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High Temperature Braided Rope Seals for Static Sealing Applications

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Abstract

Achieving efficiency and performance goals of advanced aircraft and industrial systems is leading designers to implement high temperature materials such as ceramics and intermetallics. Generally these advanced materials are applied selectively in the highest temperature sections of the engine system including the combustor and high pressure turbine, amongst others. Thermal strains that result in attaching the low expansion-rate components to high expansion-rate superalloy structures can cause significant life reduction in the components. Seals are being designed to both seal and to serve as compliant mounts allowing for relative thermal growths between high temperature but brittle primary structures and the surrounding support structures.

Designers require high temperature, low-leakage, compliant seals to mitigate thermal stresses and control parasitic and cooling airflow between structures. NASA is developing high temperature braided rope seals in a variety of configurations to help solve these problems. This paper will describe the types of seals being developed, describe unique test techniques used to assess seal performance, and present leakage flow data under representative pressure, temperature and scrubbing conditions. Feasibility of the

braided rope seals for both an industrial tube seal and a turbine vane seal application is also demonstrated.

Introduction

Aircraft engine turbine inlet temperatures and industrial system temperatures continue to climb to meet aggressive cycle thermal efficiency goals. Advanced material systems including monolithic/composite ceramics, intermetallic alloys (i.e. nickel aluminide), and carbon-carbon composites are being explored to meet aggressive temperature, durability, and weight requirements. Incorporating these materials in the high temperature locations in the system, designers must overcome materials issues such as differences in thermal expansion rates and lack of material ductility.

As will be discussed in this report, designers are finding that one way to avoid cracking and buckling of the high temperature brittle components rigidly mounted in their support structures is to allow relative motion between the primary and supporting components. Often this joint occurs in a location where differential pressures exist requiring high temperature seals. These seals or packings must exhibit the following important properties: operate

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hot (>1300 °F); exhibit low leakage; resist mechanical scrubbing caused by differential thermal growth and acoustic loads; seal complex geometries; retain resilience after cycling; and support structural loads.

Background. Rope packings can be traced back to the early days of the industrial revolution to seal stuffing boxes and valves to prevent excessive leakage. An excellent summary of types of rope seal packings is given in Mathews and McKillop¹. As engine temperatures have continued to rise novel adaptation of these seal packings were required to meet modern turbine engine and hypersonic engine requirements. NASA embarked on a program to develop high temperature (≥ 1500 °F), high pressure (up to 100 psi), flexible seals to meet aggressive sealing goals of ramjet/scramjet engines considered for future hypersonic vehicles (e.g. the National Aerospace Plane, NASP). The braided all-ceramic and hybrid seals were developed to operate hot, maintain resiliency and resist scrubbing damage over the life of the hypersonic engines. Steinetz et al.² reports on the durability and flow resistance of both seals at temperatures up to 1500 °F. The all-ceramic seal survived about half- and the hybrid braided rope seal survived the full-sliding duty cycle anticipated for the hypersonic engine. The duty cycle in these earlier applications far exceeded those required herein. Models for predicting leakage flow through these porous structures are reported in Cai et al.^{3,4} and Mutharasan et al.⁵

The feasibility of applying braided rope seals for both an industrial and turbine vane seal application was investigated in this study:

Industrial Tube Seal. In the industrial tube seal application, a seal is designed to serve as a seal and a compliant mount allowing relative thermal growth between the high temperature, low-expansion rate primary structure and a higher expansion rate structural support preventing excessive thermal strains and stresses. Two seals were examined for this study. The first all-ceramic seal consists of a tightly packed ceramic core overbraided with a ceramic sheath for low-leakage, low scrubbing environments. The second hybrid seal consists of a tightly packed ceramic core overbraided with a superalloy wire sheath, and was tested as an abrasion-resistant alternative.

Turbine Vane Seal. Designers are pursuing advanced material systems to meet high rotor inlet temperatures and minimize cooling requirements. Nickel aluminide (NiAl) is an attractive material system for high temperature engine structural applications.⁶ Key advantages over conventional superalloys include: low density 5.95 g/cm^3 is approximately two-thirds that of superalloys; high temperature oxidation resistance; high melting point—approximately 400 °F higher than conventional

nickel-based superalloys; very high thermal conductivity—approximately 3 to 8 times that of conventional superalloy materials. Because of the higher conductivity the temperature distribution in a NiAl turbine blade is more uniform, and the life-limiting “hot-spot” temperatures are reduced by as much as 100 °F. Constraining factors in applying NiAl are its limited fracture toughness ($5\text{-}8 \text{ MPa} \sqrt{\text{m}}$) and very low tensile ductility 0 to 2 percent (depending on composition and orientation) which are substantially less than conventional cast vane alloys. These material limitations require special design techniques to prevent thermal fracture and ensure a successful design.

Conventional turbine vanes are cast and furnace brazed to the inner and outer nozzle shrouds. It was discovered through early flame tests that brazed NiAl vanes could not withstand a sudden thermal shock. A more novel attachment technique, as discussed in this paper, was required to permit vane thermal expansion/contraction without fracture.

The objective of this study is to present ambient compression measurements and flow measurements under simulated pressures, temperatures and scrubbing conditions for small diameter (1/16" and 1/8") seals. Feasibility of the braided rope seals for both a turbine vane seal and an industrial tube seal application is also demonstrated.

Apparatus and Procedures

Flow Tests

Flow experiments were performed on braided rope seals in a high temperature flow and durability test rig, shown schematically in Fig. 1. Test seals of approximately 7.8 in. in length were mounted in the grooves of the piston, and the piston/seal assembly was inserted into the cylinder. The free ends of the seals were joined together in the groove by means of a short lap joint. Preload was applied to the seals through a known interference fit between the seal and the cylinder inner diameter. Preload was varied by mounting stainless steel shims in the piston groove under the seal. During flow testing, hot pressurized air entered at the base of the cylinder and flowed to the test seal that sealed the annulus created by the cylinder and piston walls. For all tests the piston-to-cylinder radial gap was 0.007 in. The Inconel X-750 test fixture is capable of testing seal flow and durability at temperatures between 70 and 1500 °F, pressures between 0 and 95 psig, and flows between 0 and 3.5 SCFM.

At high temperatures, the durability of the test seals was investigated by reciprocating the piston within the stationary cylinder. Piston stroke movements of 0.3 in. were used in these tests to simulate relative thermal growths anticipated. Movement of the piston is guided by preloaded precision linear bearings.

The rig is externally heated by two 1 kW ceramic fiber radiant heaters (Fig. 1). Both heaters are in the shape of a semi-cylindrical shell with the inside surfaces being heated. When clamped together, the ceramic fiber heaters form a continuous, radiating heating surface around the rig's cylinder and piston. Radiant heater temperatures were set about 70 °F above the required operating temperature to overcome radiant losses. The heaters, the cylinder and the piston are surrounded by 2 in. thick alumina board insulation in order to minimize heat losses.

Before the pressurized air enters the cylinder, it is heated by several electric resistance heaters. First, the air flows through a 1.15 kW primary air heater. Maximum sheath temperature of the air heater is 1650 °F, and the plumbing surrounding the heater is encased in rigid alumina insulation. The air supply tubing between the air heater and the cylinder is wrapped with three 1 kW flexible cable heaters. The cable heaters, capable of 1600 °F, are wrapped externally with flexible alumina insulation. The cable heater arrangement not only serves to eliminate heat loss through the plumbing downstream of the tubular heater, but if needed it can also boost the air supply temperature. All joints are certified as leak tight prior to a run.

During flow experiments, all temperature, pressure, and flow data were continuously monitored using a 486 PC with an analog-to-digital conversion board and commercially available data acquisition software (Labtech Notebook). The temperature and pressure of the hot flow gas were measured immediately upstream of the test seal (Fig. 1). Pressure was measured as the differential between the upstream flow pressure and atmospheric (ambient) pressure downstream of the test seal. The air mass flow through the seal was measured upstream of the air heaters where measurements could be taken at room temperature. Seal flow was collected before and after scrubbing (10 cycles of 0.3" linear stroke at 1300 °F) at temperatures of 70, 900, 1100, and 1300 °F, and at pressures of 2, 5, and 10 psid. Data was also collected for specific seal builds at higher differential air pressures of 20, 40, 60, 80 and 95 psid. Vane seal leakage tests were taken at ambient, 1300 °F and 1500 °F across the pressure range.

Thermal Growth

During data collection, special care was taken to monitor the relative thermal growth between the piston and the cylinder. The cylinder outer wall temperature and the piston inner wall temperature (the piston is hollow) were monitored, and flow data was collected only when the temperature differential between these surfaces was less than 40 °F. At operating conditions, a forty degree temperature differential results in no more than 0.0005 in. relative radial growth of the cylinder surface away from the piston surface.

Thermal growth differential also exists between the ceramic-based seal and the superalloy piston. As the piston circumferentially outgrows the seal, the seal ends move apart. In order to account for this, the seal free ends were joined together as a lap joint (Fig. 1). The lap joint prevents a free flow path from occurring. A lap joint of 3/32" length minimum was used to prevent joint opening and to mitigate the effects of 1/16" in relative piston-to-seal differential circumferential growth.

Compression Tests

Experiments were conducted in order to determine the preload behavior of seals with respect to the linear crush applied to the seals. Seal preload behavior was measured at room temperature during compressive loading using a compression/tension test fixture set up for compression only (see schematic, Fig. 2). Seals were loaded into the grooved seal holder. The amount of seal compression was measured using an LVDT monitoring the movement of the seal holder relative to a "zero" condition established with the top and bottom surfaces set in mating contact. Average compressive load (and hence preload) was calculated by dividing the measured compressive force during loading by the contact area left on the pressure sensitive film, explained below. The compressive loads in this revised manuscript are 2.5 times greater than the first printing of the paper. After the first printing, a load calibration error was detected and traced to a faulty amplifier. The compression loads (lb) and pressures (psi) herein are correct, and have been substantiated with a separate compression system.

A pressure sensitive film was mounted on the lower stationary plate such that the seal would contact only the film when the seal holder/moving plate assembly was moved into preload contact. The film color develops under compressive loading, therefore the seal leaves a "footprint" after it has been crushed against the stationary plate. The pressure sensitive film begins to develop color under compressive loads greater than or equal to 28 psi, and the shade of the developed film becomes darker as the load is increased. At seal contact pressures greater than or equal to 100 psi, the developed color is dark enough to reliably measure the dimensions of the contact area. Contact width was measured using a dial vernier caliper in several locations along the 4 in. long specimen length. Variations in contact width measurement were minimized by averaging multiple measurements.

A test procedure was developed using the compression testing fixture in order to accurately simulate the loading conditions in the flow test fixture. Preliminary compression experiments had revealed that the seals have a hysteresis, or nonrecoverable displacement after loading. Therefore accurate simulation of flow fixture conditions during compression testing was essential in order to determine preload.

In the flow fixture, a particular linear crush (equal to the seal and cylinder interference) is consistently applied to the seal specimen throughout a series of experiments. For a static condition, the seal will be acted upon by a compressive force, the preload force, that is normal to the cylinder and piston surfaces. Through successive or continuous loading, this preload force will drop as the seal settles into its final operating condition. In order to duplicate this during compression experiments, the seal was crushed with the compression test fixture to the same displacement (corresponding to a known interference) during each loading cycle. At this displacement, the normal force acting on the seal is considered the preload force.

Due to sliding conditions (installation and cycling) in the flow test fixture, both a normal and a frictional force are exerted on the seal causing the seal to settle in the groove. The friction force acts tangentially between the seal and the cylinder wall surfaces. Previous work with ceramic rope seals² indicated that the friction coefficient is generally large ($\mu = 0.6-1.0$), therefore both the normal and the friction force must be considered for accurate modeling of this additional loading of the seal. To accomplish this, a friction coefficient of $\mu = 1$ was chosen, and the magnitude of the vector sum of the preloading force and the frictional force was applied to the seal at the end of each displacement load cycle. This applied force equals the preloading force (measured at the known interference) multiplied by a factor of 1.4 (e.g. Force $\times \sqrt{2}$).

This loading procedure was repeated for at least three cycles in order to remove seal hysteresis. Preload was determined from the last (generally third) loading cycle after the majority of hysteresis had been removed. Using the last cycle compression data ensures that the seal will experience this preload after settling has occurred. This compression procedure was validated using “seal overhang” or “residual-interference” measurements collected in the flow fixture after the flow tests. After each test the amount that the seal extended radially out of the piston groove was measured. This measurement gages the seal’s compression-set or conversely the retained seal interference (e.g. preload) when loaded into the cylinder. The seal overhang data agreed to within 0.001 in. to that expected from the last cycle compression data.

Seal Specimens

Industrial Tube Seal Application

The all-ceramic rope seal was tested as the primary seal for the industrial tube seal application. The all-ceramic rope seal consists of a dense uniaxial core of ceramic fibers overbraided with a 2-layer ceramic sheath. These seals were selected for several reasons. The Nextel 550 fibers can operate to 2000 °F continuously (2200+ °F short term), are inert, and resist abrasion⁷ better than either the Nextel 312 or

440 fibers. Small, 8 μm Nextel 550 fibers were selected for both the core and the sheath to minimize leakage through the seal and between the sheath and adjacent surfaces. Table 1 gives details of the seal sheath and core construction and specific materials. A hybrid seal discussed below was also tested as an abrasion-resistant alternative.

Differential expansion between the industrial tube (low coefficient of thermal expansion) and seal holding fixture was estimated to be 0.3". Seal feasibility would be demonstrated if the seal flow was less than or equal to the flow goal (0.0064 SCFM/in. seal for a 2 psid pressure) and durability was acceptable after 10 cycles.

Turbine Vane Seal Application

For the turbine vane seal application, a hybrid seal was used consisting of a dense uniaxial core of Nextel 550 fibers overbraided with a single sheath layer composed of yarns made of 0.0016 in. (40 μm) Haynes 188 wires. Hybrid seals were selected for this application to resist scrubbing damage against a rough thermal barrier coating and to resist potential damage due to acoustic induced fretting at 1500+ °F. Fine diameter sheath wires were used to minimize sheath leakage.

The relative vane-to-seal thermal growth over one thermal cycle was estimated to be 0.04 in.. To ensure durability in the harsher engine environment, the same 10 cycles of 0.3 in. were used to examine durability of the vane seal at 1500 °F. Durability cycles were run at two linear compressions of 0.018 and 0.020 in., approximating the nominal 0.022 in. linear seal crush in the actual application. NASA room temperature compression tests revealed 0.018 in. and 0.020 in. linear compressions resulted in 500 and 675 psi seal contact pressures, respectively. Design calculations using GE seal compression data indicated that with pressure loads, the vane would move toward the suction side of the blade by 0.002 in. Depending on location around the vane perimeter, the seal would experience compressions of 0.020 in. (pressure side), 0.022 in. (centerline), or 0.024 in. (suction side).

Results and Discussion

Industrial Tube Seals

Flow Results

Primary and repeat flow tests were performed on 1/16 in. and 1/8 in. diameter all-ceramic seal specimens for preloads of 100, 110, 150, and 250 psi. Primary and repeat flow tests were performed on the 1/16 in. diameter hybrid seals for preloads of 150 and 250 psi. Table 2 summarizes all-ceramic seal and hybrid seal flow rates, and shows post-scrubbing (10 cycles of 0.3 in. scrubbing at 1300 °F) results for both primary and repeat tests for the 2 psid industrial tube seal pressure. Figures 3 to 5 present

flow vs pressure data for four temperatures (70, 900, 1100 and 1300 °F), after scrubbing (10 cycles of 0.3 in. scrubbing at 1300 °F), at 250 psi nominal preload. After each set of experiments, the piston was retracted and the seal sample examined, and the seal overhang was measured in order to verify the validity of the compression testing procedure. Flow results for the 1/16 in. and 1/8 in. all-ceramic seals exhibited good repeatability at preloads greater than or equal to 110 psi. Furthermore, flow rates for the all-ceramic seals decreased with increasing preload. The 1/16 in. diameter all-ceramic seal flow rates were less than the 1/8 in. diameter all-ceramic seal flow rates for the same preload conditions (Table 2). This observation may be attributed to a more uniform footprint between the 1/16 in. diameter seal and adjacent surfaces as evidenced in the compression tests discussed below.

The 1/16 in. hybrid seals exhibited good repeatability at 150 and 250 psi nominal preload. Hybrid seal flow decreased with increasing temperature at all preloads and for all temperature conditions.

Effect of Temperature. For all seals, the flow rates at elevated temperatures were significantly lower than flow rates at room temperature, with the exception of the 100 psi preload condition. Gas viscosity increases with temperature, which suggests that flow will decrease with temperature. However, in some instances for all-ceramic seals, flow did increase between the 900 and 1300 °F data sets. This behavior may be attributed to the thermal growth differential between the piston circumference and the seal length (the piston outgrows the seal circumferentially by approximately 1/16 in.). This relative motion of the seal ends away from each other at the lap joint may allow for increased leakage at the joint, even though an overlap joint of 3/32 in. was used. This effect is mitigated with increasing preload and may be eliminated if the thermal growth coefficients of the seal's housing and the seal are more similar. The trend of increasing flow with increasing temperature for the 100 psi preload condition may be due to leakage through the joint, as mentioned above. It is possible that with the lower preload the seal may slip easier in the groove, thus facilitating the opening of such a region in the joint.

Effect of Hot Scrubbing. Seal flow increased little after hot scrubbing for all preload conditions (Fig. 6). Sheath damage was generally minor for all cases as shown in Fig. 7, a close-up view of the lap joint of the 1/16 in. diameter all-ceramic seal 250 psi preload build. Away from the joint the sheath was intact and showed only minor fiber breakage. The initial 1/8 in. diameter all-ceramic seal (at 250 psi nominal preload) showed small localized sheath fraying (approximately 1/4 in. long at two locations). This initial 1/8 in. seal was installed with only the aid of the

lead-in chamfer on the cylinder. The 1/8 in. all-ceramic 250 psi preload repeat seal was installed with a clamping fixture during insertion of the seal/piston into the cylinder, eliminating sheath fraying. Hybrid seals resisted abrasion very well. Figure 8 shows a close-up of the hybrid seal lap joint after 10 cycles of 0.3 in. scrubbing at 1300 °F. The seal sheath was not damaged away from the lap joint. Some minor wire bending is noticed at the joint.

Comparison to Flow Goal. Examining Table 2, the 1/16 in. diameter all-ceramic seals met the flow goal of 0.0064 SCFM/in. seal for 150 and 250 psi preloads and marginally met the goal at 110 psi. The flow goal was arrived at a priori to aid in selecting seals to minimize system purge requirements. The 1/8 in. diameter seals exhibited higher leakage but met the flow goal at 260 psi preload. Other tests could be done with the 1/8 in. seal to determine threshold preloads where the seal would meet the flow goal. Low preload is preferred in the industrial application for design considerations. The 1/16 in. diameter hybrid seal met the flow goal at 250 psi preload. The seal flows met the flow goals for the design preloads considered acceptable. Furthermore, sheath damage was minimal over the thermal cycles. Based on these observations the braided seal is deemed feasible for the industrial tube seal application.

Compression Results

Compression tests were performed on all-ceramic seals in order to determine required linear crushes for 100, 110, 150 and 250 psi nominal preloads for both all-ceramic seal sizes, and 150, 250, 500 and 675 psi nominal preload for the 1/16 in. diameter hybrid seal. The 500 and 675 psi nominal preload experiments were performed in support of the turbine vane seal application described in the next section. Figure 9 shows the force vs linear crush characteristics of the 1/16 in. diameter all-ceramic seal at 250 psi nominal preload (the data is qualitatively representative of the 1/8 in. seal force vs linear compression data). Figure 10 shows the force vs linear crush characteristics for the 1/16 in. hybrid seal at 250 psi nominal preload. For all seals tested and for all preloads, the last two load vs crush lines are very close in value, indicating that the majority of seal hysteresis was removed prior to preload determination.

During a compression experiment, the seal sample is repeatably crushed to the same linear displacement. The footprint width of the last load cycle is used in conjunction with the measured force vs crush information in order to estimate the preload which corresponds to the repeated linear crush value. Figure 11 shows the relationship between the linear crush value and measured seal preload for 1/16 in. all-ceramic seals (again, this data is qualitatively representative of the data for the 1/8 in. diameter seals).

Generally, there is a plateau in their characteristic preload vs crush curve. The plateau exists because seal contact width increases with force, resulting in very little net change in preload value. This plateau indicates that for both the 1/16 in. and 1/8 in. diameter all-ceramic seals there is a range of linear crush in which preload does not significantly change, but seal flow (Table 2) changes by approximately one order of magnitude. At higher linear crushes, the plateau behavior disappears when the increase in force per unit of linear crush exceeds the increase in footprint width per unit of linear crush. The footprint width asymptotically reaches a maximum, and at that point the net preload increases sharply with linear crush.

While unit preload may not change radically along this plateau, the seal's resiliency (e.g. the ability to track distortions) is greatly increased. This point can be illustrated by examining the amount of distortion, or working deflection, the seal can follow while maintaining 50 percent or more of the seal's contact force. Table 3 compares the seal's working deflection for this criterion for the 1/16 in. and 1/8 in. seals for 100, 110 and 250 psi nominal preloads.

As Table 3 illustrates, the seal's resiliency, or working deflection, doubles when increasing the unit preload from 100 psi to 110 psi nominal and more than doubles increasing from 100 psi to 250 psi. This clearly increases the seal's ability to accommodate differential growths and manufacturing tolerances.

Footprint Observations

All-ceramic seals. Compression experiments not only produce preload information, but they also produce visual evidence of seal footprints. After the pressure sensitive film develops under a preloaded seal, observations can be made regarding the quality and continuity of the seal contact with its mating surfaces. At approximately 100 psi, seal contact for both sizes of all-ceramic seals is intermittent with large gaps between the areas in loaded contact. Note that the pressure sensitive film develops at preloads of 28 psi and greater. Some of the undeveloped regions could be in contact but not at a high enough preload to develop. However, we believe from the high flow results (Table 2) for the 100 psi preload that there are some thin open areas between the seal and piston that are leak paths.

At approximately 110 psi preload, the 1/16 in. all-ceramic seal footprint is almost continuous, and the 1/8 in. all-ceramic seal footprint is more continuous but still somewhat intermittent. At approximately 250 psi preload, the 1/16 in. all-ceramic seal footprint is very solid and continuous. This solid contact eliminates flow paths between the walls and the seal, thus further reducing overall seal leakage. The 1/8 in. seal footprint at approximately 250 psi exhibits some intermittency, but more seal is in contact at this preload than at lighter preloads. Footprint widths were measured from these film samples, and these measured

contact widths (obtained after the last load cycle) are summarized for each seal in Table 4.

Hybrid Seals. At all measured preloads, the hybrid seal footprint is solid and continuous. This solid contact eliminates flow paths between the walls and the seal, thus reducing overall seal leakage. Measured contact widths (obtained after the last load cycle) are summarized for each seal in Table 4.

Turbine Vane Seals

Flow Results

Flow tests were performed on 1/16 in. diameter hybrid seal specimens for nominal preloads of 500 and 675 psi. Flow data was collected at three temperatures (70, 1300 and 1500 °F), eight pressures (2, 5, 10, 20, 40, 60, 80 and 95 psid), and two scrubbing conditions (no scrubbing and 10 cycles of 0.3 in. scrubbing at 1500 °F).

As with the previously described lower preloads, seal flow performance for the hybrid seals did not appreciably degrade after hot scrubbing at elevated temperatures for the 500 and 675 psi nominal preload conditions. Seal flow was linearly dependent on pressure (2-95 psid). After scrubbing, the seal sheath was not damaged and only minor wire bending was noticed at the lap joint. Additionally, the flow decreased with increasing temperature at both the 500 and 675 psi nominal preload conditions.

A synopsis of flow results (after hot scrubbing) for the vane seal application showing the effects of temperature, pressure and preload on the seal flow is shown in Fig. 12. At 1500 °F and operating pressure of 95 psid, increasing the preload from 0.018 to 0.020 in. compression reduced leakage by one-third.

Vane Seal Application Specifics

Geometry. Through discussions GE and NASA arrived at a vane attachment technique indicated in Fig. 13. The turbine vane is sealed and supported at the outer shroud location using a preloaded hybrid seal of the type described herein. The seal acts as a compliant mount supporting aerodynamic loads and allows the vane to grow in the span-wise (e.g. radially outward) direction during heat-up and cool-down without excessive thermal stress. The seal also minimizes leakage of coolant bleed air past the seal into the turbine thereby minimizing parasitic thermal efficiency losses.

Installed Performance. GE demonstrated feasibility of the compliant vane seal/mount technique through both flame tunnel (thermal shock) and combustor tests. The vane and seal survived about one dozen hot cycles in the combustor test. These tests qualified the design for subsequent tests in the IHPTET Joint Technology

Advanced Gas Generator (JTAGG) test engine. The NiAl vane and seal were implemented into the JTAGG engine and successfully run for multiple cycles meeting all performance criteria. This technology combined with others contributed to meeting JTAGG Phase 1 program goals which included a 20% reduction in specific fuel consumption and a 40% increase in power-to-weight ratio in a 4000-6000 shaft horsepower-class turboprop/turboshaft engine.⁸ Figure 14 shows a close-up of the vane seal hardware after engine test showing no thermal distress and no seal-fiber breakage. The vane exhibited no thermal cracking and met all design goals. The seal operated at temperatures of 1500+ °F and allowed relative vane-to-holder movement as evidenced by trace-scrubbing marks left on the hardware.

Summary and Conclusions

As operating temperatures of advanced gas turbine and industrial systems continue to rise designers face more difficult challenges of implementing high temperature structural materials and seals to meet system performance goals. To maximize efficiency, coolant flows are being reduced to their practical minimum requiring low-leakage seals made of temperature-resistant superalloy and ceramic materials. Seals are being designed to both seal and serve as compliant mounts allowing for relative thermal growths between high temperature but brittle primary structures and the surrounding support structures.

High temperature flow and durability performances were measured for both the all-ceramic and hybrid seals for the industrial tube seal and turbine vane seal applications. Compression tests in displacement control mode were used in conjunction with pressure-sensitive film to determine seal contact pressures to establish required groove-depths to set seal preload. Displacement control mode was used to simulate the fixed interference condition the seals experience both in the flow fixture and the actual application. Braided seals exhibit hysteresis (e.g. non-recoverable displacement) during loading and have a memory of previous loading conditions. It was found that testing in displacement control mode better simulated installed loading history and provided more accurate preload information than force control mode compression testing. The compression test technique was corroborated using "seal-overhang/residual-interference" measurements made after hot tests in the flow fixture and showed very good agreement.

Based on the tests discussed herein, the following observations are made:

1. The 1/16 and 1/8 in. diameter all-ceramic rope seals met the flow goal and exhibited good durability for the design preloads, pressures, and operating temperatures

(1300 °F). Based on the screening tests performed, the feasibility of the all-ceramic rope seal has been established for the industrial tube seal application.

2. The hybrid braided rope seal high temperature flow and durability tests performed herein, combined with GE's flame tunnel, combustor, and engine tests demonstrated the feasibility of the hybrid seal/compliant mount arrangement for joining high performance, advanced material system turbine vanes to their supporting structure preventing thermally induced failure at metal temperatures 1500 °F and higher.

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Table 1.—BRAIDED ROPE SEAL CONSTRUCTION MATRIX

Seal	Diameter inches	Core				Sheath						
		Material ^a	Denier	Fiber diameter μm	Number of yarns	Material ^{a,b}	Denier	Fiber diameter μm	Number of layers	Number of filaments or yarns per tow	Braid angle θ (deg.)	Number of carriers
All-ceramic: NTWAC-1	0.064	NX550	700	8	15	NX550	700	8	2	1	30	4,8
NTWAC-2	0.124	NX550	700	8	109	NX550	700	8	2	1	45	8,8
Hybrid: NTWHY-1	0.060	NX550	700	8	35	HS188	110	40	1	10	46	12

^aCeramic fiber composition by weight percentage:

NX550 (Nextel 550): 73 Al₂O₃, 27 SiO₂

^bMetal wire composition by weight percentage:

HS188 (Haynes 188): 38 Co, 22 Cr, 14 W, 3 Fe, 1.25 Mn, 0.5 Si, 0.08 La, 0.015 B, 0.05 C.

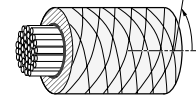


Table 2.—ALL-CERAMIC (1/16" and 1/8") AND HYBRID (1/16") SEAL FLOWS AT OPERATING TEMPERATURE FOR SEVERAL PRELOADS AT 2 psid PRESSURE

Seal type	Seal diameter, in.	Preload, psi	Linear crush, in.	Flow (SCFM/in.)		Flow goal (SCFM/in.)
				at 1100 °F	at 1300 °F	
All-ceramic	0.064	100	0.005	0.149	0.149	0.0064
All-ceramic	0.064	100	0.005	0.072	0.091	
All-ceramic	0.060	110	0.013	0.0064	0.0068	0.0064
All-ceramic	0.060	110	0.013	0.0064	0.0073	
All-ceramic	0.064	150	0.015	0.0038	0.0040	0.0064
All-ceramic	0.064	250	0.018	0.0023	0.0024	0.0064
All-ceramic	0.064	250	0.018	0.0029	0.0020	
All-ceramic	0.124	100	0.008	0.112	0.151	0.0064
All-ceramic	0.124	100	0.008	0.085	0.120	
All-ceramic	0.120	110	0.021	0.0092	0.010	0.0064
All-ceramic	0.124	150	0.031	0.0086	0.0076	0.0064
All-ceramic	0.124	150	0.031	0.0096	0.0080	
All-ceramic	0.124	260	0.037	0.0040	0.0036	0.0064
All-ceramic	0.124	260	0.037	0.0039	0.0031	
Hybrid	0.060	150	0.011	0.0107	0.0096	0.0064
Hybrid	0.060	150	0.011	0.0123	0.0114	
Hybrid	0.060	250	0.014	0.0070	0.0064	0.0064
Hybrid	0.060	250	0.014	0.0066	0.0063	

Table 3.—ALL-CERAMIC SEAL WORKING DEFLECTION FOR CRITERIA THAT SEAL MAINTAINS 50 PERCENT OR MORE OF DESIGN PRELOAD (LAST LOAD CYCLE DATA)

Seal diameter, in.	100 psi nom., base in.	Design preload 110 psi nom.	Increase in working deflection	Design preload 250 psi nom.	Increase in working deflection
		110 psi vs base		250 psi vs base	
1/16"	0.0015	0.003	2X	0.004	2.6X
1/8"	0.002	0.005	2.5X	0.005	2.5X

Table 4.—ALL-CERAMIC AND HYBRID SEAL MEASURED CONTACT WIDTHS (LAST LOAD CYCLE DATA)

Seal type	Preload, psi nominal	Linear crush, in.	Contact width, in.
All-ceramic 1/16 in. dia.	100	0.005	0.034
	110	0.013	0.050
	150	0.015	0.052
	250	0.018	0.052
All-ceramic 1/8 in. dia.	100	0.008	0.041
	110	0.021	0.053
	150	0.031	0.077
	250	0.037	0.078
Hybrid 1/16 in. dia.	150	0.011	0.042
	250	0.014	0.043
	500	0.018	0.053
	675	0.020	0.056

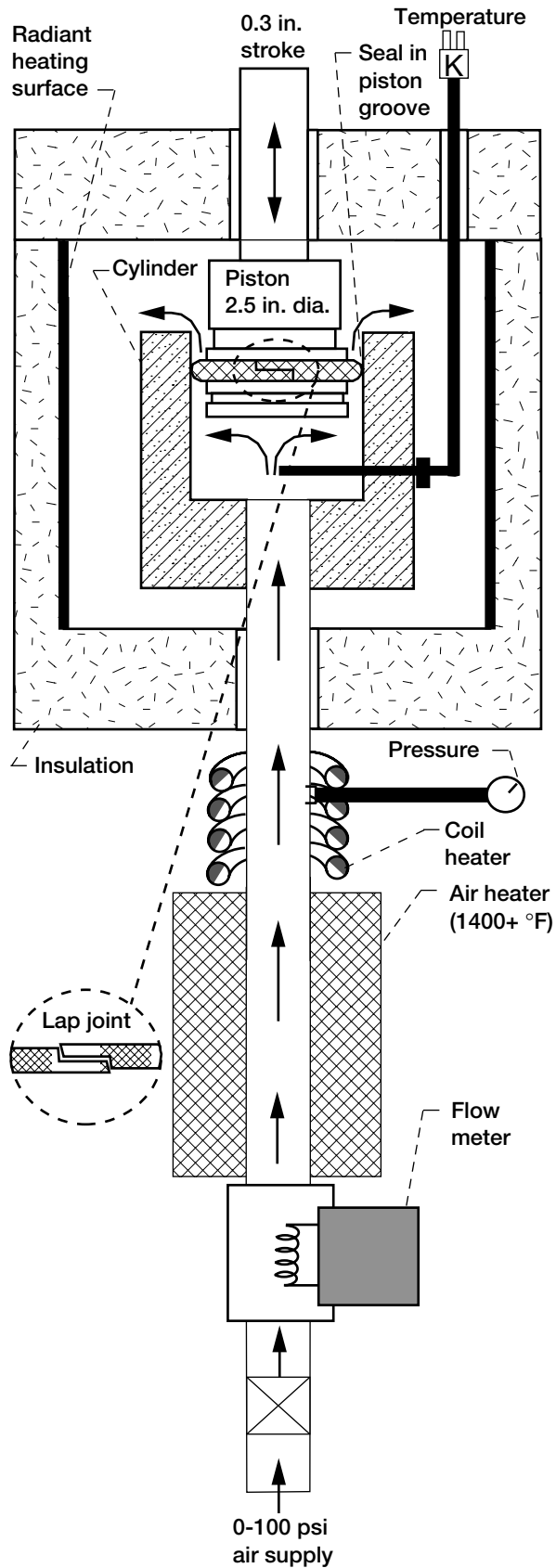


Figure 1.—Schematic of flow fixture.

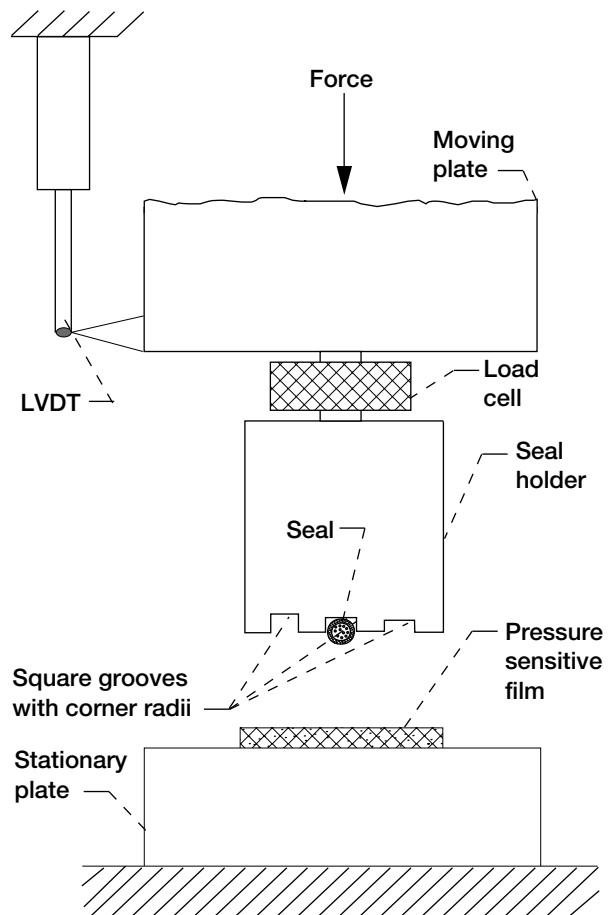


Figure 2.—Schematic of compression fixture.

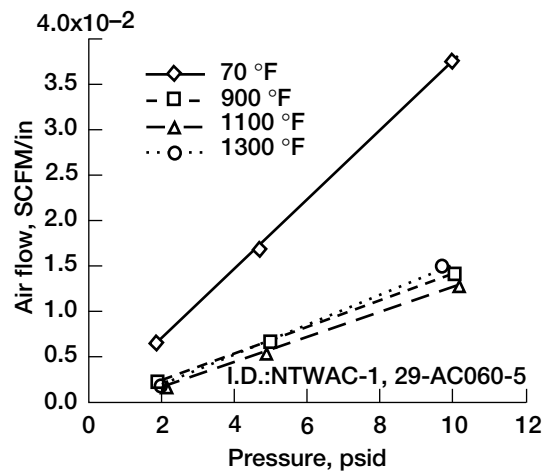


Figure 3.—Flow vs pressure data for 4 temperatures, 1/16 in. diameter all-ceramic seal, 250 psi preload, after scrubbing.

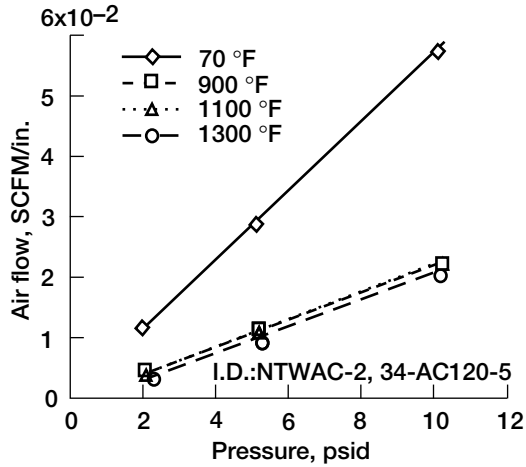


Figure 4.—Flow vs pressure data for 4 temperatures 1/8 in. diameter all-ceramic seal, 250 psi preload, after scrubbing.

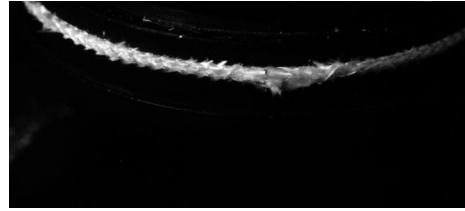


Figure 7.—Photo of 1/16 in. diameter all-ceramic seal after scrubbing, 250 psi preload.

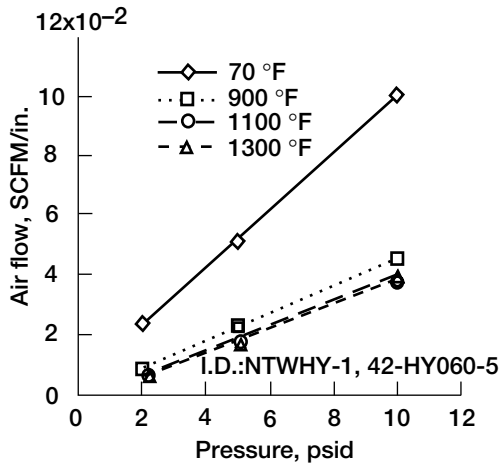


Figure 5.—Flow vs pressure data for 4 temperatures, 1/16 in. diameter hybrid seal, 250 psi preload, after scrubbing.

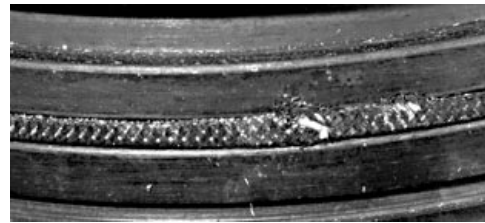


Figure 8.—Photo of 1/16 in. hybrid seal after scrubbing, 250 psi preload.

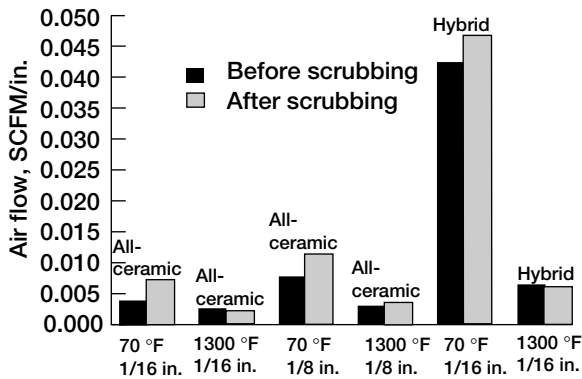


Figure 6.—Effect of scrubbing and temperature on seal flow; $\Delta p = 2$ psid; 250 psi preload; 1/16 in., and 1/8 in. all-ceramic seals and 1/16 in. hybrid seals.

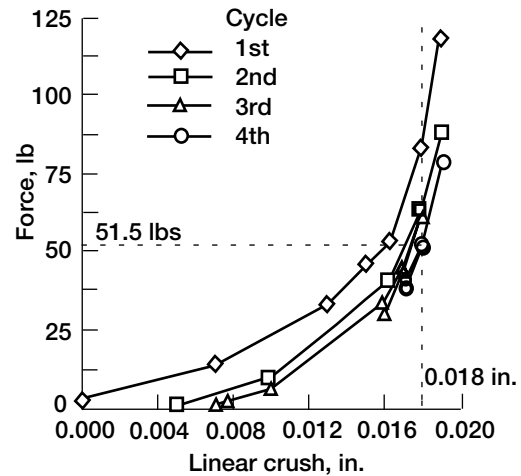


Figure 9.—Preload vs linear compression data, 1/16 in. diameter all-ceramic seal, 250 psi preload.

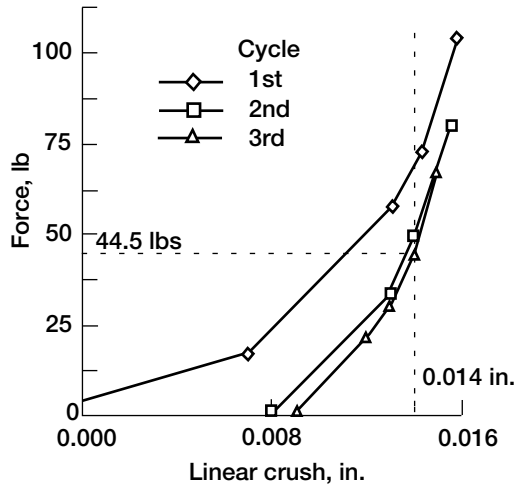


Figure 10.—Preload vs linear compression data, 1/16 in. diameter hybrid seal, 250 psi preload.

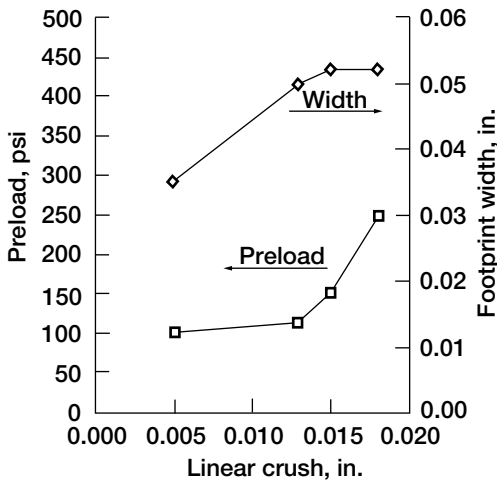


Figure 11.—Footprint width and preload vs linear compression for 1/16 in. diameter all-ceramic seals.

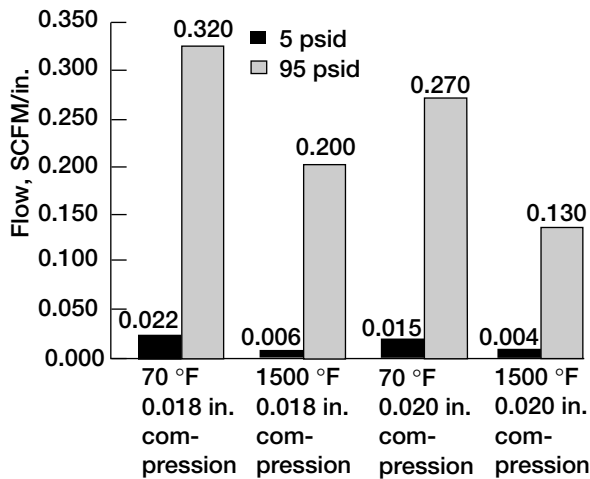


Figure 12.—The effect of temperature, pressure, and representative compression on seal flow after cycling for 0.060 in. hybrid vane seal.

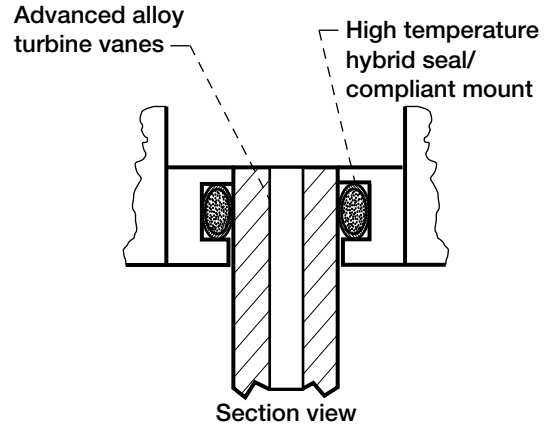


Figure 13.—Schematic of vane seal hardware.

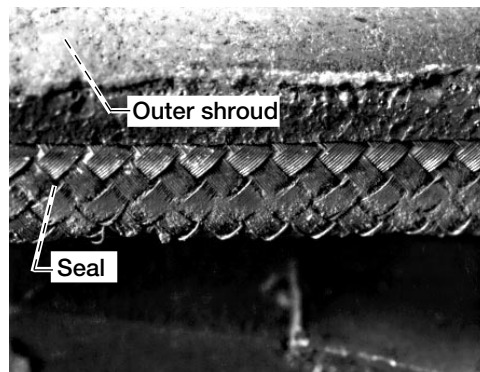


Figure 14.—Close-up (14xmag) of turbine vane seal after engine testing showing no damage.

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (<i>Maximum 200 words</i>) Achieving efficiency and performance goals of advanced aircraft and industrial systems are leading designers to implement high temperature materials such as ceramics and intermetallics. Generally these advanced materials are applied selectively in the highest temperature sections of the engine system including the combustor and high pressure turbine, amongst others. Thermal strains that result in attaching the low expansion-rate components to high expansion rate superalloy structures can cause significant life reduction in the components. Seals are being designed to both seal and to serve as compliant mounts allowing for relative thermal growths between high temperature but brittle primary structures and the surrounding support structures. Designers require high temperature, low-leakage, compliant seals to mitigate thermal stresses and control parasitic and cooling airflow between structures. NASA is developing high temperature braided rope seals in a variety of configurations to help solve these problems. This paper will describe the types of seals being developed, describe unique test techniques used to assess seal performance, and present leakage flow data under representative pressure, temperature and scrubbing conditions. Feasibility of the braided rope seals for both an industrial tube seal and a turbine vane seal application is also demonstrated.			
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