DEVELOPMENT OF ABRADABLE AND RUB TOLERANT SEAL MATERIALS FOR APPLICATION IN CENTRIFUGAL COMPRESSORS AND STEAM TURBINES

by

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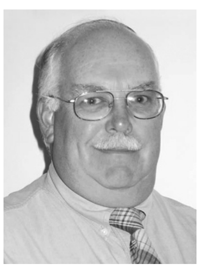
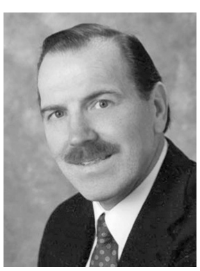


Michael S. Walker is a Senior Materials Engineering Technician with Elliott Company, in Jeannette, Pennsylvania. For the past 28 years he has been involved with the selection evaluation and testing of nonmetallic materials and organic and inorganic surface coatings for turbomachinery. He has been awarded one patent.



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ABSTRACT

The use of abradable and rub tolerant polymer seals to reduce leakage between rotating and stationary members in centrifugal compressors and steam turbines has increased over the years. Abradable materials such as mica-filled tetrafluoroethylene (TFE), nickel graphite, and aluminum alloy containing silicon/polyester are the most commonly used and have gained acceptance in the marketplace. This paper highlights the development of a new abradable silicon rubber adhesively bonded to a metal substrate. The abradability of the material was found to be excellent with no damage to the rotating member. For rub tolerant polymer seals little data are available on the effects of an aggressive rub with relation to deflection and wear at various temperatures. A series of tests was done on labyrinth seals manufactured from various forms of carbon filled polyetheretherketone (PEEK) and a polyamideimide (PAI). These tests evaluated their mechanical performance at low temperatures, room temperatures, and high temperatures. The results of the tests indicated that at room temperature and low temperatures, the seals exhibited acceptable deflection properties without damage to the rotating shaft and minimal material loss from the labyrinth teeth. However, at higher temperatures of 150°F, the PAI material had greater deflection values than the two types of PEEK, which resulted in the PAI exhibiting greater tooth height loss compared to the PEEK materials. For steam turbines, nickel chrome and nickel graphite were tested in a steam turbine and results are highlighted. This paper also shows the efficiency improvement for applying abradable seals to centrifugal compressors and steam turbines.

INTRODUCTION

In today's turbomachinery business great emphasis is placed on improving the efficiency of the rotating equipment. Efficiency improvements lead to energy savings, which has become one of the important factors in today's marketplace. One way of accomplishing an efficiency improvement is by reducing or eliminating gas leakages. Since clearances effectively control the gas leakages between rotating and nonrotating components, the application of abradables, rub tolerant, and honeycomb seals have found great attention in application for compressor and steam turbines. This paper will review the three types of seals and discuss their application in both centrifugal compressor and steam turbines. The three types of seals are:

- Abradable seals
- Rub tolerant seals
- Honeycomb seals

ABRADABLE SEALS

The use of abradable seals is one way of accomplishing reduced clearances and limits the risk of damage to the rotating/stationary member if a rub occurs. The concept of abradable seal was first used in aircraft engines. However, over the years, the use of abradable seals has become more common in centrifugal compressors and steam turbines. The abradable seals that are most common in centrifugal compressors are mica-filled tetrafluoroethylene (TFE), nickel graphite (oxygen fuel gun sprayed), and plasma sprayed aluminum alloy containing silicon/polyester resin. Dowson, et al. (1991), presented a paper on abradable seal materials where the basic concept for abradable seals in centrifugal compressor application was highlighted.

In conventional seal application the stationary static aluminum labyrinth contracts the gas as it flows through the close clearance gaps under the teeth and then expanding it between the teeth. This repeated contraction and expansion reduces the flow of the gas and lowers its flow rate. Leakage through the seal is proportional to the clearance (Figure 1). For an abradable seal, the labyrinth teeth are now on the rotating component and the smooth abradable seal is the stationary component (Figure 2).

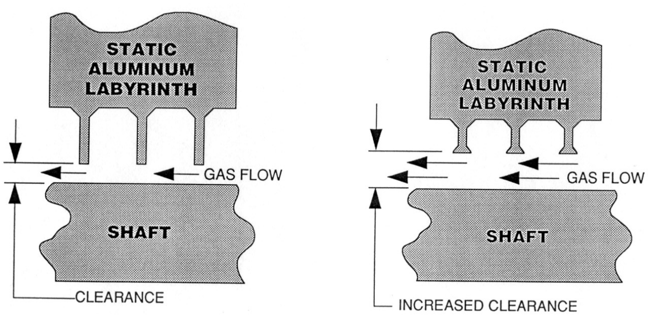

Figure 1. Conventional Seals Before and After Rub.

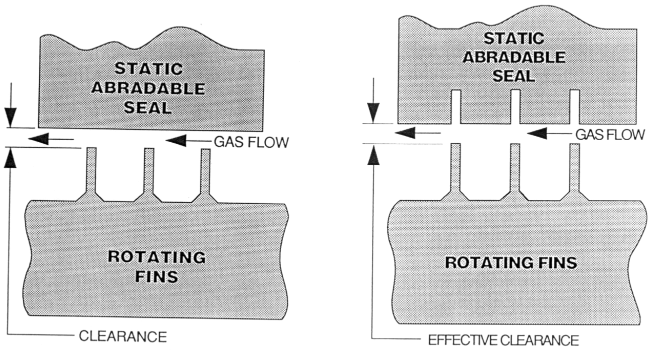

Figure 2. Abradable Seals Before and After Rub.

In the case of the abradable seal much tighter clearances can be achieved, since if contact should occur between rotor and seal, the rotating teeth will cut into the seal and remove the abradable material leaving grooved markings where contact had been made. In new designs, the rotating teeth are an integral part of the impeller (Figure 3) for both shaft and impeller eye seals.

Another application for abradable seals in centrifugal compressors is in the balance piston. This component is used to balance the axial thrust of the rotor so that the size of the thrust bearing can be reduced. The balance piston (Figure 4) rotates with the shaft, and, if contact does occur with the abradable seal, negligible effect will result. Compared to a nonabradable material, contact can lead to

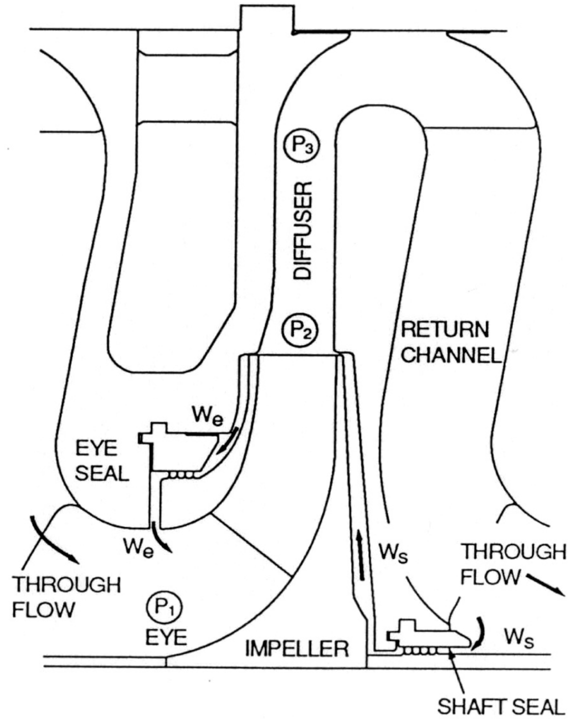

Figure 3. Centrifugal Compressor Abradable Seal Locations (A).

serious consequences for the compressor where the labyrinth teeth could be damaged leading to increased leakage. This would lead to a pressure drop causing an unbalance, which in turn would increase the loading on the thrust bearing. The benefit of applying these abradable seals is shown in Table 1.

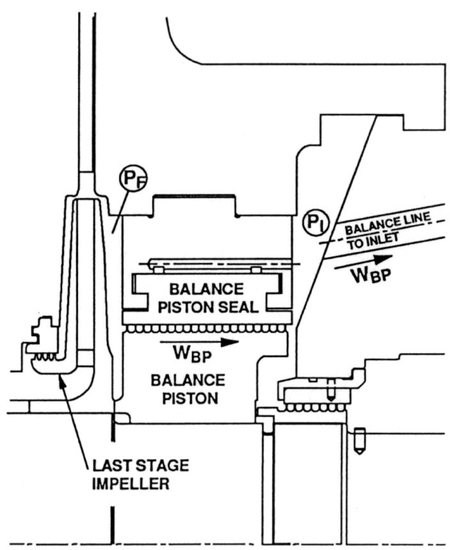

Figure 4. Centrifugal Compressor Abradable Seal Locations (B).

Table 1. Benefit of Applying Abradable Seals.

Inlet Flow (ICFM)	Impeller Eye and Shaft Seal Clearance Reduction (%)	Stage Efficiency Gain (%)
1000	24	1.1 – 2.4
10000	21 – 22	0.6 – 1.5
100000	20 - 21	0.3 – 1.1
Inlet Flow (ICFM)	Balance Piston Seal Clearance Reduction (%)	Total Efficiency Gain Stage & Bal. Piston (%)
1000	33	5.9
10000	33	1.5
100000	36	0.9

Selection of abradable material for application in centrifugal compressors is very important. There are a number of property factors that need to be considered when selecting the abradable material.

• *Abradability and erosion resistance*—In the paper presented by Dowson, et al. (1991), abradable material mica-filled TFE, nickel graphite, and silicon rubber were found to have good to very good abradability. The abradable silicon aluminum polyester, although not as good as those abradables stated previously, did perform well at lower rates of interaction and higher rubbing velocities. The authors' company has applied the silicon aluminum polyester abradable material in various centrifugal compressor applications with great success. Also since the 1991 paper, nickel graphite abradable seals have been used extensively in various applications for centrifugal compressors. However, to achieve optimum abradability and erosion resistance, special control of the hardness needs to be achieved. In the early years of manufacture of these seals, it was found that high heat input spray processes such as plasma could reduce the percent graphite in the coating and thereby reduce the abradability. During testing of an abradable nickel graphite seal the labyrinth rotating teeth were found to gall with the seal causing excessive damage to the impeller seal eye location (Figure 5).

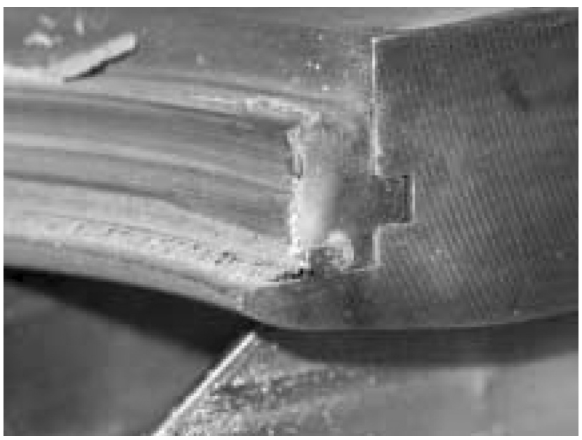

Figure 5. Damage to Nickel Graphite Impeller Seal.

• *Compatibility of the abradable material with the gas*—The mica-filled TFE is generally impervious to corrosive attack from most gaseous mixtures and would be acceptable with all hydrocarbon gases, sour natural gas, and chlorine gaseous conditions. However, for wet gaseous conditions (water > 2 percent) certain design considerations must be addressed to account for water absorption leading to possible swelling of the seal during service. The aluminum silicone abradables would operate under the same gaseous conditions that are generally applied to conventional aluminum seals. Exposed to extreme sour natural gases and chlorine gaseous conditions, these materials would be attacked severely. The nickel graphite coating could be used for all hydrocarbon gases and most sour natural gases. However, for hydrocarbon gases that contain large quantities of carbon monoxide (CO), a reaction can occur between the base coat of nickel (Ni) and CO leading to delamination of the nickel graphite abradable seal as shown in Figure 6.

• *Temperature limits of the abradable material*—The temperature limits for the various abradables are shown in Table 2.

• *Coefficient of thermal expansion of the material*—When designing seals, the coefficient of thermal expansion of the material must be taken into account at the design. The mica-filled TFE material has a coefficient well above that of steel and, therefore, dimensional changes due to temperature must be calculated in the overall design of the compressor. However, since the sprayed abradables are only 0.1 inch thick bonded to a metallic substrate, the coefficient of the substrate would apply for design purposes. For silicon rubber abradable material, the material is flexible/soft and will deform elastically to accommodate any thermal strains caused by the substrate.

Figure 6. Delamination of Nickel Graphite Seal Due to Reaction of CO with Ni.

Table 2. Temperature Limits.

Temperature Limits for Various Materials Temperature °F		
Abradable Material	Minimum	Maximum
Mica-filled Tetrafluoroethylene	-150	350
Nickel Graphite Blended Powder	-320	900
Aluminum Powder Alloy Containing Silicon and Polyester Resin	-320	650
Silicon Elastomer Containing Hollow Glass Microspheres	-100	500
Nickel Chromium Powder with Lucite Polymer	-320	1200

Recent Testing of Abradable Seal Materials

Further studies were done on testing of the silicon rubber to assess the self-erosion from wear debris in a simulated operating condition. The test trials done in Dowson, et al. (1991), allowed the wear debris to be easily disposed from the grooves. A new abradable material silicon rubber adhesively bonded to a metal substrate was tested in a seal rig and the abradability of the material was observed together with the effect of wear on both the stationary abradable material and the rotating labyrinth teeth. Also monitored was the vibration characteristic at various speeds of 1000 rpm through 11,000 rpm. These test runs were done one with no unbalance, one with a 1/4 g unbalance, and the third run with an unbalance of 3/4 g to give added rubbing. The best evaluation would be where rubs occur while trying to accelerate through the first critical as is done on the test floor.

On the first test run with no unbalance at slow speed (1000 rpm) there was an excursion where the rubbing probably occurred. Figure 7 shows a spectrum plot during this event where there is response at harmonics of speed. At critical speed near 8000 rpm

(Figure 8) amplitude was near 0.25 mils. Since the harmonics are low, additional rubbing probably did not occur. For the second test with a 1/4 g unbalance, there was only a small change in the first critical amplitude (Figure 9). A spectrum plot was done and at 190 Hz additional rubbing of the seal may have occurred (Figure 10).

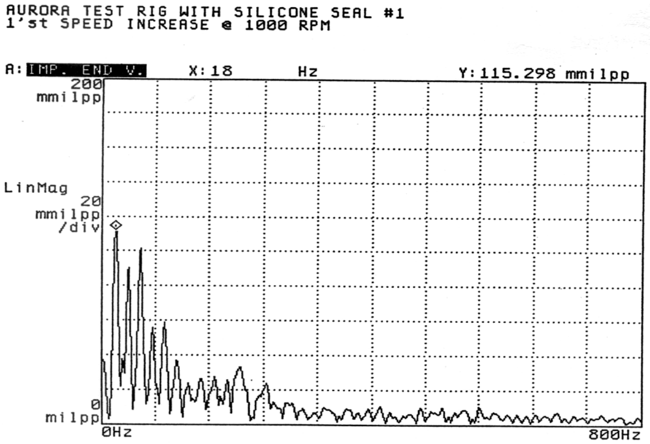

Figure 7. Spectrum Plot (A).

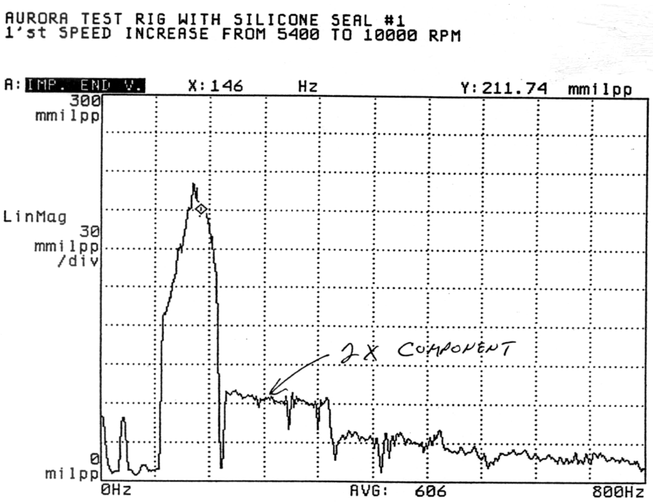

Figure 8. At Critical Speed 8000 RPM Amplitude Was 0.25 Mils.

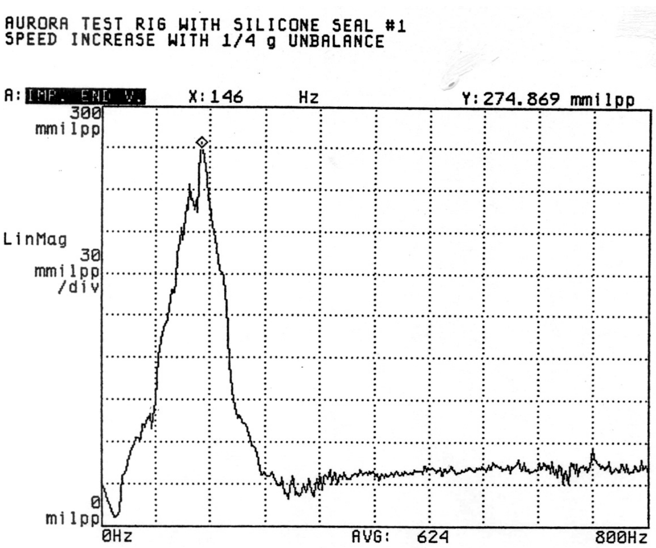

Figure 9. Small Change at First Critical.

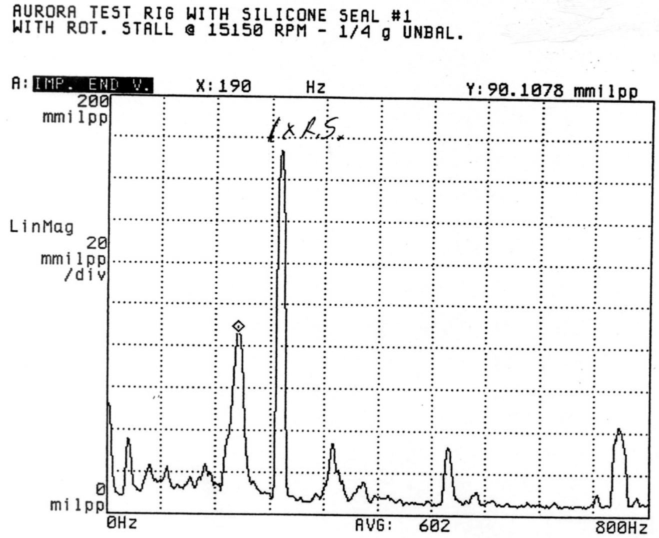

Figure 10. Spectrum Plot (B).

Earlier tests using the same rig were done where the rotor vibration was also low as shown in Figure 11 and indicating that the seal is not acting as a bearing. A third test run with a 3/4 g unbalance was tested in the test rig, and by accelerating through the first critical as is done on the test floor, one would expect to see additional rubbing. At low speed up to 3000 rpm there appears to be some initial rubbing since the seal was set with no bottom clearances. Amplitudes are very low with two instances of rubbing as shown in Figure 12. Increasing the speed up to 16,000 rpm, the amplitudes through the first critical speed between 6000 and 8000 rpm were not much higher than for the two runs of the first seal (Figure 13). Close to 16,000 rpm the amplitude is a little greater, 0.05 to 0.10 mils, due to the higher unintentional unbalance. A second rub was done on the seal up to a speed of 16,500 rpm (Figure 14). At low speeds of 1000 rpm the amplitude levels are small compared to the first run at the same low speeds. Since the seals have already been grooved, further grooving would be minimized. The test rig was run without the seals through the first critical to 9000 rpm to verify that the seals were not acting as bearings.

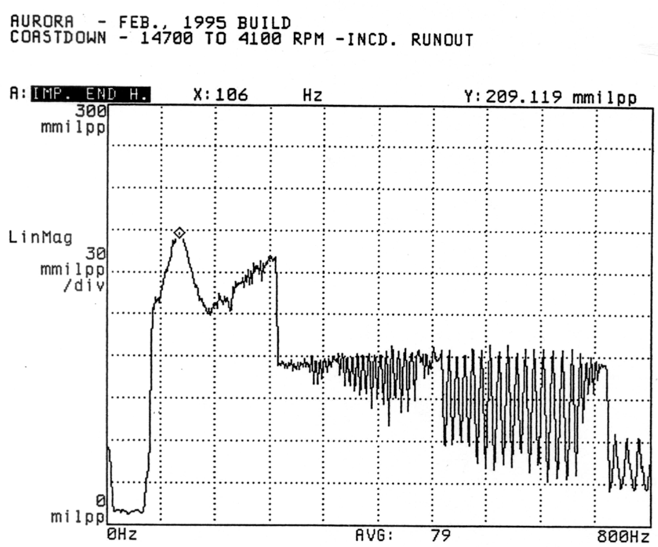

Figure 11. Rotor Vibration Low Seal Is Not Acting as Bearing.

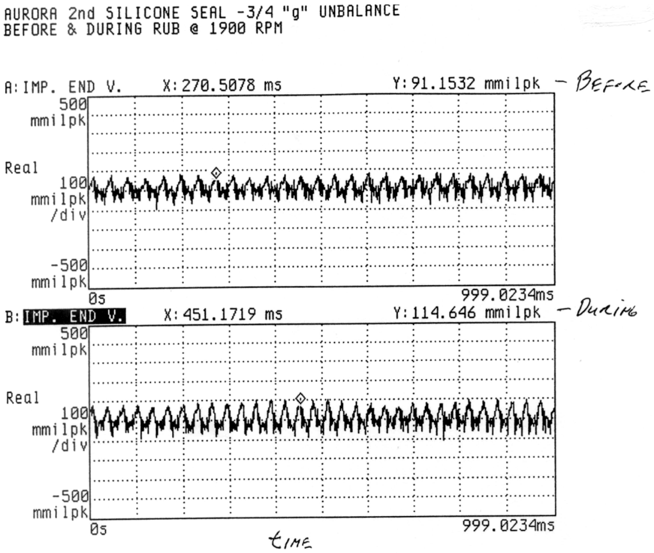

Figure 12. At Low Speed (3000 RPM) Amplitudes Are Low During Rub.

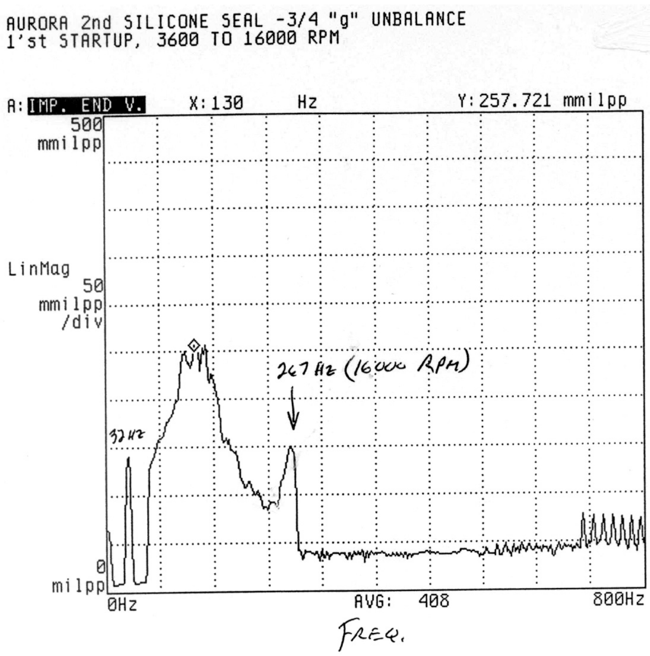

Figure 13. Amplitudes Through First Critical. (Similar to previous runs.)

Visual examination of the seals after each run was observed and the depths measured. Figures 15 and 16 show seals after runs of 1/4 g and 3/4 g. The depth of grooving for each run is given in Table 3. For all test runs, the silicon rubber seal was found to have good abradability and had no wear or heat damage on the labyrinth teeth. The adhesive bond between the seal and substrate was sound and showed no evidence of disbonding.

Steam Turbine Abradable Seals

Abradable seals can also be applied to steam turbines. Steam leakage at the gap between the stationary components and the turbine rotor can account for 25 to 30 percent of the total stage efficiency loss. The application of abradable materials to these labyrinth locations would permit tighter clearances and, therefore, reduced seal losses. The reduced seal losses could account for lower steam turbine throttle flow and, therefore, reduced operating costs for the end user. This would be especially true for noncondensing turbines as compared to condensing turbines (Dowson, et al., 1991). The benefits of applying these abradable seals are shown in Table 4.

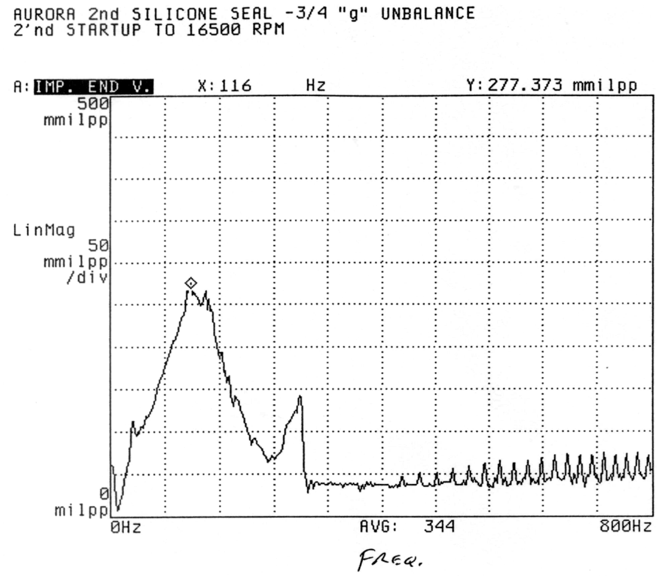

Figure 14. Response of Rub Up to Speed of 16,500 RPM.

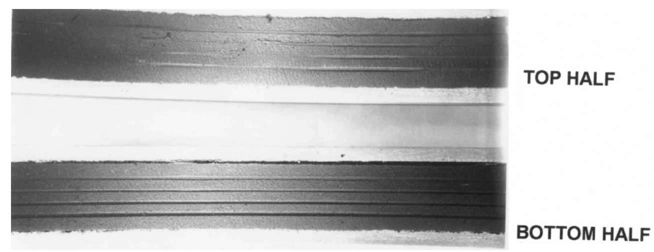

Figure 15. Condition of Seals after Run of 1/4 g Unbalance.

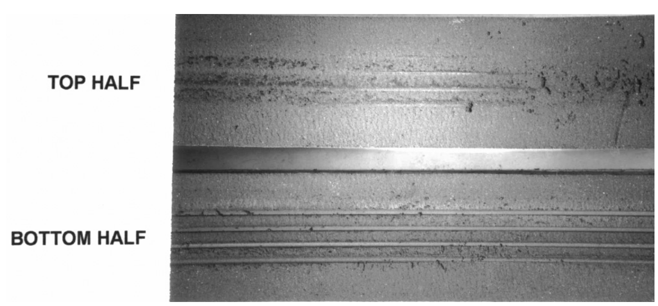

Figure 16. Condition of Seal after Rub of 3/4 g Unbalance.

Table 3. Depth Maximum of Grooving.

	Groove Depth
Configuration A	
First Run ¼ g Unbalance	0.030 inch
Second Run ¾ g Unbalance	0.050 inch
Configuration B	
First Run ¼ g Unbalance	0.010 inch
Second Run ¾ g Unbalance	0.030 inch

Table 4. Steam Turbine Abradable Seal Benefits.

Turbine	Seal Clearance Reduction (%)			Efficiency Gain (%)
	Shaft End	Diaphragm Bore	Blade Tip	
Condensing	43-76	31-39	50	0.3 – 0.5
Non-Condensing				
Single-Valve	81	68	50	1.0 – 2.1
Multi-Valve	81	68	50	2.2 – 2.4

To evaluate the abradability and performance of abradable seals in a steam turbine operating at 520°F inlet temperature, nickel graphite, and Ni chrome abradable packing case seals were incorporated in a steam turbine and tested (Figure 17). After various lengths of runs for up to one month, the seals were examined to evaluate their wear and steam effect.

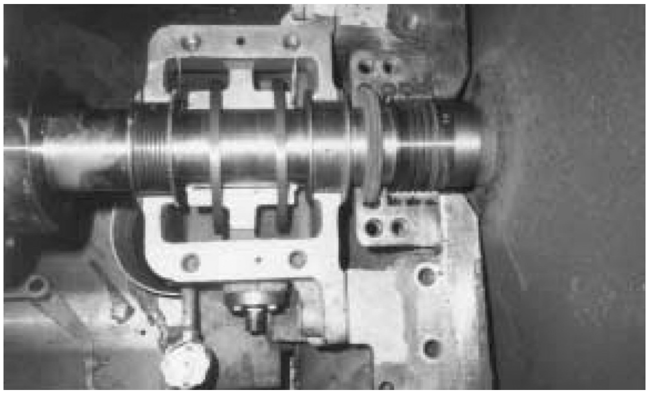

Figure 17. Steam Turbine Test Rig.

Figure 18 shows the condition of the nickel chrome lucite packing case seals prior to run and Figure 19 shows the condition of the nickel graphite packing case seals. During initial run of the steam turbine, contact was made with the seals as the packing case teeth abraded into both seals. After 48 hours the seals were removed for visual examination to determine the wear and the effect of the steam. Both the nickel chrome lucite (Figure 20) and the nickel graphite (Figure 21) showed good abradability after 48 hours of operation. The effect of the steam was minimal. The nickel graphite showed better abradability than the nickel chrome lucite due to the nickel graphite being more suitable for the lower steam temperature. The nickel chrome lucite would be more suitable for higher temperature in excess of 800°F.

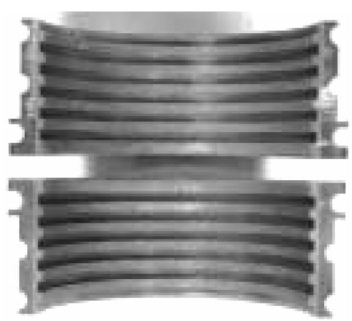

Figure 18. Nickel Chrome Lucite Packing Case Seals Prior to Run.

Figure 19. Nickel Graphite Packing Case Seals Prior to Run.

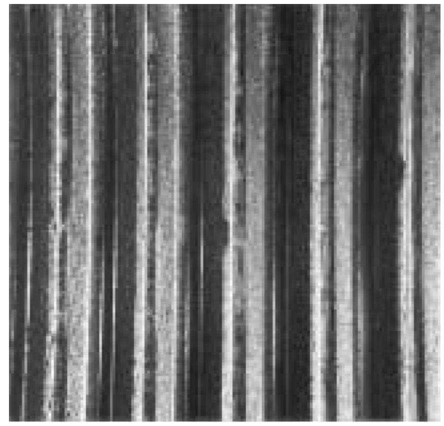

Figure 20. Nickel Chrome Lucite Packing Case Seals after 48 Hour Run.

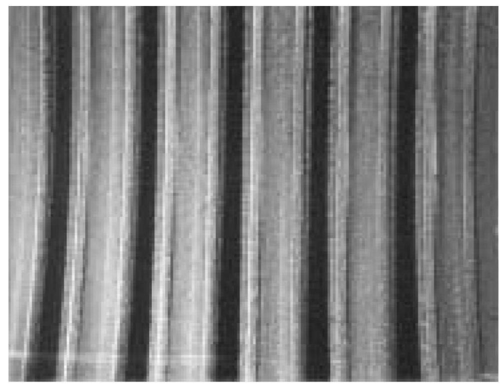

Figure 21. Nickel Graphite Packing Case Seals after 48 Hour Run.

Overall, both abradable seal materials operated satisfactorily and showed acceptable abradability.

RUB TOLERANT POLYMER SEALS

Rub tolerant labyrinth polymer seals are seals with reduced clearances and, if contact is made between the stationary seal and smooth rotating member, the stationary teeth will deflect during contact without wear or damage to the rotor or seals.

The rub tolerant plastic seals that are used in centrifugal compressors today are the new thermoplastics, which have better resistance to elevated temperatures. The thermoplastics matrix materials are tougher and offer the potential of improved hot/wet resistance.

Because of their high strains to failure, they are the only matrixes that offer the new intermediate modulus, high strength (and strain) carbon fiber to use their full strain potential in the composite. These materials include such resins as polyetheretherketone (PEEK), which is intended to maintain thermoplastic character in the final composite. Others, such as polyamideimide (PAI), which is originally molded as a thermoplastic and is then postcured in the final composite to produce partial thermosetting characteristics. The partial thermosetting characteristic of the PAI enables an improved subsequent temperature resistance (*Engineered Materials Handbook: Composites*, 1987).

When considering thermoplastic materials in rotating equipment, one has to understand their thermal properties (Table 5). The two thermoplastic materials used exclusively as labyrinth seals in centrifugal compressors are PEEK with additives and PAI. For the PEEK materials as labyrinth seals the temperature limit is dependant on the glass transition temperatures T_g of the material. Addition of additives such as chopped or continuous-wound carbon fibers or graphite powder or PTFE will not increase the T_g

of the material. The T_g is the temperature at which the crystalline polymer changes to a viscous or rubbery condition. In other words, the material has a dramatic change in properties. Generally, for labyrinth seals from PEEK material, the operation temperature is limited to 290°F.

Table 5. Properties of Thermoplastics.

Material	Tg °F	T in °F	Tensile Strength ksi	Fracture Toughness G_{IC} ft-lbf/ft^2
PAI	530 (275°C)		28	70
PEEK	290 (143°C)	650 (343°C)	--	110

For PAI materials, since the material is partial crystalline in character with some amorphous features, the T_g of the material is higher. However, when the crystalline character of the polymer is decreased, its resistance to solvents and water decreases also. The higher the degree of crystallinity, the higher the modulus and the higher the resistance to solvents and water. In the case of PAI careful consideration must be given to attack from amines, ammonia, oxidizing acids, and stray bases. Due to its partial crystallinity in character, PAI is prone to moisture absorption. Due to the moisture absorption, dimensional changes can occur that need to be addressed at the design stage and in manufacturing/storage. Generally, thermoplastic resin suppliers provide some information on water absorption after a 24 hour immersion in water. A more severe test is the 24 hour boiling water test.

Due to the high thermal expansion coefficient of both the PEEK and PAI materials, accurate calculations of the growth of the seals with respect to the diaphragms and rotating components need to be done to enable one to calculate the clearances.

Also, in the manufacture processing of PAI or PEEK into a tubular form, there exists a size limitation for polymer labyrinth seals.

- *PAI*—In tubular bulk form the size limitation is 35 inches. However, larger sizes can be constructed up to 45 inches by segmenting the seals.
- *PEEK with chopped carbon fibers*—Generally supplied in molded bulk form with a size limitation of 30 inches.
- *PEEK with 68 percent continuous-wound carbon fiber*—Generally supplied in a tubular form and there is no size limitation.

Recent Development and Testing of
Rub Tolerant Labyrinth Polymer Seals

To evaluate the rub tolerant behavior of the polymer labyrinth seals various tests were performed. These tests were performed on various polymer materials, such as PAI in tubular bulk form, PEEK with chopped carbon fiber (molded bulk form), and PEEK with 68 percent continuous-wound carbon fiber in tubular form. The tests consisted of evaluating the deflection properties of the polymer seals at room temperature, low temperature, and elevated temperature. Also evaluated was the effect of tooth design on the rub tolerant characteristic of the seal and its manufacturability. The final test was running the labyrinth polymer seals in a test rig at ambient temperature, elevated temperature (150°F), and low temperature (−50°F). The test rig consisted of a horizontal lathe where the labyrinth seal was contained in an axial fixed holder that could traverse radially. A rotating member containing a collar acted as the rotating shaft. During the shaft rotation the axial fixed holder traverses into the shaft at various degrees of contact interaction. The results of each rub are recorded together with physical changes of both the stationary polymer seal and rotating member. Also recorded were visual coloration changes on the shaft as well as damage to the polymer seals.

The rotating shaft was coated with bluing prior to each test run. This enabled one to observe relative deflection of the angular teeth of the seal and assured that all the teeth made contact with the rotating shaft. Once contact was established with the shaft, the seal holder was traversed into the rotating member at 0.005 inch intervals up to 0.025 +0.002/−0.000. The results of the test runs indicated that the radial interference remained constant but the width of the bluing groove varied with each material indicating a variation in deflection properties.

For the room temperature and subzero tests (Tables 6 and 7), there is a correlation between the bluing width and wear rate. The wider the bluing groove, the higher the wear rate (i.e., loss of tooth height). In all test runs the PAI material had the highest deflection or bending of the teeth and also had the greatest material loss. In the elevated temperature tests (Table 8), it is important to note that there was no significant change in the bluing width (i.e., tooth deflection) for any of the materials, but there was a significant increase in material wear in comparison to the room temperature and subzero test runs.

Table 6. Plastic Seal Rub Test Room Temperature (May 1999).

Date	07-May-99	07-May-99	07-May-99	07-May-99	07-May-99	07-May-99
Rotor Speed -rpm	800	800	800	800	800	800
Nominal Seal Bore - In.	10.000	10.000	10.000	10.000	10.000	10.000
Material	PAI*	PAI*	CC-PEEK*	CC-PEEK*	CW-PEEK*	CW-PEEK*
Tooth Height - In.	0.125	0.125	0.125	0.125	0.125	0.125
Tooth Angle - Degrees	10	10	10	10	10	10
Initial Material Temperature - Deg. F	75	75	75	75	75	75
Initial Tooth Dim. - In.	0.5990	0.5980	0.5980	0.5985	0.5960	0.5980
Final Tooth Dim. - In.	0.5962	0.5950	0.5980	0.5980	0.5955	0.5970
Wear - Mils	2.8	3.0	0.0	0.5	0.5	1.0
Bluing Groove Width - In.	0.094	0.125	0.053	0.055	0.0625	0.0625
Tooth Radial Deflection - In.	0.026	0.025	0.025	0.027	0.025	0.025

* PAI (Polyamideimide)
* CC-PEEK (Polyetheretherketone with Chopped Carbon Fibers)
* CW-PEEK (Polyetheretherketone with Carbon Wound Fibers)

Table 7. Plastic Seal Rub Test Cold.

Date	17-Jun-99	17-Jun-99	17-Jun-99	17-Jun-99	17-Jun-99	17-Jun-99
Rotor Speed -rpm	800	800	800	800	800	800
Nominal Seal Bore - In.	10.000	10.000	10.000	10.000	10.000	10.000
Material	PAI*	PAI*	CC-PEEK*	CC-PEEK*	CW-PEEK*	CW-PEEK*
Tooth Height - In.	0.125	0.125	0.125	0.125	0.125	0.125
Tooth Angle - Degrees	10	10	10	10	10	10
Initial Material Temperature – Deg .F	-52	-69	-47	-45	-38	-45
Initial Tooth Dim. - In.	0.5980	0.5990	0.5990	0.5995	0.5920	0.5905
Final Tooth Dim. - In.	0.5975	0.5950	0.5990	0.5992	0.5920	0.5895
Wear - Mils	0.5	4.0	0.0	0.3	0.0	1.0
Bluing Groove Width - In.	0.088	0.125	0.031	0.063	0.056	0.063
Tooth Radial Deflection - In.	0.025	0.025	0.025	0.025	0.025	0.025

* PAI (Polyamideimide)
* CC-PEEK (Polyetheretherketone with Chopped Carbon Fibers)
* CW-PEEK (Polyetheretherketone with Carbon Wound Fibers)

Table 8. Plastic Seal Rub Test Hot.

Date	08-May-00	08-May-00	08-May-00	08-May-00	17-Jun-99	17-Jun-99
Rotor Speed -rpm	800	800	800	800	800	800
Nominal Seal Bore - In.	10.000	10.000	10.000	10.000	10.000	10.000
Material	PAI*	PAI*	CC-PEEK*	CC-PEEK*	CW-PEEK*	CW-PEEK*
Tooth Height - In.	0.125	0.125	0.125	0.125	0.125	0.125
Tooth Angle - Degrees	10	10	10	10	10	10
Initial Material Temperature - Deg. F	165	165	165	165	145	155
Initial Tooth Dim. - In.	0.6010	0.5990	0.5995	0.6025	0.5995	0.5945
Final Tooth Dim. - In.	0.5900	0.5890	0.5980	0.5995	0.5975	0.5915
Wear - Mils	11.0	10.0	1.5	3.0	2.0	3.0
Bluing Groove Width - In.	0.094	0.088	0.078	0.085	0.047	0.041
Tooth Radial Deflection - In.	0.025	0.025	0.025	0.025	0.026	0.025

* PAI (Polyamideimide)
* CC-PEEK (Polyetheretherketone with Chopped Carbon Fibers)
* CW-PEEK (Polyetheretherketone with Carbon Wound Fibers)

Referring to Table 9, a single run of all three seal materials was performed at room temperature. The difference between this test and the previous ones is that the tooth angle was changed from 10 to 40 degrees. The PAI and carbon wound PEEK incurred significant wear with this increase in tooth angle, whereas the chopped carbon filled PEEK had only a slightly higher wear rate than the tests run with the 10 degree angle.

From the test results, the 10 degree angular tooth design for all three types of seal material exhibited acceptable deflection

Table 9. Plastic Seal Rub Test Room Temperature (May 2000).

Date	08-May-00	08-May-00	08-May-00
Rotor Speed -rpm	800	800	800
Nominal Seal Bore - In.	10.000	10.000	10.000
Material	PAI*	CC-PEEK*	CW-PEEK*
Tooth Height - In.	0.125	0.125	0.125
Tooth Angle - Degrees	40	40	40
Material Temperature - Deg. F	75	75	75
Initial Tooth Dim. - In.	0.5990	0.5990	0.6010
Final Tooth Dim. - In.	0.5870	0.5980	0.5930
Wear - Mils	12.0	1.0	8.0
Bluing Groove Width - In.	0.108	0.084	0.11
Tooth Radial Deflection - In.	0.025	0.025	0.025

* PAI (Polyamideimide)
* CC-PEEK (Polyetheretherketone with Chopped Carbon Fibers)
* CW-PEEK (Polyetheretherketone with Carbon Wound Fibers)

properties without damage to the rotating shaft or cracking of the laby teeth. However, the PAI had greater deflection values than the two types of PEEK, which resulted in the PAI exhibiting greater tooth height loss compared to the PEEK materials, especially at the elevated temperatures. This tooth height loss for the PAI material at elevated temperatures was in excess of 10 mils, which would result in excessive leakage.

Test results of the 40 degree tooth angle at room temperature indicate that there is a negative effect on wear rates for all three materials. This design was also more expensive and difficult to machine.

HONEYCOMB SEALS

The use of honeycomb seals to stabilize rotors in high pressure compressors has been known for a number of years. Generally labyrinth seals have been replaced by honeycomb seals when rotordynamic instability problems have occurred in high pressure compressors. The gas flow through the labyrinth can create a circumferential flow predominately away from the entrance of the seal. The circumferential flow is the cause of higher cross coupling that can lead to instability of the rotor. Honeycombs have very low cross coupling and higher direct damping. In other words, the honeycomb acts as a third bearing.

Most honeycomb seals are designed from either stainless steel or aluminum honeycombs. In this paper two new materials are being evaluated as rub tolerant honeycomb seals. The first is a polymer PEEK material and the other is a silicone rubber material. For both cases since the cavities in the materials are not honeycomb in shape these seals will be called rub tolerant cellular seals. The cellular structure is manufactured by a special process that is in the patent process. The cellular structure consists of 0.050 inch diameter cells with a wall thickness of .005 inch. In this process the cells can be varied to any depth/diameter or random selected alternative depths. The cost of utilizing this process is less than that of the stainless steel honeycomb, which has to be brazed into the substrate. Figure 22 gives an indication of the cellular structure. Both these seals will be tested in a gas seal test stand as shown in Figure 23. At the time of writing this paper, the seals have not yet been tested. Results of the tests when complete will be presented at the Turbomachinery Symposium.

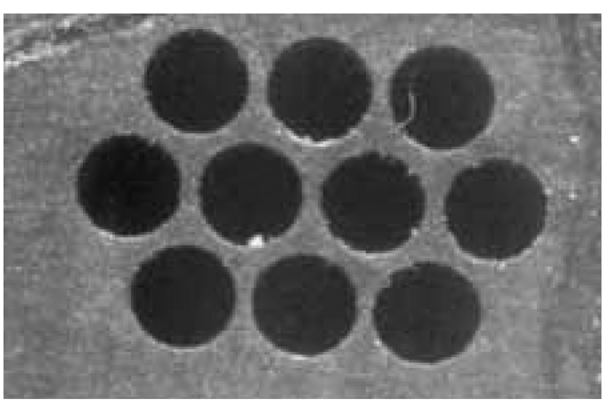

Figure 22. Cellular Structure.

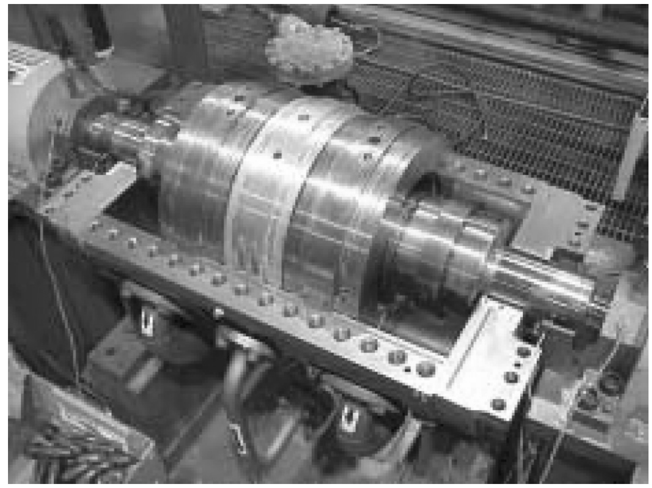

Figure 23. Gas Seal Test Stand.

CONCLUSIONS

- Abradable seals have been used successfully in centrifugal compressors for reducing clearances and improving the efficiency of compressors. The author's company has applied abradable material such as Ni graphite, aluminum silicon polyesters, and fluorosint to numerous labyrinth seal applications with great success. The testing of the abradable seal (silicon rubber) showed a lot of promise as a labyrinth abradable seal.

- Careful consideration must be applied to ensure that rub tolerant polymer seals can be utilized in centrifugal compressor labyrinths. The tests that were done at the authors' company indicated that the PAI material for labyrinth seals may not be suitable for temperatures greater than 100°F using similar clearances to that of abradables. The PAI material at a temperature of 150°F was found to wear dramatically when it came into contact with the rotating member. Other polymer materials, such as PEEK or carbon wound PEEK, may be more suitable.

REFERENCES

Dowson, P., Ross, S. L., and Schuster, C., 1991, "The Investigation of Suitability of Abradable Seal Materials for Application in Centrifugal Compressors and Steam Turbines," *Proceedings of the Twentieth Turbomachinery Symposium*, Turbomachinery Laboratory, Texas A&M University, College Station, Texas, pp. 77-90.

Engineered Materials Handbook: Composites, Volume 1, 1987, T. J. Reinhart, Materials Park, Ohio: ASM International.