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Cleveland I-X Center

Advanced High-Temperature Seal Development at NASA

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NASA Glenn Research Center is developing advanced seals to meet the demands of next generation aircraft and rocket propulsion systems. Dr. Steinetz will summarize NASA Glenn's efforts of developing seals that can operate from ambient through rocket exhaust temperatures (>2000°F) without cooling and summarize the extensive test capability used to qualify seal performances under these extreme conditions. NASA programs benefiting from this research, that will be reviewed, include advanced commercial and military aircraft, the Space Shuttle, the Space Station Emergency Crew Return X-Vehicle, and futuristic reusable launch vehicles. Though the seal technology is being developed for NASA and military programs, there are many commercial and industrial spin-off applications.

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Advanced High Temperature Seal Development at NASA Glenn Research Center

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Total Design Solutions Midwest (Session 10)
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IX Center
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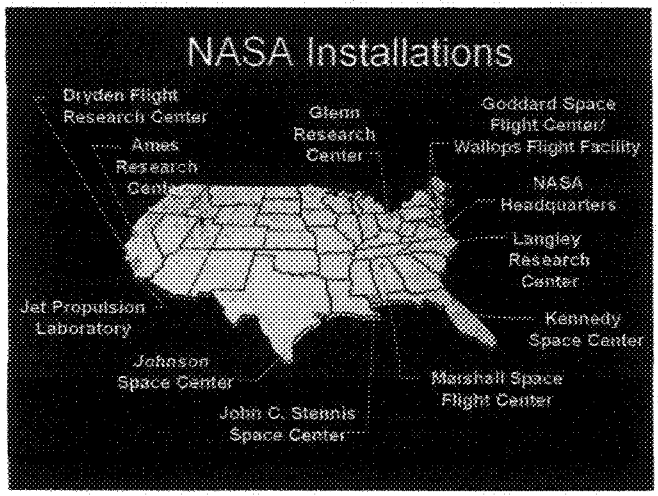
Contributors

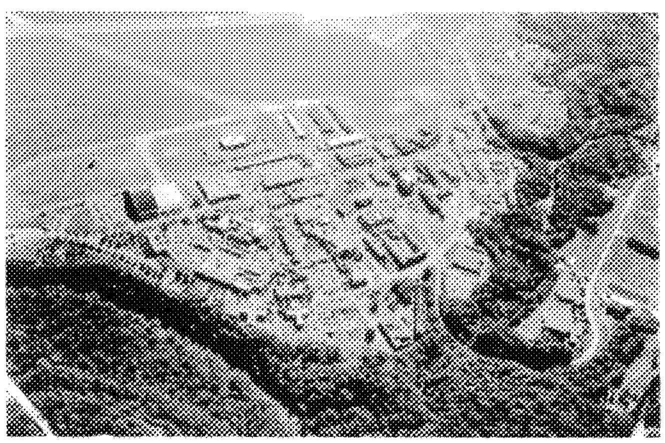
- Margaret Proctor, Irebert DelGado: Turbine Seals
- Scott Lattime: Turbine Clearance Control
- Patrick Dunlap, Jeff DeMange: Structural Seals

NASA Installations



Glenn Research Center

- Total Workforce: 3600+ Formed as NACA 1941

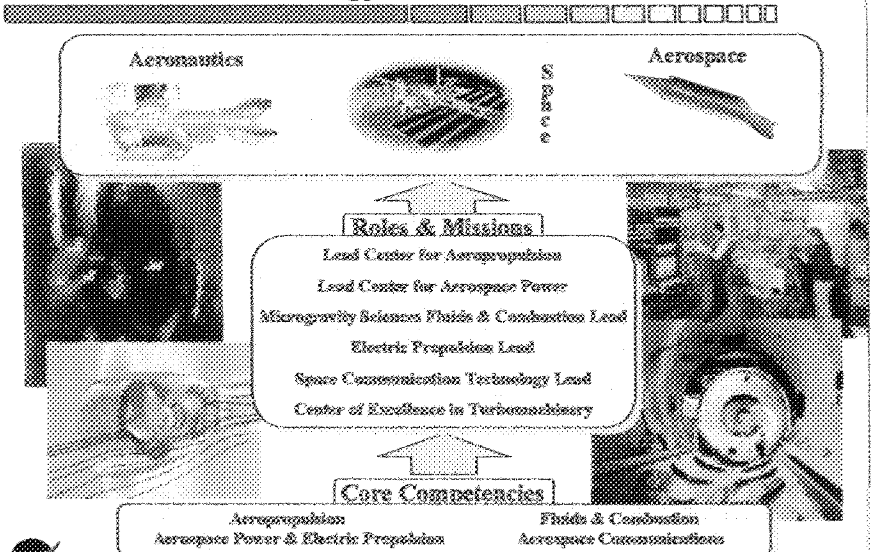


NASA Glenn Vision

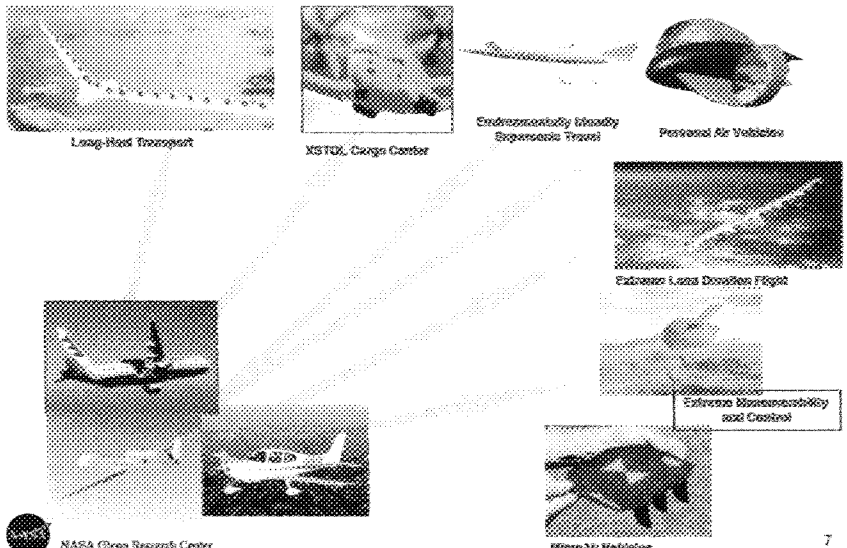
The NASA Glenn Research Center defines and develops advanced technology for high priority national needs.

The work of the Center is directed toward new propulsion, power, and communications technologies for application to aeronautics and space, so that U.S. leadership in these areas is ensured.

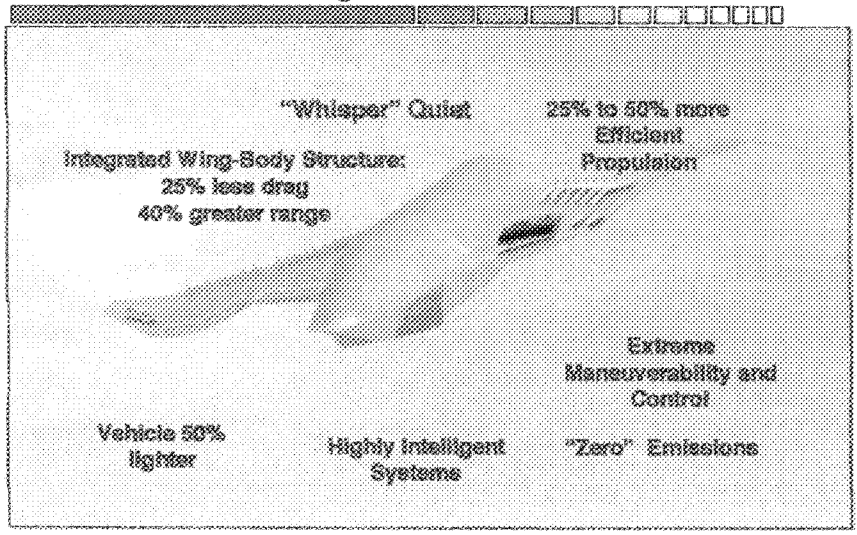
Research and Technology Products



Revolutionary Vehicles - Multiple Paths Common Technology (graphics: incrs callout point size)



Attributes of Future Flight Vehicles



Outline of Presentation

- Background
- Why are advanced Seals important to NASA's Mission?
- Turbomachinery seals under development
  - Shaft Seals: Brush, Finger, Aspirating, Compliant Foil Seals
  - Blade Tip Seals: Active clearance control
  - Advanced Test Facilities and Capabilities
- Structural Seals under development:
  - Ceramic Wafer Seal
  - Braided Seals: Ceramic, Hybrid
  - Knitted Spring Tube (Shuttle derived)
  - Carbon thermal barriers
  - Advanced Test Facilities and Capabilities
- Summary
- References

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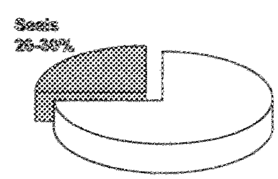
Why Seals?

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+I
Active Clearance Control (HPT)	Large Commercial GE/NASA	~1-2% SFC
Film riding seals (Turbine inter-stage seals)	Regional-AE3007/ Allison	> ~0.9% SFC > ~0.59% DOC+I
Advanced finger seals	AST Regional/ Honeywell	~1.4% SFC ~0.7% DOC+I

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: 1/8th 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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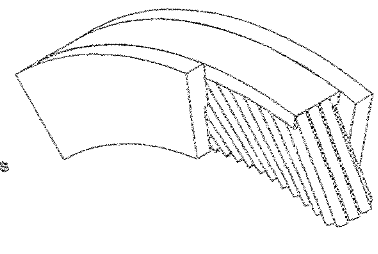
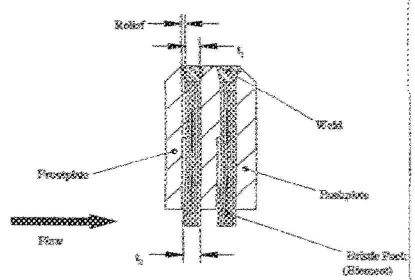
Brush Seals: Overview

Graphics Add color
Add recess in back

- **Prior Art:** Labyrinth Seal
- **Design Attributes:**
  - *1/5th the leakage of labyrinth seal*
  - Thin seal construction packages well in small design envelope
  - Pressure closing effect urges bristles toward shaft improving seal effectiveness
  - Flexible bristles accommodate shaft movements
  - Commercially available from several vendors (*Perkin-Elmer*, Cross Ltd, Technetics)



- **Design Considerations:**
  - Cost is approximately equal to labyrinth seals. Cost for aerospace grade 8.5" dia. seal = $xxxx each
  - Improperly designed interference can leat to shaft heating and possible negative consequences.



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Brush Seal: Detail

- **Applications**
  - Aircraft engines, ground based turbines, xxx
- **Leakage**
  - Effective Leakage Gap
  - Flow Modeling reference (ASME Ref style, author, year)
- **Typical Materials**
  - Haynes 25 Bristles (Cobalt based)
  - Inconel 718, 625 check Front plate and *backing plate. Welded construction.*
  - Xxx Flexi-front cover
  - Aerospace Applications
    - » Shaft generally coated with hard face coating(e.g. Chrome Carbide)
  - Ground base turbines:
    - » Shaft generally uncoated (thicker shaft walls, less issue with wear induced cracks)

Add Seal Photograph

- **Media Sealed**
  Air, steam, limited data for Oil
- **Operating Conditions Current** (Future)
  - Pressure Range: 100 psi (400 psi)
  - Gas Temperature : 1200 F (1800F)
  - Surface speeds: 1200 fps (1600 fps)

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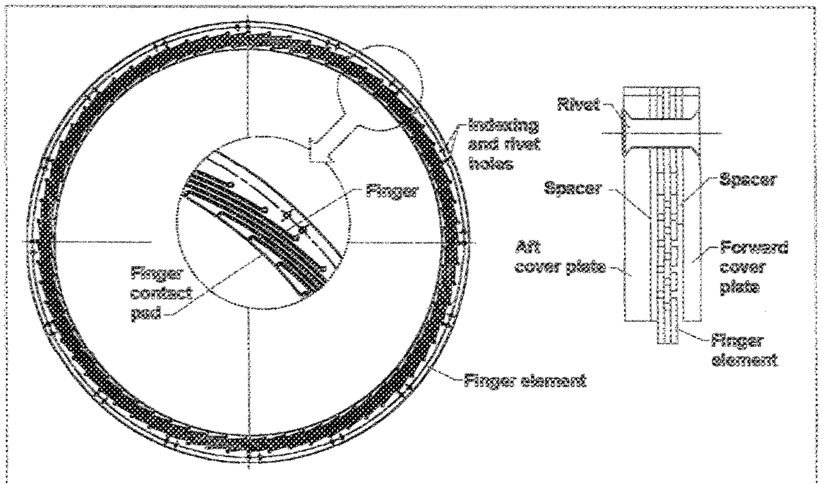
Finger Seal Design



Finger Seals: Overview

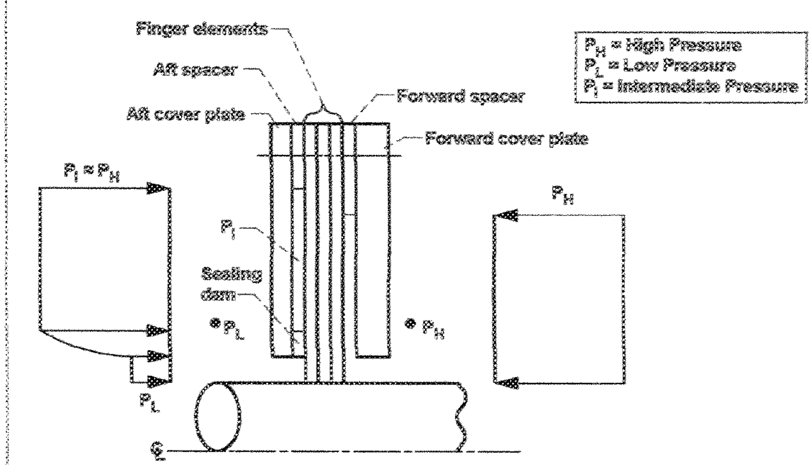
- **Prior Art:** Labyrinth Seal
- **Design Attributes:**

Seal
Image

- **Design Considerations:**

- Reference: Arora, G.K; Proctor, M.P; Steinetz, B.M. Delgado, I.R., 1999, " Pressure Balanced, Low Hysteresis, Finger Seal Test Results" NASA TM-1999-209191, AIAA 99-2686.

Pressure Balanced Finger Seal Force Balance



Brush/Finger Seal Design Considerations

Mechanical:

- Pressure Capability
- Frequency
- Seal Leakage
- Seal Stiffness
- Seal blow-down (e.g. pressure closing)
- Bristle tip forces and pressure stiffening effect
- Rotor dynamics
- Metal fatigue: HCF and LCF
- Reverse rotation

Thermal:

- Seal heat generation (esp. for high temp. applications)
- Friction induced heating of flow passing through seal
- Bristle tip temperature
- Rotor thermal stability
- Secondary flow and cavity flow

Brush/Finger Seal Design Considerations (cont'd)

Materials/Life:

- Oxidation
- Creep
- Tribological performance:
  - Friction
  - Horsepower consumed
  - Wear (rotor and seal)
- Solid particle erosion
- Seal upstream protection
- Overall life and replacement interval

Aspirating Seals: Overview

- **Prior Art:** Labyrinth Seal
- **Design Attributes:**
  - 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

Seal
Image

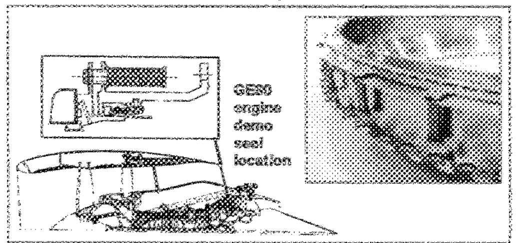
- **Design Considerations:**
- Reference: Turnquist, NA; Tseng, T.W., McNickle, A.D; Steinetz, B.M. 1999, "Full Scale Testing of an Aspirating Face Seal with Angular Misalignment," AIAA-99-2682.

Aspirating Seal Development: GE90 Demo Program

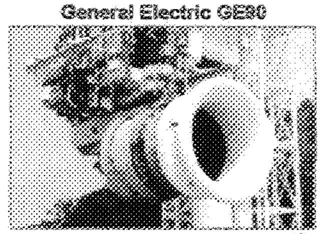
Funded UEET Seal Development Program

- **Goal:**
  - Complete aspirating seal development by conducting full scale (88 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"/0.5 sec fd 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



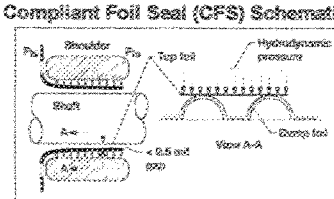
General Electric GE90



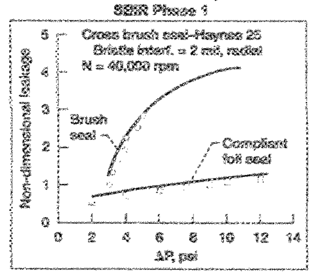
Compliant Foil Seals: Overview

- **Prior Art:** Labyrinth Seal
- **Design Attributes:**
- **Design Considerations:**

Compliant Foil Seal (CFS) Schematic



Foil Seal and Brush Seal Leakage Data
2.84 in. Diam. Journal; 68 °F
SBIR Phase 1



Why HPT Tip Clearance?

Specific Fuel Consumption/Fuel Burn

- 0.010-in tip clearance is worth ~ 1% SFC
- Less fuel burn, reduces emissions

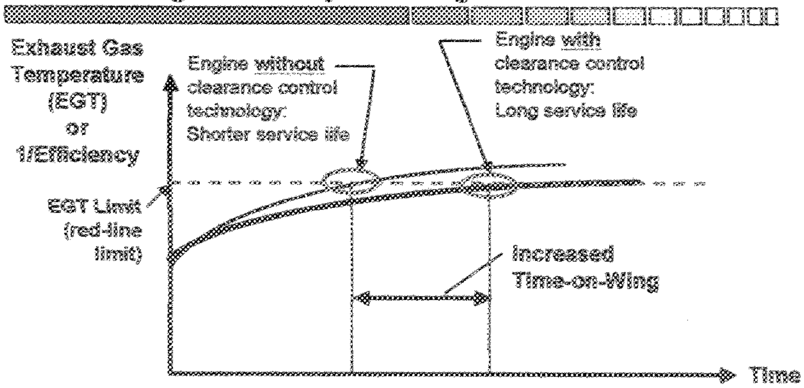
Service Life

- 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 and engine TOW (≥ 1000 cycles).
- Maintenance costs for overhauls can easily exceed $1M.

HPT Reaps the Most Benefit Due to ACC

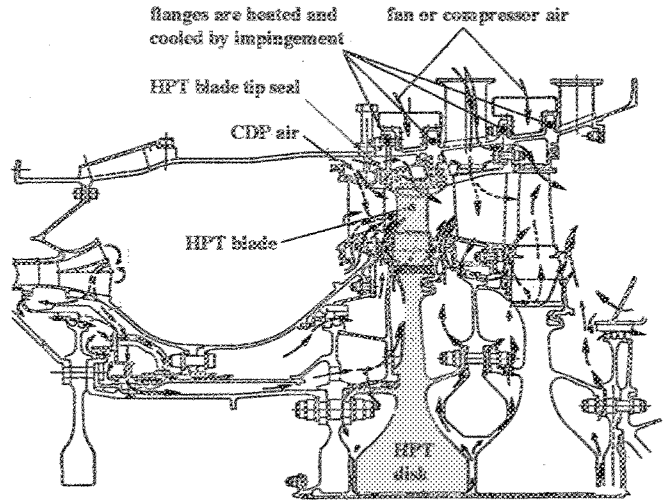
- Improved tip clearances in the HPT resulted in LCC reductions 4x>LPT and 2x>HPC. *(Kawecki, 1979)*

Active Clearance Control Technology Promotes High Efficiency and Long Life



Current:
Degradation of blade tip clearances cause significant performance and efficiency loss that leads to exceeding EGT limit, thus requiring expensive engine servicing

HPT Blade Tip Seal Location



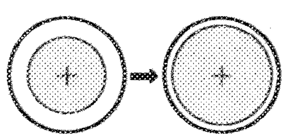
Mechanisms of HPT Tip Clearance Variation

1. Engine loads (centrifugal, thermal, internal engine pressure, and thrust)

2. Flight loads (inertial, aerodynamic, gyroscopic)

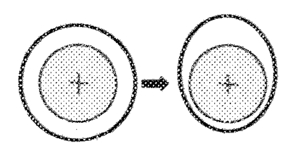
Axisymmetric Clearance Changes

- Centrifugal, thermal, internal pressure loads that create uniform radial displacement

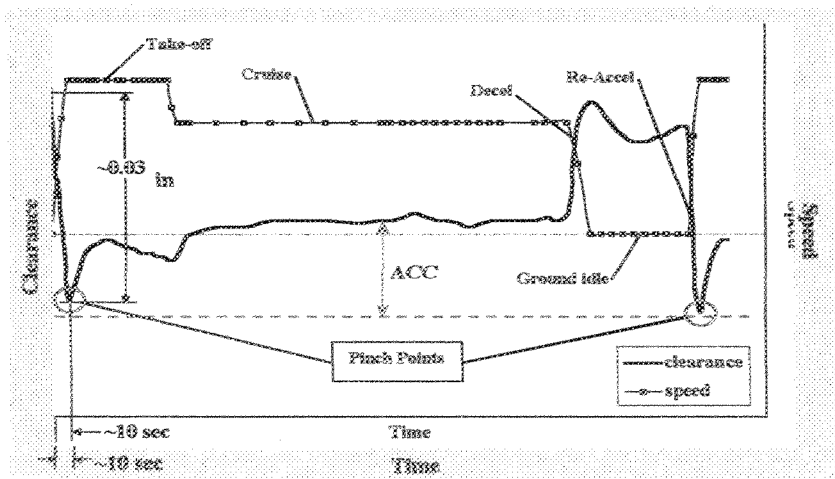


Asymmetric Clearance Changes

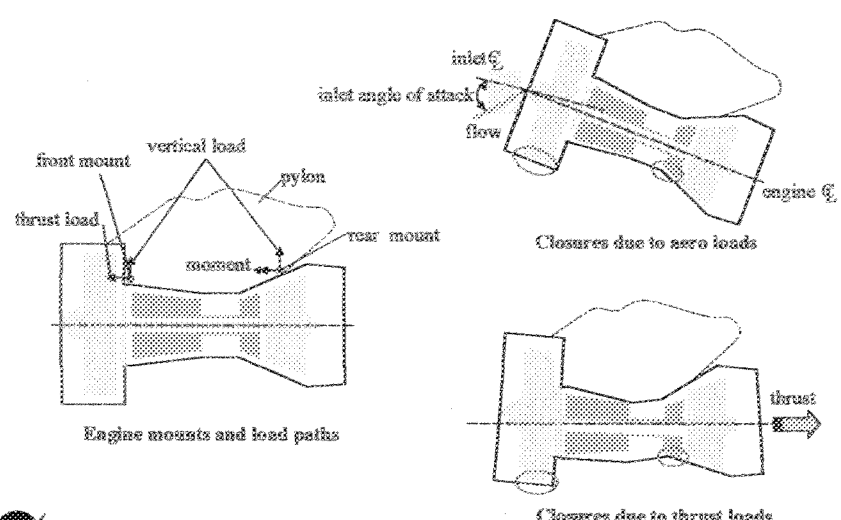
- Thermal, thrust, inertial, and aerodynamic loads that create non-uniform radial displacement



Axisymmetric Clearance Changes Due to Centrifugal & Thermal Loads



Asymmetric Clearance Changes Due to Aero & Thrust Loads



HPT Blade Tip Clearance Management Concepts

Control Schemes:

1. Active Clearance Control (ACC) -desired clearance at multiple operating points.
2. Passive Clearance Control (PCC) -desired clearance at one operating point.

Categories of Clearance Management Concepts

1. Active Thermal
2. Active Mechanical
3. Passive Thermal
4. Active Pneumatic
5. Passive Pneumatic
6. Regeneration

HPT Blade Tip Clearance Management Concepts Cont'd

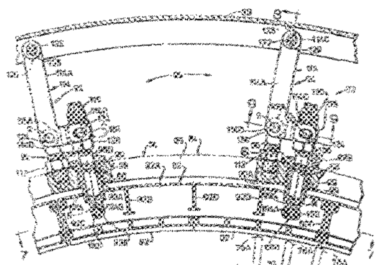
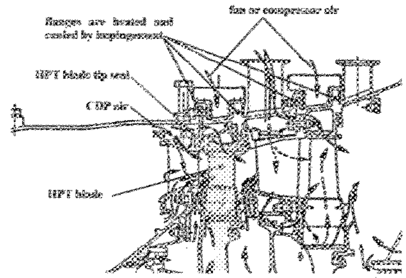


FIG.6

Active Mechanical
(Corsmeier & Pritsche, 1993)

Active Thermal (B?, 1982)



HPT ACC Requirements

Actuation	
Range	~0.05-in
Rate	~0.01-in/s (per FAA takeoff requirement)
Positional Accuracy, Concentricity	~0.005-in
Force	>1000 lbs per segment (shroud cooling and purge)
Environment	
Inlet Rotor Gas Temperature	2500-3000 °F
Shroud Backside Temperature	1200-1300 °F
Case Metal Temperature	500-700 °F
Air Temperature Outside Case	100-300 °F
Shroud Backside Pressure	~500 psi
Shroud I.D. Pressure	~350 psi
Radial _P Across Shroud	~150 psi

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HPT ACC Requirements Cont'd

Sensor	
Accuracy	~0.001-in
Response	~50kHz
Debris Tolerant	moisture, dirt, combustion products
Service Life	>20,000 flight hours
On-Wing Maintenance	e.g., flight checkout/ sensor calibration
Failsafe	redundancy, biased open, and health monitoring

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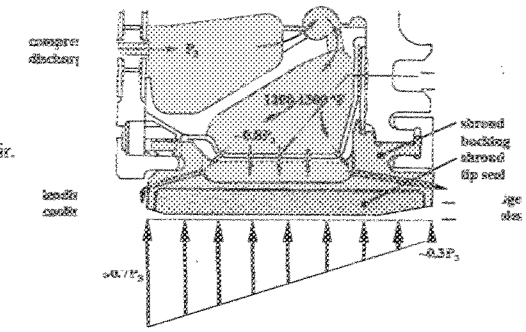
Actuator Force Due to Shroud Cooling and Purge

- A radial pressure difference exists across the shroud due to backside cooling (P_3 air).
- Must maintain a positive backflow margin (purge) from the rotor inlet air.
- Pressure inside the shroud varies axially due to the work extracted by the turbine blades.
- An ACC system must be able to overcome this load as well as the resultant moment created by the non-uniform *axial pressure distribution*.



Example:
Shroud i.d. 30-in, width: 2-in
ave. p: 120-psi
→ 240 lbf/in on the shroud diameter
no. of shroud segments: 16, ~6-in long
→ 1,440 lbf per segment

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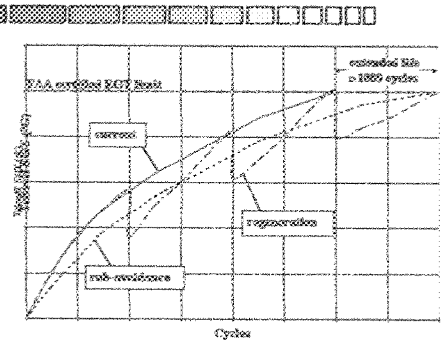
Approaches Under Investigation & Benefits

Fast Response ACC System

- Avoid rub-induced wear, possible erosion compensation, reduce SFC and EGT with reduced clearance.
- Utilize robust actuators coupled with precise positioning system.
- Employ high temperature clearance sensors (i.e., capacitance, microwave) --under development.

Regenerative Tip Seal System

- Utilizes specially engineered material systems that undergo permanent volume change to restore worn clearances (rubs and erosion).
- Reduce SFC and EGT with restored seal.
- Passive (i.e., thermal) and active (i.e., thermal, voltage potential) control.



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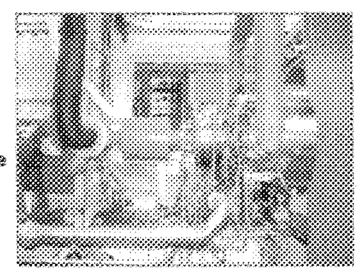
Turbine Seals: Advanced Test Rig

NASA GRC High Temperature Turbine Seal Test Rig

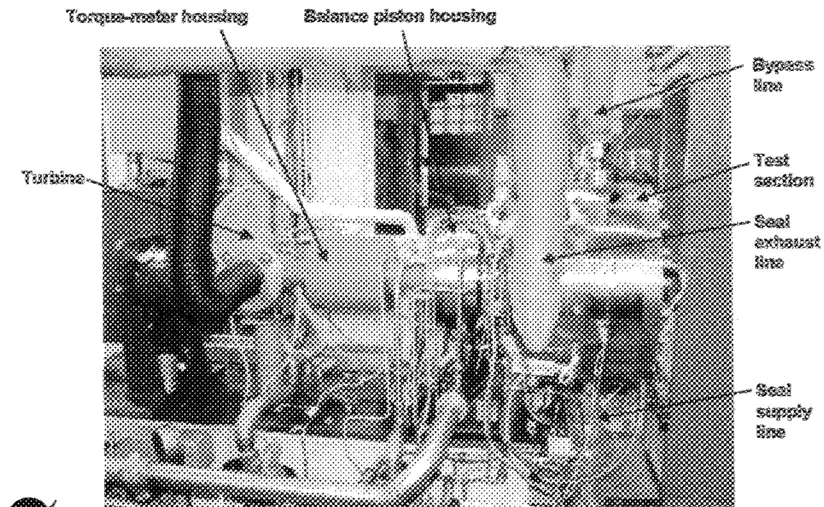
Goal: Test turbine seals at speeds and temperatures envisioned for next generation commercial, military, and space launcher (TBCC/RTA) turbine engines.



- 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.

High-Temperature, High-Speed Turbine Seal Rig



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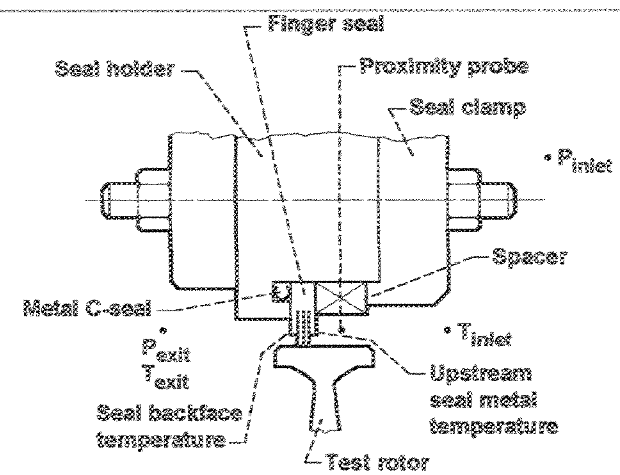
Test Seal Configuration and Location of Research Measurements



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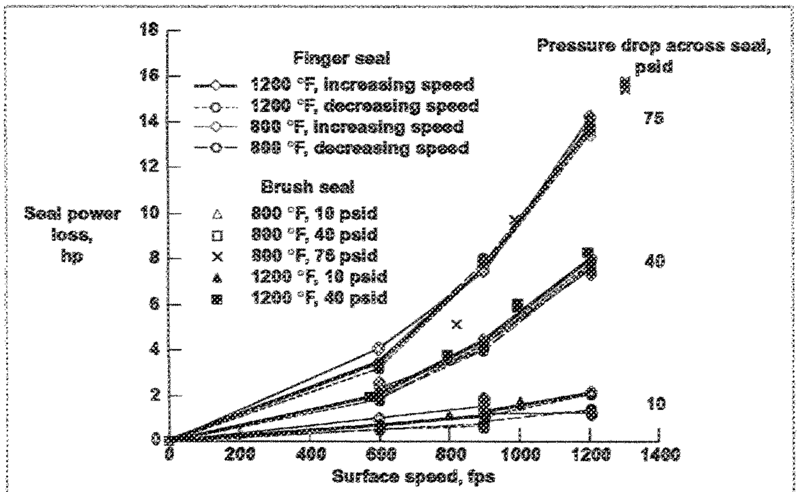
Comparison of Finger Seal and Brush Seal Power Loss Data



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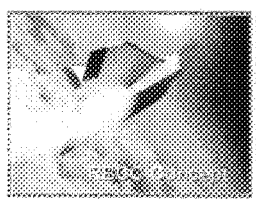
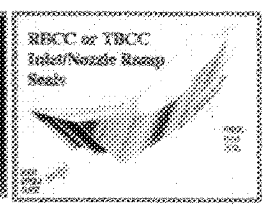
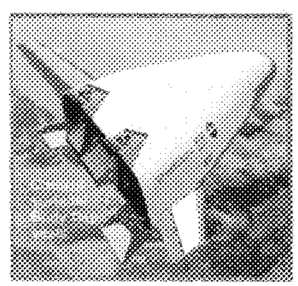
NASA Glenn High Temperature Structural Seal Development for 3rd Generation Space Transportation Programs

- Develop hot (2000–2500 °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

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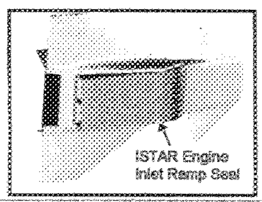
Seal Development Motivation and Objectives

- **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**

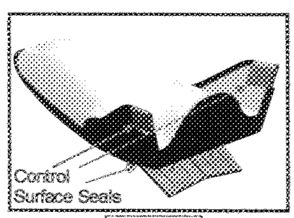
Goal: Develop long life, high temperature control surface and propulsion system seals with the aid of appropriate evaluation and analysis methods

Structural Seal Objectives and Background

- **Goal:** Develop high temperature, long life, control and propulsion system seals with the aid of appropriate test/analysis methods
- **Areas of Development**
  - Propulsion System Seals
    - 3rd Generation Reusable Launch Vehicle
      - ISTAR Engine (RBCC)
  - Control Surface Seals
    - 3rd Generation Reusable Launch Vehicle
      - X-38 / Crew Return Vehicle
      - X-37 / Space Maneuver Vehicle



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

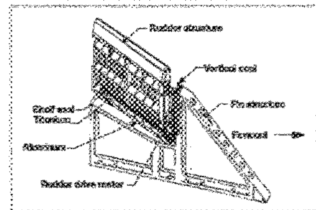


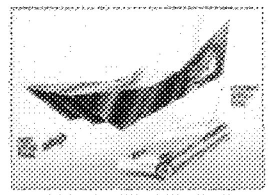
X-38 CRV

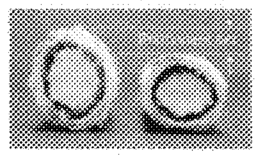
Performance Criteria for High Temperature Seals

Primary Role of High Temperature Structural Seals:

- Minimize leakage
  - Propulsion System Seals: Prevent unburned fuel from leaking into backside cavities
  - Control Surface Seals: Block excessive heat flow







✓ Good insulatory properties → **block heat flow**

✓ Good flexibility → **conform to complex airframe and propulsion system geometries**

✓ Good resiliency → **maintain contact with opposing surfaces under dynamic conditions and over many cycles**

✓ Good wear resistance → **maintain seal continuity under dynamic conditions and over many cycles**

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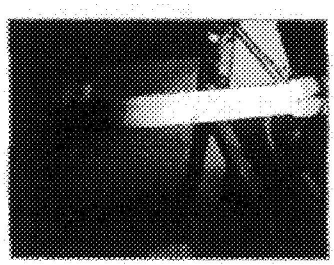
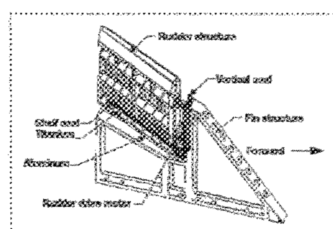
GRC X38 Seal Test Evaluation and Support

- **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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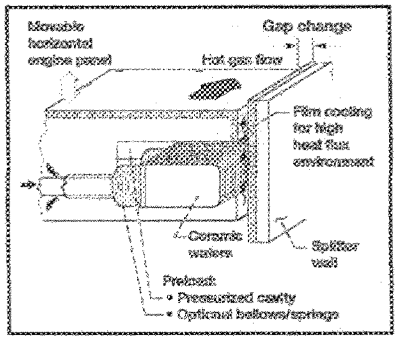
Ceramic Wafer Seal

- **Prior Art: Metal leaf seals**
- **Design Attributes:**

- **Design Considerations:**

- **Reference:**



Braided Rope Seals

- **Prior Art: Metal leaf seals**
- **Design Attributes:**

Insert image here

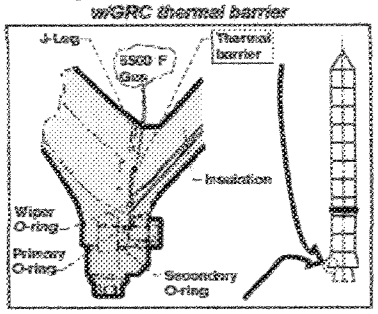
- **Design Considerations:**

- **Reference:**

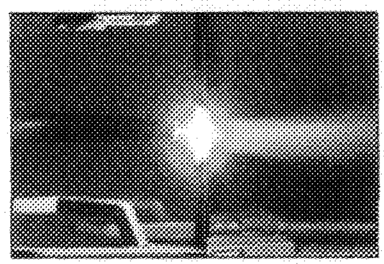
Thiokol Selects NASA GRC Thermal Barrier for RSRM Joint Redesign

- Thiokol experiences periodic hot gas effects in RSRM nozzle-joints 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 qualifying performance for Joint Numbers 1, 2, & 5.

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

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

Full scale motor tests

FSM-9 test

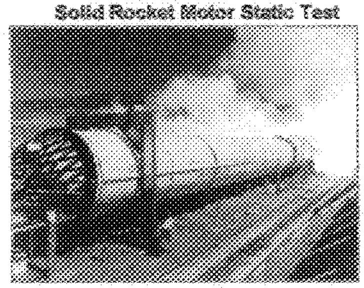
Nozzle-to-case joint	1 CFR
Joint #2	2 CFRS

ETM-2 test

Joint 1*	2 CFR
Joint 2**	2 CFR
Joint 5*	1 CFR

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

Thiokol Full-Scale Solid Rocket Motor Static Test



Add movie file here

Schedule

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

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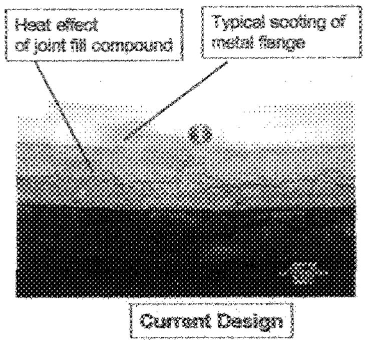
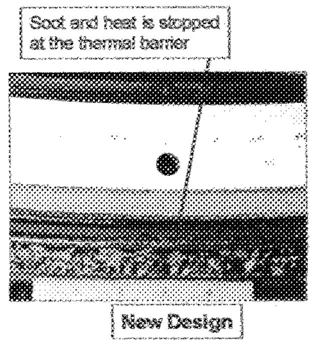
Elegant Solution: Carbon Fiber Rope Thermal Barrier





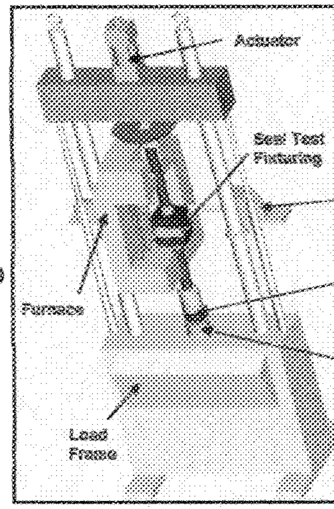
- Blocks heat and combustion products from entering nozzle joints
- Enables solid rocket motor joint assembly in significantly less time (approximately 1/6th time) as compared to the current joint fill compound approach
- Simplifies joint-assembly and reproducibility.
- Final qualifying full scale motor test: November, 2002
- Commence assembling in RSRM: First Quarter CY03

Structural Seals: Advanced Test Fixtures

Hot Compression / Scrub Seal Testing Rig Overview

System Components

- MTS Model 318.25 Servohydraulic Load Frame
  - 55 kip load frame
  - 3.3 kip, 6 in. stroke actuator
  - 220 lb, 3300 lb load cells
  - 5.5 kip alignment fixture
  - 11 gpm HPU
  - Dual servovalves (1 gpm, 15 gpm)
  - TestStar IIs controller
- ATS Series 3350 Custom Box Air Furnace
  - Temperatures up to 3000°F (14.3 kW)
  - *Kanthal Super 33 $MoSi_2$ heating elements*
  - Large working volume (9" W x 14" D x 18" H)
  - Front and back loading doors & top port
  - *Adjustable laser alignment fixturing and shield*
- Beta LaserMike Intelliscan 50 Extensometer
  - Non-contact Class II laser extensometer
  - 0 in. – 2 in. measurement range
  - ±0.25 mil accuracy
  - 1000 scans/s
  - Hot object filter



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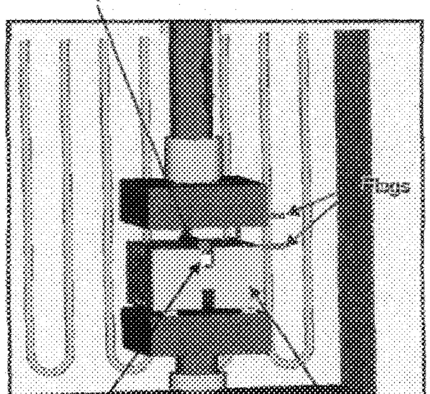
Hot Compression Rig Details

Purpose

New rig will permit measurement of seal load vs. linear compression, preload, & stiffness for various test conditions:
- Temperature
- Compression level
- Loading rate
- Load cycling vs. stress relaxation

Capabilities

- ✓ Temperatures up to 3000°F (1650°C)
- ✓ Loads up to 3300 lbs
- ✓ Stroke rates from 0.001 in/s to 8.0 in/s
- ✓ Seal lengths up to 4 in.
- ✓ Seal diameters up to 2 in.
- ✓ Variety of loading waveforms
  - Cycling (sine wave, sawtooth, user-defined profiles)
  - Stress relaxation



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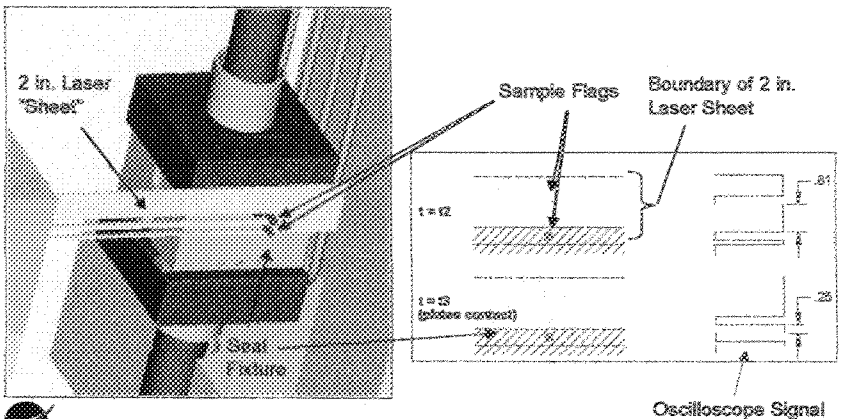
Hot Compression Rig Details: Laser Extensometer

- Laser extensometer will permit very accurate, high temperature, non-contact measurements of seal compression level
- Total displacement = Flag gap (t) – Flag gap (t_o)

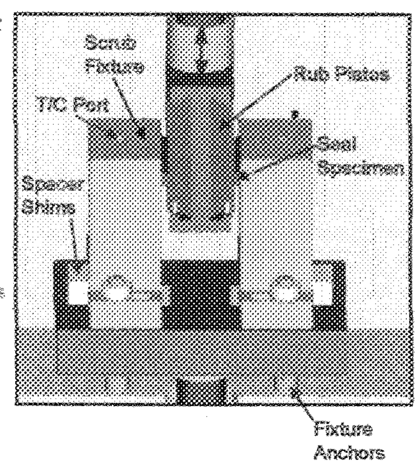


Hot Scrub Rig Details

Purpose

New rig will permit measurement of wear rates and frictional loads for various test conditions:

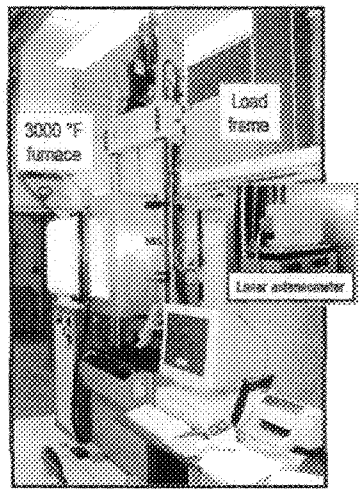
- Temperature
- Compression level
- Stroke rate and number of cycles
- Rub surface conditions (material, roughness, surface profile)



Capabilities

- ✓ Temperatures up to 3000°F (1650°C)
- ✓ Loads up to 3300 lbs
- ✓ 3 in. stroke at rates from 0.001 in/s to 8.0 in/s
- ✓ Seal lengths up to 4 in.
- ✓ Seal diameters up to 2 in.
- ✓ Gaps from 0 in. to 1.125 in.
- ✓ Variety of cyclic loading waveforms (sine wave, sawtooth, user-defined profiles)
- ✓ Pre- & post-scrub flow testing

Hot Compression / Scrub Seal Testing Rig

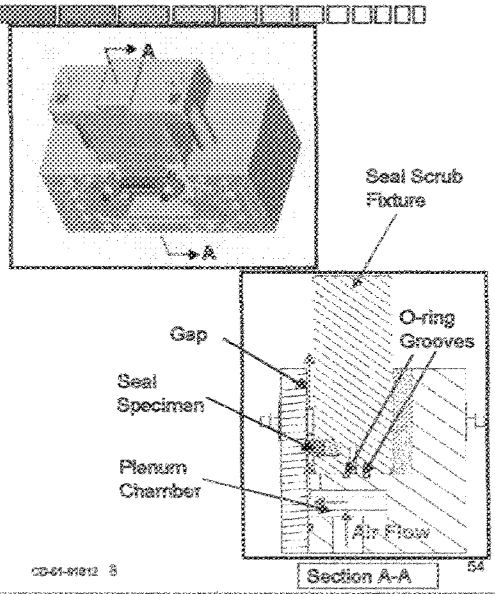


Hot Scrub Rig Details: Pre- and Post-Scrub Flow Testing

Purpose

Ambient flow fixture permits pre- and post-scrub flow evaluations of candidate seals

- Flow testing at 3000°F prohibitively expensive and complicated
- Design minimizes damage due to secondary handling (seal undisturbed between scrub test and flow test)
- Modular design facilitates testing of multiple seal configurations under different testing conditions
  - Test gases: air
  - Flow rates: 0 – 3000 slpm
  - Pressures: 0 – 120 psi
  - Gap settings: 0 – 1 in.

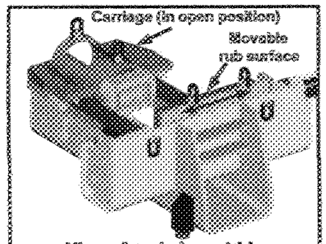


Ambient Scrub & Flow Testing Rig Overview

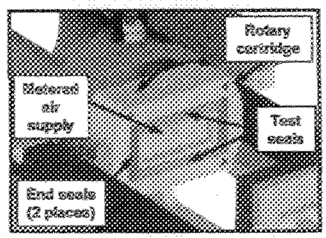
Purpose

Combined seal flow and scrub tests will be performed in new ambient test rig. Flow rates through seals will be measured for various test conditions:

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



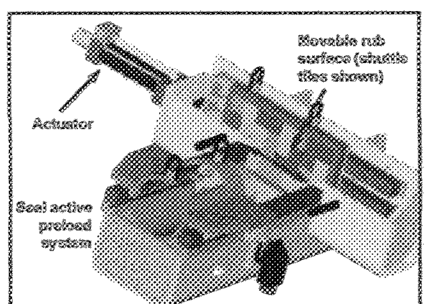
View of seals in cartridge



Ambient Scrub & Flow Testing Rig Overview (cont.)

Capabilities

- ✓ Multiple seal geometries/configurations
- ✓ Seal lengths up to 8 in.
- ✓ Scrub rates up to 12 in/s
- ✓ Scrub loads up to 10 kip (frictional loads)
- ✓ Stroke up to 12 in.
- ✓ Active (pneumatic) or passive (Belleville washers) seal preload monitoring system
- ✓ Multiple scrub directions (cartridge can be rotated)
- ✓ Variety of rub surface conditions
- ✓ Test gas: air
- ✓ Flow rates up to 3000 slpm
- ✓ Pressures range: 0 – 120 psi



View of rub surface

Sealing Trends

Turbine Engines

- Non-contacting seals capable of low leakage and long life minimizing maintenance costs
  - Foil Face Film-Riding Seals: Munson et al
  - Compliant Foil Seals: Salehi et al
- Active clearance control to avoid blade-to-shroud rubs
  - Slow exhaust gas temperature (EGT) rise thereby increasing engine time-on-wing
  - Maintain turbine engine efficiency and decrease specific fuel consumption
  - Increase engine performance
    - » Commercial engine: range and payload
    - » Contribute to meeting NASA's turbine based combined cycle access to space goal

Future Space Vehicle Systems

- High temperature (>2000°F), resilient, multi-use seals required for future highly reusable vehicles
  - Hot CMC control surfaces (e.g. Crew return vehicle - X-38, other)
  - Ram/Scramjet propulsion systems for future single and two stage to orbit launch vehicles concepts

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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 Agency's key aero- and space advanced technology development programs.

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Appendix

NASA Glenn Seals/Secondary Air Flow Workshop

Preliminary Agenda:

- **Overview and Program Needs**
- **Recent Seals/Secondary Air Management Developments**
  - Presentations on Specific Seal Developments: Brush; Finger; Rim; Face; Foil; Abradable; Tip; Static Seals
  - Material Developments
  - Space Vehicle Seals
  - Related Topics
- **Tour of Facilities**

Date:	**October 23-24, 2002**
Location:	**NASA Glenn Research Center,**
	Ohio Aerospace Auditorium (outside NASA's back gate)
Invitation	**Provide me Business Card if you desire invitation**

Open to U.S. Citizens Only and Permanent Legal Residents

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

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Notes to Graphics

- Use bullets/sub-bullet master template that I started
- Use consistent font and pt size for all chart titles.
- Insert movie files where indicated

- Output:
  - Power point presentation w/movies embedded
  - TBD (~25-40) B&W hand out pages (2 slides per page)
  - 1 set Color viewgraphs (as back-up in case projector fails

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Flow Factor

$$\Phi = \frac{\dot{m}\sqrt{T_{avg} + 459.60}}{P_u \times D_{seal}}, \quad \frac{lbm\text{-}in.\sqrt{°R}}{lbf\text{-}s}$$

where

$\dot{m}$	**Air leakage flow rate, lbm/sec**
T_{avg}	**Average seal air inlet temperature, °F**
P_u	**Air pressure upstream of seal, psia**
D_{seal}	**Outside diameter of the seal rotor, in.**

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