OVERVIEW OF NASA GLENN SEAL PROGRAM

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Overview of NASA Glenn Seal Program

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2001 NASA Seal/Secondary Air System Workshop
October 30-31, 2001
NASA Glenn Research Center
Ohio Aerospace Institute Auditorium

NASA Glenn hosted the Seals/Secondary Air System Workshop on October 30-31, 2001. Each year NASA and our industry and university partners share their respective seal technology developments. We use these workshops as a technical forum to exchange recent advancements and "lessons-learned" in advancing seal technology and solving problems of common interest. As in the past we are publishing two volumes. Volume I will be publicly available and individual papers will be made available on-line through the web page address listed at the end of this chapter. Volume II will be restricted under International Traffic and Arms Regulations (I.T.A.R.) and/or Export Administration Regulations (E.A.R.).

2001 NASA Seal/Secondary Air System Workshop

Tuesday, Oct. 30, Morning:

Registration	**8:00 a.m.–8:30 a.m.**
Introductions	**8:30 a.m.–9:30 a.m.**
Introduction	Dr. Bruce Steinetz, R. Hendricks/NASA GRC
NASA's Vision for 21st Century Aircraft	Dr. Woodrow Whitlow, Director of R&T at NASA GRC
Overview of NASA Glenn Seal Program	Dr. Bruce Steinetz/NASA GRC
Program Overviews and Requirements	**9:30 a.m.–10:30 a.m.**
Overview of NASA's UEET Program	Dr. Joe Shaw, C. Peddie/NASA GRC
Advanced Space Transportation Program	Mr. Harry Cikanek/NASA GRC
Turbine Based Combined Cycle Engine Program	Dr. Joe Shaw, P. Bartolotta, J. Seidel, N. McNelis/NASA GRC
Break	**10:30–10:45 a.m.**
Turbine Seal Development Session I	**10:45 a.m.–12:15 p.m.**
Aspirating Seal GE90 Test	Dr. Tom Tseng/General Electric Aircraft Engines
Development of High Misalignment Carbon Seals	Mr. Lou Dobek, A. Pescosolido/P&W
Hydrostatic Face Seal Development at Stein Seal Company	Mr. Alan McNickle, G. Garrison/Stein Seal
Improved Main Shaft Seal Life in Gas Turbines using Laser Surface Texturing	Mr. Alan McNickle/Stein Seal; I. Etsion/Surface Technologies
Lunch - Box Lunches OAI Sun Room	**12:15 p.m.–1:15 p.m.**

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The first day of presentations included overviews of NASA programs devoted to advancing the state-of-the-art in aircraft and turbine engine technology: Dr. Whitlow presented an overview of the Aircraft for the 21st Century Project. Dr. Shaw presented an overview of the Ultra-Efficient-Engine Technology (UEET) program that is aimed at developing highly-loaded, ultra-efficient engines that also have low emissions (NOx, unburned hydrocarbons, etc.). Dr. Shaw also provided an overview of the turbine-based-combined-cycle (TBCC)/Revolutionary Turbine Accelerator (RTA) program that is aimed at developing a turbine-engine based first stage launch system for future highly re-usable launch vehicles. Though NASA is leading this program the Air Force is also contributing technical requirements and consultation.

Mr. Cikanek of NASA's Space Project office summarized NASA's Access to Space Programs citing areas where advanced seals are required. Dr. Steinetz presented the NASA seal development program.

Representatives from GE and P&W provided insight into their advanced seal development programs. Mr. McNickle of Stein Seal presented their recent seal development status.

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Tuesday, Oct. 30, Afternoon:

Turbine Seal Development Session II	**1:15 p.m.–2:45 p.m.**
Development of Advanced Seals for Industrial Turbine Applications	Dr. Ray Chupp/General Electric-CRD
Improved Steam Turbine Leakage Control with a Brush Seal Design	Mr. Norman Turnquist, R. Chupp, General Electric CRD, R. Pastrana, General Electric Energy Services, C. Wolfe, M. Burnett, General Electric Power System
NASA High Temperature Turbine Seal Rig Development	Ms. Margaret Proctor/NASA GRC; I. Delgado/US Army
Abradable Seal Developments At Technetics	Mr. Doug Chappel/Technetics Corp.
Non-Contacting Compliant Foil Seal for Gas Turbine Engine	Dr. Mohsen Salehi, H. Heshmat/Mohawk Innovative Technology
Break	**2:45 p.m.–3:00 p.m.**
Turbine Seal Development Session III	**3:00 p.m.–4:30 p.m.**
Numerical Simulation of Flow, Pressure and Motion of Front Back Fingers in a Two Rows Finger Seal	Dr. Jack Braun/U. Akron; V Kudriastev; M. Proctor, B. Steinetz/NASA GRC
High Temperature Metallic Seal Development	Mr. Amit Datta, Advanced Components & Materials, Inc. and D. Greg More, The Advanced Products Co.
Gas Turbine Primary-Secondary Flowpath Interaction: Transient, Coupled Simulations and Comparison with Experiments	Dr. Mahesh Athavale/CFD-Research Corp. (CFD-RC)
Demonstration of TURBO/SCISEAL	Dr. Mahesh Athavale/CFD-RC
Dinner at Viva Barcelona (Westlake)	**6:00 p.m.–?**

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Representatives from GE-Corporate Research Center, Technetics, and Mohawk Innovative Technology presented their company's recent seal development status.

Ms. Proctor of NASA Glenn presented a status review of the new High Temperature, High Speed Turbine Seal rig and associated non-contacting rotor temperature measurement system.

Dr. Braun presented preliminary CFD investigations into metallic finger seals. Mr. More (Advanced Products) and Dr. Datta presented an overview of the high temperature metallic seal development. Dr. Athavale presented analytical investigations into the complex flow patterns in rim seal/cavity locations in modern turbine engines.

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Wednesday, Oct. 31, Morning:

Registration	**8:00 a.m.–8:30 a.m.**
Space Vehicle Development I	**8:30 a.m.–10:30 a.m.**
X-38 Seal Development	Dr. Donald M. Curry, R. Lewis, NASA Johnson Space Center, J. Hagen, Lockheed Martin Space Operations
2001 Overview of X-37 Program and Seals Development	Dr. Todd Steyer/Boeing
Integrated System Test of an Airbreathing Rocket	Mr. Mark Hyatt, D. Linne/NASA GRC
Design, Fabrication and Test of CMC Control Surface Structure and Joining Technology	Mr. Ted Paquette, Refractory Composites, B. Sullivan MR&D
Break	**10:30 a.m.–10:45 a.m.**
Space Vehicle Development II	**10:45 a.m.–12:15 p.m.**
3rd Generation RLV Structural Seal Development Program at NASA GRC	Mr. Patrick H. Dunlap, Jr., B. Steinetz, NASA GRC J. DeMange, OAI
Development and Capabilities of Unique Structural Seal Test Rigs	Mr. Jeff DeMange/OAI; P. Dunlap, B. Steinetz/NASA GRC D. Breen & M. Robbie/Analex
Analyses of Control Surface Seal Tested in the AMES Arc Jet Tunnel (Panel Test Facility)	Mr. Alton Reich, M. Athavale/CFD-RC; P. Dunlap, B. Steinetz/NASA GRC
Overview of Seal Development at Albany International Techniweave, Inc.	Mr. Bruce Bond/Albany-Techniweave
Lunch OAI Sun Room	**12:15 a.m.–1:15 p.m.**

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Presentations on the second day concentrated on space vehicle/propulsion seal developments. NASA is developing both the X-38 and X-37 vehicles to demonstrate technologies for each of their respective missions. Both vehicles will be taken to low earth orbit via the Space Shuttle and demonstrate on-orbit and re-entry technologies. The X-38 is a precursor technology demonstrator vehicle for the Space Station Emergency Crew Return Vehicle. Dr. Curry presented an overview of the X-38 program, control surface seal requirements, and candidate seal approaches. Dr. Steyer presented an overview of the joint NASA/Air Force X-37 program, control surface seal requirements, and candidate seal approaches. Mr. Paquette presented an Overview of the 2nd Gen. Control Surface development program aimed at developing an advanced composite (hot-structure) control surface for a future Space Shuttle replacement. Mr. Hyatt presented an overview of the ISTAR program.

Mr. Dunlap presented an overview of NASA GRC's 3rd Gen. RLV Structural Seal Development Programs aimed at developing control surface and propulsion system seals for future launch systems. Dunlap and DeMange also presented a status review of Unique Structural Seal Test Rigs currently under development for the 3rd Gen. RLV programs. Mr. Reich presented results of a CFD investigation of control surface seals tested in the NASA Ames arc jet under NASA GRC sponsorship.

Mr. Bond of Albany-Techniweave presented an overview of their ceramic and hybrid seal development - building on earlier joint NASA GRC-Techniweave seal development efforts.

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Wednesday, Oct. 31, Afternoon:

NASA GRC Materials and Sensor Developments	**1:15 p.m.–2:15 p.m.**
Overview of GRC's RLV Airframe Hot Structures/ Materials Development	Dr. Fran Hurwitz/NASA GRC
Overview of GRC's C/SiC and SiC/SiC Ceramic Matrix Composite (CMC) Materials Development	Mr. Doug Kiser, J. DiCarlo, A. Eckel M. Freedman, S. Levine , NASA GRC
Overview of GRC's Advanced Sensor and Instrumentation Development	Dr. Carolyn Mercer /NASA GRC
Adjourn	**2:15 p.m.**

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Dr. Hurwitz and Mr. Kiser of NASA Glenn presented GRC's high temperature ceramic matrix composite developments aimed at high temperature airframe thermal protection systems and propulsion structures.

Dr. Mercer presented innovative sensors under development aimed at measuring temperature, pressure, flow and strain under the extreme conditions found in advanced space systems.

NASA Glenn Seal Team Organization

Seal Team Leader: Bruce Steinetz
Mechanical Components Branch/5950

Turbine Engine Seal Development

Principal Investigator: **Margaret Proctor**

Researcher: **Irebert Delgado**

Consultant: **Dave Fleming** Operations: **Joe Flowers**

Develop non-contacting, low-leakage turbine seals

- TBCC Hot Seals: Non Contacting Seal Development
- SEC: Non Contacting Seal Development; High Speed/High Temperature Seal Rig Development
- Mohawk SBIR Ph II Compliant Foil Seals
- Honeywell Seal testing (JTTAG 3; NAVY, other)
- GE Aspirating Seal Development (UEET)
- PW High Misalignment Seal Development (UEET)
- CFDRC Coupled code development (UEET)

Structural Seal Development

Principal Investigator: **Pat Dunlap**

Researcher: **Jeff DeMange**

Design Eng: **Dan Breen**

Develop resilient, long-life, high-temp. structural seals

- Control Surface Seal Development (3rd Gen.)
- Propulsion System Seal Development (3rd Gen.)
- X-38 Control Surface Seal Development
- TPS-20 Control Surface Seal Development (S/L-100; Boeing)
- Linear Aerospike Inter-engine Seal Consultation (2nd Gen X-33/RLV)
- Shuttle Thermal Barrier Consultation

Acoustic Seal Development

Principal Investigators: **Chris Daniels/B. Steinetz**

Develop non-contacting, virtually no-leakage acoustic-based seals

- SEC: Acoustic Seal Development
- Strategic Research Fund Acoustic Seal Development

Adaptive Seal Development

Principal Investigators: **Scott Lattime/B. Steinetz**

Develop adaptive/re-generating shroud/inter-stage seals

- Rev. Aeropropulsion Components (RAC)

The NASA GRC seal program grew significantly over the past year. The Seal Team is divided into four primary areas. These areas include turbine engine seal development, structural seal development, acoustic seal development, and adaptive seal development. The turbine seal area focuses on high temperature, high speed shaft seals for secondary air system flow management. The structural seal area focuses on high temperature, resilient structural seals required to accommodate large structural distortions for both space- and aero-applications.

The acoustic seal project is a new area this year. Our goal in the acoustic seal project is to develop non-contacting, low leakage seals exploiting the principles of advanced acoustics. We are currently investigating a new acoustic field known as Resonant Macrosonic Synthesis (RMS) to see if we can harness the large RMS acoustic standing pressure waves to form an effective air-barrier/seal.

The adaptive seal project is also a new area this year. Our goal in this project is to develop advanced sealing approaches for minimizing blade-tip (shroud) or interstage seal leakage. We are planning on applying either rub-avoidance or regeneration clearance control concepts (including smart structures and materials) to promote higher turbine engine efficiency and longer service lives.

Scope of Activities: Turbine Seals

Objective:

Develop durable, low-leakage turbomachinery seals to meet demands of next generation subsonic and supersonic engines

Specific Goals:

- Develop seal technology to reduce specific fuel consumption (SFC) 2%
- Validate seal performance and design models through lab. testing under simulated speeds to (1500 fps), temperatures (to 1500°F) and pressures
- Investigate non-contacting, non-wearing seals to meet life and speed requirements
- Demonstrate seal performance in full scale engine tests
- Transition seals to engine service by 2005

Key Facilities:

In House:

- Turbine engine seal test rig upgraded to 1500 °F, 1500 fps speed
- Army T-700 & T-55 engines

Contractor: Numerous laboratory facilities including full scale engine tests (GE90)

Partners:

GE; P&W; Rolls Royce/Allison; Air Force; Army; UTRC; Honeywell (AlliedSignal); Perkin Elmer (EG&G); Stein Seal; Mohawk

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The objective of the NASA Glenn turbine engine seal development program is to develop durable, low-leakage seals to meet demands of next generation subsonic and supersonic engines.

Advanced seals including film riding aspirating, compliant foil, and advanced finger seals are being investigated to demonstrate non-contacting, low-leakage operation. Advanced test rigs such as NASA GRC's unique high speed (1500 fps) and high temperature (1500˚F) turbine seal rig will be used to assess performance characteristics of these new seals. Under contract, GE will perform engine tests of a full scale (36" diameter) aspirating seal in a ground-based GE-90 engine.

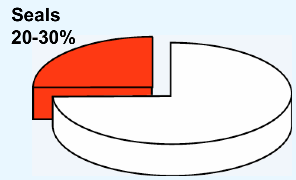
Analytical methods such as the coupled TURBO/SCISEAL code are being developed under contract with CFDRC to perform coupled main-flow (TURBO) and secondary air/seal (SCISEAL) calculations.

Why Seals?

AST Study Results: Expected Seal Technology Payoffs		
Seal Technology	Study Engine/ Company	System Level Benefits
Large diameter aspirating seals (Multiple locations)	GE90-Transport/ GE	–1.86% SFC –0.69% DOC+1
Interstage seals (Multiple locations)	GE90-Transport/ GE	–1.25% SFC –0.36% DOC+1
Film riding seals (Turbine inter-stage seals)	Regional-AE3007/ Allison	> –0.9% SFC > –0.89% DOC+1
Advanced finger seals	AST Regional/ Honeywell	–1.4% SFC –0.7% DOC+1

UEET Program Goal

Reduce Fuel Burn by 8-15%



- **Seals provide high return on technology $ investment**
  - Same performance goals possible through modest investment in the technology development
  - Example: 1/5th to 1/4th cost of obtaining same performance improvements of re-designing/re-qualifying the compressor
- **Seal contribution to program goals: 2 to 3% SFC reduction**

Advanced Seal Technology: An Important Player

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Cycle studies have shown the benefits of increasing engine pressure ratios and cycle temperatures to decrease engine weight and improve performance in next generation turbine engines. Advanced seals have been identified as critical in meeting engine goals for specific fuel consumption, thrust-to-weight, emissions, durability and operating costs. NASA and the industry are identifying and developing engine and sealing technologies that will result in dramatic improvements and address each of these goals for engines entering service in the 2005-2007 time frame.

General Electric, Allison and AlliedSignal Engines all performed detailed engine system studies to assess the potential benefits of implementing advanced seals. The study results were compelling. Implementing advanced seals into modern turbine engines will net large reductions in both specific fuel consumption (SFC) and direct operating costs including interest (DOC+I) as shown in the chart (Steinetz et al., 1998).

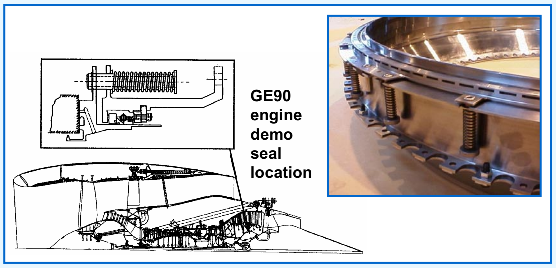
Applying the seals to just several engine locations would reduce SFC 2-3% . This represents a significant (20-30%) contribution toward meeting the overall goals of NASA’s Ultra-Efficient Engine Technology (UEET) program.

Aspirating Seal Development: GE90 Demo Program

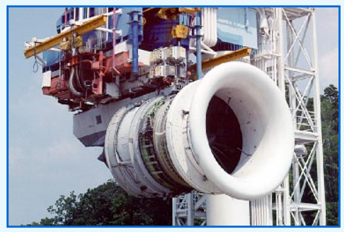
Funded UEET Seal Development Program

- **Goal:**
  - Complete aspirating seal development by conducting full scale (36 in. diameter) aspirating seal demonstration tests in GE90 engine.
- **Payoffs:**
  - Leakage <1/5th labyrinth seal
  - Operates without contact under severe conditions:
    - 10 mil TIR
    - 0.25°/0.8 sec tilt maneuver loads (0.08" deflection!)
  - Decrease SFC by 1.86% for three locations
- **Schedule:**
  - Design and analyses by 1Q FY01 (Complete)
  - Hardware fabrication by 3Q FY01 (Complete)
  - Static closure test 4Q FY01 (Complete)
  - GE90 engine test from 1Q to 2Q FY02
  - Data analysis and report by 2Q FY02
- **Partners:**
  GE/Stein Seal/CFDRC/NASA GRC

Aspirating Seal



General Electric GE90



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General Electric is developing a low leakage aspirating face seal for a number of locations within modern turbine applications. (see also Tseng, 2002 in this seal workshop proceeding for further details). This seal shows promise both for compressor discharge and balance piston locations.

The seal consists of an axially translating mechanical face that seals the face of a high speed rotor. The face rides on a hydrostatic cushion of air supplied through ports on the seal face connected to the high pressure side of the seal. The small clearance (0.001-0.002 in.) between the seal and rotor results in low leakage (1/5th that of new labyrinth seals). Applying the seal to 3 balance piston locations in a GE90 engine can lead to >1.8% SFC reduction. GE Corporate Research and Development tested the seal under a number of conditions to demonstrate the seal's rotor tracking ability. The seal was able to follow a 0.010 in. rotor face total indicator run-out (TIR) and could dynamically follow a 0.25° tilt maneuver (simulating a hard maneuver load) all without face seal contact.

The NASA GRC Ultra Efficient Engine Technology (UEET) Program is funding GE to demonstrate this seal in a ground-based GE-90 demonstrator engine in 2002/2003.

PW Bearing Compartment Seal Program PW-11

Funded UEET Seal Development Program

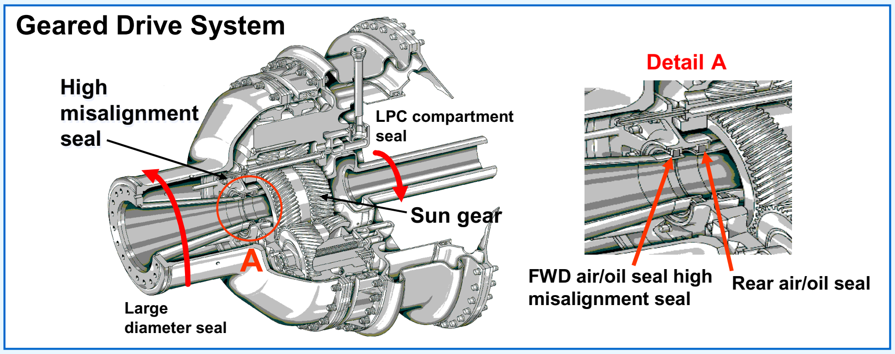
Objectives:

- Develop high misalignment seals capable of handling extremely large radial displacements due to angular and radial misalignment.

Schedule:

- Complete testing of high misalignment seals 1Q FY02

Partners: **PW/Stein Seal/NASA GRC**



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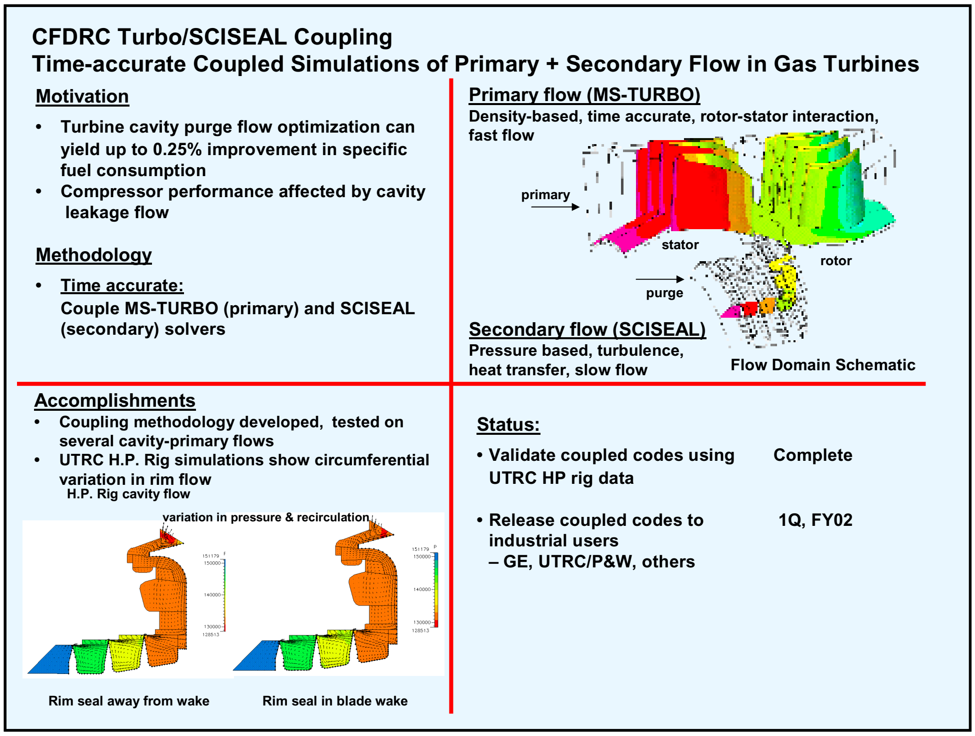
Advanced engines may incorporate geared fans. In the fan location, large bending loads coupled with structural weight limits result in fan bearing compartment seal deflections much greater than conventional carbon face seal capabilities. P&W is under contract with NASA GRC to investigate candidate carbon face and annular seals capable of large angular and radial movements. Working with Stein Seal, P&W is investigating candidate concepts designed for large angular (0.5˚) and radial (0.105”) movements and testing them under laboratory conditions (see also Dobek et al., 2002 in this seal workshop proceedings for further details). Advancements made in this program could have immediate application to main shaft bearing compartment seals.



NASA contracted CFDRC to develop a coupled main flow path/ secondary air system solver to investigate complex main/turbine cavity/rim seal flow phenomenon.

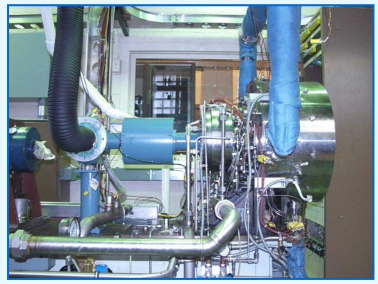
Studies have shown that excessive amounts of flow (up to 2-3% core flow) go through rim seals beyond that which is needed for cooling purposes (Munson and Steinetz, 1994). Hence SFC reductions are possible by reducing flows to what is needed for cooling purposes. New concepts and analytical methods are being developed to limit cooling to the appropriate level and provide positive out-flow of coolant preventing ingestion of hot combustion gases into the turbine rim cavity due to unsteady effects.

CFD- Research Corporation has completed the coupling of TURBO and SCISEAL for analyzing the complex main stream (TURBO) and secondary air stream (SCISEAL) interactions, including the effects of vane/blade wake interactions. The package can analyze flows from the engine centerline through the turbine rim seal location and through main flow path.

NASA also contracted with UTRC to measure the steady/unsteady turbine rim seal/cavity flows to assess the performance of baseline turbine rim seals. CFDRC has used this data set to validate the coupled TURBO/SCISEAL code. Beta release of the codes is expected in fall 2001. For further details see Athavale et al. 2002 in this seal workshop proceedings.

NASA GRC High Temperature Turbine Seal Test Rig

Goal: Test turbine seals at speeds and temperatures envisioned for next generation commercial, military, and space launcher (TBCC/RTA) turbine engines.



- **Temperature** — **Room Temperature thru 1500 °F**
- **Surface Speed** — **1500 fps at 40,455 RPM, 1600 fps at 43,140 RPM**
- **Seal Diameter** — **8.5" design; other near sizes possible**
- **Seal Type** — **Air Seals: brush, finger, labyrinth, film riding rim seal**
- **Seal Pressure** — **100 psi at 1500 °F: Current (Higher pressures at lower temperatures)**
- **Motor Drive** — **60 HP (60,000 RPM) Barbour Stockwell Air Turbine with advanced digital control for high accuracy/control**
- **Financial Support: UEET, SEC, Air Force, Other**

Test rig is one-of-a-kind. More capable than any known test rig in existence.

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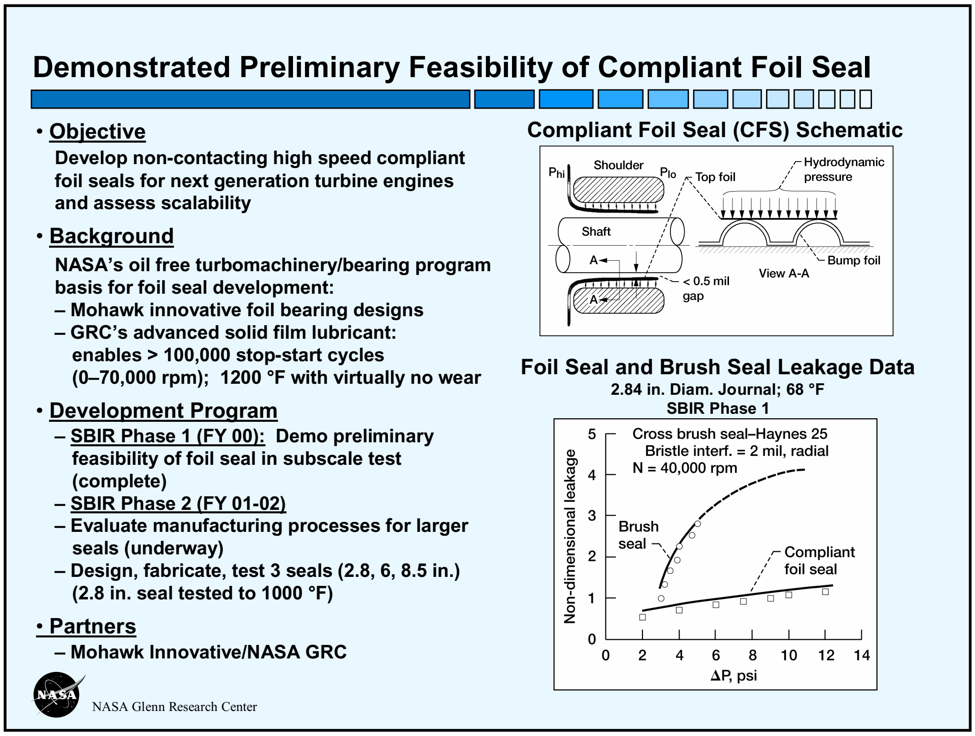
NASA GRC has finished mechanical installation and check-out tests of the new high speed (1500 fps), high temperature (1500˚F) turbine seal test rig. This test rig is designed to evaluate turbine seals (e.g. brush, finger, labyrinth) at all speeds and temperatures envisioned for next generation commercial and military turbine engines. This test rig will also be instrumental in evaluating advanced seals for NASA’s turbine based combined cycle/revolutionary turbine accelerator (TBCC/RTA) program. In this program a very high thrust-to-weight turbine engine would be integrated with a ram/scramjet to form a first stage of a future first stage launch system.

As of October 2001, the test rig had operated to surface speeds upto 1500 fps and temperatures over 1200˚F. Further information about this test rig and status can be found in Proctor et al of Volume 2 of this seal workshop proceedings.



NASA awarded to Mohawk Innovative Technology an SBIR Phase II to investigate film-riding compliant foil seals (see presentation by Salehi et al., 2002 in this seal workshop proceedings for further details). Compliant foil seals (CFS) are derived from foil bearing technology and block flow between high and low pressure cavities through very narrow gaps between the shaft and the foil. The hydrodynamic lift between the seal and the shaft prevents rotor-seal contact during operation. High temperature solid film lubricants applied to the shaft prevent wear during start-up and shut-down when limited contact occurs (DellaCorte, 2000).

As shown in the figure, leakage is very low due to the small (<0.0005 in.) clearance between the top foil and shaft. The compliant foil seal leakage is about 1/3rd that of a comparably sized brush seal at 10 psi. Because of the non-contacting, non-wearing nature of the CFS, this very low leakage characteristic should remain with cycling. Brush seal leakage, however, increases with cycling as the brush seal bristles wear to an operating clearance.

Adaptive Seal Technology Development

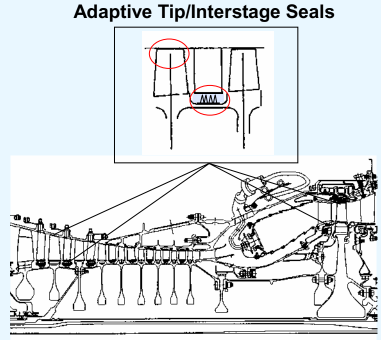
Goal:

Develop and demonstrate adaptive seal technology for turbine engine systems

Approach:

- Develop adaptive seals that maintain small running clearances by
  - Rub avoidance, or
  - Regeneration
- Seals are self-regulating to prevent unacceptable gap closure

Adaptive Tip/Interstage Seals



Payoffs:

- Overcomes primary reason for required engine servicing: Exhaust Gas Temperature (EGT) exceeding FAA certified red-line limit
- Improved blade tip and interstage sealing enables significant improvements in efficiency, payload, range, and emissions.
- Increases compressor stability & stall margin. Enables higher performance and higher stage loading - key for NASA's future aero- and space turbine engines.
- Decrease SFC by >1% possible (Ref. GE90 Engine Study)

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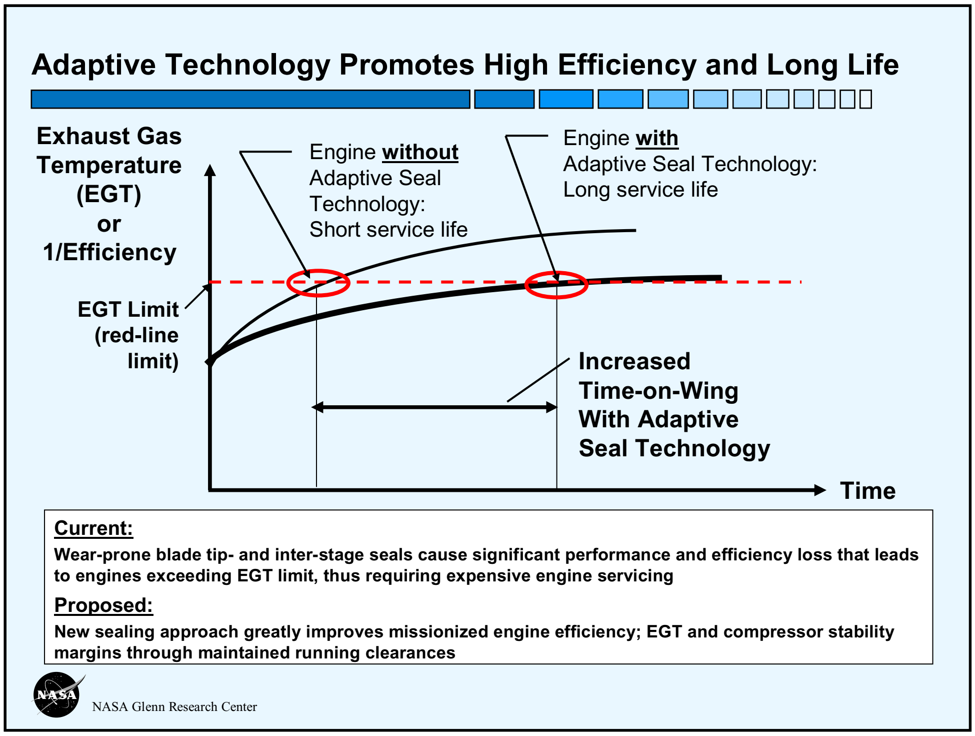
Blade tip clearance opening is a primary reason for turbine engines reaching their FAA certified exhaust gas temperature (EGT) limit. NASA GRC has embarked on a program to overcome or greatly mitigate this clearance opening problem. We are pursuing two approaches. The first is rub-avoidance in which an active clearance control system would actively move the case out of the way during the transient event to prevent wear. The second is regeneration in which damage is healed after a rub event returning clearances back to their design levels at certain prescribed cycle intervals. We are examining smart materials (e.g. shape memory alloys, etc.) amongst other unique approaches.

Benefits of clearance control in the turbine section include retained EGT margins (see also next chart), higher efficiencies, longer range, and lower emissions (because of lower fuel-burn). Benefits of clearance control in the compressor include better compressor stability (e.g. resisting stall/surge), higher stage efficiency, and higher stage loading. All of these features are key for future NASA and military engine programs.



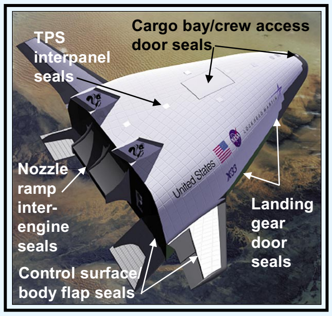
Turbine engines are certified with a “red-line” exhaust gas temperature (EGT) limit. Over time as engine clearances open, the pilot has to advance the throttle to higher settings to attain the required thrust levels. Higher thrust levels result in higher, life-limiting, first-stage rotor-inlet temperatures. Sensors measuring temperatures in the low pressure turbine monitor this exhaust gas temperature and when it reaches the red-line limit (indicating high rotor inlet temperature), the engine must be removed from the wing for service.

One goal of the advanced clearance control systems envisioned is to overcome “pinch-points” that occur during engine acceleration and prevent rubs from occurring. This will help in several ways. Designers can tighten-up the cold-build clearance which will increase performance by increasing thrust, efficiency, and mitigating compressor stability problems. Furthermore by avoiding rubs, the engine will stay on the wing longer (as indicated in the figure) resulting in lower overall operating costs.

Scope of Activities: Structural Seals

Objective:
Develop unique structural seals for extreme temperature engine, re-entry vehicle, and rocket applications.

Specific Goals:
- **Develop advanced structural seals capable of extreme (1500 – 5500 °F) temperatures.**
- **Exploit novel design techniques to meet leakage, durability, and resiliency (spring-back) goals across operating temperature range.**
- **Evaluate seal performance through compression, flow, scrub and extreme thermal tests.**
- **Develop/validate analytical models to predict leakage and resiliency performance.**
- **Demonstrate seal performance through prototype system tests.**



Key In House Facilities:
- **In process: High temperature (3000 °F) seal scrub (+ ambient flow) and compression test rigs.**
- **In process: Ambient temperature seal flow/scrub test rig**
- **Engine components lab (>2000 °F) & C-22 Rocket Facility (5130)**
- **Ames arc jet control surface seal fixture.**

Partners:
Thiokol, Albany-Techniweave; P&W; Rocketdyne; Boeing; Air Force; Other Industrial Partners.

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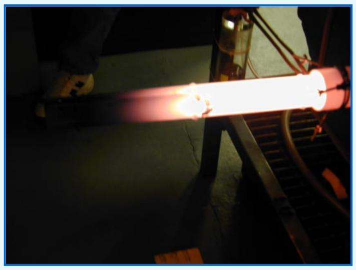
NASA GRC is also developing unique structural seals for extreme temperature engine (air breathing hypersonic and other), re-entry vehicle, and rocket applications. Challenges in these areas are extreme temperatures (1500-5500˚F), large (up to 3”) deflections, and pressures (100 - 1000 psi). Novel concepts are being developed that can satisfy these conditions while retaining their ability to follow adjacent wall movement. Seals are being constructed using advanced manufacturing techniques (e.g. braiding/weaving, other) from a range of high temperature carbon and ceramic materials.

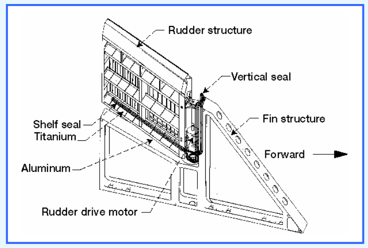
NASA has unique facilities to evaluate the flow and durability performance of these seals at temperatures up to 1500˚F (existing) and up to 3000˚F (planned: see Dunlap et al. and DeMange et al. in this 2002 seal workshop proceedings). NASA GRC also possesses a high heat flux H2/O2 rocket engine for subjecting materials and components to the extreme conditions anticipated in next generation Reusable Launch Vehicle (RLV) propulsion systems.

GRC X38 Seal Test Evaluation and Support

- Examining control surface seals for JSC for X-38 (C.R.V. demonstrator)
- Evaluated seal flow rates, compression levels, and arc jet heating resistance
- Performed furnace exposure tests on X-38 seal in compressed state at 1900°F and pre-and post-exposure flow tests:



1900 °F Furnace Tests



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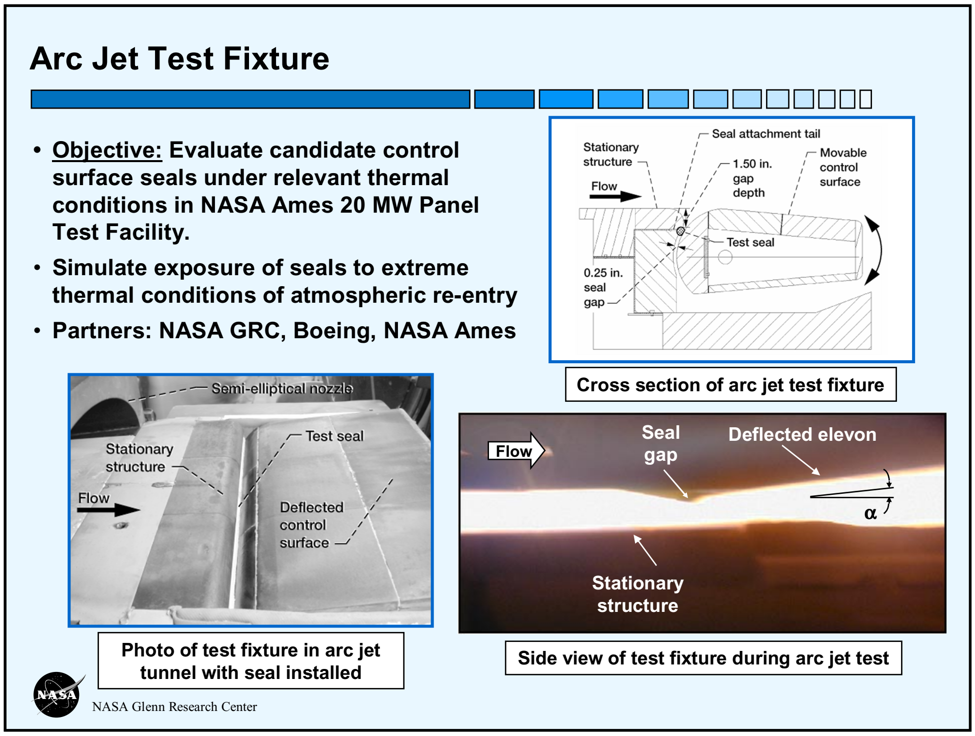
The X-38 vehicle is being developed as a precursor to a future Crew Return Vehicle to demonstrate necessary re-entry vehicle technologies including controls surface seals (see also Curry et al. in this 2002 seal workshop proceedings). For cost considerations, JSC is interested in using Space Shuttle thermal barrier/seals as control surface seals. NASA Johnson asked GRC to assist them in assessing sealing performance of the rudder/fin seal being considered for the X-38 vehicle. GRC is assisting with measuring seal flow rates and resiliency to assist in determining if Shuttle-derived thermal barriers will meet the X-38 rudder-fin heat- and flow-blocking requirements

NASA GRC has performed a range of compression (e.g. spring-back) and flow tests on thermal barriers in both their as-received and post- high temperature exposure (1900˚F) conditions (see Dunlap et al. 2001). The GRC tests showed that most of the thermal barrier/seal’s resiliency - was lost after the 1900˚F exposure test. These tests aided JSC in setting limits on acceptable gap openings in the rudder-fin location to prevent possible gap opening during re-entry due to seal permanent set. The flow tests also provided much needed permeability data for the JSC seal/gap thermal modeling effort.

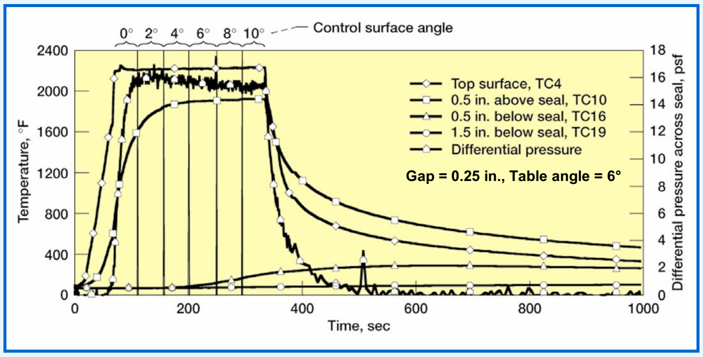


Under contract to NASA GRC, Boeing performed arc jet tests on candidate high temperature control surfaces seals for future highly-reusable launch vehicles. In this test seals were installed in a 0.25” wide gap between the stationary structure and movable control surface. Temperatures and pressures both upstream and downstream of the seals were measured at various control surface angles in the flow of the 20 MW Ames Arc Jet facility. Shown in the figure are a cross-section of the test section and a photo of the test apparatus before (lower left) and during (lower right) the arc jet test.

A matrix of seals and seal material combinations were tested for a range of aerothermal environments for a variety of advanced control surface applications (X-38, X-37, etc). See also presentation by Verzemnieks and Newquist, 2001, in last year’s workshop proceedings for further details. During arc jet operation the control surface was rotated into the flow stream at angles up to 16 degrees (including 6 degree table angle). These measurements are being used to validate an aero-thermal-structural model to be used to predict seal performance under flight re-entry conditions.

Arc Jet Test Results-X-38 Seal Installed

- **Single seal installed at 20% compression**
- **Peak temperatures:**
  - **0.5 in. above seal = 1920 °F**
  - **0.5 in. below seal = 210 °F**
  - **Temperature drop across seal location = 1710 °F (compared to 140 °F for open gap test)**



- **Average pressure differential across seal was 15.6 psf, 44% of predicted pressure drop (35 psf) during X-38 maximum heating**

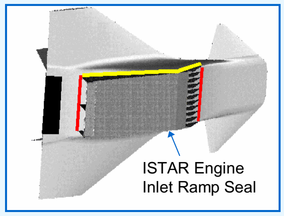
Installation of single seal caused large temperature and pressure drop across seal location as compared to open gap

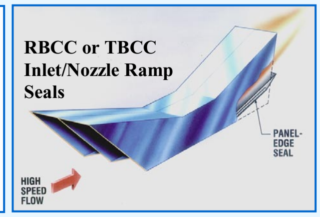
NASA Glenn Research Center

The X-38 rudder fin seal was tested in the Ames Arc Jet test. Temperatures were measured on the Shuttle tiles forming the top surface of the fixture, 0.5” above the seal, and 0.5”,1.0”, 1.5” below the seal, as shown in the figure. During the test, control surface angles were increased from 0 to 10˚ (or 6 to 16˚ total angle when including the 6˚ table angle). Pressures applied across the seal reached 15.6 psf which correspond to 44% of the predicted pressure during maximum re-entry heating for the X-38. Temperatures on the tile surface reached 2200˚F. Temperatures 0.5” above the seal reached 1920˚F and temperatures 0.5” below the seal were only 210˚F. Hence a single seal caused a 1710˚F temperature drop - encouraging news for the X-38 seal designers. Data from this test is being used to validate an aero-thermal-structural model that can then be used to extrapolate the seal’s thermal performance under the full pressure and heat loads expected during re-entry (see also Reich et al 2002 in this Seal Workshop Proceedings).

NASA GRC Seal Development for 3rd Generation Space Transportation Programs

- **Develop hot (2500+°F), flexible, dynamic structural seals for ram/scramjet propulsion systems (RBCC, TBCC, GTX)**





- **Develop reusable re-entry vehicle control surface seals to prevent ingestion of hot (6000 °F) boundary layer flow**

Hot, dynamic seals critical to meeting 3rd generation program life, safety, and cost goals

NASA Glenn Research Center

NASA is currently funding efforts to conduct research on advanced technologies that could greatly increase the reusability, safety, and performance of future Reusable Launch Vehicles (RLV). Research work is being performed under NASA's 3rd Generation RLV program on both high specific impulse ram/scramjet engines and advanced re-entry vehicles.

NASA GRC is developing advanced structural seals for both of these needs by applying advanced design concepts made from emerging high temperature ceramic materials and testing them in advanced test rigs that are under development.

3rd Generation 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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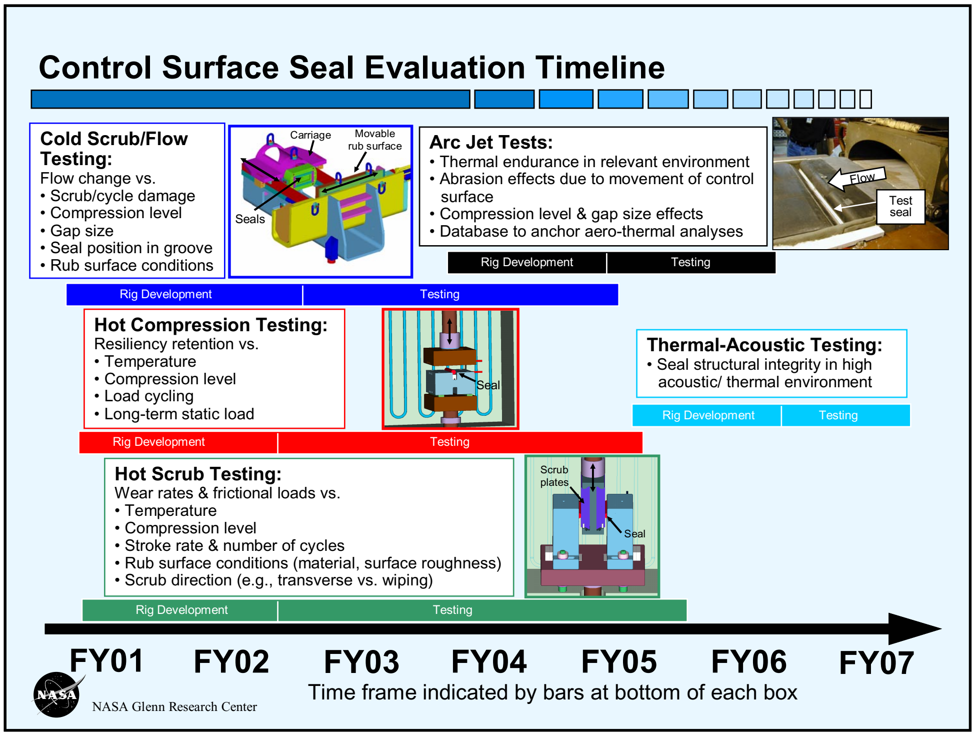
Seal technology is recognized as critical in meeting next generation aero- and space propulsion and space vehicle system goals.

Future RLV vehicles will be expected to operate at more aggressive re-entry conditions. High temperature seals are required to prevent ingestion of hot boundary layer gases into the control surface hinge-line locations. Whereas the Shuttle control surface seals operate at temperatures less than 1500˚F, seals anticipated for future RLV systems are expected to operate in the 2000-2500˚F range.

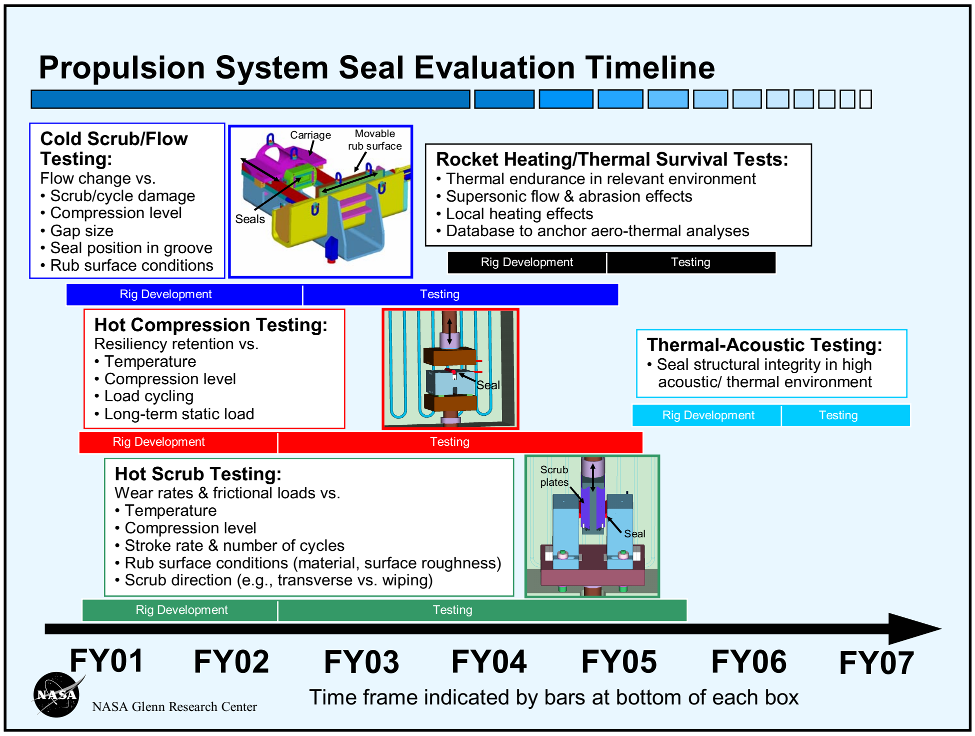
NASA is investigating advanced air-breathing hypersonic engines as possible first-stage propulsion systems for higher-performance multi-stage launch systems. Hypersonic engines attain higher specific impulse as compared to conventional rocket engines. Further they save weight by burning air from the environment rather than from a liquid oxygen tank. Optimizing engine performance over the wide speed range (Mach 3-10+) requires movable inlet and nozzle ramps to tailor engine flow area. High temperature (2500˚+F) seals are required to prevent leakage of combustion gas into backside engine cavities. These structural seals must be flexible to accommodate large (~0.25”) deflections in engine sidewalls.



NASA Glenn has implemented an ambitious program to develop and evaluate seals under thermal, pressure, sliding and acoustic conditions anticipated in future RLV control surfaces.

Shown in this chart is a pictorial timeline showing the types of tests to be performed and the goals of each test. GRC is developing in-house capability to test seals at temperatures from ambient temperature to 3000˚F. At high temperatures conventional control surface seals generally lose their resiliency. New seal concepts and preload techniques are being developed to overcome this compression-set problem (see also Dunlap et al in this 2002 seal workshop proceedings). Seals and preload systems will be compression tested in the hot compression test rig under development. A hot scrub test rig is being developed to examine seal wear rates and frictional loads vs. temperature, compression level, stroke rate and no. of cycles, to name a few. Further details of these test rig designs can be found in DeMange et al in this 2002 Seal Workshop Proceedings.

Additional arc-jet tests will be performed to investigate seal performance under simulated re-entry heating conditions using one of NASA Ames' arc jet facilities. Later in the development program, thermal-acoustic tests will be performed to assess seal and attachment structural integrity when exposed to representative thermal and acoustic loads.



NASA Glenn has implemented an ambitious program to develop and evaluate seals under thermal, pressure, sliding and acoustic conditions anticipated in future hypersonic engines.

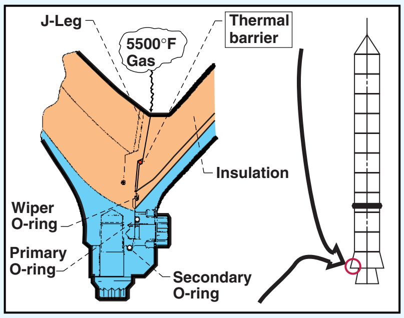
Shown in this chart is a pictorial timeline showing the types of tests to be performed and the goals of each test. The test seal flow and scrubbing test rigs being developed were designed to accommodate both the light loads and high sliding speeds for the control surface task and the relatively heavy loads and slower sliding speeds required for the hypersonic engine seal development task. Further details of these test rig designs can be found in DeMange et al in this 2002 Seal Workshop Proceedings.

Hypersonic engine seals will be subjected to high heat fluxes in the ram/scramjet engines. Candidate seals will be tested in a hydrogen-oxygen rocket at NASA Glenn. These tests will examine coolant flow rates necessary to survive the anticipated heating condition and examine the seal's ability to resist the supersonic flow and abrasion effects. Later in the development program, thermal-acoustic tests will be performed to assess seal and attachment structural integrity when exposed to representative thermal and acoustic loads.

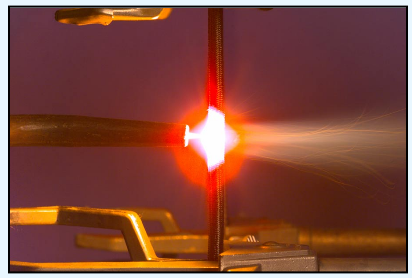
Thiokol Selects NASA GRC Thermal Barrier for RSRM Joint Redesign

- **Thiokol experiences periodic hot gas effects on RSRM nozzle-joint Viton O-rings leading to extensive reviews before flight.**
- **Glenn thermal barrier braided of carbon fiber has shown outstanding ability to prevent hot (5500˚F) gas from effecting downstream O-rings in multiple sub- and full-scale RSRM tests.**

Redesigned RSRM Nozzle-to-Case Joint w/GRC thermal barrier



GRC 5500°F Flame Test



Thiokol has selected GRC thermal barrier for Nozzle-to-Case Joint redesign and is strongly considering for Joint Numbers 1–5 redesign.

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The NASA Glenn developed braided carbon fiber thermal barrier is the primary candidate being considered by NASA and Thiokol for the redesign of the Space Shuttle re-usable solid-rocket-motor (RSRM) nozzle-to-case joint and for nozzle joints 1-5. Incorporation of the NASA Glenn developed braided carbon fiber thermal barrier into the nozzle joints of the Space Shuttle RSRMs would eliminate hot gas penetration to nozzle joint Viton O-rings and prevent extensive reviews that delay Shuttle launches. Numerous lab, sub-scale rocket and full-scale rocket tests have demonstrated the feasibility of the carbon fiber thermal barrier, as will be discussed on the next chart.

NASA Glenn Carbon Fiber Rope Thermal Barrier
Full Scale Shuttle Solid Rocket Motor Static Test

Objective

Investigate feasibility of new joint designs with carbon fiber rope (CFR) thermal barrier to protect Viton O-ring seals in full-scale solid rocket motors

Thiokol Full-Scale Solid Rocket Motor Static Test

Full scale motor tests

FSM-9 test	
Nozzle-to-case joint	1 CFR
Joint #2	2 CFRS
ETM-2 test	
Joint 1*	2 CFR
Joint 2**	2 CFR
Joint 5*	1 CFR

* Replace RTV with CFR
** Demonstrate fault tolerance of CFR

Schedule

FSM-9	May 24, 2001	Successfully demonstrated CFR in nominal joint
ETM-2	November 1, 2001	Examine flawed & nominal joint with CFR

NASA Glenn Research Center

On May 24, 2001, the NASA Glenn developed braided carbon fiber thermal barrier was successfully evaluated by Thiokol in a full-scale static motor test, designated FSM-9. In this test carbon fiber ropes (CFRs) were tested in both the nozzle-to-case joint and Joint 2. During the solid rocket motor firing, temperatures and pressures were measured both upstream and downstream of the joints. In Joint 2 for instance, measurements indicated that temperature upstream of the CFR were 3700˚ F, the temperature between the two CFRs was 500˚F, and downstream the temperature was only 175˚F - well within the Viton O-ring short-term temperature limit of 800˚F. This test successfully demonstrated the design intent of the CFR for both joints tested, clearing the way for future more aggressive full-scale static motor tests in November, 2001.

On November 1, 2001, the CFR will be tested in joints 1, 2, and 5 in a full-scale solid-rocket motor test designated ETM-2. In joints 1 and 5 CFRs will be used in place of the RTV joint compound. RTV often cures with voids that can lead to rocket gas impingement on the Viton O-rings. Replacing the RTV with the CFR should eliminate the focusing of the hot rocket gas. Past experience has shown that the CFR not only spreads any localized jets but also drops the temperature of the incoming gas to well within the O-ring temperature limits, preventing Viton O-ring distress.

It is anticipated that the CFR will be flown on the Space Shuttle in 2005.

Summary

- **Seals technology recognized as critical in meeting next generation aero- and space propulsion and space vehicle system goals**
  - **Performance**
  - **Efficiency**
  - **Reusability**
  - **Safety**
  - **Cost**

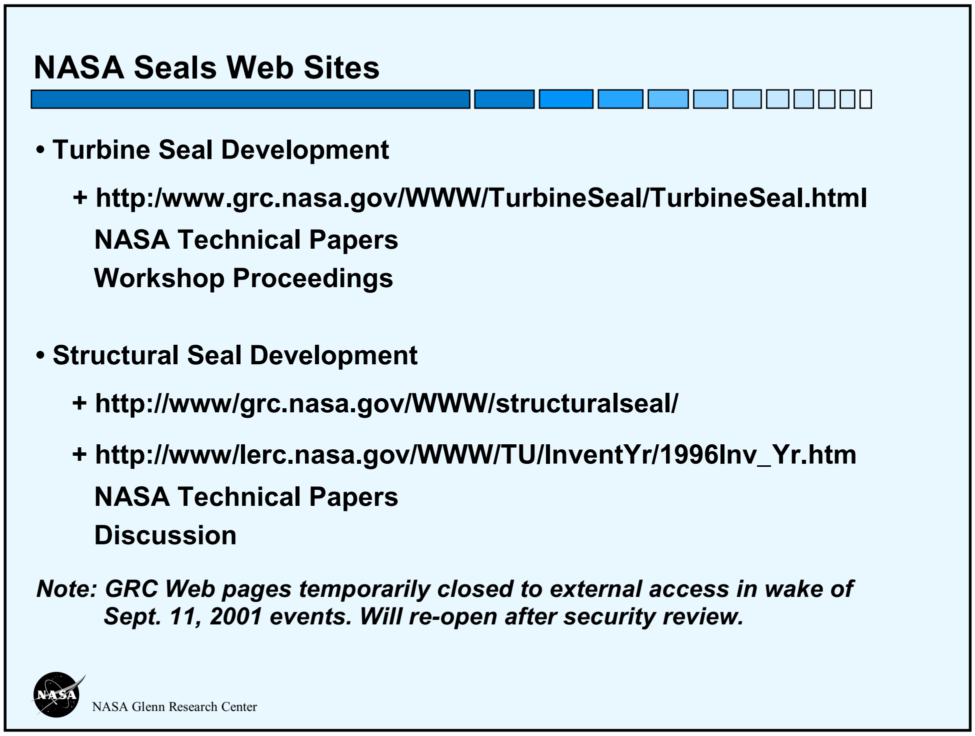
- **NASA Glenn is developing seal technology and/or providing technical consultation for the Agency's key aero- and space advanced technology development programs.**

NASA Glenn Research Center

NASA Glenn is currently performing seal research supporting both advanced turbine engine development and advanced space vehicle/propulsion system development. Studies have shown that decreasing parasitic leakage through applying advanced seals will increase turbine engine performance and decrease operating costs.

Studies have also shown that higher temperature, long life seals are critical in meeting next generation space vehicle and propulsion system goals in the areas of performance, reusability, safety, and cost goals.

NASA Glenn is developing seal technology and providing technical consultation for the Agency's key aero- and space technology development programs.



The Seal Team maintains three web pages to disseminate publicly available information in the areas of turbine engine and structural seal development. Interested people can visit these web sites to obtain information, at the addresses indicated above.

References

DellaCorte, C., 2000, “ High Temperature Solid Lubrication Developments for Seal Applications,” 1999 NASA Seal/Secondary Air System Workshop Proceedings, CP-2000-210472 VOL1.

Dunlap, P. H., Steinetz, B.M., Curry, D.,M., Newquist, C.W., Verzemnieks, J. 2001, “Further Investigations of Control Surface Seals for the X-38 Re-Entry Vehicle,” NASA TM-2001-210980, AIAA-2001-3628.

Munson, J. and Steinetz, B.M., 1994, “Specific Fuel Consumption and Increased Thrust Performance Benefits Possible with Advanced Seal Technology,” AIAA-94-2700.

Steinetz, B.M., Hendricks, R.C., and Munson, J.H., 1998 “Advanced Seal Technology Role in Meeting Next Generation Turbine Engine Goals,” NASA TM-1998-206961.

Verzemnieks, J., Newquist, C.W. 2001,”Control Surface Seal Development for Future Re-Entry Vehicles,” 2000 NASA Seal/Secondary Air System Workshop Proceedings, CP-2001- 211208/VOL1.

References:

DellaCorte, C., 2000, “ High Temperature Solid Lubrication Developments for Seal Applications,” 1999 NASA Seal/Secondary Air System Workshop Proceedings, CP-2000-210472 VOL1.

Dunlap, P. H., Steinetz, B.M., Curry, D.,M., Newquist, C.W., Verzemnieks, J. 2001, “Further Investigations of Control Surface Seals for the X-38 Re-Entry Vehicle,” NASA TM-2001-210980, AIAA-2001-3628.

Munson, J. and Steinetz, B.M., 1994, “Specific Fuel Consumption and Increased Thrust Performance Benefits Possible with Advanced Seal Technology,” AIAA-94-2700.

Steinetz, B.M., Hendricks, R.C., and Munson, J.H., 1998 “Advanced Seal Technology Role in Meeting Next Generation Turbine Engine Goals,” NASA TM-1998-206961.

Verzemnieks, J., Newquist, C.W. 2001,”Control Surface Seal Development for Future Re-Entry Vehicles,” 2000 NASA Seal/Secondary Air System Workshop Proceedings, CP-2001- 211208/VOL1.