Final Report

Structural Seal Development

NASA NCC3-879 / OAI-02-011

Submitted to
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OAI

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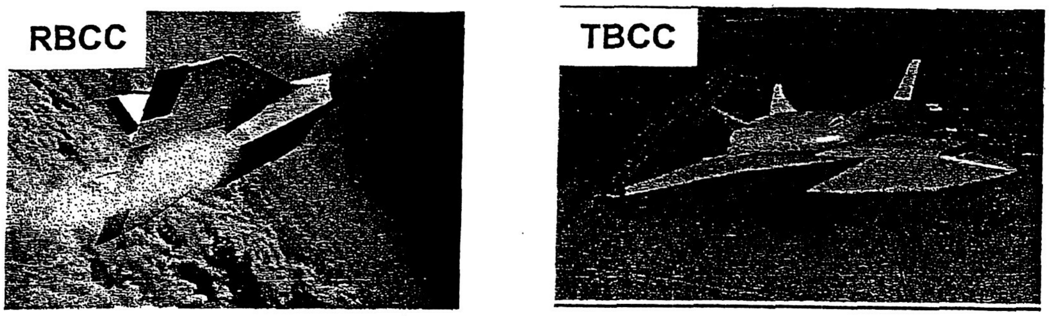
INTRODUCTION

NASA currently has aggressive goals for the development of the next generations of Reusable Launch Vehicles (RLV). Many of the goals center around significantly reducing the time and cost of deployment (including payload) for these spacecraft, as well as substantially increasing the safety of the crew and hardware. A core component in the design of these next generation spacecraft is the propulsion system. Many concepts are currently being evaluated including Rocket Based Combined Cycle (RBCC) and Turbine Based Combined Cycle (TBCC) engine technologies, shown in Figures 1a and 1b, respectively.



(a) (b)

Figure 1: Conceptual designs for Reusable Launch Vehicles utilizing (a) Rocket Based Combined Cycle and (b) Turbine Based Combined Cycle hypersonic propulsion system technologies.

The development of advanced seal technology is widely recognized as a crucial step in meeting these next generation aero- and space propulsion and space vehicle system goals. These seals need to be designed to prevent leakage of high temperature gases into undesirable locations, thus avoiding damage to the craft and potential loss of the vehicle (and consequently loss of life). Currently, however, a large technology gap exists in the hypersonic investment area for both control surface and propulsion system seals.

<u>**Structural Seals for Propulsion Systems: State of Technology**</u>
<u>Current:</u> There are no known dynamic, reusable, structural seals capable of withstanding 2000-2500°F. The only comparable technology is a limited database of seal designs and test data developed under the National Aerospace Plane (NASP) program.

<u>**Control Surface Seals: State of Technology**</u>
<u>Current:</u> Current state-of-the-art control surface seals are Shuttle-derived thermal barriers that are replaced every 8 missions. Extended use of these seals is limited

to temperatures below 1500°F. Current Shuttle seals experience large permanent set under temperature conditions anticipated for future RLV's.

NASA's 3rd Generation technology development programs are intended to develop technologies that will be required for a reusable launch vehicle (RLV) that is to be two generations beyond that of the current Space Shuttle launch system. This 3rd Generation RLV is proposed to be serviceable around the year 2025. The NASA Glenn Research Center has been awarded funding to work on two structural seal development programs: (1) Structural Seals for Propulsion Systems and (2) Advanced Control Surface Seals. The successful design and development of next generation seals in these areas will enable the achievement the NASA mission objectives.

As part of the NASA GRC seals effort, a cooperative agreement (NASA NCC3-879) was initiated between NASA and OAI. The primary goals of this agreement were

(1) To design and develop state-of-the-art testing facilities and methodologies to evaluate new seal designs
(2) To assist with the development and evaluation of seal concepts to meet requirements for propulsion system seals and advanced control surface seals

Mr. Jeff DeMange served as the Principal Investigator for this agreement.

TECHNICAL APPROACH AND ACCOMPLISHMENTS

An integral part in the development of the next generation of high temperature structural seals is a performance evaluation of promising seal candidates. Core performance criteria for seals include:

- Good insulatory properties → block heat flow
- Good flexibility → conform to complex airframe and propulsion system geometries
- Good resiliency → maintain contact with opposing surfaces under dynamic conditions and over many cycles
- Good wear resistance → maintain seal continuity under dynamic conditions and over many cycles

Advanced Test Capabilities

Prior to the current activity, NASA sought to upgrade its testing capabilities and methodologies to better assess these performance measures. Therefore, beginning in 2000, several new test rigs were designed and acquired to evaluate the capabilities of seal candidates in meeting these performance criteria.

Hot Compression / Scrub Rig

One of the new NASA test rigs was designed to evaluate two criteria independently. Using this rig, either the (1) the elevated temperature resiliency or (2) the high temperature wear resistance of promising seal candidates can be assessed depending on the fixturing setup. This rig consists of four main components:

- A servohydraulic test machine capable of both very slow (e.g. 0.001 in/s) and relatively fast (e.g. 8.0 in/s) stroke rates to test mechanical properties and wear characteristics of existing and new seal designs.
- A large (8 in W x 14 in D x 18 in H) high temperature furnace capable of temperatures approaching 3000°F to simulate actual seal in-service environments.
- A non-contact laser extensometer system and integration hardware to accurately measure seal compression and resiliency at high temperatures.
- High temperature silicon carbide (SiC) fixturing (as appropriate).

These components were purchased separately and integration was performed at NASA. A conceptual schematic of the hot compression / scrub rig is shown in Figure 2.

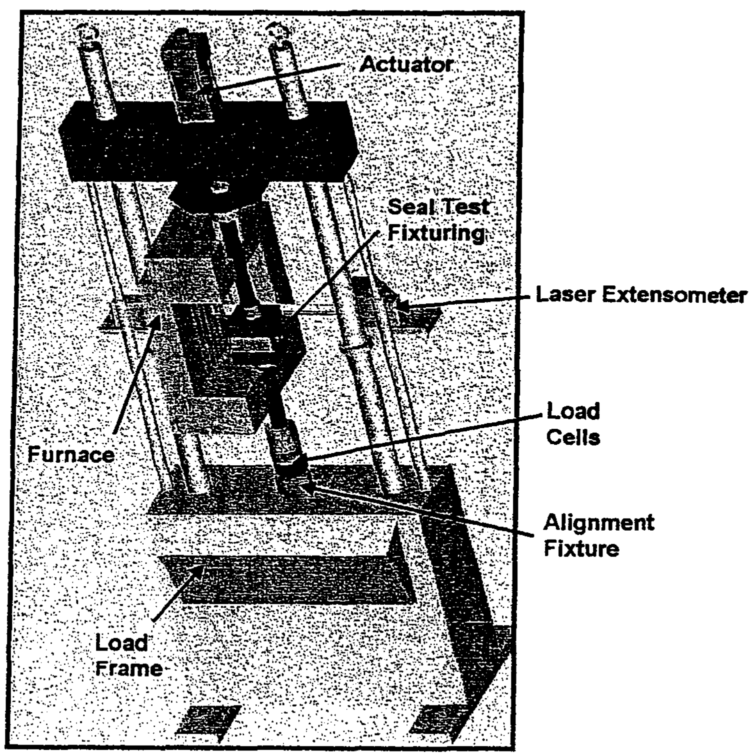


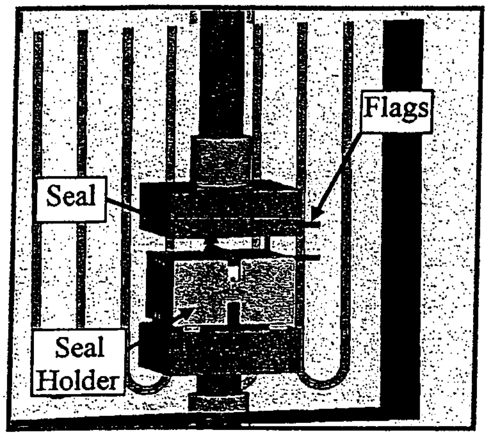
Figure 2: Conceptual schematic of NASA GRC Hot Compression / Scrub Rig (note furnace is shown in cross section).

A summary of the important specifications for each major component used in the Hot Compression / Scrub Rig is shown in Table 1.

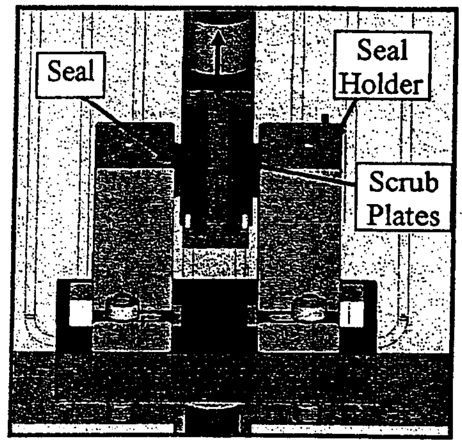
Table 1: System Components Specifications

- MTS Model 318.25 Servohydraulic Load Frame
  - 55 kip load frame
  - 3.3 kip, 6 in. stroke actuator
  - 500 lb, 3300 lb load cells
  - 5.5 kip alignment fixture
  - 11 gpm HPU
  - Dual servovalves (1 gpm, 15 gpm)
  - TestStar IIs controller
- ATS Series 3350 Custom Box Air Furnace
  - Temperatures up to 3000°F (14.5 kW)
  - Kanthal Super 33 $MoSi_2$ heating elements
  - Large working volume (9" W x 14" D x 18" H)
  - Front and back loading doors & top port
  - Adjustable laser alignment fixturing and water-cooled shield
- Beta LaserMike Intelliscan 50 Extensometer
  - Non-contact Class II laser extensometer
  - 0 in. – 2 in. measurement range
  - ±0.25 mil accuracy
  - 1000 scans/s
  - Hot object filter

In addition to these main components, two distinct sets of specially designed SiC fixturing were fabricated to evaluate seal performance. As shown in Figures 3a and 3b, one set of fixturing permits an evaluation of seal resiliency, while use of the other set of fixturing allows an assessment of seal wear performance.



(a)



(b)

Figure 3: Conceptual designs for SiC fixturing for (a) compression testing and (b) scrub testing with the Hot Compression / Scrub Rig.

An important consideration in the design and acquisition of this equipment was its ability to subject seal candidates to environments that would accurately simulate actual service conditions. Table 2 details the capabilities of the test rig in both the compression and scrub setups.

Table 2: Rig Capabilities for Compression and Scrub Setups

	Units	Compression Setup	Scrub Setup
Max. Temperature	°F	3000	3000
Load Range	lbs	0.15 - 3300	0.15 - 3300
Max. Stroke	in	1.75*	3
Stroke Rate	in/s	0.001 - 0.050**	0.001 - 8.0
Max. Seal Length	in	4	4
Max. Seal Diameter	in	2	2
Gap	in	n/a	0 - 0.625***
Loading Profiles		Monotonic, cyclic (sine wave, sawtooth, user defined), constant load	Monotonic, cyclic (sine wave, sawtooth, user defined)

* Using LaserMike (without LaserMike - up to 6 in stroke)

** Max rate while still using LaserMike taking an averaged data point (200 points averaged) every 10 mils

*** Depends upon thickness of saber plate

A significant criterion for conducting the high temperature compression tests was the accurate measurement of the amount of seal compression for a given load. In order to meet this goal, a non-contact laser extensometer was selected, as shown in Figure 4. This system uses a transmitter (with a laser source and high speed rotating mirror) to generate a 2 in. tall laser "sheet" that is captured with a receiver. Sample flags mounted onto the fixturing obstruct portions of the laser sheet, and the distance between the pins as a function of time is monitored by the LaserMike system. This equipment has been used in high temperature environments and demonstrated excellent accuracy (±.25 mils) across a broad measurement range (0-1.5 in) in preliminary room temperature tests at NASA GRC (see Figure 5).

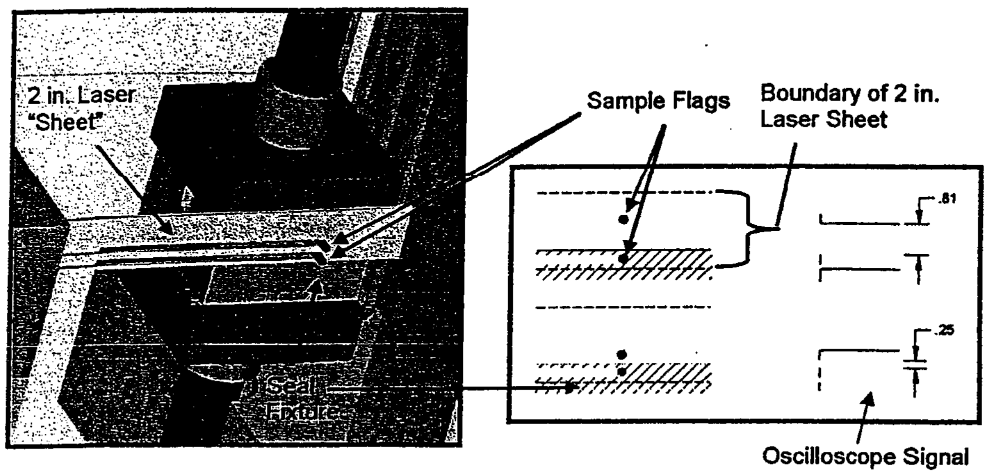


Figure 4: Schematic representation showing (a) fixturing flags obstructing portions of the laser sheet and (b) typical oscilloscope signals as a seal is compressed.

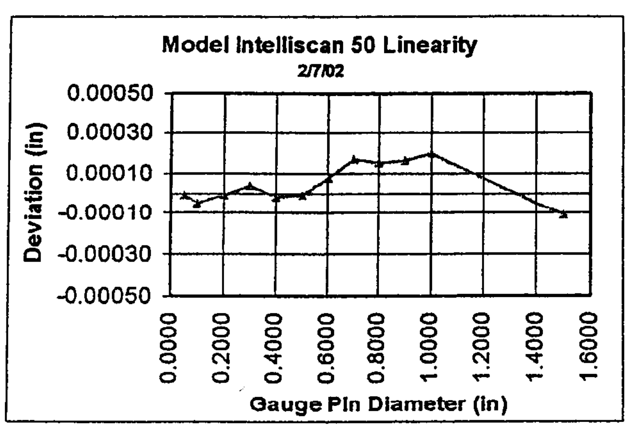


Figure 5: Linearity test conducted at room temperature with LaserMike Intelliscan 50 system showing deviation from actual gauge pin diameter.

For the scrub test, a secondary test fixture was designed and fabricated that permits evaluation of room temperature leakage rates both before and after scrub testing in the hot compression / scrub rig. This flow fixture is capable of flow rates up to 3000 SLPM and differential pressures up to 100 psid using air. An early conceptual schematic of this fixture is shown in Figure 6. The flow fixture was designed to minimize secondary damage to the seal due to handling and utilizes the same SiC seal holder used for the scrub test.

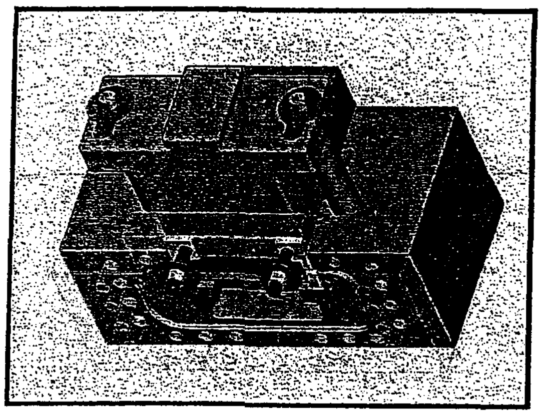


Figure 6: Early conceptual design for ambient temperature flow fixture which permits pre- and post-scrubbing evaluations of seal leakage.

As shown in Table 2, the seal and test fixturing would be subjected to aggressive temperatures in an oxidixing atmosphere. Generating meaningful test data under these conditions required the use of unique materials for the test fixturing. Therefore, the high temperature hardware for each setup was machined from a special monolithic SiC known as Hexoloy SA. This material is a dense, fine grained SiC capable of maintaining good strength and integrity in oxidizing atmospheres up to approximately 3000°F (1650°C), as shown in Figure 7.

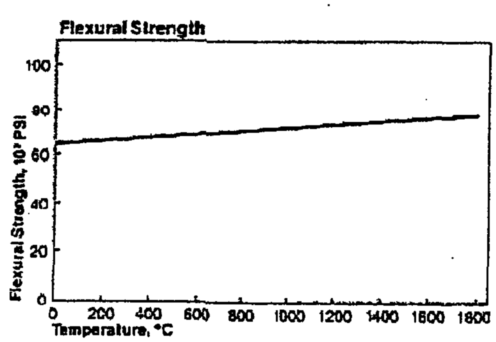


Figure 7: Flexure strength of Hexoloy SA as a function of temperature.

Additional information on the physical and mechanical properties of this material is shown in Table 3.

Table 3: Physical and Mechanical Properties of Hexoloy SA SiC

Physical Property	Units	SA
Composition (Phases)		α-SiC
Density	g/cm^3	3.10
Average Grain Size	μm	4-6
Poisson Ratio		0.14
Modulus of Elasticity (@ RT)	GPa	410
	x 10^6 psi	59
Hardness (Knoop-1000 g)		2800
Flexural Strength (4 pt @ RT)	MPa	380
	ksi	55
Compressive Strength (@ RT)	MPa	3900
	ksi	560
Fracture Toughness (@ RT)	MPa*$m^{-1/2}$	4.6
(Double Torsion & SENB)	ksi*$in^{-1/2}$	4.2
Max. Service Temp	°C	1650
	°F	3000
CTE (RT to 700°C)	μm/m-°C	4.02
	μin/in-°F	2.2
Mean Specific Heat (air)	J/g-K	0.67
Thermal Conductivity		
@ RT	W/m-K	125.6
	Btu/ft-h-°F	72.6
@200°C	W/m-K	102.6
	Btu/ft-h-°F	59.3
@400°C	W/m-K	77.5
	Btu/ft-h-°F	44.8
Emmisivity		0.9
Permeability (RT to 1000°C)		Impervious to gases over 31 MPa
Electrical Resitivity		
@RT	ohm-cm	10^2-10^6
@1000°C		0.01-0.2

Utilizing fixturing made from this material required some innovative approaches to fixing parts together as fasteners are difficult to manufacture from ceramics and cannot be reliably used at high temperatures (> 1800°F). Therefore, parts were joined with pins, anchors, etc. using special collars to ensure the pins did not fall out during testing. Based upon these assemblies, a complete stress analysis for critical features of the various fixturing components was completed (details can be obtained from the Design and Safety manual, located in Bldg 5, SW-17).

The hot compression / scrub rig installation and checkout timeline is shown in Table 4.

Table 4: Project timeline for Hot Compression / Scrub Rig

	Hot Compression Rig	Hot Scrub Rig
Fabrication Complete	Q3 FY02	Q4 FY02
Installation Complete	Q4 FY02	Q1 FY03
Checkout Complete	Q1 FY03	Q2 FY03
Ready for Tests	Q2 FY03	Q3 FY03

As of the writing of this report, progress on the compression fixturing is on schedule; the scrub fixturing has been delayed approximately 1 month. Figure 8 shows an actual photograph of the test rig and major components.

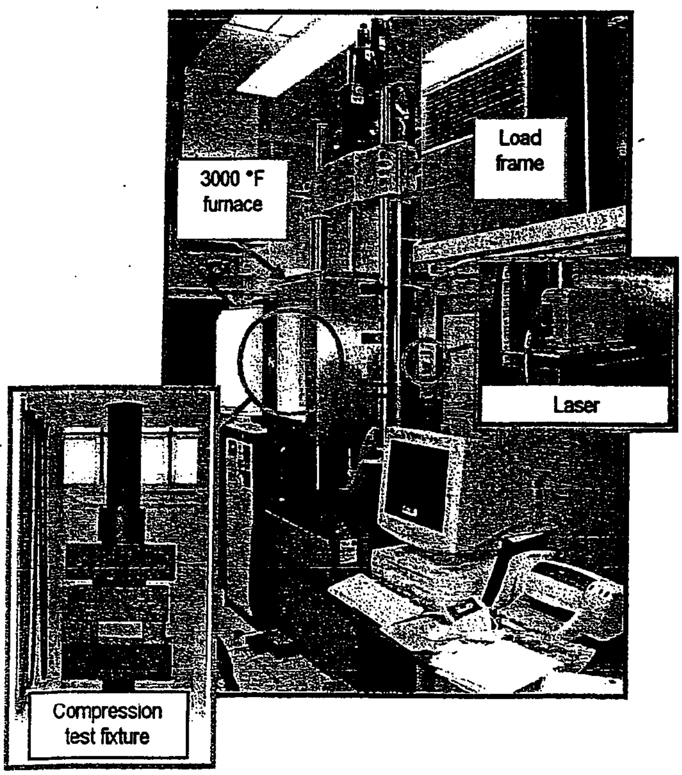


Figure 8: Photograph of Hot Compression / Scrub rig showing key components.

Ambient Flow and Scrub Rig

Another test rig was designed for NASA GRC to permit an evaluation of in-process wear related effects on seal leakage at room temperature. Using this rig, flow rates through seals could be measured under various test conditions:

- Compression level
- Gap size
- Rub surface conditions (material, surface roughness, surface profile)
- Scrub direction (e.g., transverse vs. wiping)

Conceptual schematics of the rig are displayed in Figure 9.

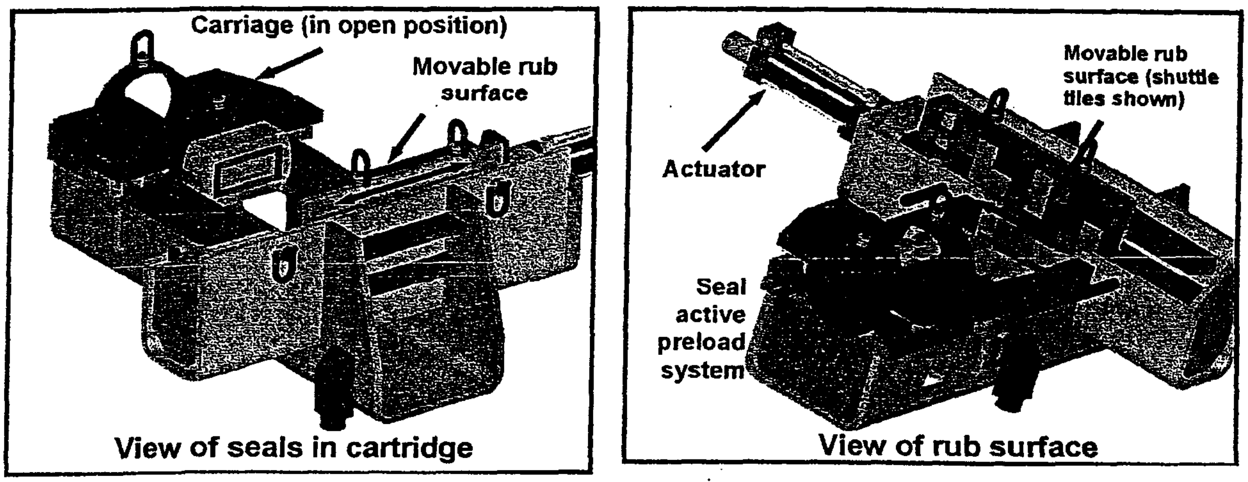


Figure 9: Conceptual schematics of Ambient Scrub and Flow rig shown in various orientations.

Due to secondary sealing issues, flow testing at high temperatures is extremely difficult and often cost prohibitive. The addition of scrubbing adds another level of complexity, and therefore this rig was designed to perform room temperature tests. Despite the lack of high temperature capacity, the rig will possess adequate capability to investigate the tribological behavior of seal candidates under relevant conditions, as shown in Table 5.

Table 5: Rig Capabilities for Ambient Flow and Scrub Rig

	Units	Ambient Flow & Scrub Rig
Max. Temperature	°F	Room Temp.
Scrub Load Range	lbs	1 - 10000
Max. Stroke	in	12
Max. Stroke Rate	in/s	12
Max. Seal Length	in	8
Max. Seal Diameter	in	2
Gap	in	0 - 1
Scrub surfaces		Variety (different materials, surface conditions, etc.)
Scrub direction		Multiple (cartridge can be rotated)
Preloading		Active (pneumatic) or passive (Belleville washers)
Test gas		air
Max. Flow Rates	SLPM	3000
Max. Pressure	psi	100

The ambient flow and scrub rig installation and checkout timeline is shown in Table 6.

Table 6: Project timeline for Hot Compression / Scrub Rig

	Ambient Scrub & Flow Rig
Fabrication Complete	Q1 FY03
Installation Complete	Q2 FY03
Checkout Complete	Q3 FY03
Ready for Tests	Q4 FY03

As of the writing of this report, progress on the rig is on schedule. Figure 10 shows an actual photograph of the test rig and major components.

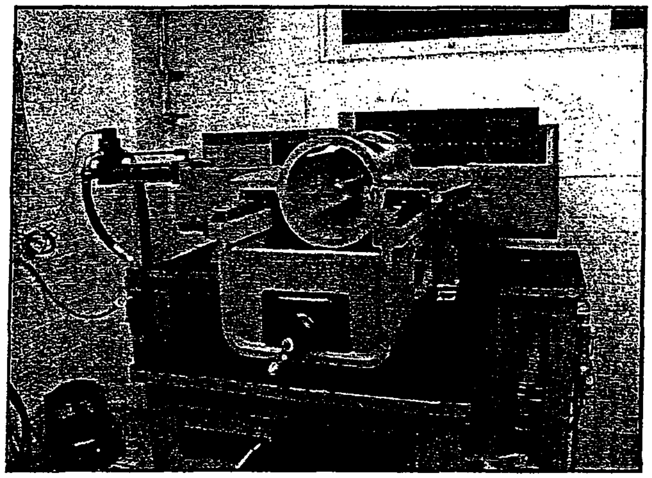


Figure 10: Photograph of Ambient Scrub and Flow Rig.

Seal Testing

In addition to the design, acquisition, and integration of these unique test rigs, several tests were conducted in support of NASA sponsored projects.

X-38 CRV Seal Tests

In order to fully investigate the effects of compression level, rope seals to be used in the rudder/fin area of the X-38 Crew Return Vehicle were compression tested in an older hand-driven test rig. These seals are used to seal the vertical and horizontal surfaces of the rudder/fin area and prevent ingestion of high temperature gases into locations containing actuators and other temperature sensitive structures, as shown in Figure 11. Lower compression levels (10%, 20%) than previously tested were used to obtain a full picture of the effects of compression on preload and residual interference (i.e. springback).

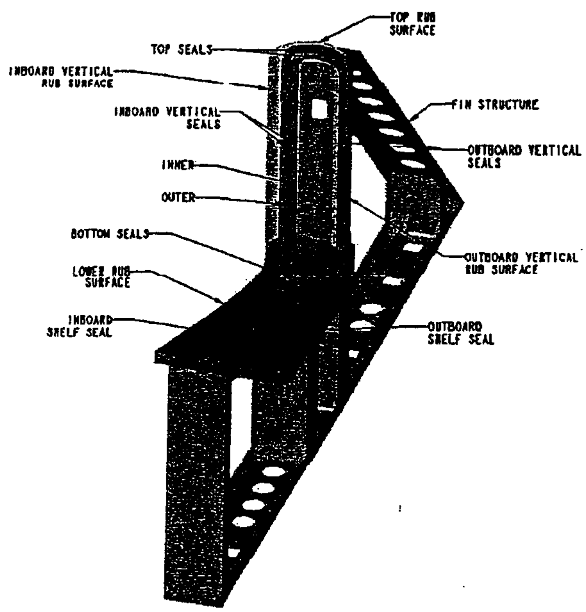


Figure 11: Schematic showing seal locations for X-38 CRV rudder/fin component.

In an additional phase of the X38 seal evaluation, samples of the rope seals were tested for leakage after being subjected to scrubbing across shuttle tile surfaces. These tests were conducted to bound the best and worst case leakage scenarios. Full details of this investigation can be found in NASA/TM-2002-211708 (AIAA-2002-3941).

ISTAR RBCC Seal Tests

As part of an ongoing effort to identify possible seal candidates for the ISTAR (Integrated Systems Test of an Air Breathing Rocket) project, flow tests were conducted on different diameter Nextel all-ceramic seals. In cooperation with CFD Research Corp., computational fluid dynamics modeling was performed to ascertain seal permeability for future predictions of engine temperatures in various locations of interest. Details of these tests are not discussed here due to ITAR restrictions.

D-Seal Tests

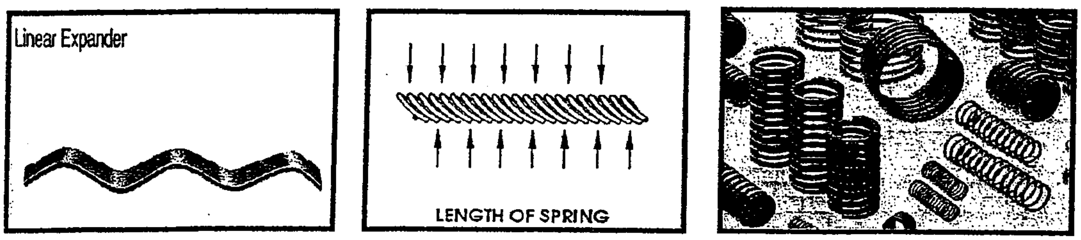
A series of seal tests was also conducted to support the Parametric Inlet project at GRC. The supersonic parametric inlet (Mach 2.35) was scheduled to be run in the 10x10 supersonic wind tunnel in the fall of 2002. The inlet requires dynamic seals in several locations to seal the edges of movable ramps and other structures and is being designed by EDAD. Room temperature compression tests were performed on several different sizes of rubber D-seals using the new seal compression test fixture previously mentioned.

Based on the results of these tests, a recommendation was made for the seal design that would best seal the edges of the ramps while minimizing loads on the adjacent structures.

Seal Development

Preloader Concepts

In addition to designing more resilient seals, NASA is developing high temperature seal preloading devices that can be placed behind seals to enhance their resiliency. These preloaders would likely be in the form of ceramic or refractory metal elastic spring elements (as shown in Figures 12a-c) placed behind the seal.

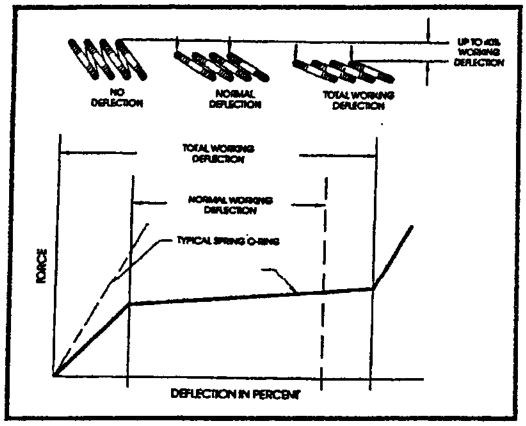


(a) (b) (c)

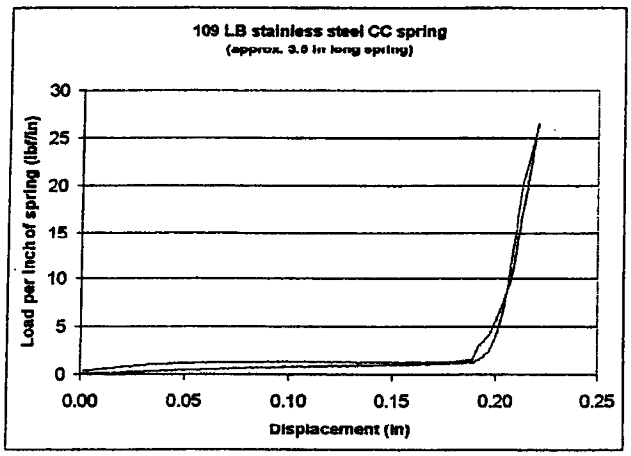
Figure 12: Examples of potential concepts for seal preloader devices: (a) linear expander or wave spring (b) canted coil spring and (c) compression spring.

These devices may improve the long-term resiliency and longevity of current and future structural seal designs. Some preliminary development of ceramic canted coil springs was conducted by Case Western Reserve University for NASA. Additionally, samples of Si_3N_4 compression springs have been obtained and will be evaluated at elevated temperatures in the near future.

Limited ambient temperature testing was also conducted on metal canted coil springs in the new Hot Compression / Scrub Rig previously described. This spring geometry offers some unique advantages versus more traditional spring structures, including an extended region of very "flat" response (i.e. a significant amount of displacement for little additional force). Figure 13a shows a theoretical response curve along with a graphic depiction of the geometry changes in the canted coil spring during deflection. Figure 13b shows a typical experimental response curve for a low stiffness stainless steel spring based upon tests done at NASA GRC.



(a)



(b)

Figure 13: Plots showing (a) theoretical performance and graphic representation of spring deflection for a typical canted coil spring and (b) actual load vs. displacement curve for low stiffness stainless steel canted coil spring.

HotBlox Evaluation

An effort was also undertaken to characterize an ultra-high temperature thermoplastic matrix composite material, known as Hotblox, available from American Technical Coatings. This material is claimed to be

> "*A nonceramic, polymeric compound which when cured at 300°F becomes an extremely hard and durable material, which can withstand temperatures beyond*

any heat source that we have found (5500°F) to date, without any changes in physical properties." (Hotblox Technical Literature)

This material was potentially attractive for a number of high temperature applications, including seals, ablative materials, etc., due to its low forming temperatures. Therefore, a series of high temperature evaluations were conducted on samples of this material, including standard furnace "bakeout" tests (up to 2000°F), burner rig tests (up to 2500°F), torch investigations (> 2700°F), and laser thermal conductivity experiments. While this material showed some early promise in terms of high temperature stability (i.e. very low weight loss), additional testing indicated issues with thermal shock resistance and oxidation issues in terms of glassy phase formation. Further testing was suspended after these results.

CONCLUSIONS

Advanced high temperature structural seals are a critical component in the successful implementation of next generation reusable space vehicles. The Structural Seals Group at NASA GRC is currently leading an effort to develop robust high temperature structural seals. As part of this endeavor, a cooperative agreement was initiated between OAI and NASA to design and acquire state-of-the-art test equipment and methodologies to evaluate and screen candidate materials and geometries for these seals. This new equipment included (1) a Hot Compression / Scrub Rig to evaluate seal resiliency or seal wear resistance at high temperatures (up to 3000°F) depending upon fixturing and (2) an Ambient Flow and Scrub Rig to assess wear effects on seal leakage *in-situ*.

Under the cooperative agreement, tests were also conducted in support of various programs including the X-38 CRV program, ISTAR, and the Parametric Inlet project. Research was also initiated to identify improved methods for achieving seal resiliency, including evaluations of high temperature seal preloader devices. Through these efforts, significant improvements in high temperature seal technology will be realized.

REFERENCES

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