

OVERVIEW OF NASA GLENN SEAL DEVELOPMENTS

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

Irebert Delgado
U.S. Army Research Laboratory
Glenn Research Center
Cleveland, Ohio

Jeffrey J. DeMange
University of Toledo
Toledo, Ohio

Christopher C. Daniels and Scott B. Lattime
Ohio Aerospace Institute
Brook Park, Ohio

Overview of NASA Glenn Seal Developments

Dr. Bruce M. Steinetz
NASA Glenn Research Center
Cleveland, OH 44135

Contributors

**Margaret Proctor, Patrick Dunlap, Irebert Delgado
Jeff DeMange, Chris Daniels, Scott Lattime**

**2003 NASA Seal/Secondary Air System Workshop
November 5-6, 2003
NASA Glenn Research Center
Ohio Aerospace Institute Auditorium**

NASA Glenn hosted the Seals/Secondary Air System Workshop on November 5-6, 2003. At this workshop NASA and our industry and university partners shared 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 the presentations from this workshop in 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.).

Workshop Agenda	
Wednesday, Nov. 5, Morning	
Registration	8:00 a.m.–8:30 a.m.
Introductions	8:30-9:30
Introduction	Dr. Bruce Steinetz, R. Hendricks/NASA GRC
Welcome	Mr. Vern (Bill) Wessel, Director, Safety and Mission Assurance
Overview of NASA's Low Emissions Alternative Power Project	Dr. Gary Seng, Dir., Aero propulsion/Power Research/GRC
Overview of NASA Glenn Seal Developments	Dr. Bruce Steinetz/NASA GRC
Program Overviews and Requirements	9:30-10:30
Overview of NASA's UEET Project	Ms. Catherine Peddie, Dr. Joe Shaw /NASA GRC
Overview of NASA's Access to Space Programs	Mr. Harry Cikanek/NASA GRC
Revolutionary Turbine Accelerator (RTA) Engine Dev. Overview	Dr. Paul Bartolotta, K. Suder, N. McNelis/NASA GRC
Break	10:30 -10:45
Turbine Seal Development Session I	10:45-12:30
GE90 Aspirating Seal Engine Demonstration Test Update	Ms. Marcia Boyle, B. Albers/GE Aircraft Engines
Overview of Industrial Seal Developments at GE-GRC	Dr. Ray Chupp/GE Global Research Center
Geared Fan High Misalignment Seal Test Status	Mr. Dennis Shaughnessy, L. Dobek/P&W E. Hartford
Overview of Turbine Seal Testing at GRC	Mr. Irebert Delgado/U.S. Army Lab, M. Proctor/ NASA
Compliant Foil Seal Investigations	Ms. Margaret Proctor/NASA GRC, I. Delgado/U.S. Army Research Laboratory
Lunch OAI Sun Room	12:30-1:30



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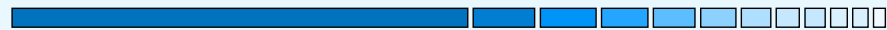
The first day of presentations included overviews of NASA programs devoted to advancing the state-of-the-art in aircraft power and turbine engine technology. Dr. Gary Seng provided an overview of NASA's Low Emissions Alternative Power Project. Ms. Peddie presented an overview of the Ultra-Efficient-Engine Technology (UEET) program that is aimed at developing highly-loaded, ultra-efficient engines that also have low emissions (NOx, unburned hydrocarbons, etc.). Mr. Cikanek of NASA's Space Project office summarized NASA's Access to Space Programs citing areas where advanced seals are required.

Dr. Bartolotta provided an overview of the turbine-based-combined-cycle (TBCC)/Revolutionary Turbine Accelerator (RTA) project. The goal of this project is to develop turbine engine technology that would enable a turbine-engine based first stage launch system for future highly re-usable launch vehicles.

Dr. Steinetz presented an overview of NASA seal developments. Representatives from GE provided insight into their advanced seal developments for both aircraft engines and ground power. Mr. Shaughnessy presented an overview of the work P&W and Stein Seal are doing on the development of high misalignment carbon seals for a geared fan application. Mr. Delgado of NASA Glenn presented an overview of turbine testing at NASA GRC. Ms. Proctor provided results from compliant foil seals investigations performed at NASA GRC.

Workshop Agenda

Wednesday, Nov. 5, Afternoon



Turbine Seal Development Session II

Test Rig for Evaluating Active Turbine Blade
Tip Clearance Control Concepts
Controls Considerations for Turbine Active
Clearance Control
Microwave Blade Tip Sensor Technology Overview
Non-contacting Seal Developments
Non-Contacting Finger Seal Design Considerations
Effect of Flow-induced Radial Load on
Brush Seal/Rotor Contact Mechanics

1:30-3:30

Dr. Scott Lattime/OAI, B. Steinetz/NASA GRC

Mr. Kevin Melcher/NASA GRC

Mr. Jon Geisheimer, Radatech Inc.

Mr. John Justak/Advanced Technologies Group

Dr. Jack Braun/U. Akron, H. Pierson/U. Akron et al

Haifang Zhao & Dr. Robert J. Stango; Marquette University

Break

3:30-3:45

Turbine Seal Development Session III

Seal Developments at FlowServe
Investigations of High Pressure Acoustic Waves
in Resonators With Seal-like Features
Numerical Investigations of High Pressure Acoustic
Waves in Resonators
Abradable Seal Developments at Technetics

3:45-5:00

Mr. Andrew Flaherty, Mr. L. Young, & Mr. W. Key, Flowserve

Dr. Chris Daniels, OAI, B. Steinetz, J. Finkbeiner/GRC

X. Li, and G. Raman/Illinois Institute of Tech.

Dr. Mahesh Athavale, M. Pindera/CFD Research

C. Daniels, B. Steinetz/NASA GRC

Mr. Doug Chappel/Technetics Co.

6:15-?

Group Dinner Viva Barcelona, Westlake



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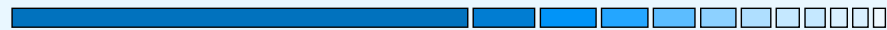
Turbine engine studies have shown that reducing high pressure turbine (HPT) blade tip clearances will reduce fuel burn, lower emissions, retain exhaust gas temperature margin and increase range. Dr. Lattime presented the design and development status of a new Active Clearance Control Test rig aimed at demonstrating advanced ACC approaches and sensors. Mr. Melcher presented controls considerations for turbine active clearance control. Mr. Geisheimer of Radatech presented an overview of their microwave blade tip sensor technology. Microwave tip sensors show promise of operation in the extreme gas temperatures present in the HPT location.

Mr. Justak presented an overview of non-contacting seal developments at Advanced Technologies Group. Dr. Braun presented investigations into a non-contacting finger seal under development by NASA GRC and University of Akron. Dr. Stango presented analytical assessments of the effects of flow-induced radial loads on brush seal behavior. Mr. Flaherty presented innovative seal and seal fabrication developments at FlowServ. Mr. Chappel presented abradable seal developments at Technetics.

Dr. Daniels presented an overview of NASA GRC's acoustic seal developments. NASA is investigating the ability to harness high amplitude acoustic waves, possible through a new field of acoustics called Resonant Macrosonic Synthesis, to effect a non-contacting, low leakage seal. Dr. Daniels presented early results showing the ability to restrict flow via acoustic pressures. Dr. Athavale presented numerical results simulating the flow blocking capability of a pre-prototype acoustic seal.

Workshop Agenda

Thursday, Nov. 6, Morning



Registration at OAI

8:00-8:30

Space Vehicle Development

8:30-10:15

Shuttle Columbia Leading Edge Impact Investigations

Mr. Matthew Melis, M. Pereira, D. Revilock,
D. Hopkins/NASA GRC

Nuclear Rocket Propulsion for Future NASA Missions

Dr. Stan Borowski,/NASA GRC

Overview of Boeing Advanced Space Vehicles
and Seal Needs

Ms. Leanne Lehman/T. Steyer/Boeing Co.

Overview of ISTAR Engine Development & Seal Needs

Mr. Ravi Nigam, R. Kreidler/Pratt & Whitney

Break

10:15-10:30

Structural Seal Development

10:30-12:00

Atlas V Solid Rocket Motor Carbon Fiber Rope
Status Review -> *Withdrawn*

Mr. Michael Sears, Dr. Gary Luke/Aerojet

High Temperature Propulsion System Structural Seals
for Future Space Launch Vehicles

Mr. Pat Dunlap, B. Steinetz/ GRC, J. Demange/U. Toledo

Advanced Control Surface Seal Development
for Future Space Vehicles

Mr. Jeff DeMange/U. Toledo, P. Dunlap, B. Steinetz/GRC

CFD Analyses of ISTAR Engine Seals: An Update

Mr. Alton Reich, M. Athavale/CFD-RC

Lunch OAI Sun Room

12:00-1:00



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Mr. Melis presented an overview of NASA GRC's leading edge impact investigations performed to support both the Columbia failure investigation and Shuttle return to flight. Dr. Borowski presented plans for nuclear propulsion to support NASA's goal of traveling to the outer reaches of the solar system in much shorter times than that possible through conventional propulsion systems. Ms. Lehman of Boeing Space and Communications presented Boeing's plans for future space vehicles and seal needs.

NASA is investigating hybrid rocket/air-breathing systems to increase propulsion system specific impulse. Mr. Nigam presented an overview of the ISTAR (Integrated System Test of an Air-breathing Rocket) program and engine seal challenges. Mr. Dunlap presented propulsion seal development efforts underway at GRC for engine ramps of future hypersonic airbreathing engines. Mr. DeMange presented control surface (e.g. hinge-line) seal development efforts underway at GRC for future re-entry vehicles. Dr. Athavale presented CFD/thermal analyses results of the ISTAR engine ramp seals indicating the challenging ramp seal thermal environments that demand high temperature seal designs.

Workshop Agenda

Thursday, Nov. 6, Afternoon



High Temperature Materials and Related Developments

1:00-2:00

Development of High Temperature Seal Preloaders

Mr. Ted Paquette/Refractory Composites,
J. Palko/CRT Technologies

High Temperature Metallic Seal Development for
Aeropropulsion Applications

Mr. Greg More/Advanced Products
A. Datta/Advanced Components & Material

BrazeFoil Honeycomb

Mr. Geosef (Joey) Straza, AeroVision International

Tour of NASA Seal Test Facilities

2:30-4:00

Adjourn



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Advanced structural seals and preloading elements require application of advanced high temperature materials. The closing session of the workshop presented seal concepts and materials being developed at several locations. Mr. Paquette presented high temperature seal preloader development work being performed by Refractory Composites, under contract to NASA GRC. Mr. Palko presented finite element analyses of these candidate preloader systems helping guide preloader design selection. Mr. More (Advanced Products) and Dr. Datta (Advanced Components and Materials) presented an overview of their high temperature metallic seal development.

Mr. Straza of Aerovision and Daniel Kay presented an innovative BrazeFoil honeycomb that combines braze alloy and honeycomb together to facilitate brazing to turbine static structures for aerospace applications.

NASA Glenn Seal Team



Seal Team Leader: Bruce Steinetz

Mechanical Components Branch/5950

Turbine Seal Development

Develop non-contacting, low-leakage turbine seals

Margaret Proctor: Principal Investigator/POC
Irebert Delgado, Dave Fleming
Dan Breen, Joe Flowers

Structural Seal Development

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

Pat Dunlap: Principal Investigator/POC
Jeff DeMange, Josh Finkbeiner
Malcolm Robbie, Gus Baker

Clearance Management

Develop novel approaches for blade-tip clearance control.

Scott Lattime: Principal Investigator/POC
Jim Smialek, Kevin Melcher, Chris Daniels
Malcolm Robbie

Emerging Areas

Acoustic Seals, Fuel Cell Seals
Pulse Detonation/Constant Vol. Combustion Engine Seals

Chris Daniels: Principal Investigator/POC
Josh Finkbeiner

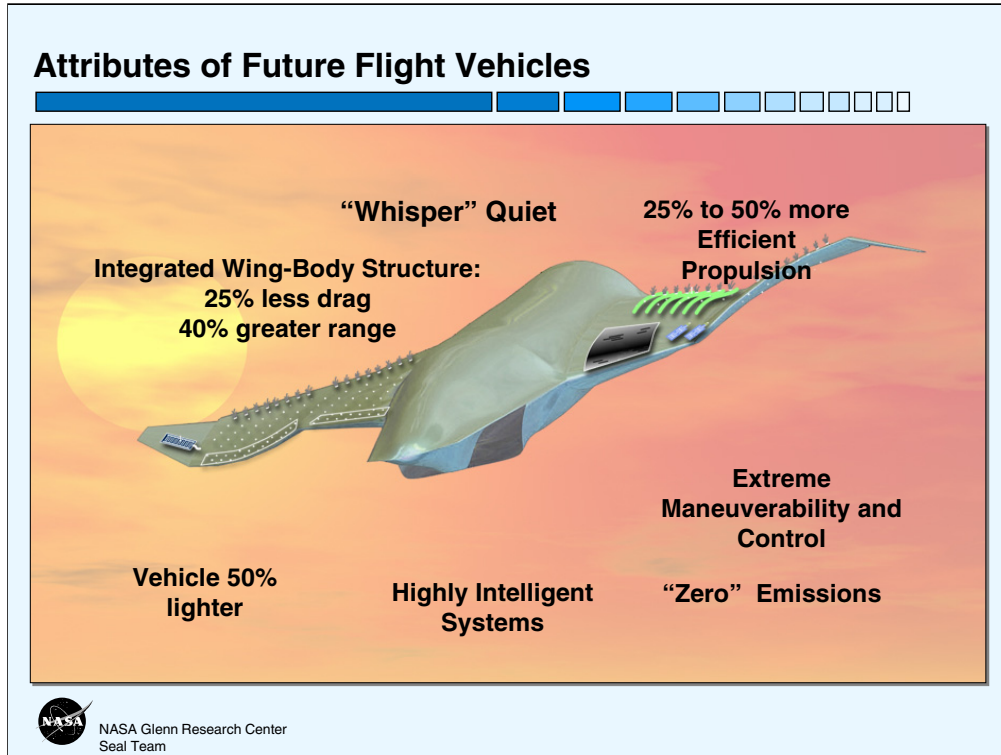


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The Seal Team is divided into four primary areas. The principal investigators and supporting researchers for each of the areas are shown in the slide. These areas include turbine seal development, structural seal development, clearance management, and seals for emerging areas. The first area focuses on high temperature, high speed shaft seals for turbine engine 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.

Our goal in the clearance management project is to develop advanced sealing approaches for minimizing blade-tip clearances and 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.

We are also contributing seal expertise in a range of emerging areas. These include acoustic seals (a GRC innovation), fuel cell seals, and seals for pulse detonation/constant volume combustion engines. GRC has received strong support for the development of pulse detonation hybrid engines and fuel cells for on-board power generation. These applications would see significant efficiency gains through the improvement of their sealing systems.



Attributes of future aircraft are illustrated here. Future vehicles will incorporate advanced materials to reduce weight and drag. Future aircraft will also use highly efficient quiet propulsion systems to reduce fuel burn, reduce emissions and reduce noise in and around airports.

One might ask: What role would advanced seals play in these future vehicles? Lower leakage engine seals reduce engine fuel burn and as a result reduce aircraft emissions. 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 (Steinetz and Hendricks, 1998). 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.

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 ~1/4th labyrinth seal
- Decrease SFC by 1.86% for three locations
- Operates without contact under severe conditions:
 - + 10 mil TIR
 - + 0.25°/0.8 sec tilt maneuver loads (0.08" deflection!)

Schedule:

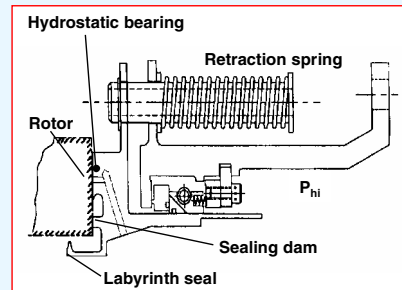
- Complete engine assembly 4Q CY03
- GE90 engine test: 1Q CY04

Partners:

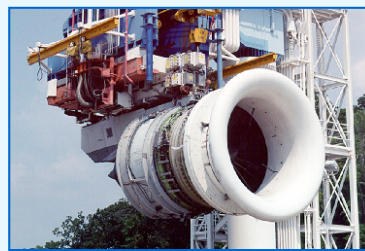
GE/Stein Seal/CFDRC/NASA GRC



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General Electric GE90



General Electric is developing a low leakage aspirating face seal for a number of locations within modern turbine applications. 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 (1/4th 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 2003. More details can be found in Boyle and Albers, 2004 in this Seal Workshop Proceedings and Turnquist, et al 1999.

NASA GRC Compliant Foil Seal Investigations

Objective:

Evaluate leakage and power loss performance of compliant foil seal

Approach:

- Evaluate leakage and lift performance using new NASA GRC seal test rig (8.5" diameter).
- Measure seal tare torque and power loss using new torque meter.

Results:

- Measured performance data from 0-25 Krpm and 0-70 psid at 70 F.
- Tests identified seal design issues.
- Examining re-design options

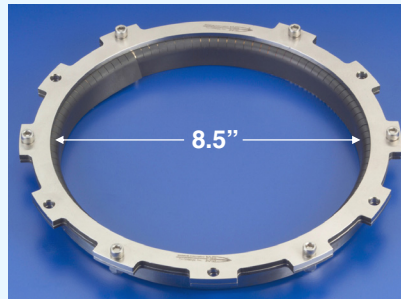
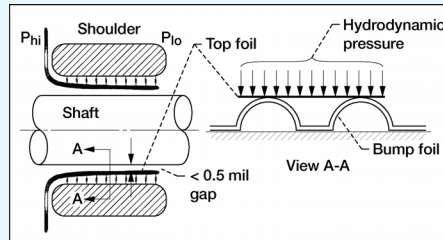
Partners:

NASA GRC/ Mohawk MiTI (SBIR Ph 2)



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Compliant Foil Seal (CFS) Schematic



NASA GRC recently completed a series of tests to evaluate the performance of a compliant foil finger seal developed by Mohawk Innovative Technologies under a NASA SBIR Phase 2 contract.

Compliant foil seals incorporate features common to foil bearings including a top foil and underlying bump foils. A main difference is the addition of a closeout on the high pressure side to prevent leakage through the bump-foils. The seal is designed to operate without contact with small clearances - important parameters for long life and low leakage. In principal, clearance is maintained between the flexible foils and the rotor shaft through a hydrodynamic film that exists between the foil and the shaft.

The tests performed at GRC on an 8.5" diameter seal revealed some shortcomings of the current seal design and rotor coating. NASA and Mohawk are investigating what design changes could be incorporated to prevent seal-to-rotor contact in the future. For further details on the seal design and test results, please see Proctor et al, 2004, in this Seal Workshop Proceedings.

Non-Contacting Finger Seal Development NASA GRC/University of Akron

Objective:

Develop non-contacting finger seal to overcome finger element wear and heat generation for future turbine engine systems

Approach:

- Solid modeling for stick and pad motion/stresses
- Fluid/solid interaction for leakage evaluation
- Experimental verification

Status:

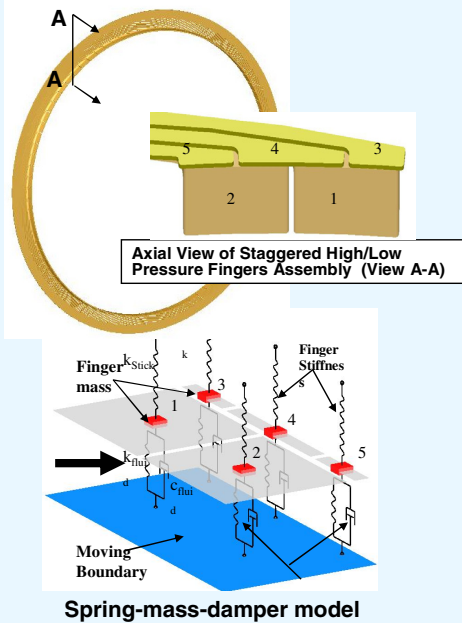
- Developed a simplified spring-mass-damper model to assess seal's dynamic response.
- CFD-ACE+ (3-D Navier-Stokes code) utilized to analyze the thermofluid behavior and to obtain stiffness and damping parameters.
- Pressure patterns, mass flows and load carrying capabilities were assessed.

Program:

NASA/Univ. of Akron Coop. Agreement:
Dr. Braun (U. of Akron) M. Proctor, Monitor



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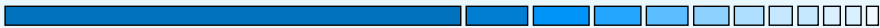


Conventional finger seals like brush seals attain low leakage by operating in running contact with the rotor (Proctor, et al, 2002). The drawbacks of contacting seals include wear over time, heat generation, and power loss.

NASA Glenn has developed several concepts for a non-contacting finger seal. In one of these concepts the rear (low-pressure, downstream) fingers have lift pads (see pads 1 & 2 in inset figure) and the upstream (high pressure side) fingers are pad-less, and are designed to block the flow through the slots of the downstream fingers. The pressure-balance on the downstream-finger lift-pads cause them to lift. The front fingers are designed to ride slightly above the rotor preventing wear. Pressure acts to hold the upstream fingers against the downstream fingers. It is anticipated that the upstream/downstream fingers will move radially as a system in response to shaft transients. Though a small pin-hole leakage path exists between the inner diameter of the upstream fingers, the rotor, and the downstream fingers, this small pin-hole doesn't cause a large flow penalty especially considering the anticipated non-contacting benefits of the overall approach.

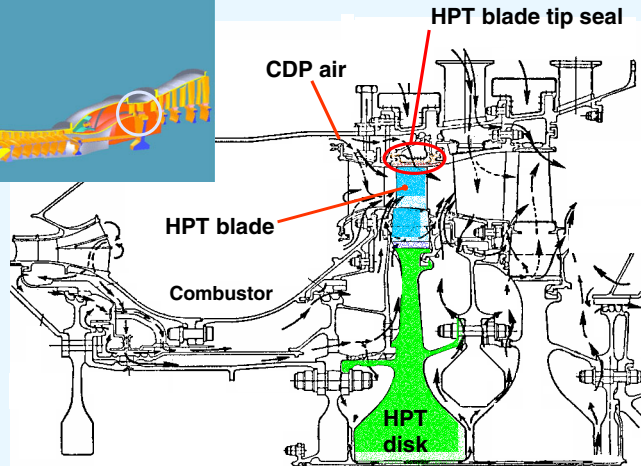
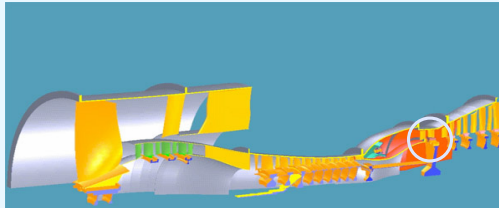
Dr. J. Braun of University of Akron is performing analyses and tests of this GRC concept through a cooperative agreement (Braun et al, 2003). University researchers developed an equivalent spring-mass-damper system to assess lift characteristics under dynamic excitation. Fluid stiffness and damping properties were obtained utilizing CFD-ACE+ (3-D Navier-Stokes code) and a perturbation approach. These stiffness and damping properties were input into the dynamic model expediting the solution for design purposes. More details can be found in Braun et al, 2004 in this Seal Workshop Proceedings. After feasibility tests are complete at the University, seals will be tested under high speed and high temperature conditions at NASA GRC.

Rotating Machinery Clearance Management



Develop and demonstrate clearance management technologies to improve turbine engine performance, reduce emissions, and increase service life through

- Rub-Avoidance
- Regeneration

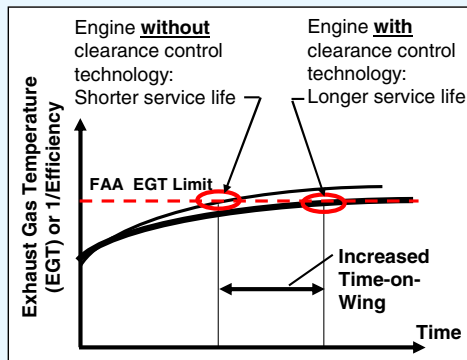


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System studies have shown the benefits of reducing blade tip clearances in modern turbine engines. Minimizing blade tip clearances throughout the engine will contribute materially to meeting NASA's Ultra-Efficient Engine Technology (UEET) and Revolutionary Turbine Accelerator (RTA) turbine engine project goals. NASA GRC is examining two candidate approaches including rub-avoidance and regeneration which are explained in subsequent slides.

Benefits of Blade Tip Clearance Control

- Fuel Savings/ Reduced Emissions (HPT)
 - 0.010-in tip clearance is worth ~1% SFC
 - Emissions Reduction (Landing/Takeoff – Ref. GE Propulsion 21 Study)
 - » NO_x
 - » CO
- Increased Cycle Life (Reduced Maintenance Costs)
 - Deterioration of exhaust gas temperature (EGT) margin is the primary reason for aircraft engine removal from service
 - 0.010-in tip clearance is worth ~10 °C EGT
 - Allows turbine to run at lower temperatures, increasing cycle life of hot section components and engine time-on-wing (~1000 cycles)
- Increased Efficiency/Operability
 - Increased payload and mission range capabilities
 - Increased high pressure compressor (HPC) stall margin



Clearance Control Technology Promotes High Efficiency and Long Life



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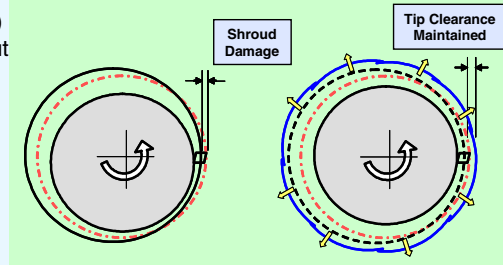
Blade tip clearance opening is a primary reason for turbine engines reaching their FAA certified exhaust gas temperature (EGT) limit and subsequent required refurbishment. As depicted in the chart on the right, when the EGT reaches the FAA certified limit, the engine must be removed and refurbished. By implementing advanced clearance control measures, the EGT rises slower (due to smaller clearances) increasing the time-on-wing.

In summary, benefits of clearance control in the turbine section include lower specific fuel consumption (SFC), lower emissions (NO_x, CO), retained exhaust gas temperature (EGT) margins, higher efficiencies, longer range (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.

Clearance Control Approaches

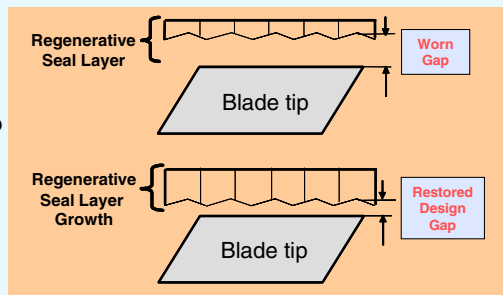
Active Clearance Control (Rub Avoidance)

- ACC system avoids blade rubs throughout mission
- Faster and more accurate control of clearances compared to current, slow-response case cooling systems
- Incorporates:
 - Compact, fail-safe actuation systems
 - High temperature, accurate, robust clearance sensors



Regenerative Seal

- Specially engineered materials grow to restore clearance (**GRC innovation**)
- Material growth rate/magnitude tailored to meet engine requirements



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NASA Glenn is pursuing two approaches to controlling clearances. The first is rub-avoidance in which an active clearance control system would actively move the seal or shroud segments out of the way during the transient event to avoid blade rubs. The second is regeneration in which clearance openings are mitigated using specially-engineered materials that re-grow. Materials are being investigated that would grow at a rate comparable to the average rate of wear anticipated. More details regarding this program can be found in Lattime and Steinetz 2004 in this Seal Workshop Proceedings, and Lattime and Steinetz, 2002.

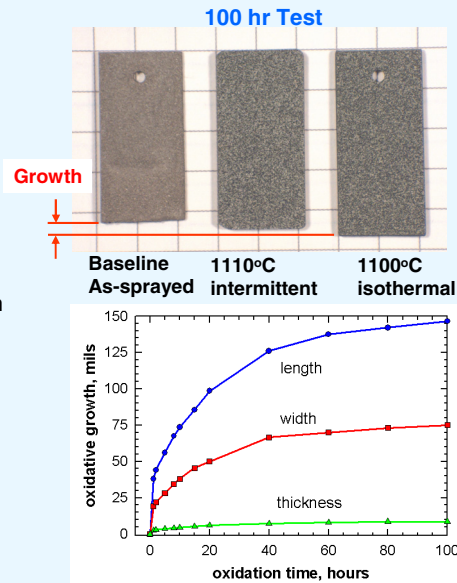
Regenerative Material Feasibility Testing

Observations:

- Significant growth occurred at HPT temperatures (~2000 °F)
- Material remained structurally stable even after 15% growth
- Materials suitable for use in HPT environment

Research Areas Currently Being Pursued:

- Material system composition effects on growth rate and magnitude
 - Collaborative effort with GRC Materials Division
- Structural design effects on reducing spallation potential



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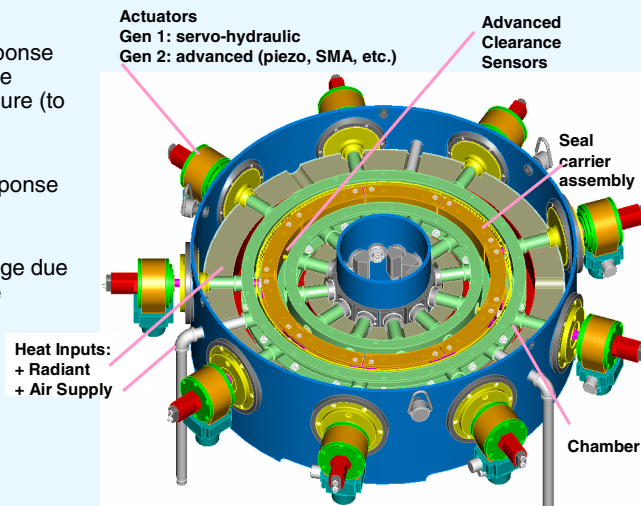
GRC is investigating novel materials that exhibit self-adaptive behavior within their environment. Under the regenerative seal material project, GRC is developing and assessing whether materials can change volume and grow at an appropriate rate to mitigate clearance openings between the high pressure turbine blades and shrouds. In one recent trial, specially engineered materials were subjected to simulated HPT engine temperatures (2000+°F) to determine the nature of their growth characteristics. Shown in the top figure are three specimens: a baseline as-sprayed sample, and two samples subjected to 100 hrs of 2000+°F temperatures. One can see from the significant length change in both the photograph and measured dimensional data, that the specimens grew up to 15% of their original dimensions (length, width, and thickness). Also the material remained structurally stable after expansion.

Having demonstrated this initial growth feasibility, we are now pursuing additional research areas. These include identifying material system composition effect on growth rates and magnitudes and examining structural design effects on reducing material spallation potential.

Active Clearance Control Concept & Evaluation Test Rig

Purpose:

- Evaluate actuator concept response and accuracy under appropriate thermal (to 1500 °F) and pressure (to 120 psi) conditions.
- Evaluate clearance sensor response and accuracy
- Measure secondary seal leakage due to segmented design and case penetration.



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NASA GRC is developing a unique Active Clearance Control (ACC) concept and evaluation test rig. The primary purpose of the test rig is to evaluate actuator concept response and accuracy under appropriate thermal (up to 1500F) and pressure (up to 120 psig) conditions. Other factors that will be investigated include:

- Actuator stroke, rate, accuracy, and repeatability
- System concentricity and synchronicity
- Component wear
- Secondary seal leakage
- Clearance sensor response and accuracy

The results of this testing will be used to further develop/refine the current actuator design as well as other advanced actuator concepts. More details regarding this test rig can be found in Lattime and Steinetz 2004 in this Seal Workshop Proceedings, and Lattime et al, 2003.

Acoustic Seal Development

Goal: Develop a non-contacting, long-life seal using high amplitude acoustic pressures

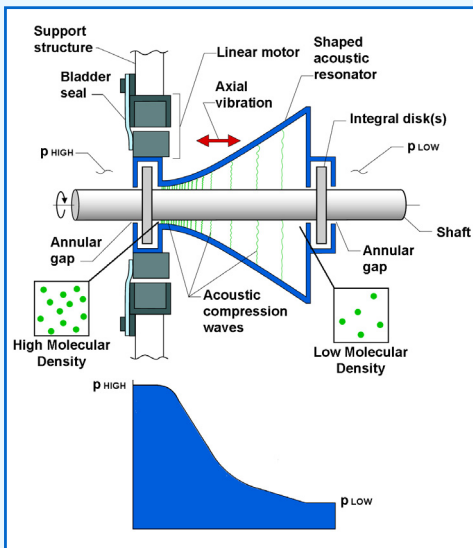
How Does It Work?


Specially shaped acoustic resonator is driven at resonance generating acoustic pressures that prevent flow between high- and low-pressure cavities effecting a seal

Significance?

Acoustic-based, virtually zero-leakage, non-contacting seals would overcome two fundamental problems of conventional seals:

- Leakage
- Wear



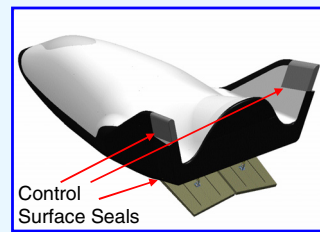
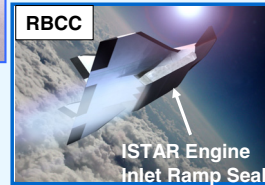
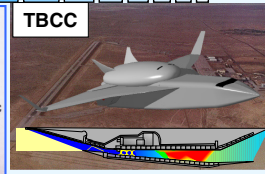
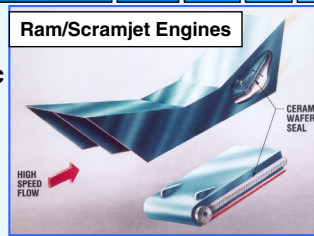
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Our goal in the acoustic seal project is to develop non-contacting, low leakage seals exploiting the principles of advanced acoustics. We are currently investigating a new acoustic field known as Resonant Macrosonic Synthesis (RMS) to determine if one can harness the large acoustic standing pressure waves to form an effective air-barrier/seal. This project builds on Lucas' work in "Resonant Macrosonic Synthesis" (Lucas, 1996). Exploiting shock-free pressure waves and specially shaped resonating cavities, Macrosonics can produce peak acoustic pressures exceeding 200 psi - many thousands of times normal acoustic pressure levels.

In an acoustic seal, large acoustic standing waves would acoustically pressurize the gas in an acoustic resonator. The acoustic compression waves would result in a high pressure boundary condition adjacent to the high pressure side of the seal apparatus (left side in figure). This high pressure boundary condition would impede the flow of pressurized gas through annular openings around the shaft thereby leading to an effective seal. Disks could be introduced to cause a line-of-sight blockage further minimizing seal leakage. More details regarding this program can be found in Daniels and Steinetz 2004 in this Seal Workshop Proceedings and Daniels et al, 2004.

NASA GRC Structural Seal Development Goals: Next Generation Launch Technology (NGLT) Program

- Develop hot (2000-2500+°F), flexible, dynamic structural seals for ram/scramjet propulsion systems (TBCC, RBCC)
- Develop reusable re-entry vehicle control surface seals to prevent ingestion of hot (6000 °F) boundary layer flow



Hot, dynamic seals critical to meeting NGLT program life, safety, and cost goals

Example: X-37; X-38 CRV

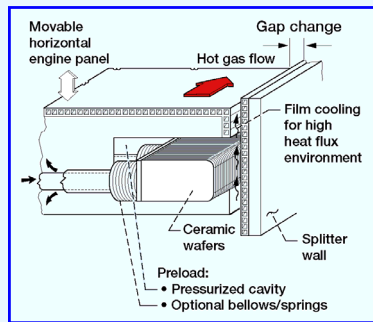


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NASA is currently funding research on advanced technologies that could greatly increase the reusability, safety, and performance of future Reusable Launch Vehicles (RLV). Research work is being performed under NASA's Next Generation Launch Technology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

NASA GRC is developing advanced structural seals for both propulsion and vehicle needs by applying advanced design concepts made from emerging high temperature ceramic materials and testing them in advanced test rigs that are under development. See Dunlap 2004, et al, and DeMange 2004, et al in this Seal Workshop Proceedings and Dunlap 2003, et al and DeMange 2003, et al for further details.

Example Structural Seals Being Investigated

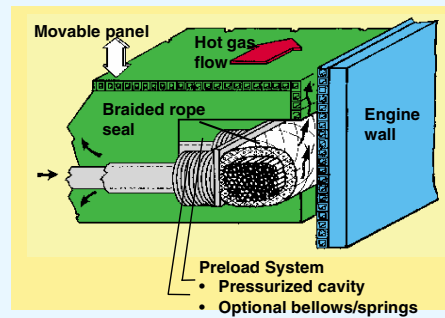


Ceramic Wafer Seal

- High temperature operation: up to 2500°F
- Low Leakage
- Flexibility: Relative sliding of adjacent wafers conforms to wall distortions
- Ceramic material lighter weight than metal system
- Tandem seals permit central cavity purge (cooling)



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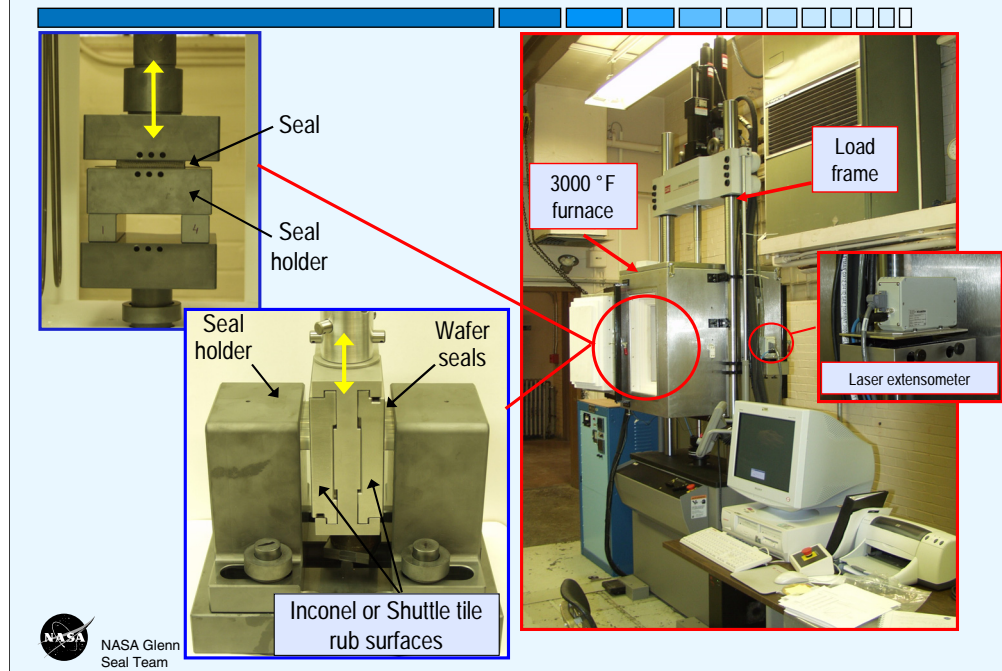
Braided Rope Seal

- High temperature operation: 1500-2200+ °F (500-1200 °F hotter than graphite seals)
- Flexible: seals & conforms to complex geometries
- Hybrid design (ceramic core/superalloy wire sheath) resists abrasion
- Tandem seals permit central cavity purge (cooling)

NASA GRC's work on high temperature structural seal development began in the late 1980's during the National Aero-Space Plane (NASP) project. GRC led the in-house propulsion system seal development program and oversaw industry efforts for propulsion system and airframe seal development for this vehicle.

Two promising concepts identified during that program included the ceramic wafer seal (Steinetz, 1991) and the braided rope seal (Steinetz and Adams, 1998) shown here. By design, both of these seals are flexible, lightweight, and can operate to very high temperatures (2200+°F). These seal concepts are starting points for the extensive seal concept development and testing planned under NASA's 3rd Generation high temperature seal development tasks.

Hot Compression/Scrub Seal Test Rig: Overview



NASA GRC has installed state-of-the-art test capabilities for evaluating seal performance at temperatures up to 3000 °F (1650 °C). This one-of-a-kind equipment will be used to evaluate existing and new seal designs by simulating the temperatures, loads, and scrubbing conditions that the seals will have to endure during service. The compression test rig (upper left photo) is being used to assess seal load vs. linear compression, preload, & stiffness at temperature. The scrub test rig (middle photo) is being used to assess seal wear rates and frictional loads for various test conditions at temperature. Both sets of fixtures are made of silicon carbide permitting high temperature operation in air.

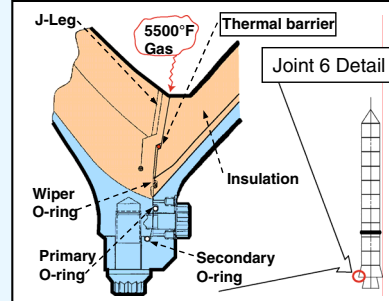
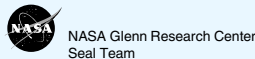
The test rig includes: an MTS servo-hydraulic load frame, an ATS high temperature air furnace, and a Beta LaserMike non-contact laser extensometer, and the special purpose seal holder hardware. Unique features of the load frame include dual load cells (with multi-ranging capabilities) for accurate measurement of load application, dual servo-valves to permit precise testing at multiple stroke rates (up to 8 in./s.), and a non-contact laser extensometer system to accurately measure displacements.

Development of Thermal Barriers for Shuttle RSRM's

- Shuttle RSRM's have had periodic hot gas effects in nozzle joints, leading to extensive reviews before flight
- Thiokol re-designed joints with GRC carbon fiber rope (CFR) thermal barrier to prevent hot (5500°F) gas from affecting downstream O-rings

Status

- Flight certification, static-motor tests have been completed for Joints 2, 5, and 6 (nozzle to case joint).
- Assembly of solid motors with thermal barriers commencing during 2003.
- Flight expected 2005 (depending on return- to-flight schedule)



Periodically several of the Shuttle's solid rocket motor nozzle joints experience hot gas effects. Over the past several years, engineers from NASA Glenn, Marshall Space Flight Center, Thiokol, and Albany-Techniweave have been investigating the feasibility of applying the NASA GRC developed carbon fiber thermal barrier to overcome this issue. (More details of this program can be found in Steinetz and Dunlap, 2001, and Steinetz and Dunlap Patent No. 6,446,979 B1). The thermal barrier reduces the temperature of the 5500°F rocket combustion gas and permits only relatively cool (<200 °F) gas to reach the O-rings. This important new technology improves on already high Shuttle safety margins and enables solid rocket motor joint assembly in significantly less time (approximately one-sixth the time) as compared to the previous joint fill compound approach with much higher degrees of reproducibility. Full-scale solid rocket motor test results showed that the thermal barrier protected the downstream O-rings even when intentional flaws were cut into the barrier.

In January, 2003, Thiokol completed flight certification tests on Joints 2, 5, 6. Assembly of the joints with the GRC thermal barriers is commencing this year. The first shuttle flight is expected in 2005 depending on Shuttle's return to flight schedule.

Application of GRC Thermal Barrier in Atlas V SRM's



Final qualification test of Aerojet solid rocket motor with thermal barriers installed (Dec. 2002)



Atlas V boosted by two Aerojet SRM's incorporating GRC thermal barriers (July 17, 2003)

- **Aerojet experienced motor failure in spring 2002 qualification test of solid rocket motors for Atlas V**
- **Based on success in Shuttle RSRM's ground tests, Aerojet installed three thermal barriers in nozzle-to-case joint to protect O-rings from hot (5500+°F), high pressure combustion gases. Certified for flight Dec. 2002.**
- **Lockheed-Martin/Aerojet Atlas V incorporated GRC thermal barriers. Successfully launched July 17, 2003!**



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Based on the success of the carbon fiber rope thermal barriers in the shuttle solid rocket motors, Aerojet decided to implement the GRC thermal barriers into the nozzle-to-case joints in the SRMs for the Atlas V. A redesign of this critical joint was required after a March 2002 test resulted in a major motor failure.

Since implementing the GRC thermal barrier plus several other joint features, Aerojet has had 3 successful ground test firings and on July 17, 2003 successfully boosted the Lockheed-Martin Atlas V Enhanced Expendable Launch Vehicle carrying a Cablevision satellite into a successful transfer orbit. Aerojet's two boosters provided thrust in excess of 250,000 lbs. each. The boosters were ignited at liftoff, burned for more than 90 seconds and then were jettisoned. The mission was valued at \$250M.

Summary

- **Seals technology recognized as critical in meeting next generation aero- and space propulsion and space vehicle system goals**
 - Performance
 - Efficiency
 - Life/Reusability
 - Safety
 - Cost
- **NASA Glenn is developing seal technology and/or providing technical consultation for the Nation's key aero- and space advanced technology development programs.**



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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.

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

NASA Seals Web Sites

- **Turbine Seal Development**

- <http://www.grc.nasa.gov/WWW/TurbineSeal/TurbineSeal.html>
 - » NASA Technical Papers
 - » Workshop Proceedings

- **Structural Seal Development**

- <http://www.grc.nasa.gov/WWW/structuralseal/>
 - » NASA Technical Papers
 - » Discussion
 - » Seal Patents
- http://www/lerc.nasa.gov/WWW/TU/InventYr/1996Inv_Yr.htm



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The Seal Team maintains three web pages to disseminate publicly available information in the areas of turbine engine and structural seal development. Please visit these web sites to obtain past workshop proceedings and copies of NASA technical papers and patents.

References

- Braun, M.J., Choy, F.K., Pierson, H.M., 2003, "Structural and Dynamic Considerations Towards the Design of Padded Finger Seals", AIAA-2003-4698 presented at the AIAA/ASME/SAE/ASEE conference, July, Huntsville, AL.
- Daniels, C., Finkbeiner, J., Steinetz, B.M., Li, Xiaofan, Raman, G., 2004, "Non-linear Oscillations and Flow of Gas Within Closed and Open Conical Resonators," AIAA-2004-0677. To be presented at the 82nd AIAA Aerosciences Meeting, Reno, NV, January.
- DeMange, J.J., Dunlap, P.H., Steinetz, B.M., 2003, "Advanced Control Surface Seal Development for Future Space Vehicles," Presentation and Paper at 2003 JANNAF Conference, Dec. 1-5, Colorado Springs, CO, NASA/TM-2004-212898.
- Dunlap, P.H., Steinetz, B.M., DeMange, J.J., 2003, "High Temperature Propulsion System Structural Seals for Future Space Launch Vehicles," Presentation and Paper at 2003 JANNAF Conference, Dec. 1-5, Colorado Springs, CO, NASA/TM-2004-212907.
- Lattime, S.B., Steinetz, Bruce M., Robbie, M., 2003, "Test Rig for Evaluating Active Turbine Blade Tip Clearance Control Concepts," NASA TM-2003-212533, also AIAA-2003-4700, presented at the AIAA/ASME/SAE/ASEE conference, July, Huntsville, AL.
- Lattime, S.B., Steinetz, B.M. 2002 "Turbine Engine Clearance Control Systems: Current Practices and Future Directions," NASA TM-2002-211794, AIAA 2002-3790.
- Lucas, T.S., 1996, "Acoustic Resonator Having Mode-Alignment-Cancelled Harmonics," US Patent 5,579,399.
- Proctor, M.P.; Kumar, A.; Delgado, I.R.; 2002, "High-Speed, High Temperature, Finger Seal Test Results," NASA TM-2002-211589, AIAA-2002-3793.
- Steinetz, Bruce M., Dunlap, Patrick H., 2002, "Rocket Motor Joint Construction Including Thermal Barrier," U.S. Patent No. 6,446,979 B1, Issue Date: September 10.
- Steinetz, Bruce M.; Dunlap, Patrick H.: 2001, "Development of Thermal Barriers for Solid Rocket Motor Nozzle Joints" Journal of Propulsion and Power, Vol. 17 No. 5, pp. 1023-1034, September/October, also NASA-TM-1999-209191, June 1999.
- 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.
- Steinetz, Bruce M.; Adams, Michael L.: 1998, "Effects of Compression, Staging and Braid Angle on Braided Rope Seal Performance", J. of Propulsion and Power, Vol. 14, No. 6, also AIAA-97-2872, 1997 AIAA Joint Propulsion Conference, Seattle, Washington, July 7-9, 1997, NASA TM-107504, July 1997.
- Steinetz, B.M.: 1991, "High Temperature Performance Evaluation of a Hypersonic Engine Ceramic Wafer Seal," NASA TM-103737
- Turnquist, N.A.; Bagepalli, B; Lawen, J; Tseng, T., McNickle, A.D., Kirkes; Steinetz, B.M., 1999, "Full Scale Testing of an Aspirating Face Seal", AIAA-99-2682.



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