NASA/TM—2006-214416 AIAA–2006–4934

Performance Evaluations of Ceramic Wafer Seals

Patrick H. Dunlap, Jr.
Glenn Research Center, Cleveland, Ohio

Jeffrey J. DeMange
University of Toledo, Toledo, Ohio

Bruce M. Steinetz
Glenn Research Center, Cleveland, Ohio

November 2006

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to *help@sti.nasa.gov*

- Fax your question to the NASA STI Help Desk at 301–621–0134

- Telephone the NASA STI Help Desk at 301–621–0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2006-214416 AIAA–2006–4934

Performance Evaluations of Ceramic Wafer Seals

Patrick H. Dunlap, Jr.
Glenn Research Center, Cleveland, Ohio

Jeffrey J. DeMange
University of Toledo, Toledo, Ohio

Bruce M. Steinetz
Glenn Research Center, Cleveland, Ohio

Prepared for the
42nd Joint Propulsion Conference and Exhibit
cosponsored by the AIAA, ASME, SAE, and ASEE
Sacramento, California, July 9–12, 2006

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

November 2006

Acknowledgments

The authors gratefully acknowledge Richard Tashjian (QSS) for his assistance in test support.

This work was sponsored by the Fundamental Aeronautics Program at the NASA Glenn Research Center.

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

Available electronically at http://gltrs.grc.nasa.gov

Performance Evaluations of Ceramic Wafer Seals

Patrick H. Dunlap, Jr.
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Jeffrey J. DeMange
University of Toledo
Toledo, Ohio 43606

Bruce M. Steinetz
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

Future hypersonic vehicles will require high temperature, dynamic seals in advanced ramjet/scramjet engines and on the vehicle airframe to seal the perimeters of movable panels, flaps, and doors. Seal temperatures in these locations can exceed 2000°F, especially when the seals are in contact with hot ceramic matrix composite sealing surfaces. NASA Glenn Research Center is developing advanced ceramic wafer seals to meet the needs of these applications. High temperature scrub tests performed between silicon nitride wafers and carbon-silicon carbide rub surfaces revealed high friction forces and evidence of material transfer from the rub surfaces to the wafer seals. Stickage between adjacent wafers was also observed after testing. Several design changes to the wafer seals were evaluated as possible solutions to these concerns. Wafers with recessed sides were evaluated as a potential means of reducing friction between adjacent wafers. Alternative wafer materials are also being considered as a means of reducing friction between the seals and their sealing surfaces and because the baseline silicon nitride wafer material (AS800) is no longer commercially available.

I. Introduction

High temperature, dynamic structural seals are required on future hypersonic vehicles in several locations. Vehicle airframe seals are required along the edges and hinge lines of movable control surfaces, around landing gear doors, and around access panels and doors (Fig. 1). The perimeters of movable hypersonic engine ramps must also be sealed for safe, efficient operation. This includes panel edge seals to seal gaps between the panels and adjacent engine sidewalls as well as seals along hinge lines. Figure 2 illustrates a panel edge seal location in a candidate hypersonic engine for the National Aerospace Plane (NASP). Researchers at NASA Glenn Research Center (GRC) carried out an in-house program to develop seals for the NASP engine and oversaw industry efforts for airframe and propulsion system seal development for this vehicle during the late 1980's and early 1990's.[1] The braided and textile-based seals of those studies met many requirements but fell short of leakage, durability, and resiliency goals and were not fully developed when the program was terminated. Further development occurred at GRC as part of NASA's Next Generation Launch Technology (NGLT) program, but that program was also terminated before the seals could be fully matured. To overcome these performance shortfalls, GRC is continuing to develop advanced seals for future hypersonic vehicles as part of several new programs.

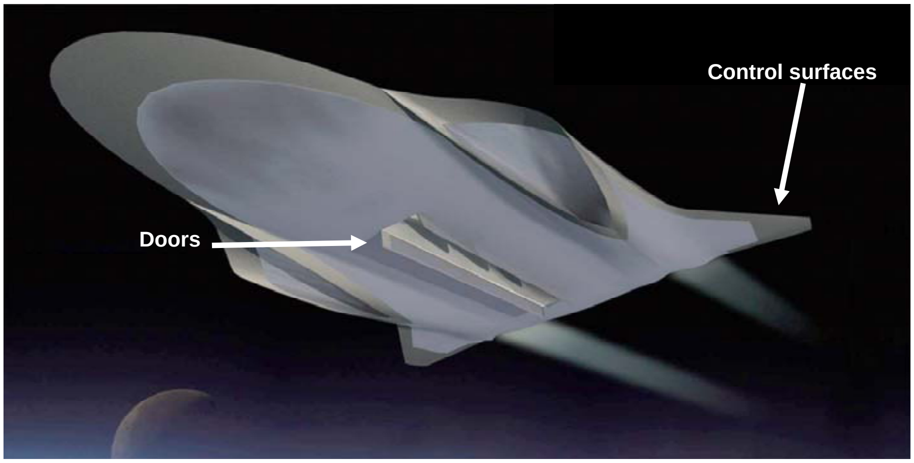


Figure 1. Airframe seal locations on a future hypersonic vehicle.

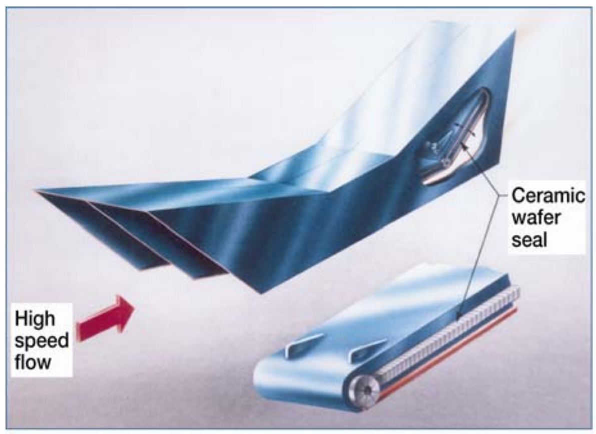


Figure 2. NASP engine panel edge seals designed to seal the gaps between movable ramps and adjacent engine sidewalls.

A. Seal Design Requirements

Seals on future hypersonic vehicles must operate in high heat flux, oxidizing environments and restrict the flow of hot gases at extreme temperatures that can exceed 2000°F. They must be flexible enough to accommodate distorted sealing surfaces while still providing positive, resilient sealing. The seals must also be sufficiently durable to meet required life goals. They must resist scrubbing damage as they are rubbed over rough, distorted sealing surfaces without incurring excessive increases in leakage due to wear. In many instances they must limit loads against sealing surfaces that may be fragile or covered with protective coatings. In some locations the seals must mate against rough ceramic matrix composite (CMC) structures without sticking to coatings on the panel surfaces. This can be particularly challenging if the seal has to interact with a glass sealant that is designed to melt at high temperatures to heal cracks in the materials below it. The seals must perform all of these functions while still serving as effective flow blockers. Additional details on design requirements for hypersonic engine seals and control surface seals can be found in the papers by Dunlap, et al.[2] and DeMange, et al.[3] respectively.

B. Seal Development Approach

Because of the extreme temperatures involved in these applications, GRC is developing new seal designs that exploit recent advancements in high temperature ceramics. One such design is the ceramic wafer seal shown in Fig. 3. This seal is composed of a series of thin ceramic wafers installed in a channel and preloaded from behind to maintain contact with the opposing sealing surface. The wafers are able to seal against distorted sealing surfaces by sliding past each other to conform to the shape of the surface. Candidate preload devices include high temperature canted coil springs and compression springs. A study performed by Dunlap, et al.[2] showed that a system composed of monolithic silicon nitride wafers (Honeywell AS800) and silicon nitride compression springs is an excellent candidate to meet the sealing needs of future hypersonic vehicles. Flow rates reported for these wafers were only about 3% of those for the best textile-based seals even after 1000 scrub cycles against monolithic silicon carbide at 2000°F.

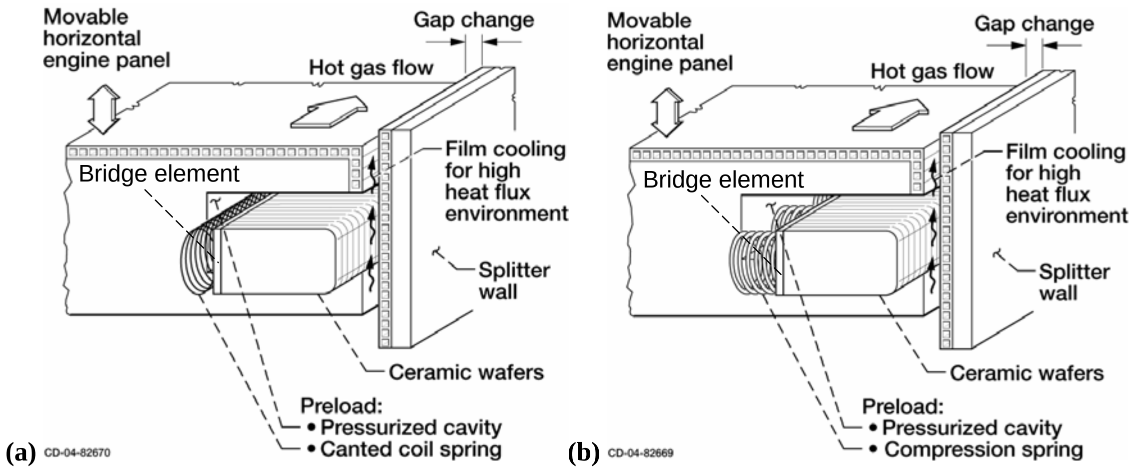


Figure 3. Schematics of ceramic wafer seal with (a) canted coil springs or (b) compression springs as preload devices

C. Goals for Current Study

Previous hot scrub tests performed on AS800 ceramic wafer seals were all conducted using relatively smooth rub surfaces composed of either Inconel 625 or monolithic silicon carbide.[2,4] In the current study, the interaction between ceramic wafer seals and rough CMC sealing surfaces is investigated by performing a series of hot scrub tests and room temperature flow tests. Approaches for minimizing friction between the wafer seals and rub surfaces and between adjacent wafers are also investigated. GRC recently learned that the AS800 material used in the most recent wafer seal performance studies is no longer commercially available. Therefore, another goal of this study is to identify candidate materials for the wafers as a replacement for AS800.

II. Test Apparatus and Procedures

A. Seal Specimens

1. Silicon Nitride Wafer Seals

The baseline wafer seals tested in the current study were made of Honeywell AS800 monolithic silicon nitride. They were 0.5 in. wide, 0.910 in. tall, and 0.125 in. thick and had corner radii of 0.050 in. (Fig. 4). Note that wafers used in previous tests were closer to 0.92 in. tall, but those used in the current study were re-ground to a uniform height before testing. A series of tests were conducted on these seals to characterize their performance against carbon-silicon carbide (C/SiC) sealing surfaces including high temperature scrub tests and room temperature flow tests before and after the scrub tests.

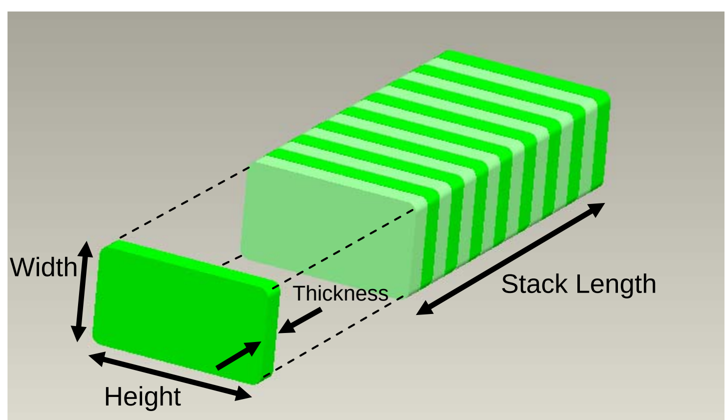


Figure 4. Wafer seal geometry terminology.

2. Recessed Aluminum Wafer Seals

A new wafer seal design with recessed sides was also evaluated in this study with the intent of reducing friction and stickage between adjacent wafers (Fig. 5). These wafers were similar in size to the AS800 wafers except they were 0.92 in. tall instead of 0.910 in. and 0.25 in. thick rather than 0.125 in. They also had recesses on both sides that were nominally 0.375 in. wide and 0.003 in. deep. The recessed area did not extend across the entire side of the wafer but instead terminated about 0.1 in. from the surface of the wafer that would be in contact with the sealing surface. The raised boss of material around three sides of the wafer was left behind to prevent leakage from flowing directly between adjacent wafers.

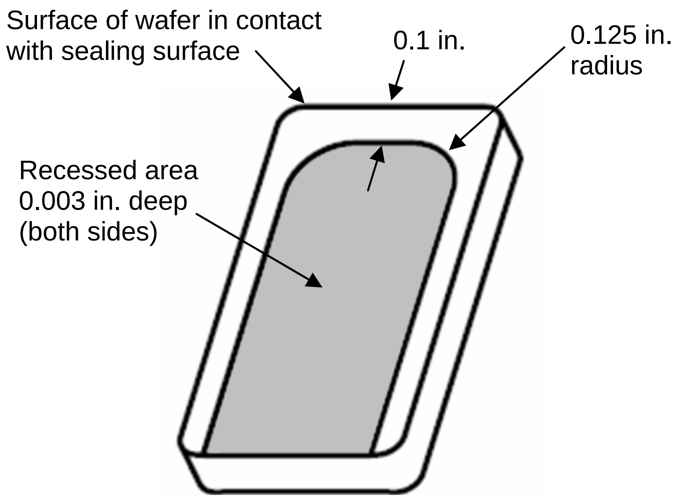


Figure 5. Schematic of new recessed wafer design showing recessed area in gray.

A recent study by Dunlap et al.[2] showed that the orientation of the wafers in a groove with respect to the differential pressure across the wafers allows a "seal activating" pressure to build up behind the seal. This pressure can be as large as 93 percent of the pressure differential across the seals and helps augment the preload devices to keep the seals in contact with the sealing surface (Fig. 3). The recessed areas on the new wafer seal design were oriented to allow some of the pressure behind the wafers to move between adjacent wafers and serve as a hydrostatic cushion of air to reduce friction between adjacent wafers and allow them to move more easily with respect to each other and seat against the opposing sealing surface.

As a first step in assessing the performance of the recessed wafers, room temperature flow tests were conducted to determine if the recessed areas caused higher leakage rates past the seals as compared to the baseline wafer geometry without these features. Because these flow tests were performed at room temperature, and the amount of flow past the wafers was believed to be more a function of wafer geometry than wafer material, it was decided to fabricate the recessed wafers out of aluminum 7075-T73511. The high temperature capabilities provided by ceramics were not required in these room temperature tests. Fabricating the recessed wafers out of aluminum also allowed them to be produced more quickly and at a lower cost than if they were made of ceramic.

B. Hot Scrub Tests

Hot scrub tests were performed on the AS800 silicon nitride wafer seals using a state-of-the-art test rig at GRC. This test rig is capable of performing either high temperature seal scrub tests or compression tests at temperatures up to 3000°F using different combinations of test fixtures made of monolithic silicon carbide (Hexoloy α-SiC). The main components of this test rig are a servohydraulic load frame, an air furnace, and a non-contact laser extensometer (Fig. 6). The load frame has a top-mounted actuator capable of generating a load of 3300 lb over a 6 in. stroke at rates from 0.001 to 8 in./sec. Additional details on the capabilities of this test rig can be found in the paper by Dunlap et al.[4]

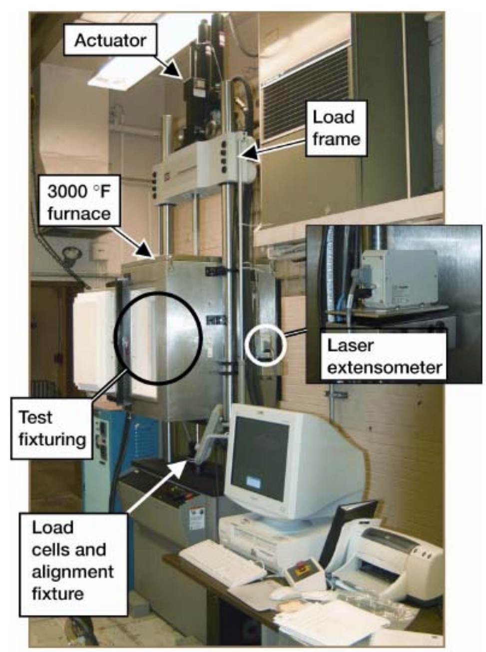


Figure 6. Photograph of hot scrub and compression test rig showing main components: load frame, high temperature furnace, and laser extensometer.

In this study, scrub tests were performed at 2200°F in which the AS800 wafers were scrubbed against C/SiC rub surfaces (Fig. 7). These rub surfaces had an average surface roughness before testing of 148 μin. in the direction of scrubbing and 137 μin. in the transverse direction. The seals were installed in grooves in two stationary seal holders on either side of a pair of movable rub surfaces. The rub surfaces were assembled in a holder that was connected to the actuator through the upper load train of the test fixture. The gaps between the rub surfaces and the seals were set at nominally 0.1 in. for these tests.

Four silicon nitride compression springs were installed in the bottom of each seal groove to keep the wafers preloaded against both rub surfaces. The springs were installed on 1.15-in. centers below the wafers, and a load transfer element (i.e., bridge element) was placed on top of the springs to support the wafers and distribute the load from the springs. Thirty two wafers were installed into each seal holder to fill the 4-in.-long seal grooves. The amount of compression on the seals and springs was set through an interference fit between the seals and the rub surfaces resulting in a preload of about 2 lb per inch of seal.

During these tests, the seals were held in place in the holders while the rub surfaces were scrubbed up and down against them. For each load cycle a sine wave was used with a stroke length of 0.5 in. in each direction and a stroke rate of 1 Hz. There was no hold time between scrub direction changes. The seals were subjected to 250 scrub cycles per test for a total of 250 in. of scrubbing. The 250 in. scrub distance was selected to simulate a mission application. The same set of AS800 wafers was subjected to two scrub tests (i.e., two missions) for a total of 500 in. of scrubbing. Frictional loads were measured by a 500-lb load cell (accuracy ± 0.15 lb) under the furnace below the test fixture base. Seal wear rates were determined by examining the condition of the seals before and after each test and by measuring changes in flow rates.

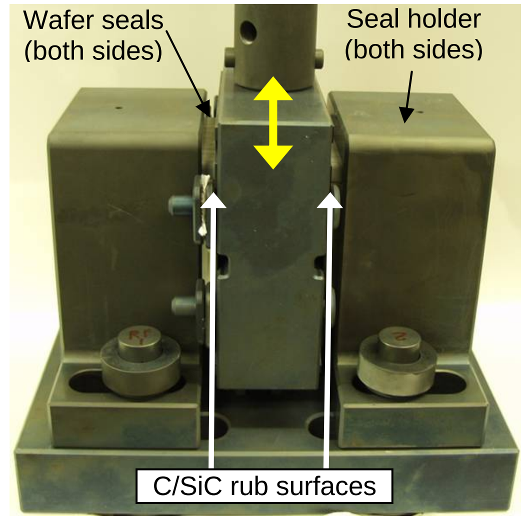


Figure 7. Hot scrub test fixture setup.

C. Flow Tests

1. Test Fixture Used for Flow Tests on AS800 Wafer Seals

Two different test fixtures were used for the room temperature flow tests performed in this study. The first test fixture was used for flow tests of the AS800 wafer seals before and after hot scrub testing (Fig. 8). This fixture consists of an aluminum base, a seal holder used to hold the wafers, a spacer sheet to set the flow gap, and a cover plate that holds the C/SiC panel that was used in the hot scrub tests. This setup allows leakage rates past the seals to be measured while they are in contact with the same rub surfaces used in the hot scrub tests.

The wafer seals were tested in a groove in the seal holder and were preloaded from behind by four silicon nitride compression springs mounted on 1.15-in. centers. As with the scrub tests, a load transfer element was used between the springs and wafers to support the wafers and uniformly distribute the load. Preload was applied to the wafers and springs through an interference fit between the seals and the C/SiC panel in the cover plate. All tests were performed using a 0.1 in. seal gap.

During testing, flow meters upstream of the flow fixture measured the amount of flow that passed through the test seal. The maximum capacity flow meter that was used had a range of 0 to 26.5 standard cubic feet per minute (SCFM) and an accuracy of 1 percent of full scale. The differential pressure across the seals was monitored using a pressure transducer with a 0 to 100 psig range and an accuracy of 0.11 percent of full scale.

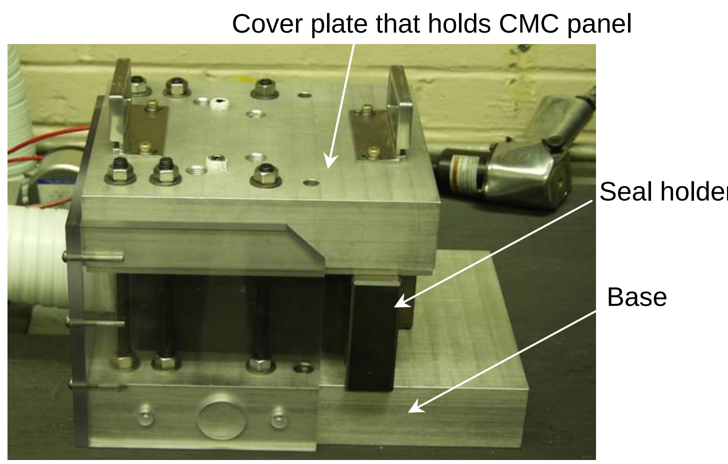


Figure 8. Test fixture used for flow tests on AS800 wafer seals.

2. Test Fixture Used for Flow Tests on Recessed Aluminum Wafer Seals

A different test fixture was used for the flow tests performed on the recessed aluminum wafer seals. This test fixture, shown schematically in cross section in Fig. 9, was designed so that seals of different sizes could be tested in removable cartridges that are inserted into the main body of the test fixture. Seals can also be evaluated in this fixture using different seal gaps and different amounts of linear compression.

As with the tests performed on the AS800 wafers, the recessed wafers were tested in a groove in the seal cartridge and were preloaded from behind by four silicon nitride compression springs mounted on 1.15-in. centers. A load transfer element between the springs and wafers supported the wafers and uniformly distributed the load. Preload was applied to the wafers and springs through an interference fit between the seals and a smooth, stainless

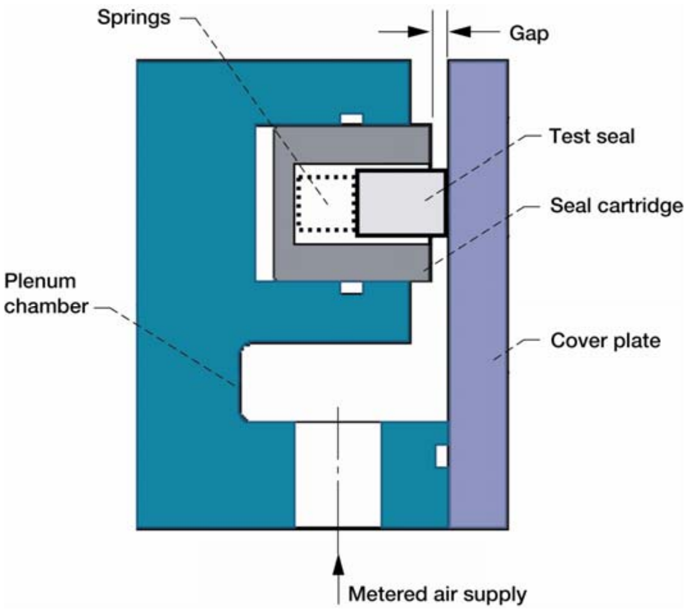


Figure 9. Cross sectional schematic of test fixture used for flow tests on recessed aluminum wafer seals.

steel cover plate. A 0.125 in. seal gap was used for these tests to compare leakage rates for these wafer seals to those for tests performed previously on the baseline wafer design without recessed sides.

The dimensions of the groove in which the seals were installed were selected based on the results of a design of experiments study performed to minimize wafer seal leakage.[5] The groove width clearance (i.e., width of the wafers with respect to the groove width) was set at 0.001 in., while a groove length clearance (i.e., length of the stack of wafers with respect to the groove length) of 0.005 in. was used.

During testing, flow meters upstream of the test fixture measured the amount of leakage past the wafer seals. The maximum capacity flow meter that was used had a range of 0 to 3.5 SCFM with an accuracy of 1 percent of full scale. A pressure transducer (0 to 100 psig, accuracy 0.11 percent of full scale per manufacturer) upstream of the test seal measured the differential pressure across the seal with respect to ambient conditions, and a thermocouple measured the upstream temperature. Additional details about the hardware and procedures used to perform these tests can be found in the paper by Dunlap et al.[5]

III. Results and Discussion

A. Hot Scrub Test Results: Silicon Nitride (AS800) Wafer Seals vs. C/SiC

Peak friction loads per inch of seal for the upward and downward strokes of each scrub cycle are presented in Fig. 10 for the two scrub tests performed against the C/SiC panels at 2200°F. Note that the upward stroke produces a tensile load on the load cell and is represented by a positive friction load, while the downward stroke produces a compressive load on the load cell and is shown as a negative load. Throughout both tests, the peak friction loads for both directions of stroke were comparable.

During the first scrub test, the friction loads started at approximately 3 lbf per inch of seal at the beginning of the test and gradually rose as the test proceeded until they reached about 9 lbf per inch of seal by the end of the test. After the first scrub test was completed, the seals were removed from the hot scrub test fixture, and room temperature flow tests were performed on them. The test fixture was then reassembled for the second hot scrub test. Friction loads for the second test picked up close to where they left off at the end of the first test and continued to increase with additional scrub cycling. By the end of the second test, peak loads reached 20 lbf per inch of seal.

Figure 11 combines data from the two scrub tests performed between the AS800 wafer seals and C/SiC rub surfaces at 2200°F into one data set and compares it to results previously reported by Dunlap et al.[2] for tests performed against other rub surface materials at a variety of test temperatures. (Note that all data presented in this figure is for the downward stroke of each test, and all values are reported as positive numbers.) This figure shows that the friction loads measured for the AS800 wafers against C/SiC were higher than those recorded in previous tests. After 500 in. of scrubbing against relatively smooth Inconel 625 and monolithic silicon carbide rub surfaces, peak friction loads remained below 2.5 lbf per inch of seal even at temperatures as high as 2200°F. In comparison, peak loads for the tests against C/SiC at 2200°F were about eight times higher after 500 in. of scrubbing.

There are several indications why the friction loads for the test against C/SiC are higher than they were for tests performed previously against other rub surface materials. Before scrub testing, the average surface roughness of the C/SiC panels was 148 μin. in the direction of scrubbing and 137 μin. in the transverse direction. After the two scrub tests, the average roughness in the scrubbing direction rose to 160 μin., while the roughness in the transverse direction was even higher at 206 μin. For the tests performed previously using Inconel 625 and monolithic silicon carbide rub surfaces, the surface roughnesses were much lower. Average surface roughnesses for the Inconel 625 rub surfaces ranged from 3 to 6 μin. before testing to 43 μin. after scrub testing.[4] The monolithic silicon carbide rub surfaces exhibited similarly low surface roughness values of 25 to 29 μin. before testing and 38 μin. after testing.[2]

Clearly, the C/SiC rub surfaces were much rougher than the other rub surface materials both before and after testing. This difference likely contributed to the higher friction loads recorded for the AS800 wafers against C/SiC.

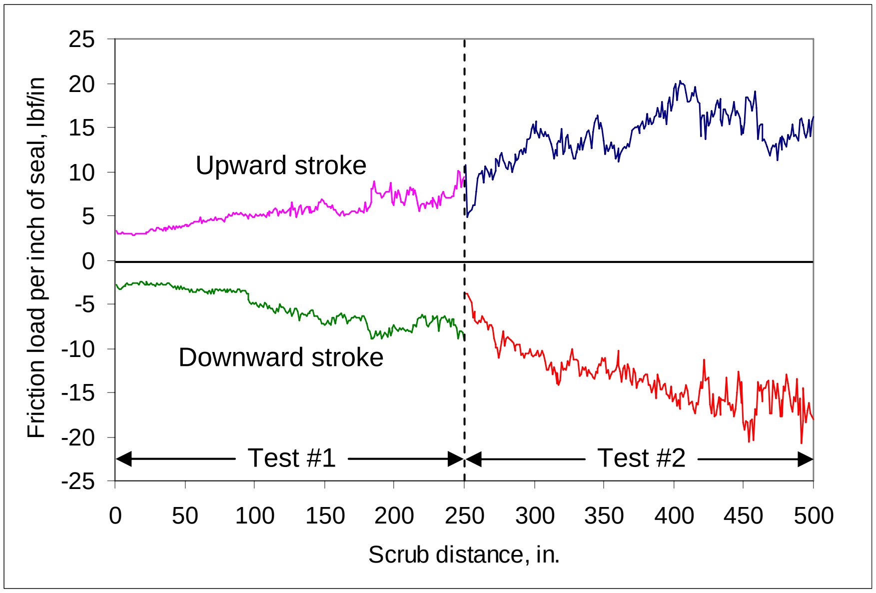


Figure 10. Peak friction loads per inch of seal during the upward and downward strokes of each scrub cycle for scrub tests performed at 2200°F between AS800 wafer seals and C/SiC rub surfaces.

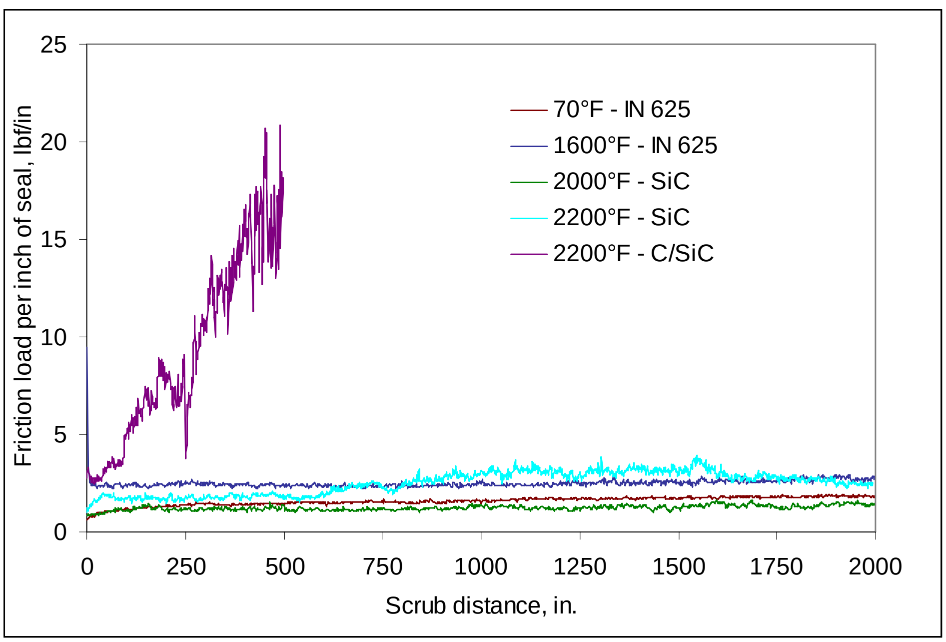


Figure 11. Peak friction loads during downward stroke of each scrub cycle for scrub tests performed at various temperatures between AS800 wafer seals and Inconel 625, monolithic silicon carbide, and C/SiC rub surfaces.

As noted above, the surface roughness of the C/SiC rub surfaces was higher after testing than it was before testing. This increase in surface roughness during testing helps explain why the friction loads increased as the two tests proceeded. Figure 12 provides further evidence of why the friction loads against C/SiC increased during testing and why they were higher than those for the tests against Inconel 625 and monolithic silicon carbide. This figure shows one set of seals and one of the two rub surfaces before testing, after the first scrub test (i.e., 250 in. of total scrubbing), and after the second scrub test (i.e., 500 in. of total scrubbing). Before hot scrub testing, the seals and rub surfaces were in their unblemished, as-received condition (Figs. 12a and 12b). After the first scrub test, there is evidence of a build up of black material that was transferred from the C/SiC rub surface to the wafers due to adhesive wear (Fig. 12c). Figure 12d shows signs of minor scuffing of the rub surface after the first 250 in. of hot scrubbing. The condition of the wafers and rub surface after the second hot scrub test is shown in Figs. 12e and 12f. The areas on the wafers in which the black material had built up during the first scrub test were larger after the second test indicating that additional material was deposited on the wafers. The rub surface also shows further signs of scuffing after a total of 500 in. of hot scrubbing against the wafers. Although there were signs of wear on both the wafer seals and rub surfaces, the seals showed few other signs of damage and were actually quite durable. None of the wafers were chipped or broken during testing. The silicon nitride compression springs that preloaded the wafer seals from behind were also in good condition after the two scrub tests.

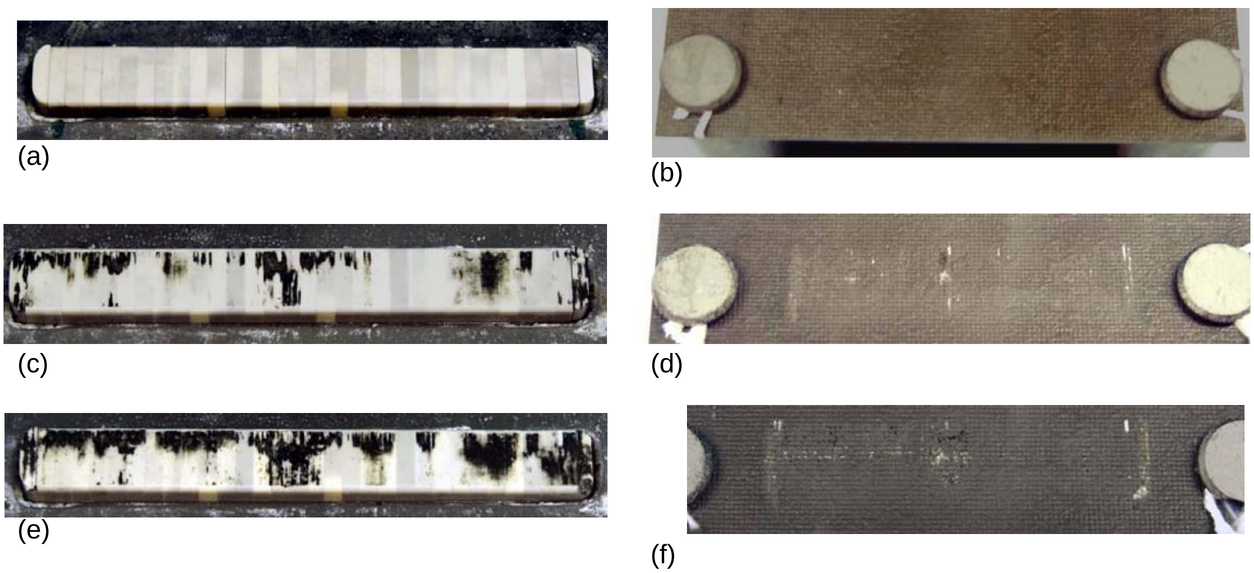
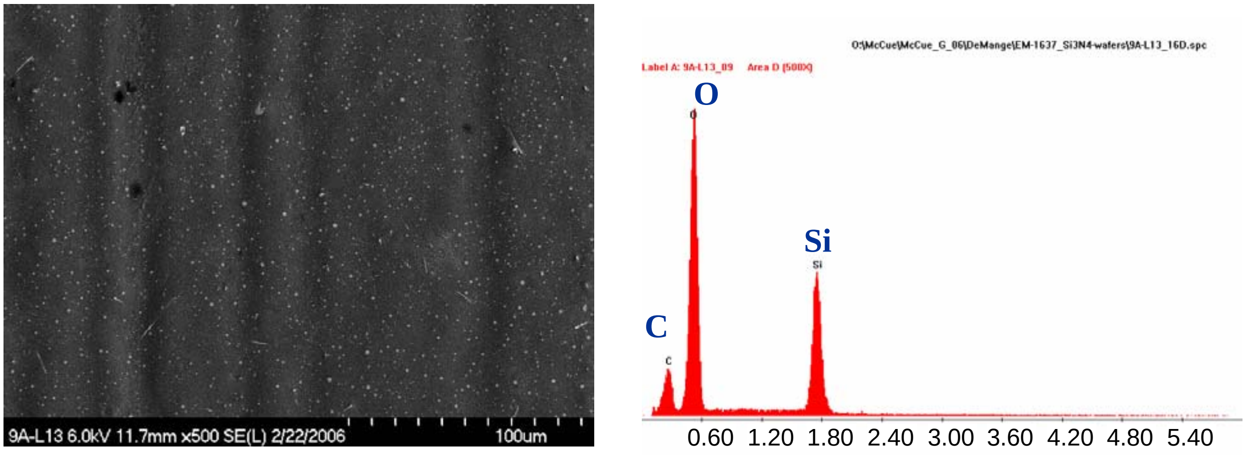


Figure 12. Photographs of (a) seals and (b) C/SiC rub surface before testing, (c) seals and (d) C/SiC rub surface after first 2200°F scrub test, and (e) seals and (f) C/SiC rub surface after second 2200°F scrub test.

Figure 13a is a scanning electron microscope (SEM) image at 500X of an AS800 wafer after the two hot scrub tests against C/SiC for a virgin area of the wafer that was not in contact with the C/SiC rub surface. The material is relatively uniform and smooth with no signs of damage. Figure 13b shows the results of an energy dispersive spectrometer (EDS) analysis of the area in Fig. 13a illustrating peaks for the various chemical elements present in that area. The highest two peaks are for silicon (Si) and oxygen (O) indicating that a glassy layer had deposited on the surface of the silicon nitride wafer during testing. A smaller carbon (C) peak is also present.

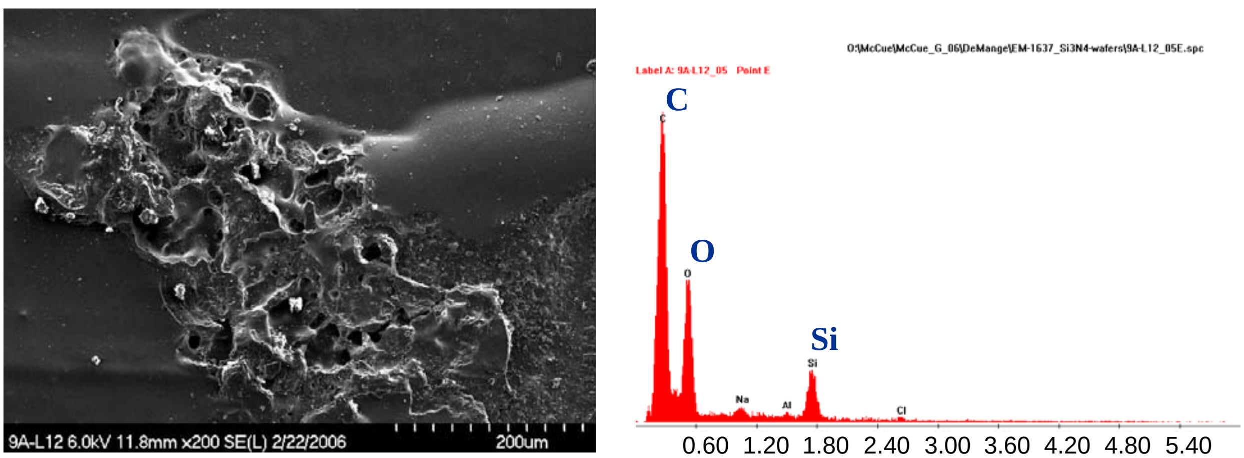
Figure 14a is an SEM image at 200X of the black material deposited on the same wafer seal shown in Fig. 13 except in an area that was in contact with the C/SiC rub surface. This image shows the rough morphology of the black deposits. Results of an EDS analysis performed on this area are shown in Fig. 14b. For this analysis the highest peak is the carbon peak with shorter oxygen and silicon peaks also present. The outer surfaces of the C/SiC panels that were used for the hot scrub tests were coated to protect the composite material from oxidation at high temperatures. This coating contains carbon, boron, and silicon and is typically referred to as CBS coating (GE Power Systems Composites). Based on the relative differences in peak heights shown in Fig. 14b as compared to those in Fig. 13b, it appears that carbon from the coating was deposited on the surface of the wafers during the hot scrub tests. The detection of carbon in the deposits also helps explain why they were very dark in color.

Another concern that arose after the hot scrub tests between the AS800 wafers and the C/SiC panels was stickage between adjacent wafers. After the tests were completed and the wafer seals were removed from the seal holders, some of wafers were stuck together and had to be broken apart to be separated. This behavior was not observed for previous scrub tests against Inconel 625 and monolithic silicon carbide rub surfaces. It is believed that small amounts of the same materials that deposited on the wafer surface that was in contact with the C/SiC panels also worked their way in between the wafers and caused them to stick together. A potential approach for minimizing this concern would be to utilize recessed wafers. The recessed areas on each side of the wafers would minimize the regions where glass could accumulate between adjacent wafers and reduce the tendency for them to stick together.



(a) (b)

Figure 13. (a) SEM image of area of AS800 wafer seal that was not in contact with C/SiC rub surface during hot scrub test at 2200°F and (b) results of EDS analysis showing peaks of chemical elements present in that area.



(a) (b)

Figure 14. (a) SEM image of black material deposited on AS800 wafer seal in area that was in contact with C/SiC rub surface during hot scrub test at 2200°F and (b) results of EDS analysis showing peaks of chemical elements present in that area.

B. Flow Test Results: Silicon Nitride (AS800) Wafer Seals Before and After Hot Scrub Test Against C/SiC

Room temperature flow data for the AS800 wafer seals before and after hot scrub testing against C/SiC rub surfaces at 2200°F are presented in Fig. 15. Note that these leakage rates were measured while the seals were in contact with the same C/SiC rub surfaces used in the hot scrub tests. This figure shows that leakage rates increased after the first scrub test and again after the second scrub test as compared to those measured before hot scrub testing. At 100 psig, for example, leakage rates increased by about 12% after the first scrub test (i.e., 250 in. of total scrubbing) as compared to those measured before scrub testing. After the second scrub test (i.e., 500 in. of total scrubbing), leakage rates increased again such that they were 34% higher at 100 psig than those recorded before scrub testing. The progressive build up of adhesive wear material on the seals exhibited in Figs. 12 and 14 likely contributed to the increase in leakage rates from test to test. As material was transferred from the C/SiC rub surfaces to the wafer seals, the wafers became rougher with large areas of wear material built up on their surfaces. When the wafer seals were put in contact with a C/SiC panel for a flow test after a hot scrub test, these high spots prevented the wafers from seating as well against the panels and created leakage paths past the seals. This then lead to higher leakage rates.

Previous flow tests performed on AS800 wafer seals before and after scrubbing against smooth Inconel 625 and monolithic silicon carbide rub surfaces revealed lower leakage rates than those recorded herein against C/SiC panels before and after scrub testing.[2] For reference purposes, at a differential pressure of 100 psig the leakage rate past the wafers after 2000 in. of hot scrubbing at 2000°F against monolithic silicon carbide was 0.42 SCFM/in. After 500 in. of scrubbing at 2200°F against C/SiC, Fig. 15 shows a leakage rate for the wafers of 3.06 SCFM/in. This increase in leakage rates can be traced to two factors. The flow rates measured in previous studies were recorded with the wafers sealing against a smooth aluminum plate, whereas those reported herein were measured with the wafers in contact with a rough C/SiC panel that had experienced a hot scrub test. Composite panels exhibit a very non-uniform surface due to the woven nature of the fiber matting used in their construction. This undulating surface naturally causes leakage paths to form between the "nose" of the wafer and the CMC surface. The other factor comes from the condition of the wafers in each series of tests. For previous flow tests performed on wafers that were scrub tested against smooth Inconel 625 and monolithic silicon carbide rub surfaces, the wafers experienced very little wear and showed few signs of material build up on their sealing surfaces. These smooth surfaces produced lower leakage rates. For the leakage tests performed after hot scrub testing against C/SiC, much more material built up on the surface of the wafers and contributed to higher leakage rates, as discussed earlier.

Although the leakage rates reported in Fig. 15 are higher than those measured previously for the wafer seals, they are still lower than those for the lowest-leakage, textile-based seals.[6] As an example, the flow rate at 100 psig for a 0.6-in.-diameter braided rope seal with a core of uniaxial fibers (AC1 design) was 11 SCFM/in. with the seal under 20 percent compression. In comparison, the leakage rate at 100 psig for the AS800 wafers after 500 in. of scrubbing against C/SiC at 2200°F is still only 28% of that for the AC1 seal. Furthermore, the leakage rates for the AC1 seal design were measured with the seal in contact with a smooth aluminum cover plate while those for the AS800 wafer seal were measured against a rough C/SiC panel.

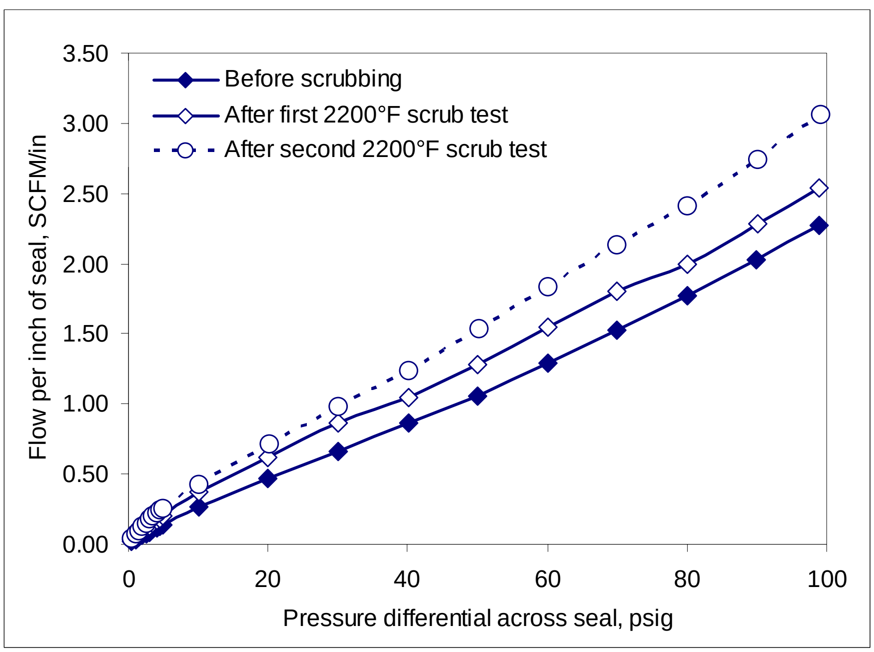


Figure 15. AS800 wafer seal flow rates versus pressure differential before and after hot scrub testing against C/SiC at 2200°F. Gap size = 0.100 in.

C. Flow Test Results: Recessed Aluminum Wafer Seals

Flow versus pressure data are presented in Fig. 16 for three tests each on the new recessed wafer seal design and the standard wafer without recesses. Both sets of wafers were nominally 0.5 in. wide, 0.92 in. tall, and 0.25 in. thick and were tested against a smooth stainless steel cover plate. Figure 16 shows that the flow rates for both sets of wafers fell roughly in the same range. It is unclear why the data diverged at pressures above 70 psig with half of the tests exhibiting a flow versus pressure line that remained relatively linear and the other half showing curves whose flow rates ramped up at a higher rate. Additional tests are being performed to try to better understand the sources of this behavior. Comparing flow data for the recessed wafers against a smooth cover plate (Fig. 16) to wafers tested against a CMC sealing surface (Fig. 15) one can see the effect on leakage due to the uneven, rough CMC surface.

Based on the finding that the leakage rates for the recessed wafers were comparable to those for the standard wafer seal design, this new design shows promise for meeting the needs of future applications. As mentioned previously, the recessed wafers may be implemented to help overcome problems in which adjacent wafers stuck together when scrubbed against C/SiC panels with coatings on their surfaces. The recessed areas on each side of the wafers would minimize the regions where glass could accumulate between adjacent wafers and lessen the tendency for them to stick together when in contact with CMC panels. The recessed areas provide another benefit for reducing friction between wafers. The recesses should allow some of the pressure behind the wafers to move between adjacent wafers and serve as a hydrostatic cushion of air to reduce friction between them and allow them to move more easily with respect to each other to seat against the opposing sealing surface.

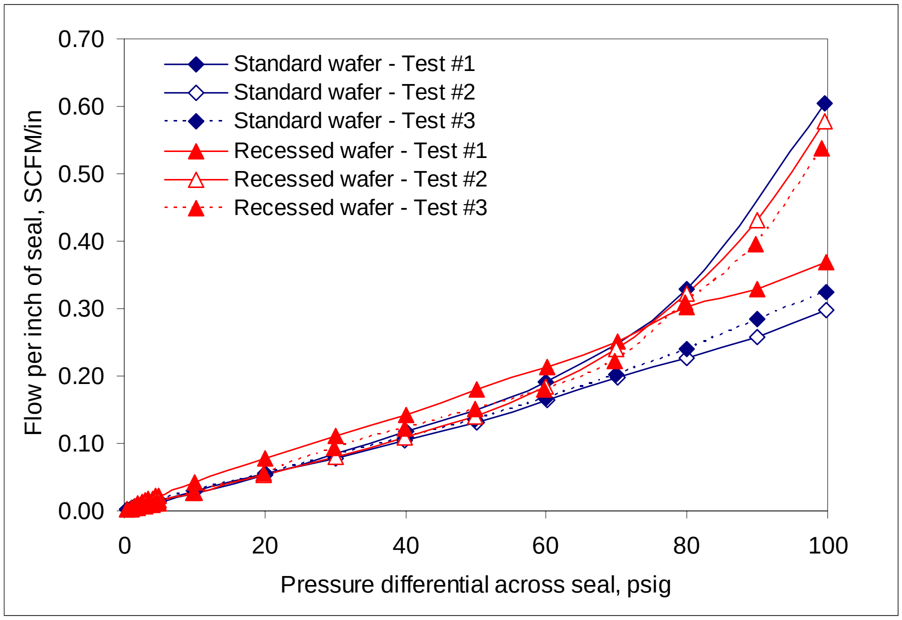


Figure 16. Flow rates versus pressure differential for standard wafers and recessed wafers for gap size of 0.125 in.

D. Alternative Wafer Materials

As mentioned previously, AS800 silicon nitride is no longer commercially available, so other materials must be identified for future wafer seal implementations. Another factor driving the need to identify alternative wafer seal materials is the high friction loads recorded during the scrub tests between AS800 wafers and C/SiC rub surfaces at 2200°F. If a material can be identified that slides more smoothly against C/SiC and other CMC materials, use of that material can help reduce friction loads that the wafer seals generate against sealing surfaces made of CMC materials.

Table 1 lists a number of candidate materials for future wafer seals along with their properties where known and the vendors that supply them. The properties for AS800 are also provided as a reference to compare against those for other materials. All of these materials are currently under consideration as a replacement for AS800, and different materials may be selected for different applications. For applications in which the wafers must be extremely durable, the two silicon nitride materials may be considered along with Hexoloy SP silicon carbide, the materials developed by 3-One-2, and mullite.

For applications in which the wafer seals may be somewhat more expendable, less durable seal materials may be employed. One candidate material is Ultra Temp Foam 50 (Foundry Service & Supply, Inc.), a type of fused silica insulating block often used in furnaces and in the foundry industry. This material has a uniform, open cell structure, excellent thermal insulating properties, and exceptional resistance to thermal shock. Due to its foamed, open cell structure, Foam 50 is not as hard as AS800. A concern has been expressed that hard wafers (such as those made of AS800) could damage coatings on structures made of CMC materials (e.g., flaps, panels). This concern could be addressed by using “sacrificial” wafers made of Foam 50 that slowly wear away as they are scrubbed against CMC sealing surfaces to minimize damage to these expensive structures. Foam 50 is also less dense than AS800, so wafers made of Foam 50 would weigh less than comparably sized wafers made of AS800. Another benefit is that Foam 50 is less expensive than AS800.

Table 1: Properties for various candidate wafer seal materials

Material	Manufacturer	Density	Poisson Ratio	Elastic Modulus	RT Flexure Strength (4-pt)	Weibull Modulus	Fracture Toughness	CTE	Thermal Conductivity
		(g/cm^3)		(GPa)	(MPa)		($MPa*m^{1/2}$)	($10^{-6}/°C$)	(W/m-K)
Silicon Nitride Materials									
AS800[7]	Honeywell	3.3	0.28	310	588 - 689	20	8.1	3.9	80
NT-154[8]	Saint Gobain	3.22	0.27	310	630 - 1000	10-15	5.5 - 6.0	2.4	37.6
SN240[9]	Kyocera	3.3	0.28	300	1020		7.0	2.8	27
Other Materials									
Hexoloy SP[10] SiC	Saint Gobain	3.04	0.14	400	240	19	4.3	4.2	110
Ti_3SiC_2 [11]	3-One-2	4-5		270-320	250 - 400		6 - 9	8 - 12	30 - 45
Ti_2AlC [11]	3-One-2	4-5		270-320	250-400		6 - 9	8 - 12	30 - 45
Mullite[12] $3Al_2O_3$-$2SiO_2$	CoorsTek	2.8		150	170		2	5.3	3.5
Ultra Temp Foam 50[13] Porous silica	Foundry Service & Supplies, Inc.	0.74-0.87		4.8-5.5				7.2	1.2 - 2.6

IV. Summary and Conclusions

Future hypersonic vehicles will require high temperature, dynamic seals in advanced ramjet/scramjet engines and on the vehicle airframe to seal the perimeters of movable panels, flaps, and doors. Seal temperatures in these locations can exceed 2000°F, especially when the seals are in contact with hot CMC sealing surfaces. A ceramic wafer seal design developed by NASA GRC is a strong candidate to meet the needs of these applications. Previous hot scrub tests and room temperature flow tests performed on AS800 ceramic wafer seals were all conducted against relatively smooth surfaces such as Inconel 625 or monolithic silicon carbide. To evaluate the interaction between AS800 wafers and rough CMC materials that may be employed as sealing surfaces on future hypersonic vehicles, a series of hot scrub tests and room temperature flow tests were performed between the wafers and C/SiC panels. GRC also recently learned that the AS800 material used in the most recent wafer seal performance studies is no longer commercially available; therefore alternative materials must be identified for future wafer seal implementations. Based on the results of these tests and other research, the following conclusions were made:

1. High friction loads were observed between AS800 silicon nitride wafer seals and C/SiC rub surfaces during a scrub test at 2200°F. Inspections of the wafers after testing revealed evidence of adhesive wear with material transfer from the rub surfaces to the wafers. The wafer seals remained quite durable, though, as none of them chipped or broke during testing. Additional work must be done to minimize the friction forces between the wafers and CMC sealing surfaces for future wafer seal applications.
2. Flow rates for the AS800 wafer seals against the C/SiC rub panels were higher than those recorded previously against smooth sealing surfaces. This was likely due to the uneven surface and roughness of the C/SiC panels and the wear material that built up on the surface of the wafers during scrub testing. Although these leakage rates were higher, they were still only 28% of those recorded for the best textile-based seals.
3. A new wafer seal design with recessed areas on the sides of the wafers exhibited comparable flow rates as those for the baseline wafer design without recesses. By minimizing the regions where glass could accumulate between adjacent wafers, the recessed design should lessen the tendency for wafers to stick together when in contact with coatings on surfaces made of CMC materials. The recesses should also allow some of the pressure behind the wafers to move between adjacent wafers and serve as a hydrostatic cushion of air to reduce friction between them and allow them to seat better against the opposing sealing surface. Based on these results, the recessed wafer design should be pursued further.

References

[1]Steinetz, B.M., DellaCorte, C., Machinchick, M., Mutharasan, R., Du, G., Ko, F, Sirocky, P.J., and Miller, J.H., "High Temperature Dynamic Engine Seal Technology Development," NASA TM–105641, April 1992.

[2]Dunlap, P.H., Steinetz, B.M., and DeMange, J.J., "Further Investigations of Hypersonic Engine Seals," NASA/TM—2004-213188, August 2004.

[3]DeMange, J.J., Dunlap, P.H., and Steinetz, B.M., "Advanced Control Surface Seal Development for Future Space Vehicles," NASA/TM-2004-212898, January 2004.

[4]Dunlap, P.H., Steinetz, B.M., and DeMange, J.J., "High Temperature Propulsion System Structural Seals for Future Space Launch Vehicles," NASA/TM-2004-212907, January 2004.

[5]Dunlap, P.H., Finkbeiner, J.R., Steinetz, B.M., and DeMange, J.J., "Design Study of Wafer Seals for Future Hypersonic Vehicles," NASA/TM-2005-213858, October 2005.

[6]Dunlap, P.H., Steinetz, B.M., DeMange, J.J., and Taylor, S.C., "Toward an Improved Hypersonic Engine Seal," NASA/TM-2003-212531, July 2003.

[7]AS800 Silicon Nitride Technical Data Sheet, Honeywell International, Inc.

[8]NT154 Silicon Nitride Technical Data Sheet, Saint-Gobain Ceramics & Plastics, Dec. 2005.

[9]"Characteristics of Kyocera Technical Ceramics," Kyocera Corporation, Jan. 2006.

[10]Hexoloy SP Silicon Carbide Technical Data Sheet, Saint-Gobain Ceramics, Oct. 2003.

[11]Maxthal Data Sheet, 3-One-2 LLC.

[12]Ceramic Material Properties Chart, CoorsTek, Inc., 2005.

[13]Insulating Foam 50 Technical Data Sheet, Foundry Service & Supplies, Inc.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
November 2006

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Performance Evaluations of Ceramic Wafer Seals

5. FUNDING NUMBERS
WBS 599489.02.07.03.06

6. AUTHOR(S)
Patrick H. Dunlap, Jr., Jeffrey J. DeMange, and Bruce M. Steinetz

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–15696

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM—2006-214416
AIAA–2006–4934

11. SUPPLEMENTARY NOTES
Prepared for the 42nd Joint Propulsion Conference and Exhibit, cosponsored by the AIAA, ASME, SAE, and ASEE, Sacramento, California, July 9–12, 2006. Jeffrey J. DeMange, University of Toledo, 2801 W. Bancroft Street, Toledo, Ohio 43606; and Patrick H. Dunlap, Jr. and Bruce M. Steinetz, NASA Glenn Research Center. Responsible person, Patrick H. Dunlap, Jr., organization code RXM, 216–433–3017.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 37
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Future hypersonic vehicles will require high temperature, dynamic seals in advanced ramjet/scramjet engines and on the vehicle airframe to seal the perimeters of movable panels, flaps, and doors. Seal temperatures in these locations can exceed 2000 °F, especially when the seals are in contact with hot ceramic matrix composite sealing surfaces. NASA Glenn Research Center is developing advanced ceramic wafer seals to meet the needs of these applications. High temperature scrub tests performed between silicon nitride wafers and carbon-silicon carbide rub surfaces revealed high friction forces and evidence of material transfer from the rub surfaces to the wafer seals. Stickage between adjacent wafers was also observed after testing. Several design changes to the wafer seals were evaluated as possible solutions to these concerns. Wafers with recessed sides were evaluated as a potential means of reducing friction between adjacent wafers. Alternative wafer materials are also being considered as a means of reducing friction between the seals and their sealing surfaces and because the baseline silicon nitride wafer material (AS800) is no longer commercially available.

14. SUBJECT TERMS
Seals; Flow; Design; Test; High temperature

15. NUMBER OF PAGES
19

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	