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HIGH TEMPERATURE PERFORMANCE EVALUATION OF A COMPLIANT FOIL SEAL

NASA Seal/Secondary Air Flow System Workshop
October 25-26, 2000

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This presentation is a summary of work completed recently under two different contract activities and MiTi IR&D. The support of NASA/GRC is acknowledged.

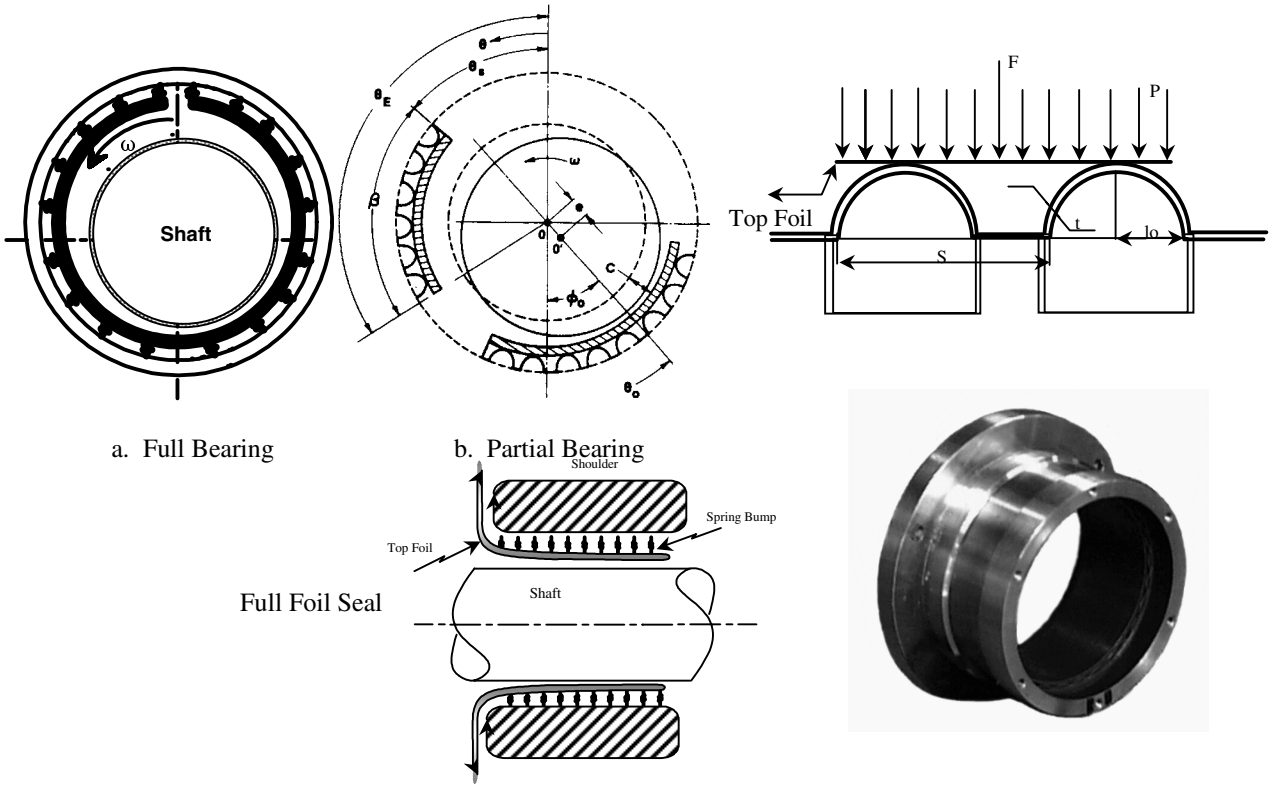
Outline

- Overview of Compliant Surface Foil Seal (CFS)
  - Configuration-Principles
- Experimental System
  - Bearing/Seal Simulator
  - Rotordynamics
- Test Results
  - Dynamic Response of Simulator
  - Compliant Foil Seal Performance
  - Tests with Brush and Labyrinth Seals
- Conclusions

During this presentation the basic configuration and operating principles of the compliant foil seal will be presented, followed by a brief discussion of the test rig facilities used to validate the seal performance; the test results and finally a summary of the material presented.

It should be noted that a portion of the presentation will focus on the rotor system dynamics with the seal. The reason for this emphasis will become evident as the test results are reviewed.

Compliant Foil Bearing and Seal Structure



This chart shows the basic concept for the compliant foil seal and it's foil bearing heritage. The upper left two figures are end view cross sections showing the MiTi approach to foil bearing design, namely a single top smooth foil supported by compliant spring elements. The key spring elements design parameters are shown in the upper right portion of the figure. To achieve the desired structural stiffness the corrugated bump pitch (s), material thickness (t) and bump height and radius may be varied.

A segmented or multi-pad bearing/seal arrangement is also possible as shown in the middle of the figure.

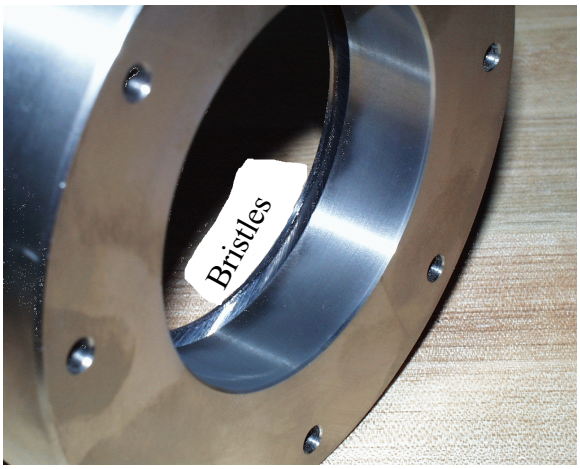
Regardless of design, the corrugated bumps can be tailored to provide circumferential and axial variable stiffness. The variable stiffness accommodates the developed hydrodynamic pressures which in turn permit liftoff and separation of the top foil from the shaft at low speed.

Since the corrugations run axially, an end flange is included to provide the sealing feature.

The figure in the lower right portion of the chart is the first prototype fabricated seal as tested.

Tested Seals

Compliant Foil Seal 99-0067

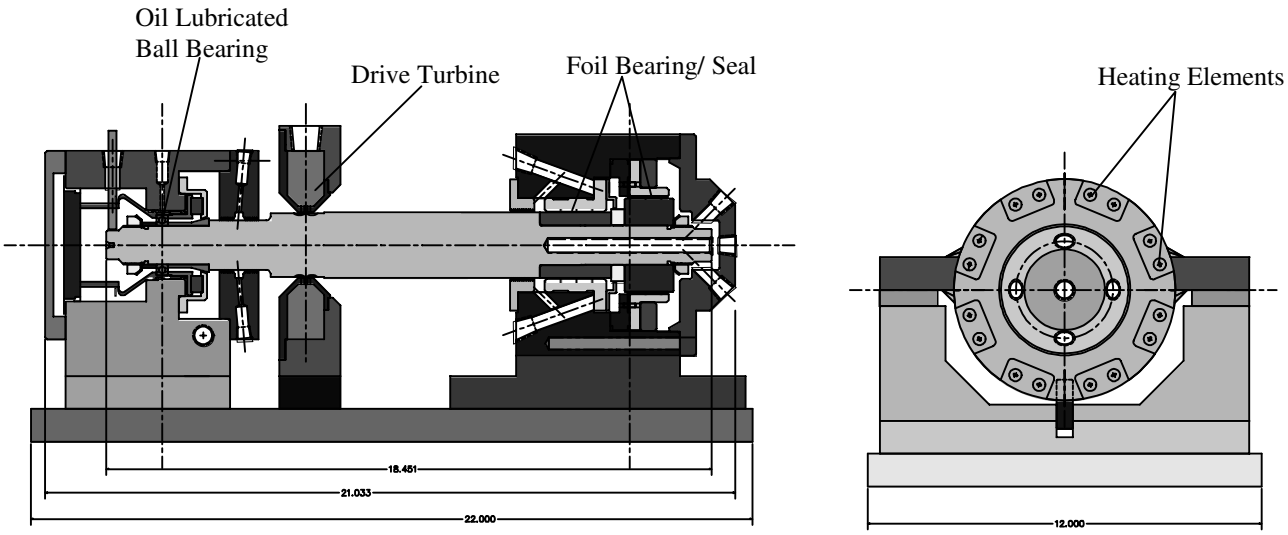


Brush Seal

Fabricated by Cross MFG CO. LTD

Shown here is the 72 mm diameter compliant foil seal and a comparable brush seal purchased from Cross for comparative tests. The foil seal is approximately 15 mm in length for an L/D ratio of approximately 0.2.

High Temperature Bearing/Seal Dynamic Simulator



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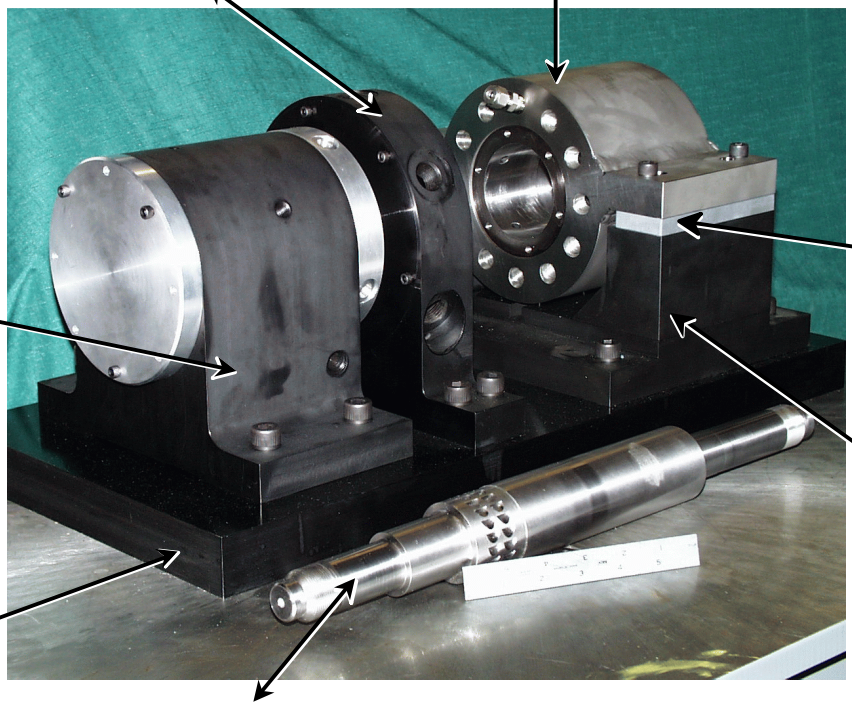
The high temperature test rig used to evaluate the compliant foil seal is shown here. Working from left to right we have an oil lubricated damped angular contact ball bearing, an integral impulse drive air turbine and the foil bearing and seal housing. The oil-free foil bearing and seal aft housing incorporates 16 cartridge heaters to raise housing temperature to 1000 F and two series of holes which are used to introduce high pressure air into the seal compartment or to vent to ambient atmosphere. Pressurized air may also be heated to 1000 F.

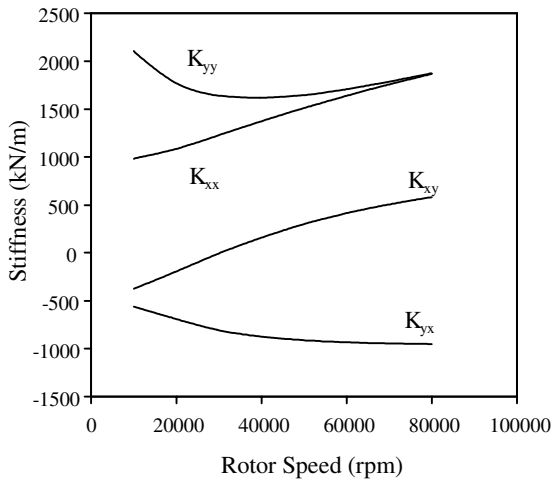
The rotor weight was approximately 8 Kg and operating speeds to almost 60,000 rpm are possible.

Test Rig Hardware

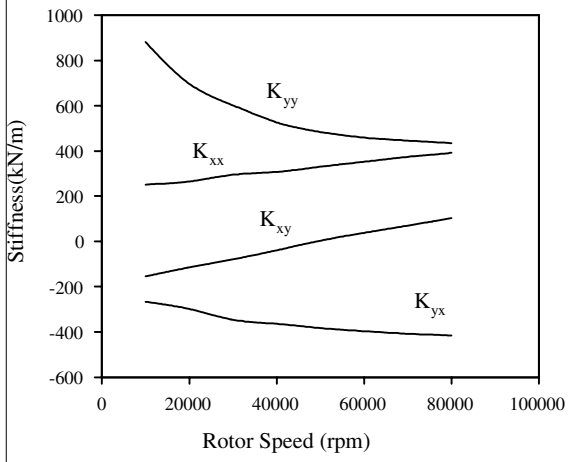


This photo shows the key test rig components as fabricated.

Foil Bearing & Seal Stiffness



Foil Bearing

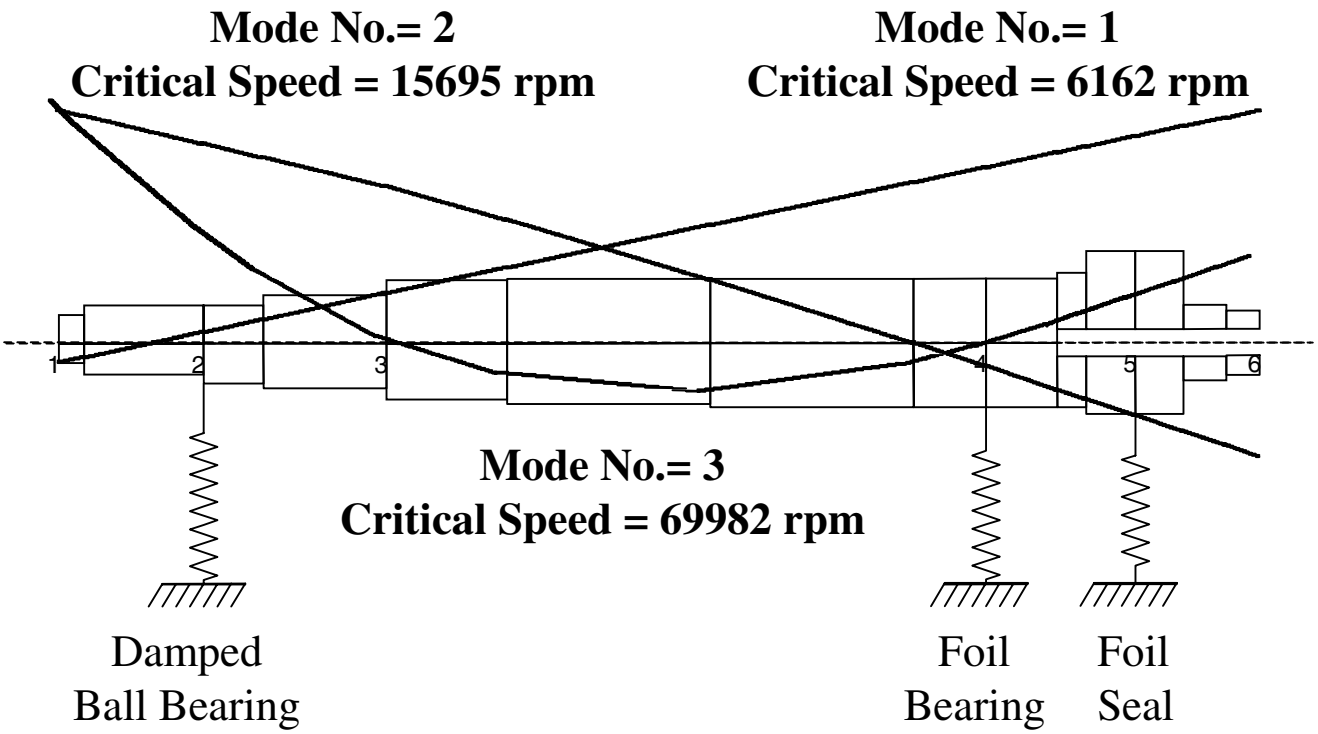


Foil Seal

As stated earlier, the foil seal has many of the same characteristics of the foil bearing. This similarity is evident in the two stiffness vs speed curves. It should be noted that both the foil bearing and seal have both direct and cross coupled stiffness as is expected for a hydrodynamic bearing. However, with both the bearing and the seal it is possible to configure and design the compliant elements to minimize the magnitude of the cross coupled terms and hence the generation of any destabilizing forces (e.g. Alford).

It should be noted that while the characteristics of the bearing and seal are similar, that the magnitude of the foil seal stiffness terms is less than the bearing. None-the-less, this stiffness and likewise the corresponding damping of the foil seal can have a positive impact on rotor system dynamics.

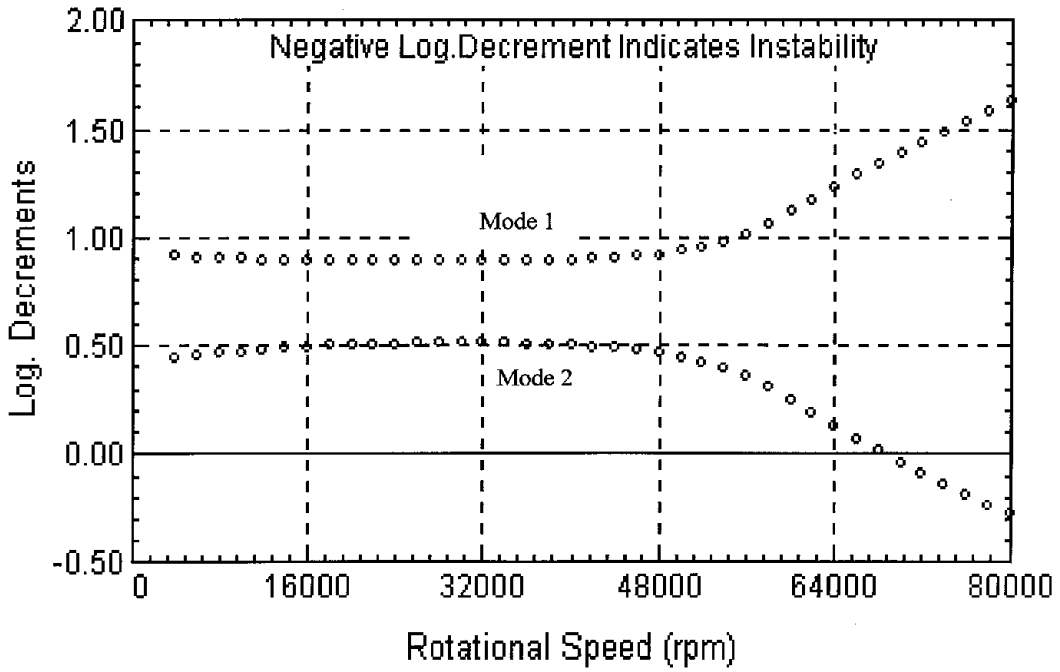
Critical Speed Analysis - Mode Shapes



Using estimated speed independent bearing coefficients the preliminary rotor critical speeds and mode shapes were determined as shown here. With a maximum operating speed of just under 60,000 rpm, the first bending critical speed is not expected to pose any limitation on system operation or testing.

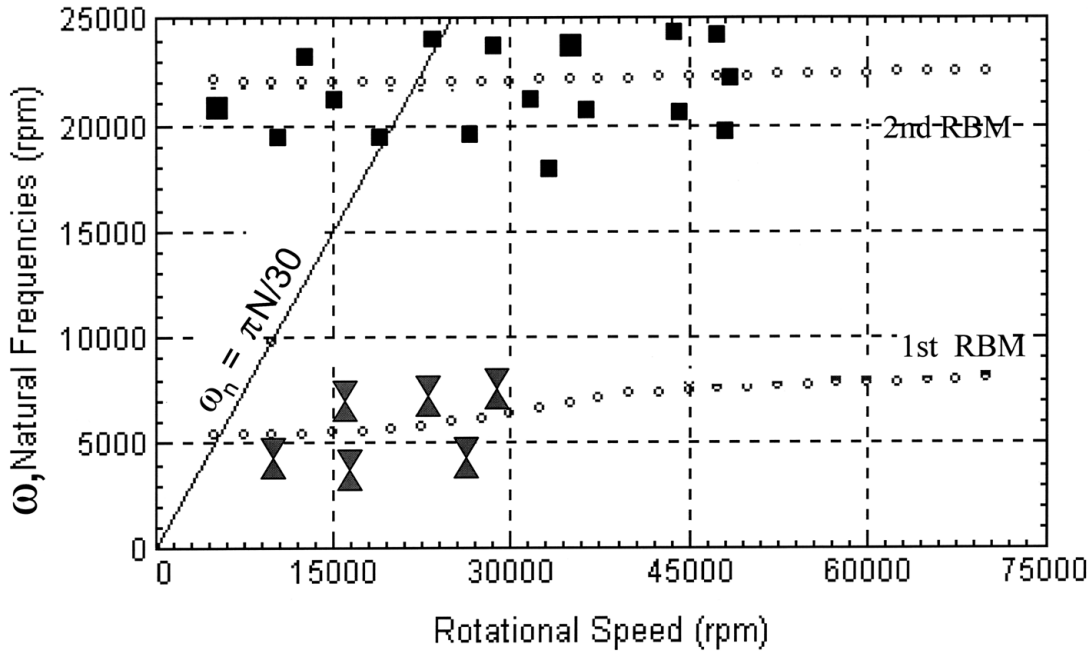
The first mode should be well controlled since there is motion at both the foil bearing and seal. Similarly, based on the amplitudes at the ball bearing and foil seal location the second mode should be well controlled.

Stability Map



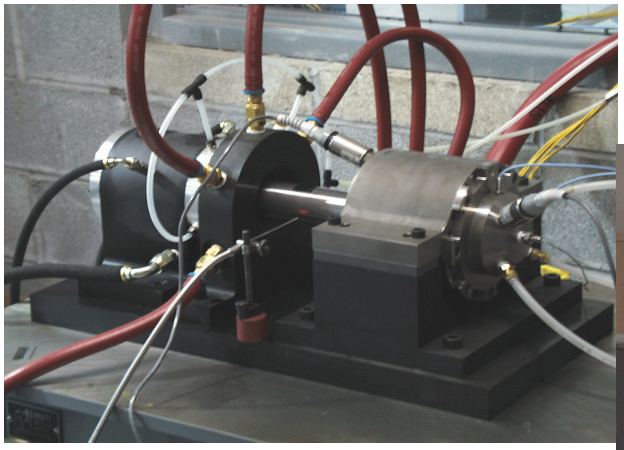
The stability map, which plots logarithmic decrement vs speed, shows that the rotor bearing system is expected to be stable at speeds in excess of 64,000 rpm.

Natural Frequencies - Foil/Seal Rotor System



One of the first things accomplished during checkout and initial operation of the test rig was to verify the analytically predicted rotor modes. This allows us a measure of validation of the bearing coefficients. As seen here, both the first and second measured modes correlate well with the predictions, giving confidence in the bearing and seal stiffness predictions as a function of speed.

Simulator & Instrumentation Setup

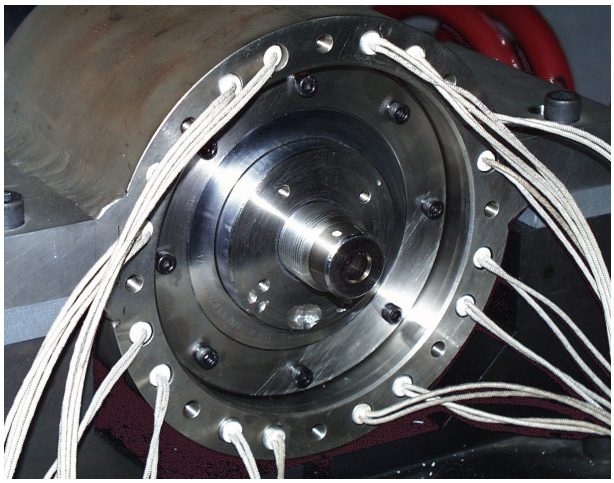


Hybrid Simulator

Instrumentations

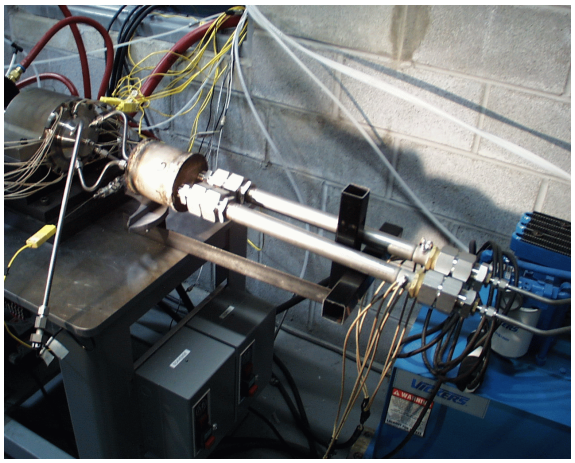
Shown here are the test rig installed in the test cell and the instrumentation set up including the PC based Labview data acquisition system, the dual channel FFT analyzer and the FM tape recorder.

Test Rig High Temperature Components



Cartridge Heaters

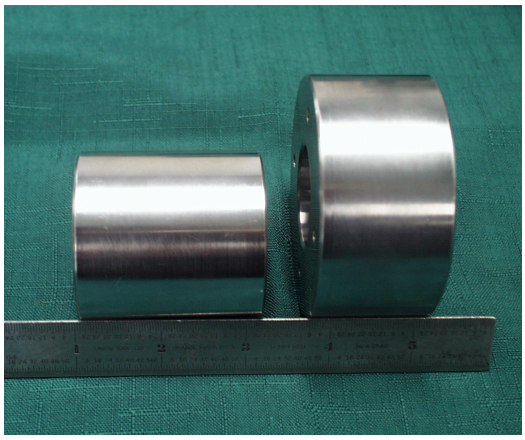
Shell & Tube Pre-Heaters



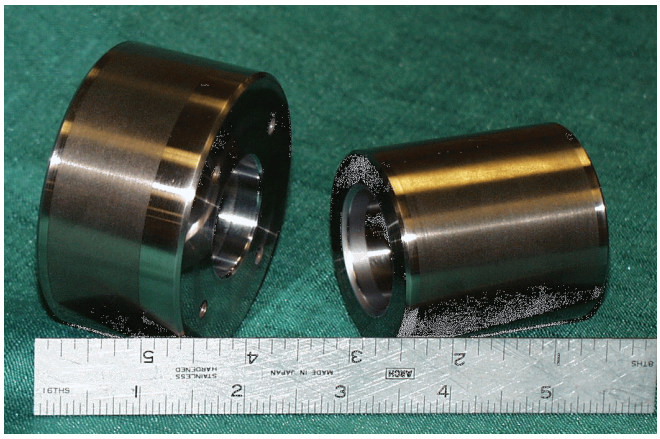
These two photos show the features incorporated for high temperature operation. The left figure shows the cartridge heaters installed in the bearing and seal housing. The aft view also shows the end of the foil seal.

The right figure shows the high temperature inline air heaters used to inject the high temperature pressurized air into the seal chamber.

Compliant Foil Seal/Bearing Journals



Low Temperature Journals

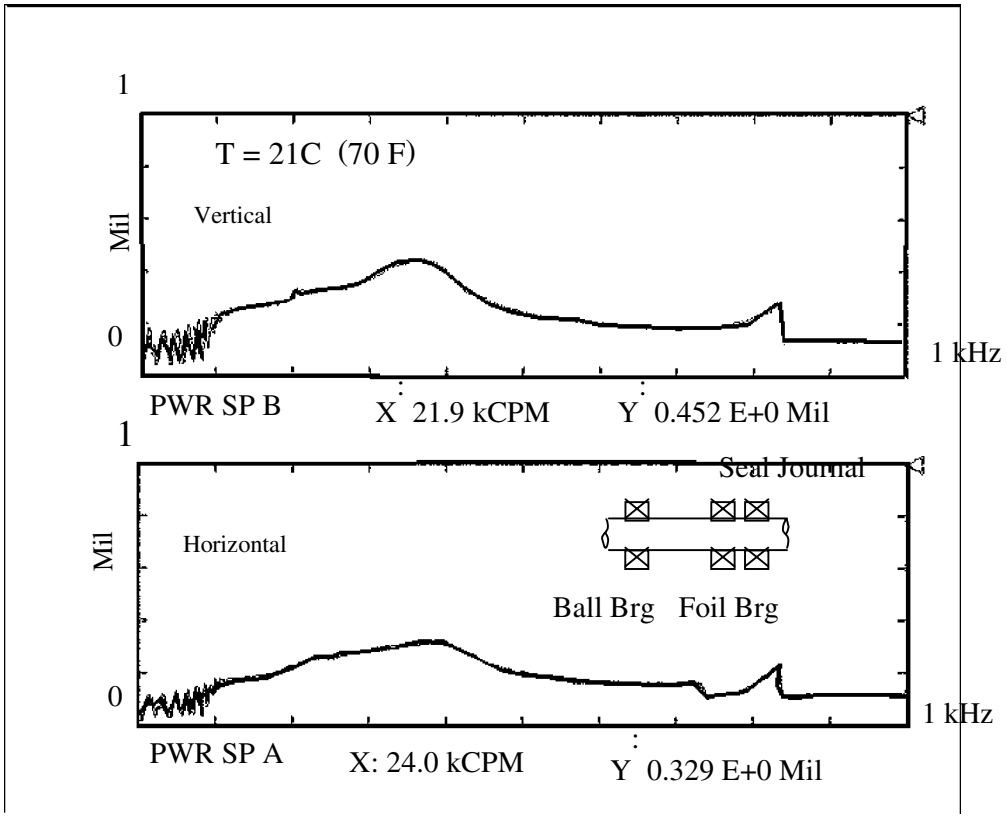


High Temperature Journals

These two figures show the foil bearing and journal seals. The left figure shows the electrolyze coated journals used for low temperature tests.

The right figure shows the journals coated with PS304 for high temperature testing.

CFS Coast Down at Room Temperature



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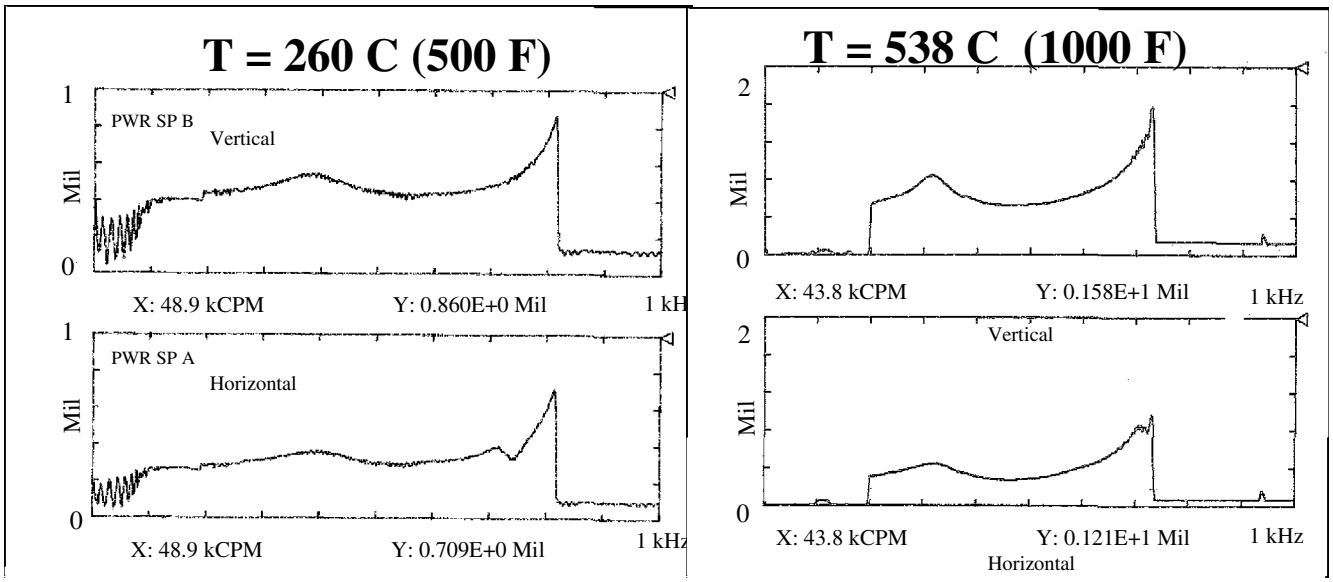
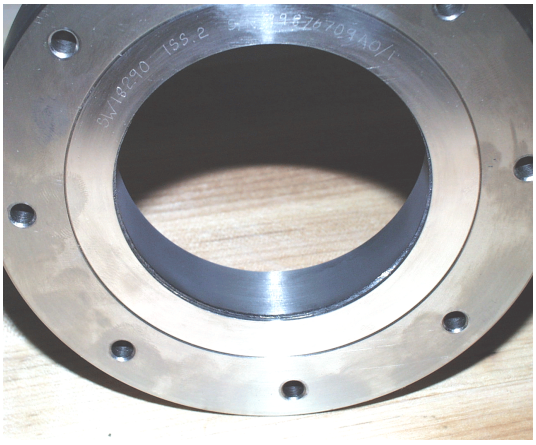
These peak hold synchronous vibration coat down plots show that the rotor system is well controlled throughout the entire expected operating speed range with both the foil bearing and seal installed.

Coast Down w/CFS at Two Temperatures

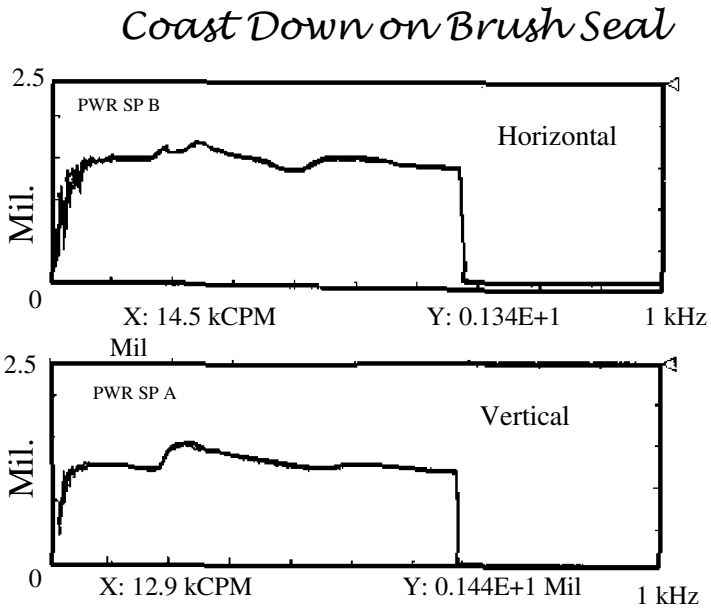


As temperature is increased first to 500F and then to 1000F rotor response is still well controlled. However, it should be noted that the response amplitude of rotor vibration increases over the room temperature baseline. This increase in vibration amplitude is most likely due to a reduction in material modulus and hence bearing stiffness as temperature increased.

Coast Down On Brush Seal at RT

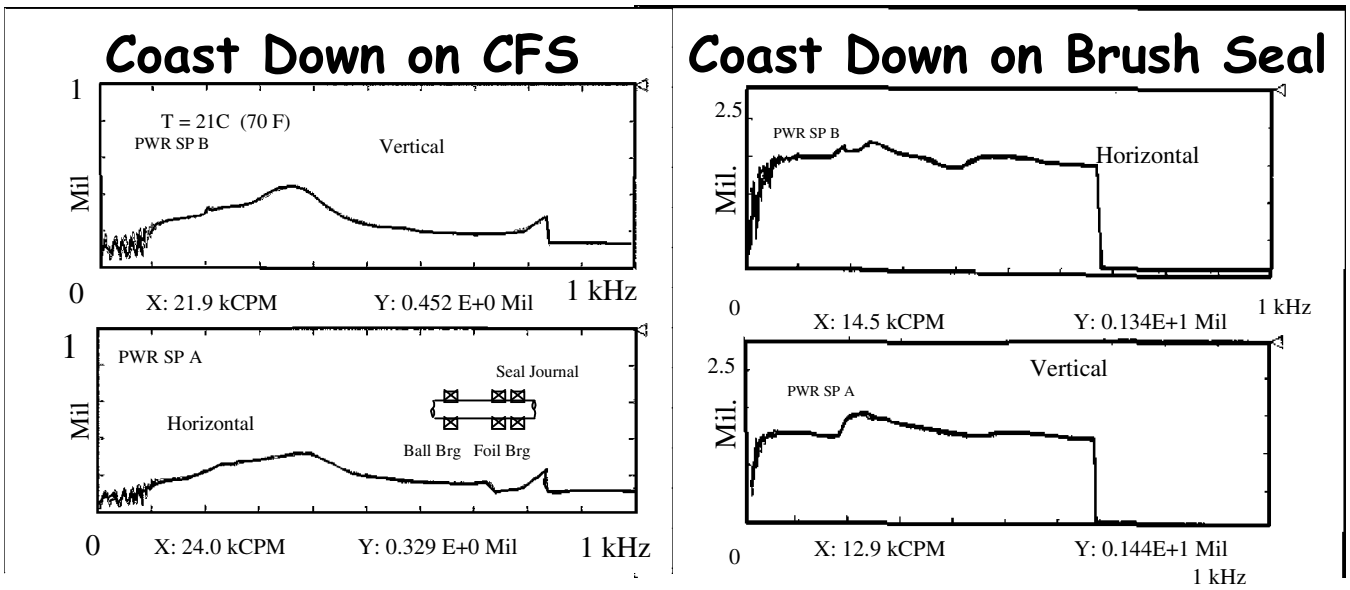


Brush Seal By Cross TM



This chart shows the brush seal as tested along with the resulting rotor response. The brush seal was installed with a 0.002 inch interference.

Compliant Foil Seal vs Cross™ Brush Seal Coastdown



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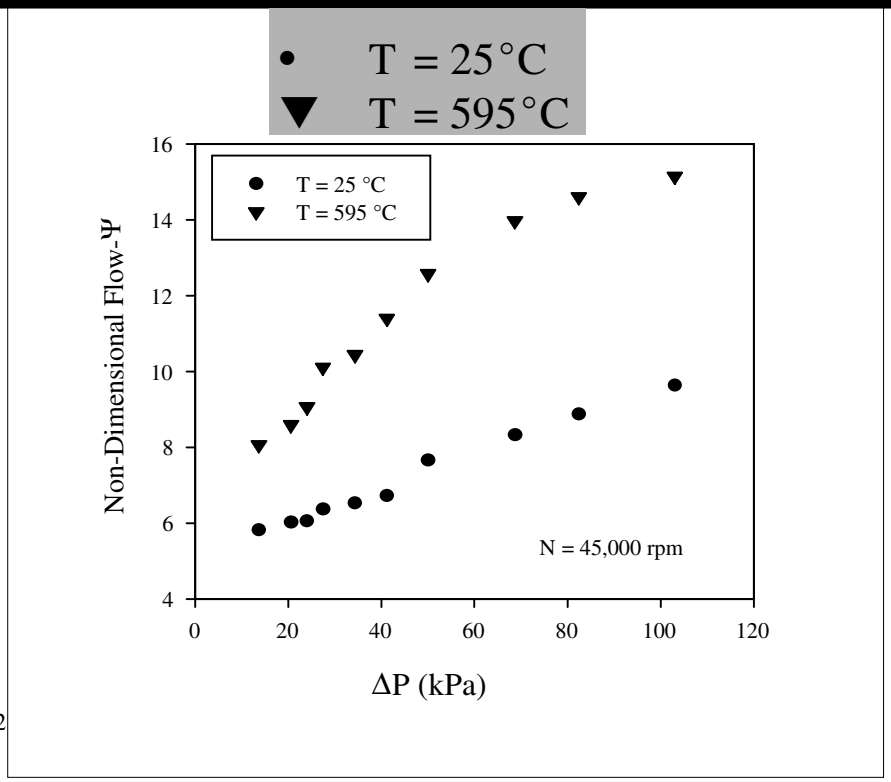
This chart compares the rotor response performance of both the compliant foil seal and the brush seal at room temperature. Note the vibration amplitude scales (ordinate) for the brush seal is 2.5 mils while the foil seal max scale is 1 mil and that peak vibration amplitude for the foil seal is less than 0.5 mils while the peak rotor vibration is 1.34 mils when the brush seal was installed. This vibration response shows that the stiffness and damping contribution from the foil seal has a positive impact on the rotor.

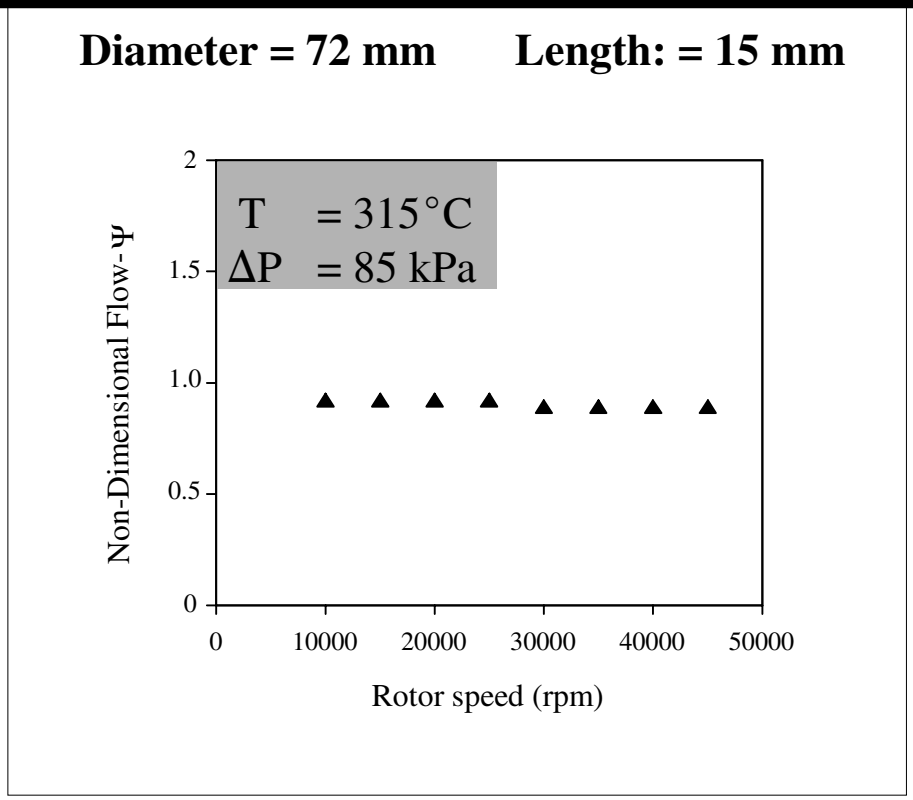
CFS Performance with Temperature



$$\Psi = \frac{\dot{m}}{\rho^{05} \Delta P_u^{0.5} D^2}$$

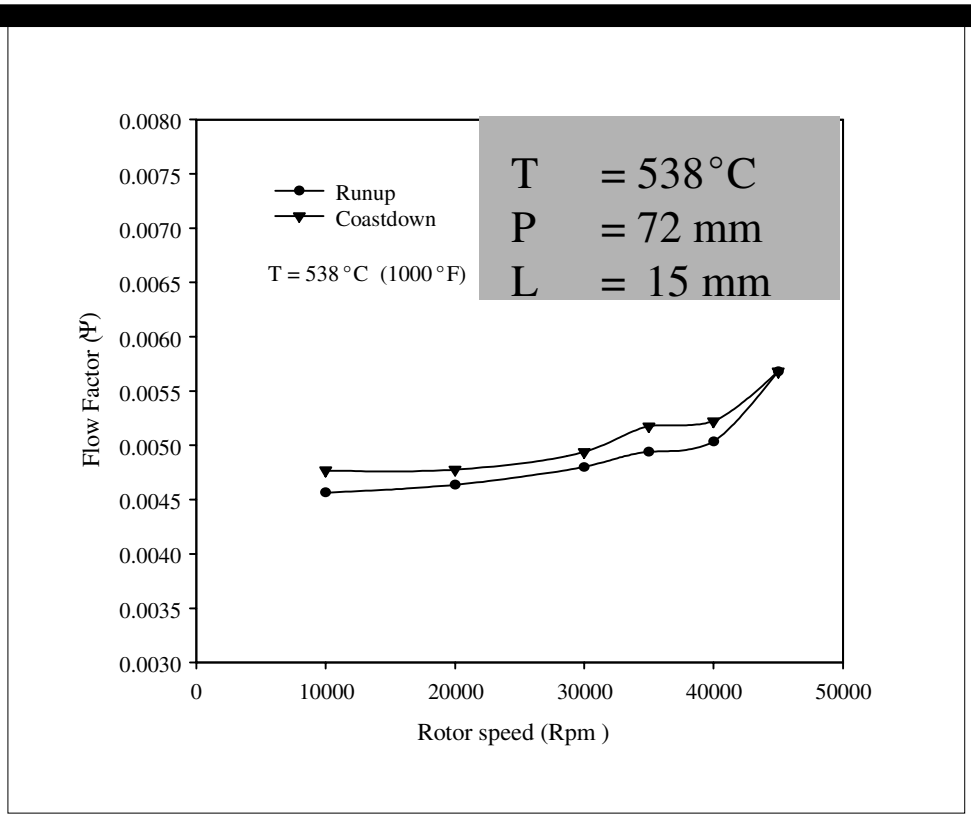
Once the rotor performance was deemed acceptable, evaluation of the compliant foil seal was performed. As seen here the foil seal performance does degrade slightly as differential pressure and temperature increases. In both cases however, the increased leakage is nearly linear over the range of pressures tested. The results presented here are for a spin speed of 45,000 rpm and at both room temperature and 595C.

CFS Performance with Rotor Speed



In this test, the differential pressure was held constant as speed was increased. As seen the flow or seal leakage remained constant over the entire speed range tested.

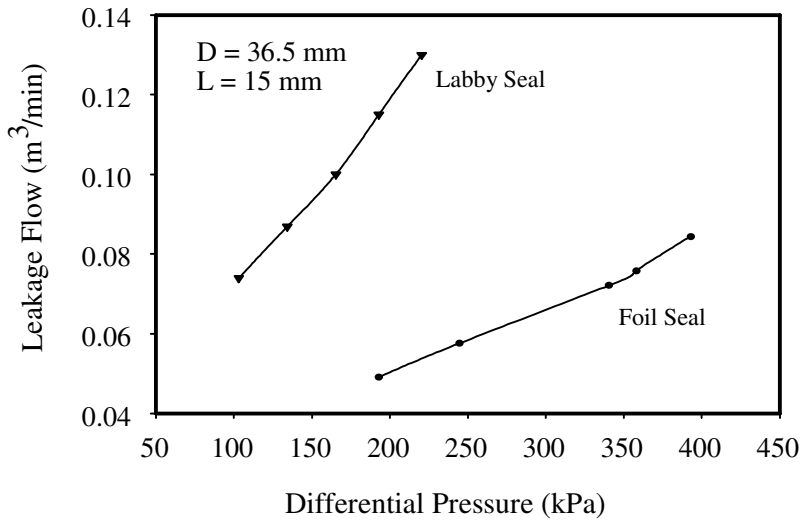
CFS Performance @ 1000 F



$$\Psi = \frac{\dot{m}\sqrt{T}}{P_u D}$$

This chart, which plots flow factor as a function of spin speed for the 72 mm diameter seal shows that the leakage remains fairly constant for the entire speed range and that performance is fairly repeatable having taken data both during the acceleration and deceleration. Flow factor data for the CFS was plotted versus speed in this case since the this is one measure used to assess brush seal performance.

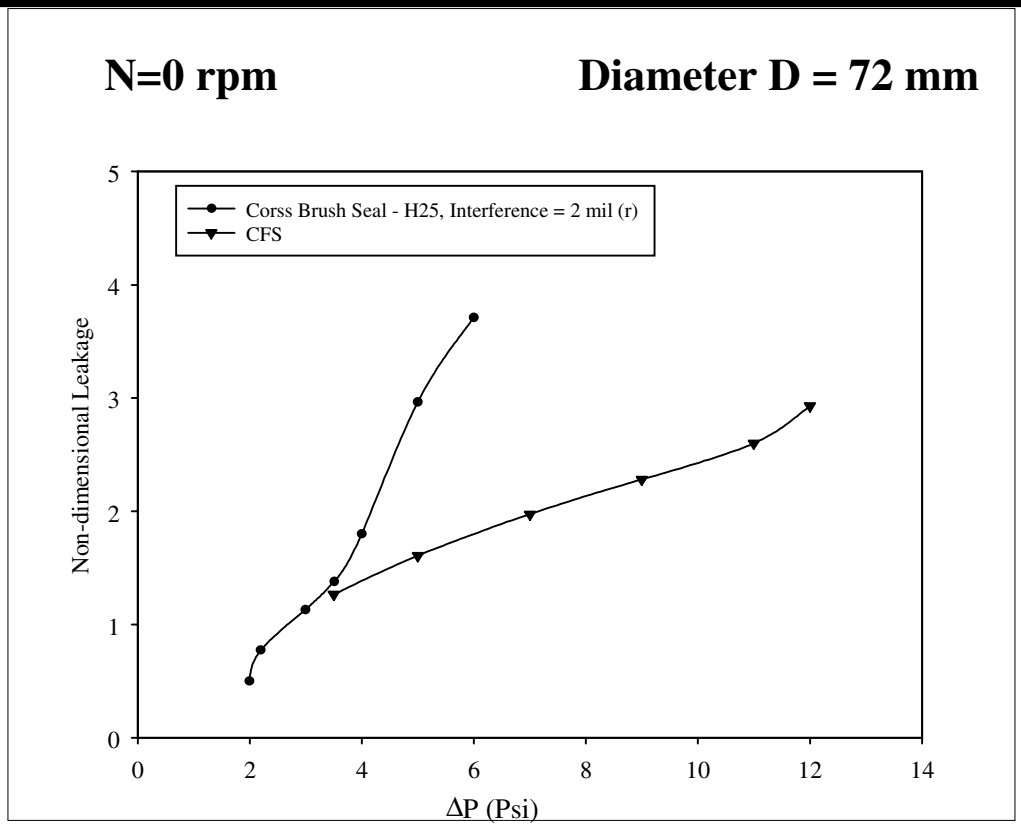
Static Test with Labyrinth Seal and CFS



Having demonstrated operation of the compliant foil seal, the next step was to demonstrate its superiority over a comparable labyrinth seal. The experimental data presented here is for a static or non-rotating condition. This testing with the 36 mm diameter foil seal vs a comparable labyrinth seal shows that the foil seal leakage increases nearly linearly with differential pressure and that the leakage is significantly lower than that for the labyrinth seal.

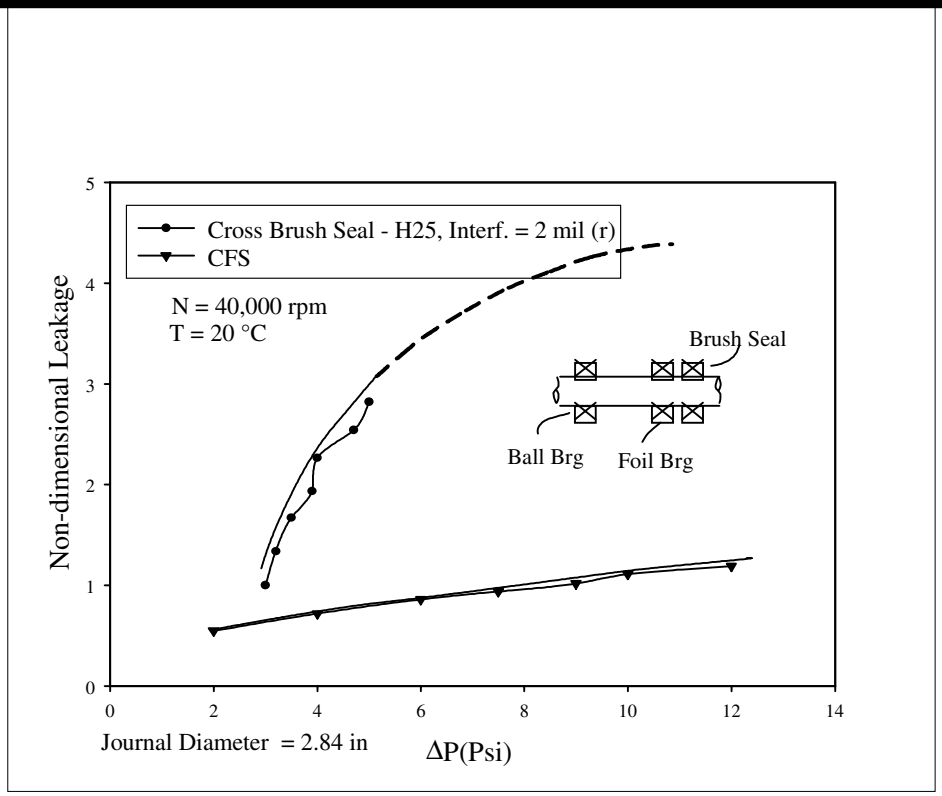
The performance of the compliant foil seal is to be expected since the nominal operating clearance is less than the labyrinth seal, being on the order of 0.5 mil as opposed to approximately 3-6 mils. Under dynamic conditions this same performance trend is expected.

Compliant Foil Seal vs Cross™ Brush Seal



This chart compares the compliant foil and brush seal non-dimensional leakage versus differential pressure under static non-rotating conditions. The experimental data shows that the foil seal leakage again increases nearly linearly with differential pressure and that the leakage is significantly lower than that for the brush seal. As a matter of fact, the brush seal which was made of Haynes 25 bristles and installed with a 0.002 inch interference fit could only sustain a 6 psi differential pressure. This low achieved differential pressure is likely due to fence height.

CFS and Brush Seal Comparison

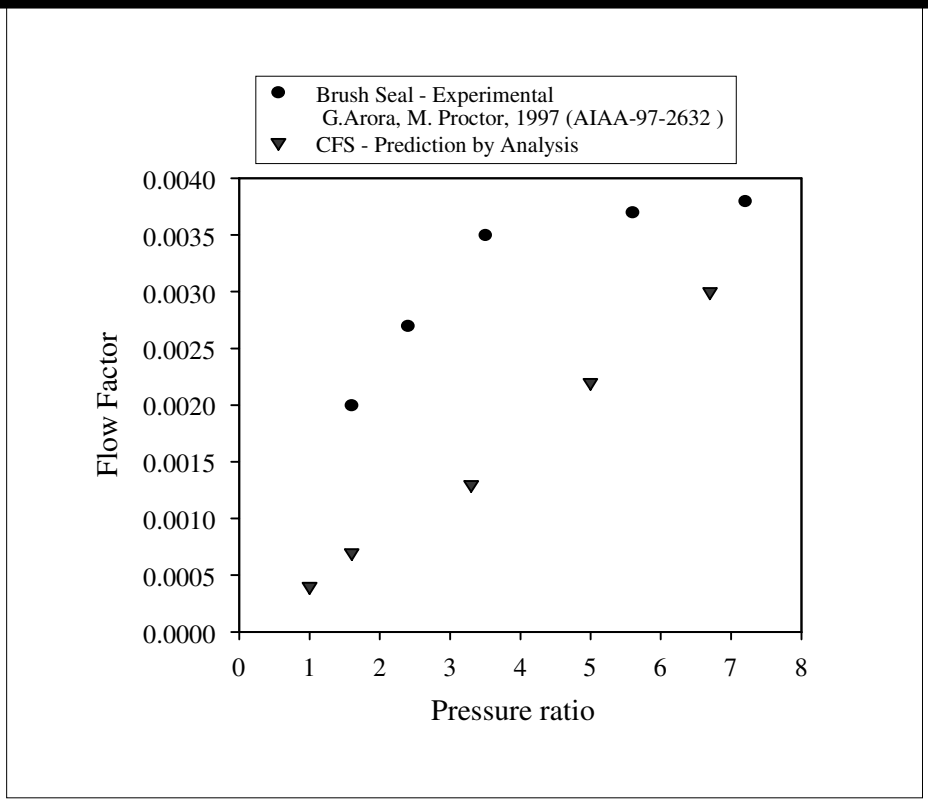


A dynamic room temperature, 40,000 rpm comparison of the 72 mm diameter foil and brush seals is shown here. As seen before the foil seal leakage increases linearly with a low slope while the brush seal leakage increases dramatically over the same range of pressures.

Brush Seal Wear Track on Journal

This figure shows the wear tracks evident on the rotor seal surface. Several wear tracks are evident. The two primary wear tracks resulted from flipping the brush seal around so that a new running surface could be used for different tests. A close examination of the shaft at the inboard wear track reveals it to be wider than the original bristle stack due most likely due axial flexing of the bristles under the axial pressure gradient.

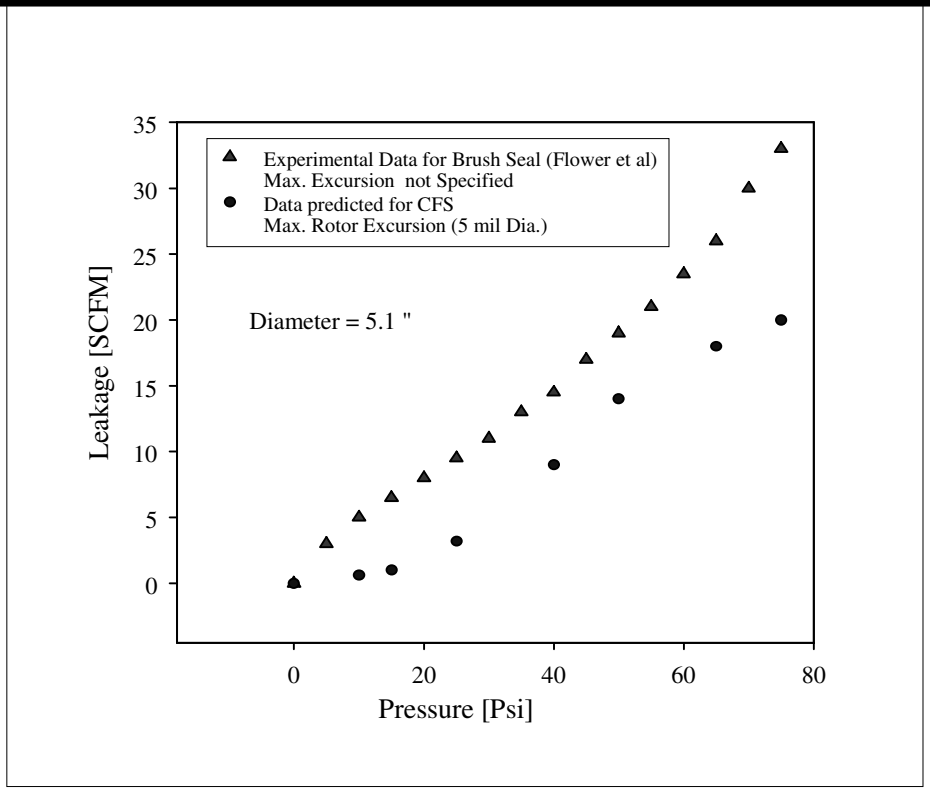
Brush Seal Test Results vs CFS by Analysis



To further validate the feasibility of the foil seal, published data for brush seals was used to assist in establishing comparable CFS designs that could then be analytically compared to the brush seal. As seen here predictions indicate that the CFS should out perform comparable brush seals even at pressure ratios as high as 7 to 8. The data used here was published by Arora and Proctor in 1997 in paper AIAA-97-2632.

While the differential sealing pressures evaluated under this effort were limited to less than 60 psi, it is recognized that higher pressure testing will be needed to validate the high pressure performance.

Brush Seal Test Results vs CFS by Analysis



Another comparison of the CFS against brush seal data published by Flowers et al is shown here. As shown previously, the comparable foil seal design is expected to have less leakage than the brush seal even at differential pressures of 80 psi.

Summary and Conclusions

- **A hybrid small gas turbine engine simulator was successfully designed and tested for a range of speeds and temperatures (0-56,000 rpm, 20-640 ˚C)**

- **Feasibility of the non-contact compliant foil seal (CFS) was demonstrated**
  - Hi-Temperature operation w/NASA PS304 coating & MiTi Bearing & Seal
  - Rotor vibrations reduced
  - CFS exceeded performance of Brush and Labyrinth seals w/o wear

- **The CFS has great potential for hi-speed, hi-temperature applications**
- **Further work**
  - Demonstrate rotor excursion capabilities
  - Demonstrate scaling

The key points to be gleaned from the effort reported herein are that the CFS has been demonstrated in conjunction with a foil bearing in a small gas turbine simulator at temperatures as high as 1000F and outperformed a comparable brush seal.

Having demonstrated the feasibility of the CFS, it would appear that this new seal design has application potential in a wide range of machines. What remains is to demonstrate performance at higher pressure ratios, consistent performance at large rotor excursions and the ability to manufacture the seal in much larger sizes exceeding by an order of magnitude that which has been tested to date.