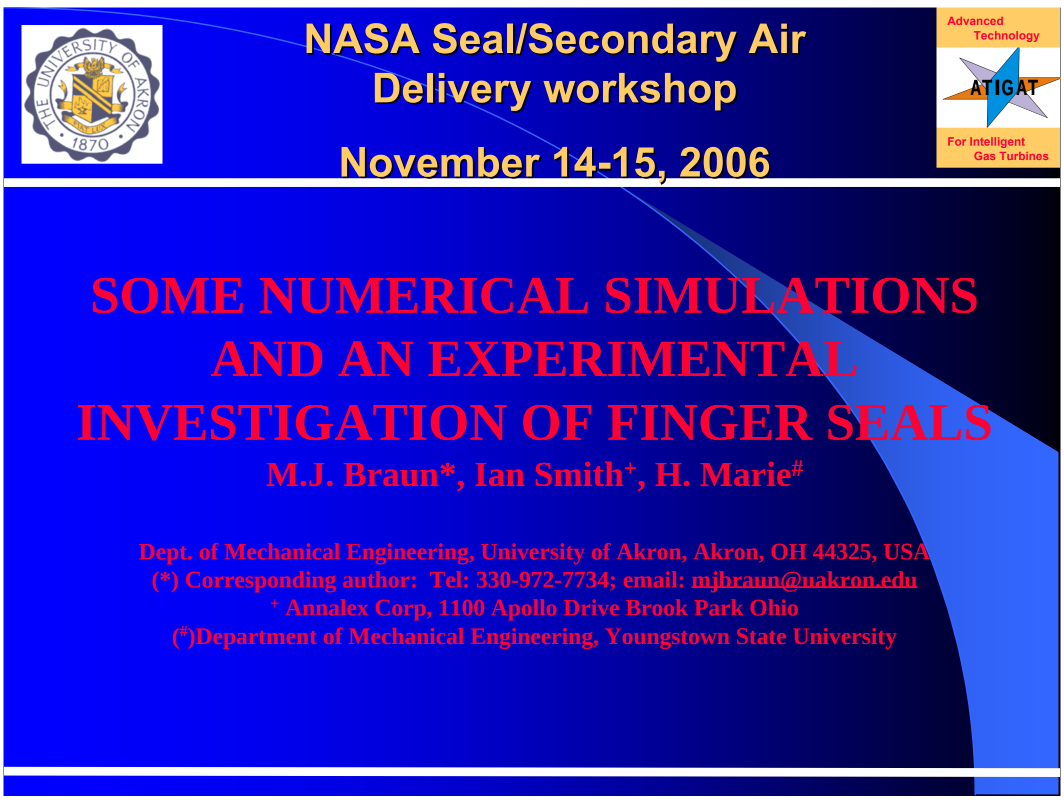
SOME NUMERICAL SIMULATIONS AND AN EXPERIMENTAL INVESTIGATION OF FINGER SEALS

Minel J. Braun
University of Akron
Akron, Ohio

Ian Smith
Analex Corporation
Brook Park, Ohio

Hazel Marie
Youngstown State University
Youngstown, Ohio



Advanced Technology For Intelligent Gas Turbines (ATIGAT)

ACKNOWLEDGEMENT

The authors want to express their gratitude to M. Proctor and B. Steinetz of NASA Glenn Research Center, Cleveland, Ohio for the financial support and technical consultations.

CONCEPT AND COMPONENTS

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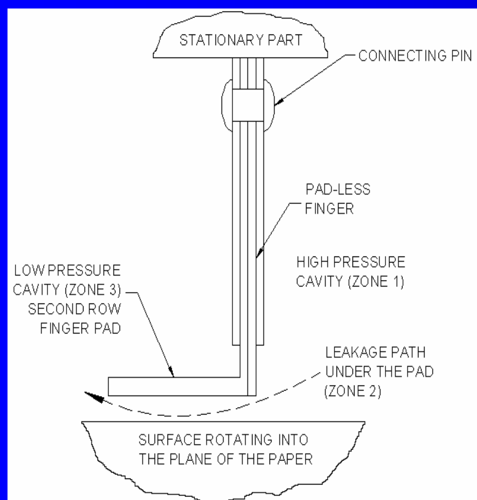
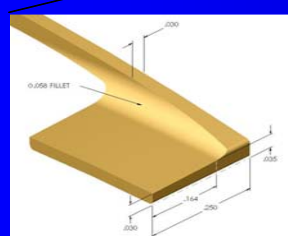
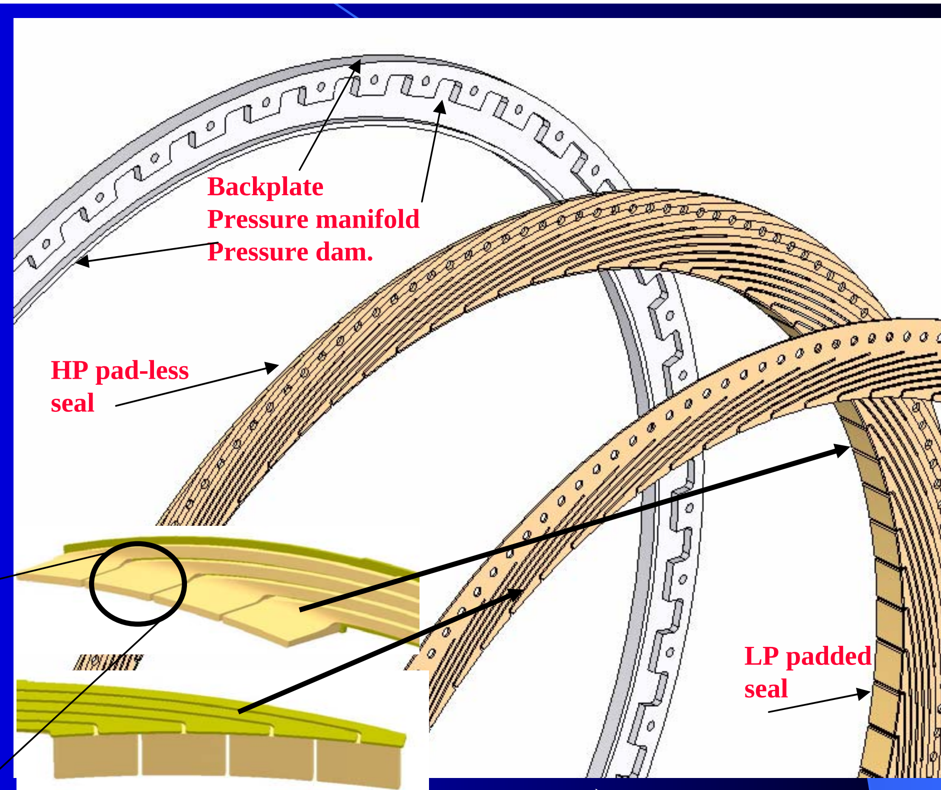


General Configuration





Full Wafer of Padded Fingers (8.5” ID, 9.666” OD, 81 Fingers) and details (b, c) of the Arrangement of the High and Low Pressure Fingers

ACTUAL HARDWARE

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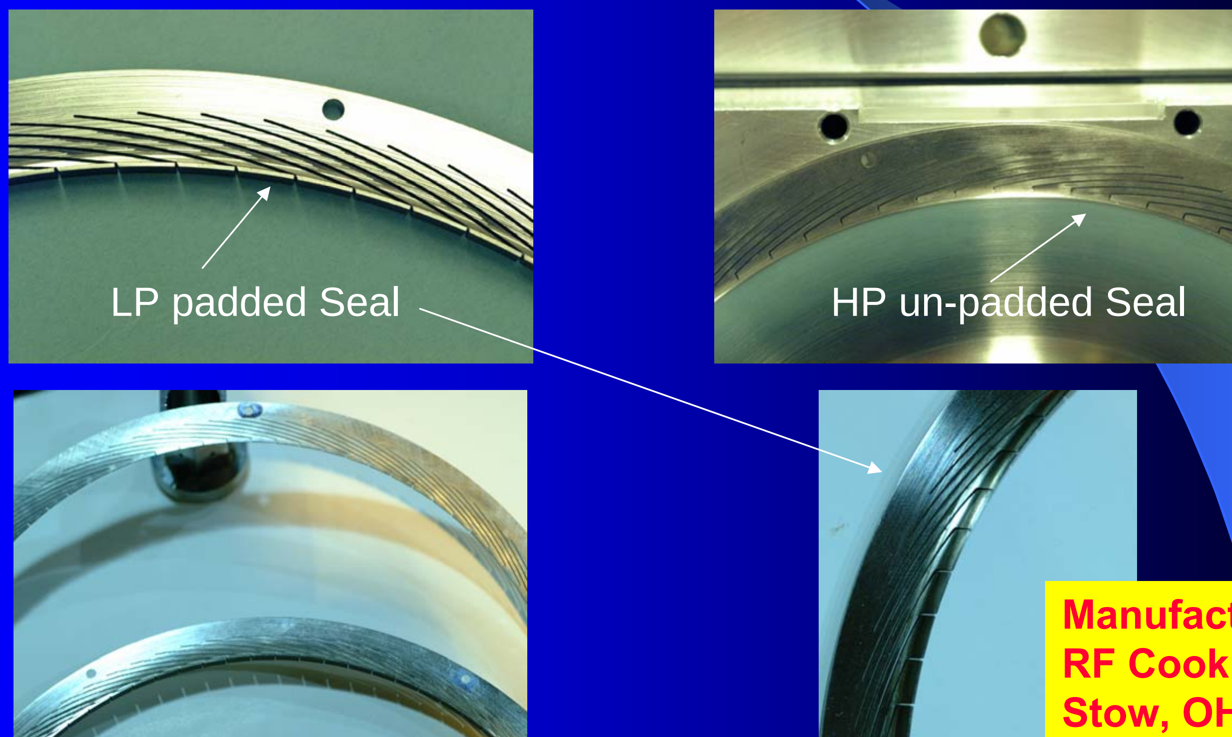

Manufactured by:
RF Cook
Stow, OH 44224

Padded and Unpadded Sections of HP- and LP-seals

DESIGN PARAMETERS

(Variations in the Design of the Finger Stick and Foot)

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Besides sealing, the other main goal of a successful finger seal design is to exhibit appropriate compliance to outside forces. The ability of the seal to ride or float along the rotor without rubbing or excessive heating is essential to the successful operation of the seal.

The compliance of the finger must only occur in the radial plane;

The seal needs to be as sturdy as possible in the axial direction.

The compliant finger that moves radially outward with rotor growth and motion has to be able to ride the rotor back down as the rotor diameter recovers or the rotor moves “away”.

Thus there is an optimum stiffness for the finger;

DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

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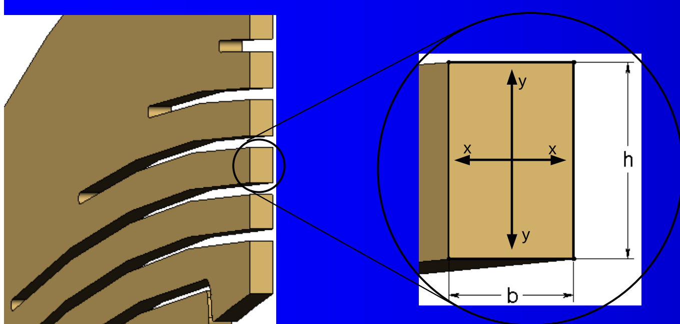
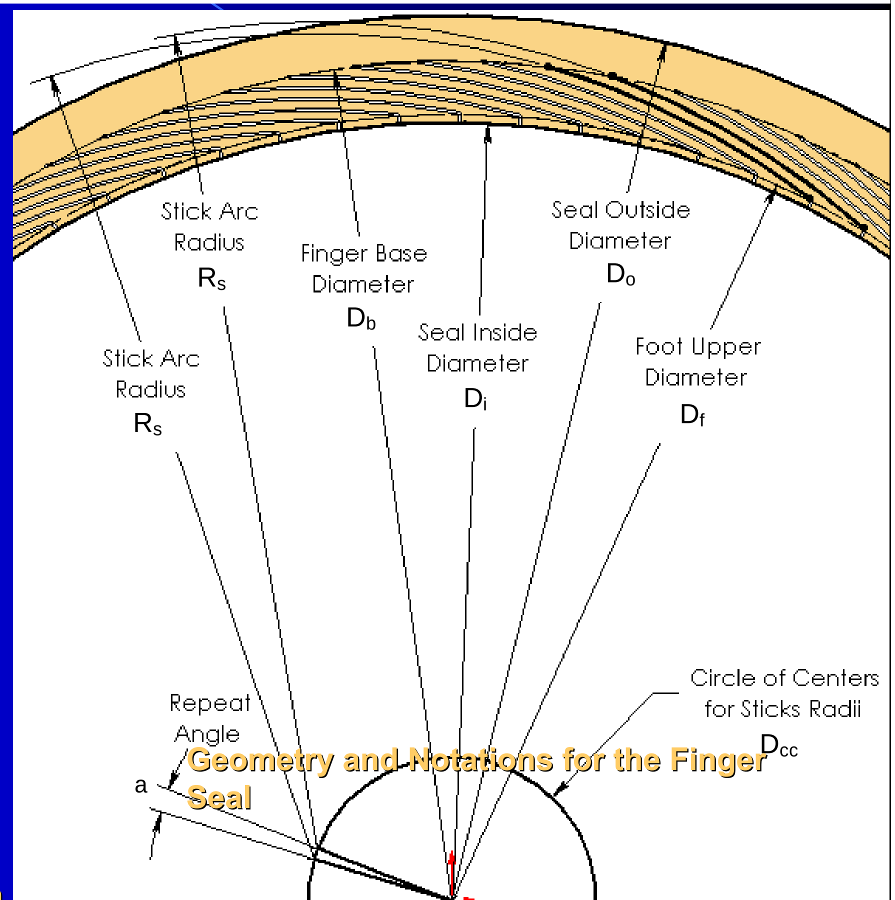
(1) D_{cc} Stick Arcs Circle of Centers.
(2) R_s Stick Arc Radius.
(3) D_b Finger Base Diameter.
(4) D_f Foot Upper Diameter.
(5) 'a' Finger Repeat Angle.
(6) I_s Finger Interstice Width.
(7) L_c Circumferential Foot Length.
(8) 'b'-Laminate thickness.



View of Finger Stick Cross-Section



Geometry and Notations for the Finger Seal

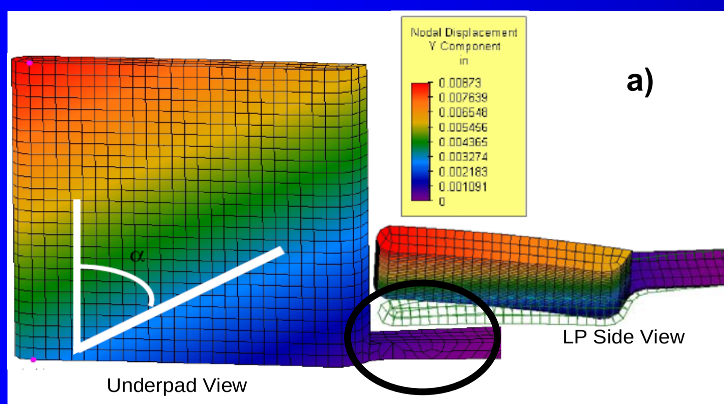
DESIGN PARAMETERS (cont'd)

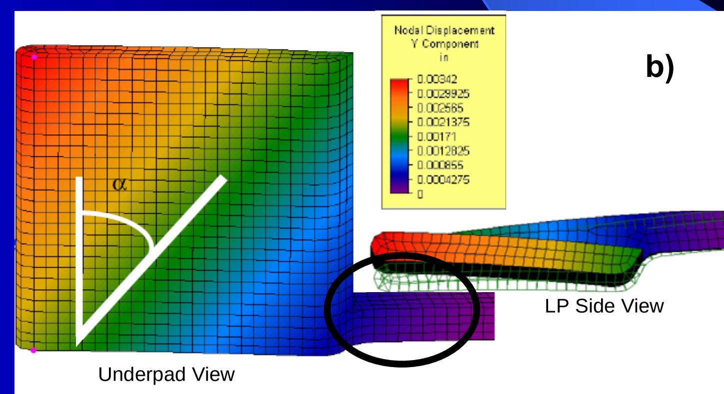
(Variations in the Design of the Finger Stick and Foot)

Variations in Finger Pad Design

The finger seal obtains its hydrodynamic lifting capabilities from the pattern of the padded fingers underside, which "rides" the surface of the shaft. The objective in the design of the pad was to determine an optimal configuration that would enable the pad portion to lift from the rotating rotor and to run on a thin film of air during operation while minimizing the leakage rate

The desirable motion of the pad is one that is in sync with the motion of the stick while minimizing its rotation out-of-plane with respect to the stick. If the pad rotated around its heel, it could potentially both open the clearance for leakage and "dig" into the shaft at the origin of the pad rotation. Therefore the design of the pad had to minimize this situation.





Radial Out-of-Plane Twisting as Viewed from Underneath the Pad and from the Low-Pressure Side: (a) Stick Thickness of b=0.015-in, (b) Stick Thickness of b=0.030-in

DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

Variations in Finger Pad Design

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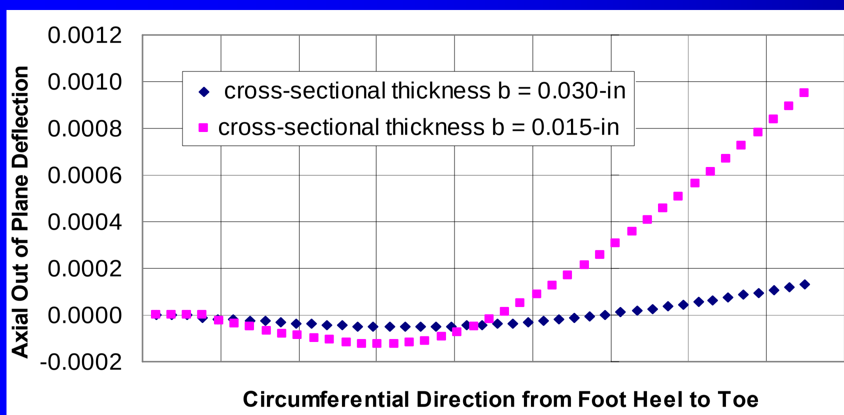
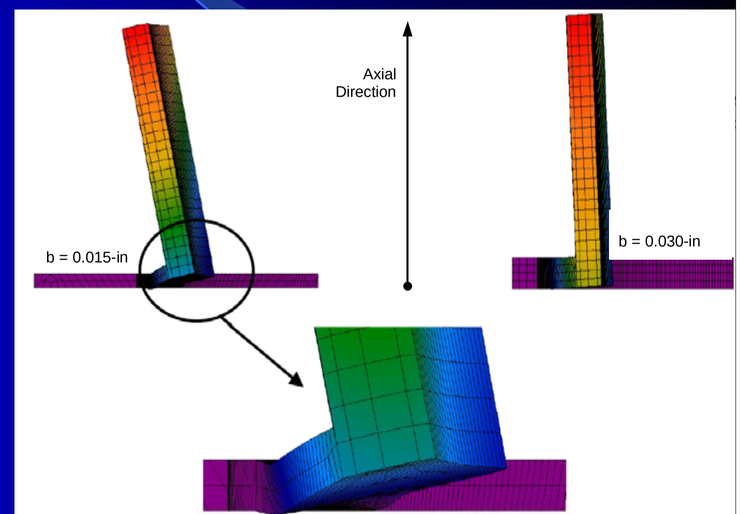


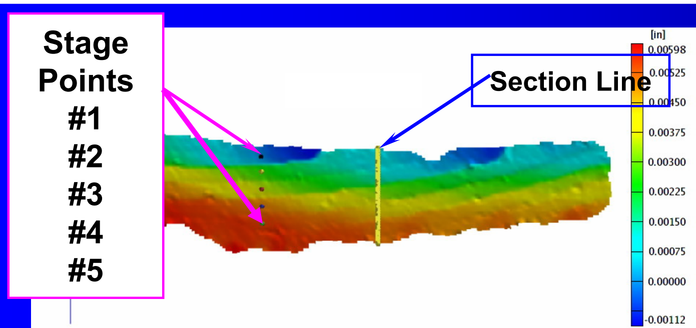
Shape of the underpad surface Axial Out-of-Plane Twisting for Stick Thickness of b=0.015-in and b=0.030-in



Another view of pad and stick deformation

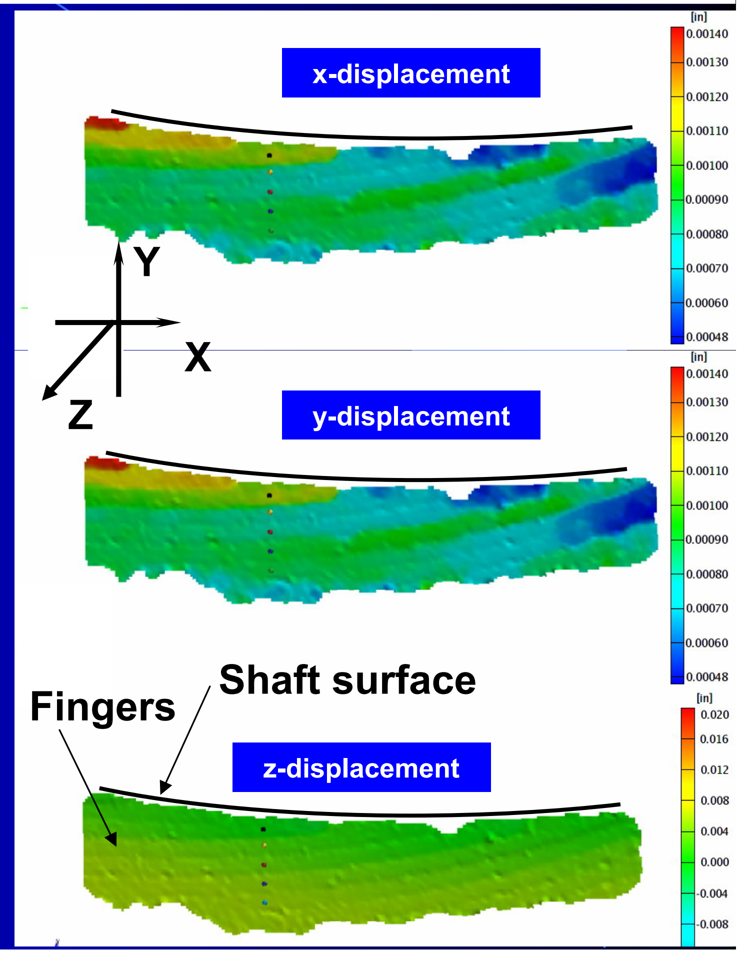
FINGER BEHAVIOR WITH ROTATING SHAFT AND AXIAL PRESSURE DIFFERENTIAL Δp=5 PSI

x-, y- and z- Displacements



Experimental Conditions:
Rotation: 7000 RPM
Axial pressure: 0 to 5 PSI

Photos of the fingers (the region shown in the above pictures) are taken by two cameras from different angles at the same time. The x (circumferential), y (radial), and z (axial) displacements are obtained by analyzing the pairs of the images.



CONCLUDING REMARKS (1)

Finger Behavior with Rotating Shaft and Axial Pressure Differential

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- All the fingers vibrate because of the rotation of the shaft. Lifting force on the pad is very sensitive to the clearance between the pad and the shaft surface.
- In one coordinate direction, all the fingers move in the same manner
- At different radial locations, the x-displacement varies in the same manner
- The y- and z- displacements are different at different radial locations
- The z-displacement is smallest at the root of the fingers and at the back plate supporting point

CONCLUDING REMARKS (2)

Finger Behavior with Rotating Shaft and No Axial Pressure Differential

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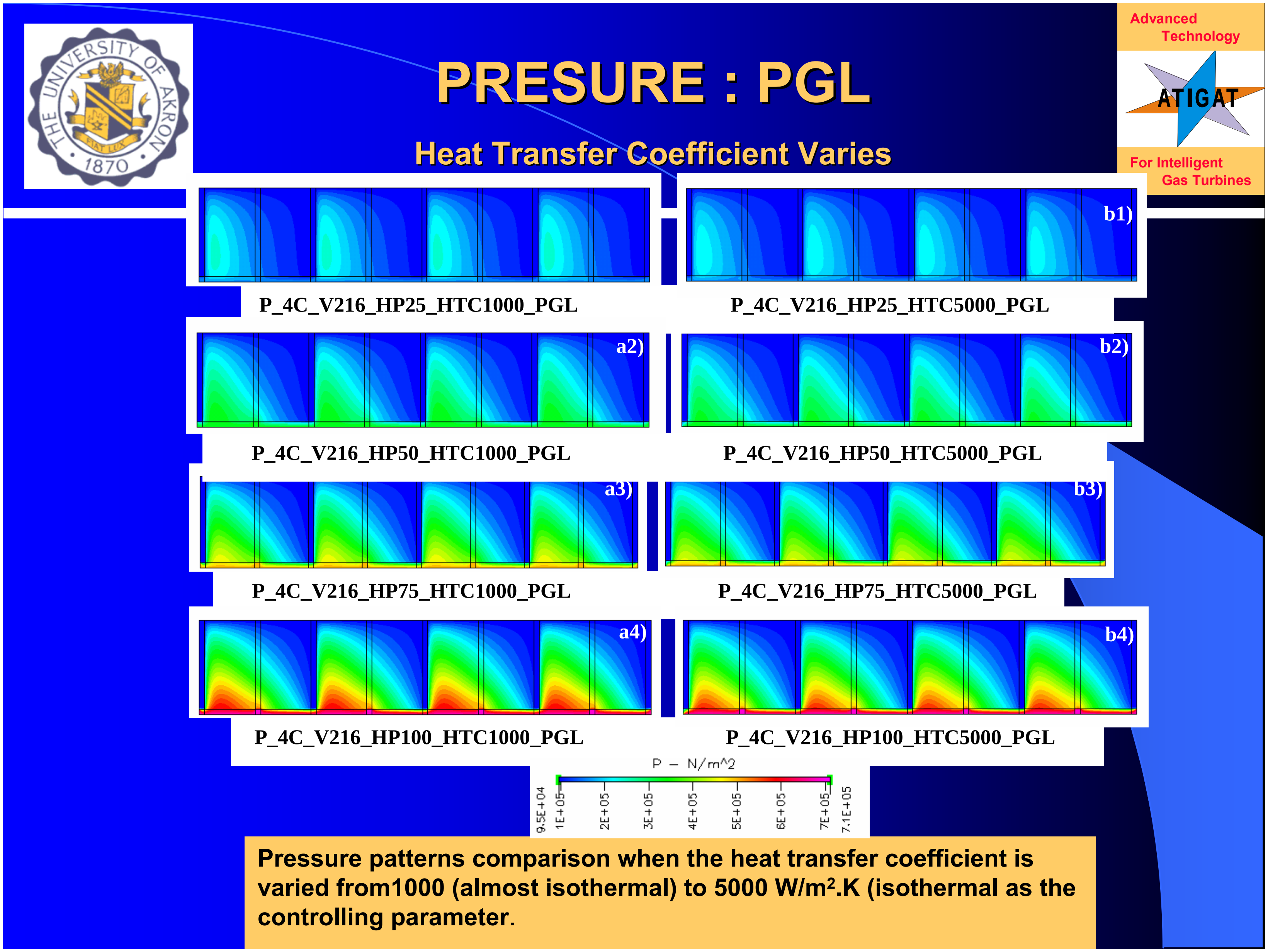
- With the shaft rotating while no axial pressure drop, all the fingers move/vibrate independently. There is no phase correlation observed between the vibrations of the fingers.
- The displacement decreases from the finger tips to the finger roots
- At one location, the displacement magnitude of the vibration in three (x-, y-, z-) directions are roughly the same
- The movements of the fingers proved that all the fingers are lifted by the pressure build up under the bad due to the rotation of the shaft.


PRESURE : PGL
Heat Transfer Coefficient Varies
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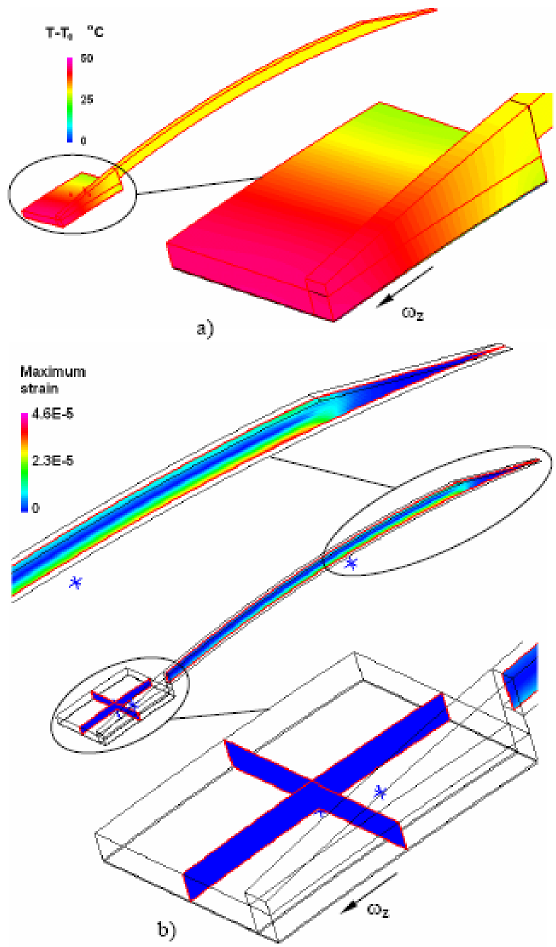
b1)
P_4C_V216_HP25_HTC1000_PGL
P_4C_V216_HP25_HTC5000_PGL
a2)
b2)
P_4C_V216_HP50_HTC1000_PGL
P_4C_V216_HP50_HTC5000_PGL
a3)
b3)
P_4C_V216_HP75_HTC1000_PGL
P_4C_V216_HP75_HTC5000_PGL
a4)
b4)
P_4C_V216_HP100_HTC1000_PGL
P_4C_V216_HP100_HTC5000_PGL
P – N/m^2
9.5E+04
1E+05
2E+05
3E+05
4E+05
5E+05
6E+05
7E+05
7.1E+05
Pressure patterns comparison when the heat transfer coefficient is varied from1000 (almost isothermal) to 5000 W/m².K (isothermal as the controlling parameter.



(a) Temperature and (b) strain in the pad and leg. Adiabatic conditions, 20,000rpm

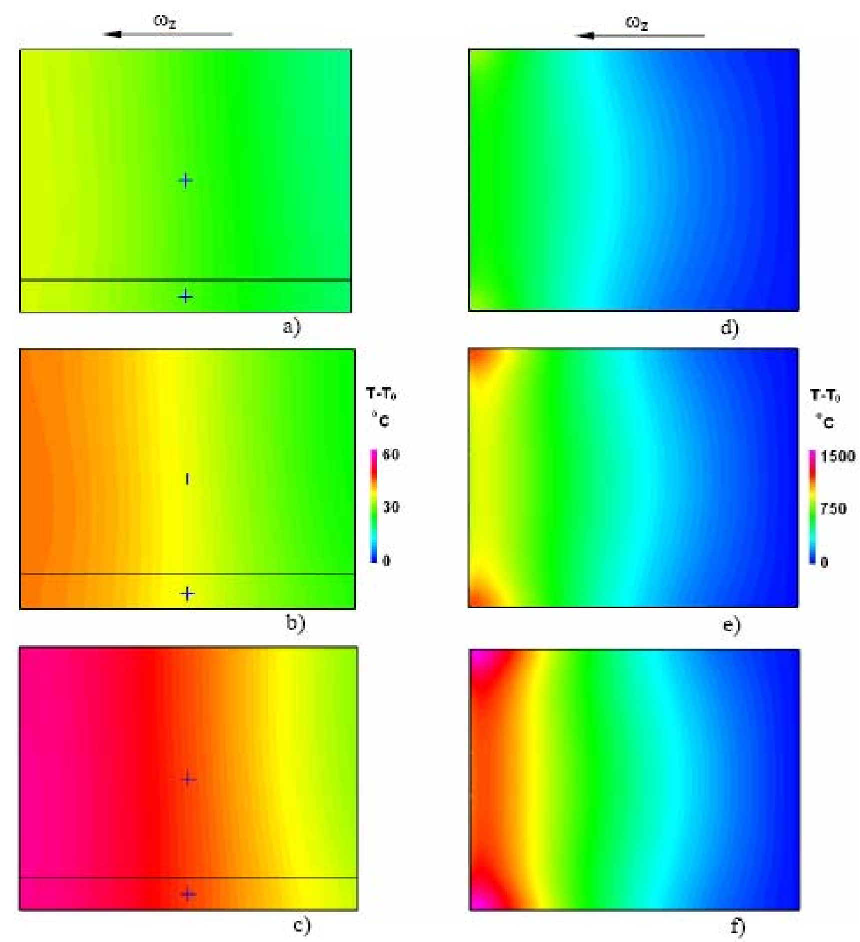


Figure 8. Temperature on the bottom of the pad for moving fingers (a, b, c) and rigid fingers (d, e, f). Shaft rotates at 20,000 rpm (a, d), 30000 rpm (b, e) and 40000 rpm (c, f) respectively. Temperature boundary conditions are shown in Figure 3c.

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EXPERIMENTAL WORK

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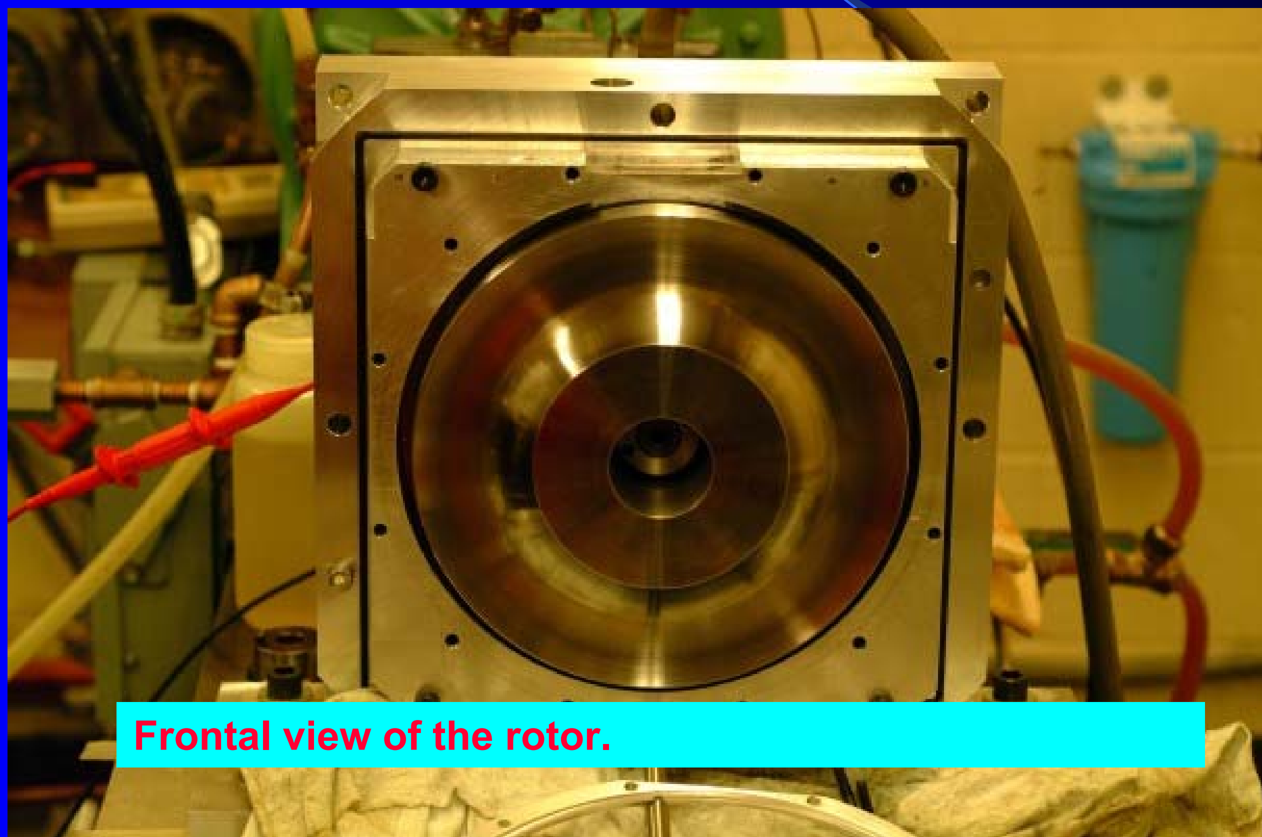
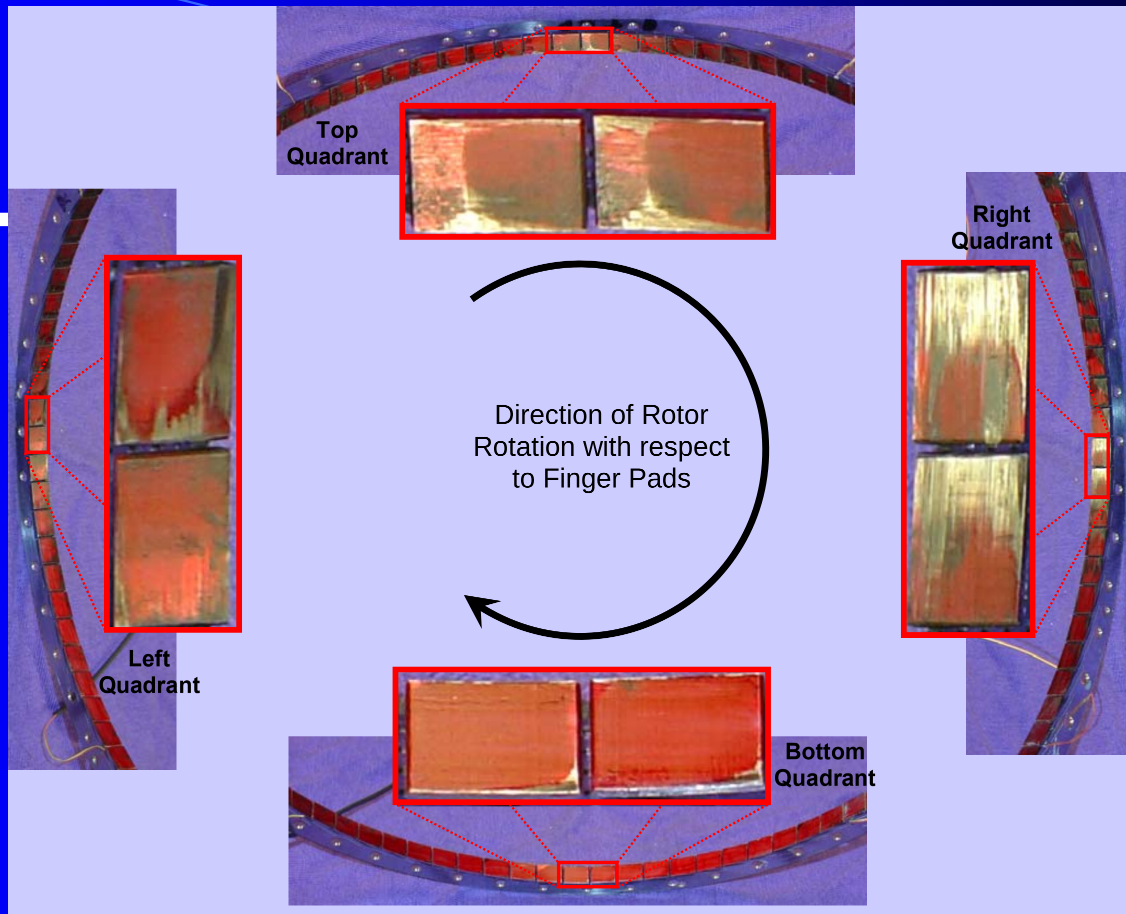
ROTOR: FRONTAL VIEW



Frontal view of the rotor.



Circumferential Wedge Pad Laminate: Finger Underside Pads Surface Showing Ink Wear Marks after a Total Run Time of 97 min at a nominal speed of 9,950 rpm; This included 4 start-ups and 4 coast-downs. Seal Quadrants Positioned as Viewed from the Low-Pressure Side

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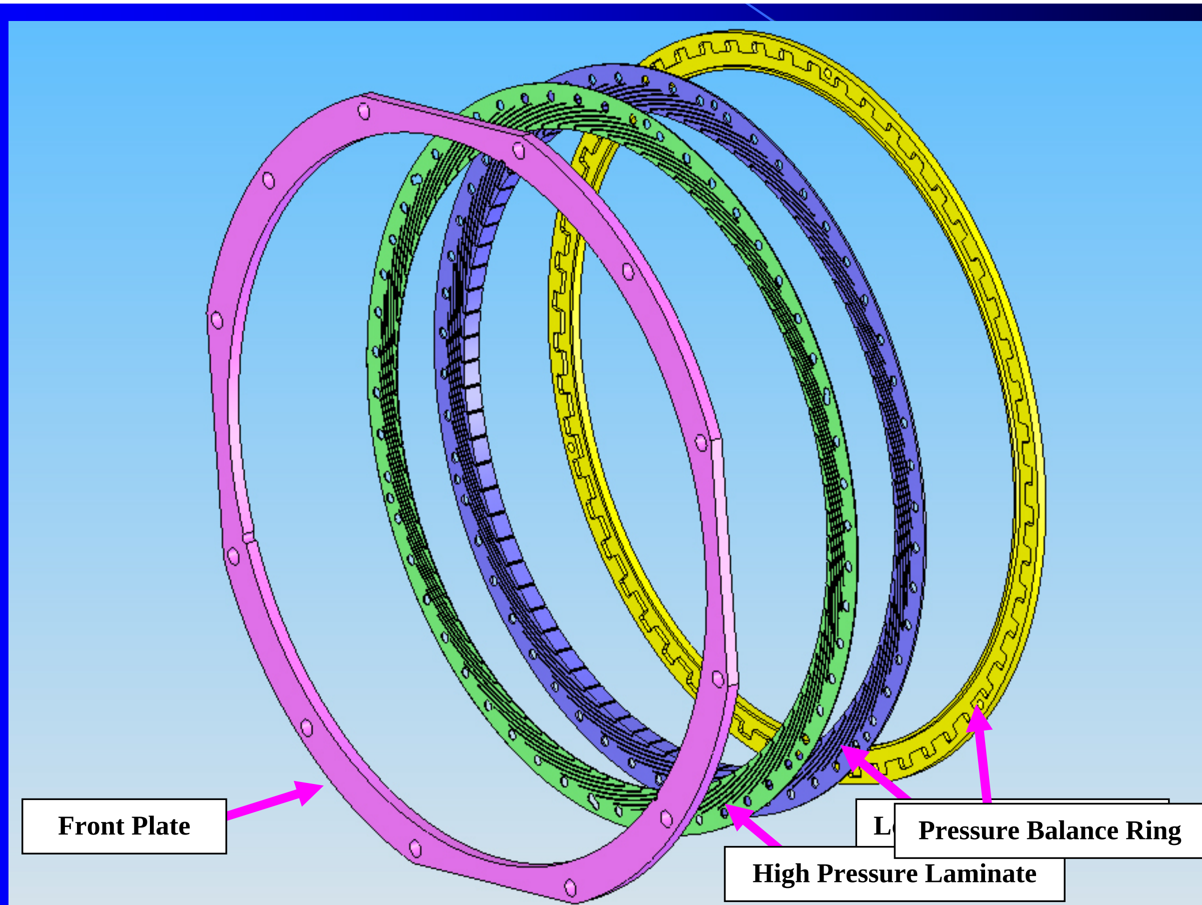
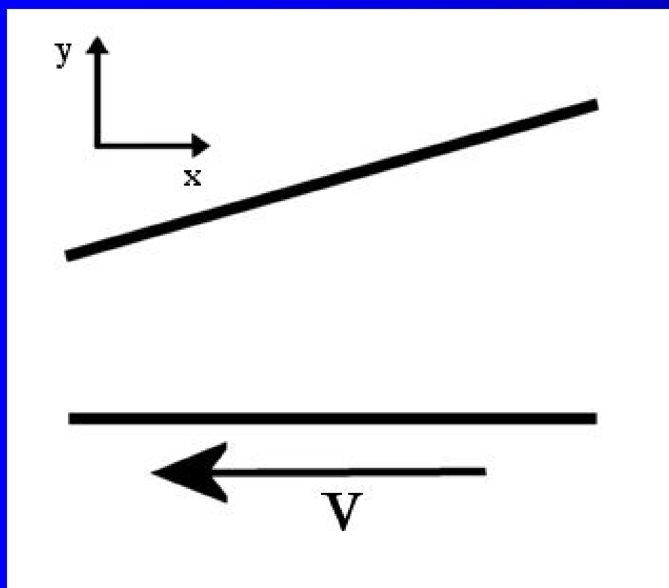
Experiment Objectives

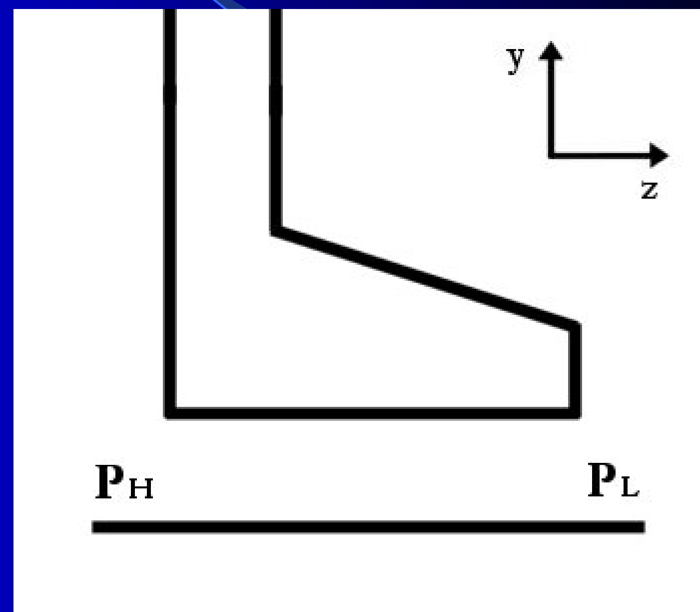
- Obtain performance data on various finger seal designs and configurations
- Gain a better understanding of finger seal functionality, in order to foster future compliant seal concepts

Seal Assembly



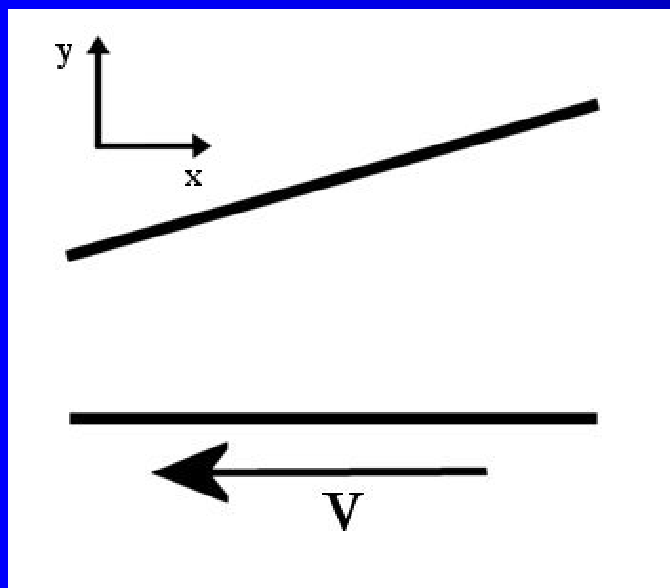
Single Wedge Pad Geometry

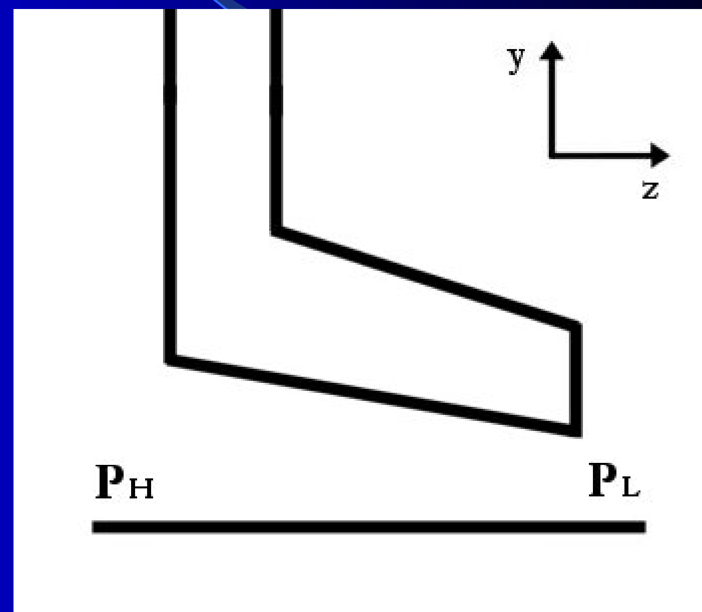




- Converging circumferential wedge accelerates air entrained by rotor surface, generating a lifting force under each pad

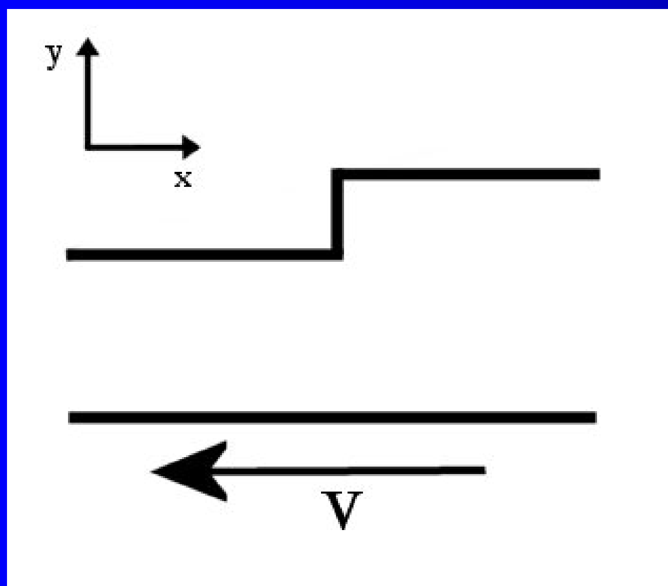
Double Wedge Pad Geometry

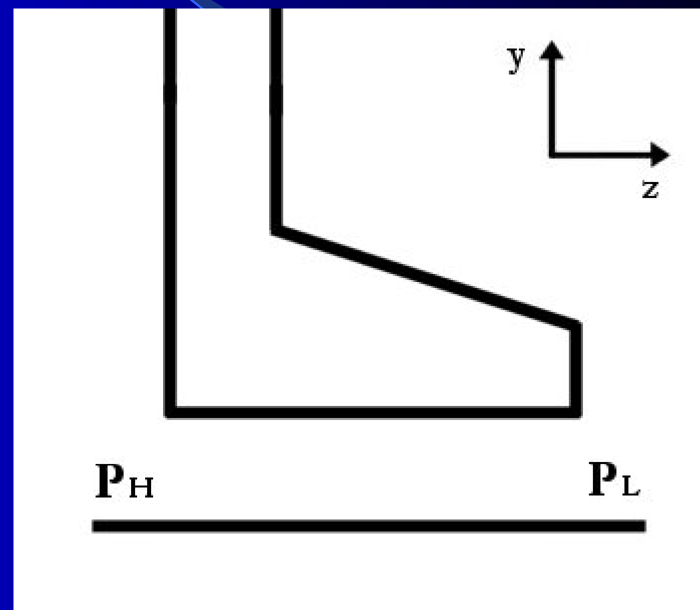




- Converging axial wedge generates additional lift from escaping air

Step Pad Geometry





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Design Goals of the Double Pad

- Provide lifting ability to both the high and low pressure laminates
- Reduce leakage paths between adjacent finger pads

Design Goals of the Double Pad

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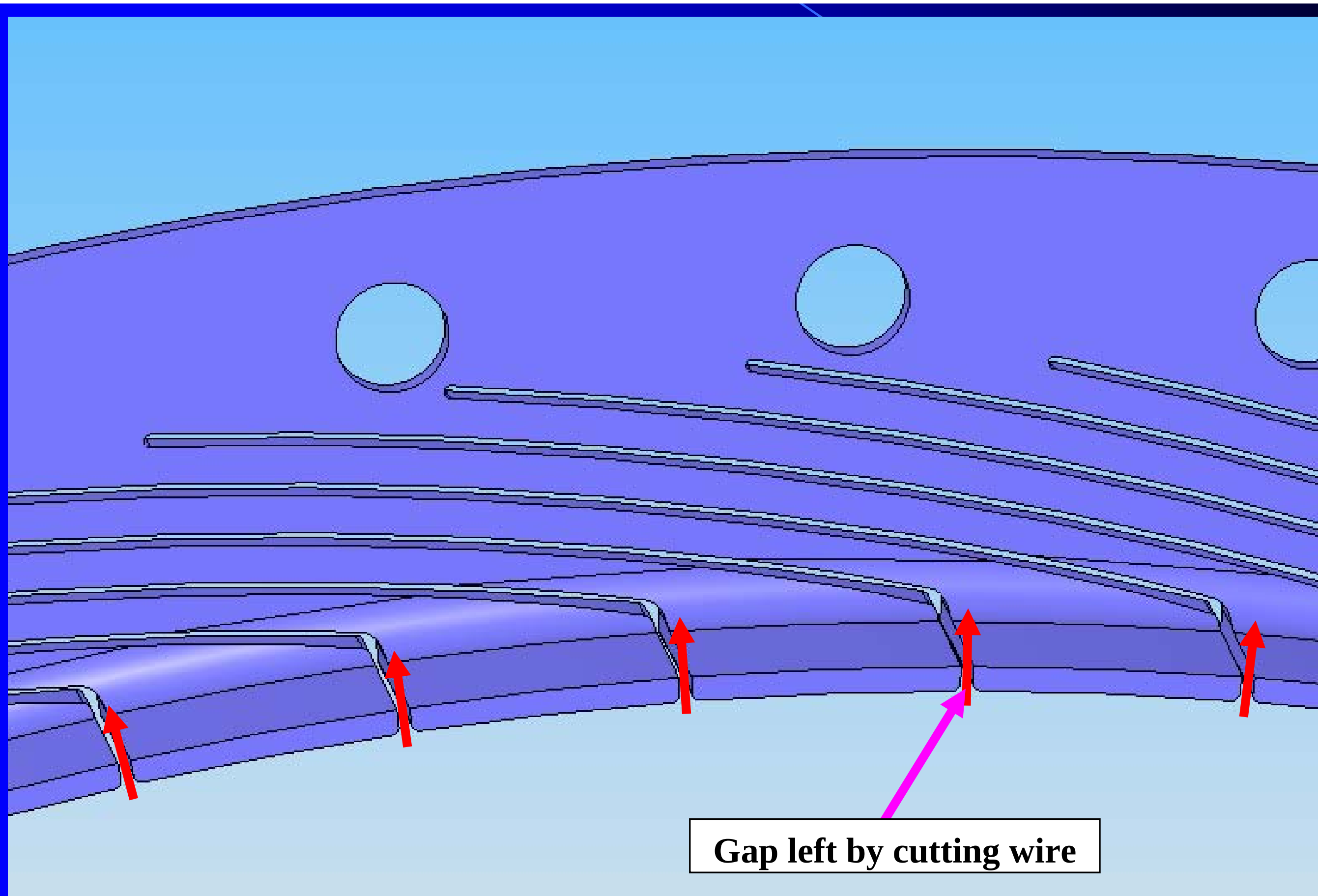

Design Goals of the Double Pad

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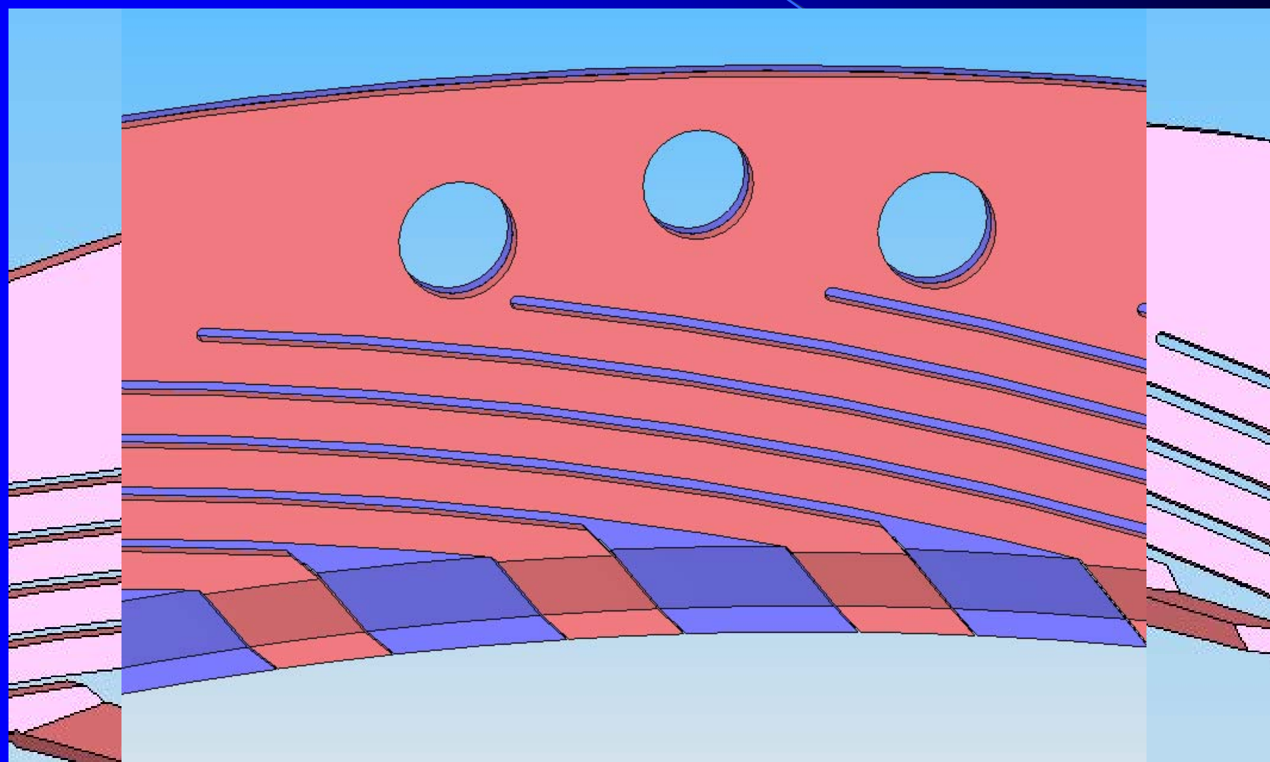
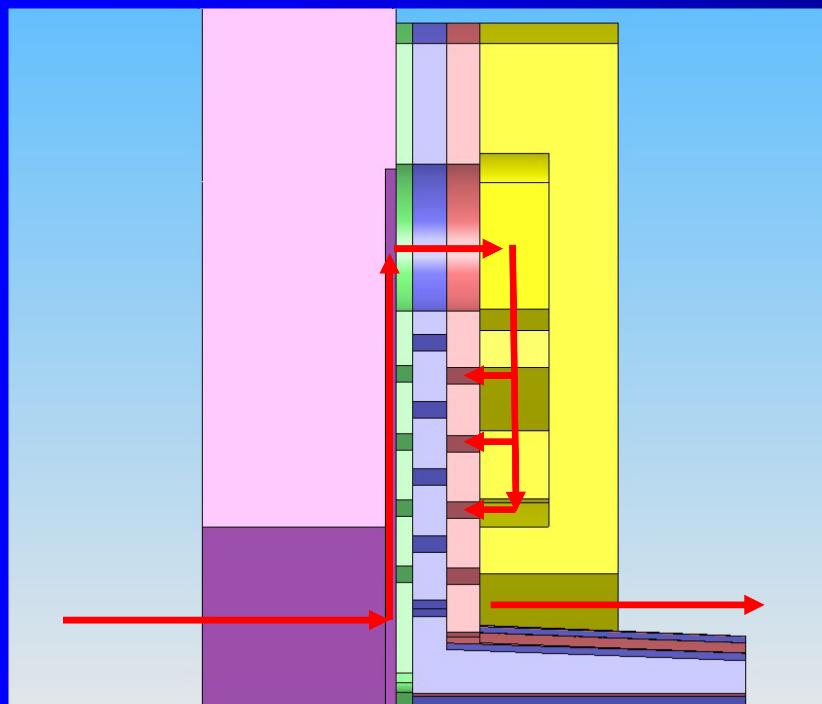


- Interlocking pads cut down leakage and create a continuous lifting surface

Front Plate Designs



- Original front plate allows upstream air to pass directly through to the pressure balance ring
- Decreasing front plate inner diameter restricts flow through the pressure balance ring

Procedure for Dynamic Testing

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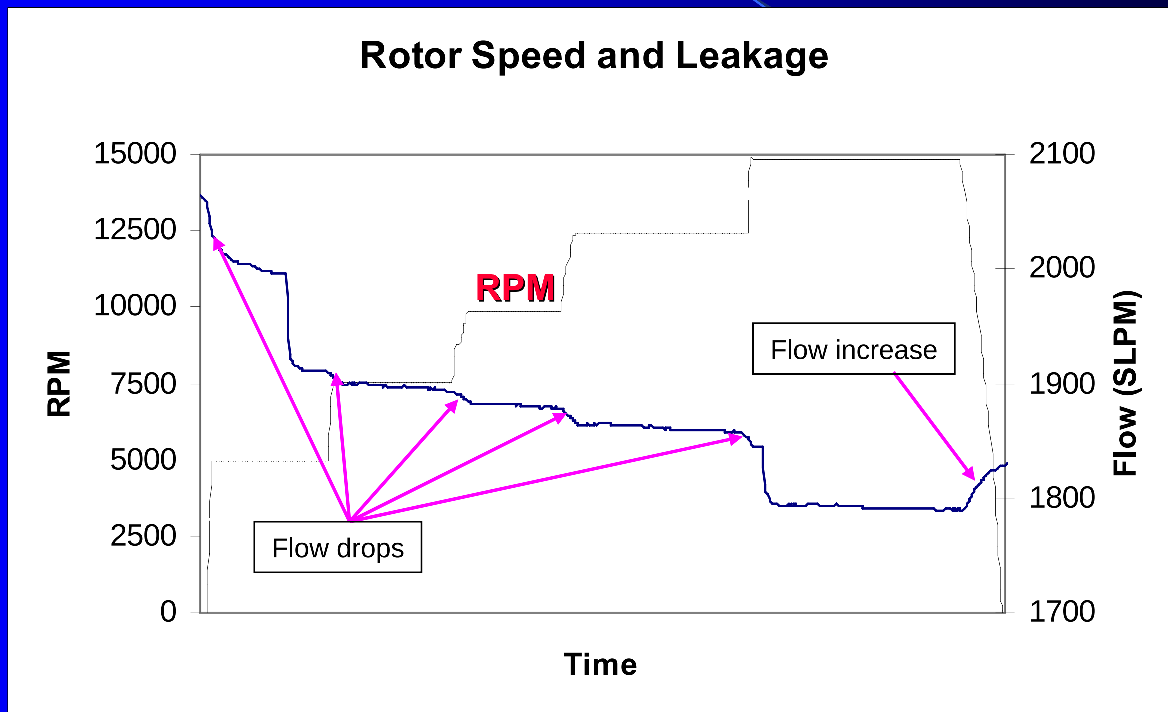
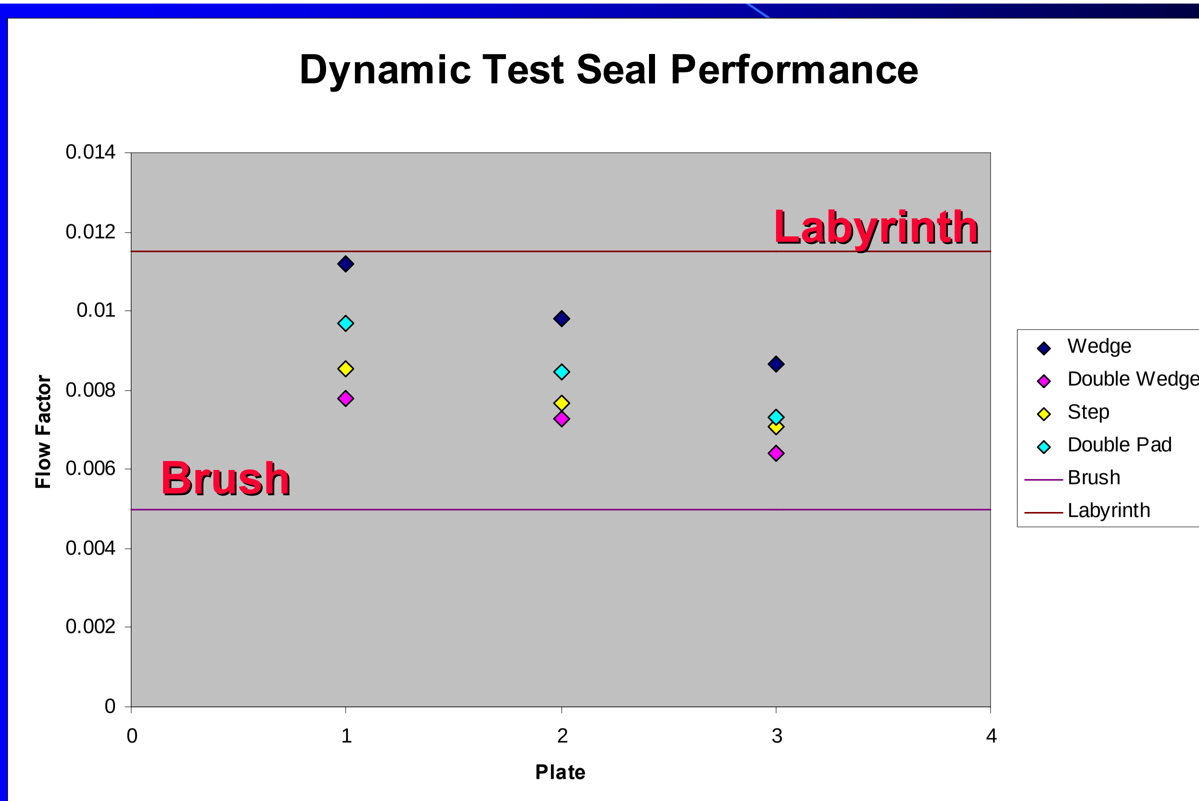
- Establish pressure differential of 10 psi
- Accelerate rotor to 5,000 RPM
- Allow pad temperatures to stabilize
- Repeat for 7,500, 10,000, 12,500, and 15,000 RPM
- Bring rotor to a stop
- Detach and examine seal for wear marks in ink

Effect of Rotor Speed on Flow



- Moving rotor surface creates a resistance to flow
- This can be seen when leakage drops at each increase in speed, and increases when the rotor is brought to a stop

Effectiveness of All Seal/Plate Combinations



Operating Conditions – 10 psi, 70° F, 15,000 RPM

Thermocouple Locations for Monitoring Pad Touchdowns

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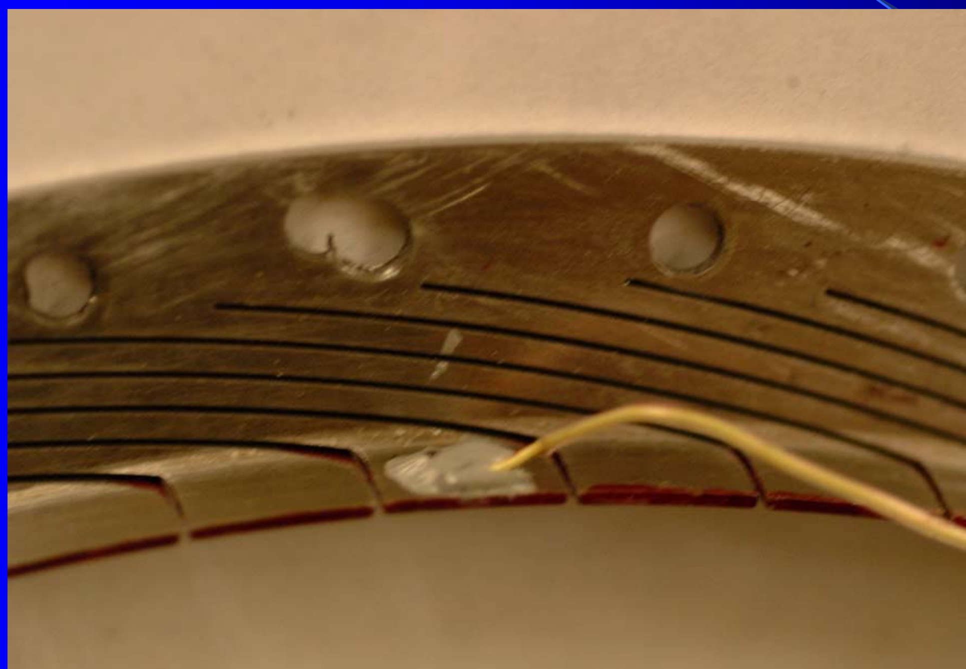
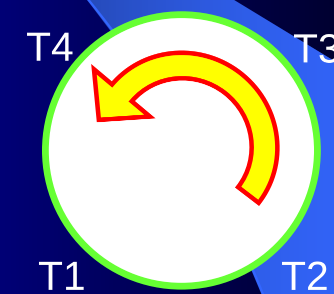
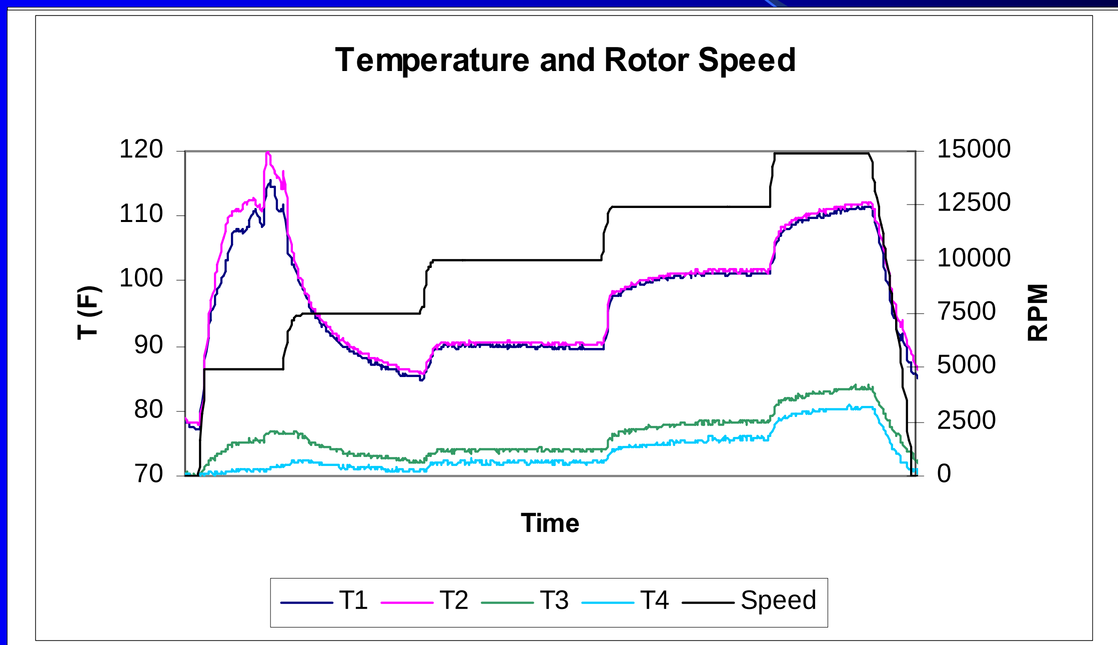




The Locations View from Front of Test Section

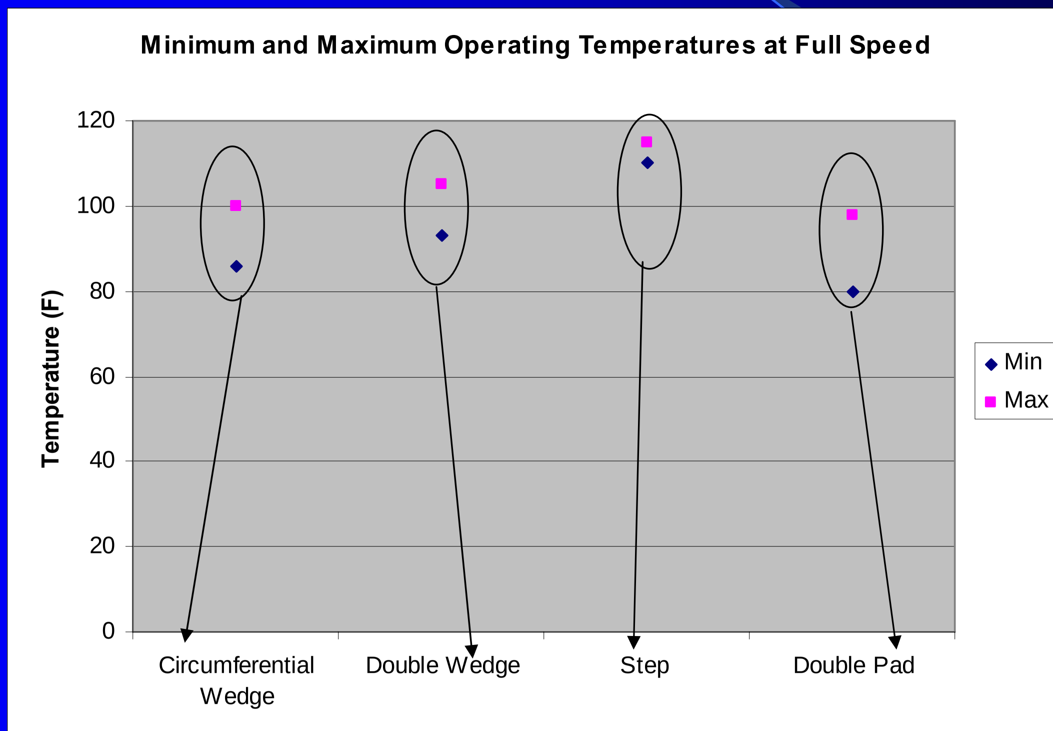
- Thermocouples are bonded by epoxy to the tops of finger pads in 4 locations

Typical Temperature Behavior

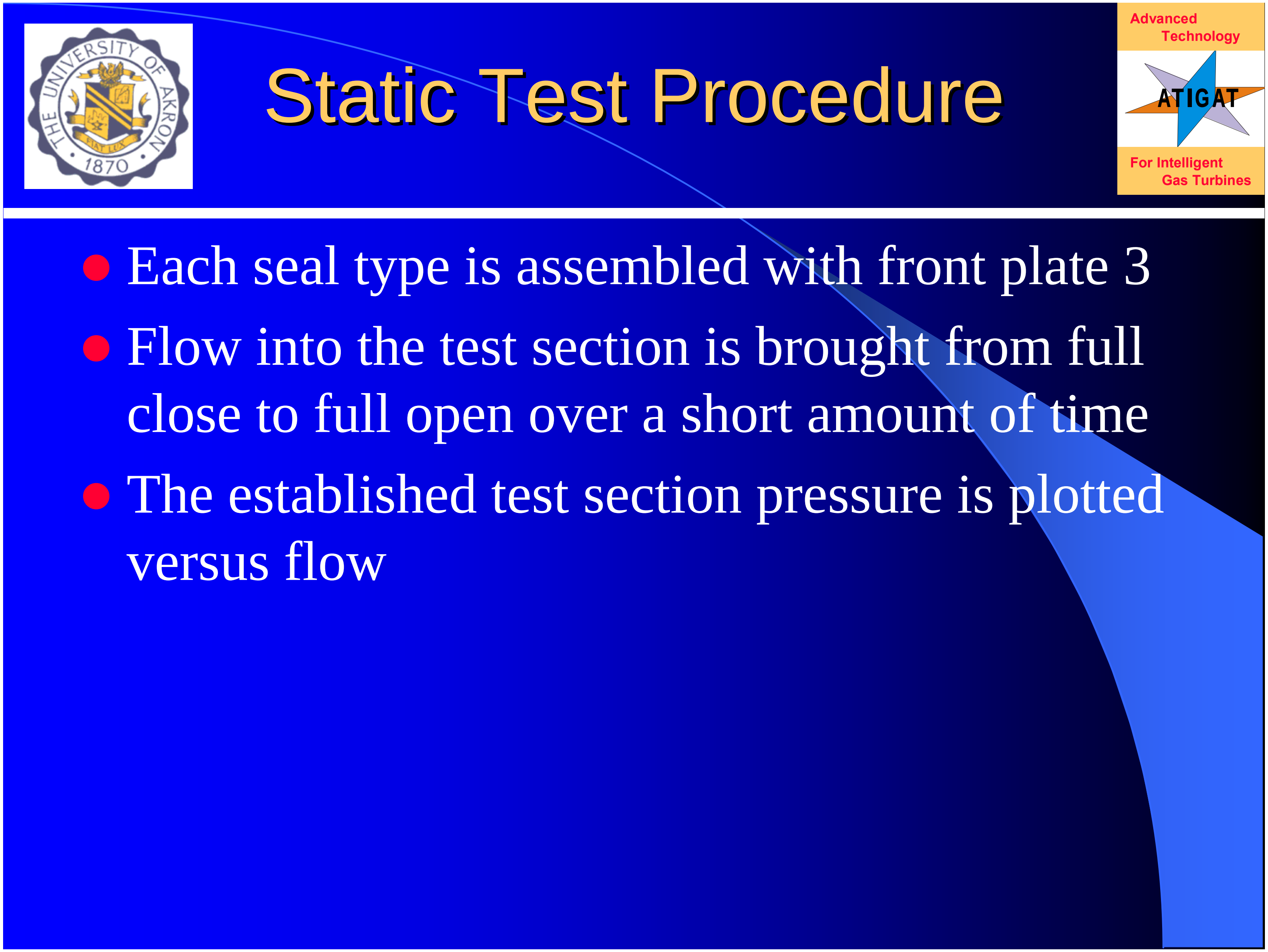


- Temperature closely follows speed profile
- Finger pad rubbing can be clearly seen

Dynamic Test Temperature Variation



Operating Conditions – 10 psi, 70° F, 15,000 RPM


THE UNIVERSITY OF AKRON 1870
Static Test Procedure
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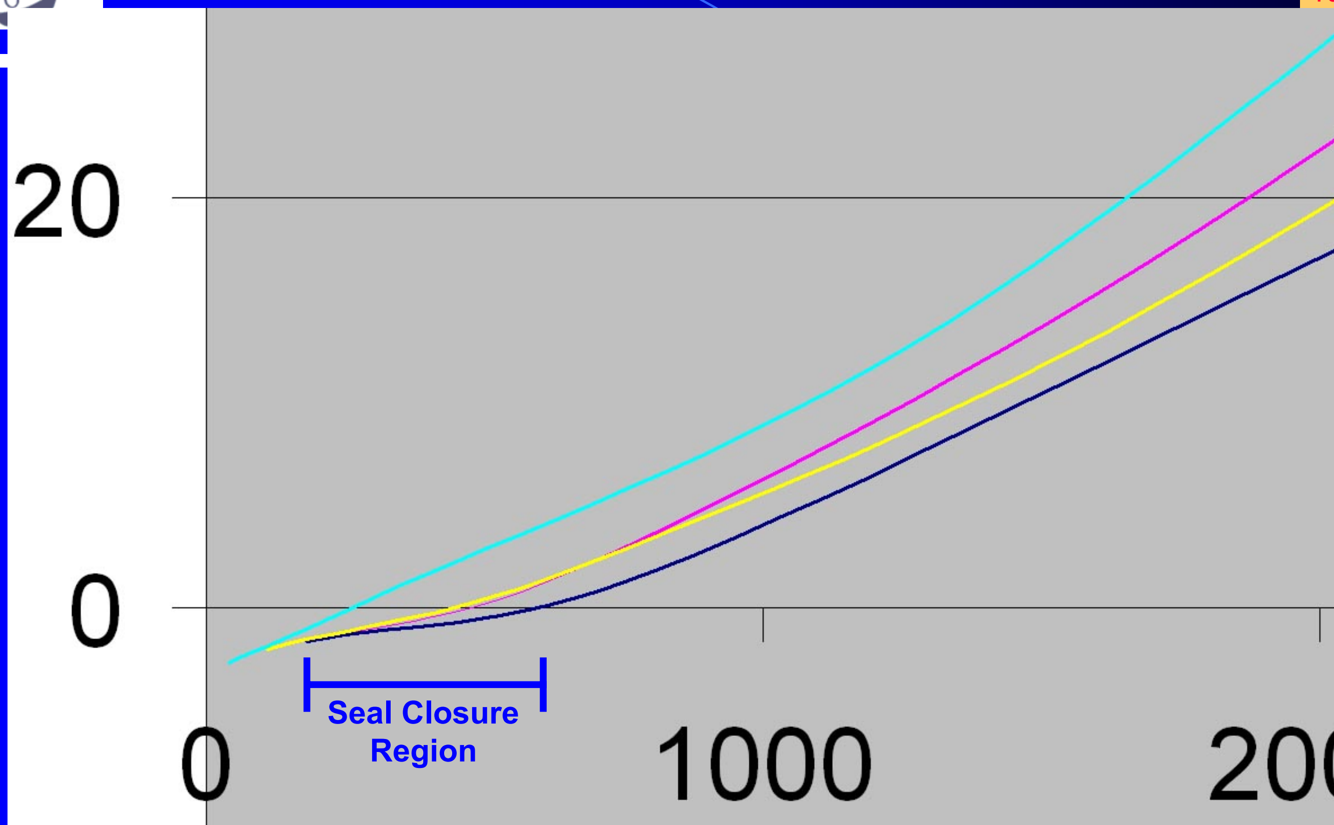
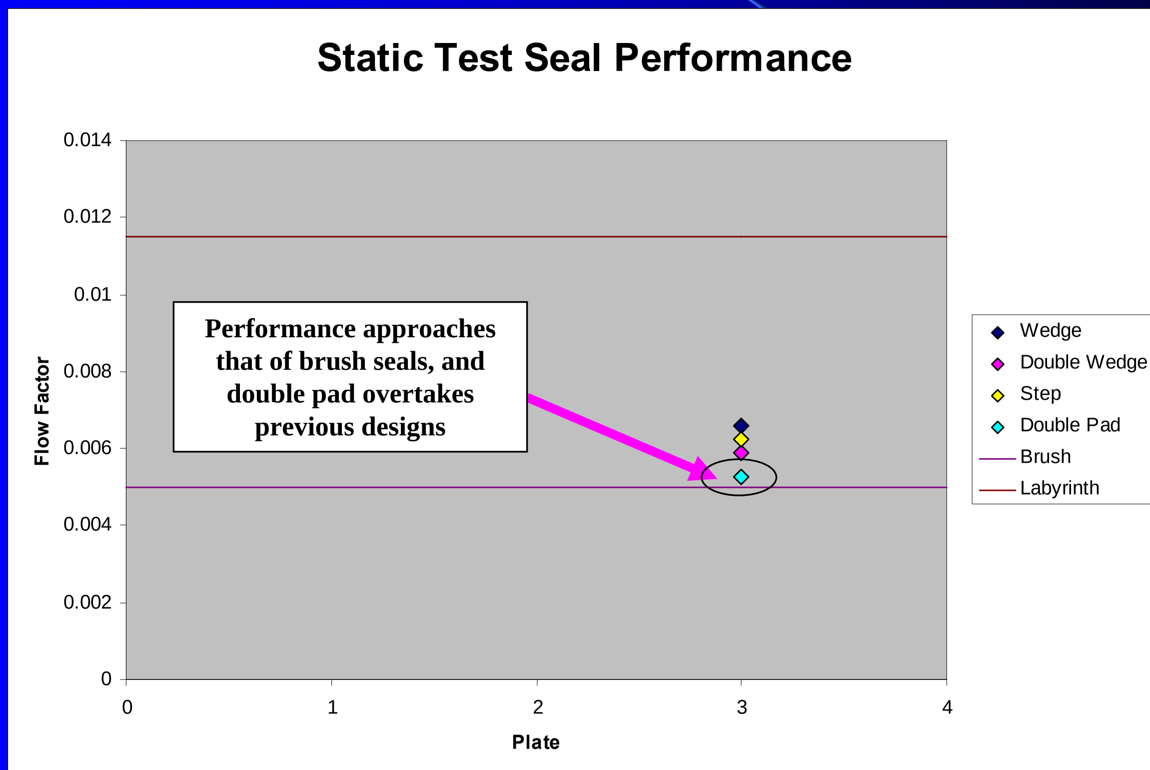
Each seal type is assembled with front plate 3
Flow into the test section is brought from full close to full open over a short amount of time
The established test section pressure is plotted versus flow

Maximum Static Test Pressure

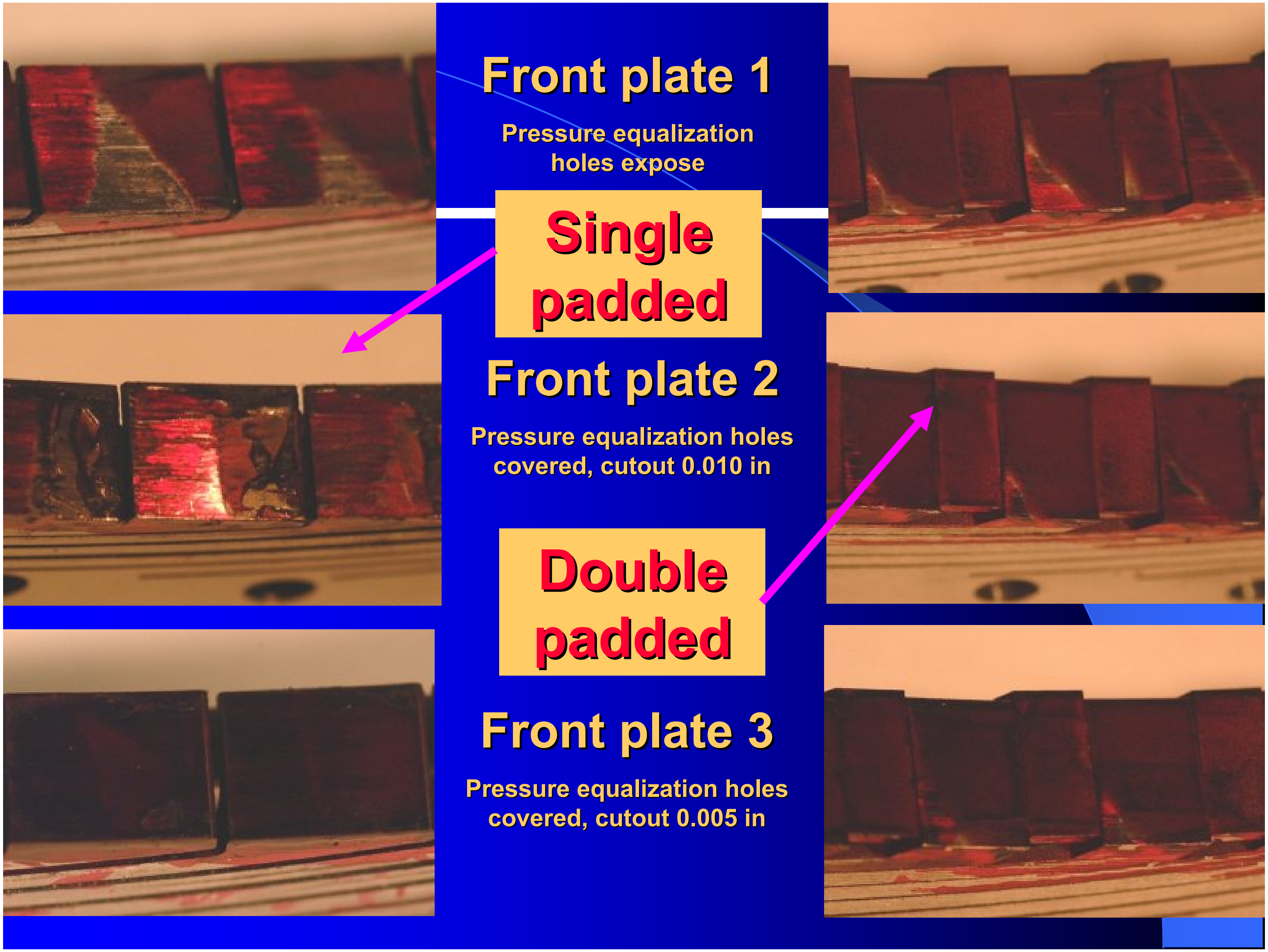


Operating Conditions – 3rd Front Plate, 70° F, 0 RPM

Seal Effectiveness at 60 psi



Operating Conditions – 3rd Front Plate, 60 psi, 70° F, 0 RPM


Front plate 1
Pressure equalization holes expose
Single padded
Front plate 2
Pressure equalization holes covered, cutout 0.010 in
Double padded
Front plate 3
Pressure equalization holes covered, cutout 0.005 in

Conclusions
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All seal types have been shown to lift effectively, and experience only minor wear during startup
The double pad design outperforms previous seals, providing lower operating temperatures, and less leakage at higher pressures
Future experimentation at higher pressures, temperatures, and operating speeds will show the full potential of finger sealing technology

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That is all folks