

THIRD GENERATION RLV STRUCTURAL SEAL DEVELOPMENT PROGRAMS AT NASA GRC

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NASA is currently developing technologies for the 3rd Generation Reusable Launch Vehicle (RLV) that is being designed to enter service around the year 2025. In particular, NASA's Glenn Research Center (GRC) is working on advanced high temperature structural seal designs including propulsion system and control surface seals. Propulsion system seals are required along the edges of movable panels in advanced engines, while control surface seals seal the edges and hinge lines of movables flaps and elevons on the vehicle. The overall goal is to develop reusable, resilient seals capable of operating at temperatures up to 2000 °F. High temperature seal preloading devices (e.g., springs) are also being evaluated as a means of improving seal resiliency. In order to evaluate existing and potential new seal designs, GRC has designed and is installing several new test rigs capable of simulating the types of conditions that the seals would endure during service including temperatures, pressures, and scrubbing. Two new rigs, the hot compression test rig and the hot scrub test rig, will be used to perform seal compression and scrub tests for many cycles at temperatures up to 3000 °F. Another new test rig allows simultaneous flow and scrub tests to be performed on the seals at room temperature to evaluate how the flow blocking performance of the seals varies as they accumulate damage during scrubbing. This presentation will give an overview of these advanced seal development efforts.

3rd Generation RLV Structural Seal Development Programs at NASA GRC

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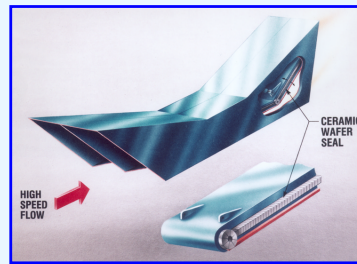
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Background & History

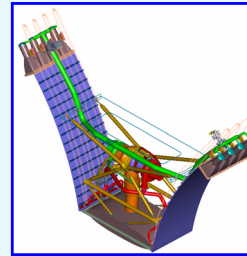
- **NASA GRC is recognized as Center of Excellence for high temperature structural seal development:**
 - Led seal development effort for NASP (National Aero-Space Plane) project (1986-1992):
 - In-house propulsion system seal development program
 - Oversaw propulsion system seal development efforts at PW, Rocketdyne, & GE
 - Oversaw airframe and engine inlet seal development efforts at Boeing Phantom Works & Rockwell
 - Worked with Rocketdyne/Lockheed Martin on high temperature seal for linear aerospike engine ramps that accommodates large deflections (1998-2001)



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NASP Propulsion System Seals



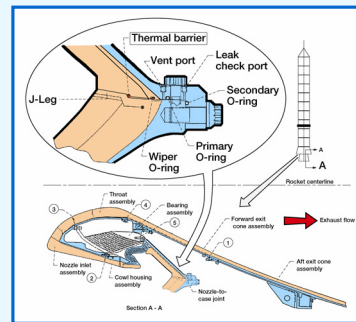
Linear Aerospike Engine

NASA GRC's work on high temperature structural seal development began in the late 1980's and early 1990's during the NASP (National Aero-Space Plane) project. Bruce Steinetz led the in-house propulsion system seal development program and oversaw industry efforts for propulsion system and airframe seal development for this vehicle. The figure at the upper right shows a propulsion system seal location in the NASP engine. The seals were located along the edge of a movable panel in the engine to seal the gap between the panel and adjacent engine sidewalls.

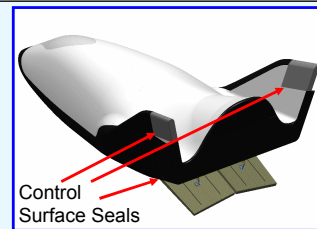
More recently, we worked with Rocketdyne on high temperature seals for the linear aerospike engine ramps. In applications such as the former X-33 program, multiple aerospike engine modules would be installed side by side on the vehicle. Seals are required between adjacent engine modules along the edges and base of the engines, as shown in the figure on the lower right. The seals have to withstand the extreme temperatures produced by the thrusters at the top of the ramps while accommodating large deflections between adjacent ramps. We came up with several promising seal concepts for this application and shared them with Rocketdyne.

Background & History (cont.)

- Working with Thiokol/NASA Marshall to improve nozzle joint designs in Space Shuttle RSRM's. Thiokol is implementing more reliable J-Leg design and NASA GRC thermal barrier and eliminating joint-fill compound that can develop potentially damaging gas paths (1998-2002)
- Working with NASA JSC to develop and evaluate control surface seals (e.g., rudder/fin seals) for X-38/ Crew Return Vehicle (1999-2002)



Thermal Barrier for Shuttle RSRM



X-38 Seals



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We have also been working with Thiokol over the past few years on improved nozzle joint designs for the Space Shuttle reusable solid rocket motors (RSRM's). Looking at the figure on the upper right, the seal location is where the nozzle bolts on to the bottom of the rocket. The current nozzle joint design uses RTV to seal the joints upstream of the O-rings. Occasionally though, gas paths can form in the RTV and focus hot gases on the O-rings. In an effort to solve this problem, Thiokol came to us to see if we had a seal that could be placed upstream of the O-rings. We came up with a braided carbon rope seal design that they are currently evaluating in as many as six of the nozzle joints as a way to overcome this problem and eliminate the RTV joint-fill compound. Thiokol is currently certifying the thermal barrier for flight so that re-designed joints incorporating the thermal barriers can enter service on a Space Shuttle mission in early 2005. We also recently received a patent for this seal design.

We have also been working with Don Curry and his group at JSC for about three years to develop and evaluate control surface seals for the X-38/Crew Return Vehicle, particularly in the rudder/fin location. During this time we have performed a series of temperature exposure, compression, flow, scrub, and arc jet tests on the baseline X-38 rudder/fin seal design. Results of these tests verified that this seal is satisfactory for the X-38 application. In addition to supporting the X-38 program, tests performed on these seals are serving as a baseline for our advanced control surface seal development efforts.

Structural Seal Development Motivation and Objectives

- **Why is advanced seal development important?**

- Seal technology recognized as critical in meeting next generation aero- and space propulsion and space vehicle system goals
- Large technology gap exists in Hypersonic Investment Area for both control surface and propulsion system seals:
 - No control surface seals have been demonstrated to withstand required seal temperatures (2000-2500°F) and remain resilient for multiple temperature exposures while enduring scrubbing over rough sealing surfaces
 - No propulsion system seals have been demonstrated to meet required engine temperatures (2500+°F), sidewall distortions, and environmental and cycle conditions.

- **NASA GRC Seal Team leading two 3rd Generation RLV structural seal development tasks to develop advanced control surface and propulsion system seals**

Goal: Develop long life, high temperature control surface and propulsion system seals and analysis methods and demonstrate through laboratory tests.



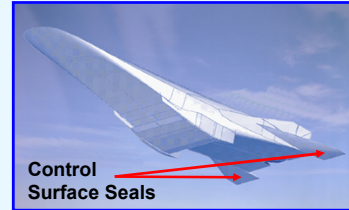
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A large technology gap has been identified for both control surface and propulsion system seals. There are no existing control surface seals capable of withstanding required seal temperatures of up to 2500°F while remaining resilient for multiple heating cycles and enduring many scrub cycles over rough sealing surfaces. Also, there are no propulsion system seals that can endure engine temperatures as high as 2500+°F while sealing against distorted engine sidewalls in an extreme environment. These advanced seals are required for the next generation of aero-space vehicles. To fill this technology gap, the Seals Team at GRC has successfully advocated for two 3rd Generation RLV seal development tasks to come up with new, advanced control surface and propulsion system seals.

Control Surface Seal Challenges and Requirements

- **X-38 case study used to define seal requirements:**

- Limit hot gas ingestion and leakage
- Limit transfer of heat to underlying low-temperature structures
- Withstand temperatures as high as 2000-2500°F for multiple heating cycles
- Maintain resiliency (spring back) for multiple heating cycles
- Limit loads against opposing sealing surfaces
- Resist scrubbing damage against opposing sealing surfaces
- Perform all functions for >10X increase in service life over current Shuttle seals



Challenge: Design hot, resilient seals that meet mission reusability requirements



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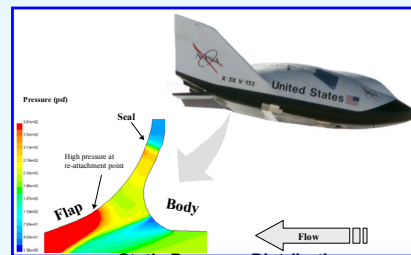
Now focusing specifically on control surface seals, this chart shows the challenges and requirements that new seal designs must meet. Because we have done a good deal of work in testing control surface seals for X-38, we are using these seals as a baseline upon which to improve. We are also using the X-38 application as a case study to define the requirements for advanced control surface seals. These seals must limit hot gas ingestion and leakage through the sealed gaps to prevent the transfer of heat to low-temperature structures (including actuators) downstream of the seal. Gas temperatures that reach the seal can be as hot as 2500°F. The seals must be able to withstand these extreme temperatures and remain resilient, or “springy”, for multiple heating cycles. The lower image on this chart shows what happens to the X-38 seal design after exposure to 1900°F temperatures in a compressed state. The seals took on a permanent set and did not spring back to their original cross sectional shape. This can be a problem if the seal does not stay in contact with the opposing sealing surface and allows hot gases to pass over the seal and into regions where low-temperature materials reside. We are working on seal designs that would not have this problem and would remain resilient for many heating cycles. At the same time, the seals must not be too stiff so that they don’t impart excessive loads on to the structures that they are sealing against. The seals must also be resistant to wear as they are being scrubbed over the relatively rough sealing surfaces. The goal of this program is to develop seals that meet all of these requirements with a 10X increase in service life over the current seals used on the Space Shuttle that are replaced about every 8 missions.

Control Surface Seal Development Plans

- Evaluate new seal concepts under representative conditions (temperatures, pressures, scrubbing)
- Develop high temperature seal preloading devices (e.g., springs) as potential means of improving seal resiliency
- New NASA GRC test rigs under development include:
 - Hot compression rig (stroke rate: as low as 0.001 in/sec at 3000°F)
 - Hot scrub rig (stroke rate: up to 8 in/sec at 3000°F)
 - Cold flow/scrub test rig (ΔP : 0 to 2 psid)
- Environmental exposure tests will be performed in other facilities:
 - Arc jet tests (NASA Ames Panel Test Facility)
 - Thermal acoustic tests (NASA LaRC or WPAFB)
- Aero-thermal-structural analyses of seals using tightly integrated CFD-FEA analysis tools



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This chart shows how we are planning to develop our advanced control surface seals. We are coming up with new seal designs and plan to evaluate them in several new test rigs under representative conditions of temperature, pressure, and scrubbing. In an effort to improve seal resiliency, we are developing high temperature seal preloading devices that would be placed behind the seals to add to their “springiness.” We are currently installing three new test rig setups in our labs at GRC. The first two rigs listed, our hot compression test rig and hot scrub test rig, actually use the same load frame and furnace with different test fixturing inside the furnace to perform the different tests. The load frame, furnace, and laser extensometer for these rigs have been installed, and we are currently installing and checking out the high temperature (3000°F) test fixturing that will be used inside the furnace to perform either compression or scrub tests.

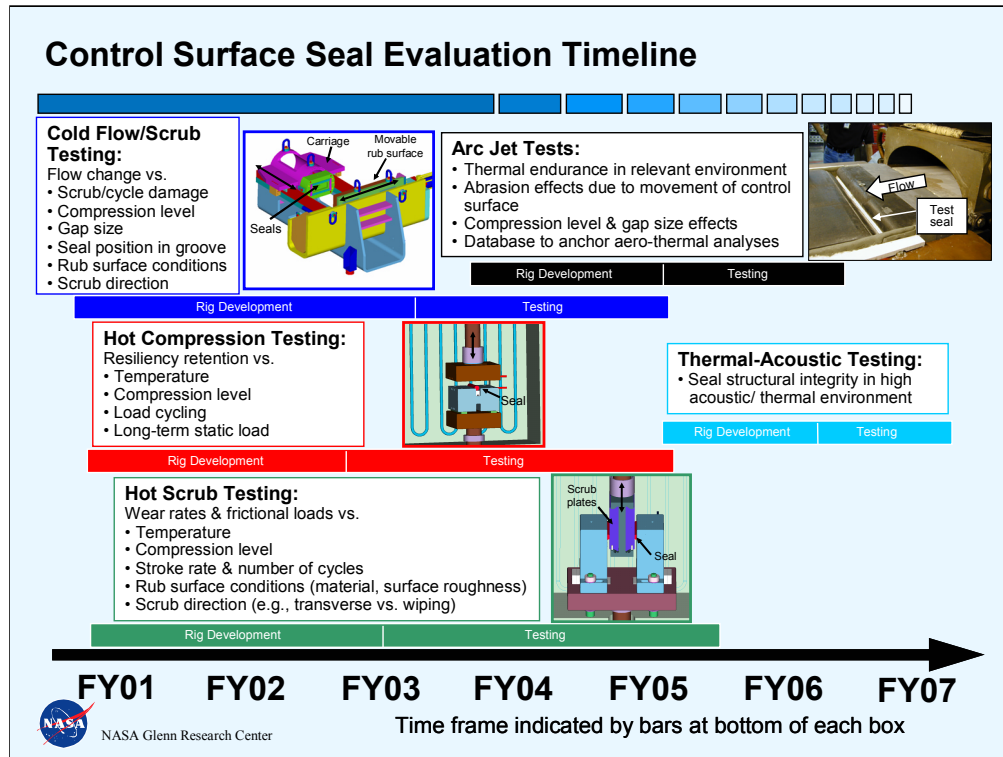
For the compression tests, the seals will be compressed between two plates and will be subjected to multiple compressive load cycles to generate load versus displacement curves for each cycle. We will be able to measure the resiliency, or spring back, of the seals at different temperatures for many load cycles. We will also be able to perform stress relaxation tests in which we load a seal at a given compression and see how the load falls off over time.

For the scrub tests, we will be moving a rub surface up and down in between two seals to scrub the seals against the surface for many cycles. We will monitor the friction between the seals and the rub surface and examine how the seals wear over time at different temperatures.

The other test rig we are installing will allow us to perform simultaneous flow and scrub tests on the seals at room temperature. We will be able to pass flow through the seals at the same time that they are being scrubbed against a moving rub surface to see how the flow blocking performance of the seals varies as they accumulate damage during scrubbing.

In addition to the tests rigs that we are building up for our lab at GRC, we also plan to perform tests at other facilities. Several years out, we plan to perform arc jets tests on our new seal designs at the NASA Ames Panel Test Facility. This facility produces extremely hot, re-entry-type gases that would pass over and impinge on the seals. This would simulate conditions that the seals would experience during re-entry. We also plan to evaluate our new seal designs in a thermal-acoustic facility either at NASA LaRC or at Wright Patterson AFB. These tests would expose the seals to both thermal and acoustic loads and evaluate their performance.

Finally, we are working with CFD Research Corp. to have them perform aero-thermal-structural analyses and develop models of our porous seal designs. We plan to use these models to predict temperatures and pressures that the seals would be exposed to as well as temperature drops across the seals that would be expected for a given seal configuration or design. These models will be validated against test data recorded in the flow, arc jet, and thermal-acoustic tests. The image at the lower right shows an example of the results that the thermal analyses would produce.

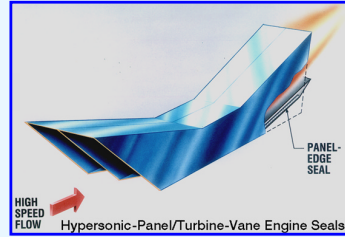


This chart shows a timeline for how and when we plan to have our rig development and testing occur during this program. Each rig and series of tests is color-coded so that an overall description and image of each test rig are shown above a bar indicating the time frame for rig development and testing. We are currently installing and checking out our new cold flow/scrub, hot compression, and hot scrub test rigs. We plan to begin hot compression and hot scrub testing during FY03, and we plan to have our cold flow/scrub test rig ready for testing by the summer of 2003. Further out on the schedule are the arc jet tests that we would perform around FY05-06 and the thermal-acoustic tests that we plan to perform in FY06-07.

Propulsion System Seal Challenges and Requirements

- **NASP and I^{STAR} case studies used to define seal requirements:**

- Withstand very high engine temperatures, up to 6000°F in combustor during scramjet operation
- Limit leakage of hot gases and unburned propellant into backside cavities
- Withstand chemically hostile environment
 - Oxidation limits material selection
 - Possible hydrogen embrittlement
- Seal distorted sidewalls and remain resilient for multiple heating cycles → flexible seals required
- Survive hot scrub environment with acceptable change in flow rates
- Try to minimize cooling requirements; cooling schemes can be complex and heavy
- Engine operation and mission safety demand highly reliable seals



Challenge: Design hot, flexible seals that require minimal coolant and meet engine life goals

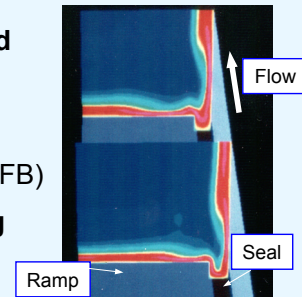


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As mentioned previously, we also have a task for development of propulsion system seals. We used NASP and ISTAR seal case studies to determine our requirements for advanced propulsion system seals. Like the control surface seals, these seals must operate at very high temperatures and limit the leakage of hot gases into cavities behind the seals. In addition, propulsion system seals must prevent unburned propellant from getting into these cavities. If unburned propellant were to build up in a backside cavity it is possible that it could lead to an explosion. These seals must also withstand chemically hostile environments including oxidation and possible hydrogen embrittlement depending on the propellant. The seals must be flexible and resilient enough to conform to distorted sidewalls that they seal against and must endure scrubbing against these walls. To survive these extreme conditions, we plan to utilize high temperature materials to minimize the use of cooling schemes that can be complex and heavy. The seals must meet all of these requirements while operating safely and reliably.

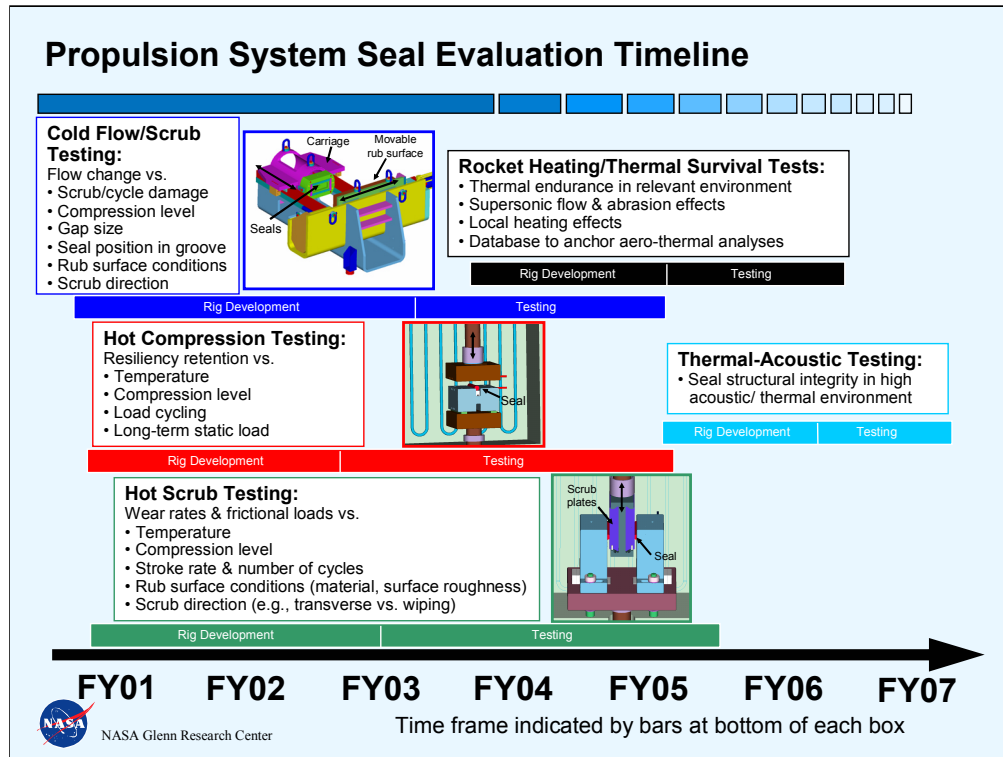
Propulsion System Seal Development Plans

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 - Rocket heating/thermal survival tests (NASA GRC C-22 Rocket Facility)
 - Thermal acoustic tests (NASA LaRC or WPAFB)
- Aero-thermal-structural analyses of seals using tightly integrated CFD-FEA analysis tools



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Like the control surface seals, we plan to come up with new propulsion system seal designs and evaluate them in our new test rigs. We plan to test these seals in the same test rigs but with different test fixturing than what is used for the control surface seals and under somewhat different pressure, temperature, and scrubbing conditions. One different test facility that we plan to test these seals in is NASA GRC's Cell 22 Rocket Test Facility. This facility will subject the seals to extreme thermal conditions similar to what they would experience in an advanced propulsion system. These tests will be performed in place of the arc jet tests that we will perform on the control surface seals. We also plan to perform a series of aero-thermal-structural analyses on new propulsion system seal concepts. An example of the results of such an analysis is shown in the lower right hand corner of this chart.



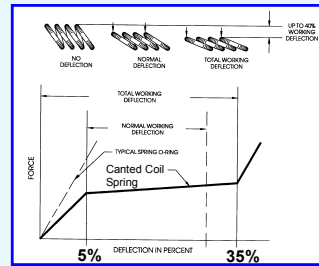
This chart is very similar to the one shown earlier for the control surface seals. The main difference is that the rocket heating/thermal survival tests are shown here in place of the arc jet tests that were shown for the control surface seals.

Ceramic Canted Coil Spring Development: Candidate Seal Preloading Device

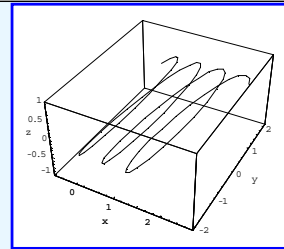
- **Cooperative agreement with Case Western Reserve University to develop high temperature (up to 2500°F) ceramic canted coil spring as potential seal preloading device**

- **FY02 Accomplishments**

- Continued evaluating materials (YAG vs. silicon nitride) and processing approaches
- Extruded and fired simple forms of silicon nitride springs in preparation for strength testing
- Worked on tools to analyze and design ceramic springs to guide spring fabrication



Typical deflection curve for canted coil spring: provides large working deflection



Canted coil spring model



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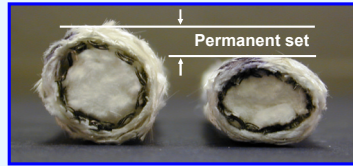
For the past 18 months we've had a cooperative agreement with Case Western Reserve University to have them develop ceramic springs as potential high temperature seal preloading devices. We wanted them to develop ceramic canted coil springs because of the unique loading profile they could provide. Canted coil springs are different from regular tension or compression springs in the direction that they are loaded. Tension and compression springs are typically loaded in a direction parallel to a line down the center of the spring. Canted coil springs, though, are loaded across the coils as shown in the figure at the top right of this chart. They can be produced in long lengths that would be laid in a groove behind a seal to provide additional resiliency, or spring back, to the seals. Another unique feature of these springs is that as the coils of the spring deflect under a load, the force produced by the spring on the opposing surface stays rather constant over a broad range of deflections. This produces a force vs. deflection curve that is close to flat as shown in the figure at the upper right. This would be a beneficial feature for the seals because it would provide resiliency to the seals without producing excessive loads against the opposing sealing surface.

CWRU evaluated both YAG and silicon nitride as possible materials for the springs, and looked into different processing approaches. They fabricated a laboratory-scale extruder and used it to produce simple forms of silicon nitride springs. They also worked on analytical tools that could be used to design the springs and guide spring fabrication.

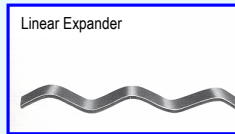
Development of High Temperature Seal Preloading Devices

- **Conducting competitive procurement to develop high temperature seal preloading devices in FY03**

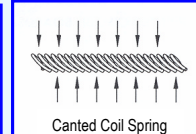
- Posted abstract on Sept. 27, 2002 as request for information from potential vendors:
<http://prod.nais.nasa.gov/cgi-bin/eps/bizops.cgi?gr=D&pin=22>
- Planning to post Statement of Work and solicit for proposals in early Nov. 2002
- FY03 funding for this effort: ~\$100K



Seals Before and After 1900°F Exposure
Showing Loss of Seal Resiliency



Linear Expander



Canted Coil Spring



Candidate Seal Preloading
Devices

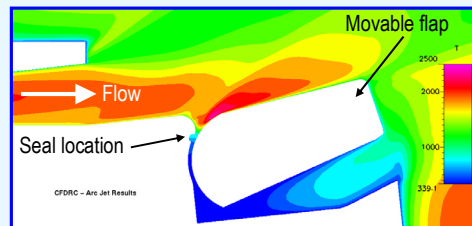


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In FY03 we are conducting a competitive procurement to continue developing high temperature seal preloading devices. We posted an abstract on the internet on September 27, 2002 to request information from potential vendors that would be interested in bidding on this effort. We are currently finishing the Statement of Work and plan to post it in early November to begin the formal solicitation process. About \$100K is being dedicated toward this effort in FY03, but this could be just the first year of a multi-year effort. Candidate devices that we have considered for this application include linear expanders, canted coil springs, and compression springs, but other configurations will be considered.

Summary of Significant FY02 Accomplishments

- **Continued evaluation of baseline Shuttle-derived seals for X-38 control surface seal applications**
 - Performed additional flow and scrub tests
 - Results summarized in NASA TM-2002-211708, "Investigations of Control Surface Seals for Re-Entry Vehicles"
 - Lessons learned form basis for advanced control surface seal development program
- **CFD Research Corp. completed aero-thermal-structural analyses of gap seals tested in NASA Ames arc jet facility. Temperatures and pressures predicted near porous seal corresponded well with actual test data.**



Temperature predictions by CFD RC arc jet model (in K)

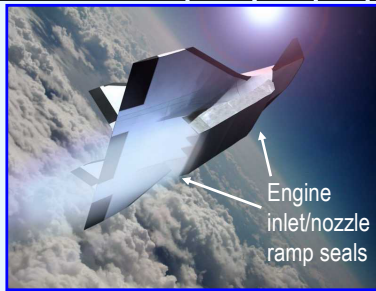


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We have had many accomplishments over the past year. We've continued to test the baseline seals for the X-38 rudder/fin application including additional flow tests on seals that were scrub tested down at JSC. The results of all the tests that we have performed on these seals over the past three years including compression, flow, scrub, and arc jet testing are summarized in NASA TM-2002-211708, "Investigations of Control Surface Seals for Re-Entry Vehicles." We are using the results of these tests as a baseline upon which to improve in our advanced control surface seal development task.

CFD Research Corporation completed a series of aero-thermal-structural analyses on control surface seals that were tested in the arc jet facility at NASA Ames. The temperatures and pressures that they predicted near the porous seal corresponded well with the actual test data. This type of analysis will be used to predict seal performance for future mission conditions. The figure shows sample temperature predictions near the seal and test fixture for one of the test runs.

Summary of Significant FY02 Accomplishments (cont.)



ISTAR Engine
(P&W/Aerojet/Boeing/Rocketdyne)

- **Established close working relationship with ISTAR contractor, Pratt & Whitney**
 - Measured flow rates for candidate ISTAR engine seals for P&W
 - Met with P&W in Aug. 2002 to review P&W seal concepts and test plans
- **Contracted with CFD RC to perform aero-thermal-structural analyses on ISTAR engine seals (in cooperation with P&W) to predict seal temperatures and pressures to guide seal design and material selection**



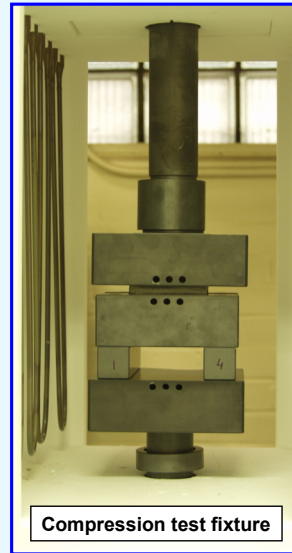
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During FY02 we established a close working relationship with Pratt & Whitney, one of the contractors working on the new ISTAR propulsion system. Using our room temperature linear flow fixture, we measured flow rates for several candidate dynamic seals for the ISTAR engine. We've also been reviewing their concepts and test plans for static and dynamic seals for the engine. We set up a contract with CFD Research Corporation to have them perform analyses on seals for the ISTAR engine to predict the temperatures and pressures that the seals would have to endure. The seal flow rates that we measured are being used to calculate seal permeabilities that are then used in these analyses. The results of the analyses will be used to help P&W select their final seal materials and designs.

Summary of Significant FY02 Accomplishments (cont.)

- **New test rig acquisition and fabrication:**

- Completed installation of hot seal compression test rig
- Successfully checked out furnace up to 3000 °F
- Completed design and ordered all high temperature silicon carbide test fixtures for hot seal scrub test rig
- Completed fabrication of room temperature seal flow/scrub test rig; currently installing it in test cell



Compression test fixture



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Over the past year we completed installation of our new hot seal compression test rig. We installed and checked out the load frame, 3000°F furnace, and laser extensometer and recently installed the high temperature compression test fixturing. We also completed the design of the high temperature scrub test fixturing and ordered all of those parts. For the cold flow/scrub test rig, we completed fabrication of the rig and are currently installing it in our test cell. Jeff DeMange will give an overview of the capabilities of these new test rigs in the following presentation.