ADVANCED CONTROL SURFACE SEAL DEVELOPMENT FOR FUTURE SPACE VEHICLES

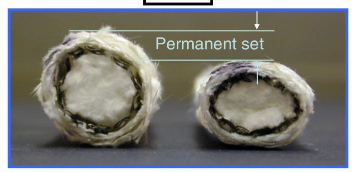
Jeffrey J. DeMange
University of Toledo
Toledo, Ohio

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

Control Surface Seal Challenges and Design Requirements

- Limit hot gas flow and heat transfer to underlying low-temperature structures
- Withstand temperatures of:
  - 2100 °F for tile-based TPS
  - 2600 °F for CMC control surfaces
- Stay resilient for multiple load/heating cycles
- Limit loads against sealing surfaces
- Resist scrubbing damage

X-37



Baseline Seal

Goal: Develop long life, high temperature control surface seals and demonstrate performance in relevant environments

NASA Glenn Research Center

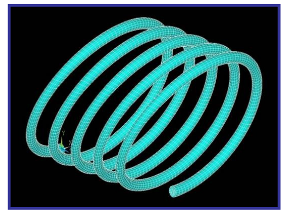
THE UNIVERSITY OF TOLEDO

High temperature control surface seals have been identified as a critical technology in the development of future space vehicles. These seals must withstand temperatures of up to 2600 °F and protect underlying temperature-sensitive structures (such as actuators and airframe components) from high heat fluxes. In addition, the seals must maintain their sealing capability by remaining resilient during flight conditions. The current baseline seal, used on the Shuttle orbiters and the X-38 vehicle, consists of a Nextel 312 sheath, an internal Inconel X-750 knitted spring tube, and hand-stuffed Saffil batting. Unfortunately at high temperatures (> 1500 °F), the seal resiliency significantly degrades due to yielding and creep of the spring tube element. The permanent set in the seals can result in flow passing over the seals and subsequent damage to temperature sensitive components downstream of the seals. Another shortcoming of the baseline seal is that instances have been reported on Shuttle flights where some of the hand-stuffed Saffil batting insulation has been extracted, thus potentially compromising the seal. In vehicles where the thermal protection systems are delicate (such as with Shuttle tiles), the control surface seals must also limit the amount of force applied to the opposing surfaces. Additionally, in many applications the seals are subjected to scrubbing as control surfaces are actuated. The seals must be able to withstand any damage resulting from this high temperature scrubbing and retain their heat/flow blocking abilities.

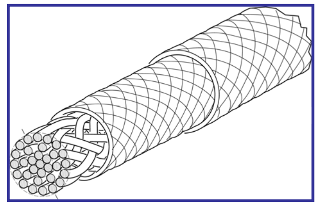
Control Surface Seal
Advanced Design Approaches

Improvements to…

- **Resiliency**
  - Spring Tube
    - Materials – ODS superalloys (MA 754, PM 2000)
    - Architecture – Wire diam., knit pattern, etc.
  - Preloaders
    - Type – Canted coil, compression, wave springs
    - Materials – Refractory alloys, ceramic, CMC
  - Core structure/architecture
- **Flow blockage**
  - Core structure/architecture
- **Core integrity**
  - Core structure/architecture
- **Wear resistance**
  - Materials – Oxidation resist. metals (Haynes 214, PM 2000, Kanthal A1)
  - Architecture



Canted Coil Spring



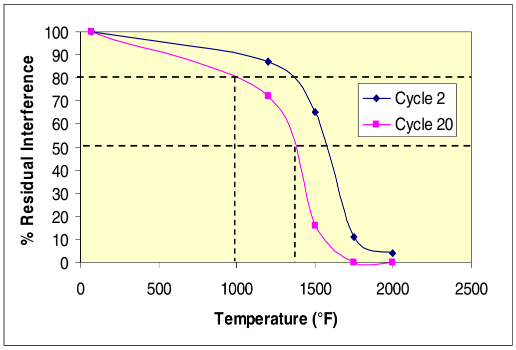
Braided Core Design

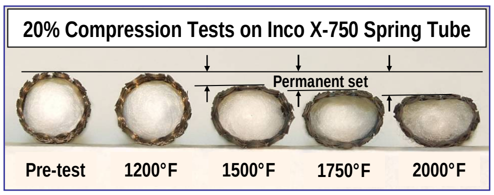
NASA Glenn Research Center

THE UNIVERSITY OF TOLEDO

Currently, the Seals Team at NASA GRC has ongoing efforts in several areas to improve the baseline seal design. These include developing improved spring tube elements with higher temperature capabilities to impart enhanced resiliency to the seals. Another promising approach to improving resiliency involves the use of high temperature preloaders (such as compression springs, canted coil springs, etc.) placed behind the seals. Investigations into engineering the core structure to optimize resiliency and flow blocking characteristics are also being conducted. An optimized core structure would improve core integrity and prevent extraction of the insulating material. Finally, improvements to the wear resistance of the seals are being pursued through material substitutions and architectural changes to the seal outer layers.

Resiliency: Baseline Spring Tube Study





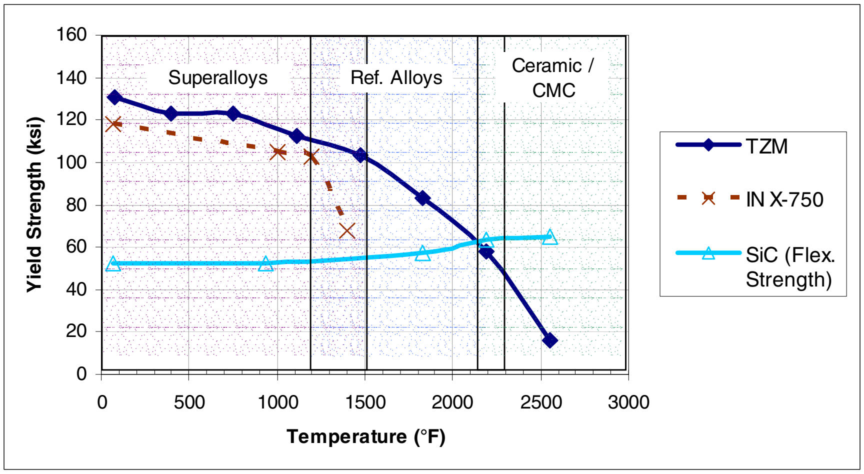
- **High Temp. Compression Tests**
  - Inco X-750 Spring Tube for X-38 / Shuttle seal
    (Boeing Spec MB160-047, ST5)
  - Tested at RT, 1200 °F, 1500 °F, 1750 °F, 2000 °F
    - Compressed 20%
    - 20 cycles
- **Results**
  - Significant drop in resiliency >1200 °F
  - After 20 cycles
    - 80% Resiliency – 1000 °F
    - 50% Resiliency – 1400 °F

NASA Glenn Research Center

THE UNIVERSITY OF TOLEDO

In order to better understand the performance envelop of the Inconel X-750 spring tube element in the baseline seal, NASA GRC conducted a series of high temperature compression tests. Results from the tests demonstrated a substantial decrease in resiliency of the spring tube above 1200 °F. Not surprisingly, this behavior mirrors the temperature dependent yield strength behavior of the alloy. These results also provide some rough design guidelines for use temperatures of seals with this spring tube element. For example, in order to retain 50% resiliency, the maximum use temperature is approximately 1400 °F. This temperature is still well below anticipated temperature in many of the X-vehicles.

The Materials Challenge



- ***Superalloys*** – Limited strength/creep beyond 1500 °F – 1800 °F
- ***Refractory Alloys*** – Good strength/creep to ~2300 °F, poor oxidation resistance
- ***Ceramic/CMC*** – Good strength/creep >2300 °F, limited elasticity

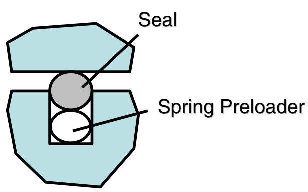
NASA Glenn Research Center

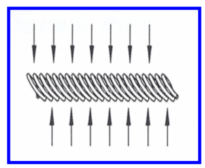
The aggressive high temperature environments these seals are used in result in significant challenges regarding the fabrication of these seals. As previously noted, the superalloy systems (such as Inconel X-750) cannot adequately endure the high temperatures anticipated in these next generation space vehicles. A moderate improvement in the performance of the seals can likely be realized by substitution with the newer oxide dispersion strengthened (ODS) alloys, such as Inconel MA754 and Plansee PM 2000. However, in order to increase the use temperature of these seals near the anticipated application temperatures, different material systems such as refractory alloys or ceramic/CMC must be considered. While these materials exhibit improved high temperature strength and creep properties when compared to the superalloy systems, they also posses some severe limitations. For example the refractory alloys generally demonstrate poor oxidation resistance and require protective coatings. The ceramic and CMC materials have limited elasticity making it difficult to fabricate seals or preloaders into complex shapes. The reduced elasticity also limits the “stroke” of these devices to accommodate large changes in gap size. However, despite these challenges, ceramic-based preloader have been fabricated for GRC and have shown promise in high temperature testing.

Preloaders:
A Potential Solution to Resiliency Issue

The use of separate preloaders behind the seals offers several potential benefits:

1. Better ***resiliency*** – preloader is insulated by thermal barrier seal
2. Better ***control of force*** applied to opposing surfaces (can be "dialed" in)
3. Improved ***flow/heat blocking*** ability when used with "dense" seals





Canted Coil Spring

Si_3N_4 Comp. Springs

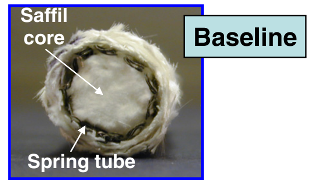
NASA Glenn Research Center

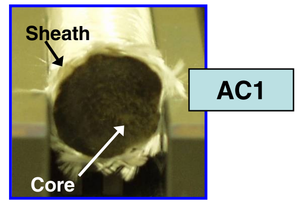
THE UNIVERSITY OF TOLEDO

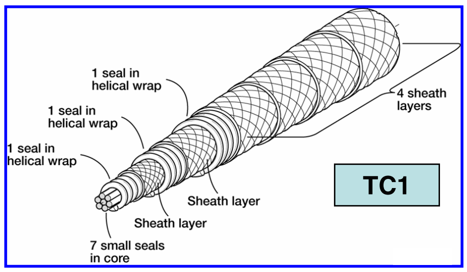
NASA GRC is vigorously pursuing development of high temperature preloading devices to improve the resiliency of high temperature sealing systems. These preloaders would generally be installed behind a thermal barrier seal to maintain positive sealing capabilities. The preloading devices offer several potential benefits over current SOA seals, including better resiliency, the ability to better "dial in" stiffness properties, and the capacity to use highly effective flow-blocking seals that may be too stiff otherwise. Several variants of these preloaders are under investigation, such as high temperature canted coil springs and ceramic compression springs.

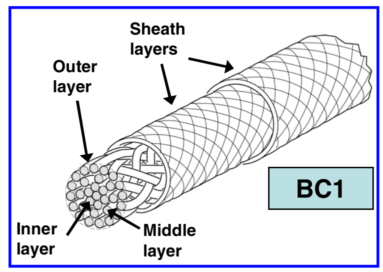
Test Specimens

- **Baseline Shuttle/X-38 design**
  - 2x N312 / IN X-750 / Saffil batting
- **Engineered core designs**
  - AC1
    - 2x N550 / N312 uniaxial fibers
  - BC1 (Albany Techniweave)
    - 2x N440 / 3 layers braided N440 seals
  - TC1 (Albany Techniweave)
    - 4x N440 / alternating layers N440 seal wrap & N440 sheath / N440 uniaxial seals
- **Canted Coil Spring Preloader**
  - 302 SS MB109 Spring (Bal Seal)







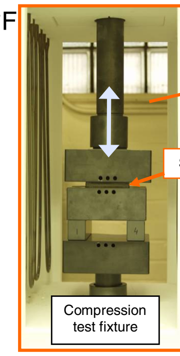


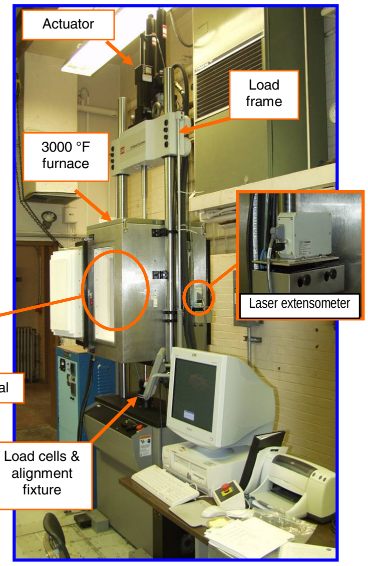
NASA Glenn Research Center

Several next-generation control surface seal prototypes and preloaders were evaluated for improved seal performance. The current control surface seal described earlier was used as a baseline for evaluations. Several seals with "engineered" cores were also fabricated and tested. While these seals do not possess internal spring elements, the construction of the core was designed to possibly enhance resiliency, flow blocking, and core integrity. Stainless steel canted coil spring (CCS) preloaders were also investigated.

Hot Compression Testing

- **System components**
  - Servohydraulic load frame (MTS)
  - Custom box air furnace (ATS)
  - Laser extensometer (Beta LaserMike)
- **Test Procedure**
  - 4 in. long specimens
  - Temperature – RT and 2000 °F
  - Preload to 1.0 lb
    (0.25 lb/in of seal)
  - 20 cycles
    - Load at 0.001 in/s to 20%
    - Dwell for 60 s
    - Fully unload at 0.001 in/s

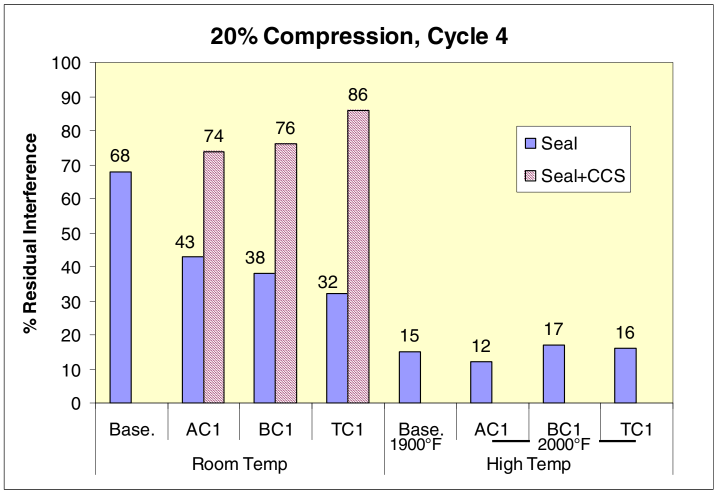




NASA Glenn Research Center

Room temperature and high temperature (2000 °F) compression testing of the seal specimens previously described was conducted using NASA's new high temperature compression rig. The rig consists of several main components including a servohydraulic load frame, a 3000°F air furnace, and laser extensometer to accurately measure compression levels. Four inch seal specimens were tested under low-rate cyclic loading.

Compression Test Comparison - Resiliency



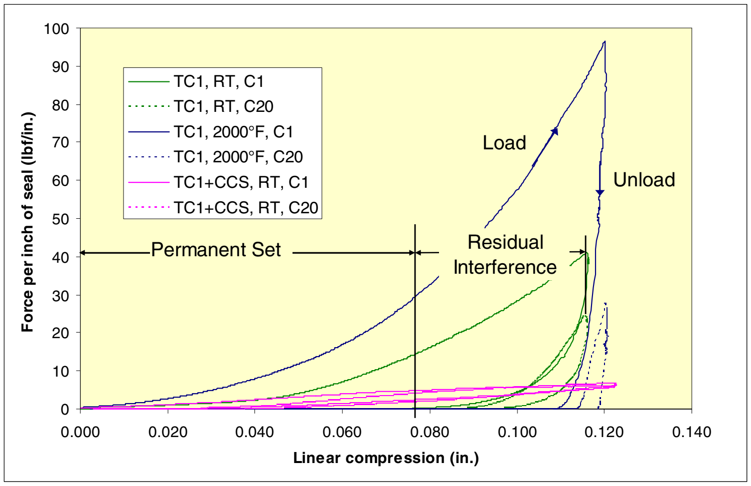
Note: Std. design tested in slightly different setup

- Significant drop in resiliency at high temperatures for all seals (Std. shows the most drop)
- Engineered core designs not significantly better than baseline design at room temp. or high temp.
- Substantial improvement in resiliency (up to 26%) by using canted coil spring vs. std. design

NASA Glenn Research Center

Results from the compression testing illustrated that the engineered core seals did not in-and- of-themselves improve resiliency vs. the baseline seal. However incorporation of the canted coil spring loader produced substantial improvements both in comparison to the engineered cores themselves (168% improvement) and to the baseline seal design (up to a 26% improvement). At high temperatures the baseline seal suffered a significant loss in resiliency which is not surprising based on the high temperature performance of the Inconel X-750 spring tube. At these temperatures, the engineered core alternatives demonstrated similar performance compared to the baseline spring tube seal.

Compression Test Comparison – Force vs. Displacement



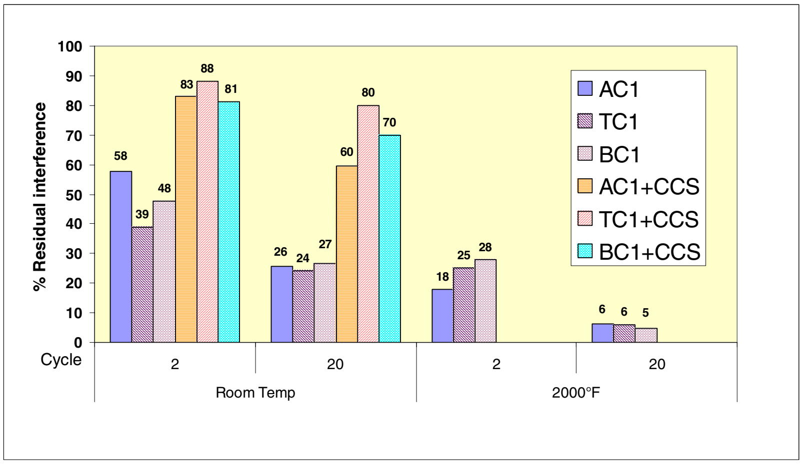
- TC1+CCS design showed significantly lower force (closer to std. design @ 2 lbf/in) and better load retention during cycling
- Substantial drop in load vs. cycling for RT (15%) and 2000 °F (72%)

NASA Glenn Research Center

THE UNIVERSITY OF TOLEDO

A representative plot of seal load vs. linear compression for the TC1 seal design showed a significant drop in load capacity with this seal at both room temperature and high temperature. This indicates permanent set in the seals and a potential reduction in sealing abilities. By contrast, the room temperature test conducted on the seal with the CCS preloader demonstrated marked improvement in load retention, signifying sustained sealing capability. In addition, the compression curve for this seal+CCS showed fairly “flat” load vs. displacement performance, similar to the canted coil spring by itself. This behavior is beneficial in that the seal system can accommodate large strokes with minimal increases in force applied to opposing surfaces.

Compression Test Comparison – Resiliency Engineered Core Designs



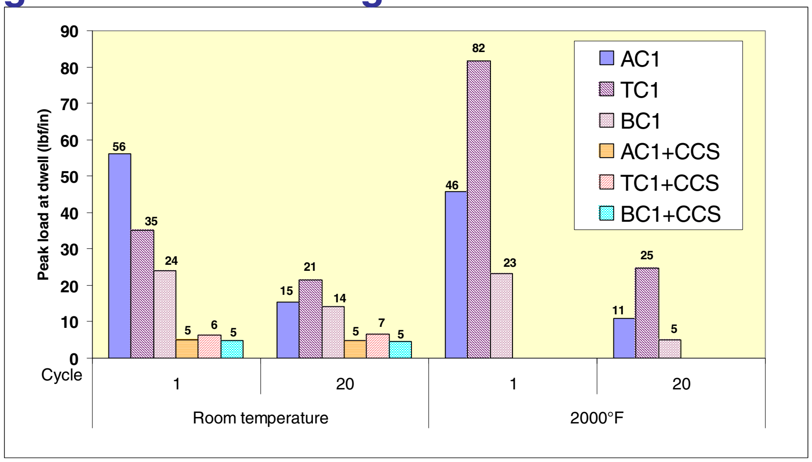
- Residual interference decreased with load cycling
- By 20th load cycle all seals had similar residual interference at room temperature and 2000 °F respectively (without springs)
- Canted coil springs behind seals improved residual interference by 2.3-3.3x by 20th load cycle (most sustained improvement is with TC1 design)

NASA Glenn Research Center

THE UNIVERSITY OF TOLEDO

A closer examination of the resiliency for the engineered core alternatives showed that initially at room temperature the AC1 seal had the best performance. After load cycling, all seals demonstrated a reduction in residual interference due to compaction in the groove and exhibited similar resiliency values after 20 cycles. The canted coil spring yielded a substantial enhancement in resiliency for all the seals with the TC1 design showing the most sustained improvement as the candidates were load cycled. At high temperature, all the seal candidates demonstrated similar performance, especially after 20 cycles.

Compression Test Comparison – Peak Load Engineered Core Designs



- AC1 was stiffer than TC1 and BC1 at room temp.
- TC1 showed significant increase in force at 2000°F, AC1 and BC1 showed drop in load
- After 20 cycles the room temp. and 2000 °F peak loads for the TC1 seal were similar, AC1 and BC1 were slightly higher at room temp.
- Seals on top of canted coil springs produced loads comparable to springs by themselves

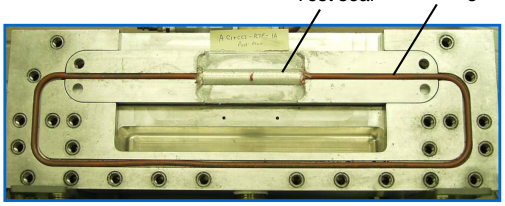
NASA Glenn Research Center

THE UNIVERSITY OF TOLEDO

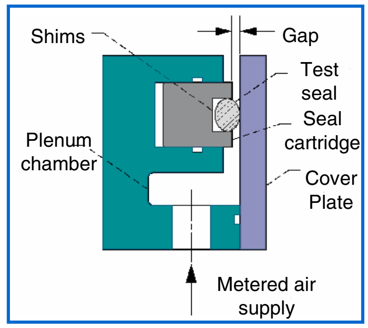
A comparison of the peak loads at room temperature showed that during the first cycle, the AC1 design had the greatest stiffness. After 20 cycles, the loads between the three seals were similar with the TC1 design exhibiting the smallest drop in load capacity. The seals on top of the canted coil springs yielded nearly identical loads for the three alternatives and demonstrated minimal effect of load cycling. At 2000 °F, the TC1 design had the highest load and appeared to become stiffer in contrast to the AC1 and BC1 seals. The reasons for this increase are unknown, but the phenomenon was repeatable. However, after 20 cycles, the peak loads for the TC1 seal at room temperature and high temperature were similar perhaps indicating this effect diminished with load cycling.

Flow Testing

- **System components**
  - Al flow fixture (4 in -12 in lengths)
  - 0-5 psid pressure transducer
  - 0-3000 SLPM flowmeters (100, 750, 1500, 3000 SLPM flowmeters)
- **Test Procedure**
  - 4 in long specimens
  - 0.25 gap (nominal)
  - 20% compression
  - 2 psid



Test Setup for 4-in. Seal

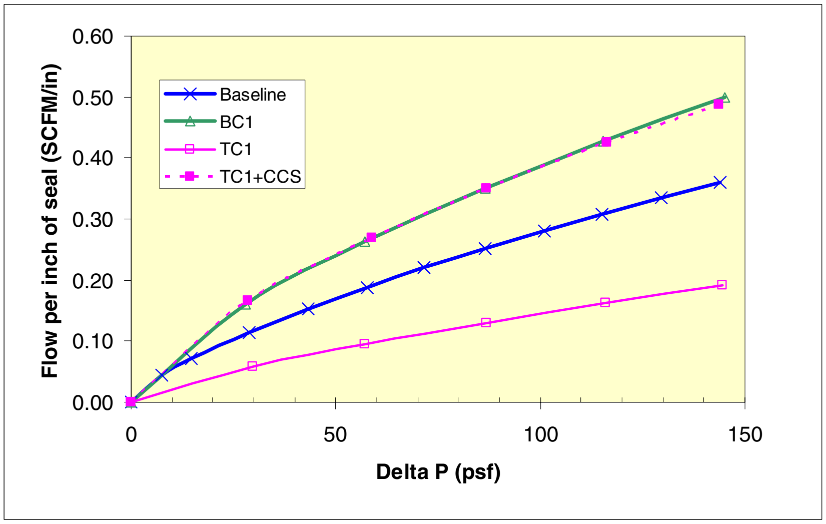


NASA Glenn Research Center

THE UNIVERSITY OF TOLEDO

Low pressure (2 psid) flow testing was also conducted on the seal candidates using a modification to the linear flow fixture at GRC to accommodate shorter samples. The seals were tested under 20% compression using a nominal 0.250 gap.

Flow Test Comparison



- The TC1 design showed improvement in flow vs. the baseline design
- TC1 had approx. ½ the flow of the baseline design at 144 psf (1.0 psi)
- When the CCS was used with the TC1 design, a notable increase in flow was observed

NASA Glenn Research Center

Flow tests with the engineered core designs showed mixed results relative to the baseline seal. The BC1 seal had worse leakage performance when compared to the baseline. This was probably the result of the seal being undersized by 0.060 in. relative to the groove. By contrast, the TC1 design demonstrated better flow-blocking performance. This seal was also slightly undersized (0.020 in. smaller than the groove width), but had a higher core density relative to both the baseline and BC1 designs. Despite this improvement, the TC1 seal would not be suitable in applications where force on opposing surfaces may be an issue (such as with Shuttle tile) due to its relatively high stiffness value. As discussed earlier, a preloader can reduce this force and was therefore tested. The combination of the TC1 seal and CCS demonstrated higher leakage rates than the baseline seal (up to 40% higher). The reason for this behavior is likely due to the slightly undersized seal (vs. groove width) that did not compress as much as the seal without a spring preloader and therefore did not adequately fill the groove. Careful sizing of the seal relative to the groove should help to alleviate this problem.

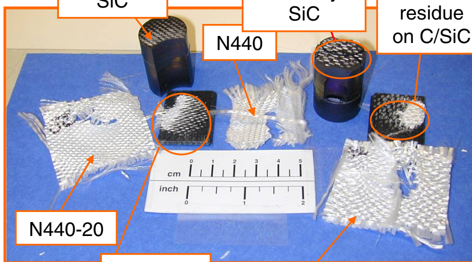
CMC Control Surface Compatibility Tests

- **Materials**
  - Nextel 440 and 720 fabrics - 3M and Albany Techniweave
  - Hexoloy SiC fixturing - Saint-Gobain
  - C/SiC CMC test panel – GE
  - C/C CMC test panel – SAIC
    - Coated with C-CAT SiC/TEOS/Type A Sealant on top and bottom surfaces
    - Coated with Ceraset (Dupont) on sides (after samples were cut)
- **Tests**
  - Samples heated to 2600 °F+ @ nominal 500°F/hr in air
  - Loaded with a 5 lb weight (7-8 psi)

NASA Glenn Research Center

Testing was also conducted to assess the compatibility (i.e. bonding) of seal sheath materials against some of the new thermal protection system (TPS) ceramic matrix composite (CMC) materials at high temperatures. These TPS systems are anticipated to be used in many of the upcoming reusable space vehicles. The tests were conducted by vertically stacking the materials in an 2600 °F air furnace and subjecting the test stack to a 5 lb load.

CMC Compatibility Test Results

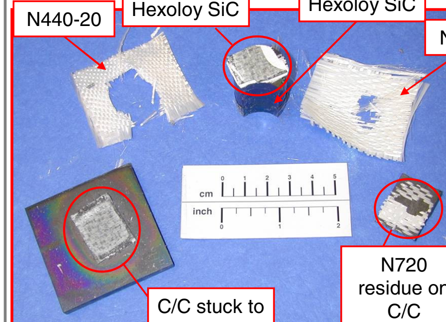


C/SiC

- All Nextel fabric samples showed some degree of sticking to the GE C/SiC test panels when exposed to 2600 °F+ in air
- There was minimal sticking between the Hexoloy SiC fixturing and the GE C/SiC
- N720 appeared to be a little more "brittle" than N440 after heat exposure at 2600 °F+ in air

C/C

- There was significant sticking of the C/C CMC to both Nextel 440 and Nextel 720 fabric
- There was significant sticking of the C/C CMC to the Hexoloy SiC fixturing
- N720 appeared to be a little more "brittle" than N440 after heat exposure at 2600 °F+ in air



NASA Glenn Research Center

THE UNIVERSITY OF TOLEDO

Results for the two CMC candidates showed varying degrees of sticking in all cases. In the worst instances, portions of Nextel fabric were ripped out as the stack was disassembled. During an actual flight, this type of damage could result in seal damage and/or control surface damage. Further work on optimizing the oxidation coatings for these CMC materials and their interaction with sheath fabrics will likely be needed to mitigate this issue.

Summary

- New seals with canted coil preloaders demonstrated promise for next generation control surface seals
  - Up to a 26% improvement in room temperature resiliency vs. baseline spring tube design
  - Load comparable to baseline design
  - Engineered cores eliminate core extraction observed with baseline design
- Twisted core design (TC1) showed best combination of resiliency and flow blocking ability
- CMC preliminary evaluations showed potential issues with sheath material candidates (Nextel fabric) sticking to C/SiC and C/C CMC
- Future work:
  - Advanced control surface seals
    - Optimize seal + preloading device combinations that meet resiliency and flow blocking goals at high temperature
    - Evaluate and optimize durability of engineered core seals
  - X37 control surface seal development
    - Conduct high temperature scrub and compression testing as well as RT flow testing on flaperon seal candidates against CMC test panels

NASA Glenn Research Center

Testing of several new control surface seal candidate systems at NASA GRC has indicated significant promise in improving upon the current baseline seal design. The use of preloaders along with improved seal designs have demonstrated substantial enhancements in resiliency as well as expanded operational envelopes (in terms of ability to accommodate large gap changes and block the flow of high temperature gases). Future work will need to be done to fully optimize these seal systems and asses their suitability in upcoming space vehicles, such as the X-37 spacecraft.