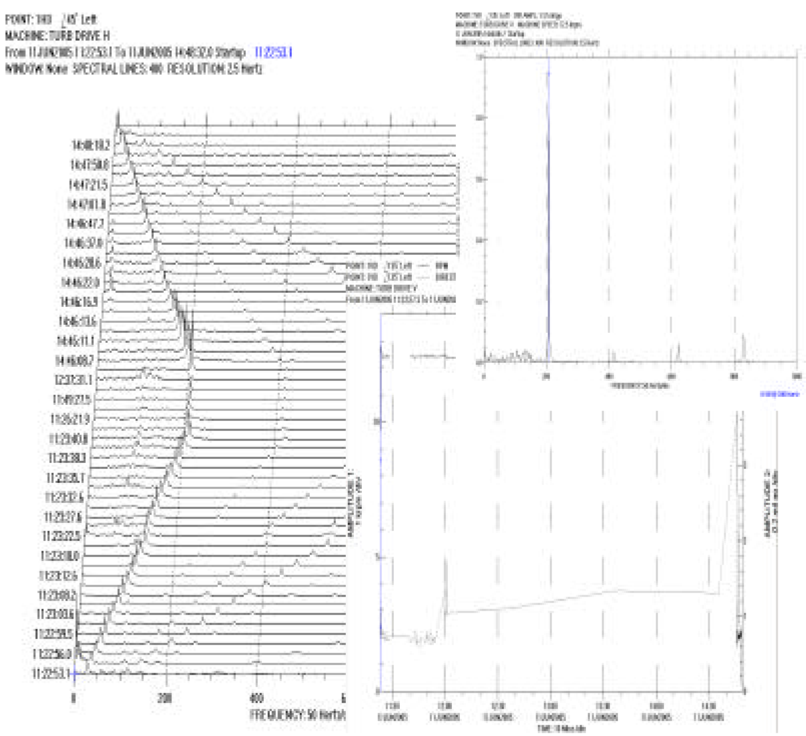


Traditional design process would pick a 'safety factor' from the known material property and stress data for 'safe life' design......

a probabilistic life assessment has been completed for broader understanding of risk associated with various operating lives and starts / upset conditions.



Dynamic Pressure test



What is happening in operation to create vibratory stress levels 10x greater than expected and how to avoid?

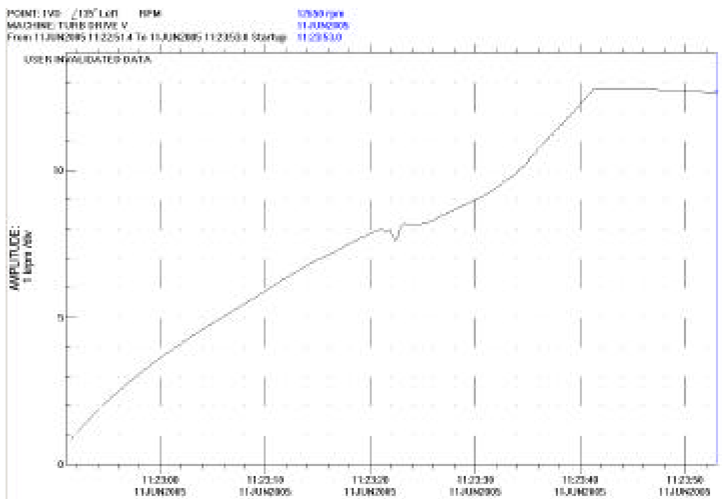
True operating conditions with actual system condition starts from the plant operations log examined….

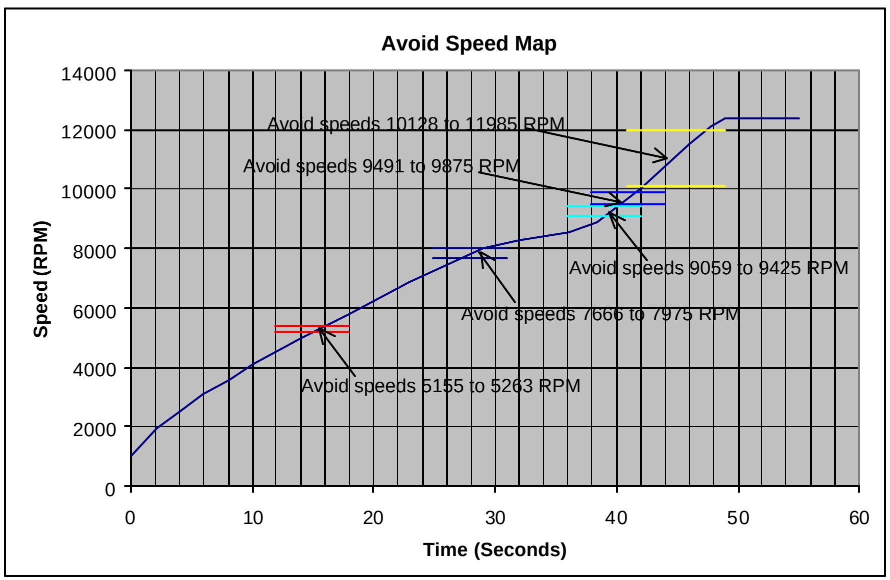
Key discovery: the pressure across the Expander was much higher than expected design conditions– this results in super-sonic speed in Nozzles > sonic wakes of IGVs.

Dynamic pressures sensor test of start sequence required to understand and validate; unit equipped w/ pressure taps > tested

Remedial Steps

Remedial Steps





Starts stresses have been proven significant at the multiples of the IGV stimulus nodal diameters…..

Can the operations live with modified start to ensure 'quick pass' through the resonant modes?

Control system was examined….and generally the answer is 'YES', again further reducing and change for damaging cycles

Conclusions

- After modification of the geothermal steam process system, changing the expander components materials and adding proper surface treatment the life of the impeller has increased, but further efforts were needed for acceptable maintenance intervals.
- Recent joint effort by engineering and customer’s technical and operational team on increasing the life span of the unit has led to further improvements of the maintenance interval life of the impeller.

Conclusions

•During the start-ups, with small IGV opening and the pressure differential currently set on system, super sonic flow exists through the IGV and thus creates strong IGV sonic wakes. This in turn increase damaging cycles causing reduction in the life of the material.

•Modification in start sequence, results of dynamic stress analysis, and expander design details have helped to achieve a substantial increase in operational life.