COMPLIANT FOIL SEAL INVESTIGATIONS

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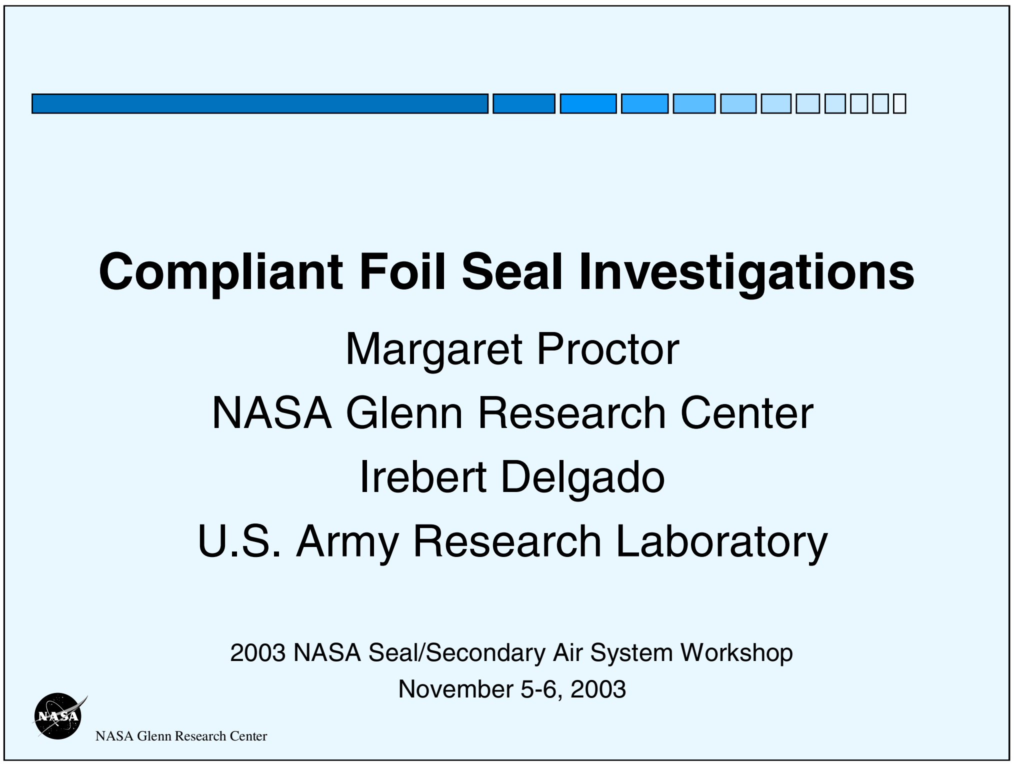

Room temperature testing of an 8.5 inch diameter foil seal was conducted in the High Speed, High Temperature Turbine Seal Test Rig at the NASA Glenn Research Center. The seal was operated at speeds up to 30,000 rpm and pressure differentials up to 75 psid. Seal leakage and power loss data will be presented and compared to brush seal performance. The failure of the seal and rotor coating at 30,000 rpm and 15 psid will be presented and future development needs discussed.

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2003 NASA Seal/Secondary Air System Workshop
November 5-6, 2003

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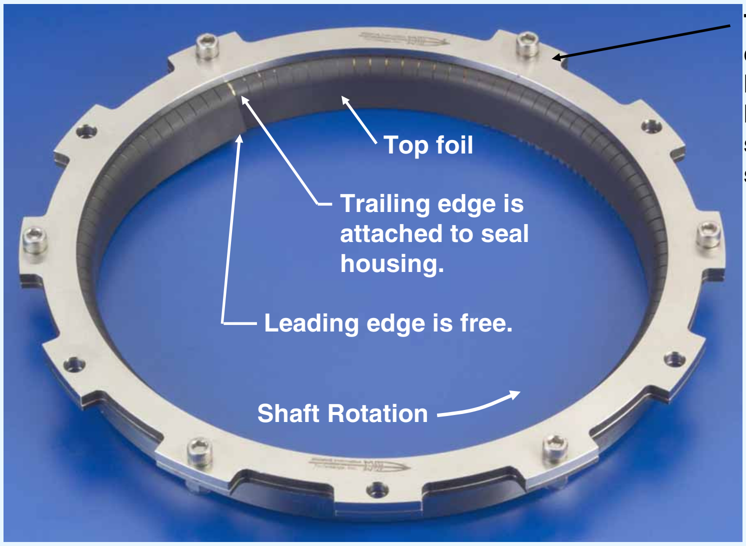
NASA Glenn Research Center has been working with Mohawk Innovative Technology, Inc. (MiTi) to develop a Compliant Foil Seal for use in gas turbine engines. MiTi was awarded phase I and phase II SBIR contracts to analyze, develop, and test foil seals. As part of the Phase II contract, MiTi delivered an 8.5 inch diameter foil seal to NASA GRC for testing. Today I will be presenting some results of testing the 8.5 inch foil seal at NASA.

Mohawk’s 8.5 inch Foil Seal Prior to Test



Top foil is clamped to seal housing on high pressure side of seal by seal clamp.

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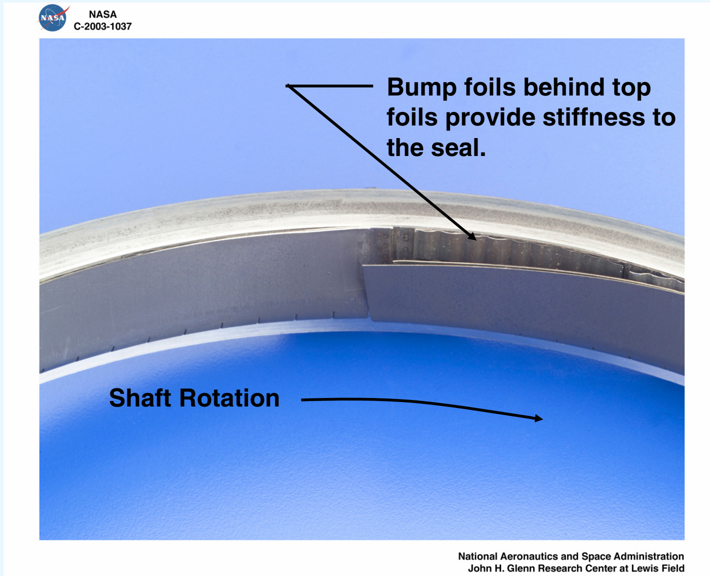
This foil seal is an extension of MiTi’s foil bearing technology. The foil seal is essentially a foil bearing that uses a pair of top foils with slotted extensions to block the axial flow from passing thru the bump foils located behind the top foils. The two top foils are clocked to each other so that the extension tabs of one top foil block the slots of the other. The trailing edge of the top foil is fixed to the seal housing and the leading edge is free. Rotor rotation is counter clockwise looking from the high pressure side. The top foil is coated with MiTi’s Korolon 800 coating.

Down Stream Edge of Foil Seal



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The bump foils can be seen behind the top foil in this view of the downstream side of the seal near the leading edge. When the seal is installed over the rotor the top foil conforms to the rotor od.

Test Summary of 8.5 inch Foil Seal

- **Tests Completed:** **Room temperature static, 7-17-03**
  Room temperature performance 7-21-03

- **Leakage and Power Loss measured at:** **0,10, 15, 20, 25 Krpm**
  0 to ~70 psid
  Pressure cycled up and down twice at each speed.

- **Shaft orbits indicated problem at 30,000 rpm, 15 psid**
  - **folded "figure 8"-shape, decreased speed to 25 Krpm**
  - **orbits worsened, aborted turbine drive**
  - **very large orbits during deceleration**

- **Seal and rotor coating severely damaged.**

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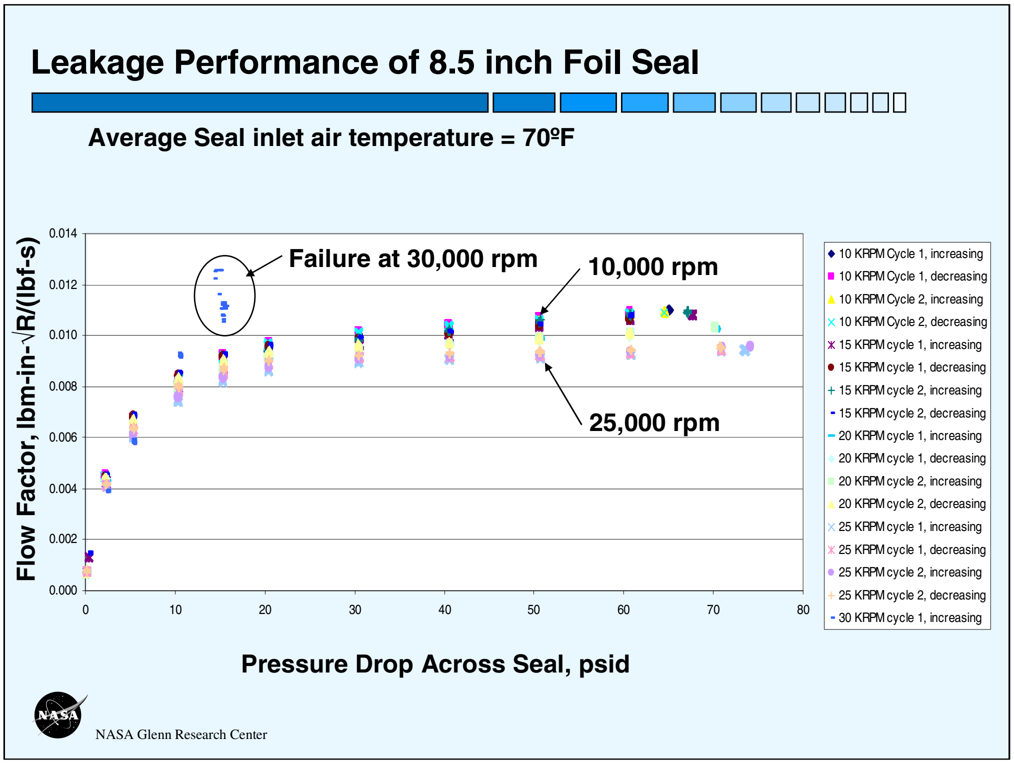
Room temperature static and performance tests were conducted on the 8.5 inch foil seal. Results were obtained at speeds up to 25000 rpm and pressure differentials from 0 to 70 psid. At each speed the pressure was cycled up and down twice. 2 psid was applied during the initial rotation to ensure air flow to carry away the heat generated due to rubbing between the top foil and the CrC coated rotor that occurs prior to top foil lift off. At 30,000 rpm and 15 psid, the rig shaft orbits indicated a problem. Speed was decreased to 25000 rpm. The orbits worsened and we shutdown the air turbine. The shaft orbits became very large during deceleration. Post test inspection found the seal and rotor coating were severely damaged.

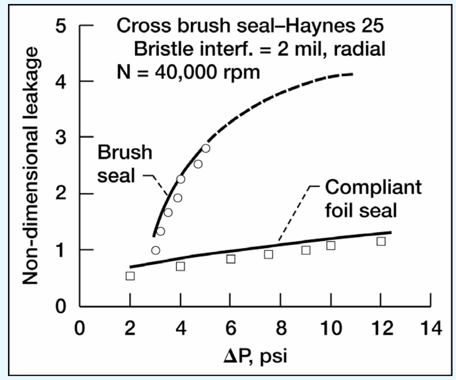


This is a plot of the seal leakage flow factor versus pressure drop across the seal obtained during the performance test. For all speeds the flow factor increases with increasing pressure differential until about 25-30 psid where it levels off indicating that the flow is choked. The flow factor decreases as speed increases due to reduced clearance cause by centrifugal growth of the rotor. During the failure event at 30,000 rpm and 15 psid the flow factor increased substantially and rapidly. This sudden increase in flow factor indicates an opening of the seal clearance caused by either loss of the seal coating or wear of the seal top foil.

Leakage Performance Comparison

- The 8.5 inch foil seal flow factor levels out between 0.009 to 0.011.
- Previous testing has shown finger and brush seals to have flow factors at 0.004 to 0.006.
- MiTi previously tested a 2.84 inch foil seal and found its leakage performance to be much better than a brush seal.
- The leakage performance of the 8.5 inch foil seal is about twice that of finger or brush seals. Since this is counter to previous findings at smaller diameter seals, it is concluded that there are some scale up issues that need to be addressed.

Foil Seal and Brush Seal Leakage Data
2.84 in. Dia. Journal; 68 °F
SBIR Phase 1



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From the previous chart we see that the flow factor for the 8.5 inch foil seal leveled out between 0.009 and 0.011.

Previous testing at NASA has shown that finger and brush seals have flow factors of 0.004 to 0.006.

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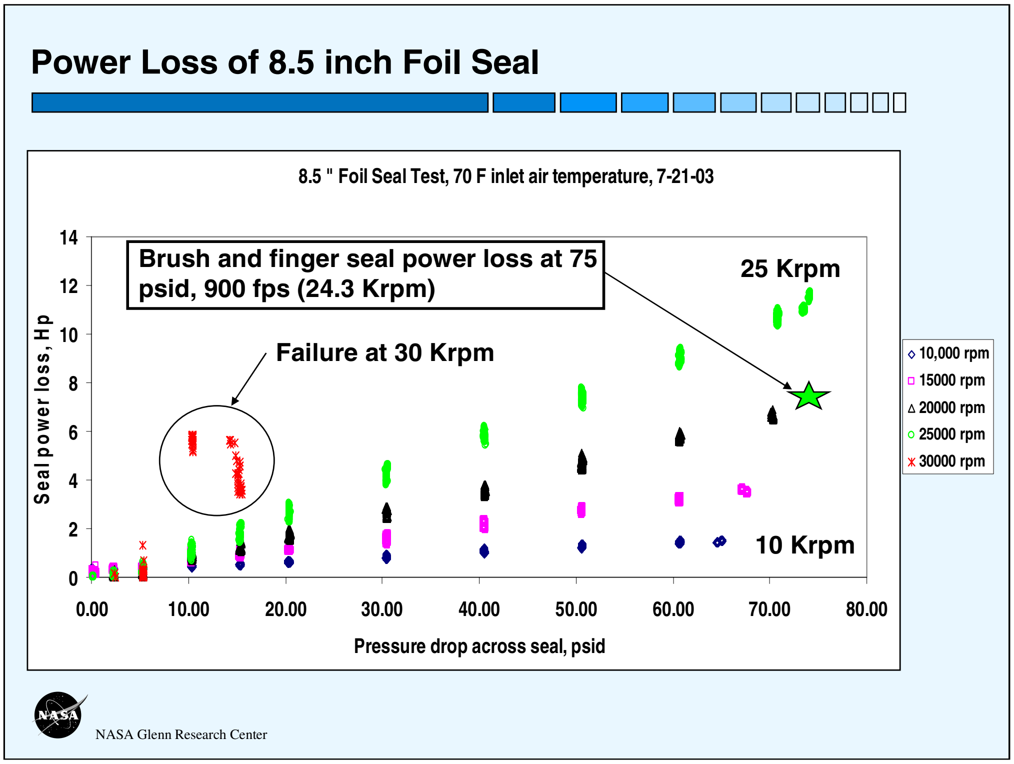


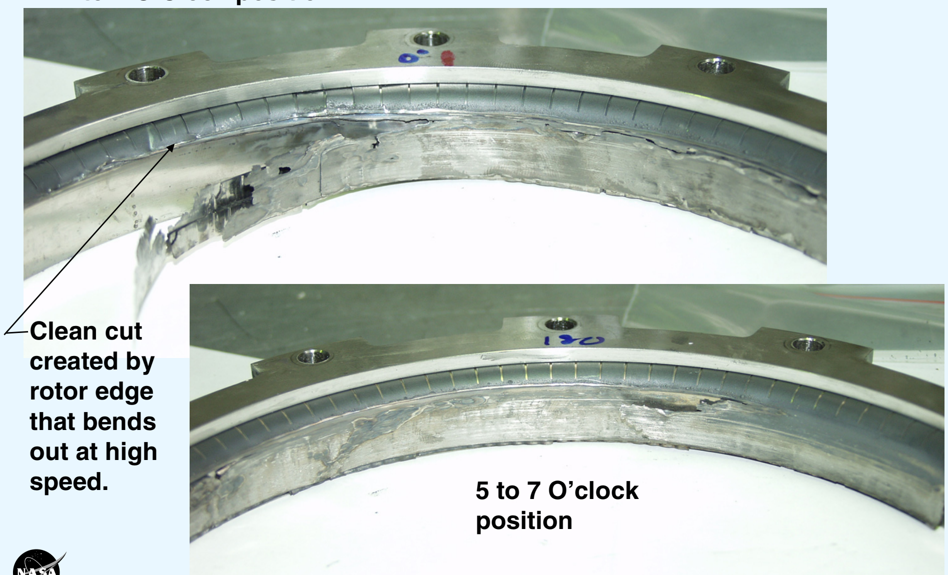
This is a plot of the measured 8.5 inch foil seal power loss versus pressure drop across the seal for each speed tested. A torquemeter was used to measure the total torque of the seal test rig with the seal installed. The tare torque of the seal test rig without a test seal installed is subtracted from the total torque to derive the seal torque. The seal power loss is computed as the seal torque multiplied by speed. The seal power loss increases with speed and with pressure differential.

Noting that the seal power loss of the 8.5 inch foil seal at 25,000 rpm or 927 ft/s and 75 psid is 11-12 Hp and comparing it to previously published data for the finger and brush seal at 1200 F inlet air temperature, 900 ft/s and 75 psid which had a seal power loss of 7.5 to 8 Hp, it is concluded that the 8.5 inch foil seal tested has a higher power loss than a brush or finger seal.

The seal power loss at 30,000 rpm and 15 psid was higher than one might expect based on the data for lower speeds. Also the power loss at 30,000 rpm and 10 psid was quite high and indicates rubbing was occurring at that point.

Damaged 8.5 inch Foil Seal

11 to 1 O'Clock position



Clean cut created by rotor edge that bends out at high speed.

5 to 7 O'clock position

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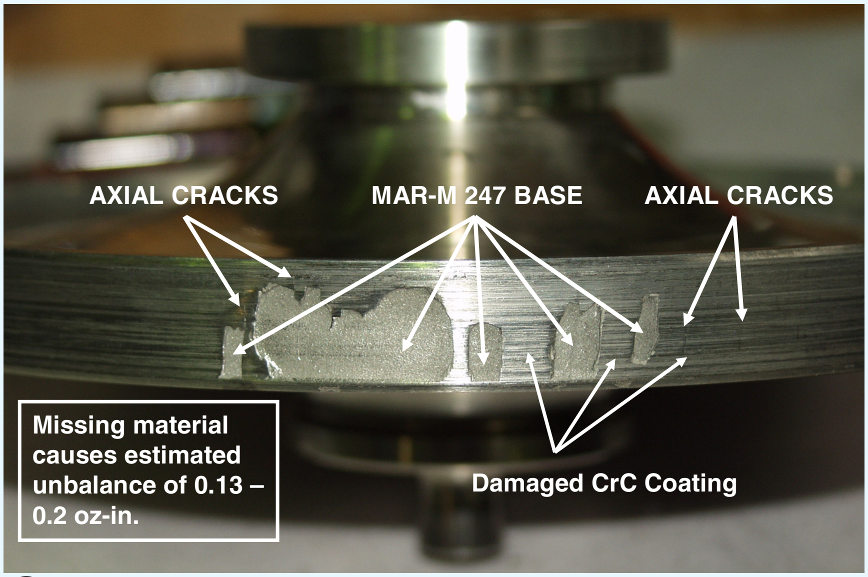
This is the 8.5 inch foil seal after room temperature testing to 30,000 rpm. The seal is damaged beyond use. Parts of the top foils and bump foils were found blown behind the rotor at disassembly. The Korolon coating is rubbed off and the top foil was burned through at places. Note the clean cut at the bend in the top foil. This cut aligns with the edge of the test rotor. The test rotor has an I-beam cross section at the rim. Hence at high speeds the edges of the rotor rim bend out radially farther than the axial center of the rim. This displacement combined with the chamfer on the edge of the rotor makes a nice cutting tool.

Damaged Rotor Coating



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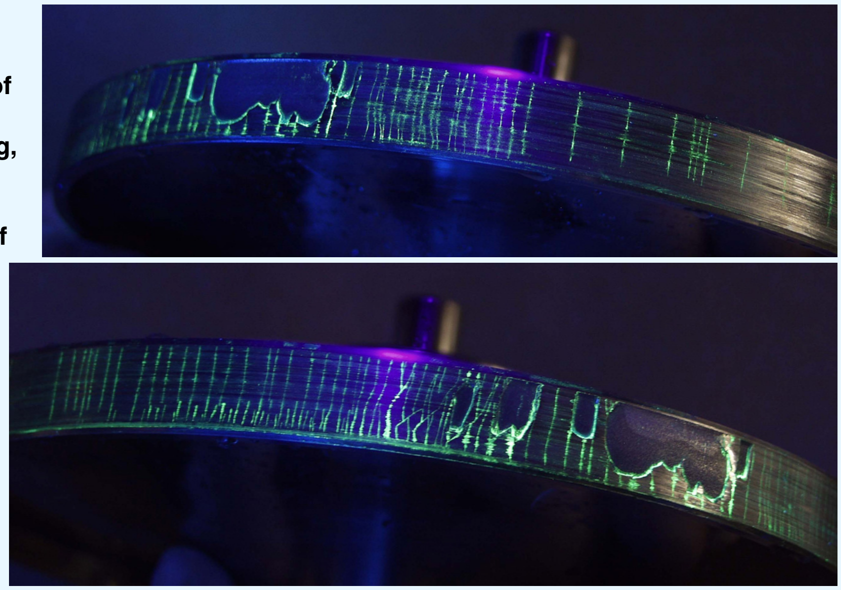
The rotor coating failed. The Mar M-247 rotor had a 0.010 inch thick CrC coating applied by high velocity oxygen fuel thermal spraying. By measuring the areas of the missing coating and the depth of the damage, the unbalance of the missing material is estimated to be 0.13-0.2 oz-in, which is 27-40 times greater than the balance specification for the rotor. Some hairline axial cracks are visible.

Rotor under fluorescent penetrant dye inspection

Axial cracks, typical of heat checking, indicate fatigue failure of the coating.



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Many axial cracks are visible in the rotor coating under fluorescent penetrant dye inspection. These axial cracks are typical of heat checking and indicate fatigue failure of the coating. The fatigue failure is likely due to the mismatch in coefficients of thermal expansion for the rotor material Mar M-247 and the CrC coating.

Conclusions

- 8.5 inch foil seal leakage is higher than brush or finger seals and smaller foil seals. More optimization of the seal is needed to reduce leakage for large diameter seals and to understand scaling issues.
- Power loss of the 8.5 inch foil seal increases with speed and pressure differential and is about 50 percent higher than brush or finger seals at 900 fps and 75 psid.
- The foil seal was successfully tested at speeds to 25,000 rpm which corresponds to a DN of 5.4 million, surpassing previous maximum DN demonstrations of foil bearing technology.
- The damage to the seal was likely caused by a loss of clearance due to centrifugal growth of the rotor and fatigue failure of the coating, which initiated a thermal runaway condition.
- Rotor coating selection and application needs a redesign.
- A good understanding of the seal operating environment and operating limits is paramount to success.

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Self-explanatory.