HIGH TEMPERATURE PROPULSION SYSTEM STRUCTURAL SEALS FOR FUTURE SPACE LAUNCH VEHICLES

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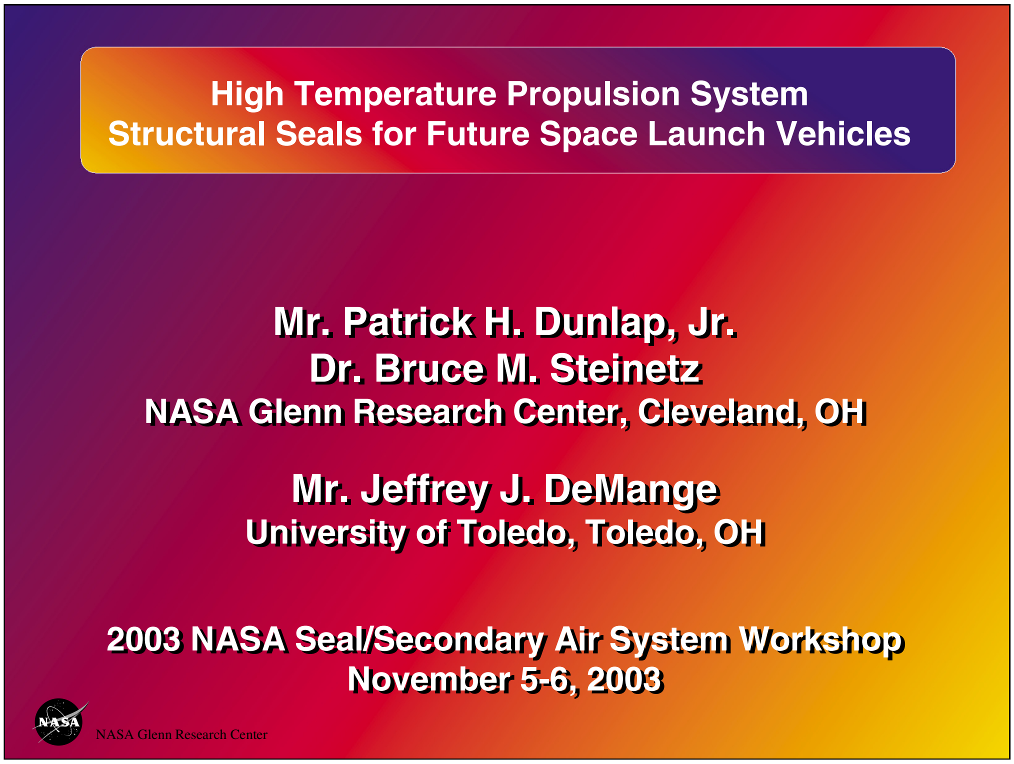

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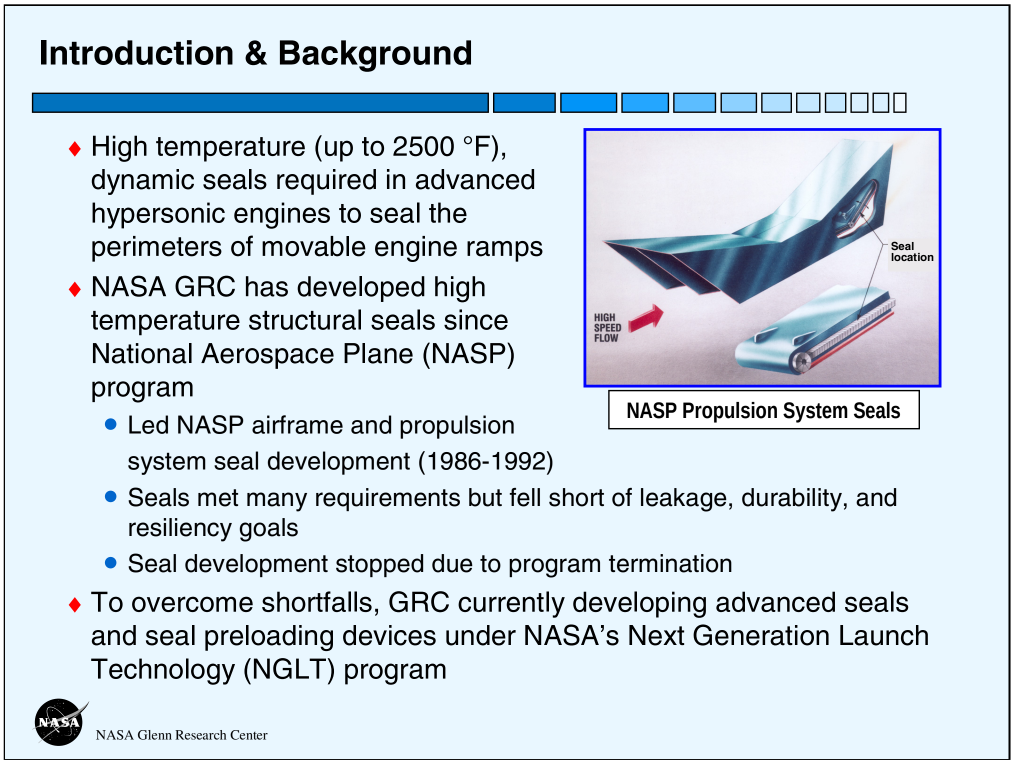

Introduction & Background

- High temperature (up to 2500 °F), dynamic seals required in advanced hypersonic engines to seal the perimeters of movable engine ramps
- NASA GRC has developed high temperature structural seals since National Aerospace Plane (NASP) program
  - Led NASP airframe and propulsion system seal development (1986-1992)
  - Seals met many requirements but fell short of leakage, durability, and resiliency goals
  - Seal development stopped due to program termination
- To overcome shortfalls, GRC currently developing advanced seals and seal preloading devices under NASA's Next Generation Launch Technology (NGLT) program

NASP Propulsion System Seals

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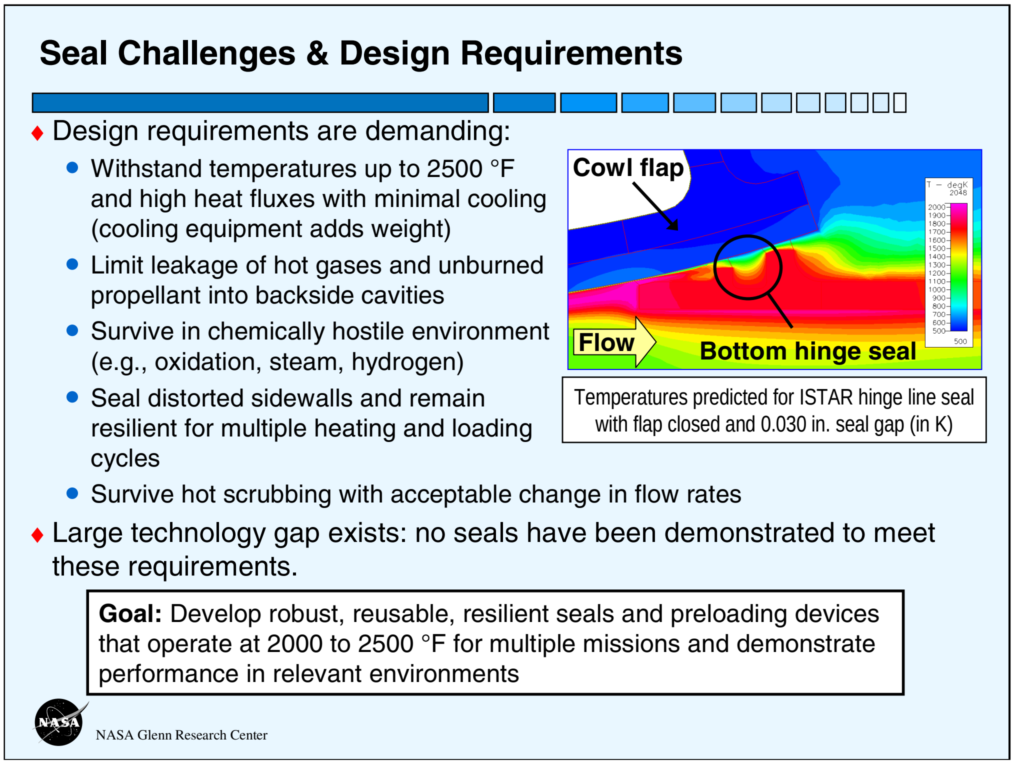
High temperature, dynamic structural seals are required in advanced hypersonic engines to seal the perimeters of movable engine ramps for efficient, safe operation in high heat flux environments at temperatures from 2000 to 2500 °F. NASA GRC became involved in the development of high temperature structural seals in the late 1980's and early 1990's during the National Aerospace Plane (NASP) program. Researchers at GRC carried out an in-house program to develop seals for the NASP hypersonic engine and oversaw industry efforts for airframe and propulsion system seal development for this vehicle. The figure shows one of the seal locations in the NASP engine. Seals were needed along the edges of movable panels in the engine to seal gaps between the panels and adjacent engine sidewalls.

Seals developed during the NASP program met many requirements but fell short of leakage, durability, and resiliency goals. Due to program termination the seals could not be adequately matured. To overcome these shortfalls, GRC is currently developing advanced seals and seal preloading devices for the hypersonic engines of future space vehicles as part of NASA's Next Generation Launch Technology (NGLT) program.



Seal Challenges & Design Requirements

- Design requirements are demanding:
  - Withstand temperatures up to 2500 °F and high heat fluxes with minimal cooling (cooling equipment adds weight)
  - Limit leakage of hot gases and unburned propellant into backside cavities
  - Survive in chemically hostile environment (e.g., oxidation, steam, hydrogen)
  - Seal distorted sidewalls and remain resilient for multiple heating and loading cycles
  - Survive hot scrubbing with acceptable change in flow rates
- Large technology gap exists: no seals have been demonstrated to meet these requirements.

Temperatures predicted for ISTAR hinge line seal with flap closed and 0.030 in. seal gap (in K)

Goal: Develop robust, reusable, resilient seals and preloading devices that operate at 2000 to 2500 °F for multiple missions and demonstrate performance in relevant environments

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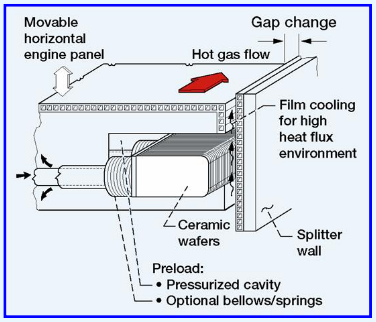
Hypersonic engine seals have a demanding set of design requirements. As engine systems are developed for future vehicles, seal temperatures are expected to increase to as much as 2000 to 2500 °F. To meet engine performance, safety, and life goals, the seals must withstand these extreme temperatures with minimal active cooling to limit the need for complex, heavy seal purge cooling systems. Engine seals must limit the leakage of hot, pressurized (~100 psi) gases and unburned propellant into backside cavities to prevent explosive mixtures from forming there. The seals must operate in an oxidizing/steam environment and resist hydrogen embrittlement if hydrogen is used as a propellant. Structural and thermal loads on the engine sidewalls can cause distortions that the seals must accommodate. To stay in contact with the walls, the seals must remain resilient and flexible for multiple heating cycles. The seals will also be rubbed over these distorted, rough walls as the engine panels holding the seals are actuated. The seals must survive the hot scrubbing without incurring increases in leakage due to wear.

A large technology gap exists because no seals have been demonstrated to meet these challenging requirements. It is GRC’s goal to develop robust, reusable resilient seals and preloading devices that meet these requirements for multiple missions and demonstrate their performance in relevant environments.

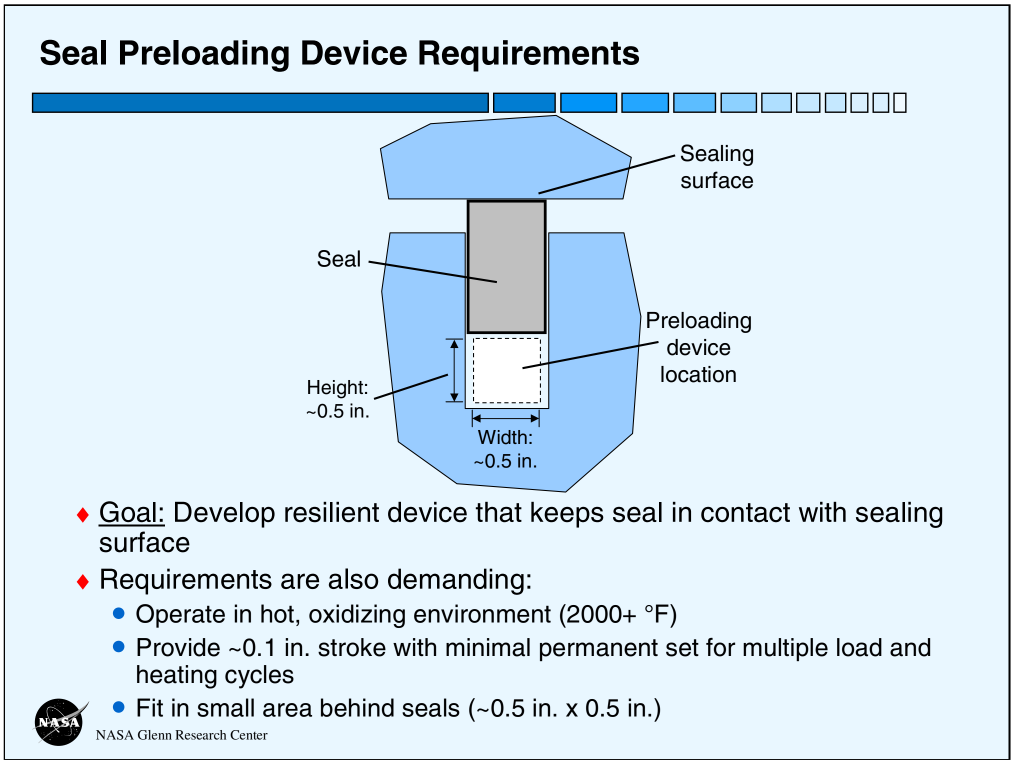
Seal Specimens



- Ceramic wafer seals originally developed during NASP program
  - Preloading device behind wafers maintains contact with sealing surface
  - Evaluated several wafer materials: aluminum oxide, silicon carbide, silicon nitride
- Current design:
  - Material: monolithic silicon nitride (Honeywell AS800)
  - Size: 0.5 in. wide x 0.92 in. long x 0.125 in. thick

Ceramic wafer seals were originally developed during the NASP program. They are composed of a series of thin ceramic wafers installed in a channel in a movable panel and preloaded from behind to keep them in contact with the opposing sealing surface. Materials that were evaluated for the wafer seals during the NASP program included a cold-pressed and sintered aluminum oxide, a sintered alpha-phase silicon carbide, a hot-isostatically-pressed silicon nitride, and a cold-pressed and sintered silicon nitride. A detailed analytical comparison of all the materials that were considered ranked the advanced silicon nitride ceramics as the most promising material for future consideration.

Given that these tests were performed in the late 1980’s, considerable improvements have been made since then to produce stronger and tougher ceramic materials. Because of these improvements and the high ranking of silicon nitride as a candidate wafer seal material, GRC selected silicon nitride as the best candidate for these seals. The wafers tested in the current study were made of monolithic silicon nitride (Honeywell AS800) and were 0.5-in. wide, 0.92-in. tall, and 0.125 in. thick. They had corner radii of 0.050 in.



Seal Preloading Device Requirements

- ♦ Goal: Develop resilient device that keeps seal in contact with sealing surface
- ♦ Requirements are also demanding:
  - Operate in hot, oxidizing environment (2000+ °F)
  - Provide ~0.1 in. stroke with minimal permanent set for multiple load and heating cycles
  - Fit in small area behind seals (~0.5 in. x 0.5 in.)

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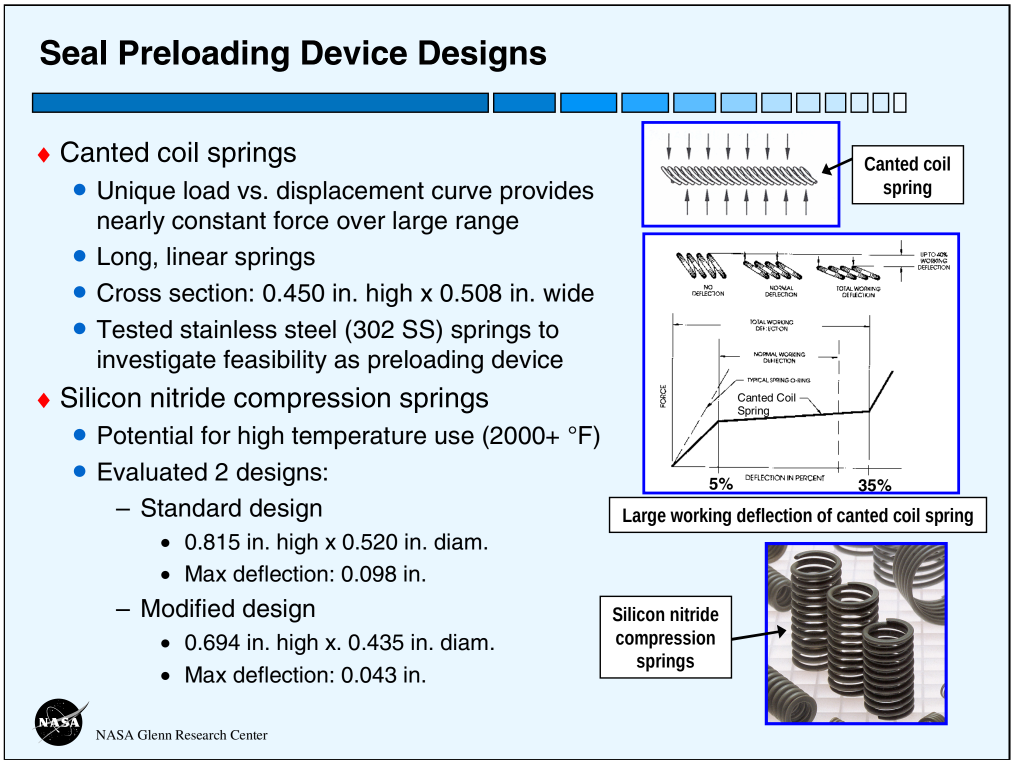
The high temperature seal preloading devices that are being developed and evaluated would be installed behind the seals to ensure sealing contact with the opposing sealing surfaces. The requirements for these devices are also quite challenging. They must operate in the same environment and temperature as the seals while providing the required stroke (nominally 0.1 in.) with a permanent set of less than 20 percent of that stroke for multiple loading and heating cycles. Complicating this effort further is the limited amount of space available for the preloader behind the seals. The cross sectional area of the device must fit in a space that would be about 0.5 in. wide by about 0.5 in. high. Ideally the device would be about as long as the seal and able to be installed around corners. The device must be stiff enough to support the seal and keep it pressed against the sealing surface but soft enough that it does not apply excessive loads to that surface.



Seal Preloading Device Designs

- Canted coil springs
  - Unique load vs. displacement curve provides nearly constant force over large range
  - Long, linear springs
  - Cross section: 0.450 in. high x 0.508 in. wide
  - Tested stainless steel (302 SS) springs to investigate feasibility as preloading device
- Silicon nitride compression springs
  - Potential for high temperature use (2000+ °F)
  - Evaluated 2 designs:
    - Standard design
      - 0.815 in. high x 0.520 in. diam.
      - Max deflection: 0.098 in.
    - Modified design
      - 0.694 in. high x. 0.435 in. diam.
      - Max deflection: 0.043 in.

Canted coil spring

Large working deflection of canted coil spring

Silicon nitride compression springs

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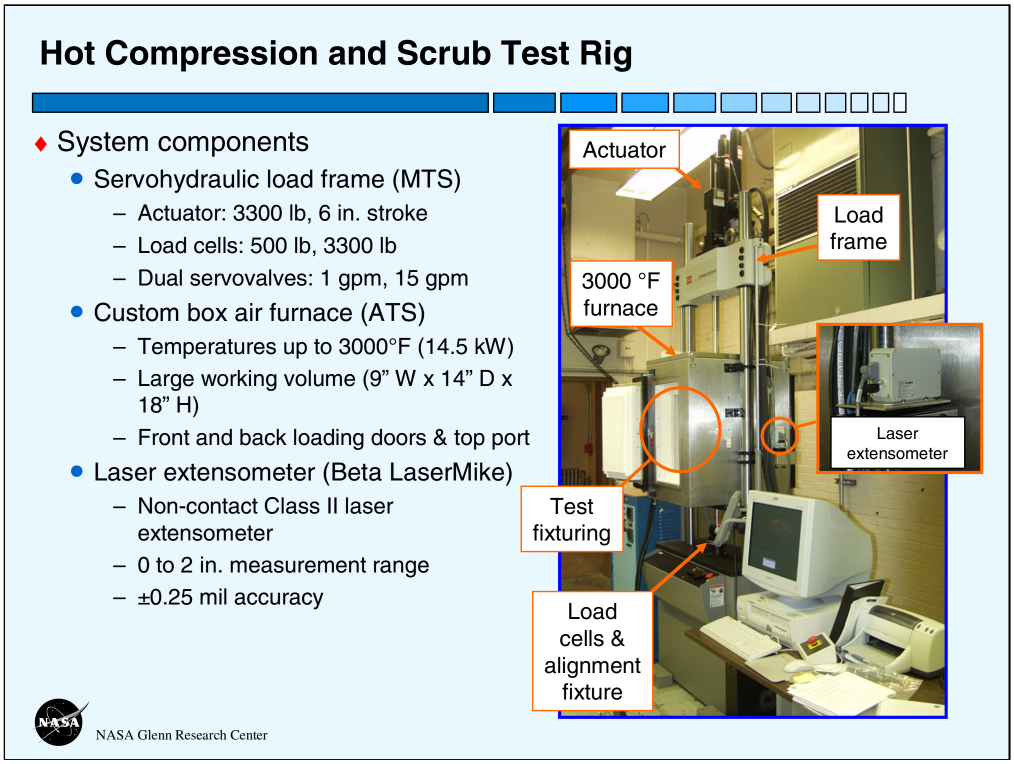
Two types of seal preloading devices were evaluated in this study. The first was a canted coil spring produced by Bal Seal Engineering Company, Inc. These springs have several unique features that could make them very good seal preloading devices. Unlike typical compression springs that generate increasing amounts of force as they are compressed, the force produced by canted coil springs remains nearly constant over a large deflection range. This is an appealing feature for a seal preloading device because it could provide a large amount of stroke and resiliency to a seal without applying excessive loads to the seal or the opposing sealing surfaces. Another advantageous feature of canted coil springs is that they are produced in long, linear lengths that would allow them to be installed in a groove directly behind a seal and potentially around corners. The baseline canted coil springs evaluated in this study were Bal Seal part number 109MB-(84)L-2 and were made of 302 stainless steel. Stainless steel springs were used to investigate the feasibility of this seal preloader concept.

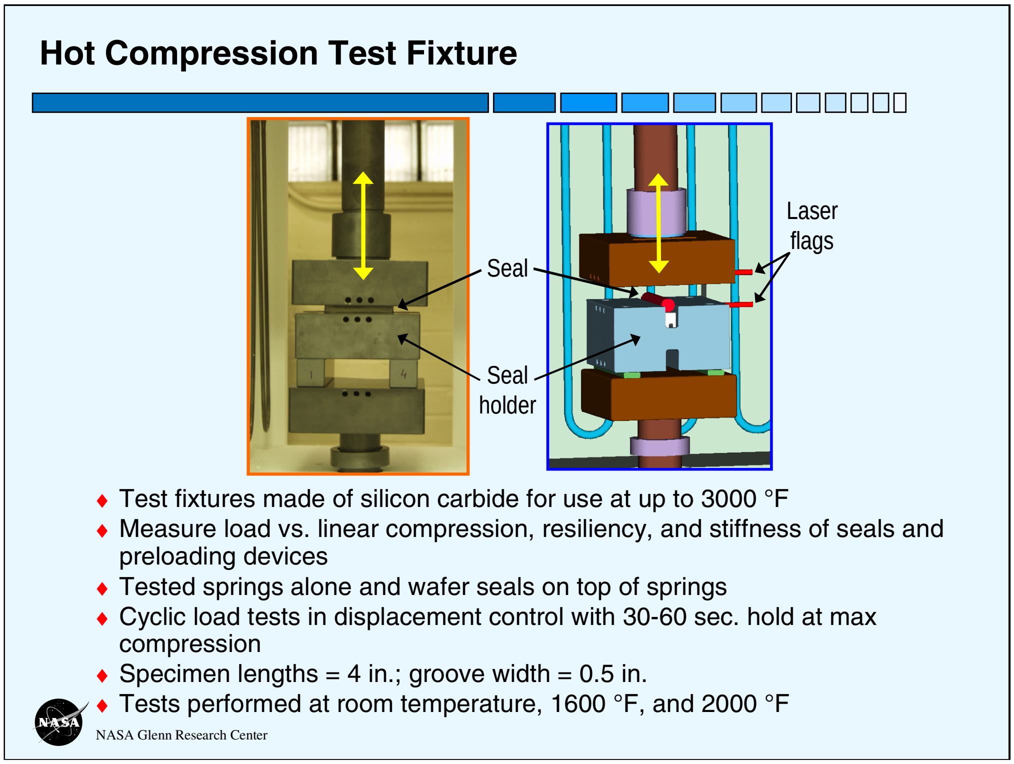
Another concept that was evaluated as a potential seal preloading device was a silicon nitride compression spring produced by NHK Spring Co., Ltd. Two different designs were tested: a standard spring and a modified design. Because they are made of silicon nitride, these springs have the potential to be used as high temperature (2000+ °F) seal preloading devices.



Hot Compression and Scrub Test Rig

- System components
  - Servohydraulic load frame (MTS)
    - Actuator: 3300 lb, 6 in. stroke
    - Load cells: 500 lb, 3300 lb
    - Dual servovalves: 1 gpm, 15 gpm
  - Custom box air furnace (ATS)
    - Temperatures up to 3000°F (14.5 kW)
    - Large working volume (9” W x 14” D x 18” H)
    - Front and back loading doors & top port
  - Laser extensometer (Beta LaserMike)
    - Non-contact Class II laser extensometer
    - 0 to 2 in. measurement range
    - ±0.25 mil accuracy

Compression tests and scrub tests were performed on the preloading devices and seals using a new state-of-the-art test rig at GRC. This test rig is capable of performing either high temperature seal compression tests or scrub tests at temperatures of 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. 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. The box furnace has a working volume that is 9 in. wide by 14 in. deep by 18 in. high. Test fixtures are configured inside the furnace so that the stationary base for each test setup sits on top of a loading rod on a load cell below the furnace. Two different load cell ranges are available, 500 lb or 3300 lb, depending on the seal that is being tested and the loads that are expected during a test. The 500 lb load cell has an accuracy of ± 0.15 lb (± 0.03% of full scale), and the accuracy of the 3300 lb load cell is ± 2.64 lb (± 0.08% of full scale). The load cells are used to measure compressive loads applied to the seals during a compression test or frictional loads on the seals during scrub testing. The laser extensometer was used to measure the amount of compression during testing. The laser system has a measurement range of up to 2 in. and an accuracy of ± 0.00025 in.



Hot Compression Test Fixture

- Test fixtures made of silicon carbide for use at up to 3000 °F
- Measure load vs. linear compression, resiliency, and stiffness of seals and preloading devices
- Tested springs alone and wafer seals on top of springs
- Cyclic load tests in displacement control with 30-60 sec. hold at max compression
- Specimen lengths = 4 in.; groove width = 0.5 in.
- Tests performed at room temperature, 1600 °F, and 2000 °F

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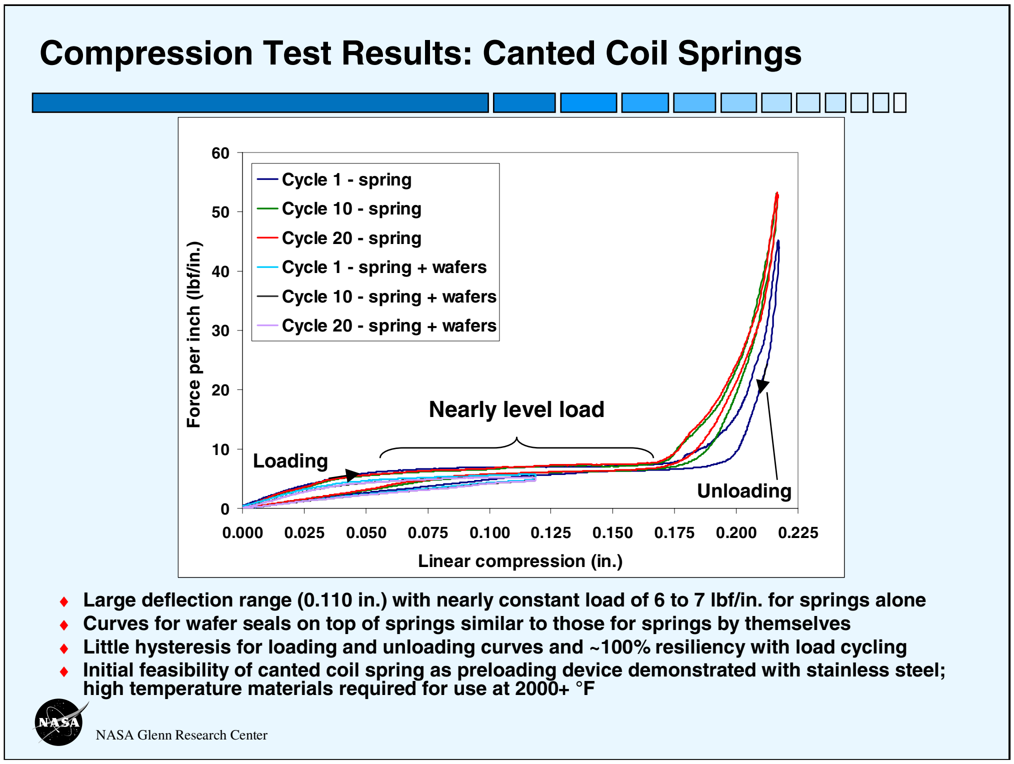
Compression tests were performed inside the furnace using this test set up. These tests were performed to determine the resiliency and stiffness of the preloading devices and to generate load versus displacement (i.e., linear compression) data. Test specimens were installed into a holder that rested on the stationary base described above. A movable platen attached to the actuator was translated up and down to load and unload the test specimens.

Compression tests were conducted at room temperature on the canted coil spring by itself and with a set of 31 wafer seals on top of a canted coil spring to see how the seals and spring performed together. Tests were conducted on individual silicon nitride compression springs at both room temperature and at 2000 °F. Tests were also performed with 31 wafer seals on top of a set of silicon nitride springs (modified spring design) to see how they performed together. These tests were performed at 1600 °F. Four springs were placed below the wafers on 1.15-in. centers. A thin load transfer element (0.02-in.-thick silicon carbide) was placed between the springs and the wafers to distribute the load from the four springs to the wafers.

Test specimens were typically loaded and unloaded for a total of 20 cycles for each test. The silicon nitride compression springs, however, were tested for 10 cycles. Each load cycle consisted of loading a test specimen at a rate of 0.001 in/sec to the specified amount of compression, holding at that compression level for 30 to 60 sec., and then unloading at 0.001 in/sec to the starting point. There was no hold time after the specimen was unloaded between load cycles.



Compression Test Results: Canted Coil Springs

- Large deflection range (0.110 in.) with nearly constant load of 6 to 7 lbf/in. for springs alone
- Curves for wafer seals on top of springs similar to those for springs by themselves
- Little hysteresis for loading and unloading curves and ~100% resiliency with load cycling
- Initial feasibility of canted coil spring as preloading device demonstrated with stainless steel; high temperature materials required for use at 2000+ °F

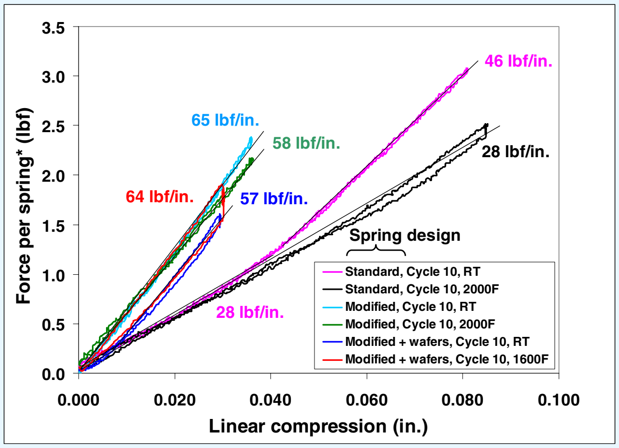
This is a representative plot of the compression test results for cycles 1, 10, and 20 of tests on a canted coil spring by itself and for a set of wafer seals on top of a spring. The initial portion of the loading curves for the spring by itself showed a gradual increase in force vs. linear compression up to a deflection of about 0.060 in. where the load leveled off at about 6 lbf/in. At this point, the curves flattened out and the force remained nearly constant until the spring deflection reached about 0.170 in. (38% of free height) and the coils began contacting each other. Over this 0.110 in. deflection range, the load slowly rose from 6 to 7 lbf/in. The force on the spring rose sharply beyond deflections of 0.170 in. This unique force vs. deflection curve is typical of a canted coil spring. The large deflection range in which the load remained nearly constant makes canted coil springs appealing as seal preloading devices because they could provide a large amount of stroke and resiliency to a seal without applying excessive loads to the seal or the opposing sealing surfaces.

Results for a room temperature compression test performed using a set of 31 wafer seals on top of a canted coil spring show that the loading and unloading curves for this test were very similar to those for the spring by itself, and there was little hysteresis in the curves. The results of this test also showed no permanent set or loss of resiliency as load cycles 1 and 20 were almost identical.

This series of tests on stainless steel canted coil springs demonstrated the initial feasibility of using this type of spring as a seal preloading device. The authors recognize that the springs would have to be made out of a different material for applications at 2000+ °F.

Compression Test Results: Silicon Nitride Compression Springs

*Note: 4 springs tested under wafer seals; 1 spring used for other tests



- No permanent set at room temperature, 1600 °F, or 2000°F for any test
- Little hysteresis for tests of springs alone
- Some hysteresis for wafer seals on top of springs; possibly due to friction between wafers and groove side walls
- 2000°F testing had more effect on standard springs than on modified design
- Springs show promise for use as high temperature seal preloading devices

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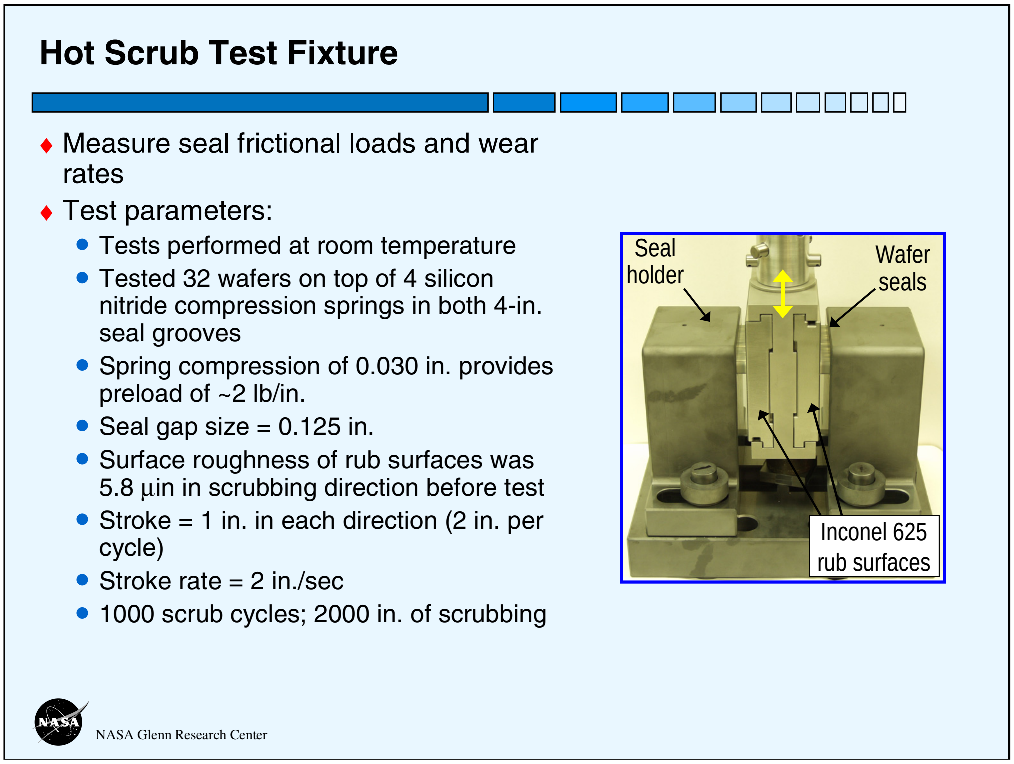
This figure shows the results of the compression tests performed on the silicon nitride compression springs with and without wafer seals installed on top of them. In all of these tests there was no permanent set or relaxation observed after 10 load cycles at room temperature, 1600 °F, or 2000 °F. For clarity, the figure only shows the curves for cycle 10 of each test because they were almost identical to the curves for all other load cycles. For all of the tests performed on the silicon nitride springs by themselves, there was very little hysteresis in their load vs. linear compression data. For the tests performed with seals on top of the springs, there was virtually no hysteresis for the room temperature tests but a small amount for the tests at 1600 °F. It is possible that during the high temperature test, there was some small amount of friction between the wafers and the side walls of the seal groove that caused this hysteresis as the wafers and springs were unloaded during each load cycle.

Spring constants for each test case are also shown. The modified spring design had a spring constant of 65 lbf/in. at room temperature and 58 lbf/in. at 2000 °F, indicating that the springs were slightly less stiff at high temperatures. The elastic modulus of silicon nitride at 2000 °F is about 5% lower than it is at room temperature which helps explain this behavior. The standard spring design showed a different type of loading behavior, though. Its load versus linear compression curve at room temperature had two different regions. In the linear compression range up to about 0.040 in., the standard spring had a spring constant of about 28 lbf/in. From 0.040 in. to 0.083 in., the spring became stiffer with a spring constant of 46 lbf/in. This type of behavior did not occur during the test at 2000 °F, though, as the spring constant remained at 28 lbf/in throughout the test.

Overall, these results show that the silicon nitride springs show promise for use as high temperature seal preloading devices.



Hot Scrub Test Fixture

- Measure seal frictional loads and wear rates
- Test parameters:
  - Tests performed at room temperature
  - Tested 32 wafers on top of 4 silicon nitride compression springs in both 4-in. seal grooves
  - Spring compression of 0.030 in. provides preload of ~2 lb/in.
  - Seal gap size = 0.125 in.
  - Surface roughness of rub surfaces was 5.8 µin in scrubbing direction before test
  - Stroke = 1 in. in each direction (2 in. per cycle)
  - Stroke rate = 2 in./sec
  - 1000 scrub cycles; 2000 in. of scrubbing

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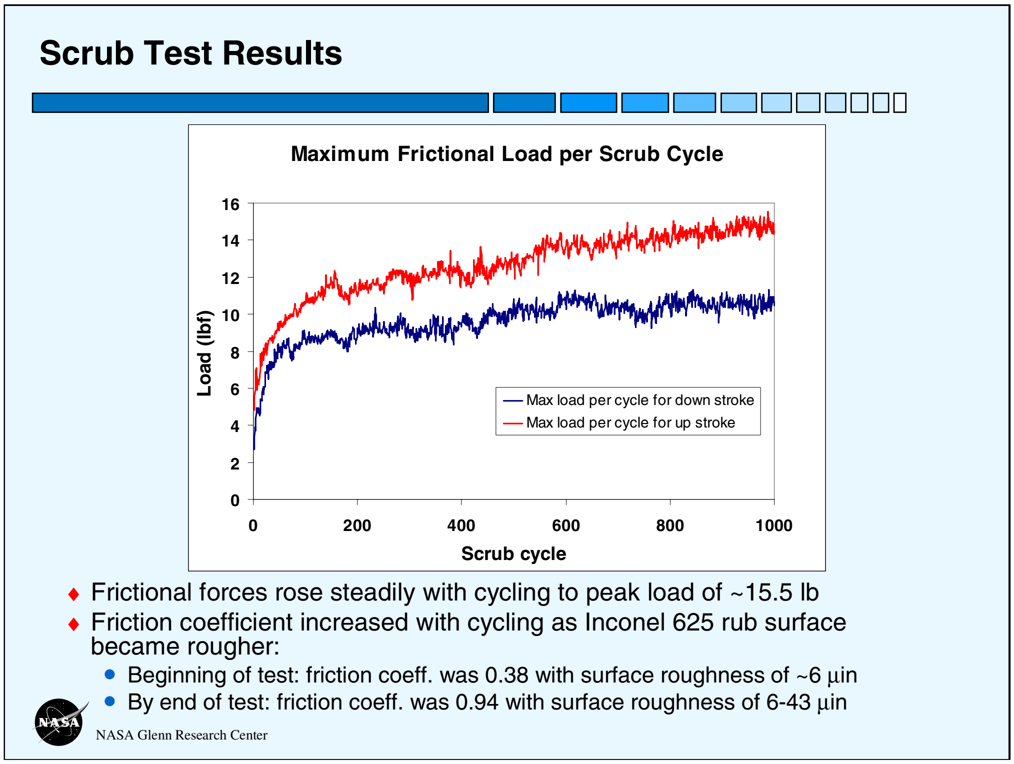
The main test rig that was used for the compression tests was also used to perform scrub tests on the seals using this set of test fixtures. Tests were performed at room temperature to evaluate seal wear rates and frictional loads as the seals were scrubbed against Inconel 625 rub surfaces. The rub surfaces had an average surface roughness before testing of about 6 µin in the scrubbing direction and 3 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 through the upper load train to the actuator. The gaps between the rub surfaces and the seals were set by spacer shims in front of and behind the seal holders. A gap size of 0.125 in. was used for these tests.

Four silicon nitride compression springs (modified spring design) were installed in the bottom of each seal groove to keep the wafer seals preloaded against both rub surfaces. A load transfer 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 (0.030 in.) 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 triangle wave was used with a stroke length of 1 in. in each direction and a stroke rate of 2 in./sec. There was no hold time between scrub direction changes. The seals were subjected to 1000 scrub cycles at 1 Hz for a total scrub length of 2000 in. for each test. Frictional loads were measured by the load cell 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 seal weight changes and changes in flow rates.



Scrub Test Results

- Frictional forces rose steadily with cycling to peak load of ~15.5 lb
- Friction coefficient increased with cycling as Inconel 625 rub surface became rougher:
  - Beginning of test: friction coeff. was 0.38 with surface roughness of ~6 µin
  - By end of test: friction coeff. was 0.94 with surface roughness of 6-43 µin

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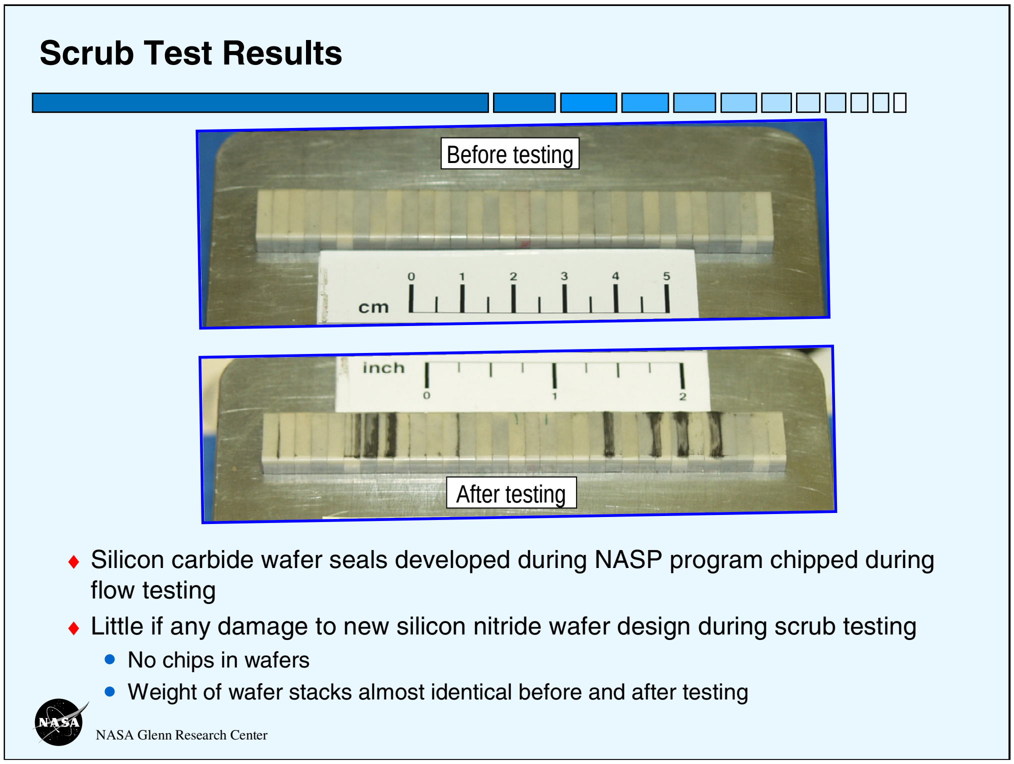
Peak frictional loads during the up and down strokes of each scrub cycle are presented in this figure for the room temperature scrub test. During this test, the frictional loads started around 6 lbf at the beginning of the test and gradually rose as the test proceeded until they reached about 15.5 lbf by the end of the test. The seals were installed so that the springs behind them provided a load against the Inconel 625 rub surfaces of about 2 lbf/in. over both 4-in. seal lengths. This resulted in a normal load of 16 lbf during testing. Based on this normal load, the friction coefficient from about 0.4 to almost 1.0 by the end of the test. Before this scrub test, the average surface roughness of the rub surfaces was about 6 µin in the scrubbing direction and 3 µin in the transverse direction. After testing, the surface roughness had risen to a range of 6 to 43 µin in both directions. This increase in surface roughness during testing likely contributed to the increase in frictional forces as the test proceeded.



Scrub Test Results

- Silicon carbide wafer seals developed during NASP program chipped during flow testing
- Little if any damage to new silicon nitride wafer design during scrub testing
  - No chips in wafers
  - Weight of wafer stacks almost identical before and after testing

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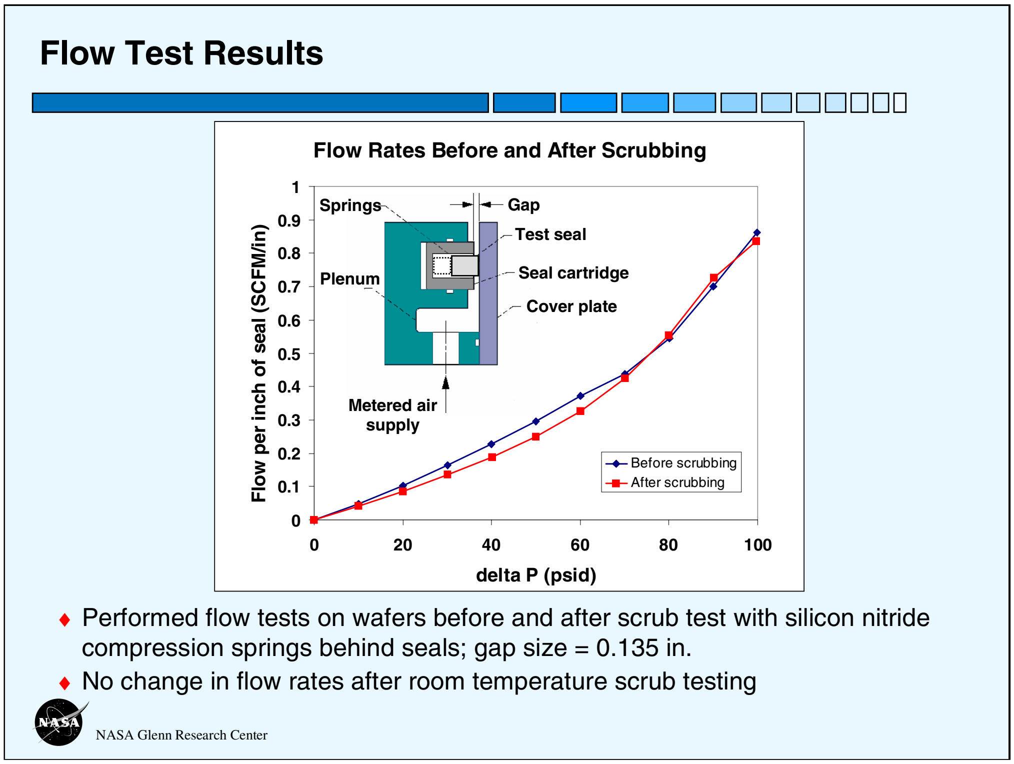
After the scrub test was completed, the seals and rub surfaces were inspected for signs of damage. These figures show what the seals looked like before and after scrubbing. The seals showed little if any damage after testing. Wear debris from the rub surface can be seen on some of the wafers in locations that correspond to areas on the rub surface that were worn during the test. None of the wafers were chipped or broken during testing, and the total weight of both wafer sets before and after testing was almost identical. Silicon carbide wafer seals tested during the NASP program were much more damage-prone and chipped during static flow testing even without scrubbing. The silicon nitride wafers tested in the current study appear to be much more robust and damage-resistant.



Flow Test Results

- Performed flow tests on wafers before and after scrub test with silicon nitride compression springs behind seals; gap size = 0.135 in.
- No change in flow rates after room temperature scrub testing

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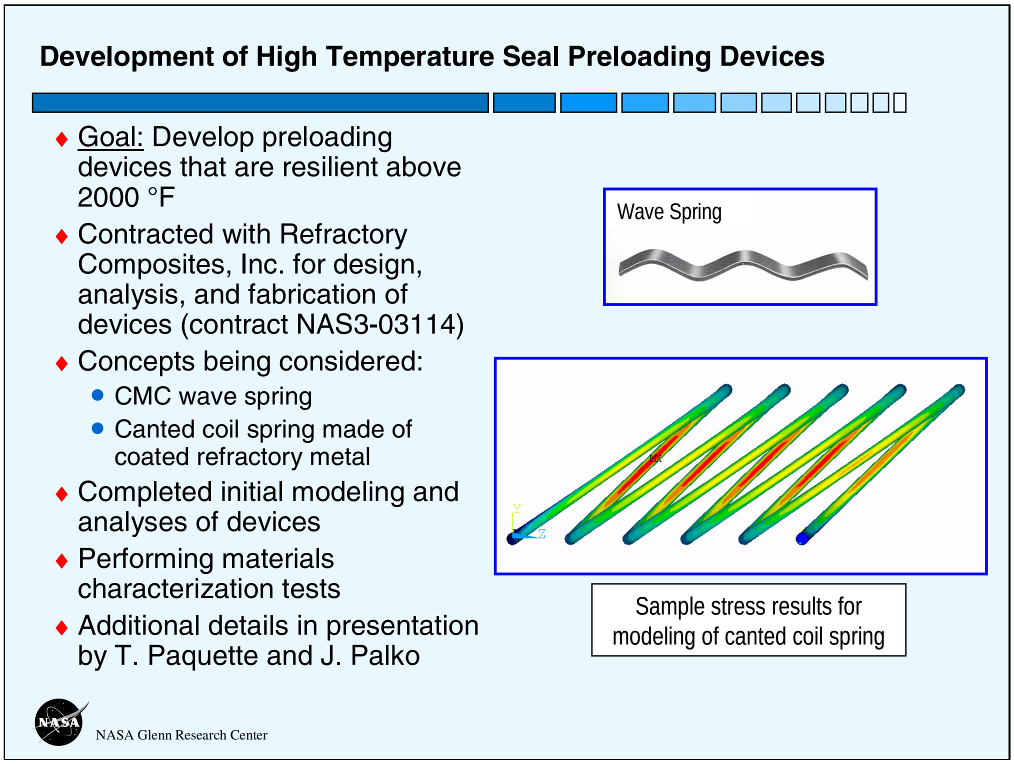
Flow test results for the wafer seals before and after scrub testing are presented here for a gap size of 0.135 in. These tests were performed with four silicon nitride springs installed behind the wafers to keep them preloaded against the cover plate. Flow rates for the wafers before and after scrubbing were almost identical in both cases. This is consistent with the observation that the wafers were not damaged during the scrub test. These results are encouraging because they show that the seals are still effective at blocking flow even after 1000 scrub cycles at room temperature.



Development of High Temperature Seal Preloading Devices

- Goal: Develop preloading devices that are resilient above 2000 °F
- Contracted with Refractory Composites, Inc. for design, analysis, and fabrication of devices (contract NAS3-03114)
- Concepts being considered:
  - CMC wave spring
  - Canted coil spring made of coated refractory metal
- Completed initial modeling and analyses of devices
- Performing materials characterization tests
- Additional details in presentation by T. Paquette and J. Palko

Wave Spring

Sample stress results for modeling of canted coil spring

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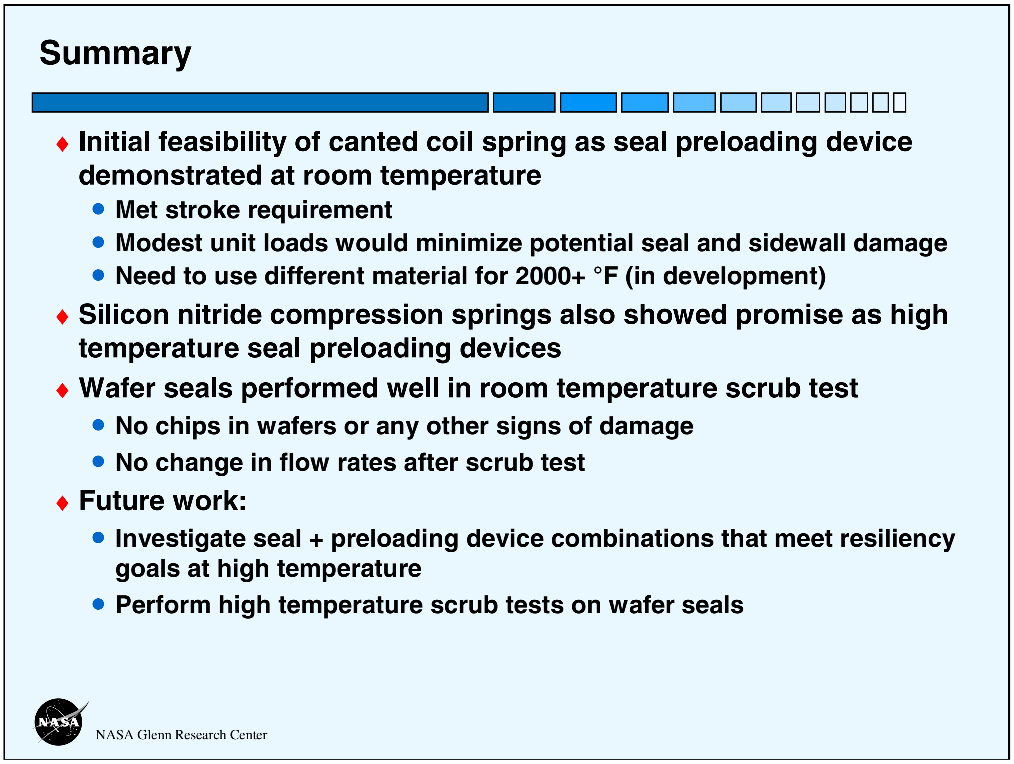
In this study, tests were performed on canted coil springs made of stainless steel to evaluate their performance at room temperature and assess the feasibility of using this type of spring as a seal preloading device. While the results of these tests were promising, higher temperature seal preloaders are required for future applications in which the temperature of the seals and preloading devices will reach 2000 to 2500 °F. Researchers at GRC have contracted with Refractory Composites, Inc. for the design, analysis, and fabrication of such devices. Two concepts are currently being considered: a ceramic matrix composite (CMC) wave spring and a canted coil spring made of a refractory metal with an oxidation coating. RCI and their subcontractor Connecticut Reserve Technologies, Inc. have completed the initial modeling and analyses for these devices and are currently performing materials characterization tests on candidate materials. Additional details on this effort will be shown later in the presentation by Ted Paquette and Joe Palko.



Summary

- **Initial feasibility of canted coil spring as seal preloading device demonstrated at room temperature**
  - **Met stroke requirement**
  - **Modest unit loads would minimize potential seal and sidewall damage**
  - **Need to use different material for 2000+ °F (in development)**
- **Silicon nitride compression springs also showed promise as high temperature seal preloading devices**
- **Wafer seals performed well in room temperature scrub test**
  - **No chips in wafers or any other signs of damage**
  - **No change in flow rates after scrub test**
- **Future work:**
  - **Investigate seal + preloading device combinations that meet resiliency goals at high temperature**
  - **Perform high temperature scrub tests on wafer seals**

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Based on the results of these tests, the following conclusions were made:

1. Canted coil springs are promising seal preloading devices. Room temperature compression tests performed with wafer seals on top of a spring showed that the spring met the stroke requirement with no permanent set or loss of resiliency for 20 load cycles. The modest unit loads produced by this type of spring would minimize potential damage to the seals and adjacent sealing surfaces. These feasibility tests were performed on springs made of stainless steel. High temperature materials will need to be used for applications at 2000+ °F.

2. Silicon nitride compression springs also show promise as high temperature seal preloading devices. After repeated loading at temperatures up to 2000 °F the springs showed little hysteresis and excellent resiliency.

3. Silicon nitride wafer seals performed very well in the room temperature scrub test. There were no signs of damage after the wafers were scrubbed against Inconel 625 rub surfaces at room temperature for 2000 in. of scrubbing (1000 cycles). None of the wafers were chipped or broken, and the total weight of each wafer set before and after testing was almost identical. Flow rates for the wafers before and after scrubbing were also almost identical.

More work needs to be done to investigate seal and preloading device combinations that ultimately satisfy all of the seal requirements. The authors plan to investigate other wafer shapes and sizes to see if those changes affect seal durability and frictional forces. Longer scrub tests will also be performed at high temperatures to examine seal durability for more than 1000 scrub cycles.