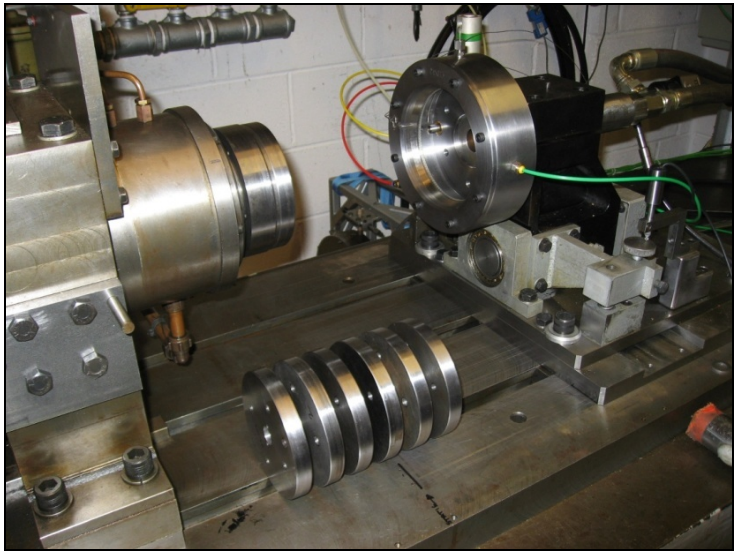
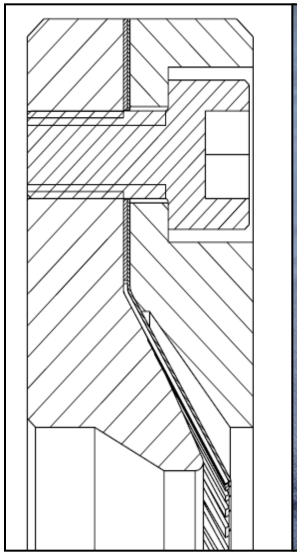
Pressure Activated Leaf Seal Technology Readiness Testing
GT2014-27046





Presented by Peter Crudgington - Director

Cross Manufacturing Co. (1938) Ltd

in conjunction with **CMG TECH**

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Acknowledgements

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- Smooth Rotor Testing
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  - Dynamic
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- Simulated Shrouded Turbine Blade Testing
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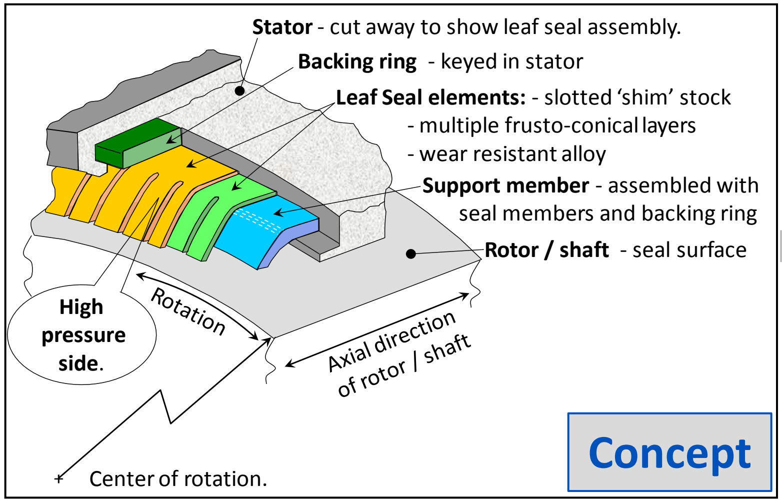
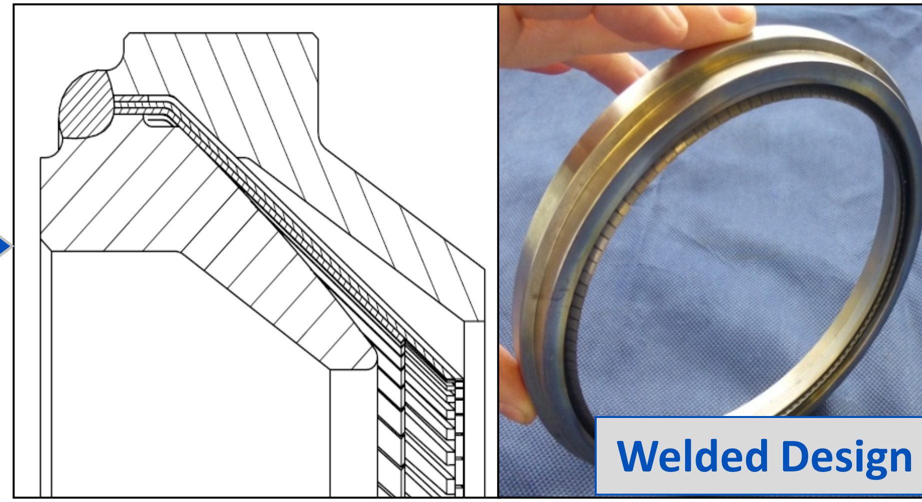
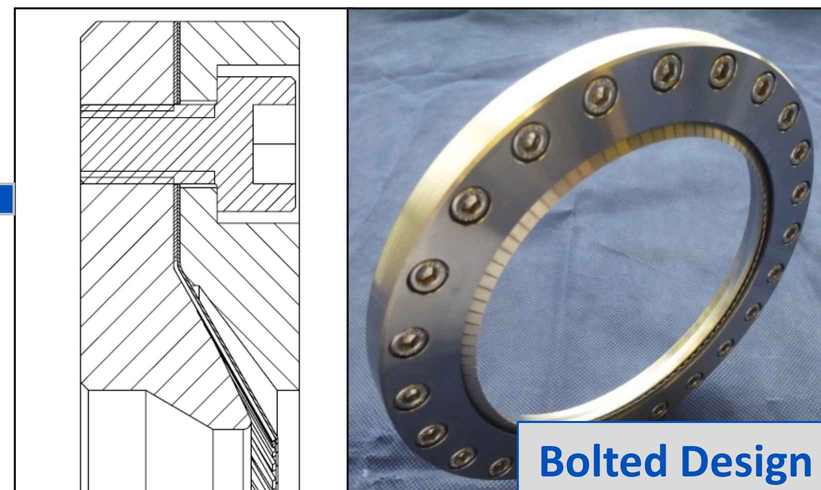
- Future Work

Introduction
PALS Design







Larger diameter
&
Segmented design

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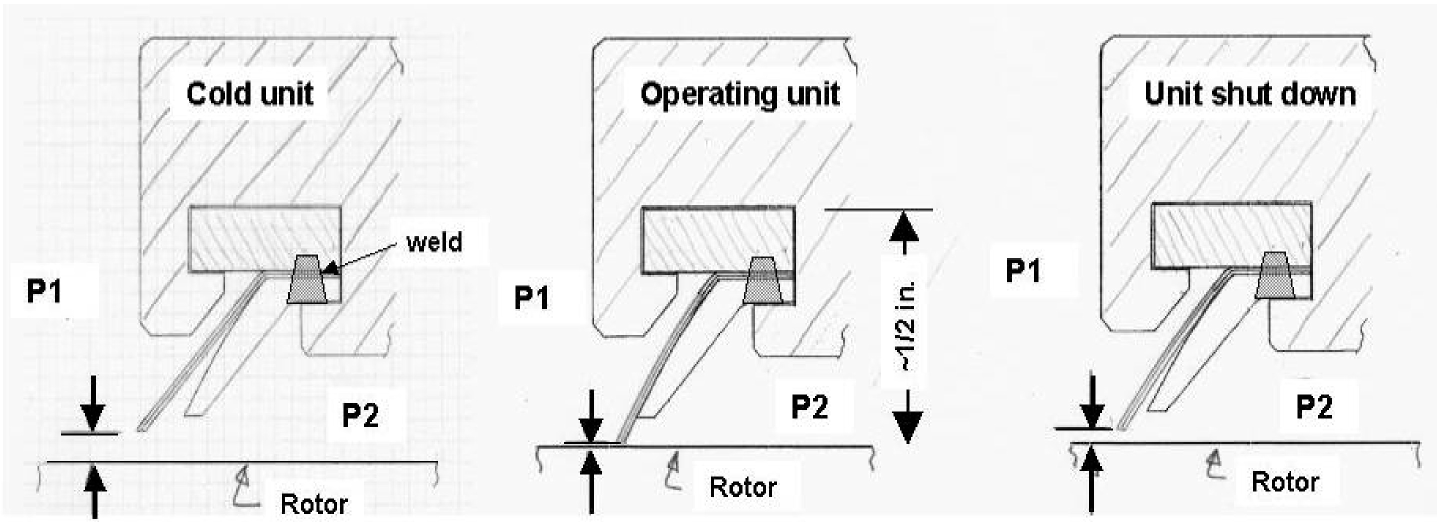
Introduction
Pressure Activated Leaf Seal (PALS) Concept



Cold clearance - <u>large.</u>
- **P1 = P2**
- **Seal elements *<u>not in</u>* contact with support.**
- **Seal rubs avoided.**

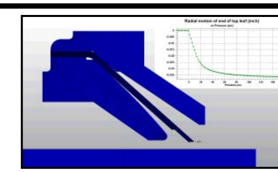
Operating clearance - <u>small</u>.
- **P1 >> P2**
- **Seal elements *<u>in</u>* contact with support.**
- **Leakage minimized, for performance gain.**

Shutting down clearance - <u>increasing.</u>
- **Δ P decreasing with RPM.**
- **Seal elements *<u>retract</u>* from support.**
- **Seal rub damage avoided.**

Large startup & shut down clearance: → ***<u>Rub avoidance.</u>***

Minimum operating clearance: → ***<u>Performance gain</u>*.**

Non-contacting operation: → ***<u>Long seal life.</u>***



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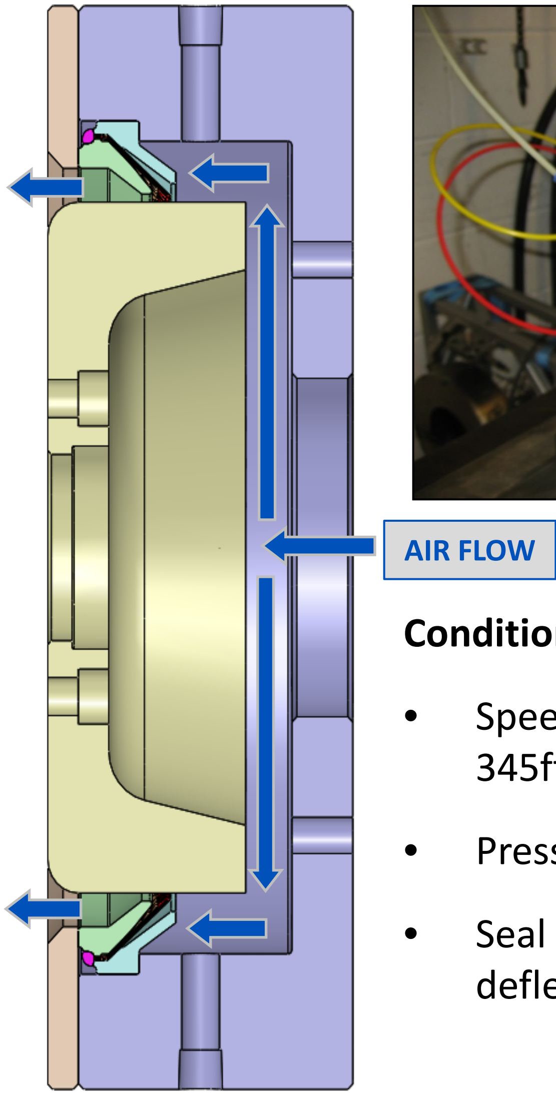
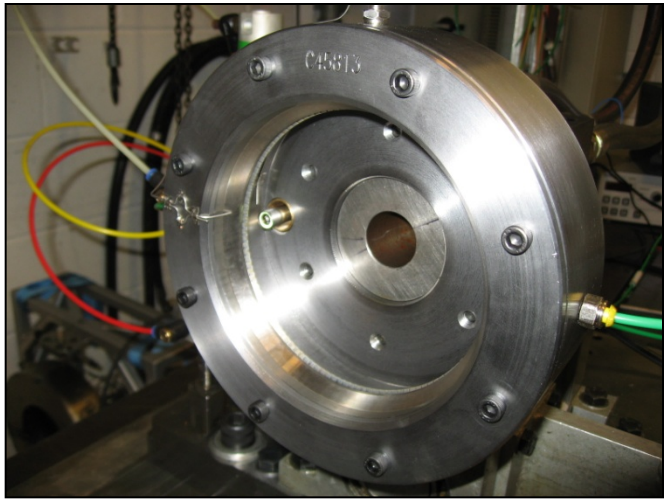
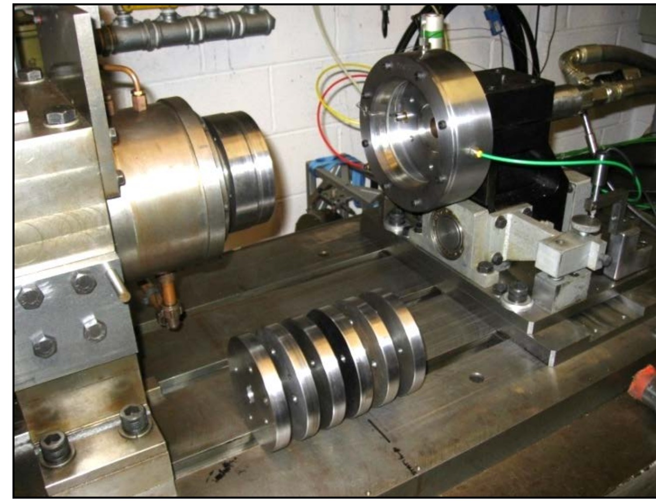
Smooth Rotor Testing Overview



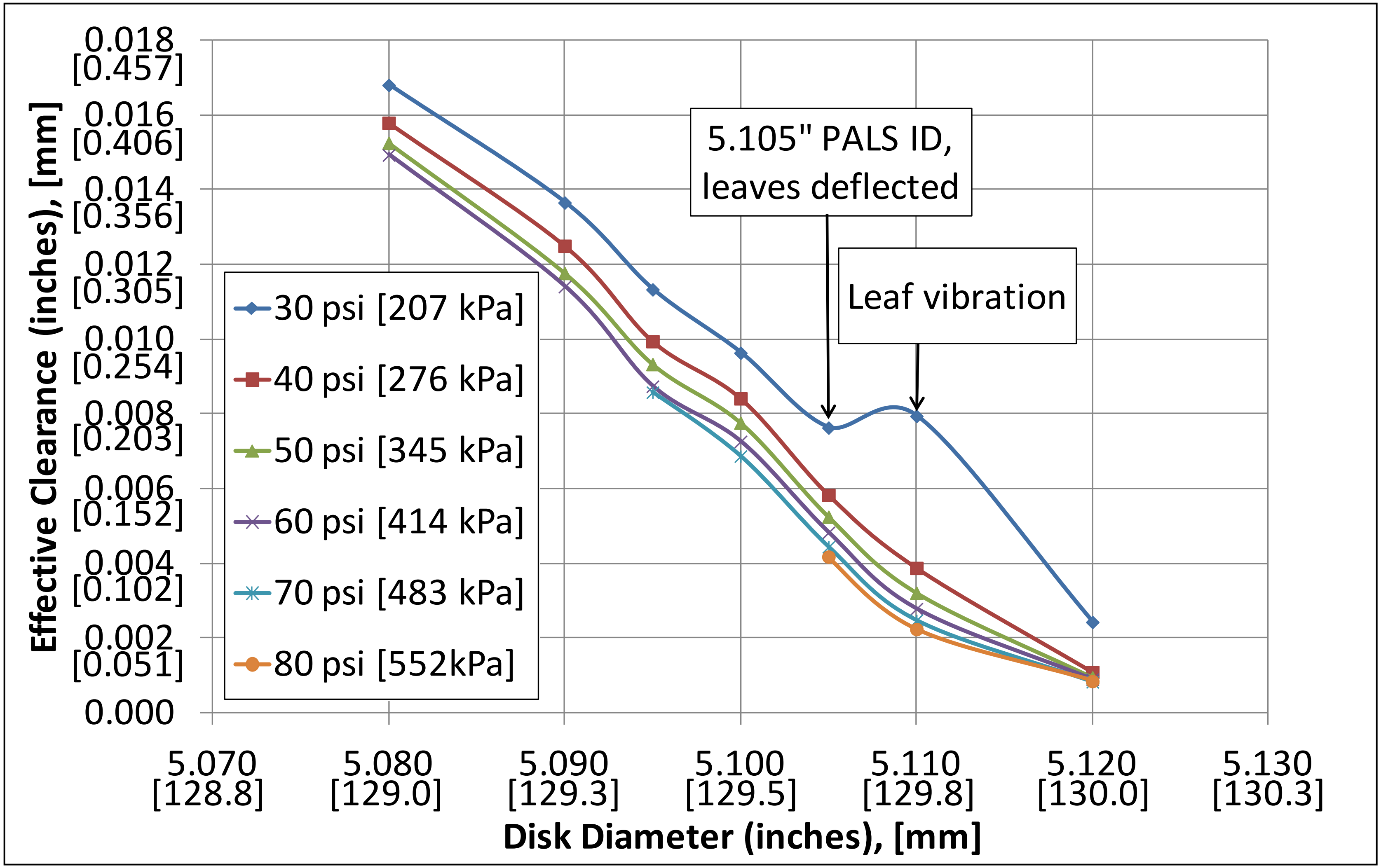




Conditions:

- Speed – Typically 300ft/s (up to 345ft/s)
- Pressure Drop – Up to 120psi
- Seal Diameter pre Wear-in – 5.105” deflected (5.185” un-deflected)
- Rotor Diameter – 5.080” to 5.133”
- Fluid – Compressed air
- Rotor material – Aubert & Duval 819B (Ni-Cr-Mo Alloy) uncoated

Smooth Rotor Testing
Static Leakage with Various Disk Sizes



Smooth Rotor Testing
Dynamic Offset Test

- 13500rpm
- 50psi
- 5.105” Seal Bore Size
- 5.115” Disk Size
- 0.010” Radial Offset to create a 0.005” rub.
- Effective Clearance 0.007” prior to rub
- Effective Clearance 0.0077” after rub

•After test, bore of seal re-edm’d to 5.114”

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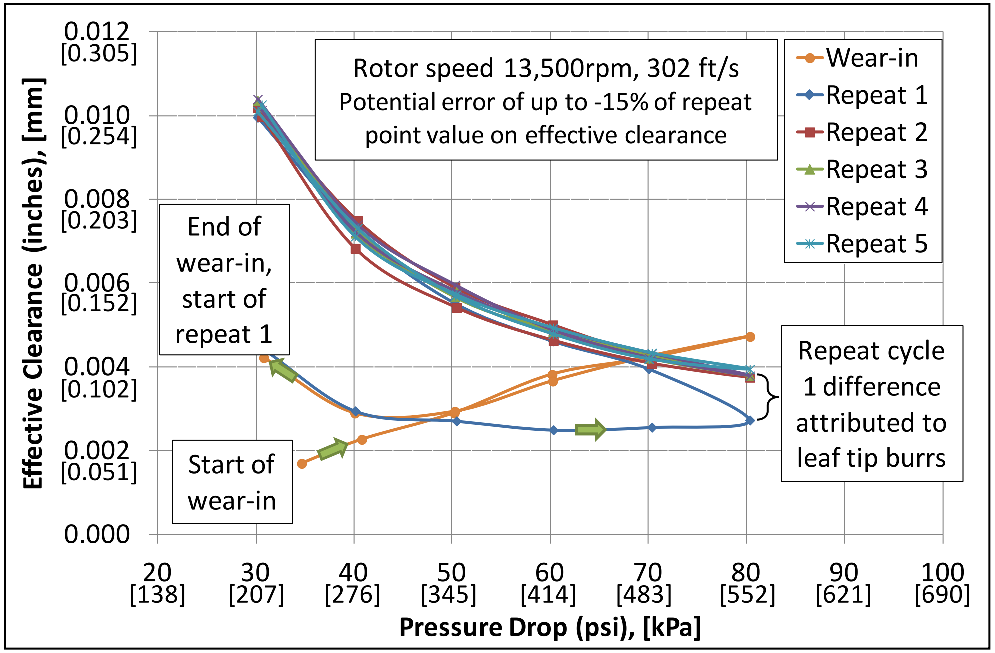
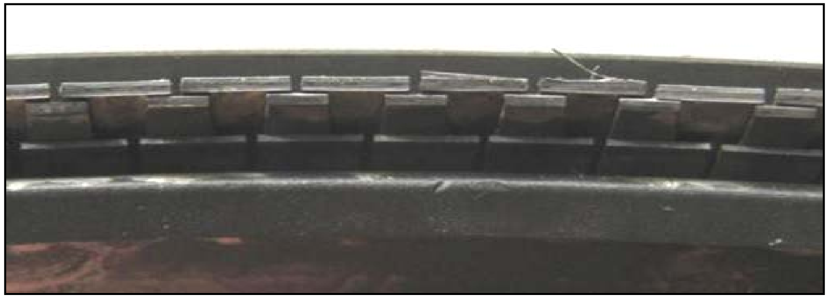
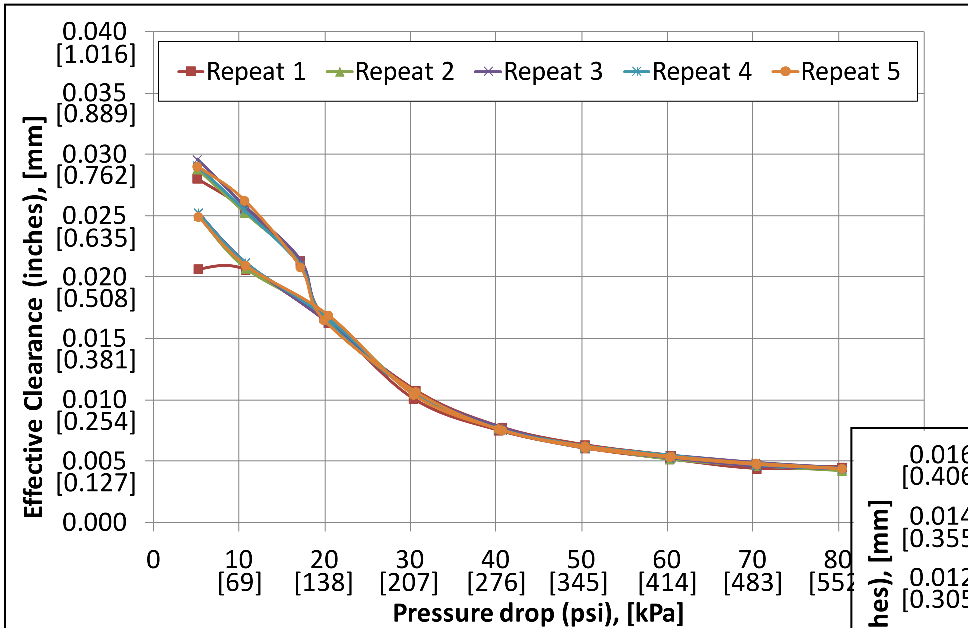
Smooth Rotor Testing - Wear-in Results
Rotor Ø5.133”, Seal (deflected) Ø 5.114”



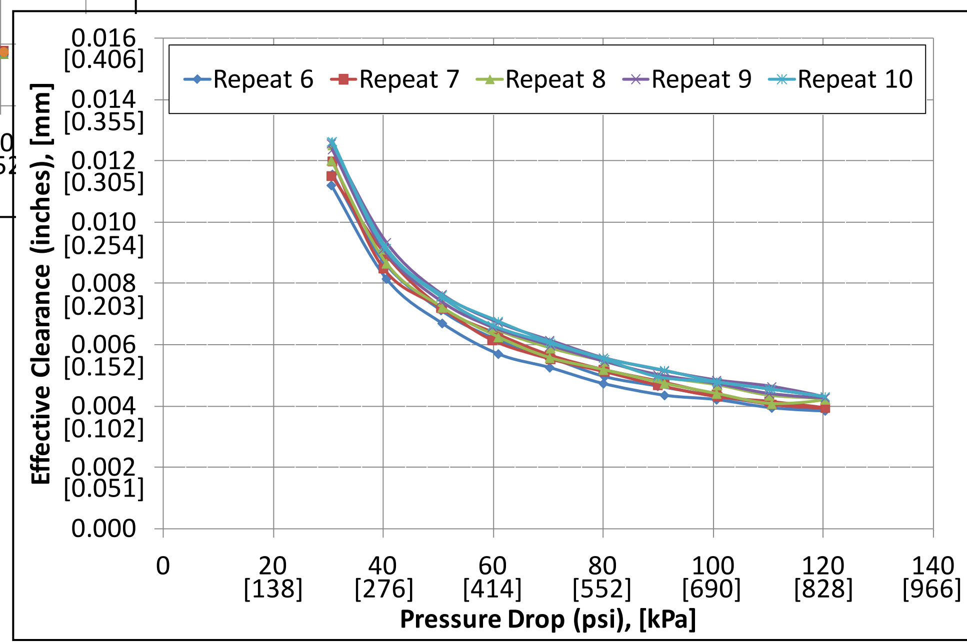


- Orange line - ‘Wear-in’, the first time the seal is run
- Blue line repeat 1– post wear in burr stabilisations
- Consistent effective clearance throughout repeat 3 to 5
- Leaf tips wear to the rotor to establish good synchronicity
- Burrs form on both top and bottom leaves in both positive and negative axial direction

Smooth Rotor Testing
Repeatability – Static Rotor Ø5.133”

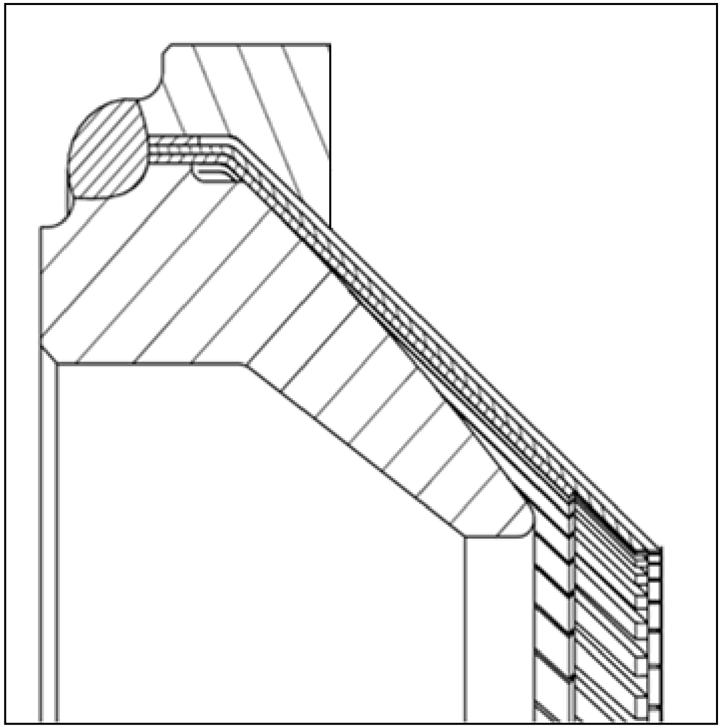


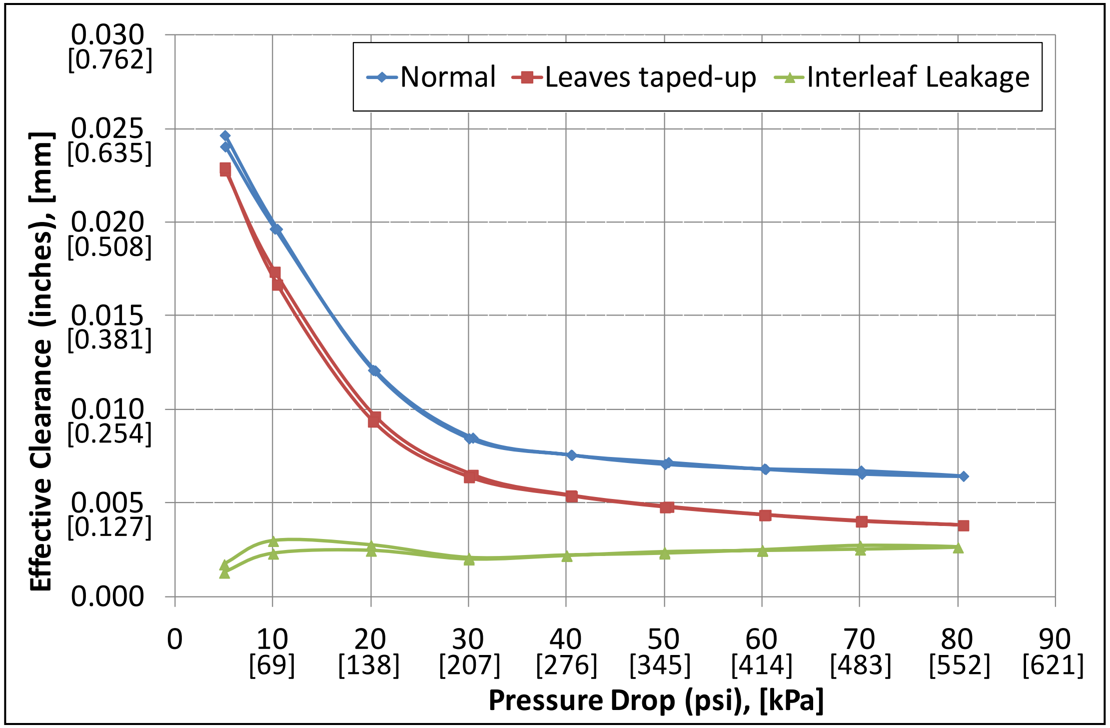
- Low pressure static leakage sweeps up to 80 psid post wear-in
- Repeatable closure with pressure
- No hysteresis



- Higher pressure static leakage sweeps up to 120 psid post wear-in
- Repeatable closure with pressure
- No hysteresis

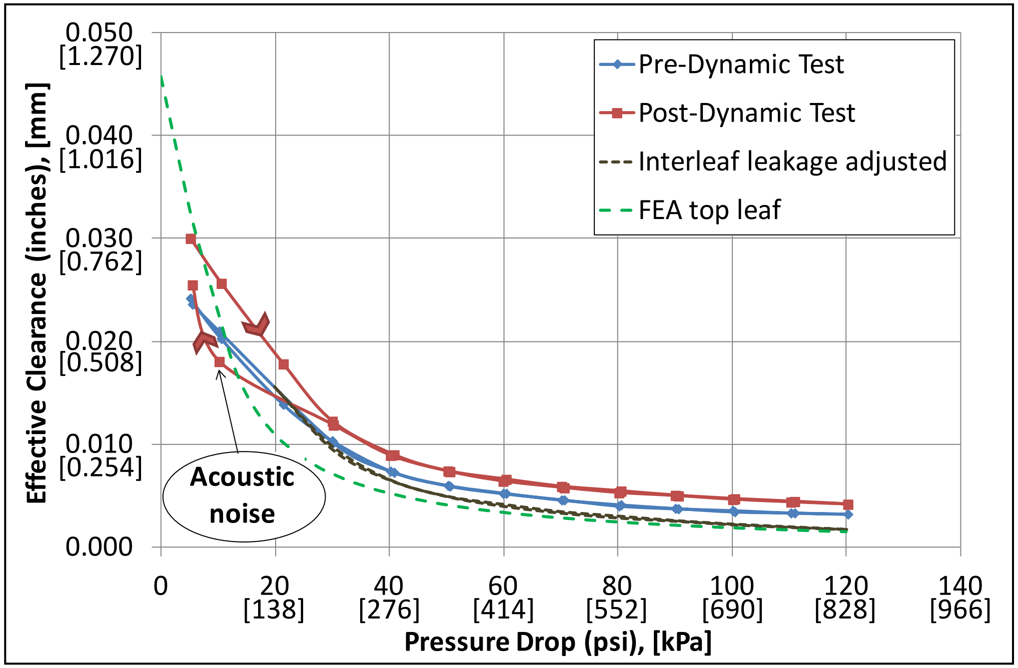
Smooth Rotor Testing
Interleaf Leakage – Static Rotor Ø5.133”



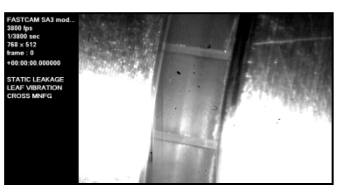


- Removed front shroud to expose leaves
- Tested statically as standard
- Upstream face of top leaves taped to block air flow between leaves
- Tested statically with taped leaves
- Difference in effective clearance accounted to interleaf leakage

Smooth Rotor Testing
Analytical Comparison- Static Rotor Ø5.133”



- Post wear-in closure
- Ø5.133” rotor
- Ø5.202” un-deflected PALS bore
- Analytical results follow closely to the measured results adjusted for interleaf leakage
- Acoustic noise was present at low pressures during the post dynamic testing



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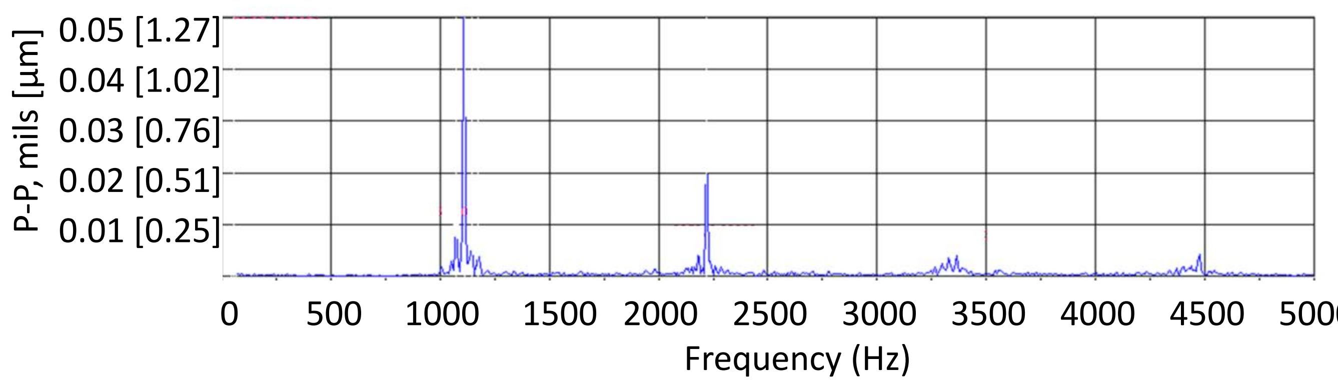
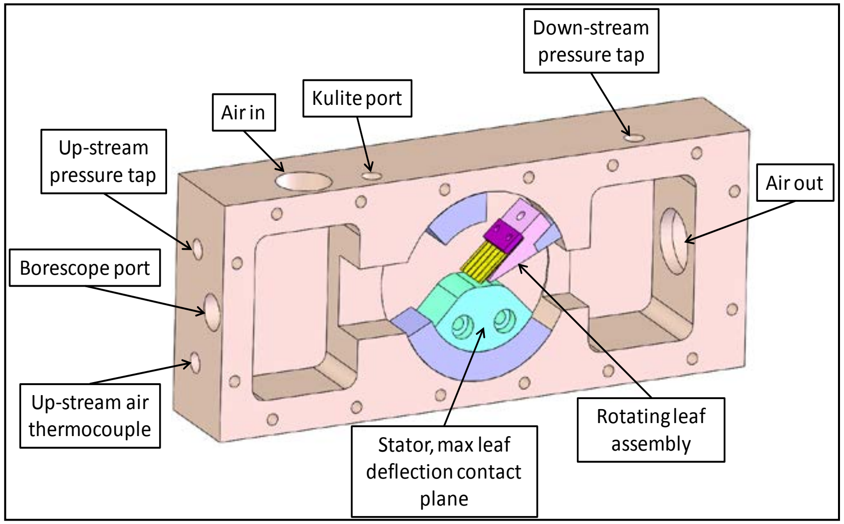
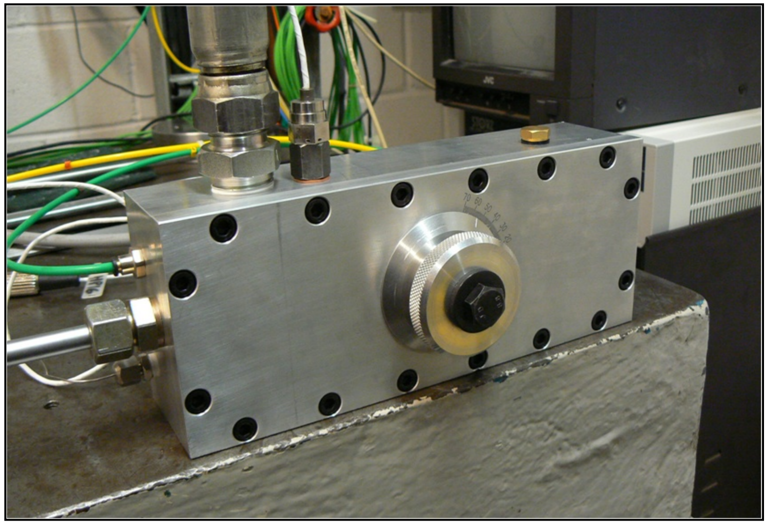
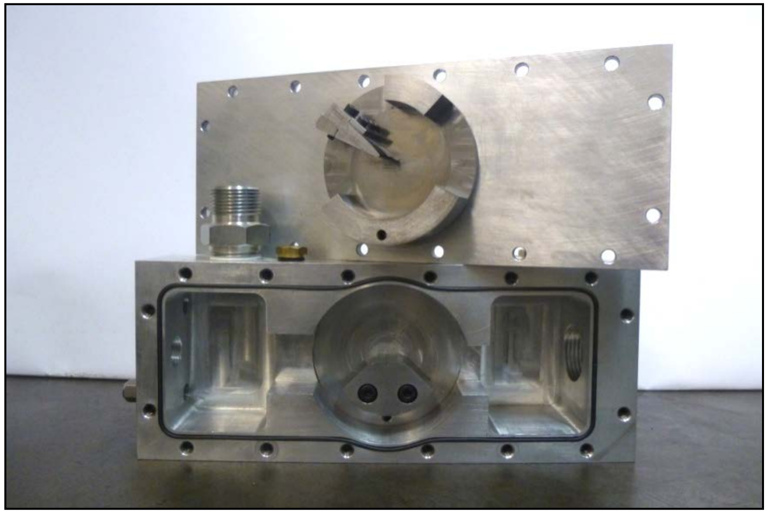


Acoustic Noise Investigation
Experimental Set-up







- Leaf vibration resulted in an audible noise at low differential pressures
- Noise stopped at pressures above 30psid
- 2D bespoke rig designed and build to investigate potential causes along with existing static and dynamic set-ups

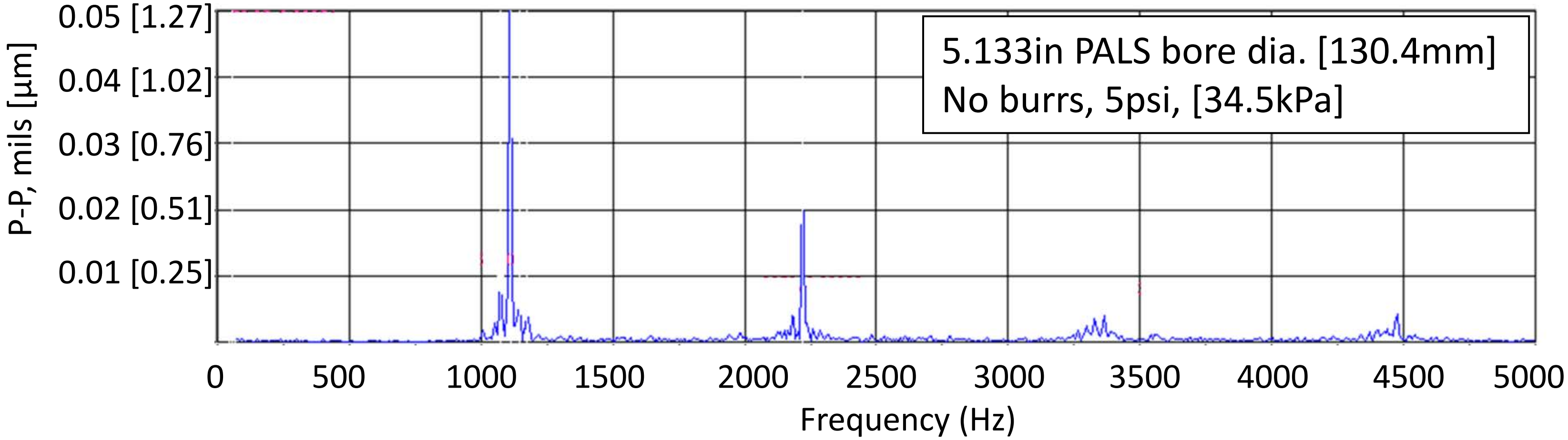
Acoustic Noise Investigation
Hypothesized Cause and Discreditation

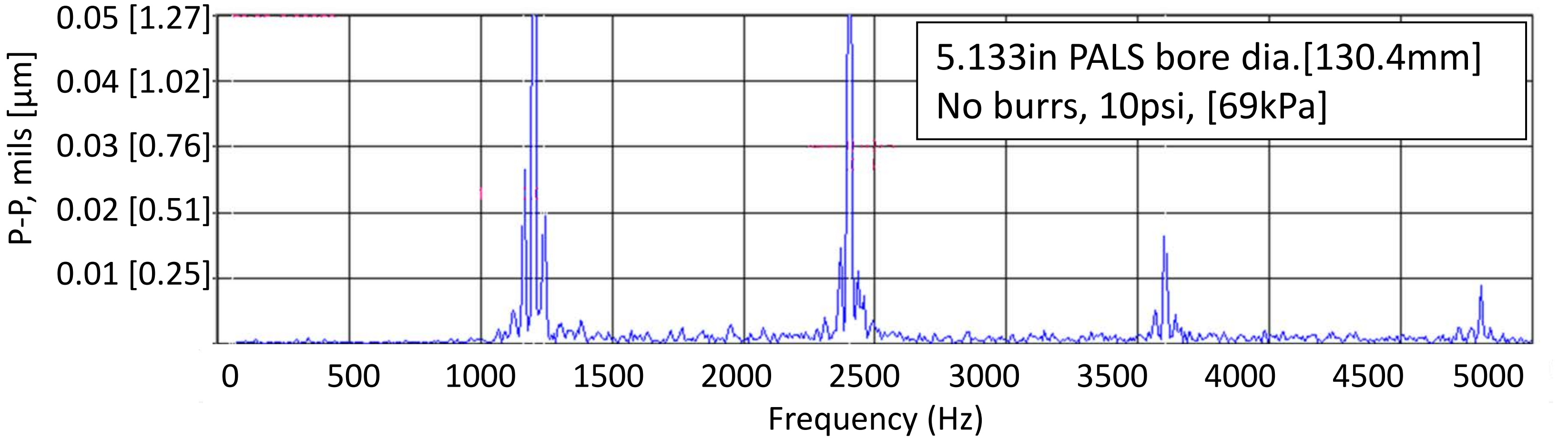
Hypothesis	**Result**
Upstream pressure fluctuations	× Disproved – Unaffected by controlled bypass leakage
A cavity in the air supply system resonates at the frequency of the leaves	
After wear-in burrs at the tip of the middle leaf silence the noise by supporting top leaves	× Disproved – Comparison testing from post wear-in and re-machined chisel like bore. No noise or vibration
Vortex shedding from leaf tips excites leaves at their natural frequency	
Wear-in changes leaf natural frequency	× Disproved – Shim testing proved interleaf gap controlled noise and vibration
Flow approach relative to leaf angle a factor in vortex shedding	× Disproved –Leaf angle ineffective on noise and vibration

Acoustic Noise Investigation
Hypothesized Cause and Discreditation

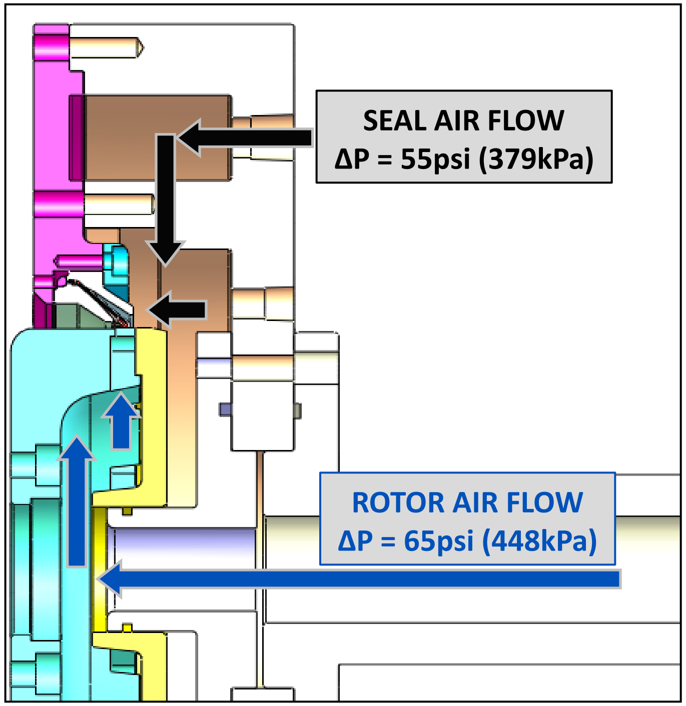
Hypothesis	Result
HCF cracking	× Disproved – No evidence of HCF from visual inspections using a microscope and dye penetrant
Cushion of air between the support and the leaves	× Disproved – No need for testing due to noise elimination before venting test
Insufficient damping	× Disproved – Manual excitation unsuccessful
Interleaf gaps allow relative motion without damping	✓ Proved – Shim testing proved interleaf gap greater then .001" (0.025mm) would instigate noise and vibration
Blunt leaf ends redirect flow up leaves	✓ Proved – Re-cut leaves with chisel end ensuring at full pressure only the top leaves were in contact with the rotor. No noise or vibration

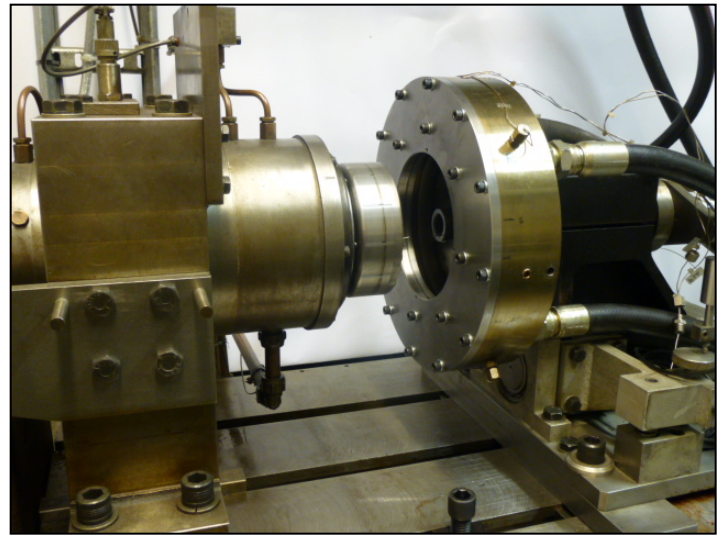
Acoustic Noise Investigation
Established Cause – Interleaf Separation

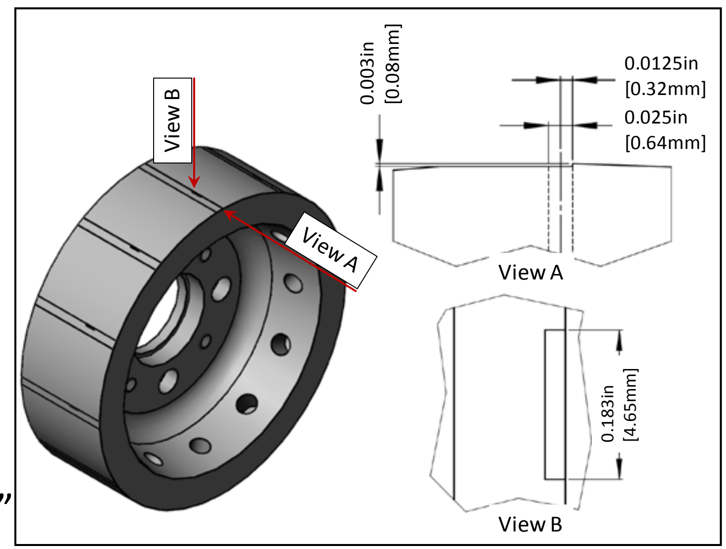




Simulated Shrouded Turbine Blade Test Overview – Dynamic



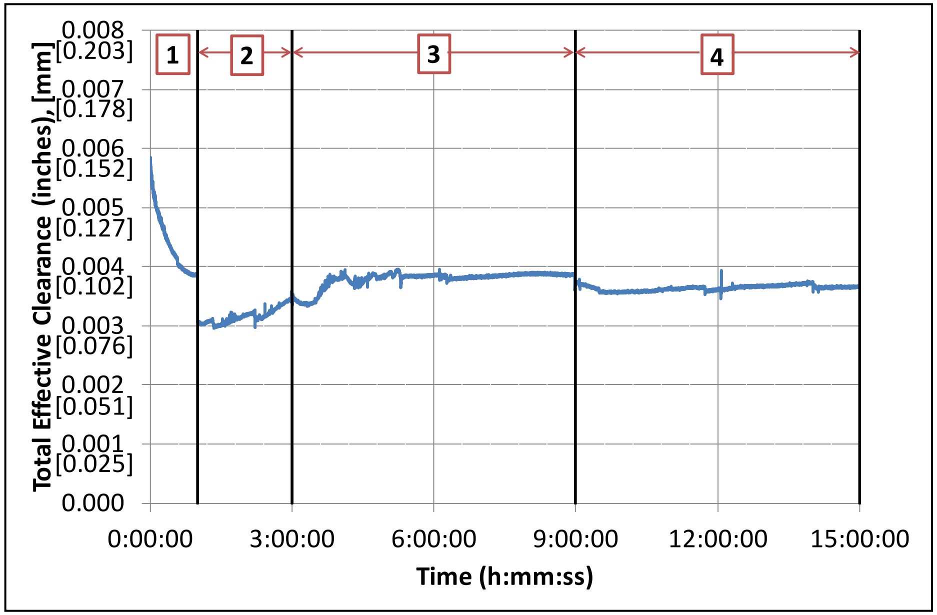




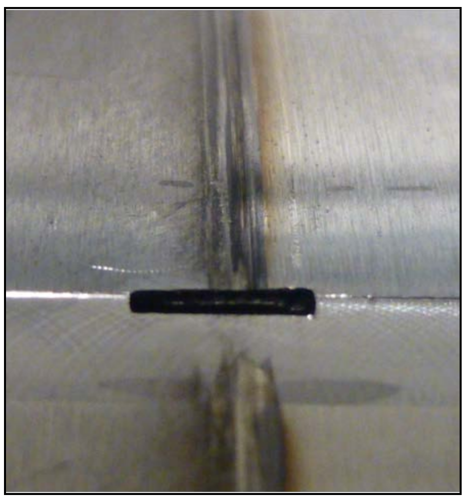
Conditions:

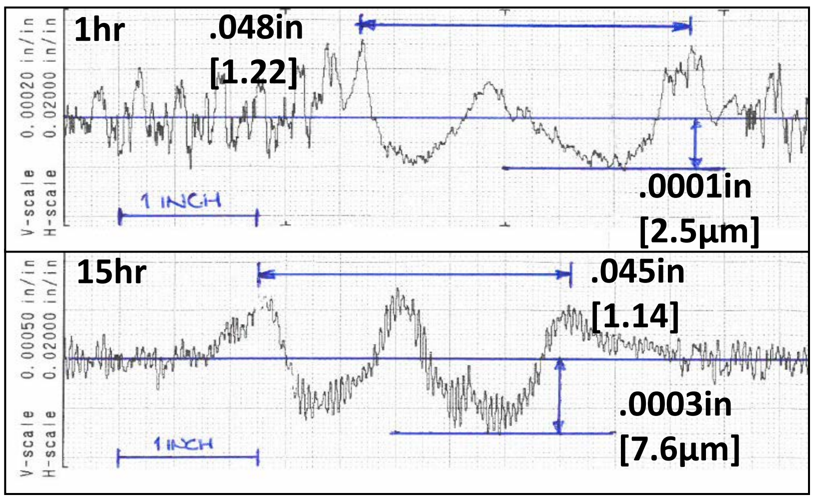
- Speed – 20,000rpm
- Slot frequency – 4000Hz
- Rotor Diameter – Ø5.120”
- Cold build clearance – 0.018”
- Fully deflected leaf interference – 0.003”

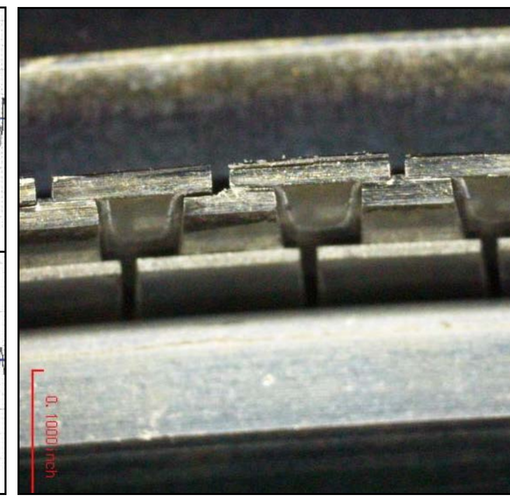
Simulated Shrouded Turbine Blade Test
15 Hour Steady State Results - Dynamic



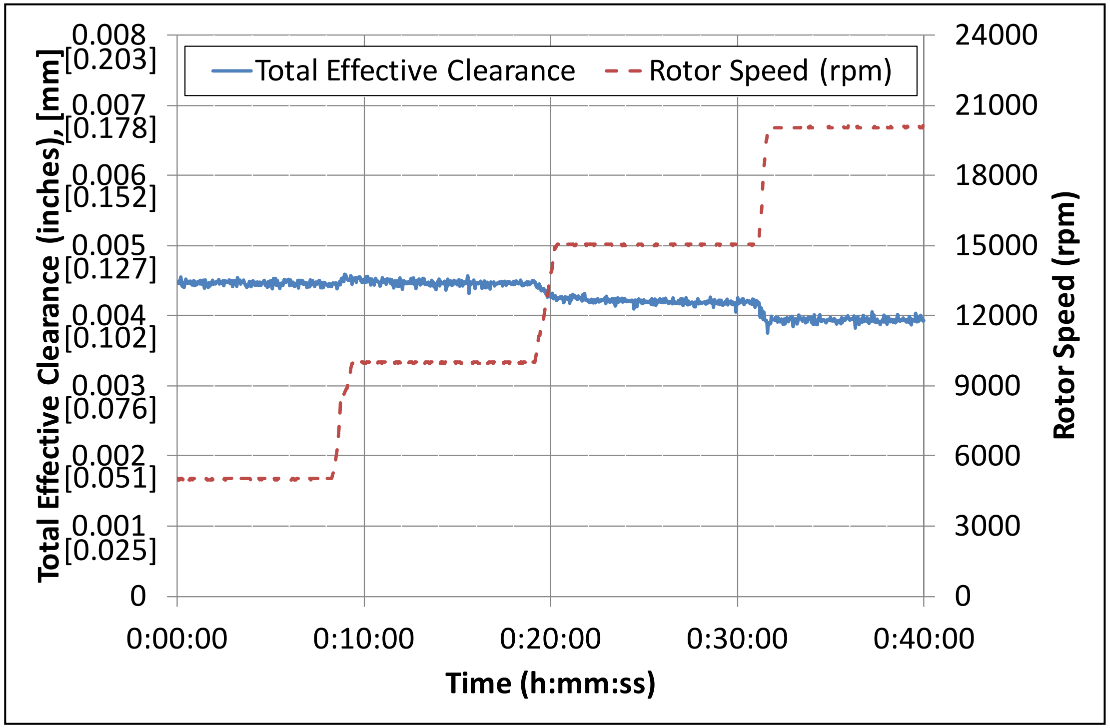
- Rotating down the step
- 15 hrs broken down into 4 stages with inspection
- Total effective clearance reported
- Initial period of wear-in before stabilisation



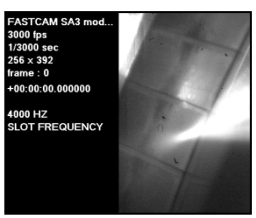




Simulated Shrouded Turbine Blade Test Reverse Rotation Results - Dynamic



- Rotating up the step
- Rotor speeds from 5,000rpm to 20,000rpm
- Slot frequency from 1000Hz to 4000Hz
- Improved effective clearance with speed
- Comparable results to the 15hr steady state test
- Stable running



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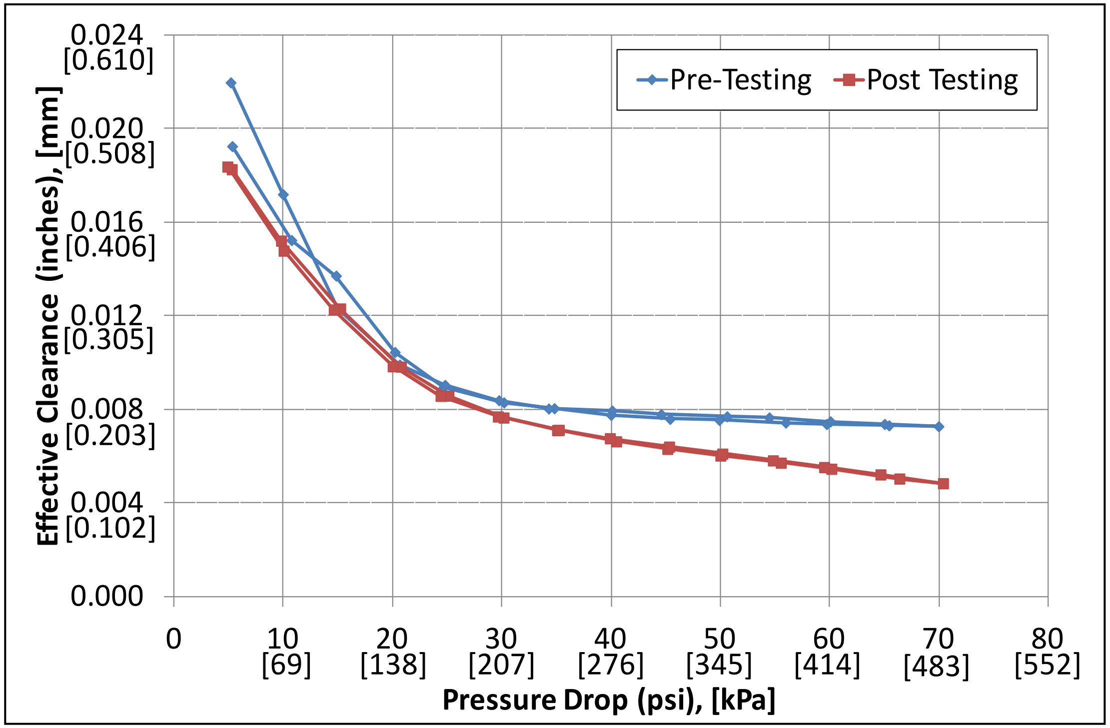
Simulated Shrouded Turbine Blade Test
Pre and Post Test Comparison - Static



- Noise and vibration present on the pre testing test at pressure drops under 20psi both increasing and decreasing the pressure
- No noise post dynamic tests
- Improvement on total effective clearance

Summary

- The PALS design is technology ready

- Smooth rotor testing – No loss of integrity
  - Velocity of 300ft/s
  - Pressure drop of 120psi
  - Radial offsets and 360° rub

- Wear in process
  - Relax manufacturing tolerances

Summary

- Acoustic noise accounted to interleaf separation
- Simulated shrouded turbine blade testing - Suitability for turbine blade tip applications
  - 15 hours consistent performance
  - Seal pressure drop of 55psi
  - Rotor pressure drop of 65psi
  - Rotor pressure 10psi higher than seal pressure
  - Radial step of .003”
  - Step frequency of 4000Hz

Future Work

- Influences of manufacturing tolerances and preload
- Additional reverse rotation testing on simulated shrouded turbine blade with varying degrees of radial offset, eccentricity and rotor pressure to investigate the effects on stability, wear, excitation and high cycle fatigue
- An analytical approach to predicting wear rate based on operating conditions

Assessment of application in sCO2 turbomachinery

- sCO2 turbomachinery small size requires leakage control in limited space.
  - **PALS effective clearance is < 0.004in (0.1mm) and has small cross-section.**
- sCO2 turbomachinery operating speed is typically very high.
  - **PALS performance is independent of speed.**
- sCO2 turbomachinery operating pressure is high and can require high DP seals.
  - **PALS design for high pressure is unrestricted.**
- sCO2 turbomachinery rotor stability can be affected by 'flashing' within seals.
  - **PALS single pressure drop mitigates this concern.**
- sCO2 turbomachinery power loss within seals and from windage.
  - **PALS non-contacting leaves and low leakage should diminish power loss.**
- sCO2 turbomachinery manufacturing cost.
  - **PALS 'Wear-in' capability can reduce tolerance requirements and cost.**

PALS Compared to Other Seals

	Startup Rub Vulnerability	Operating Rub Tolerance	'Wear-in' Seal Compliance	Low Leakage	Long Seal Life	High Seal ΔP Capability	Reverse Rotation Hazard	Axial Length	Rotor Dynamic Issues	Cost
Labyrinth Seals	↓	↓	↓	↓	↑ W/o rub.	↑	↑	↓	↓	↑
Abradible Labyrinth Seals	↑ (somewhat)	↑ (somewhat)	↓	↑ (somewhat)	↑	↑	↑	↓	↓	↑ (somewhat)
Brush Seals	↑	↑	↑	↑	↑ (somewhat) Improved to 8+ years.	↑ (somewhat) 400psid capability.	↓	↑	↑	↓
Pressure Actuated Leaf Seals	↑	↑ (somewhat) Limited	↑ ~ 0.004in	↑	↑	↑	↑	↑	↑	↑

Symbol key: ↓ Unfavorable comparison ↑ Favorable comparison ↑ (somewhat) Somewhat favorable comparison

Recommendation

- Pressure Actuated Leaf Seal technology readiness test results and favorable evaluation of attributes vs other seals show benefit potential for their application in sCO_2 turbomachinery.

- Consideration of their use in sCO_2 turbomachinery is recommended.

Thank You for Listening

Any Questions?

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