NASA/CP—2002-211911/VOL1

2001 NASA Seal/Secondary Air System Workshop

October 2002

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NASA/CP—2002-211911/VOL1

2001 NASA Seal/Secondary Air System Workshop

Proceedings of a conference held at and sponsored by
NASA Glenn Research Center
Cleveland, Ohio
October 30–31, 2001

National Aeronautics and
Space Administration

Glenn Research Center

October 2002

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The Aerospace Propulsion and Power Program at NASA Glenn Research Center sponsored this work.

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Executive Summary
Volume 1

The 2001 NASA Seal/Secondary Air System Workshop covered the following topics:

(i) overview of NASA's Vision for 21st Century Aircraft
(ii) overview of NASA-sponsored Ultra-Efficient Engine Technology (UEET)
(iii) reviews of sealing concepts, test results, experimental facilities, and numerical predictions
(iv) reviews of material development programs relevant to advanced seals development

The NASA UEET overview illustrates for the reader the importance of advanced technologies, including seals, in meeting future engine system efficiency and emission goals. The NASA UEET program goals include an 8- to 15-percent reduction in fuel burn, a 15-percent reduction in CO_2, a 70-percent reduction in NO_x, CO, and unburned hydrocarbons, and a 30-dB noise reduction relative to program baselines.

General Electric and Pratt & Whitney presented advanced seal development work being performed within their organizations. The NASA-funded GE/Stein Seal Company team has successfully demonstrated a large (3-ft-diam) aspirating seal that can withstand all anticipated pressures, speeds, and rotor run-outs anticipated for a GE90 L.P. turbine balance piston location. Laboratory tests at GE Corporate Research & Development demonstrated the seal could accommodate a 1-in-5000-hr severe maneuver tilt load without rubbing, in which the rotor tilts 0.080 in. toward the seal face! Stein Seal Company and GE have fabricated a full-scale seal to be tested in a GE90 ground test engine in early 2003. Pratt & Whitney and the Stein Seal Company are investigating carbon seals to accommodate large radial movements anticipated in future geared-fan gearbox locations.

Mohawk presented a foil seal arrangement that applies foil-bearing technology to arrive at a noncontacting moderate-leakage seal. This foil seal is being developed by Mohawk under an NASA SBIR contract and exploits NASA Glenn's advanced solid film lubricant developments. Greg More of Advanced Products presented screening test data for candidate metal foil materials being considered for very high temperature (>1500+°F) static metal foil seals.

Space Seal Developments: NASA is funding several programs to investigate advanced reusable space vehicle technologies (X–38) and advanced space ram/scramjet propulsion systems. The X–38 and future highly reusable launch vehicles pose challenging control surface seal demands that require new seal concepts made from emerging high-temperature ceramics and other materials. Ram/scramjet engines require high-temperature sliding seals to seal inlet and nozzle ramps. Seal challenges posed by these advanced propulsion systems include high-temperature operation, resiliency at the operating temperature to accommodate sidewall flexing, and durability to last many missions.

Dunlap presented NASA Glenn's programs aimed at developing seals for the above challenges. Glenn is developing high-temperature seal scrub and compression test fixtures capable of up to 3000 ºF operation. Reich presented CFD simulations of control surface seal tests performed by GRC/Boeing at NASA Ames 20-MW panel test facility. The analyses predicted upstream (e.g., hot side) seal and TPS (thermal protection system) temperature reasonably well. Bond of Albany Techniweave presented techniques for braiding ceramic fiber and carbon fiber seals to meet NASA's needs. Mercer presented GRC's advanced sensor developments for harsh conditions.

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Volume 1

NASA'S VISION FOR 21ST CENTURY AIRCRAFT

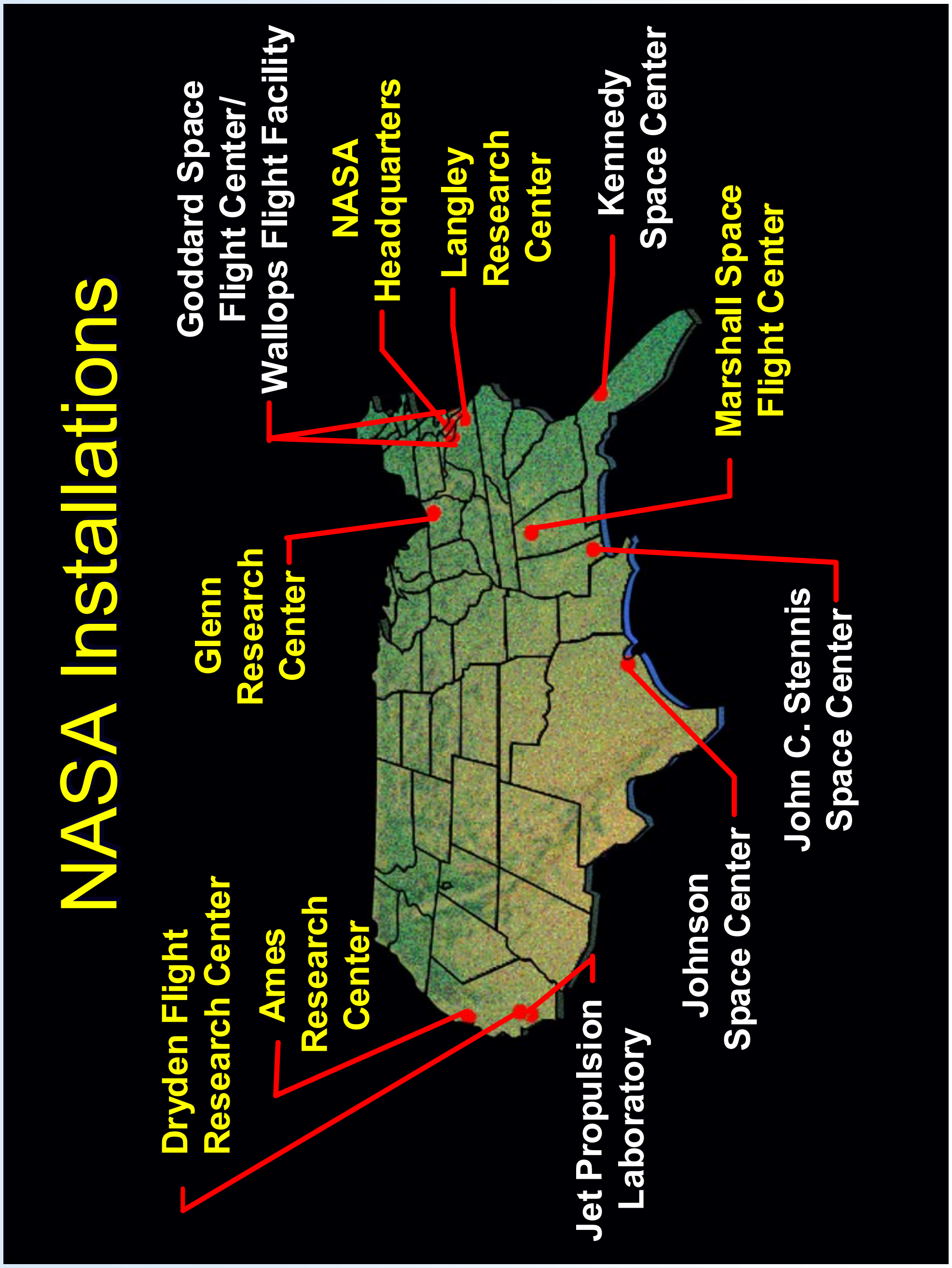
Woodrow Whitlow, Jr.
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

NASA's Vision for 21st Century Aircraft

Dr. Woodrow Whitlow, Jr.
October 30, 2001

NASA Vision

NASA is an investment in America's future. As explorers, pioneers, and innovators, we boldly expand frontiers in air and space to inspire and serve America and to benefit the quality of life on Earth.


NASA Installations
Goddard Space Flight Center/ Wallops Flight Facility
NASA Headquarters
Langley Research Center
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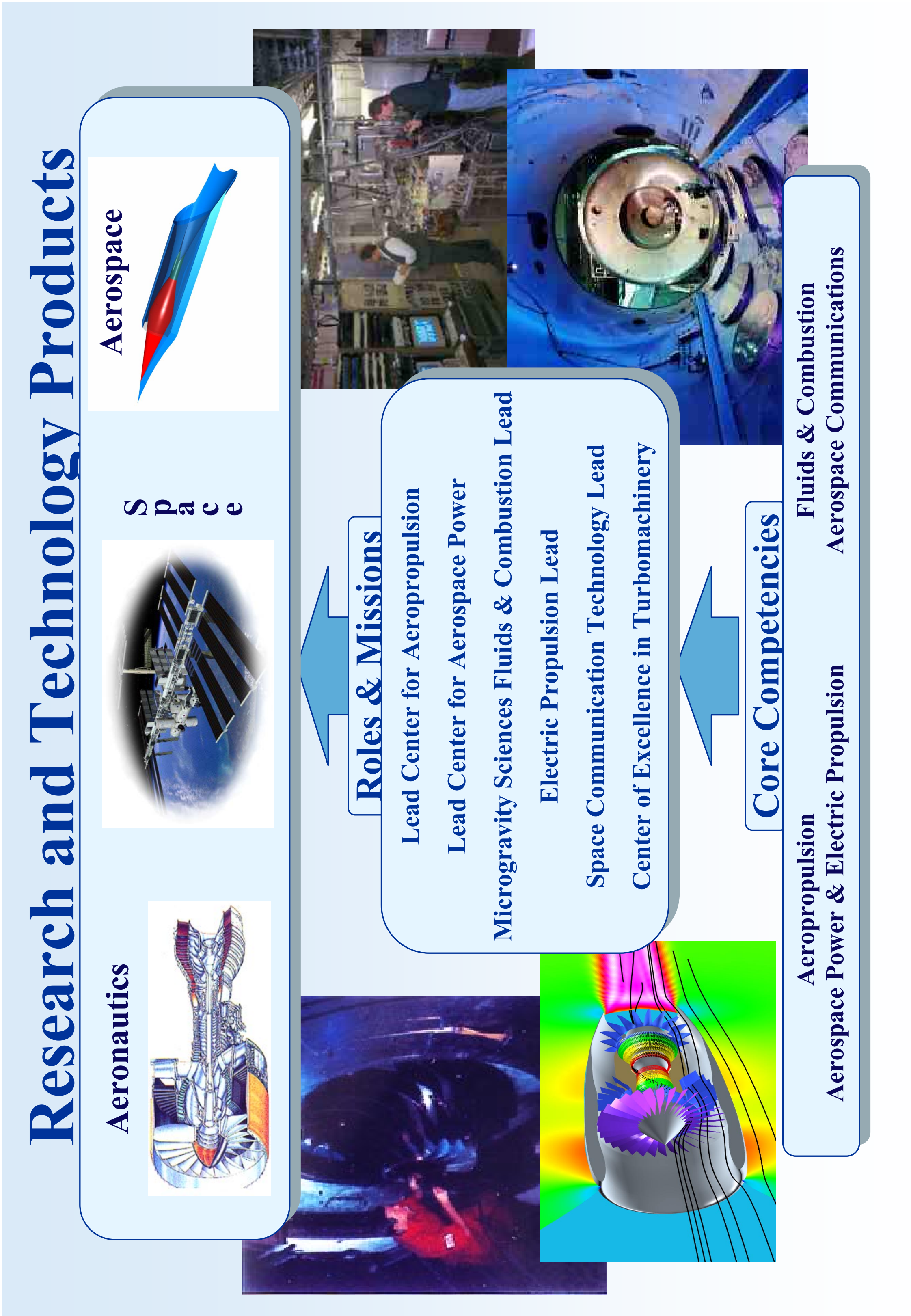
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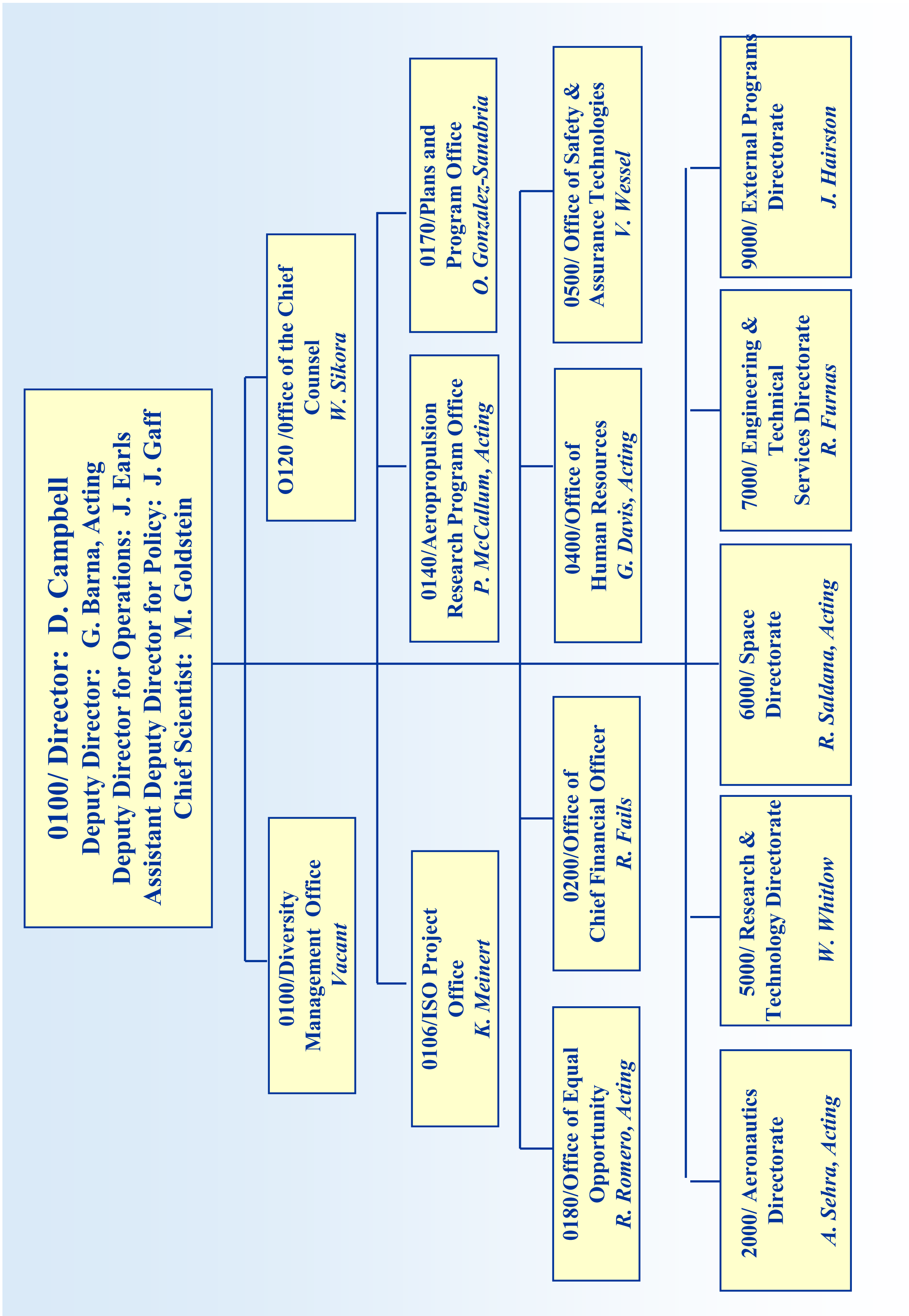
Aerospace Communications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Deputy Director for Operations: J. Earls
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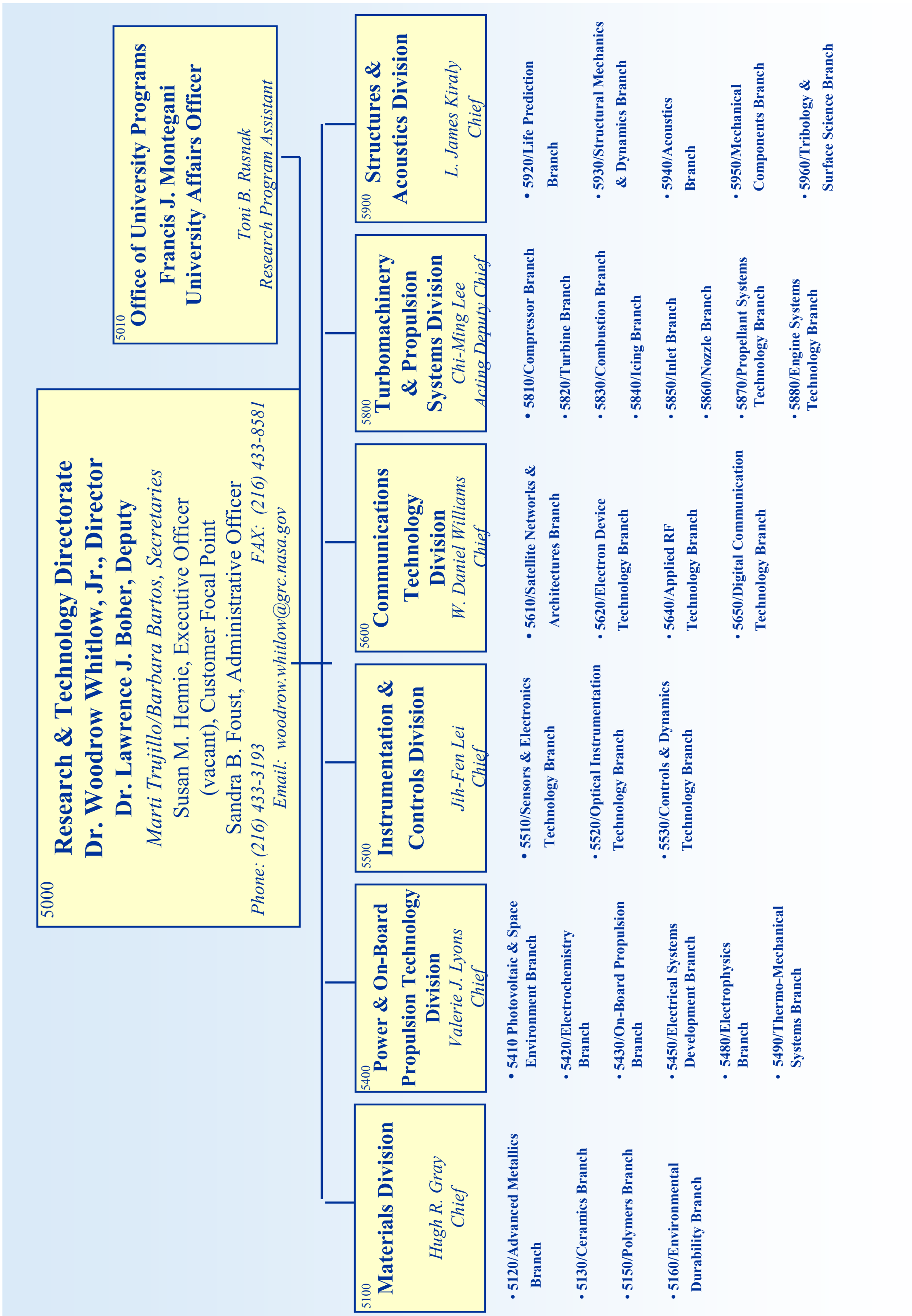
5000
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• 5950/Mechanical Components Branch
• 5960/Tribology & Surface Science Branch

Future Plans

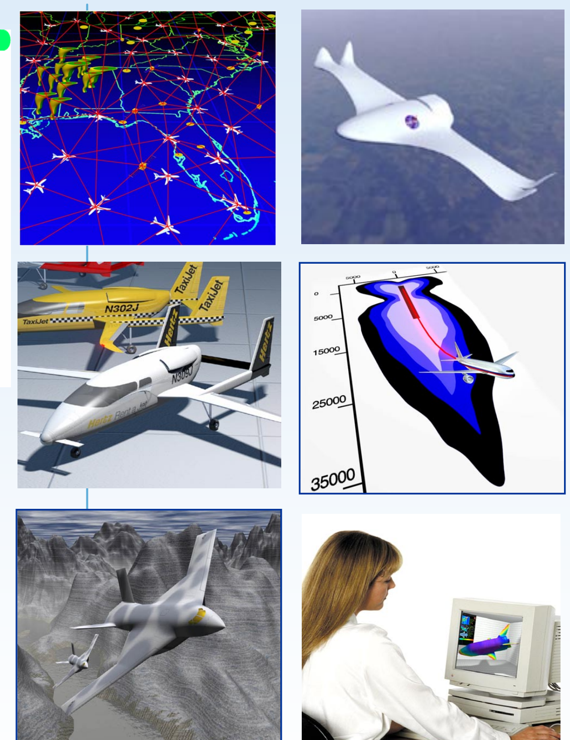
- Advanced aero, space, & aerospace propulsion systems
- Nanotechnology & nanostructural engineering
- Biomedical engineering & biotechnology
- Information, data, & communications technology
- Advanced health monitoring devices
- Diagnostic instruments and controls
- Longer life, lower cost, lightweight turbomachinery
- Computationally designed materials & structures
- Improved modeling, analysis, & computational methods
- Advanced aerospace power systems

Aviation Blueprint

The Vision

What if we created an entire New Era of Aviation?

- Vastly improved System Safety & Capacity
- Revolutionary Vehicle Performance
- Good Neighbor - Airports
- Clean and Quiet - Airplanes
- On demand mobility - Freedom
- Military air-superiority
- Skilled Workforce & Revolutionary Tools



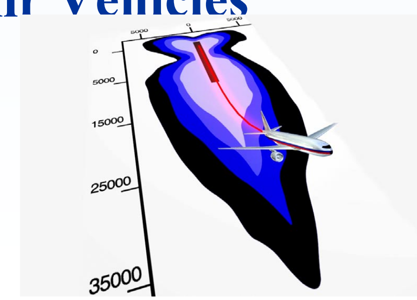
The next Century of Aviation

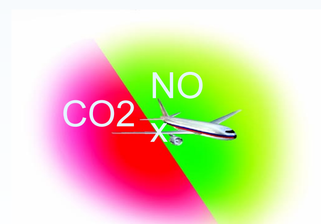
Aviation Blueprint

Revolutionary Vehicles

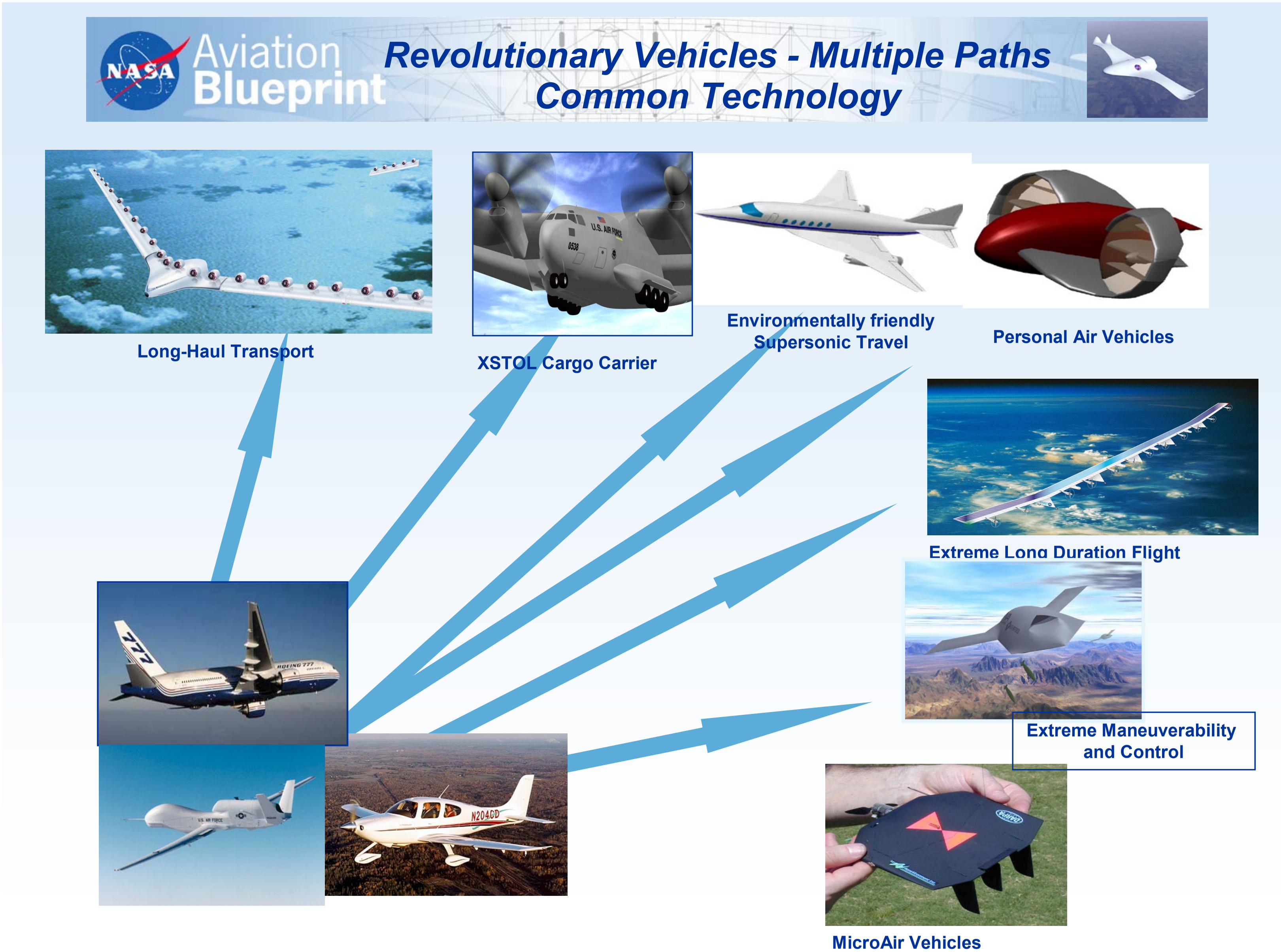
Revolutionary New Vehicles Needed That Solve Barriers and Open new Opportunities to Unconstrained Mobility

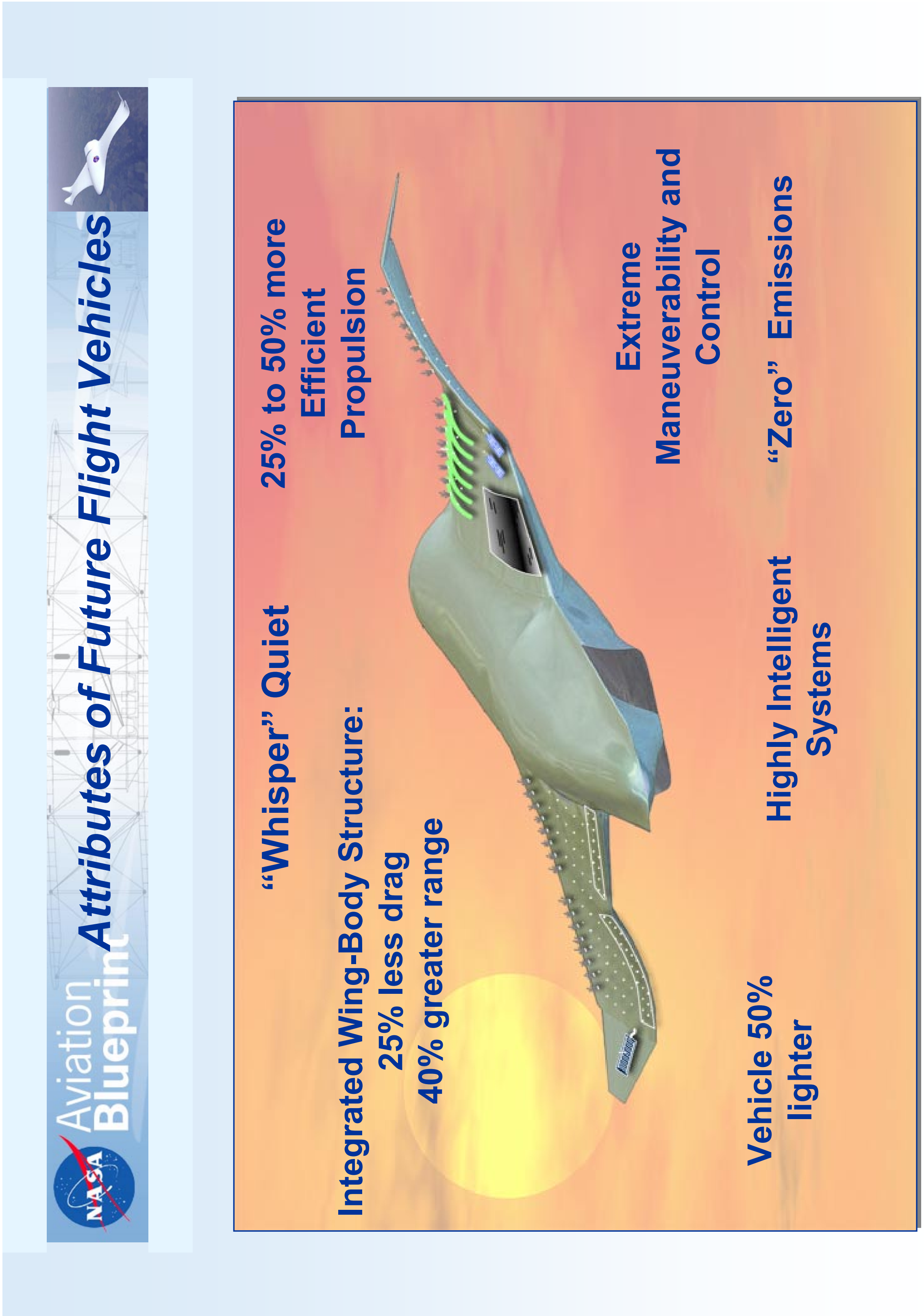
- Noise Reduction
- Reduce Emissions and Fuel Burn
- Improved Safety
- Reduced Wing Tip Vortices
- Increased Speed of Air Travel
- Ability to get People and Cargo in and out of Very Short Airfields
- Sustained Military Air Superiority
- To enable Personal Air Vehicles

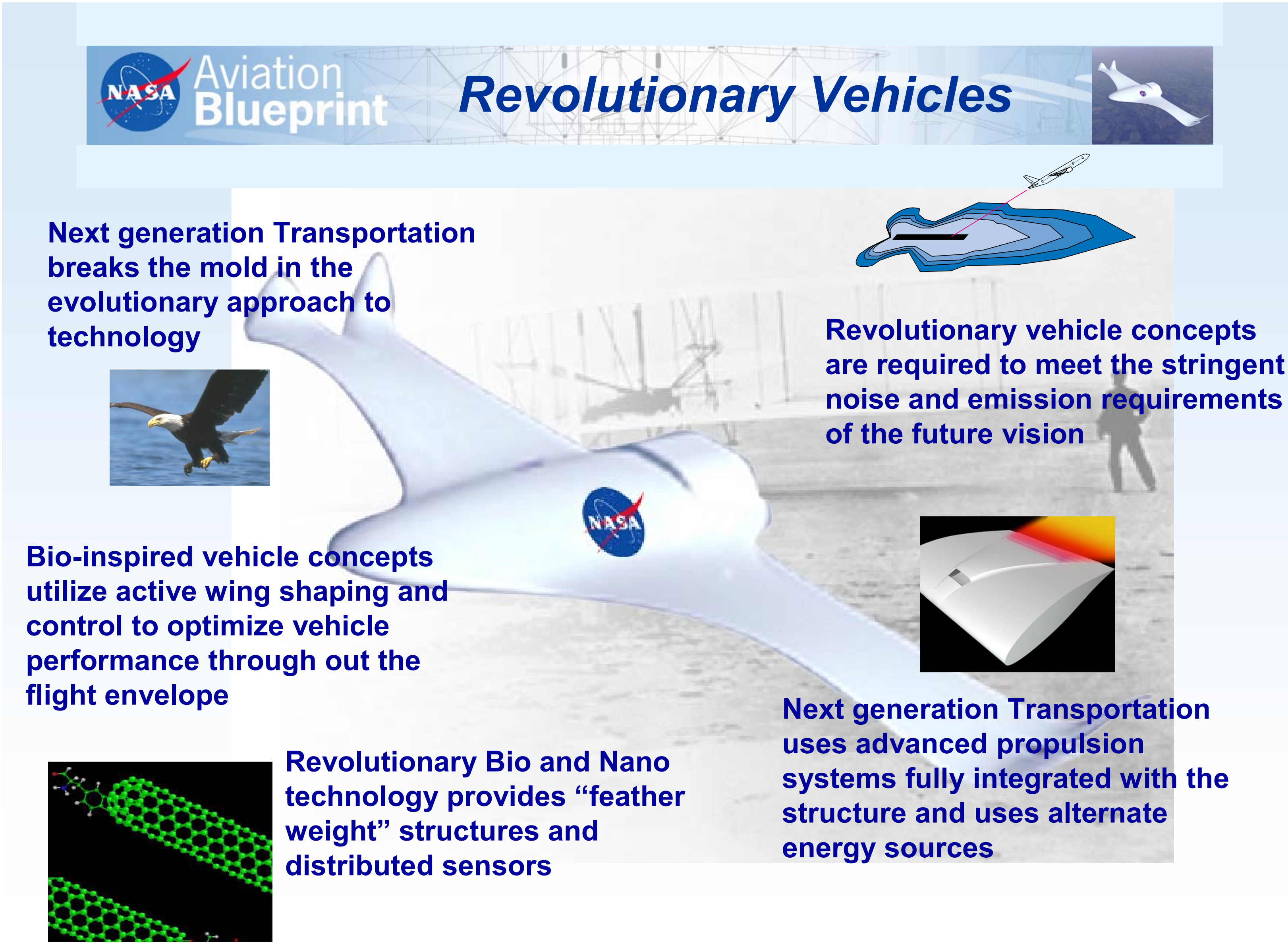


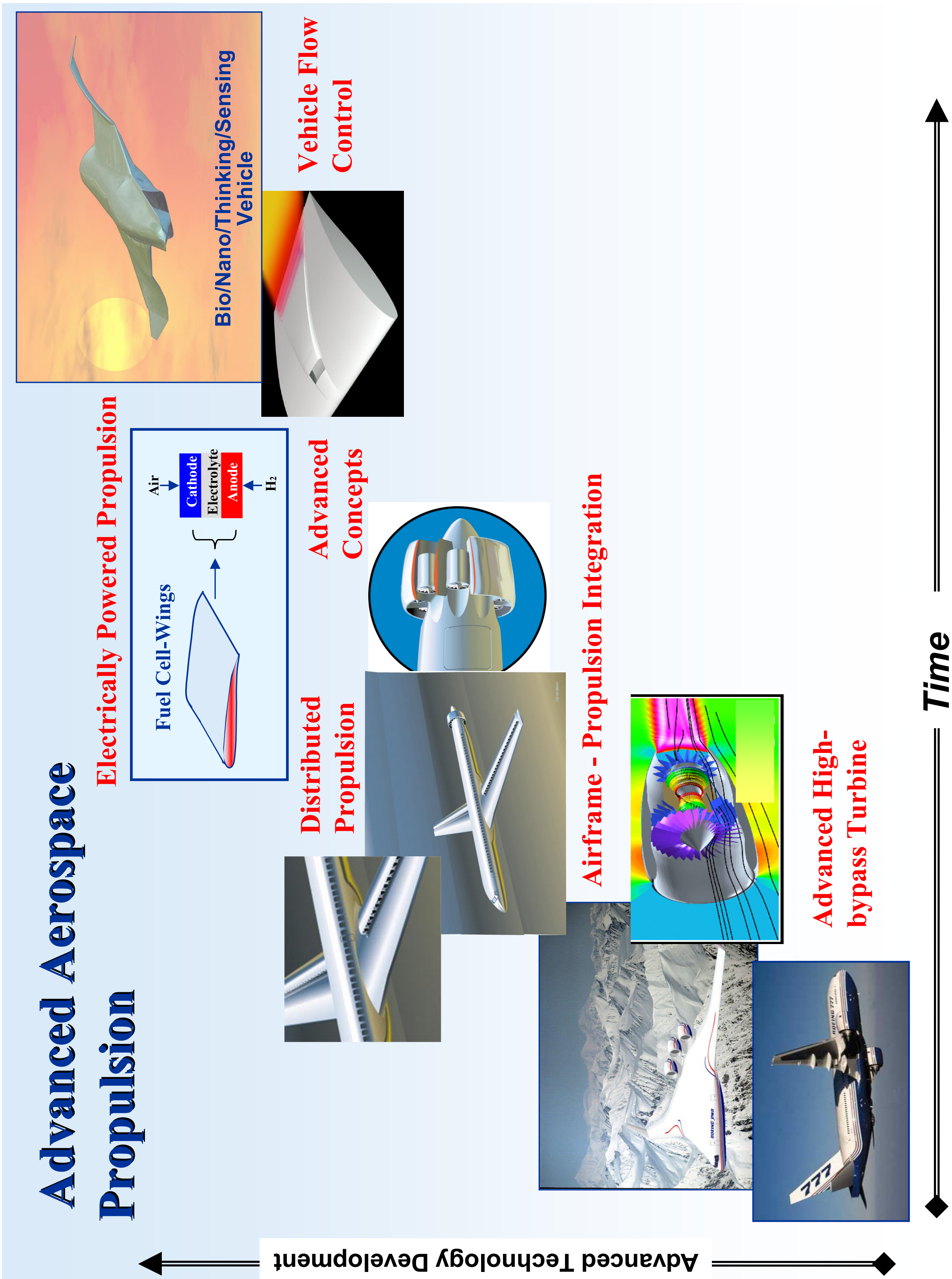


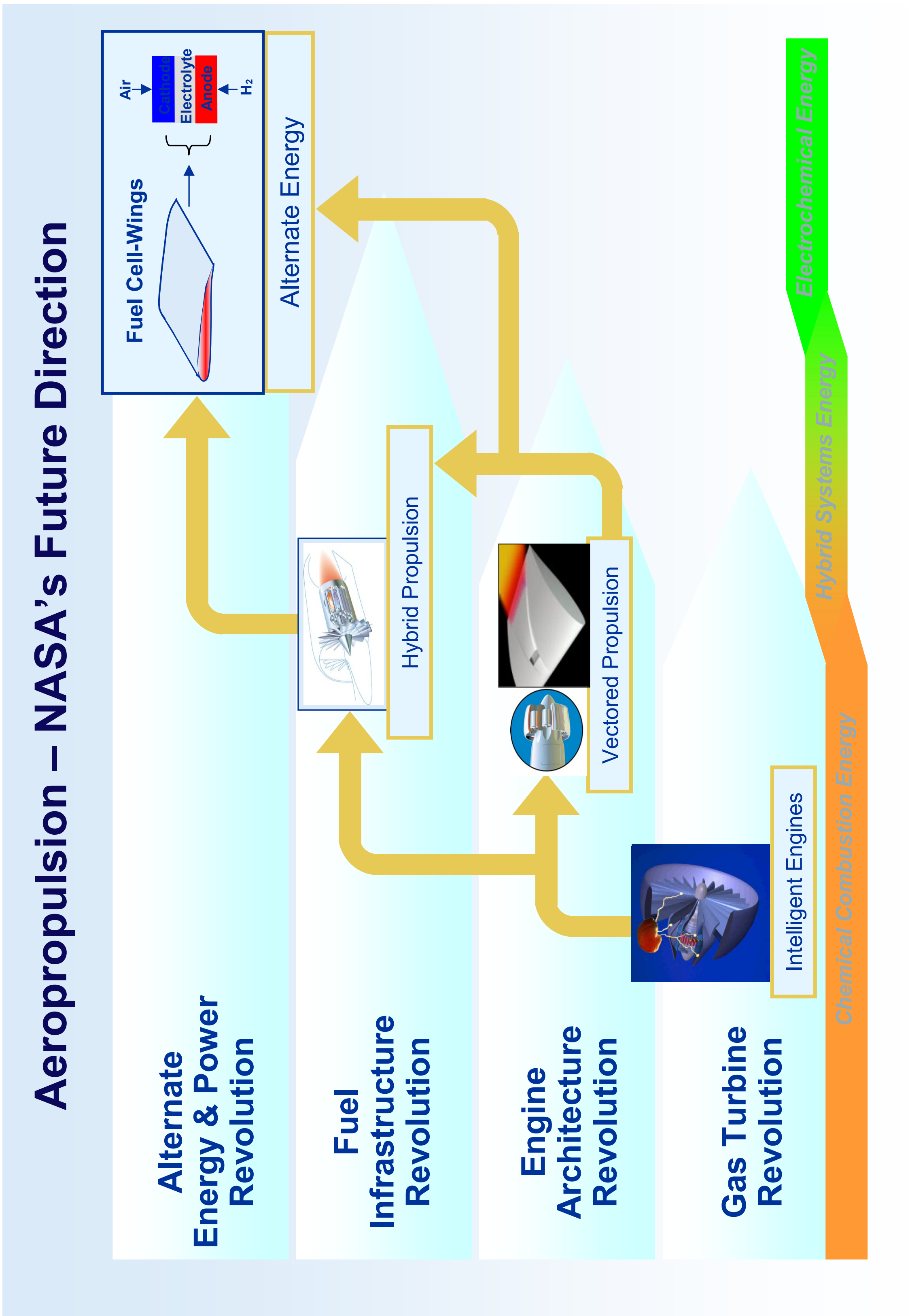
- 80% NOx and 50% CO2 reduction
- 100% NOx and CO2 reduction for revolutionary concepts


Aviation Blueprint
Revolutionary Vehicles - Multiple Paths
Common Technology
Long-Haul Transport
XSTOL Cargo Carrier
Environmentally friendly Supersonic Travel
Personal Air Vehicles
Extreme Long Duration Flight
Extreme Maneuverability and Control
MicroAir Vehicles


Aviation Blueprint
Attributes of Future Flight Vehicles
"Whisper" Quiet
25% to 50% more Efficient Propulsion
Integrated Wing-Body Structure:
25% less drag
40% greater range
Extreme Maneuverability and Control
Vehicle 50% lighter
Highly Intelligent Systems
"Zero" Emissions


Aviation Blueprint
Revolutionary Vehicles
Next generation Transportation breaks the mold in the evolutionary approach to technology
Revolutionary vehicle concepts are required to meet the stringent noise and emission requirements of the future vision
Bio-inspired vehicle concepts utilize active wing shaping and control to optimize vehicle performance through out the flight envelope
Next generation Transportation uses advanced propulsion systems fully integrated with the structure and uses alternate energy sources
Revolutionary Bio and Nano technology provides "feather weight" structures and distributed sensors


Advanced Aerospace Propulsion
Electrically Powered Propulsion
Fuel Cell-Wings
Air
Cathode
Electrolyte
Anode
H_2
Bio/Nano/Thinking/Sensing Vehicle
Vehicle Flow Control
Advanced Concepts
Distributed Propulsion
Airframe - Propulsion Integration
Advanced High-bypass Turbine
Time
Advanced Technology Development



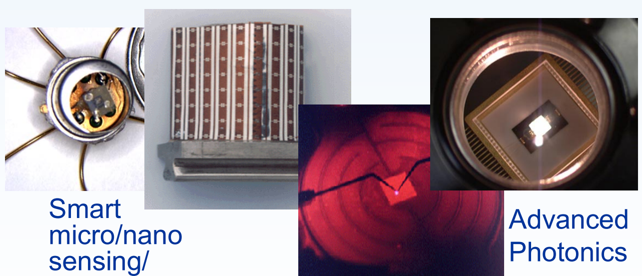
Aeropropulsion – NASA's Future Direction
Alternate Energy & Power Revolution
Fuel Infrastructure Revolution
Engine Architecture Revolution
Gas Turbine Revolution
Fuel Cell-Wings
Air
Cathode
Electrolyte
Anode
H2
Alternate Energy
Hybrid Propulsion
Vectored Propulsion
Intelligent Engines
Electrochemical Energy
Hybrid Systems Energy
Chemical Combustion Energy

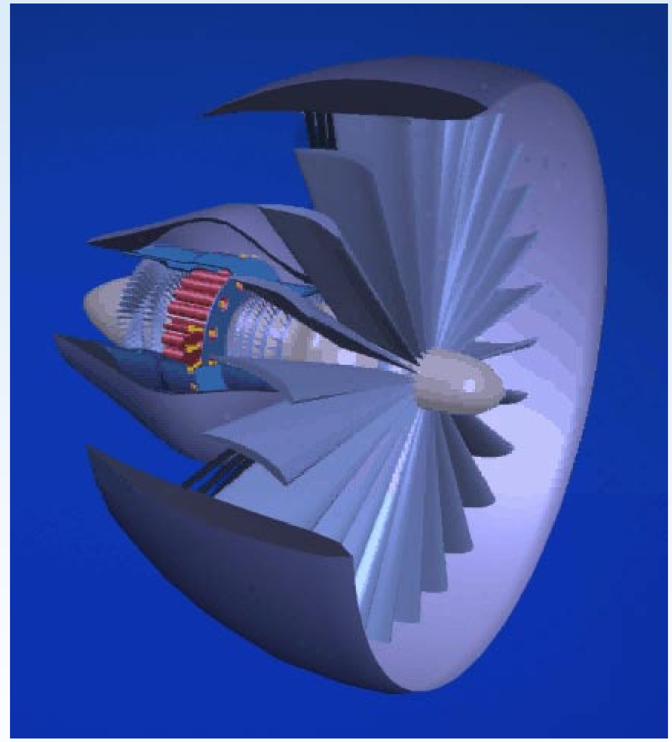
Gas Turbine Revolution

Variable Capability, Ultra High Bypass Ratio Intelligent Engines: Fundamental Technologies

Intelligent Engine System Asset Management

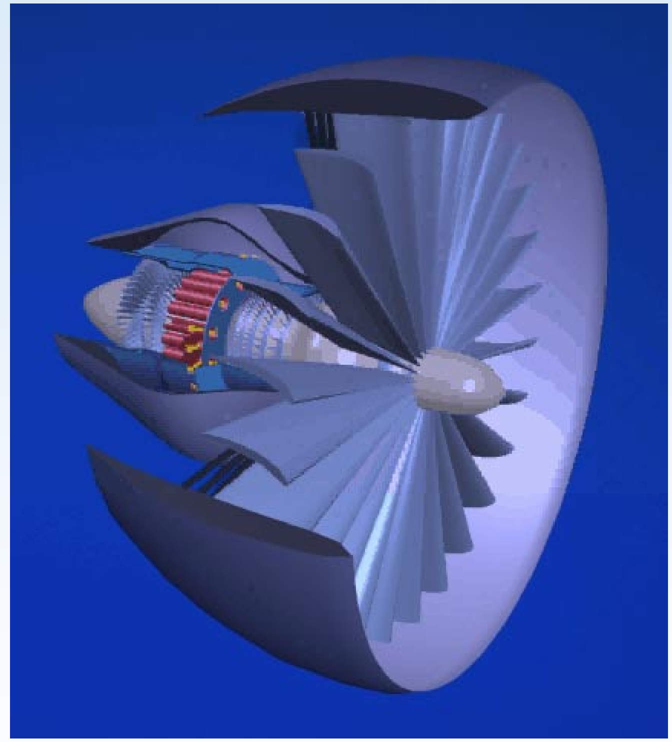
- Embedded micro- and nano-sensors
- Coupled simulation and data-feedback health/performance management
- Autonomic engine control strategies

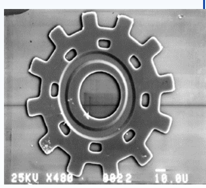




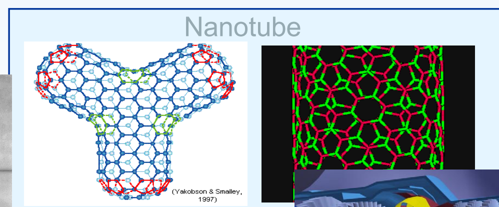
Variable Capability, Ultra High Bypass Ratio Intelligent Engines: Fundamental Technologies

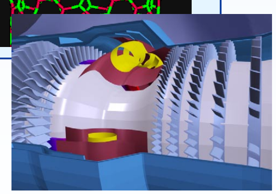
- Micro-Flow Management
- Acoustic Masking
- Innovative Combustion Strategy
- Morphing Structures
- Adaptive Structures
- Adaptive Engine Cycles





Micromachined actuator

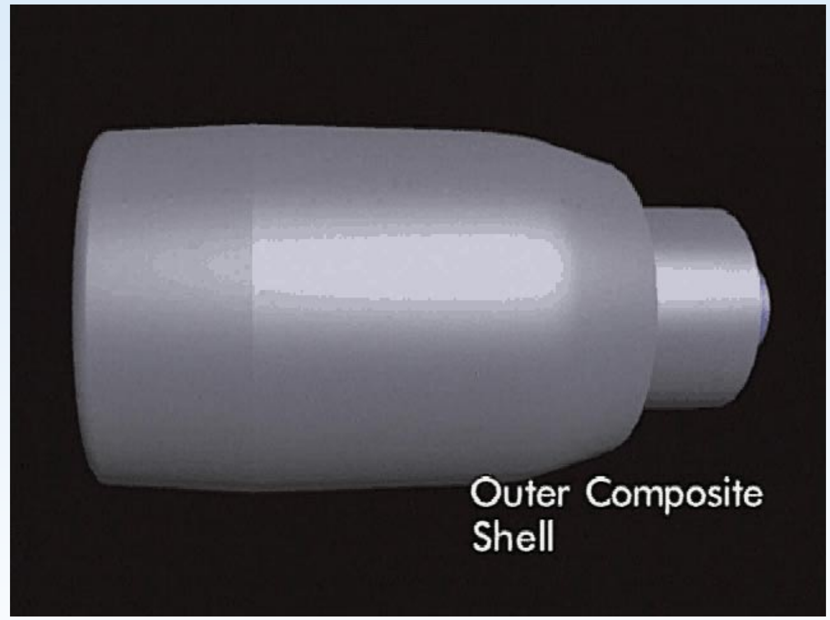


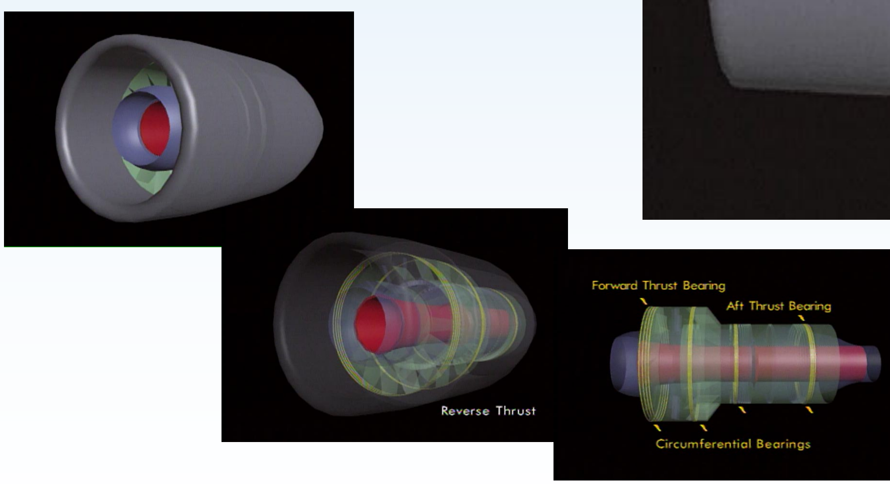


Variable Capability, Ultra High Bypass Ratio Intelligent Engines: Fundamental Technologies

Exoskeletal Engine

- Outer shell rotating
- All composite engine
- Magnetic bearings

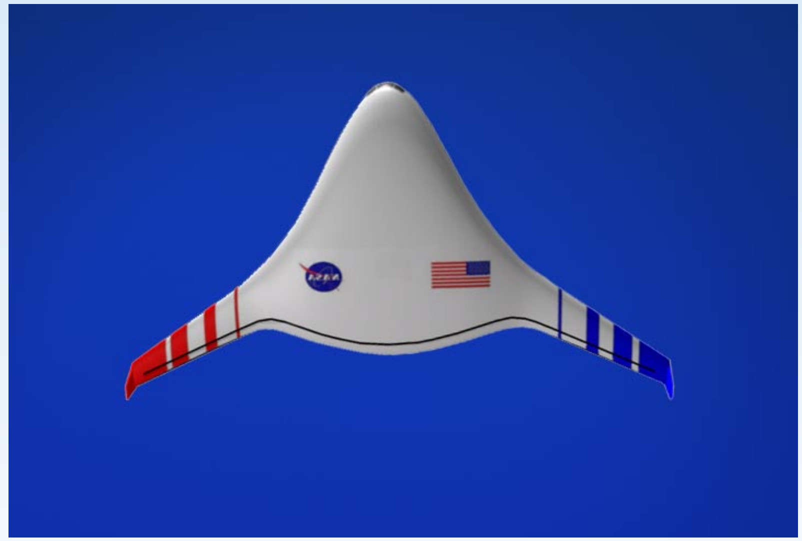


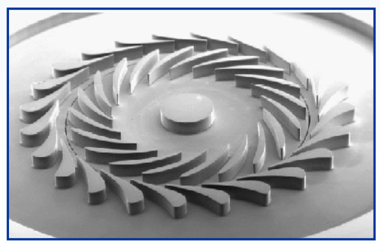


Distributed Vectored Propulsion

Distributed Engines

- Multiple low-cost, low power engines deployed along wing
- Distributed thrust and thrust vectoring
- Aircraft boundary layer ingestion
- Micro-turbine engines distributed over aircraft wings



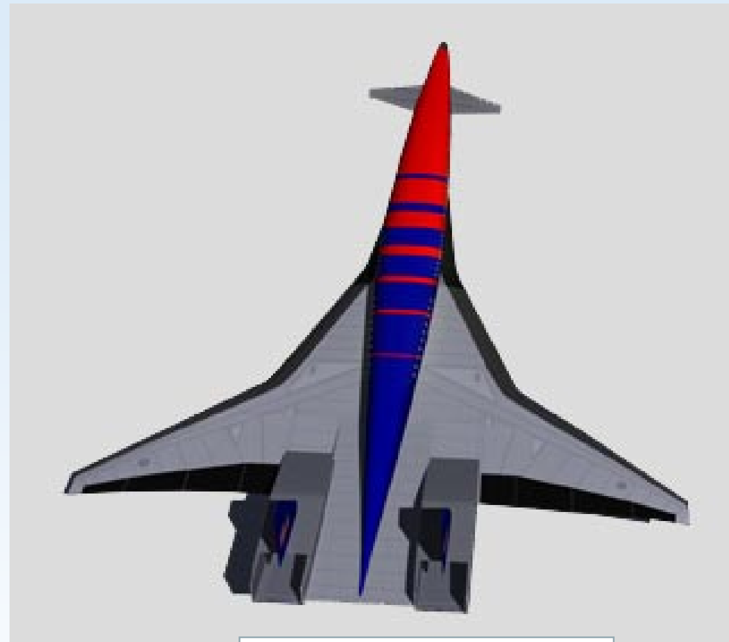


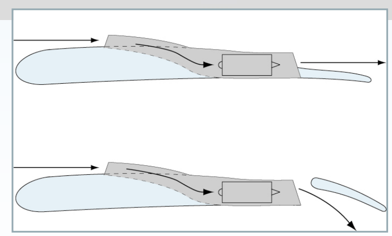
SiC Micro Turbine

Distributed Vectored Propulsion

Distributed Exhaust

- High aspect-ratio nozzles embedded in the wing trailing edge
- Ducted Polymer Matrix Composite (PMC) nozzles
- Embedded inlets & nozzles employing flow-control

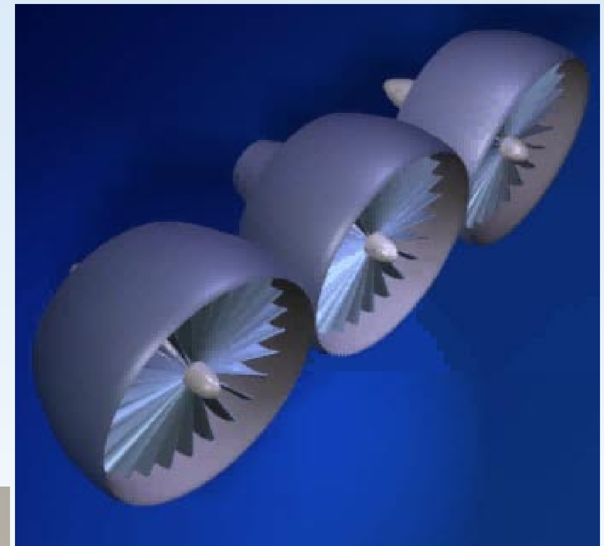




Distributed Vectored Propulsion

Multi-Fan Core

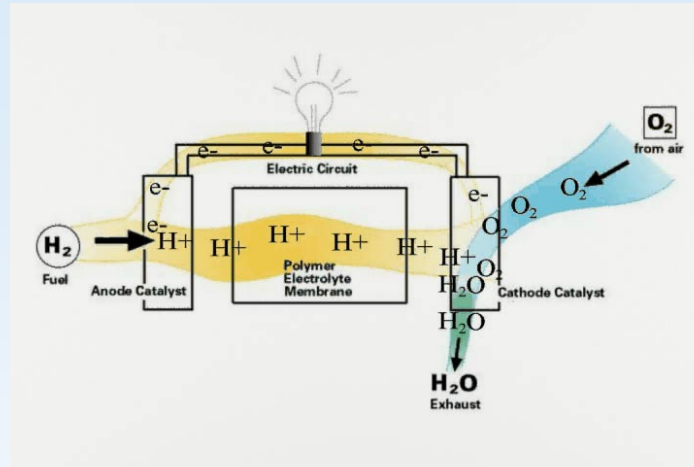
- High-efficiency core powering multiple fans
- Advanced mechanical power transmission



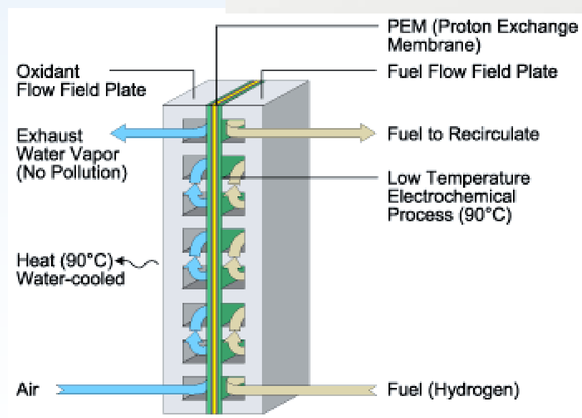
Alternative Energy Propulsion

Fuel Cell Powered Electric Propulsion System

- Proton Exchange Membrane (PEM) Fuel Cell
- Zero NOx and HC emissions
- Water emission or use of chemical reformer

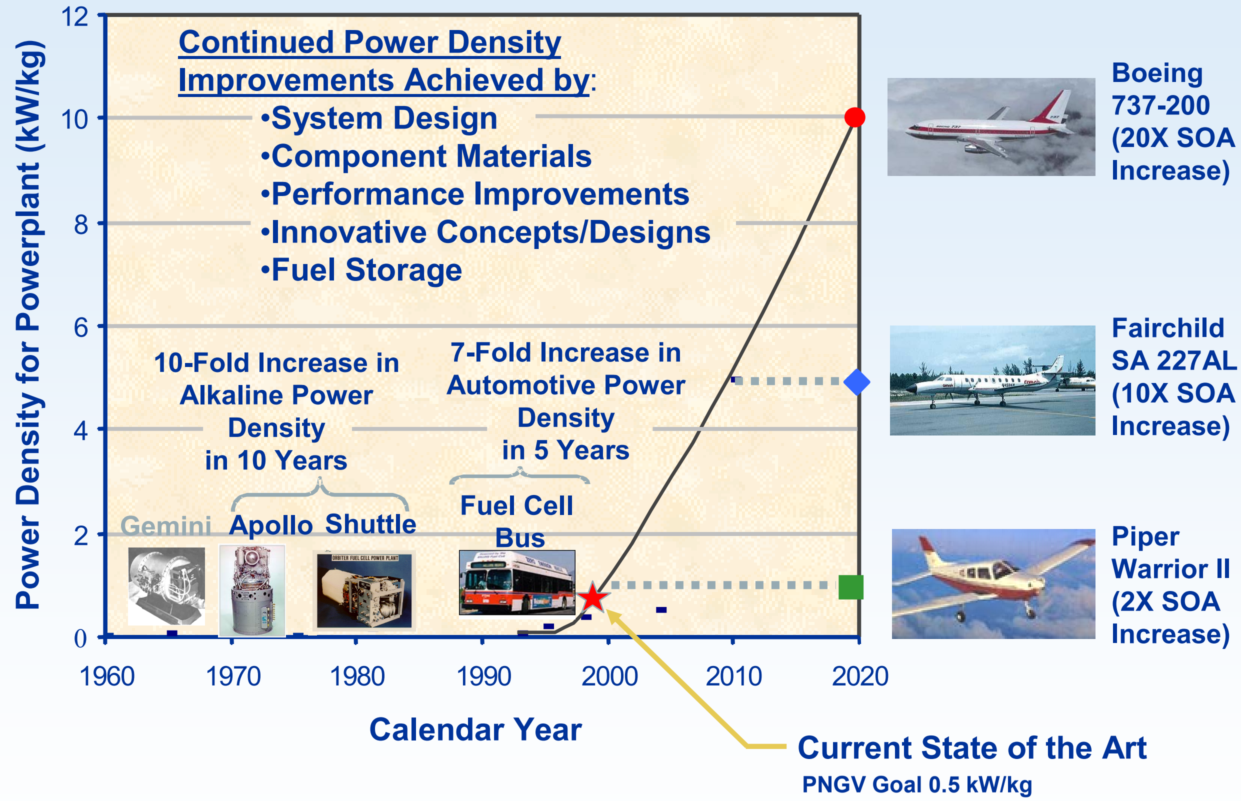


Basic Hydrogen PEM fuel cell operation and hardware



Alternative Energy Propulsion

Potential Fuel Cell Enabled Electric Propulsion



OVERVIEW OF NASA GLENN SEAL PROGRAM

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Irebert Delgado
U.S. Army Research Laboratory
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Jeffrey J. DeMange, Christopher C. Daniels, and Scott B. Lattime
Ohio Aerospace Institute
Brook Park, Ohio

**Overview of
NASA Glenn Seal Program**

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NASA Glenn Research Center
Cleveland, OH 44135**

**Contributors
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Jeff DeMange, Chris Daniels, Scott Lattime**

**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.**

NASA Glenn Research Center

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.

2001 NASA Seal/Secondary Air System Workshop

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.–?**

NASA Glenn Research Center

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.

2001 NASA Seal/Secondary Air System Workshop

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.**

NASA Glenn Research Center

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.

2001 NASA Seal/Secondary Air System Workshop

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.**

NASA Glenn Research Center

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)

NASA Glenn Research Center

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

NASA Glenn Research Center

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.

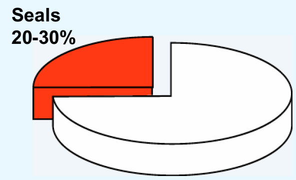
Analytical methods such as the coupled TURBO/SCISEAL code are being developed under contract with CFDRC to perform coupled main-flow (TURBO) and secondary air/seal (SCISEAL) calculations.

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

NASA Glenn Research Center

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).

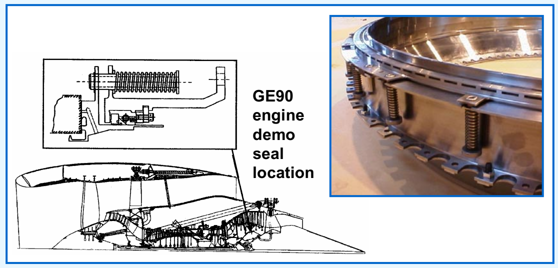
Applying the seals to just several engine locations would reduce SFC 2-3% . This represents a significant (20-30%) contribution toward meeting the overall goals of NASA’s Ultra-Efficient Engine Technology (UEET) program.

Aspirating Seal Development: GE90 Demo Program

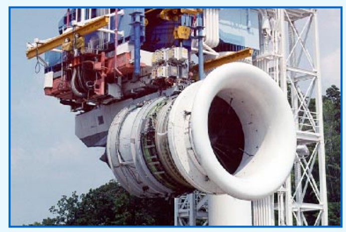
Funded UEET Seal Development Program

- **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



NASA Glenn Research Center

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

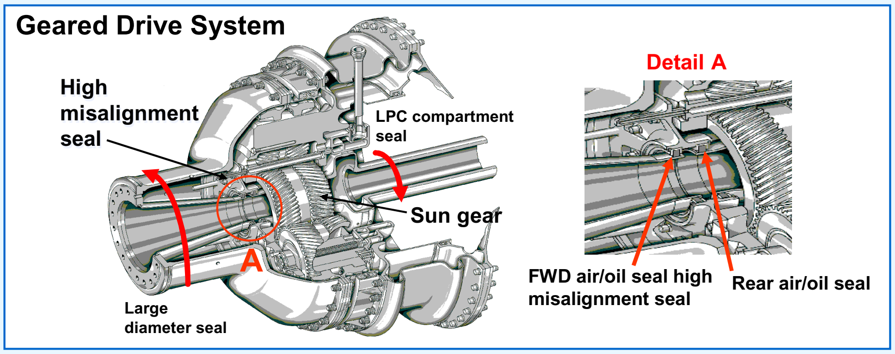
Objectives:

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

Schedule:

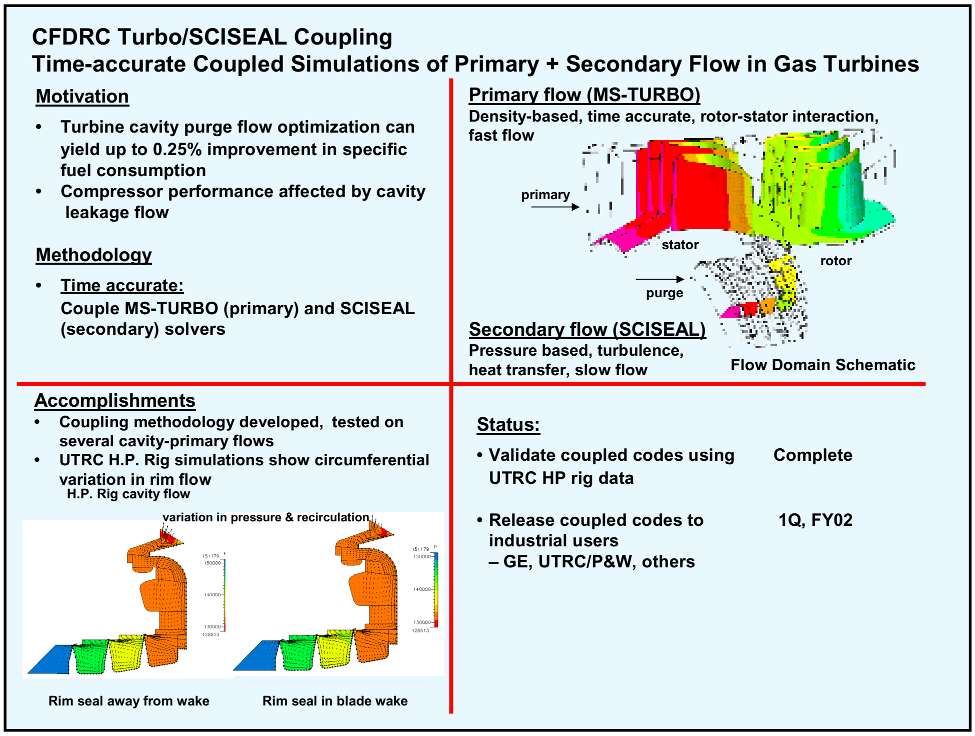
- Complete testing of high misalignment seals 1Q FY02

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



NASA Glenn Research Center

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.

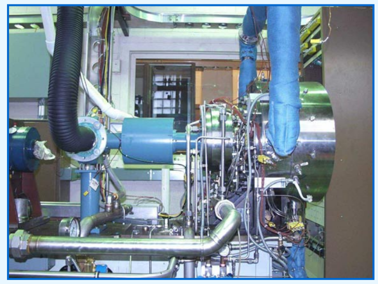
Studies have shown that excessive amounts of flow (up to 2-3% core flow) go through rim seals beyond that which is needed for cooling purposes (Munson and Steinetz, 1994). Hence SFC reductions are possible by reducing flows to what is needed for cooling purposes. New concepts and analytical methods are 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.

NASA Glenn Research Center

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.

Demonstrated Preliminary Feasibility of Compliant Foil Seal

• **Objective**

Develop non-contacting high speed compliant foil seals for next generation turbine engines and assess scalability

• **Background**

NASA's oil free turbomachinery/bearing program basis for foil seal development:

– Mohawk innovative foil bearing designs
– GRC's advanced solid film lubricant: enables > 100,000 stop-start cycles (0–70,000 rpm); 1200 °F with virtually no wear

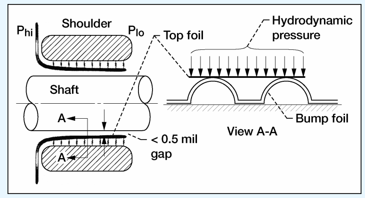
• **Development Program**

– SBIR Phase 1 (FY 00): Demo preliminary feasibility of foil seal in subscale test (complete)
– SBIR Phase 2 (FY 01-02)
– Evaluate manufacturing processes for larger seals (underway)
– Design, fabricate, test 3 seals (2.8, 6, 8.5 in.) (2.8 in. seal tested to 1000 °F)

• **Partners**

– Mohawk Innovative/NASA GRC

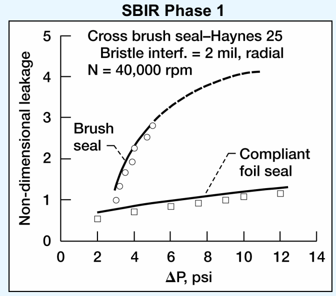
Compliant Foil Seal (CFS) Schematic



Foil Seal and Brush Seal Leakage Data

2.84 in. Diam. Journal; 68 °F

SBIR Phase 1



NASA Glenn Research Center

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

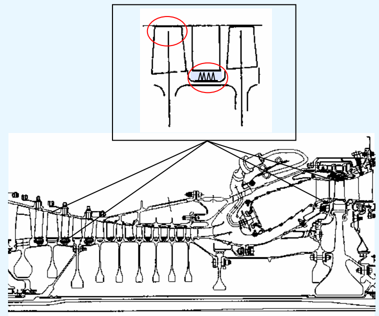
Goal:

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



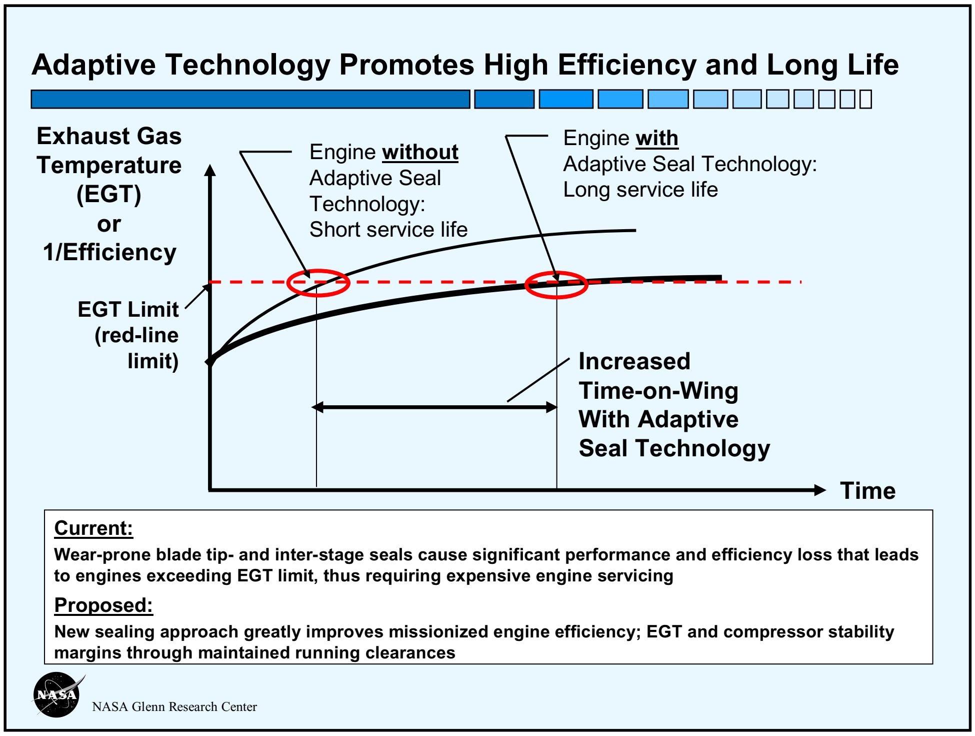
Payoffs:

- 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)

NASA Glenn Research Center

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.

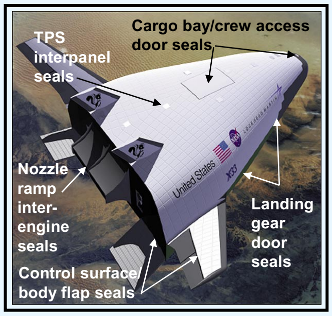
Benefits of clearance control in the turbine section include retained EGT margins (see also next chart), higher efficiencies, longer range, and lower emissions (because of lower fuel-burn). Benefits of clearance control in the compressor include better compressor stability (e.g. resisting stall/surge), 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.

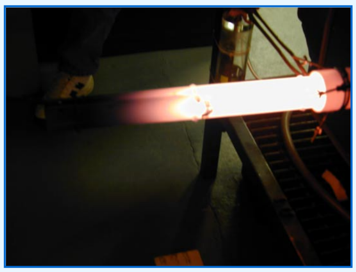
NASA Glenn Research Center

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.

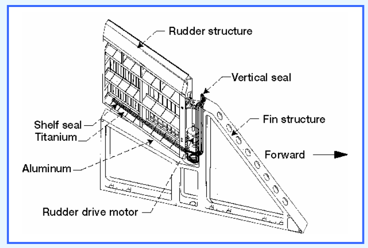
NASA has unique facilities to evaluate the flow and durability performance of these seals at temperatures up to 1500˚F (existing) and up to 3000˚F (planned: see Dunlap et al. and DeMange et al. in this 2002 seal workshop proceedings). NASA GRC also possesses a high heat flux H_2/O_2 rocket engine for 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:



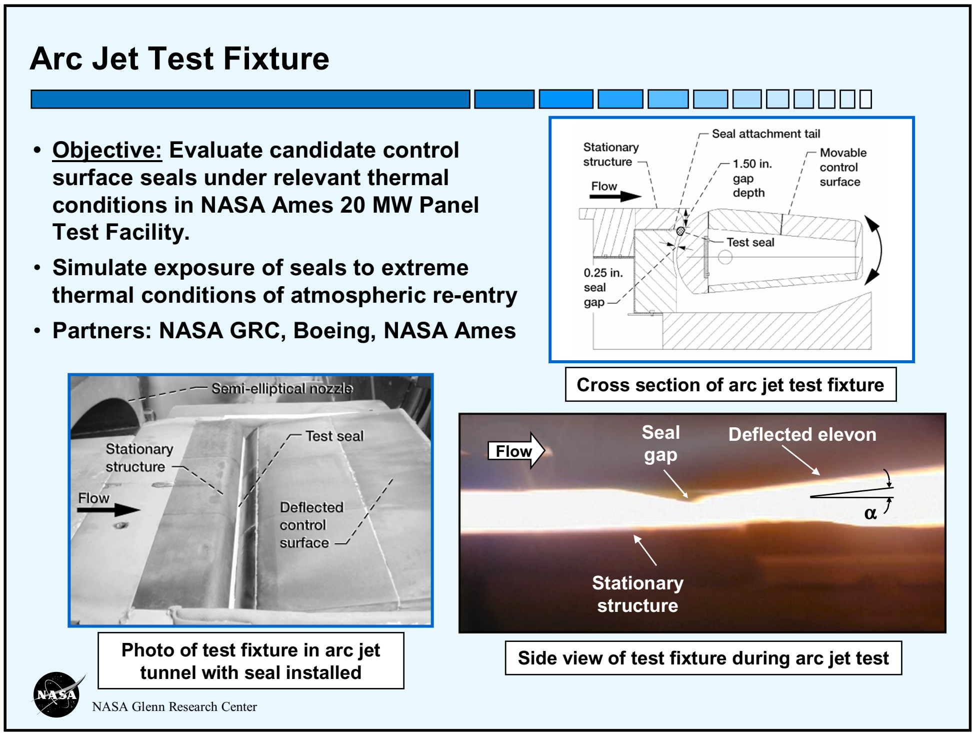
1900 °F Furnace Tests



NASA Glenn Research Center

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.

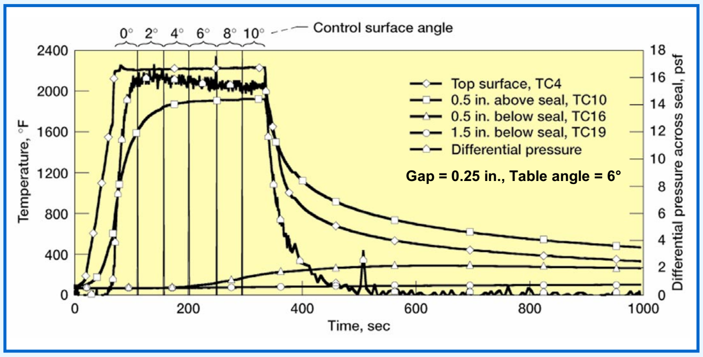


Under contract to NASA GRC, Boeing performed arc jet tests on candidate high temperature control surfaces seals for future highly-reusable launch vehicles. In this test seals were installed in a 0.25” wide gap between the stationary structure and movable control surface. Temperatures and pressures both 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

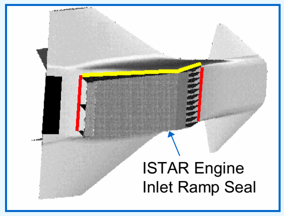
Installation of single seal caused large temperature and pressure drop across seal location as compared to open gap

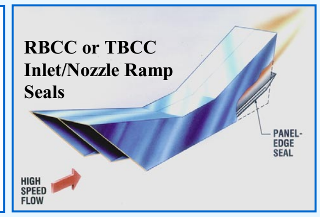
NASA Glenn Research Center

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**

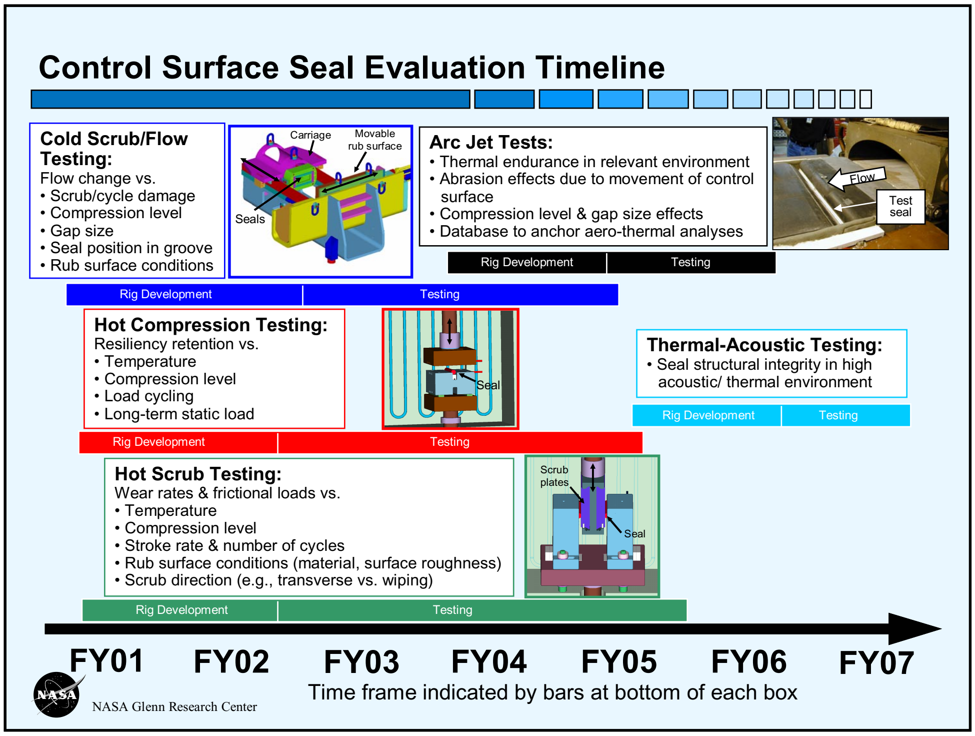
Goal: Develop long life, high temperature control surface and propulsion system seals and analysis methods and demonstrate through laboratory tests.

NASA Glenn Research Center

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.

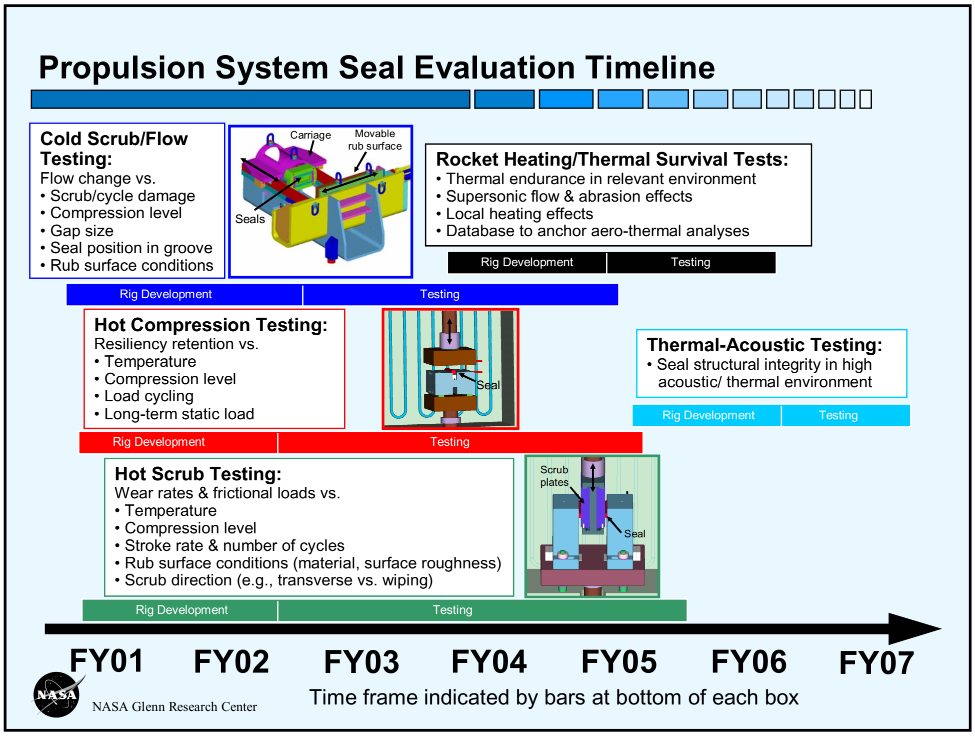
NASA is investigating advanced air-breathing hypersonic engines as possible first-stage propulsion systems for higher-performance multi-stage launch systems. Hypersonic engines attain higher specific impulse as compared to conventional rocket engines. Further they save weight by burning air from the 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.

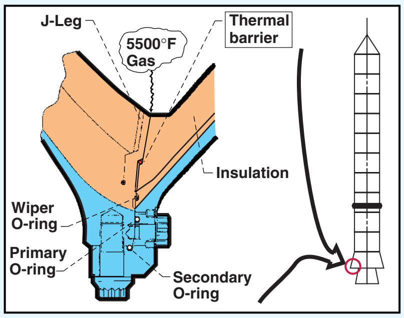
Shown in this chart is a pictorial timeline showing the types of tests to be performed and the goals of each test. The test seal flow and scrubbing test rigs being developed were designed to accommodate both the light loads and high sliding speeds for the control surface task and the relatively heavy 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.

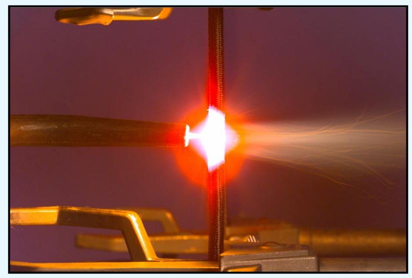
Thiokol Selects NASA GRC Thermal Barrier for RSRM Joint Redesign

- **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.

NASA Glenn Research Center

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

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

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.

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/**

+ **http://www/lerc.nasa.gov/WWW/TU/InventYr/1996Inv_Yr.htm**
  NASA Technical Papers
  Discussion

Note: GRC Web pages temporarily closed to external access in wake of Sept. 11, 2001 events. Will re-open after security review.

NASA Glenn Research Center

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.

NASA Glenn Research Center

References:

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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.

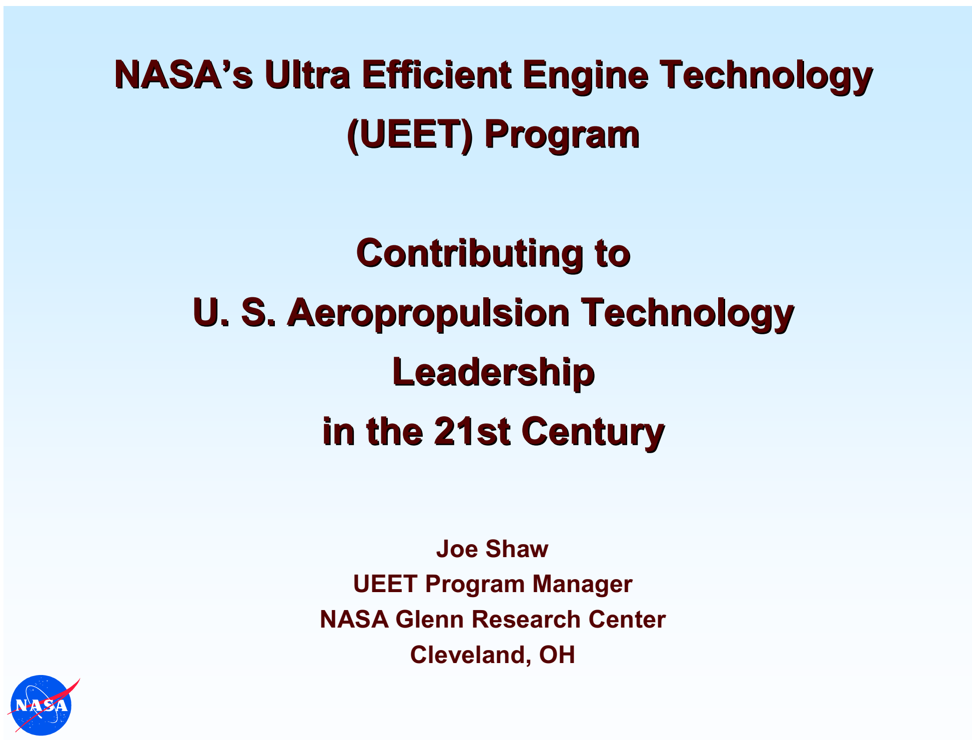
Munson, J. and Steinetz, B.M., 1994, "Specific Fuel Consumption and Increased Thrust Performance Benefits Possible with Advanced Seal Technology," AIAA-94-2700.

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.

OVERVIEW OF NASA'S UEET PROGRAM

Robert J. Shaw
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio



Program Overview

UEET Ultra Efficient Engine Technology

Vision: ***Develop and hand off revolutionary turbine engine propulsion technologies that will enable future generation vehicles over a wide range of flight speeds.***

Goals:

Propulsion technologies to enable increases in system efficiency and, therefore, fuel burn reductions of up to 15 % (equivalent reductions in CO_2)

Combustor technologies (configuration and materials) which will enable reductions in LTO* NO_x of 70% relative to 1996 ICAO standards.

** LTO - Landing/Take-off*

Vision

UEET Ultra Efficient Engine Technology

Develop and hand off revolutionary propulsion turbine engine technologies that will enable future generation vehicles over a wide range of flight speeds.

We support the vision and are committed to the success of NASA's Ultra Efficient Engine Technology (UEET) Program.

Richard Hill, Air Force Research Laboratory

Gerald Brines, Allison-Rolls Royce

Mahmood Naimi, Boeing Commercial Airplane Company

Fred Krause, General Electric Aircraft Engines

Dimitri Mavris, Georgia Tech

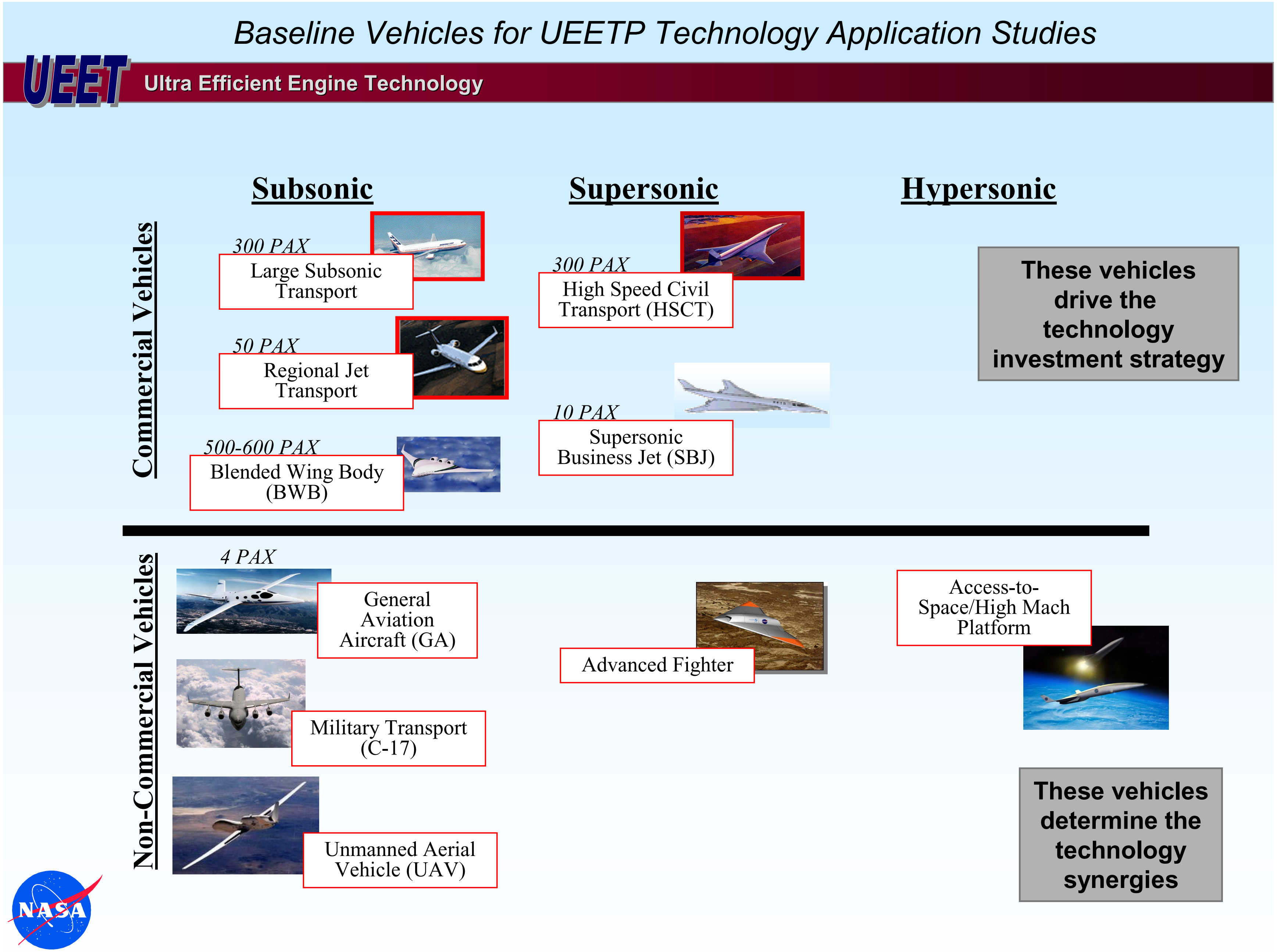
Vinod Nangia, Honeywell

Jeffrey W. Hamstra, Lockheed-Martin

Robert J. Shaw, NASA Glenn Research Center

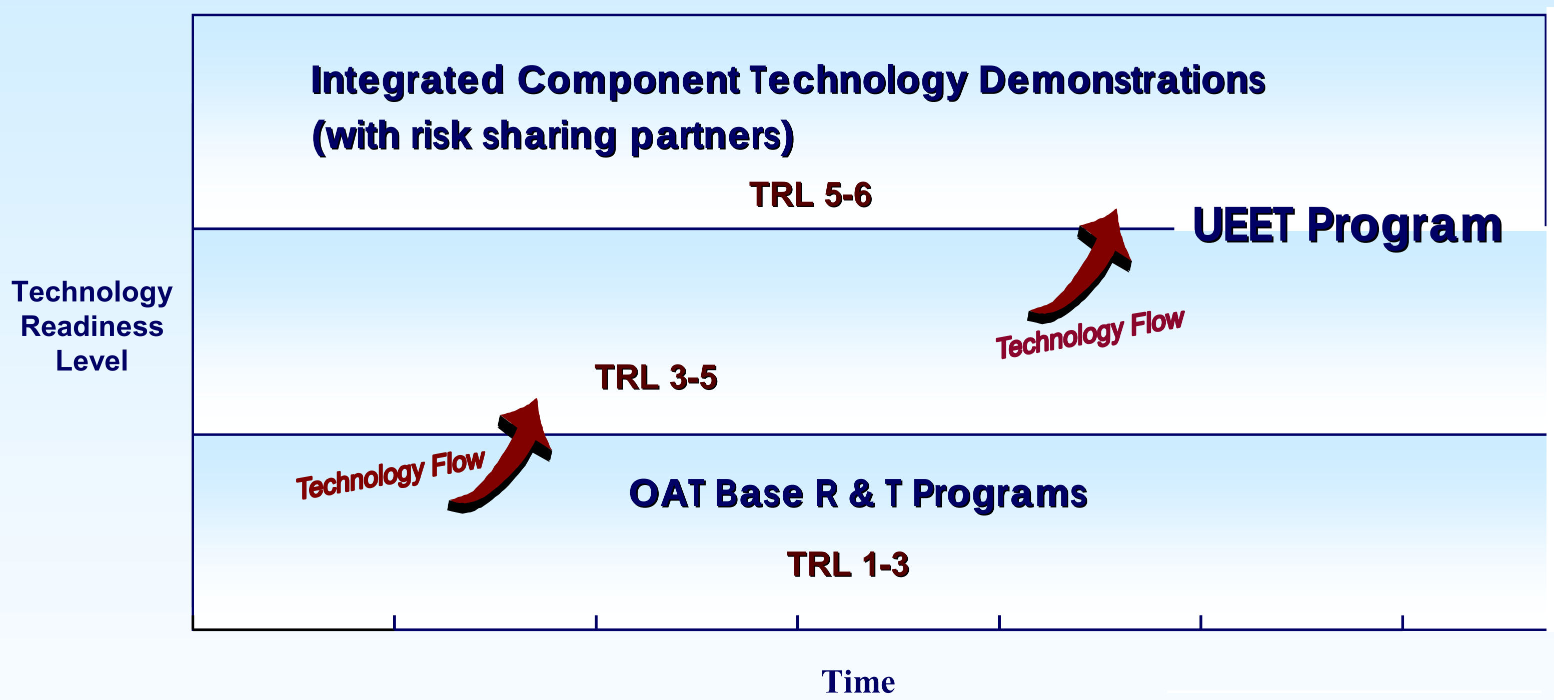
Robert D. Southwick, Pratt & Whitney

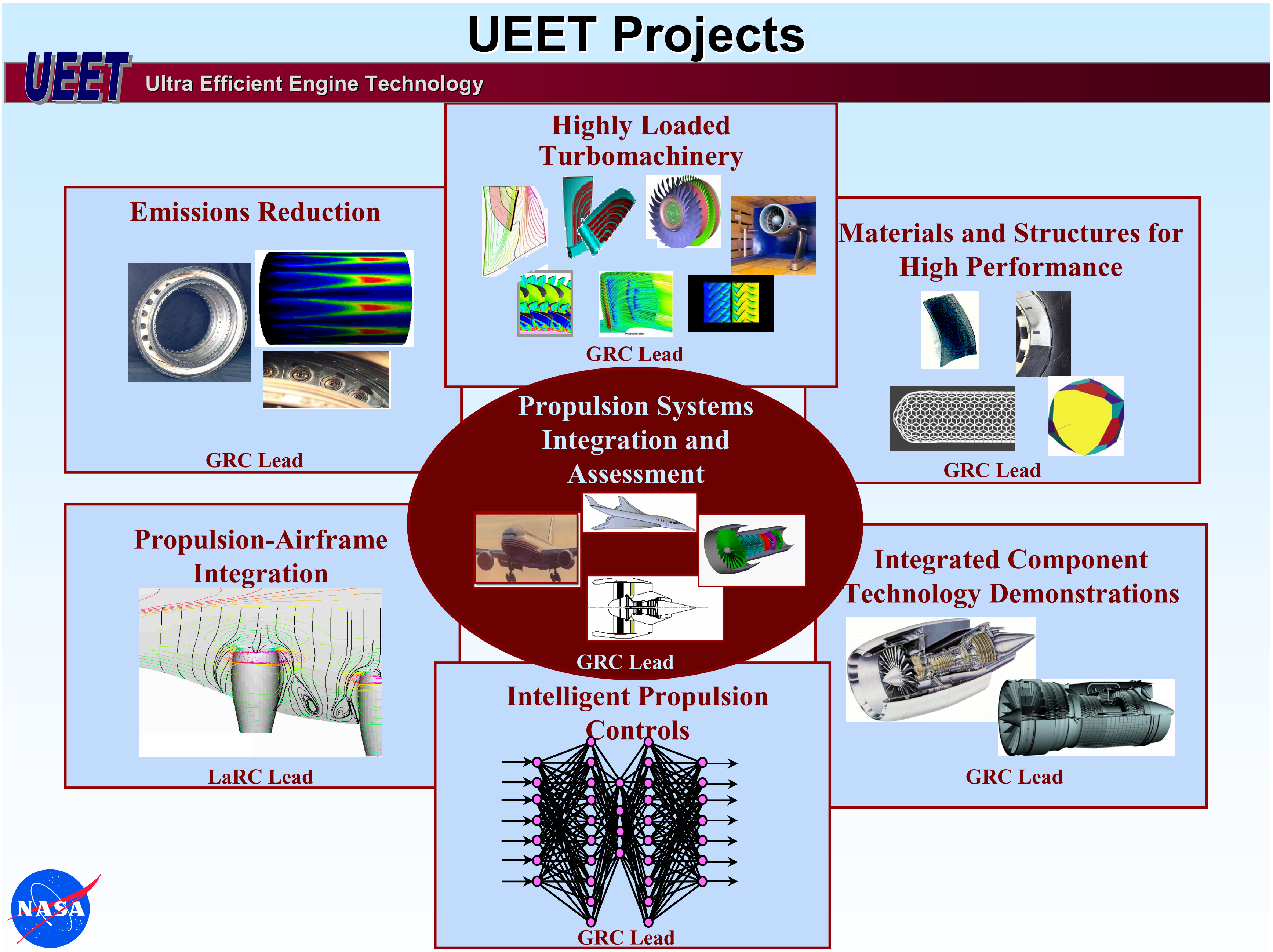
Scott Cruzen, Williams International


Baseline Vehicles for UEETP Technology Application Studies
UEET
Ultra Efficient Engine Technology
Subsonic
Supersonic
Hypersonic
Commercial Vehicles
300 PAX
Large Subsonic Transport
50 PAX
Regional Jet Transport
500-600 PAX
Blended Wing Body (BWB)
300 PAX
High Speed Civil Transport (HSCT)
10 PAX
Supersonic Business Jet (SBJ)
These vehicles drive the technology investment strategy
Non-Commercial Vehicles
4 PAX
General Aviation Aircraft (GA)
Military Transport (C-17)
Unmanned Aerial Vehicle (UAV)
Advanced Fighter
Access-to-Space/High Mach Platform
These vehicles determine the technology synergies
NASA

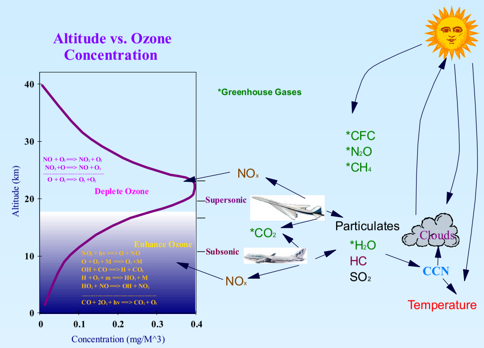
Program Hierarchy

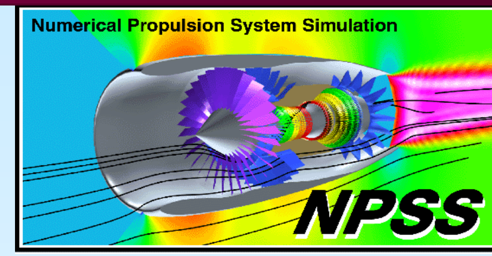
UEET Ultra Efficient Engine Technology




UEET Projects
UEET
Ultra Efficient Engine Technology
Highly Loaded Turbomachinery
GRC Lead
Emissions Reduction
GRC Lead
Materials and Structures for High Performance
GRC Lead
Propulsion Systems Integration and Assessment
GRC Lead
Propulsion-Airframe Integration
LaRC Lead
Integrated Component Technology Demonstrations
GRC Lead
Intelligent Propulsion Controls
GRC Lead
NASA

UEET Ultra Efficient Engine Technology





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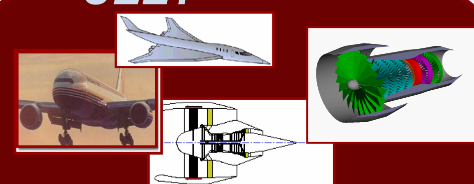
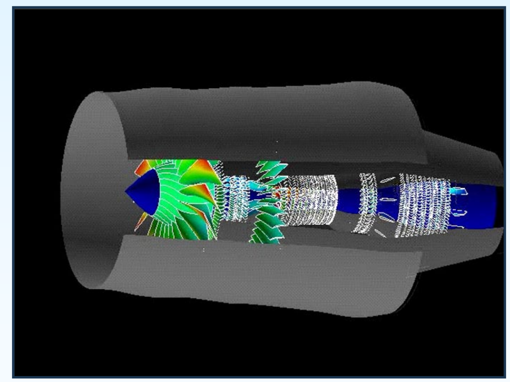


Propulsion Systems Integration & Assessment Project



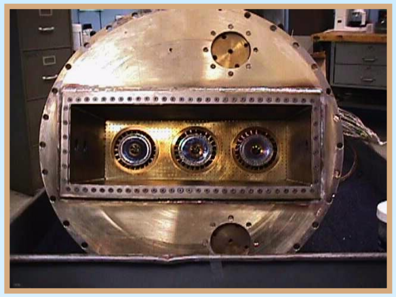
Provide system level guidance for programmatic decision making

- System trade studies
- Technology assessments (metrics tracking and rollup)

Assess the effects of engine exhaust products on the atmosphere and humans

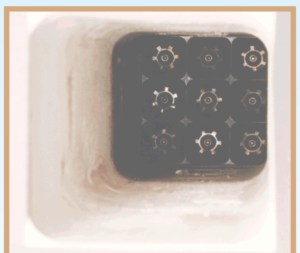
Perform high fidelity system simulations to reduce experimental testing required and predict characteristics of future turbine engine propulsion systems

UEET Ultra Efficient Engine Technology



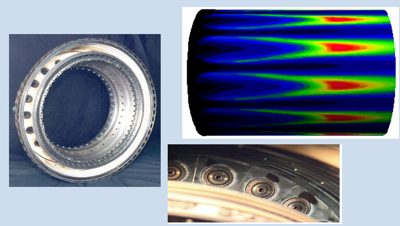
Annular rig

Engine validation
(partnership with industry)

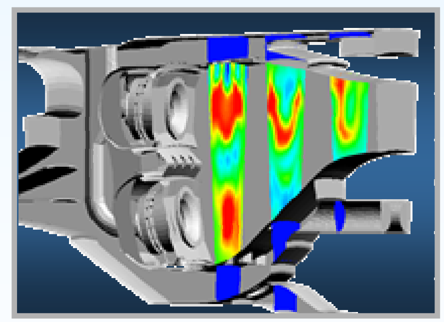


Flame tube

UEET

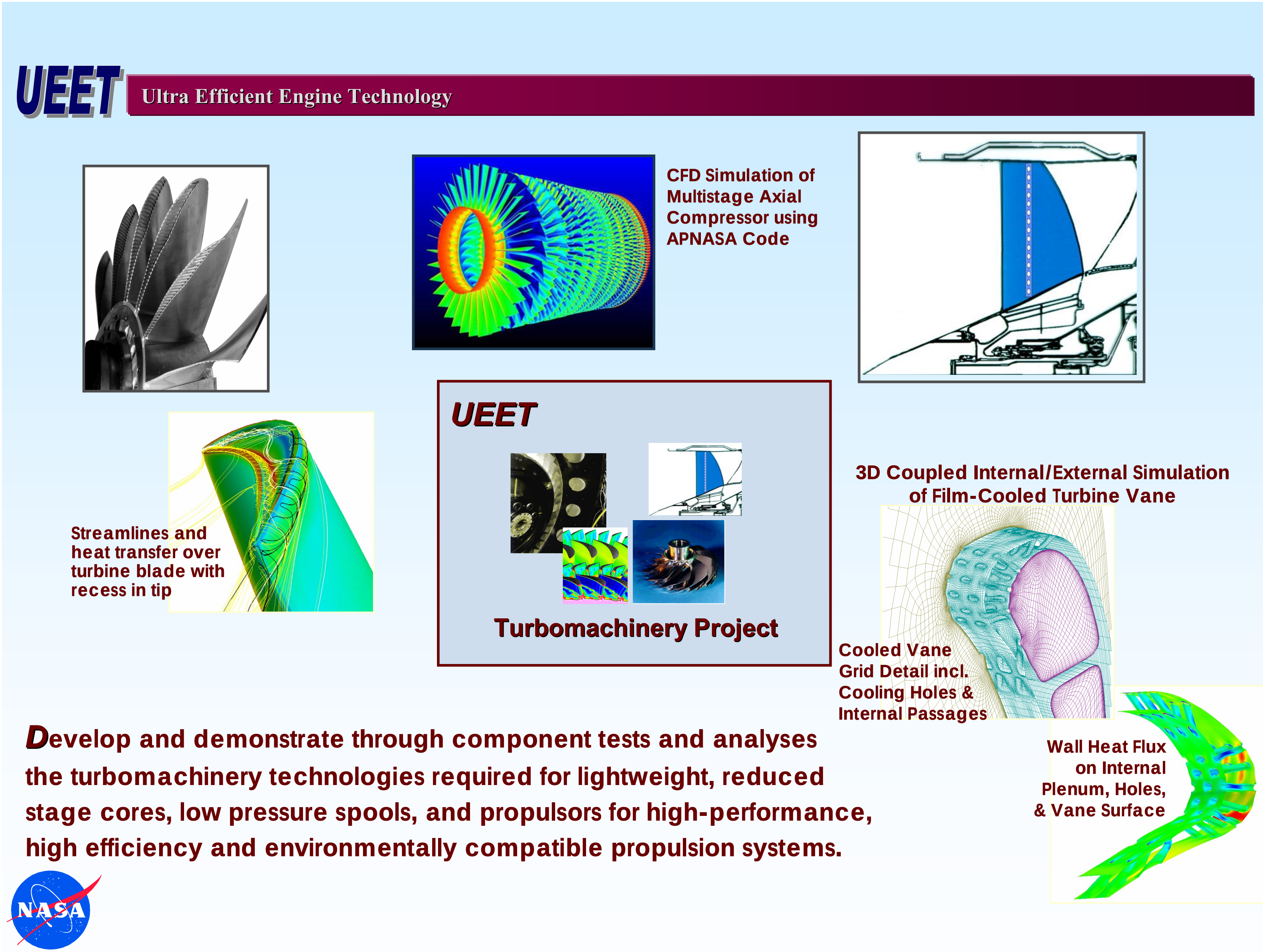


Combustion Project

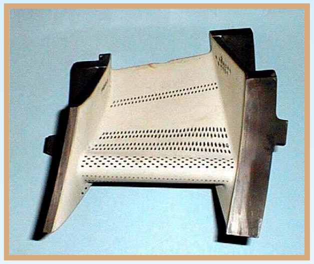


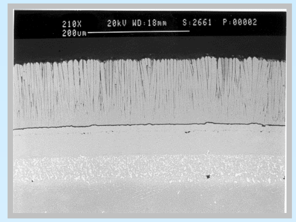
***W**ork with the U. S. industry to provide technology readiness to reduce combustion emissions of future aircraft:*

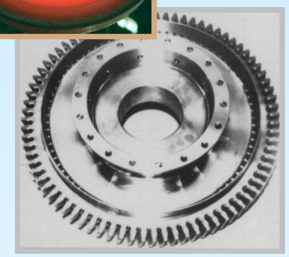
- *70% LTO NO_x reduction for large and regional subsonic engines*
- *Ultra low levels of cruise NOx for supersonic aircraft*
- *Validated combustor analysis and design codes*


UEET
Ultra Efficient Engine Technology
CFD Simulation of
Multistage Axial
Compressor using
APNASA Code
UEET
Turbomachinery Project
Streamlines and
heat transfer over
turbine blade with
recess in tip
3D Coupled Internal/External Simulation
of Film-Cooled Turbine Vane
Cooled Vane
Grid Detail incl.
Cooling Holes &
Internal Passages
Wall Heat Flux
on Internal
Plenum, Holes,
& Vane Surface
Develop and demonstrate through component tests and analyses the turbomachinery technologies required for lightweight, reduced stage cores, low pressure spools, and propulsors for high-performance, high efficiency and environmentally compatible propulsion systems.
NASA

UEET Ultra Efficient Engine Technology







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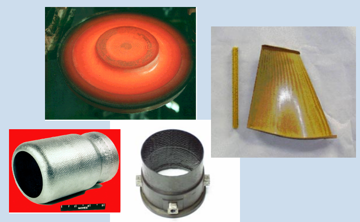
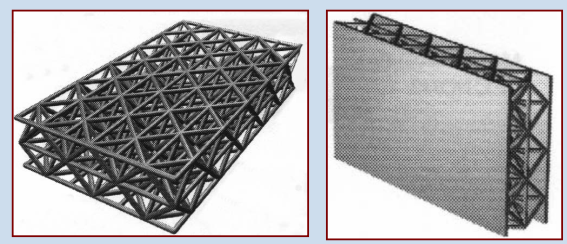


Materials and Structures Project

Develop and demonstrate high temperature engine material systems which will enable future high performance, environmentally compatible turbine engine propulsion systems

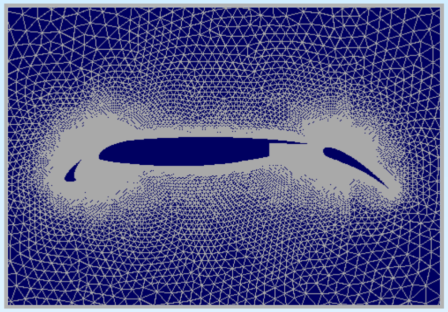
- Ceramic matrix composite (CMC) combustor liner
- CMC turbine vane
- Turbomachinery disk and turbine airfoil

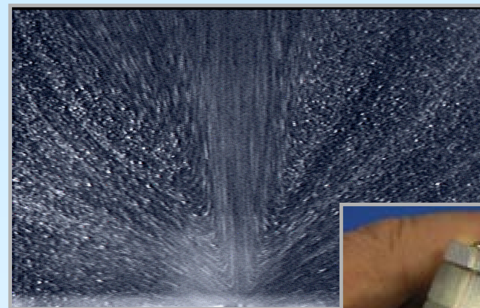
Develop innovative low weight structural concepts

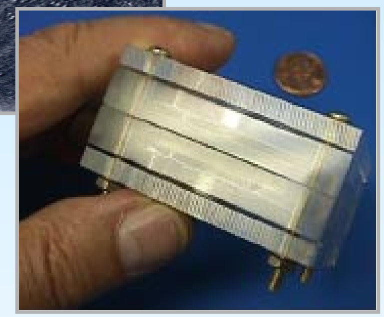


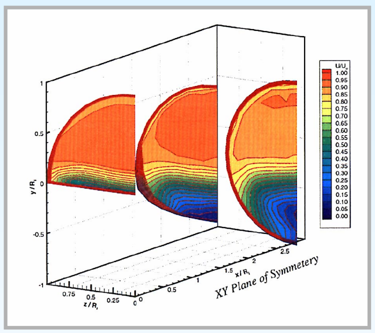
UEET

Ultra Efficient Engine Technology

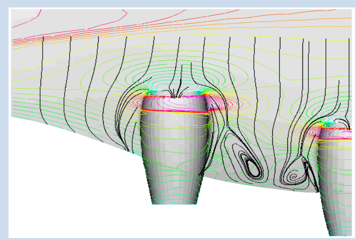




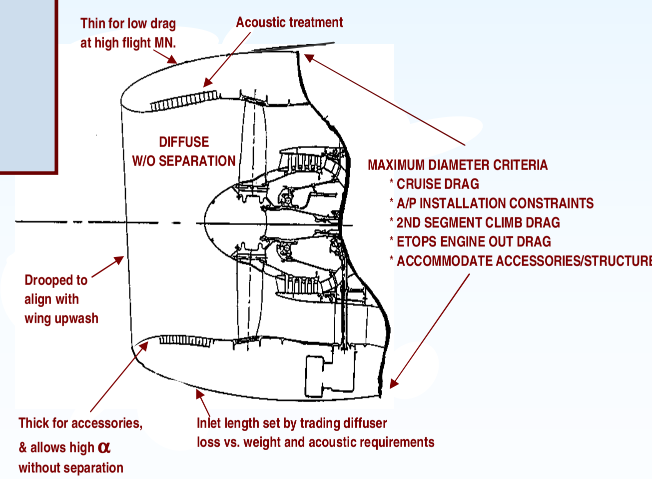




UEET



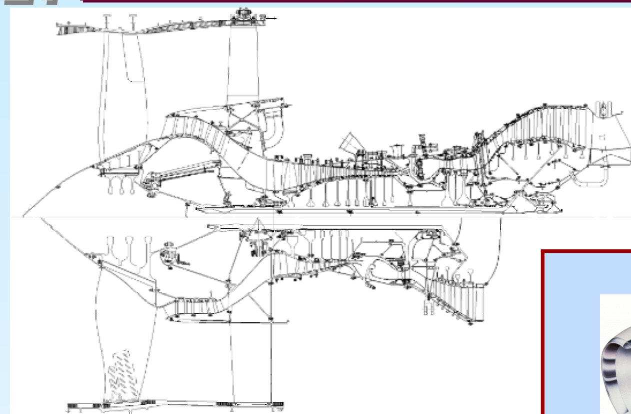
Propulsion/Airframe Integration Project

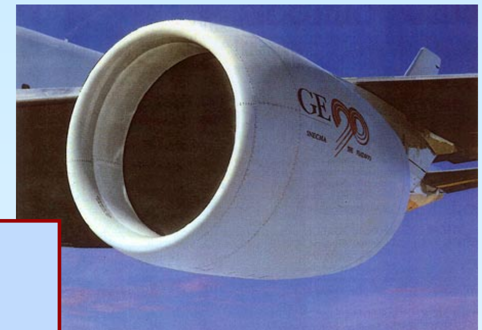


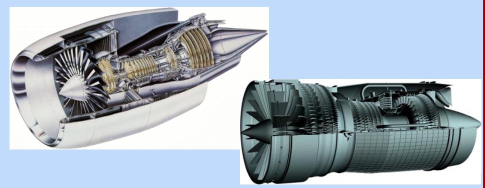
Develop and demonstrate technologies which will enable low drag, high performance propulsion system integration for a wide range of vehicle classes

- **Validated, rapid turnaround design tools**
- **Active flow control**
- **Active shape control**

UEET Ultra Efficient Engine Technology





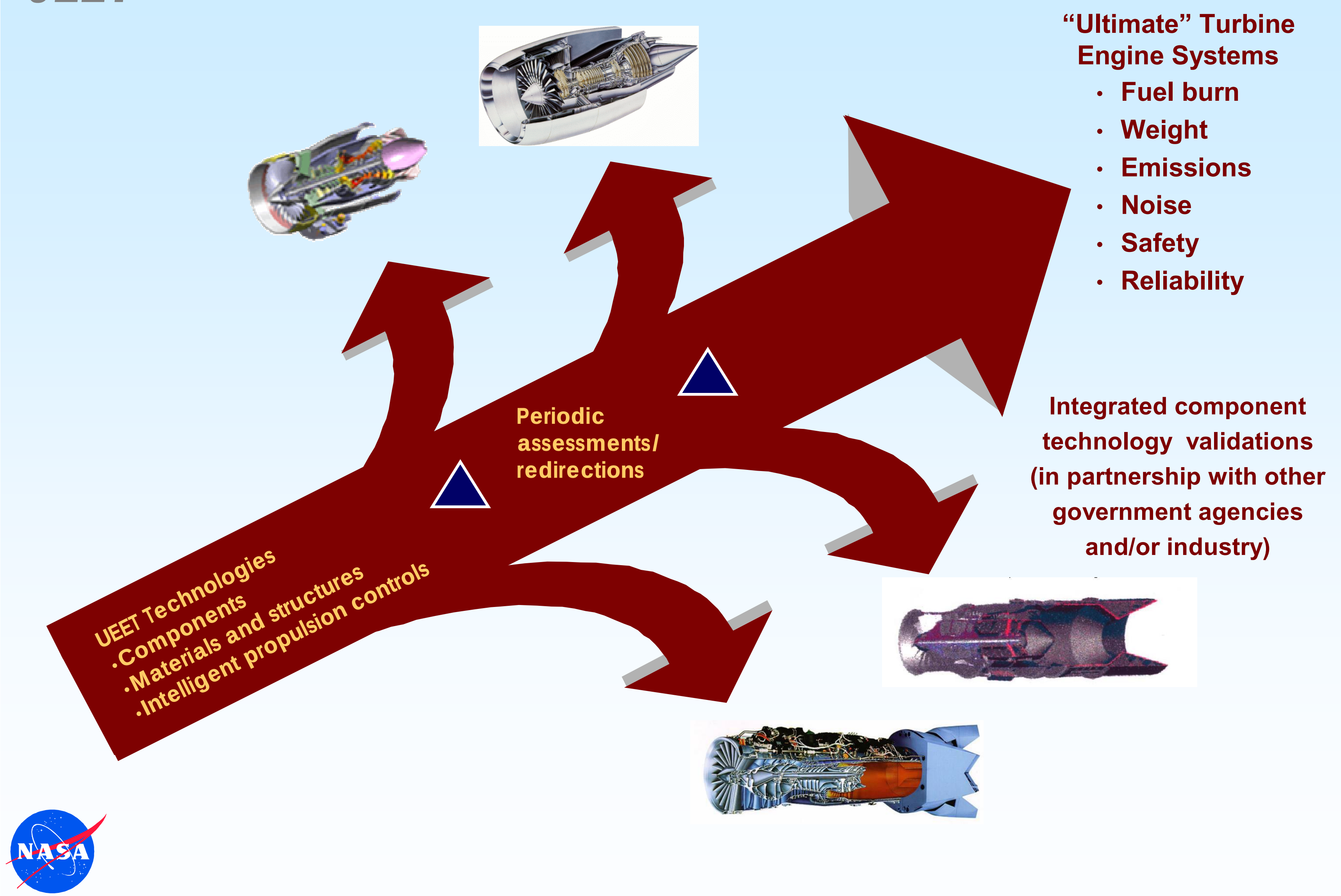


Integrated Component Technology Demonstrations Project

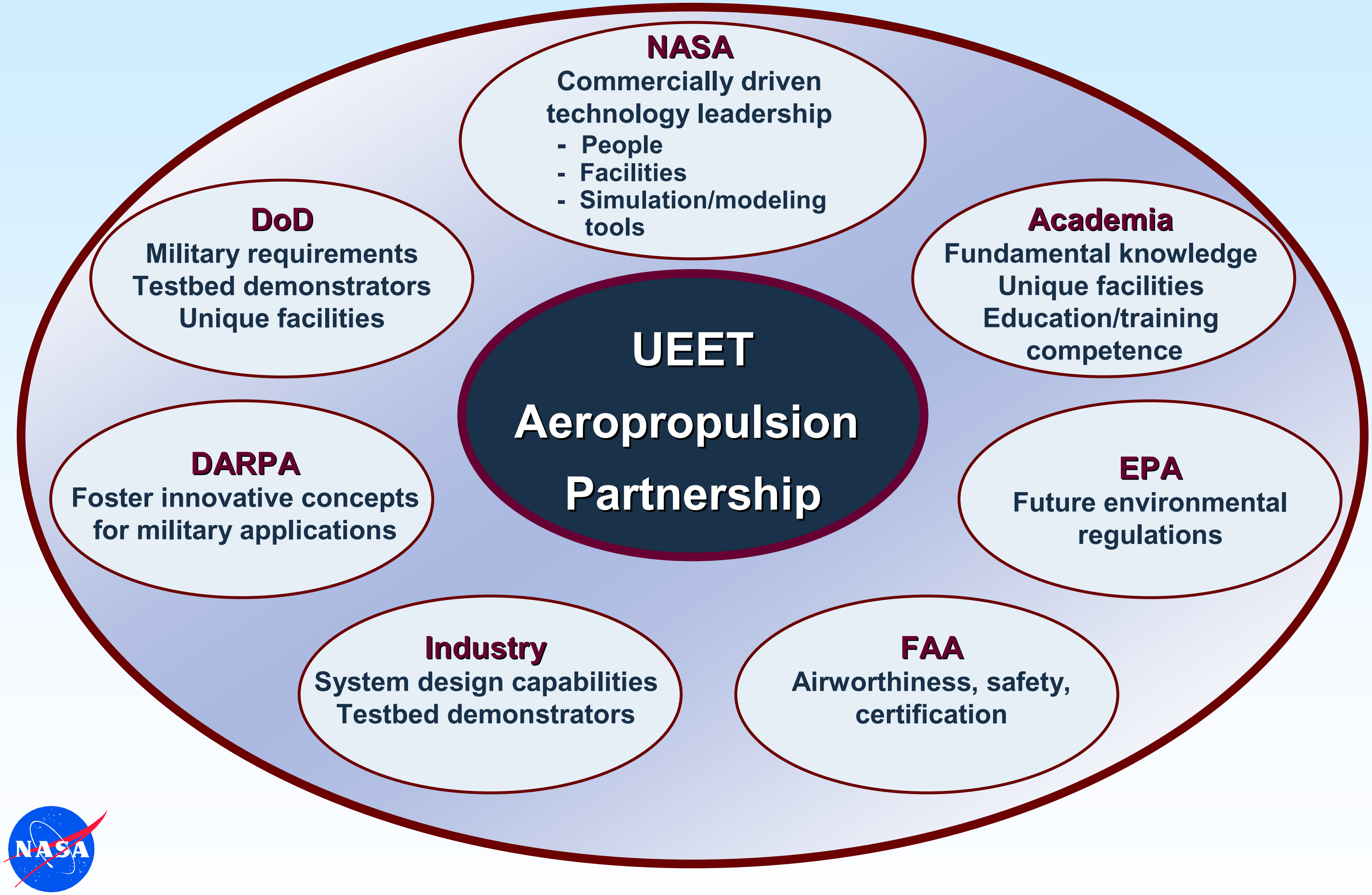
- NASA / DOD / U.S. industry a means to conduct technology demonstration tests of advanced turbine engine components and materials as part of an integrated system (TRL 6).
- Assessment of NASA and contractor technologies for demo program consideration.
- Significant technology risk reduction.
- Confidence in advanced technologies to facilitate incorporation in follow-on product insertion programs.

The UEET "Roadmap"

UEET Ultra Efficient Engine Technology



Each Partner Brings Unique Strengths to the National Partnership



Concluding Remarks

UEET Ultra Efficient Engine Technology

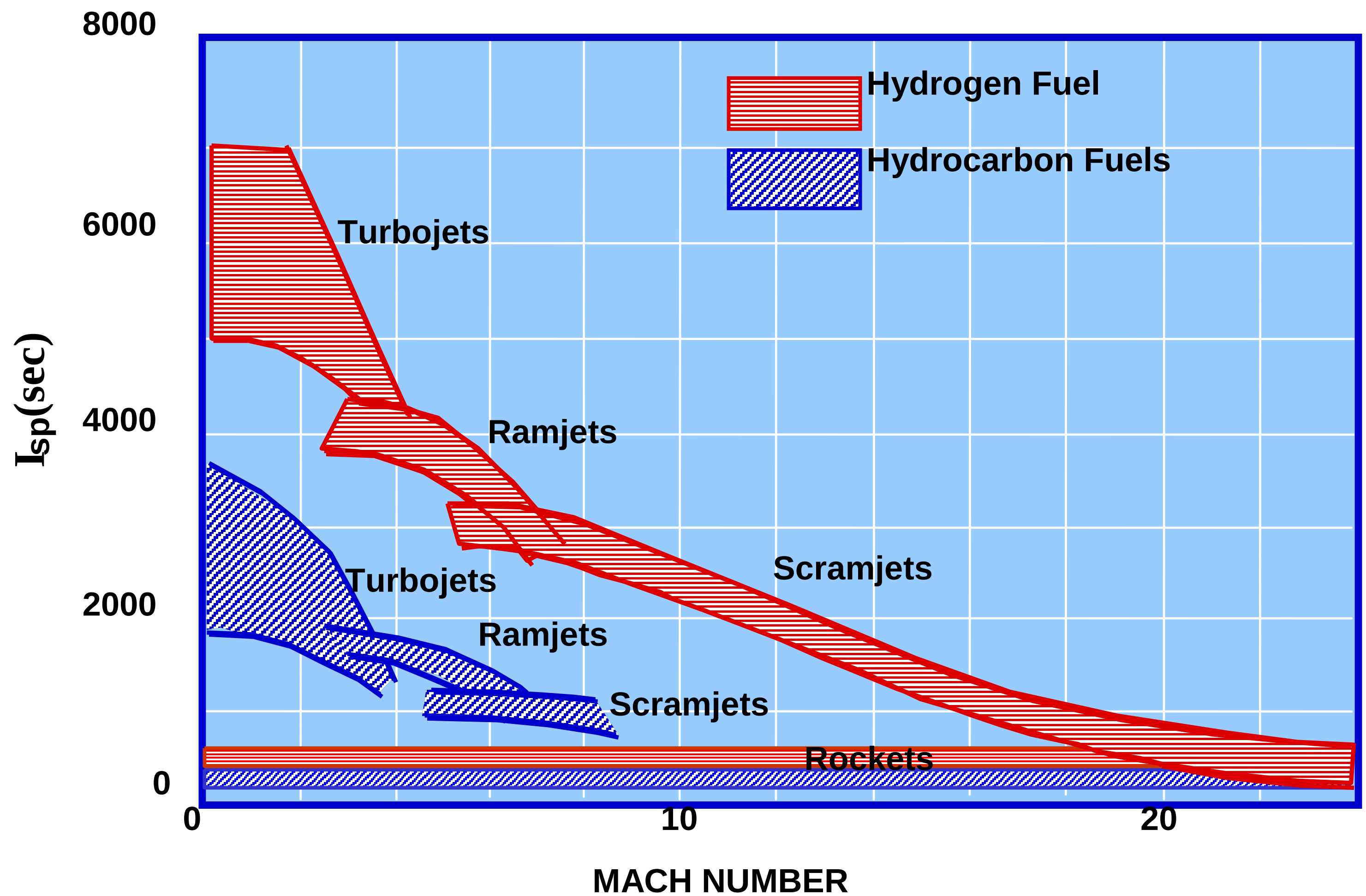
- The UEET Program will provide the revolutionary technologies needed to enable future turbine engine propulsion systems for a wide variety of aerospace vehicles.
- Systems requirements studies done with the U.S. Industry and Academia will provide key inputs to determining the long term direction for the program.
- The UEET Program content will be adjusted on a regular basis so as to pursue the highest payoff technology set.
- The UEET Program will partner wherever appropriate with NASA Base R&T Programs to transition technologies.
- The UEET Program will actively seek partners to carry the technologies to a TRL6 to enable timely transitions to future industry application specific designs.

NASA'S ADVANCED SPACE TRANSPORTATION PROGRAM—RTA PROJECT SUMMARY

Paul Bartolotta and Nancy McNelis
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Why Turbine Accelerators

Advanced Space Transportation Program



TBCC Interrelationships

Advanced Space Transportation Program

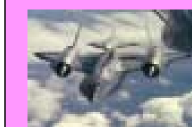
Turbine Based System : Key to Enabling Tomorrow's Propulsion Systems

Access to Space

Space Shuttle

- $10,000/lb payload (Goal : $100/lb)
- Long Turn Around Time
- High Maintenance
- Re- usability <20 missions
- Limited Launch & Landing sites
- 8- 10 missions per year

Military



SR71

- Max. Mach = 3+
- Thrust/Weight = 4 (low)
- Maintenance High
- Elaborate Lubricants
- Durability Low

Air Travel

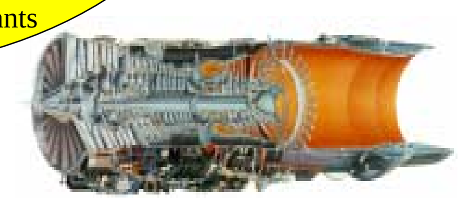
Concorde

- Max Mach = 2.
- $/Passenger: high (London to NY: $10,000)
- Sonic Boom

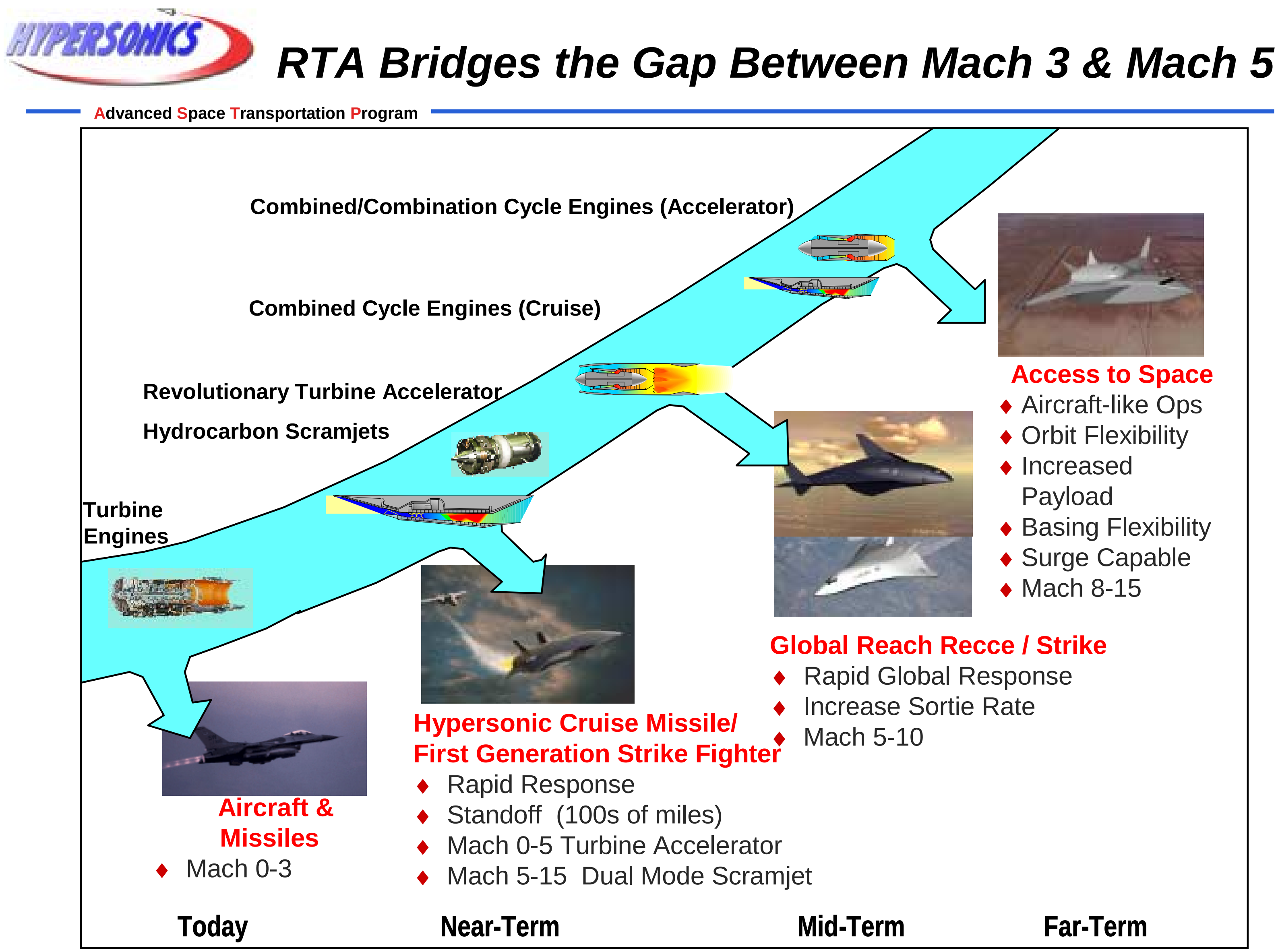
TBCC Features

Quick Turn Around Time (Airline like Operations)
Re- useable > 1000 missions
Versatile Usage & Launch and Landing sites
Low Maintenance
High Durability
1000's of Flights per Year
Mach >4
Thrust/Weight > 10
Cost: $ /lb Payload Low
Conventional Fuels & Lubricants

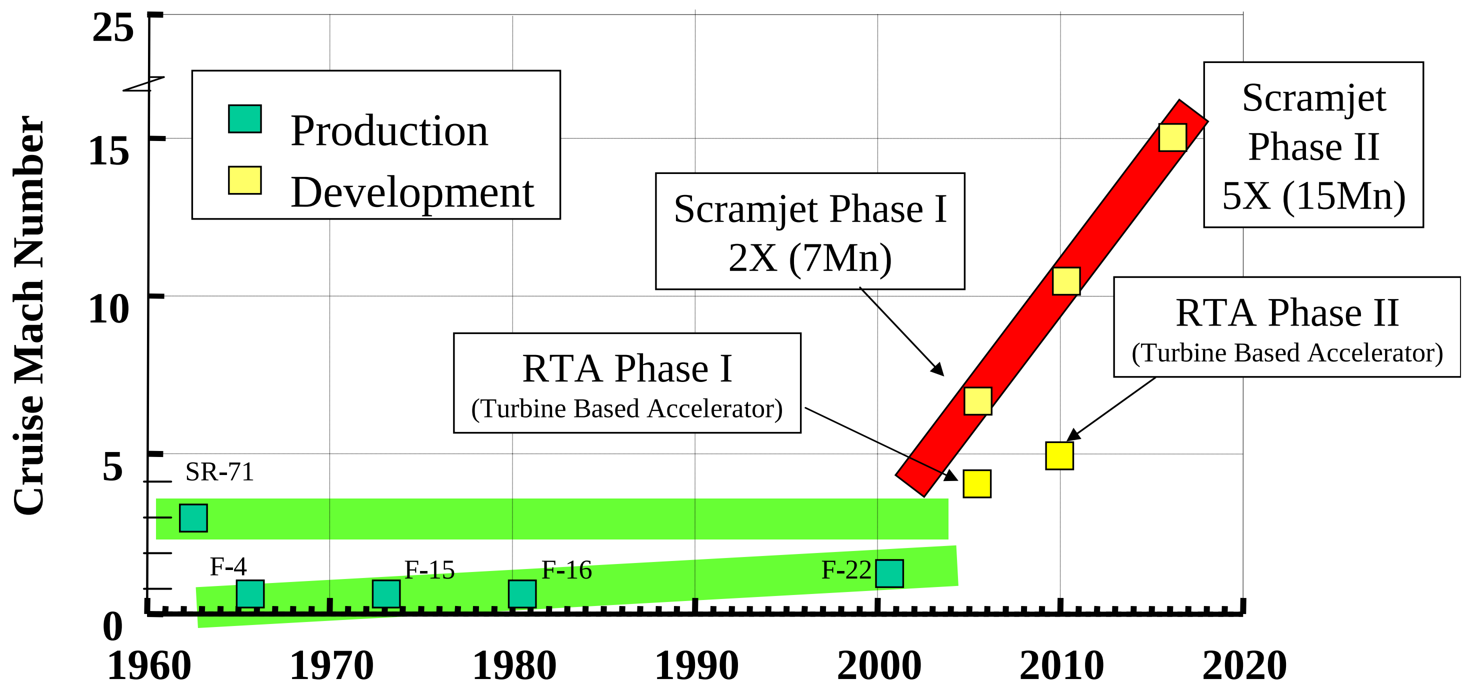
Future



RTA Bridges the Gap Between Mach 3 & Mach 5



A Paradigm Shift For Mach Number

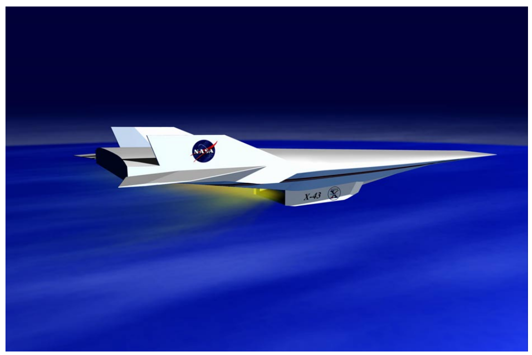


Airbreathing Propulsion Class, Baseline SR-71

HYPERSONICS

Advanced Space Transportation Program

Turbine Base Combination Cycle (TBCC)



- **Single Stage To Orbit (SSTO)**
  - Turbine Accelerator Integrated with Dual Mode Scram Jet in Combined Flow Path
  - Over/under Configuration
  - Hyper-X type vehicle (Baseline)

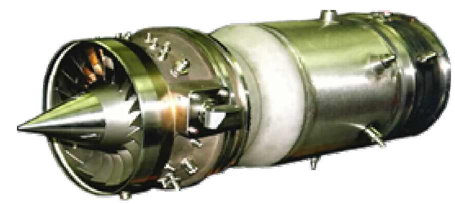
- **Technology Challenges** *(T/W 15-20)*
  - Turbine Accelerator
  - Shared Inlet
  - Dual Fuel (H/C & H2) in Single Vehicle
  - Transition Mode
  - Shared Mixer Ejector & Nozzle
  - Thermal Management
  - PAI

- **Two Stage To Orbit (TSTO)**
  - First Stage:
    Turbine Accelerator with Afterburner or Ram Jet
  - Second Stage:
    AB RBCC and/or Rockets

- **Technology Challenges** *(T/W 10-15)*
  - Turbine Accelerator
  - Inlet Performance
  - Staging Separation
  - Thermal Management
  - PAI

Revolutionary Turbine Accelerator (RTA)

Thrust/Weight 15-20
Mach 4-5 Capable
Long Life



- **Current State-of-the-Art**
  - J58 Mach 3+ capable engine
  - T/W =4
- **Benefits of Technology**
  - Mach 4-5 turbine accelerator
  - Simplifies ramjet/scramjet geometry (decreases weight)
  - Improves system capacity & operability
  - Improves safety, survivability, abort capability & launch flexibility
  - Increases reliability & durability
- **Technical Challenges**
  - High Mach compressor
  - Thermal management
  - Hot rotating components
  - Advanced materials
  - Propulsion/Airframe Integration
- **Participants**
  - GRC (lead), LaRC, MSFC
  - AF, NAVAIR

Advanced Space Transportation Program

RTA Project Areas of Emphasis

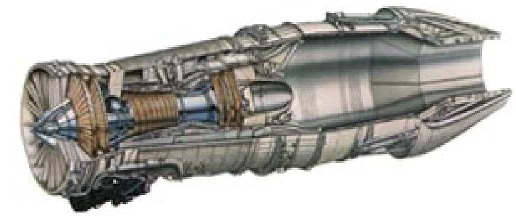
Subscale Ground Based Testbed (GBT) Demonstrator (2001-2007)

Develop & Demonstrate enabling turbine technologies required to meet ASTP objectives

Demonstrate technologies on a proper scaled ground based testbed GBT

Utilize GBT as a system to evaluate

- Advanced Turbine Technologies
- Windmilling at high Mach speeds
- The "ilities" (I.e., Operability, Reliability, Durability)

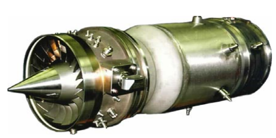


Ground Based Testbed (GBT)

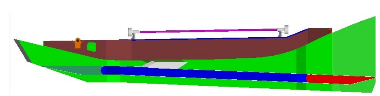
X43-B Flight Demonstration Propulsion Systems (2001-2003)

Limited design effort for TBCC system in support of X43-B downselect

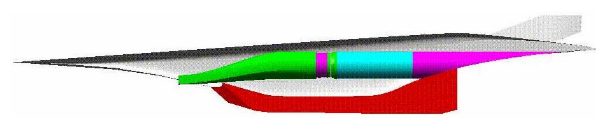
- Conceptual design of TBCC propulsion system (RTA plus Dual Mode Scramjet) that could be available for CY 2009 first flight
- Effort builds upon DoD IHPTET results
- First flight in 2009 requires a technology freeze in 2005
- If effort were continued & flown on X43-B, the PAI technology challenges will be addressed



Small-scale RTA



Dual Mode Scramjet (DMSJ)



X43-B flight demo vehicle

HYPERSONICS

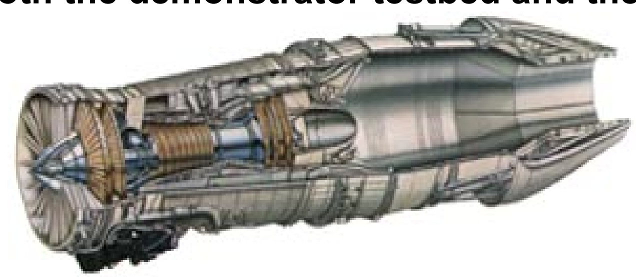
Advanced Space Transportation Program

RTA GBT Goals & Objectives

- **Mission:** Develop & demonstrate a reusable turbine based propulsion system to meet future space access requirements (i.e., lower costs & increased safety)

- **Goal:** Develop and evaluate enabling technologies that significantly lower the cost for access-to-space and increase safety by providing performance margins which insure high reliability and durability.

- **Approach:**
  1. Develop & evaluate enabling technologies to improve performance above SOA.
  2. Incorporate and evaluate new advanced technologies (from ASTP as well as UEET, IHPTET, and VAATE) as they mature.
  3. Conduct investment studies for enabling technologies specific to RTA propulsion systems and use as key input to technology selection process
  4. Design and build a mid scale RTA ground based testbed (GBT)
  5. Utilize a combination of system studies & simulations to project propulsion system performance characteristics for both the demonstrator testbed and the full-scale vision propulsion system.



UEET: Ultra Efficient Engine Technology program
IHPTET: Integrated High Pressure Turbine Engine Technology program
VAATE: Versatile Affordable Advanced Turbine Engine program

Summary

Advanced Space Transportation Program

- **Advantages of Turbine Based Combined Cycle**
  - *High ISP at M<5*
  - *Re-Useable w/ Versatile Launch & Landing*
  - *Quick Turn Around Time (Aircraft Like Operations)*
  - *Robust, Low Maintenance & Provides Performance Margins*
- **Critical Technologies Identified & Tech Development & Demo Plans Initiated**
  - *Thermal Management*
  - *High Mach Capable Components*
  - *Materials and Structures*
  - *Operations / Systems*
- **RTA Project 2-Phase Approach**
  - *Ground Test Bed to Evaluate & Demonstrate Advanced Technologies, Operability and Performance, Reliability, and Durability – **FY 06***
  - *TBCC Flight Demo (X43B w/ over/under configuration) – **FY 09 (Unfunded)** to Demonstrate Integration & Transition of High Speed & Low Speed Propulsion Systems and Critical Propulsion / Airframe Integration Issues*
- **Success Dependent on Integrated / Coordinated Industry / Govt Teaming**
  (Airframer / Engine Contractor / System Analysis / Research / Testing / etc)

ASPIRATING SEAL GE90 TEST

Thomas W. Tseng
General Electric Aircraft Engines
Cincinnati, Ohio

Alan D. McNickle
Stein Seal Company
Kulpsville, Pennsylvania

Bruce M. Steinetz
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Norman Turnquist
General Electric Corporate Research and Development
Niskayuna, New York

2001 NASA Seal/Secondary Air System Workshop October 30-31, 2001 at GRC

Aspirating Seal GE90 Test

Aspirating Seal GE90 Test

Tom Tseng
GE Aircraft Engines
Cincinnati, Ohio

A.D . McNickle
Stein Seal Company
Kulpsville, Pennsylvania

Bruce Steinetz
NASA John H. Glenn Research Center
at Lewis Field
Cleveland, Ohio

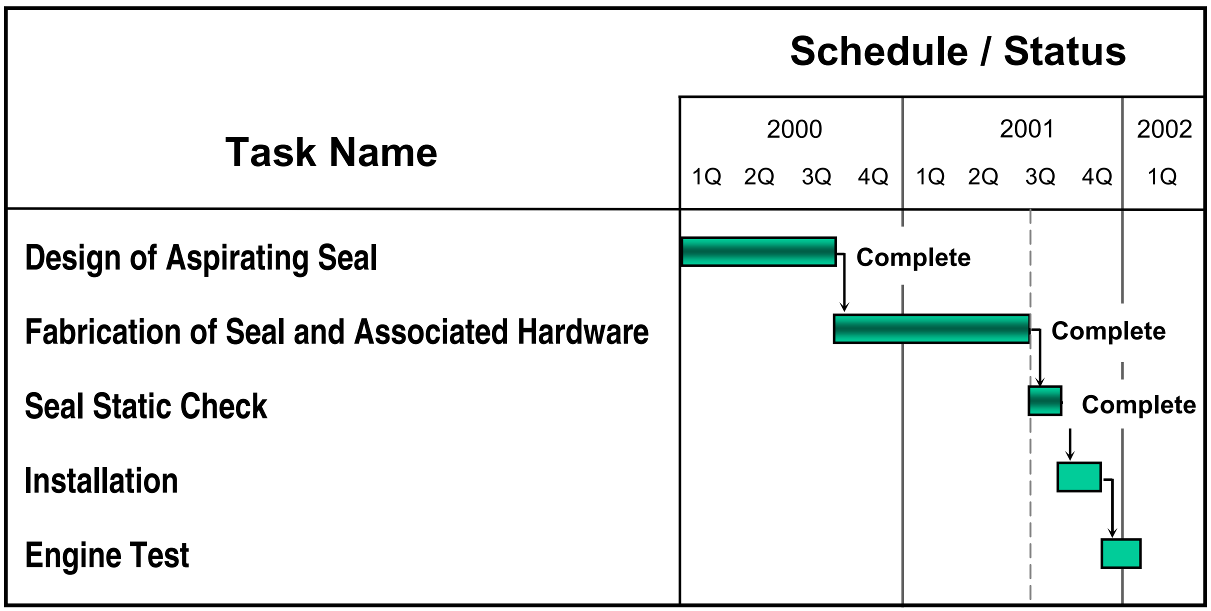
Norman Turnquist
GE Corporate Research and Development
Niskayuna, New York

Aspirating Seal GE90 Test

Objective: Complete the Development of the Aspirating Seal for Engine Applications by Demonstrating the Seal in the GE90 Engine After Rig Verification

Payoffs:

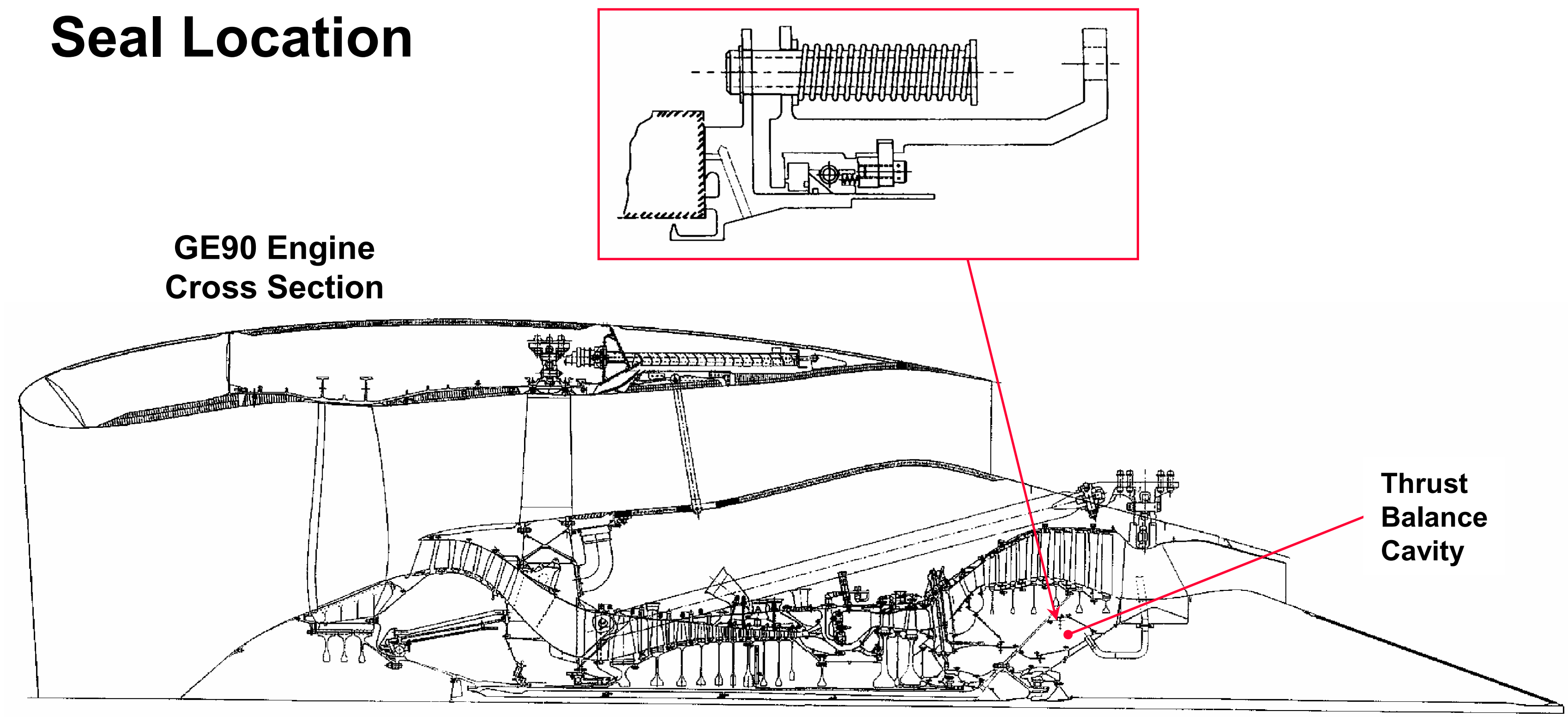
- **Leakage <1/5th Labyrinth Seal**
- **Operates Without Contact for Long Life.**
- **Decreases SFC by 1.86% and DOC+I by 0.69% for Three Locations**



Supports Level 1 Milestone: Aspirating Seal Demonstration (March 2002)

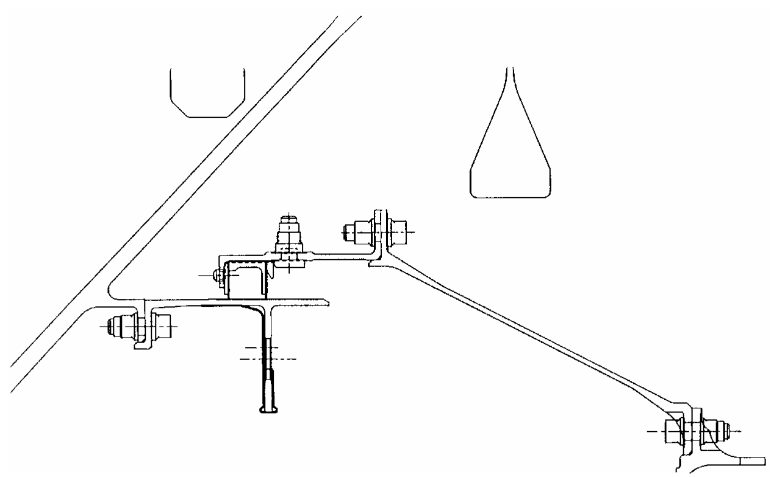
Aspirating Seal GE90 Test

Seal Location

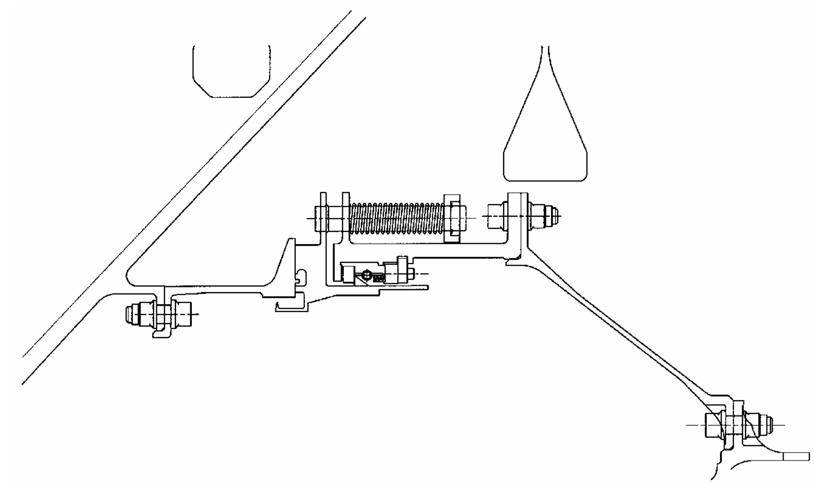


Aspirating Seal GE90 Test

Seal Position



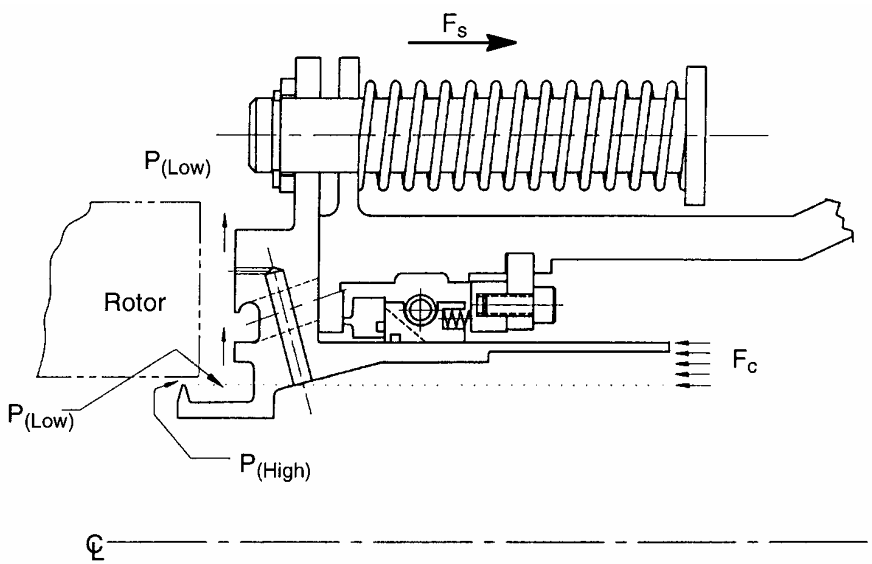
Production



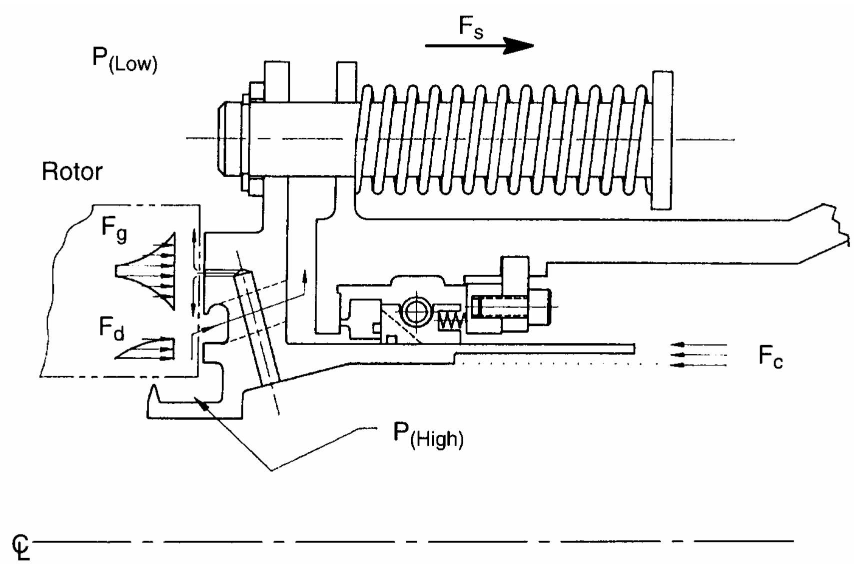
Aspirating Seal

Aspirating Seal GE90 Test

Aspirating Seal



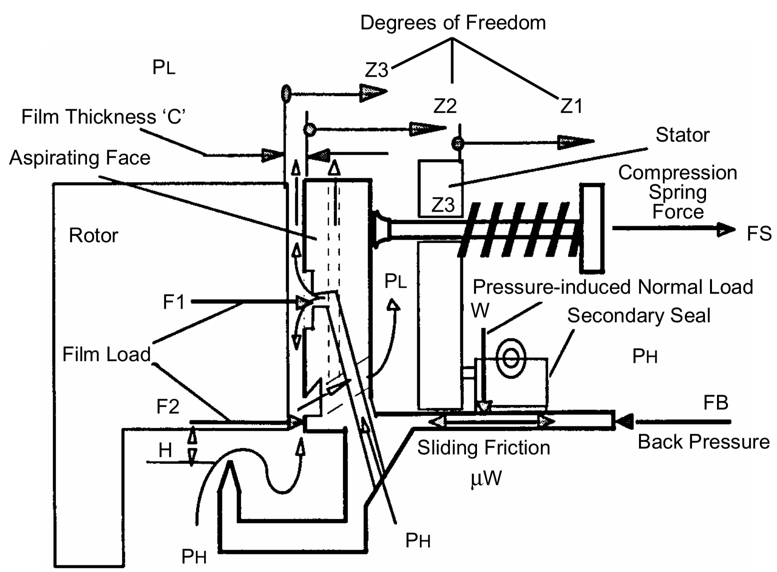
Aspirating Seal at Shutdown Phase



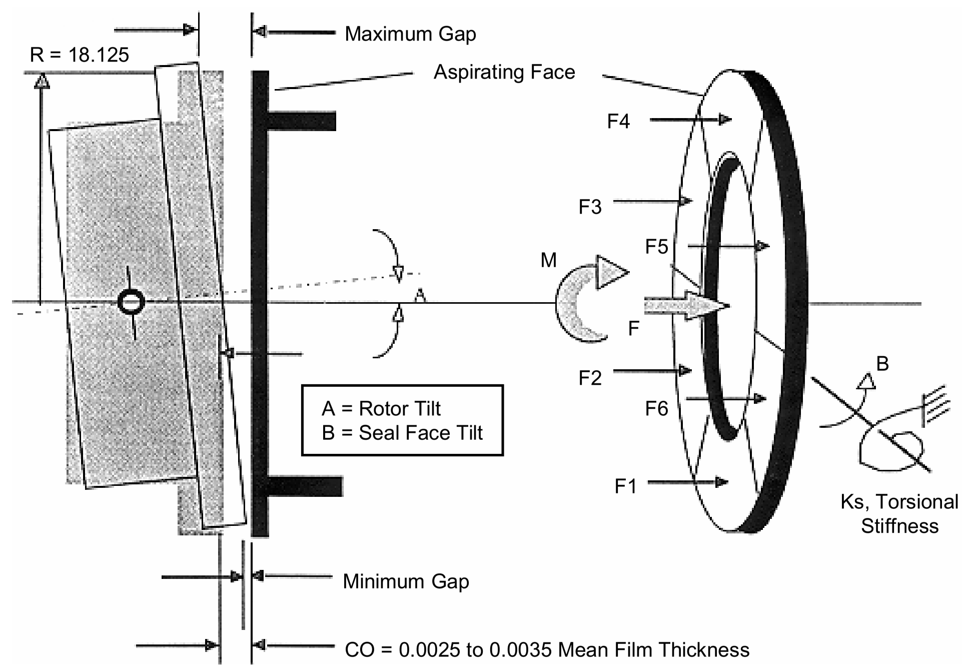
Aspirating Seal at Steady-State Operation

Aspirating Seal GE90 Test

Seal Analytical Model



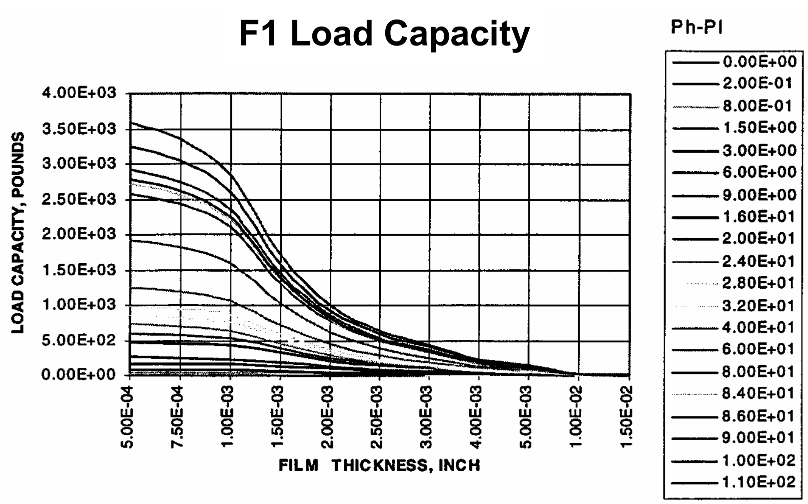
Transient Dynamic Model of an Aspirating Face Seal



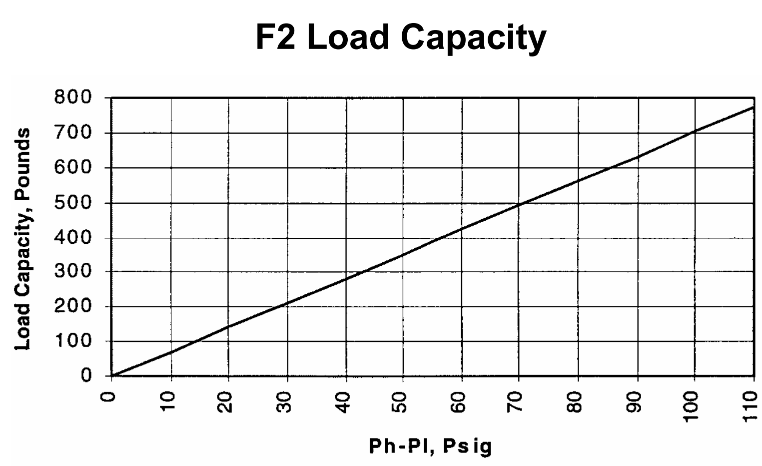
Tilt Analysis of an Aspirating Seal

Aspirating Seal GE90 Test

Seal Analytical Model



Variation of Load Capacity, F1, of the Main Hydrostatic Film Bearing with Film Thickness and Pressure Drop

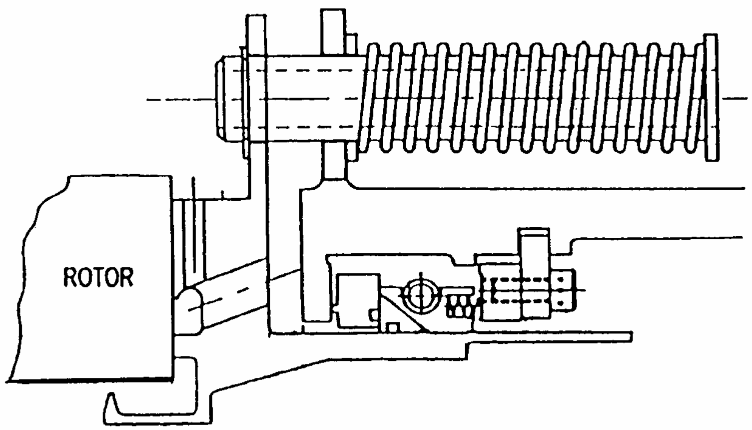


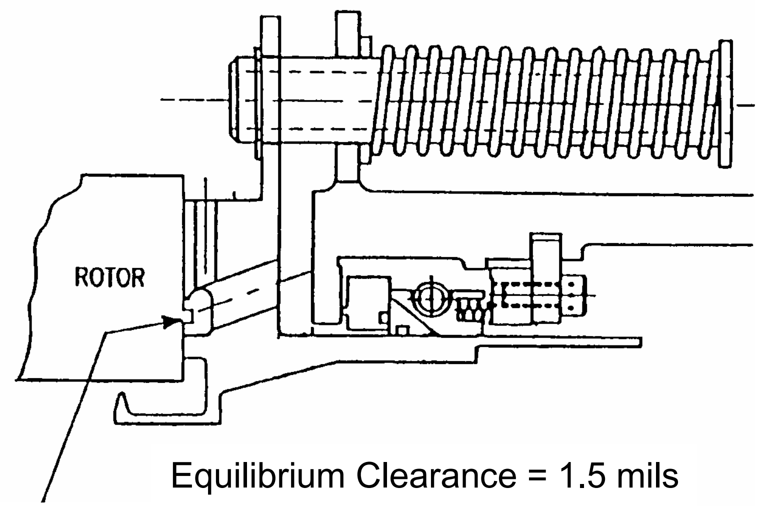
Variation of Load Capacity, F2, at the Seal Dam with Pressure Drop

Note: Loads were Derived from SCISEAL.

Aspirating Seal GE90 Test

Seal / Rotor Configurations





Flow Deflector Eliminates the Mixing of Flows from Air Dam and Air-bearing Regions.

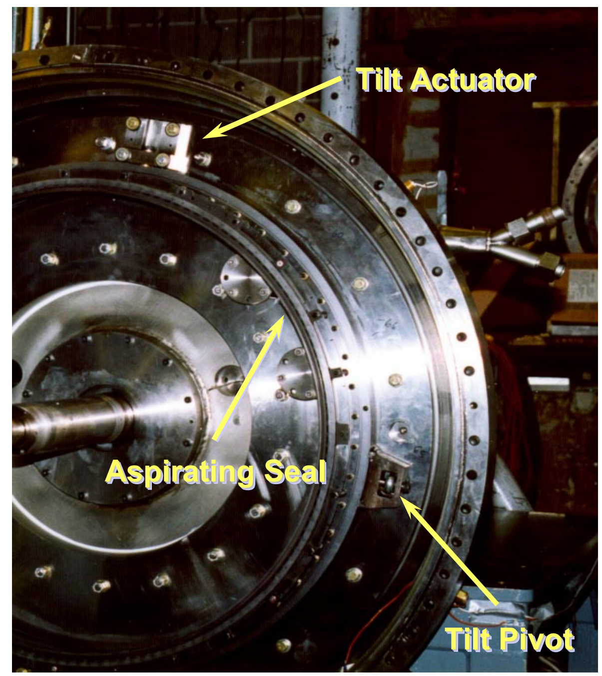
- Mixing Flows Produce Excessive Pressure within Air-bearing Region

Aspirating Seal GE90 Test

List of Accomplished Aspirating Rig Verification Tests

- 15-inch Diameter Subscale Tests
  - 1000 hours Endurance Test
    (760 fps, 1000°F, 99 psid)
  - Dust Ingestion Test
    (400 fps, Room Temperature, 100 psid)

- 36-inch Diameter Full-scale Rig Tests
  (400 fps, Room Temperature, 100 psid)
  - Start / Stop Cycles
  - Runner Axial Face Runout: 5 and 10 mils
  - Simulated Maneuver Tilt

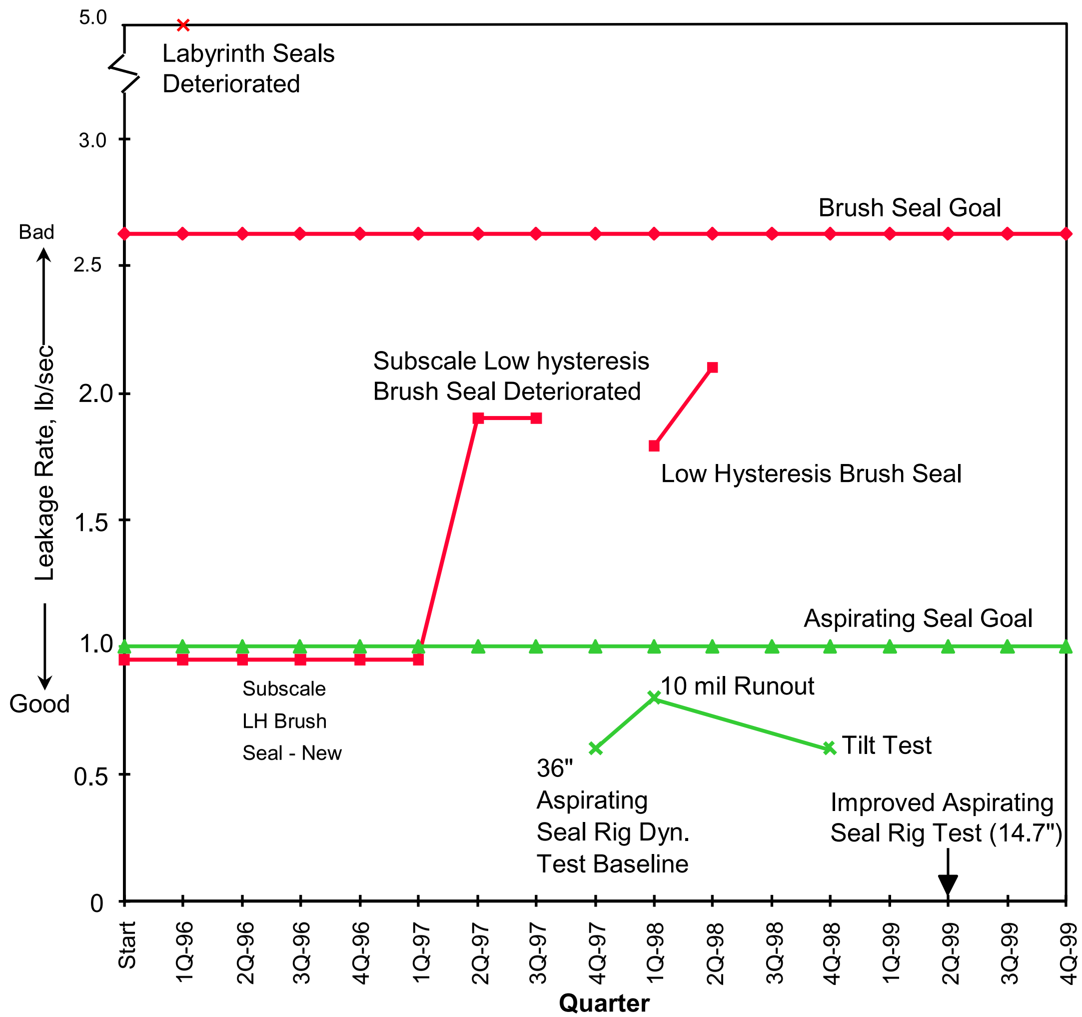


Full-scale Rig

2001 NASA Seal/Secondary Air System Workshop October 30-31, 2001 at GRC

Aspirating Seal GE90 Test

Seal Performance Comparison



Aspirating Seal

- Met Seal Leakage Goal
- Exhibited Less than Half Deteriorated Brush Seal Leakage
- Non-contacting Operation Provides for No Deterioration

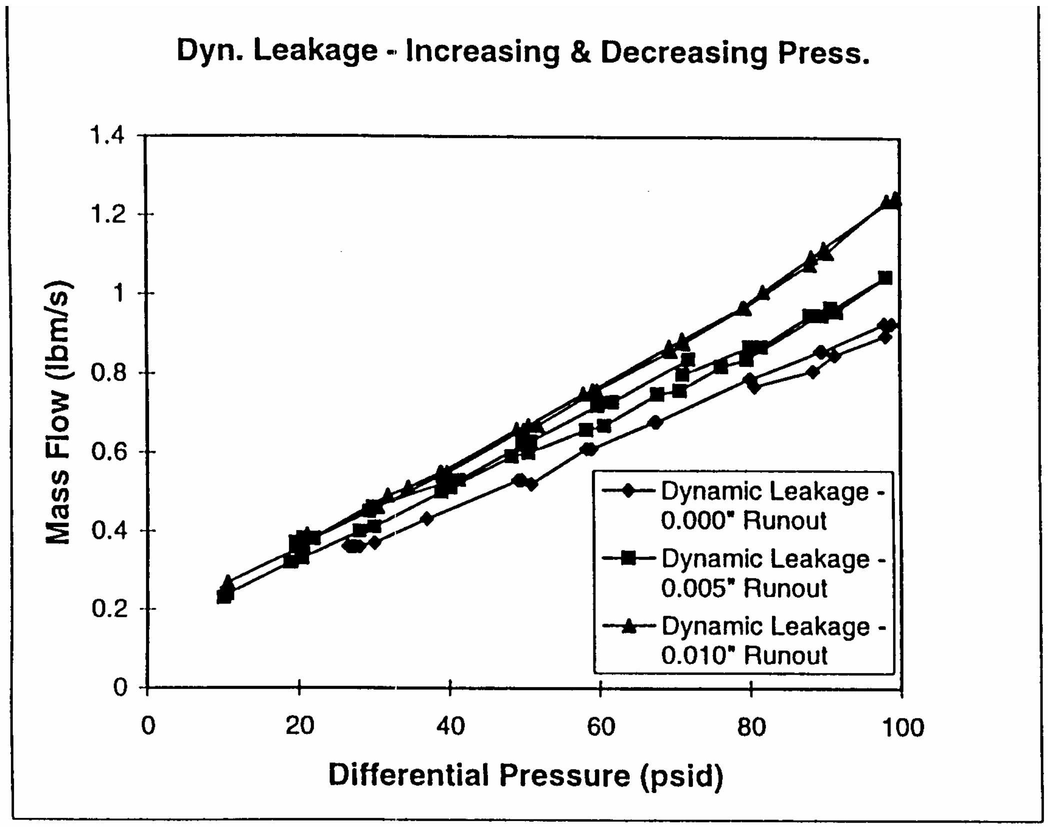
- Leakage Rate-Goals / Status for Brush Seals
- Aspirating Seals

Aspirating Seal GE90 Test

Test Results with Flow Deflector

at Room Temperature

Dynamic Leakage for 0.000, 0.005, and 0.010-inch Rotor TIR



- **Seal Closure Occurs at 2-3 psid for All Cases**

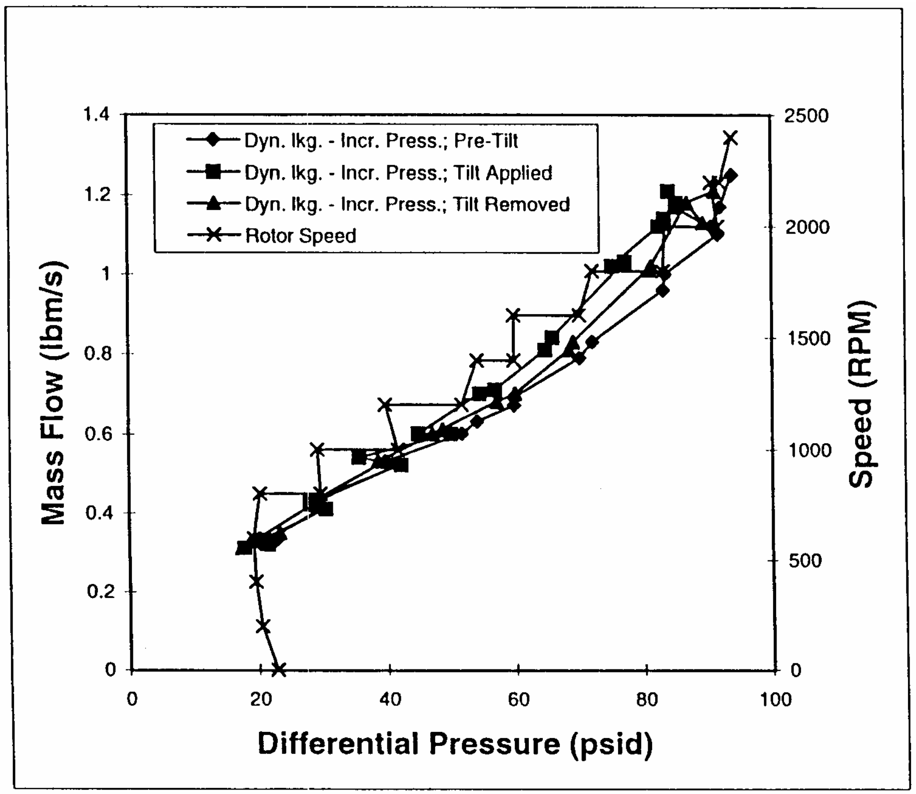
Aspirating Seal GE90 Test

Test Results - Dynamic Leakage with Tilt

at Room Temperature

Tilt 0.27° in 0.4 second, Hold to Collect Data, Remove in 0.4 second

***Note:* 0.007-inch Rotor Axial TIR, 141 μin. Rotor Surface Roughness**



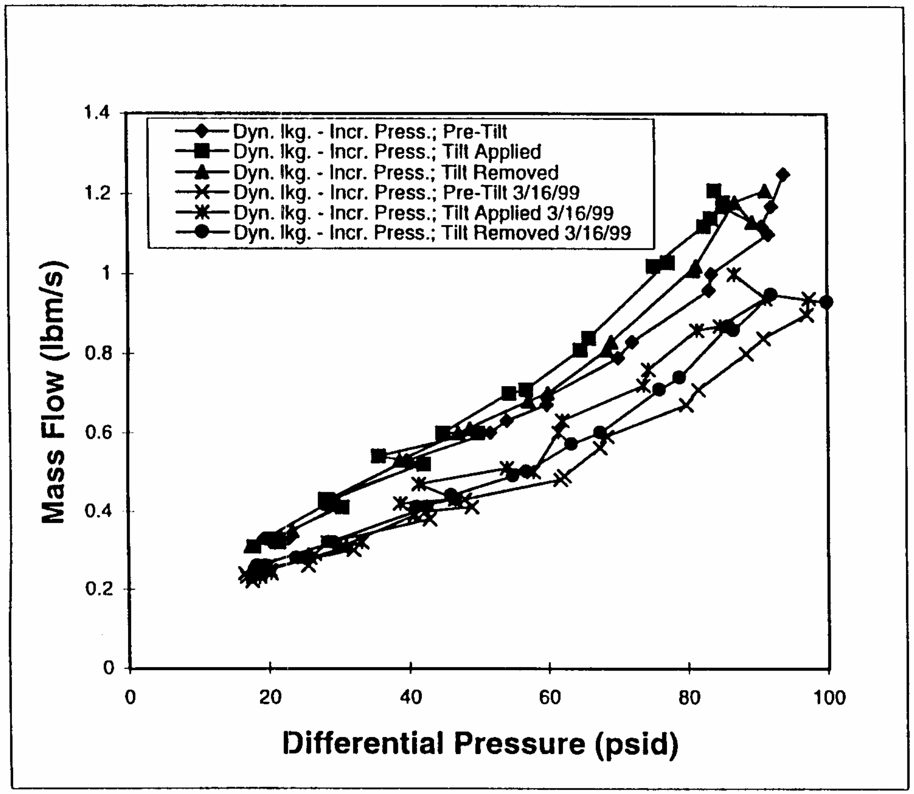
- **At Maximum Conditions, Pressure Falls by 10% with Tilt While Leakage Remains Essentially Constant; Recovery Is > 95%**

Aspirating Seal GE90 Test

Test Results - Dynamic Leakage with Tilt

at Room Temperature

Comparison of Seal Performance with 141 µin. Rotor Surface Roughness and 13-19 µin. Rotor Surface Roughness (03/16/99 data).

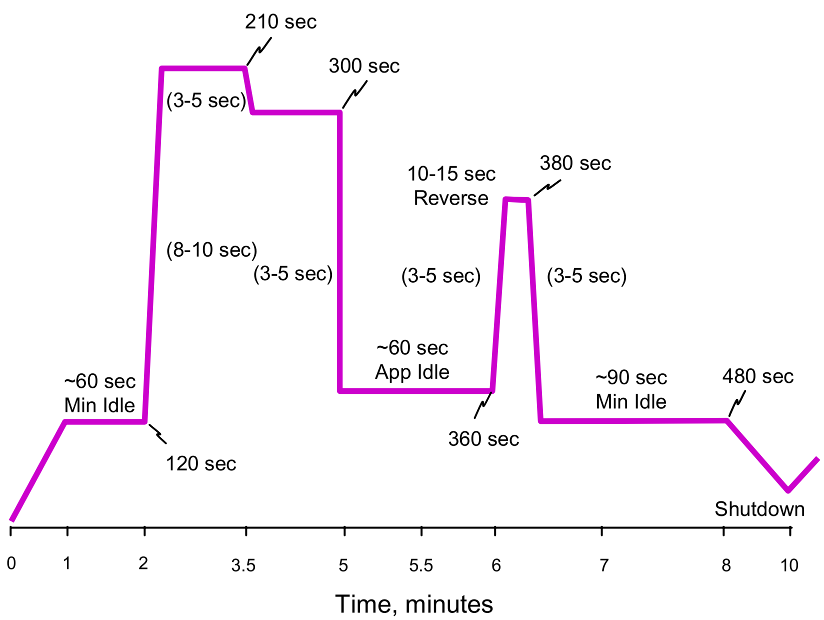


- **Seal Performance Improves by 24% at Maximum Conditions When Rotor Surface Roughness is Improved to 13-19 µin**

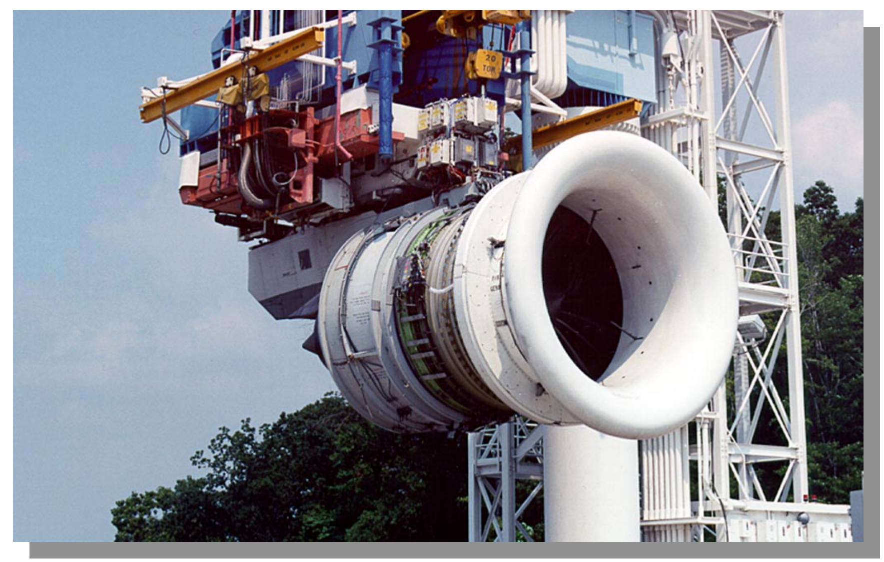
Aspirating Seal GE90 Test

Engine Test Plan: Test the Aspirating Seal "Piggyback" on a Previously Planned GE90 Development Test

Goal: 250 Test Hours with 1000 C-Cycles



C-Cycle

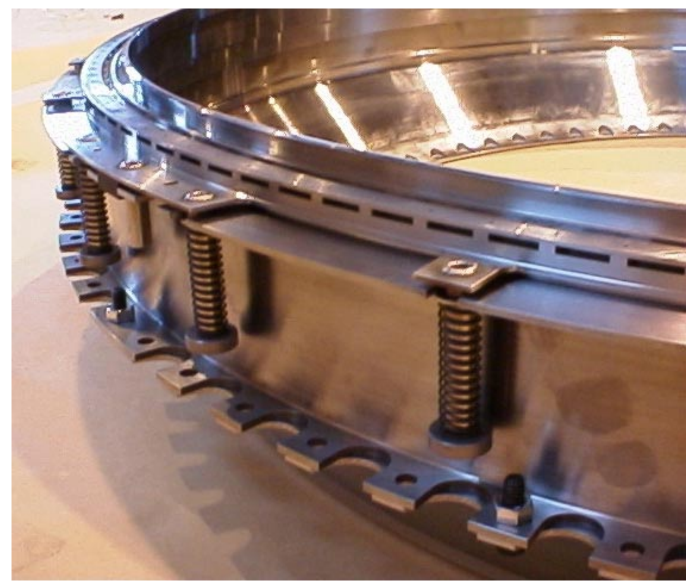


GE90 Test Stand

Aspirating Seal GE90 Test

Conclusions

- Aspirating Seal Designs were Fully Verified by Sub and Full-scale Rig Tests in Preparation for GE90 Engine Test
- All Engine Seal Hardware Fabrication was Completed
- Planned GE90 Test Date: 1st Quarter of 2002



DEVELOPMENT OF HIGH MISALIGNMENT CARBON SEALS

Lou Dobek and Alessio Pescosolido
Pratt & Whitney
East Hartford, Connecticut

George Szymborski and Seb Caromile
Stein Seal Company
Kulpsville, Pennsylvania

The Ultra Efficient Engine Technology (UEET) program is a NASA-funded program to develop and demonstrate technology for quiet, fuel-efficient, low-emissions next generation commercial gas turbine engines.

An essential role for achieving lower noise levels and higher fuel efficiency is played by the power transmission gear system connected to the fan.

Geared systems driving the fan will be subjected to inertia and gyroscopic forces resulting in extremely high angular and radial misalignments.

Because of the high misalignment levels, compartment seals capable of accommodating angularities and eccentricities are required. Pratt & Whitney and Stein Seal Company selected the segmented circumferential carbon seal as the best candidate seal type to operate at highly misaligned conditions and developed a test program to determine misalignment limits of current segmented circumferential seals. The long-term goal is to determine a seal design able to withstand the required misalignment levels and provide design guidelines.

A technical approach is presented, including design modification to a "baseline" seal, carbon grade selection, test rig configuration, test plan and data acquisition. Near term research plans and back-up seal designs are also presented.

Development of High Misalignment Carbon Seals

Lou Dobek
Alessio Pescosolido

Stein Seal
George Szymborski
Seb Caromile

High Misalignment Carbon Seals

Background

Tomorrow's Engines with geared fans will be subjected to extreme conditions such as:

High angular and radial seal misalignments

Gyroscopic loads - angular misalignment

Sun input gear orbiting - radial/eccentric misalignment

Seals capable of accommodating high misalignment and low pressure differentials must be developed.

Background information on principal causes of extreme conditions in Advanced Commercial Engines. Such conditions impose on seals high misalignment, high rubbing speed, large diameters and low pressure differentials.

High Misalignment Carbon Seals

Objectives:

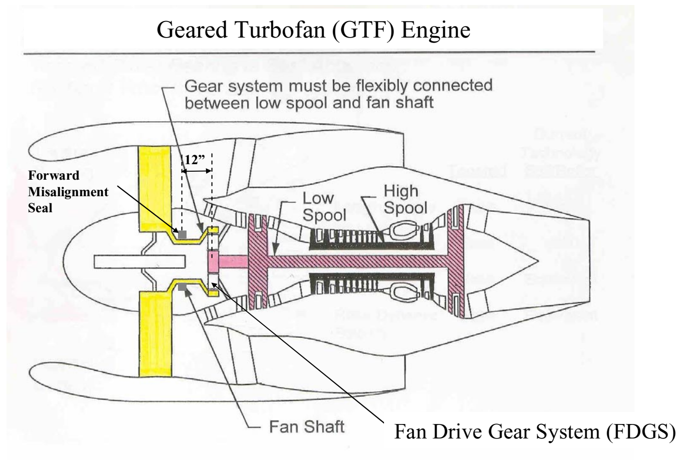
- Determine misalignment capabilities of existing circumferential segmented seals and develop design(s) to meet requirements.
- Enabling technology for Geared Turbofan (GTF) Engine.

Other industry applications benefiting from new seal technology

- F119 - Circumferential segmented seal employed
- High misalignment seal applications
- Other aircraft engine manufacturers will see improved background in today's misalignment and low pressure differentials seal capabilities.

Overview of FY '00 objectives: start development of the high misalignment seal with baseline testing. Other possible industry beneficiaries of improved seal technology are also listed.

High Misalignment Carbon Seals



Sketch of Geared Turbo Fan position and connection to the rest of the engine. Input shaft to GTF is connected to LPC shaft and the GTF output shaft is connected to the fan shaft.

High Misalignment Carbon Seals

	FWD. AIR/OIL SEAL	REAR AIR/OIL SEAL
Required Life (hours)	30,000	30,000
Delta P (psi)	<50	<50
Surface Speed (ft/s)	50	129
Buffer Air Temperature (deg. F)	350	350
Angular Misalignment (deg)	0.5	0.2
Eccentricity (inches)	0.005	0.02
Sealing Diameter (inches)	2.95	2.95
Type	Segmented/ bellows/ other	Segmented/ other

Seal Operating Conditions

Seal operating conditions (required life, pressure differentials, speeds, misalignment levels and others).

Critical requirements are highlighted.

High Misalignment Carbon Seals

Seal Selection

- **Types Considered**
  - Segmented circumferential
  - Face
  - Bellows
- **Considerations**
  - Seal mass
    - Must operate with high inertia loads
  - Strength
    - Ability to survive potential high impact loads
  - Flexibility
    - Conformance to rotating surface and misalignment

This slide describes seal selection.

Only contact seals were considered.

High Misalignment Carbon Seals

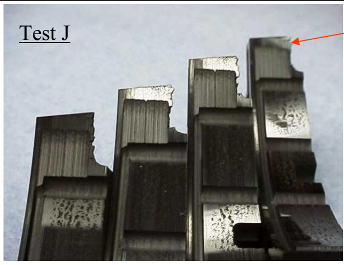
Segmented Circumferential Seal Chosen

- Low seal mass
  - Small cross-section made of lightweight carbon material
- Conformability to shaft / misalignment
  - Segmented design allows better tracking
- Simple design
  - No secondary seal

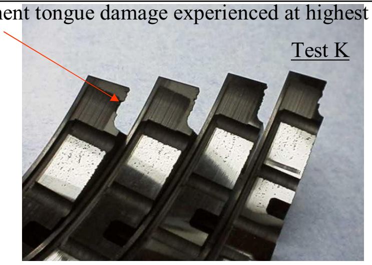
This slide discusses selection of the segmented circumferential seal. Historically face seals have large sections, thus greater mass. A face type seal requires a secondary device which could complicate operation at high misalignment.

High Misalignment Carbon Seals

Segment tongue damage experienced at highest angularities



Chipped carbon segments after 0.5° ang. misal. test



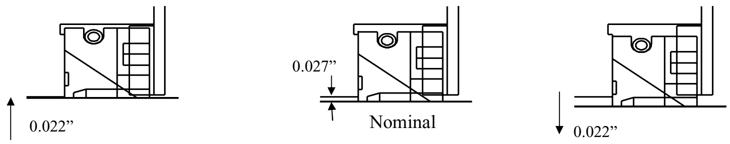
Similar damage after combined misal. test

Test J - Seal runner after test. Similar in test K

Seal runner after test K, similar after test J

High Misalignment Carbon Seals

Baseline Seal



Normal design practice

- 0.027 max. radial clearance between housing & shaft.
- Max radial movement 0.022

This slide discusses the baseline seal for this program and lists its advantages and disadvantages. The seal has a longer than normal tongue and socket but is within current design practice.

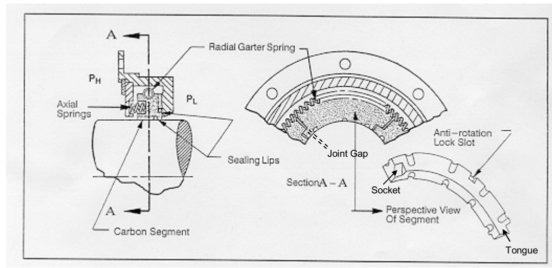
High Misalignment Carbon Seals

To meet future design requirements the following concerns must be addressed:

- Joint wear
- Lock slot wear from contact with anti-rotation pin
- Extension (garter) spring movement
- Compression spring movement

Issues too complex to resolve.

Alternate design needed to meet overall goals



This slide discusses the effect of trying to use current design practice for large shaft misalignments. There are too many concerns that are difficult to address and the configuration is not being considered.

High Misalignment Carbon Seals

Information to be used for alternate design:

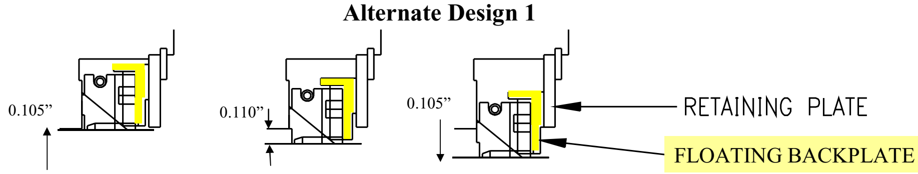
- Tests have shown higher angularities damage segment tongues
  Problem can be fixed with tongue re-design
- Carbon wear to be addressed in alternate design concepts

Where do we go from here:

- Complete 0.040” radial offset test
  - More data/experience for designing/developing alternate design
- With added info, design and develop 2 concepts:
  1) Floating backplate
  2) Floating backplate and bushing

High Misalignment Carbon Seals

Alternate Design 1



- **New design concept** – Floating backplate up to a .110 radial clearance
- Eliminates joint, lock slot, spring movement concerns

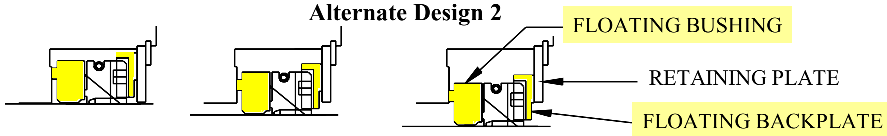
- **Must look at:**
- Anti-rotation of floating backplate
- Friction between plates
- Face and bore dams must be increased
- Material for plates

ADVANTAGES	DISADVANTAGES
•Normal tongue and socket joint	•High garter spring load
•Normal tongue and socket gap	•Complex, unproven backplate design
•Minimal joint wear	•More costly
•Minimal lock slot and key wear	•Larger face and bore dam widths
	•Higher heat generation

This slide describes the design to be used for radial clearances above .040”. To minimize inertia effects, light weight materials for the floating backplate will be evaluated. Hardenable material or hard coated surfaces will be considered to reduce friction between the floating backplate and retaining plate.

High Misalignment Carbon Seals

Alternate Design 2



•**New design concept** – Floating backplate and floating bushing up to a .110 radial clearance between housing & shaft.
•Max radial movement to be .105
•Allows for near normal segmented seal design
•**Must look at:**
•Anti-rotation of floating backplate
•Friction between plates
•Material for bushing and plates

ADVANTAGES	DISADVANTAGES
•Normal seal ring design •Normal garter spring design •Normal tongue and socket joint •Normal tongue and socket gaps •Minimal joint wear •Normal size face and bore dam widths •Less bore wear and heat generation •Minimal lock slot and key wear	•Complex design •Backplate design unproven •More costly •Ceramic floating bushing •Floating bushing unproven in aerospace applications •Requires more space than other designs

This slide describes an alternative design for the large clearances in this application. Addition of the floating bushing allows the segmented seal to operate as a normal clearance device. Stein has used floating bushings in industrial applications.

High Misalignment Carbon Seals

CONCLUSIONS

- Established limits of baseline circumferential segmented seal. 0.5° angularity and 0.010" eccentricity achievable with modified baseline seal.
- 0.5 deg tests damaged segment tongue. Tongue re-design can eliminate problem.

Air Leakage

- Higher air leakage occurred at higher angularity tests.
- Air leakage increased linearly with ΔP.
- Little effect of speed on air leakage.

Oil Weepage

- Very low throughout all testing.

Wear

- Angularity tests produced higher radial wear.

Recommendations

- New design needed to reach overall goal of 0.5° angularity and 0.105" eccentricity.
- Test modified baseline seal at 0.040" eccentricity. Use data to design / develop 2 alternate concepts.
- Develop and test floating backplate designs.

IMPROVED MAIN SHAFT SEAL LIFE IN GAS TURBINES USING LASER SURFACE TEXTURING

Alan D. McNickle
Stein Seal Company
Kulpsville, Pennsylvania

Izhak Etsion
Surface Technologies, Ltd.
Nesher, Israel

Stein Seal Company

Overview

SurTech
Surface Technologies

GOALS:

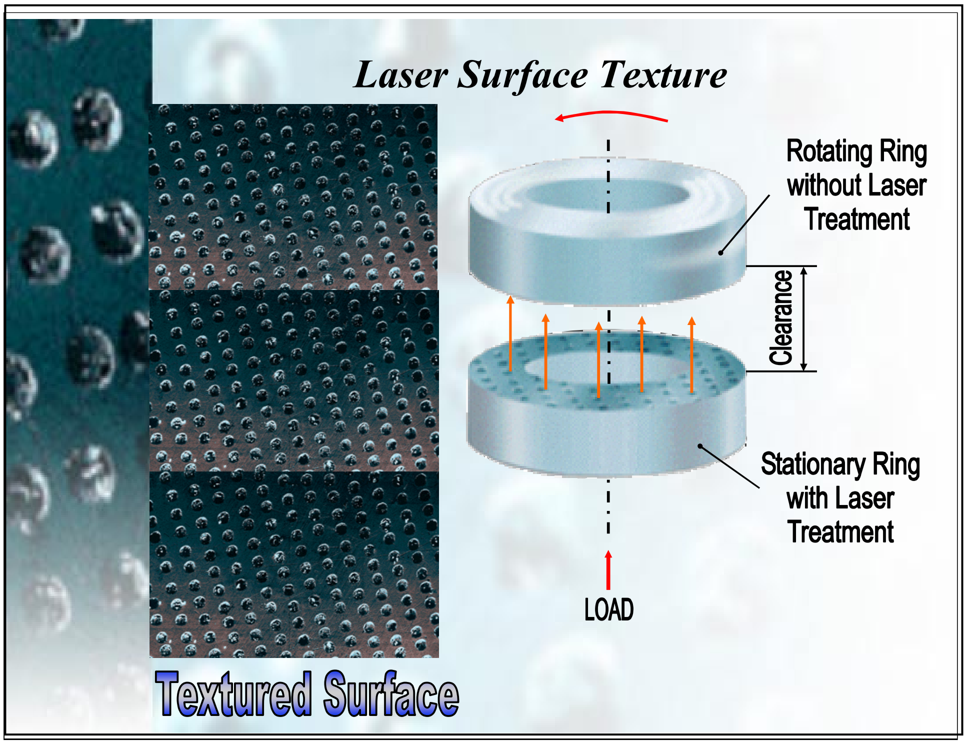
- Develop computer code for hydrodynamic force evaluation
- Develop Laser Surface Texturing (LST) for mechanical seals
- Increase Seal Life & Performance

APPLICATIONS:

- Gas Turbines (aviation & land based)
- Turbomachinery
- Automotive Engine Components
- Mechanical Seals

FUNDING (PARTIAL):

- **B**i-national **I**ndustrial **R**esearch & **D**evelopment Fund (BIRD)
  - » Sponsored by the Israeli government
  - » With participation of foreign company (Stein Seal Co.)


Laser Surface Texture
Rotating Ring without Laser Treatment
Clearance
Stationary Ring with Laser Treatment
LOAD
Textured Surface

Laser Surface Texturing System

- Reliable, non contact method for surface treatment
- Treatment of all types of materials, including metal, graphite, ceramics, composites, etc.
- Environmentally friendly.
- Computerized control of pore parameters allowing optimal shaping of various areas.
- Fast coverage of large areas.

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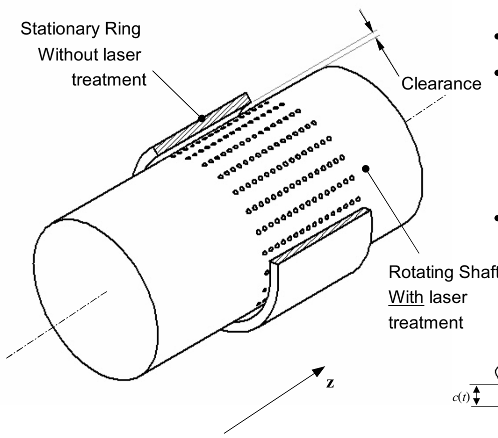
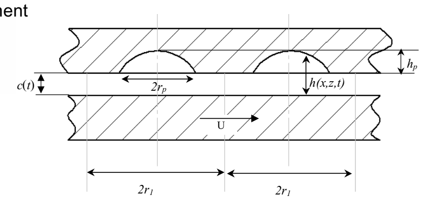
Seal Schematic with LST applied

SurTech Surface Technologies



- LST is applied to the shaft (runner).
- Pore pattern is application specific
  - .0039” O pore (100 µm)
  - .000079” depth (2 µ m)
  - Density (spacing pattern)
- 7.100” O carbon circumferential seal chosen.



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Dynamic Rig Tests

SurTech Surface Technologies

TWO TEST RIGS UTILIZED

1. Wear Test Machine
    - Carbon disc on rotor
    - 100 hour dry running test (room temp.)
    - Evaluates torque, disc temperature, & wear
2. Dynamic Test Rig
    - Simulates generic gas turbine “Take-Off” condition.
    - Utilizes aviation carbon circumferential seal
    - Baseline & LST Runners

Stein Seal Company

Surface Finish Definitions

SurTech Surface Technologies

- Baseline
  - Uses typical runner with “off-the-shelf” surface finish
    - » 8 RMS finish, runout .001”
- LST
  - Same as Baseline
  - Plus LST process
- LST with improved surface finish
  - Improves the “off-the-shelf” finish
    - » 4 RMS finish, circularity .0005”, runout .001”
    - » Included post LST process

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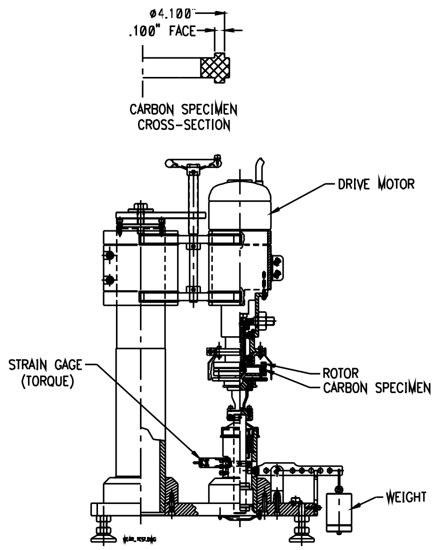
Wear Test Rig

SurTech Surface Technologies



FEATURES:
- Bench top tester
- Permits quick rotor change-outs.
  - Two rotors coatings used:
    - » Tungsten Carbide
    - » Chrome Carbide
  - Baseline & LST rotors

CONDITIONS:
- 100 hour test at room temperature
- 210 ft/sec rotor speed
- 2 psi unit load
- Dry running

DATA ACQUIRED:
- Temperature (Stator)
- Torque
- Coefficient of friction
- Carbon wear rate

Stepped face seal gas bearing static test rig. The seal hardware is a sub-scale version of the actual development seal.

The rig is used to collect information such as:

leakage vs. pressure

clearance vs. pressure

Proximity probes measure the gas film clearance. Effects of taper across the seal and/or rotor can also be tested.

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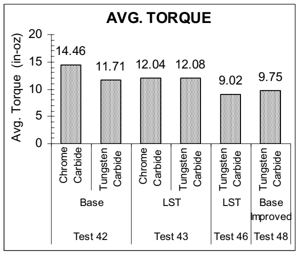
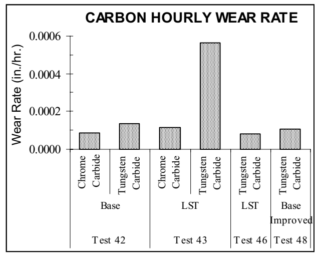
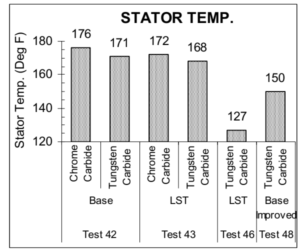
Wear Test Results (100 hour test)

SurTech Surface Technologies





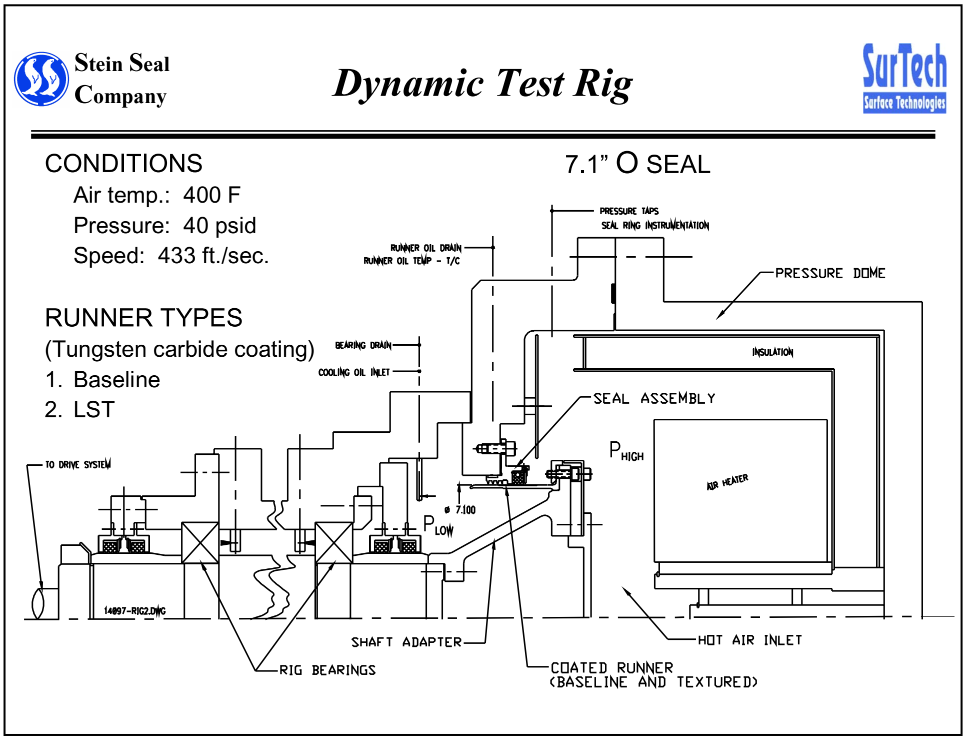


14097 weartest.xls

SUMMARY RESULTS

- Rotors: Baseline, LST, LST with improved finish, and Baseline with improved finish.
- High wear resulted during one test (Test #43, tungsten carbide)
  - Temperature and torque values comparable to other tests.
  - Cause for high wear: Rotor surface roughness exceeded micro-pore’s depth
- Test #46 utilized LST rotor with “improved surface finish”.
- Test # 48 utilized Baseline rotor with “improved surface finish” (data after 16 hours)

- **<u>Conclusion:</u>** Performance is enhanced with “improved surface finishes”


Stein Seal
Company
Dynamic Test Rig
SurTech
Surface Technologies
CONDITIONS
Air temp.: 400 F
Pressure: 40 psid
Speed: 433 ft./sec.
RUNNER TYPES
(Tungsten carbide coating)
1. Baseline
2. LST
7.1” O SEAL
PRESSURE TAPS
SEAL RING INSTRUMENTATION
RUNNER OIL DRAIN
RUNNER OIL TEMP - T/C
PRESSURE DOME
BEARING DRAIN
COOLING OIL INLET
INSULATION
SEAL ASSEMBLY
P HIGH
AIR HEATER
TO DRIVE SYSTEM
ø 7.100
P LOW
14097-RIG2.DWG
SHAFT ADAPTER
HOT AIR INLET
RIG BEARINGS
COATED RUNNER
(BASELINE AND TEXTURED)

Seal Cross Section - Rig Test

Stein Seal Company

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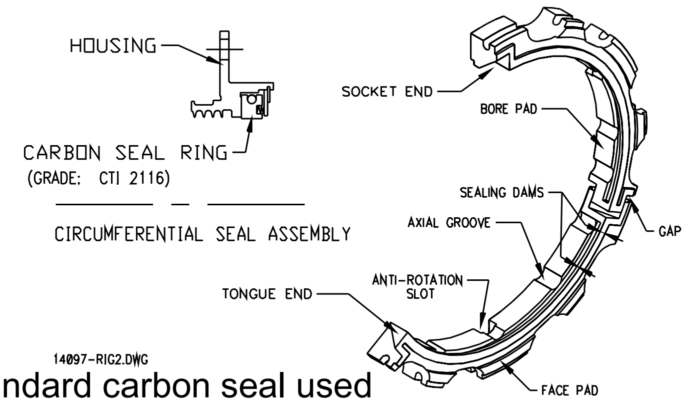

- Standard carbon seal used
  - Carbon graphite grade: USG-2116
- T/C's installed in two segments

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Typical Test Results
Baseline vs. LST Runner

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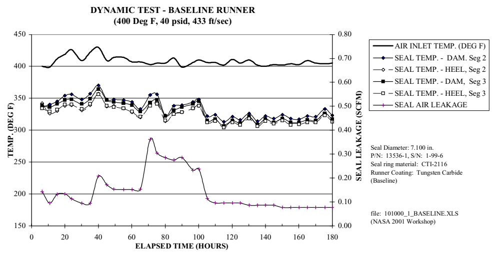

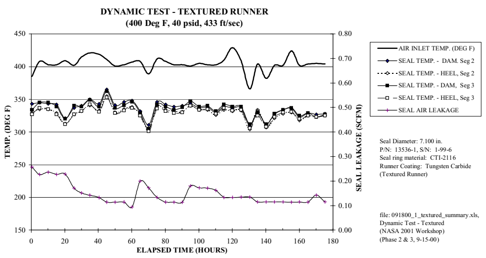

- Typical performance graph for rig tests
  - Elapsed time vs.:
    - » Seal Ring Temp. &
    - » Seal Leakage
  - Inlet air temp: 400 F
- Seal leakage tends to reduce with time as seal wear occurs.
  - Seal ring wears to the distorted runner shape due to thermally and centrifugal effects.

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Dynamic Test Results
Seal Wear & Estimated Life

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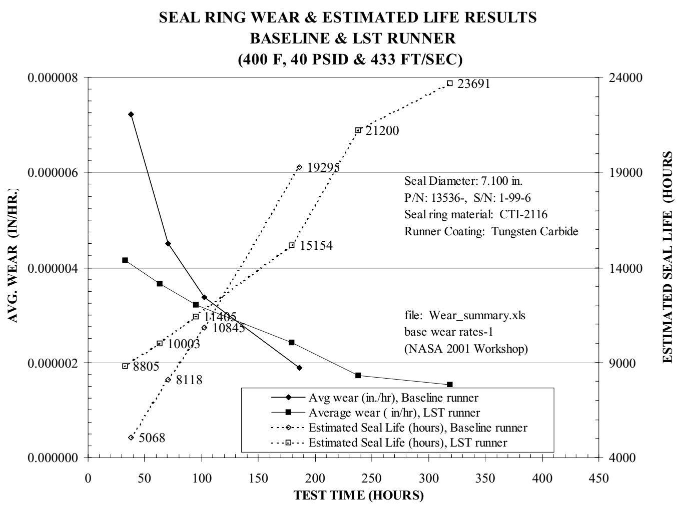


- Compares LST & Baseline runners.
- Seal wear measured at time intervals shown with graph symbol.
- Seal life based on seal ring worn to non-usable condition.
- Baseline runner yielded longer seal life.

Stein Seal Company

Runner Improvement Implemented

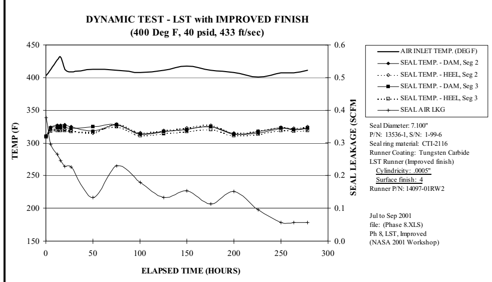
SurTech Surface Technologies

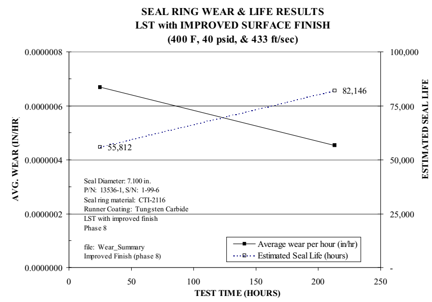
- Runner surface finish improved
  - Cylindricity
  - Surface Finish
  - Roundness
- LST re-applied with post process operations
  - Smooth “bulges” at pore periphery
  - Lap runner OD

Stein Seal Company

Dynamic Test Results
LST with Improved Runner Finish

SurTech Surface Technologies



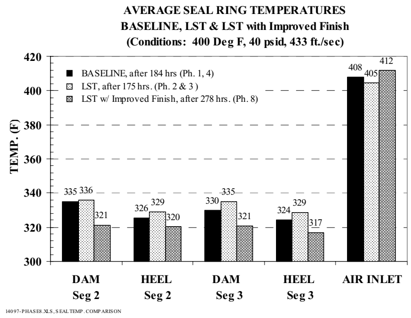


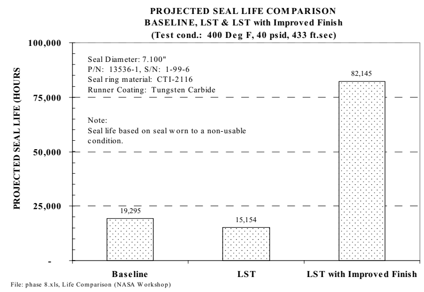
- Seal ring temperature is approx. 18 °F cooler with LST & improved finish
- Seal life measured at two time intervals
  - (25 hr & 278 hr)
- Seal life increased significantly (4.3:1) with LST & improved finish
  - Compared to Baseline Runner.

Stein Seal Company

Seal Ring Temperature & Wear Life Comparison

SurTech Surface Technologies





- Seal ring temps. were generally cooler (~ 18 F) with LST and the improved surface finish.``
- Seal life increased 4.3:1 with LST & Improved Surface Finish

DEVELOPMENT OF ADVANCED SEALS FOR INDUSTRIAL TURBINE APPLICATIONS

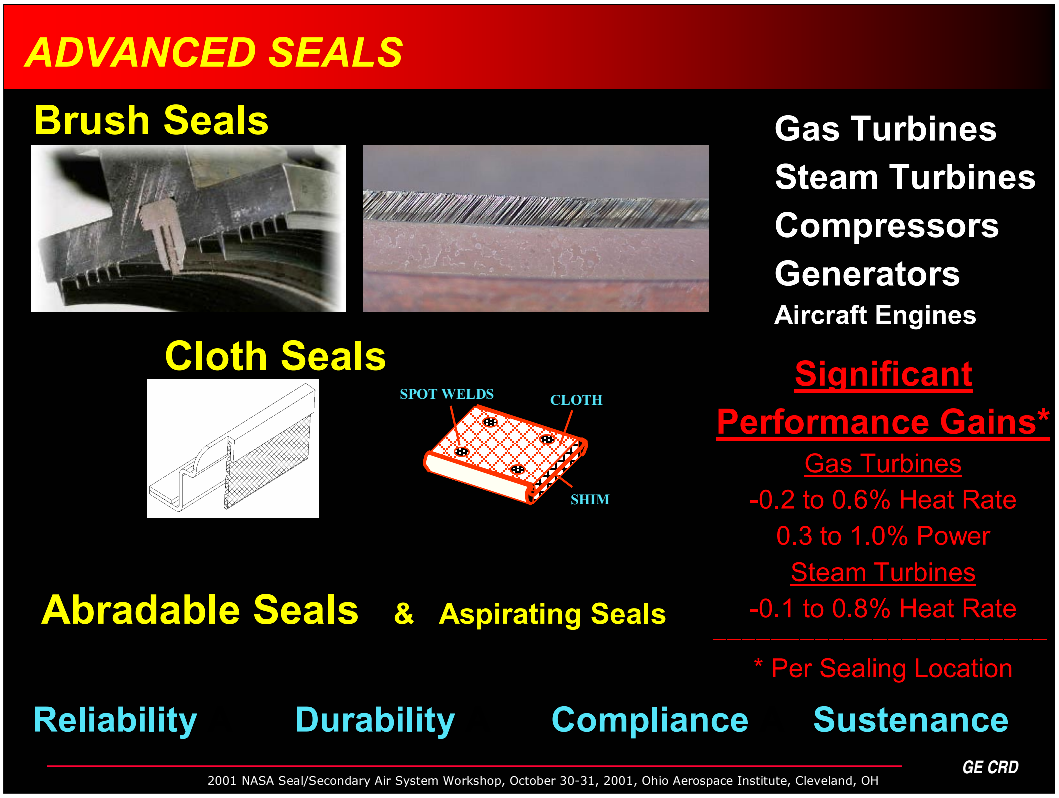
Raymond E. Chupp, Mahmut F. Aksit, Farshad Ghasripoor,
Norman A. Turnquist, Saim Dinc, and Jason Mortzheim
General Electric Corporate Research and Development
Niskayuna, New York

Mehmet Demiroglu
Advanced Innovative Technologies, Inc.
Troy, New York

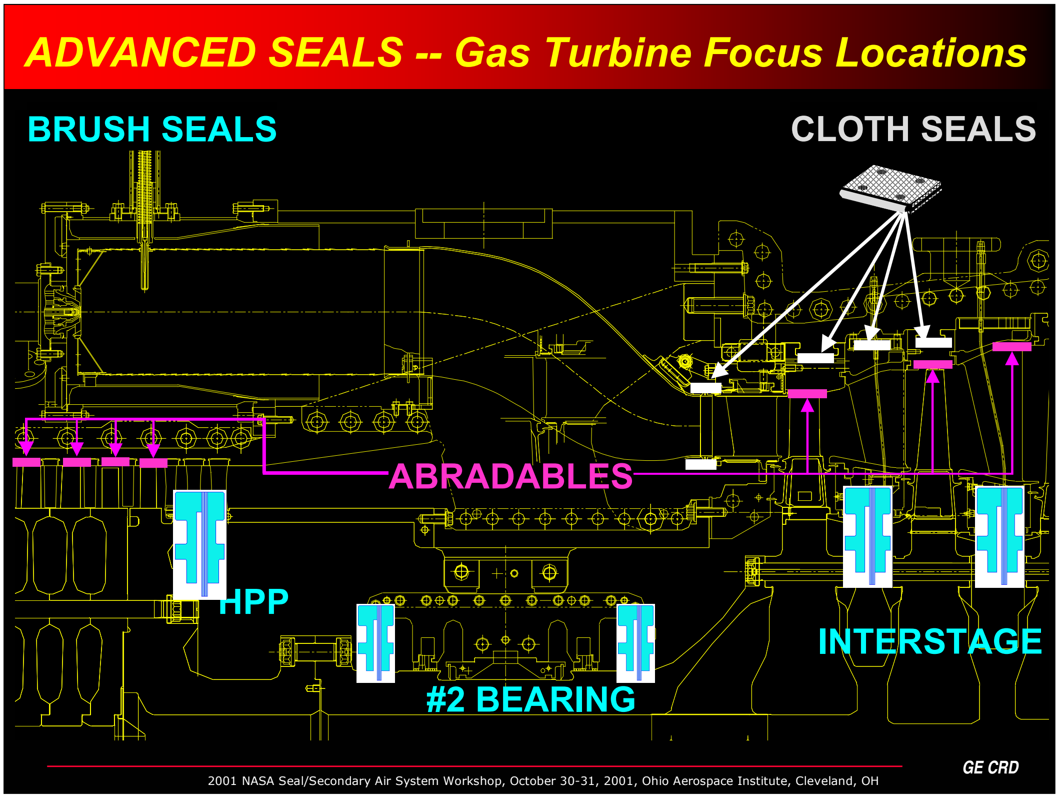
A critical area being addressed to improve industrial turbine performance is reducing the parasitic leakage flows through the various static and dynamic seals. Implementation of advanced seals into General Electric (GE) industrial turbines has progressed well over the last few years with significant operating performance gains achieved. Advanced static seals have been placed in gas turbine hot gas-path junctions and steam turbine packing ring segment end gaps. Brush seals have significantly decreased labyrinth seal leakages in gas turbine compressors and turbine interstages, steam turbine interstage and end packings, industrial compressor shaft seals, and generator seals. Abradable seals are being developed for blade-tip locations in various turbine locations. This presentation summarizes the status of advanced seal development for industrial turbines at GE.

Improved sealing has been under development for several years for GE industrial turbine applications. The work summarized in this presentation is being carried out at GE's Corporate Research and Development center in cooperation with GE Power Systems customers. A team of over a dozen individuals at CRD focus on developing advanced seals for several turbine locations.

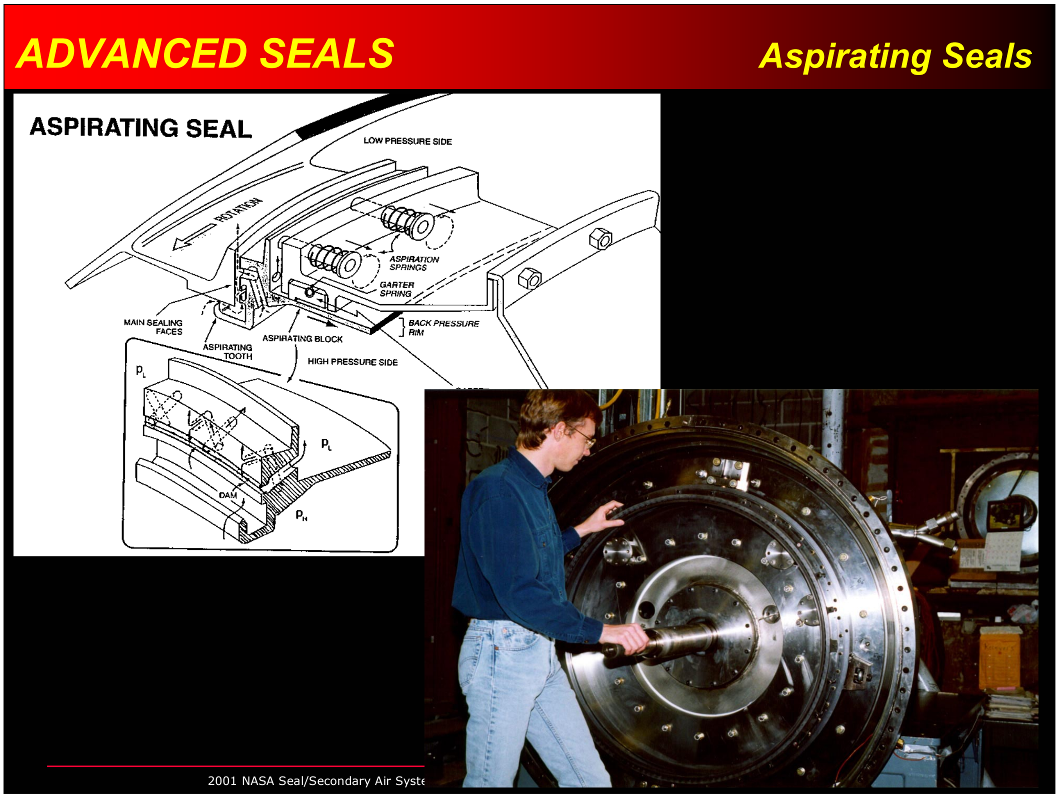
This presentation will include discussion of the development approach for seals, analysis methods, test facilities, and brief descriptions of development for the various seal types.



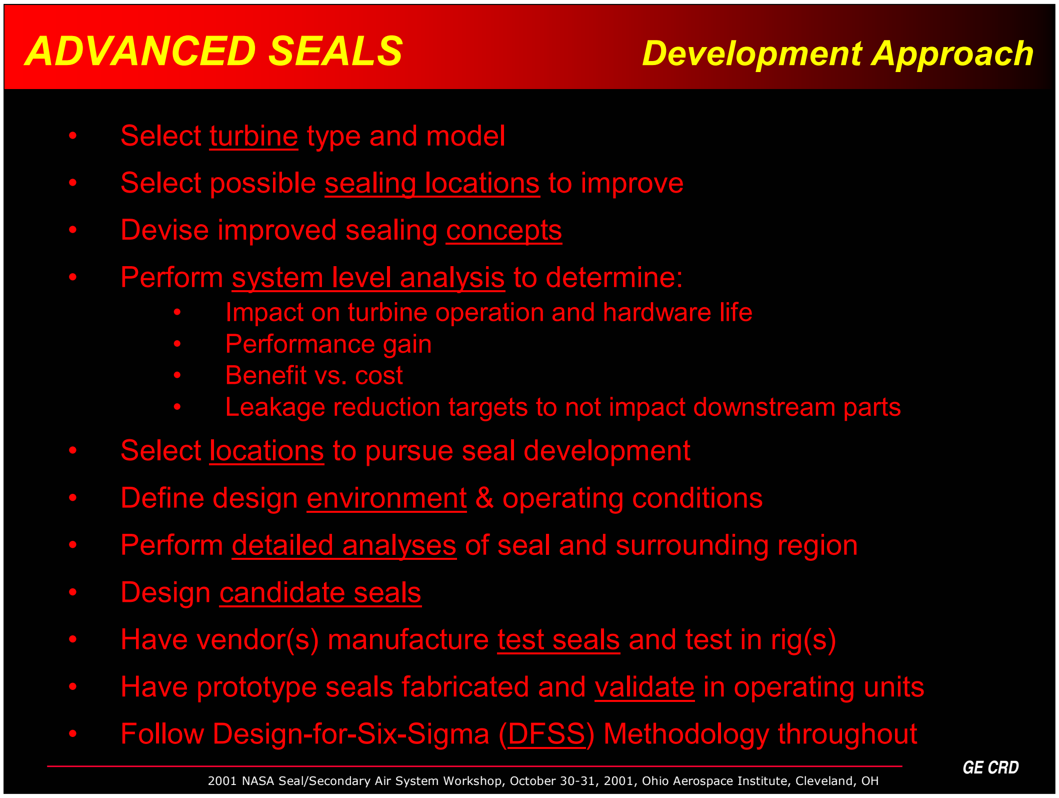
Improved sealing in industrial gas and steam turbines reduces parasitic leakages and thus gives better control of the the air system. This results in significant improved performance in both heat rate (efficiency) and power output. Applications for improved sealing include gas turbines, steam turbines, aero engines, industrial compressors, and generators. Several types of static and dynamic seals have been developed as shown in this chart.



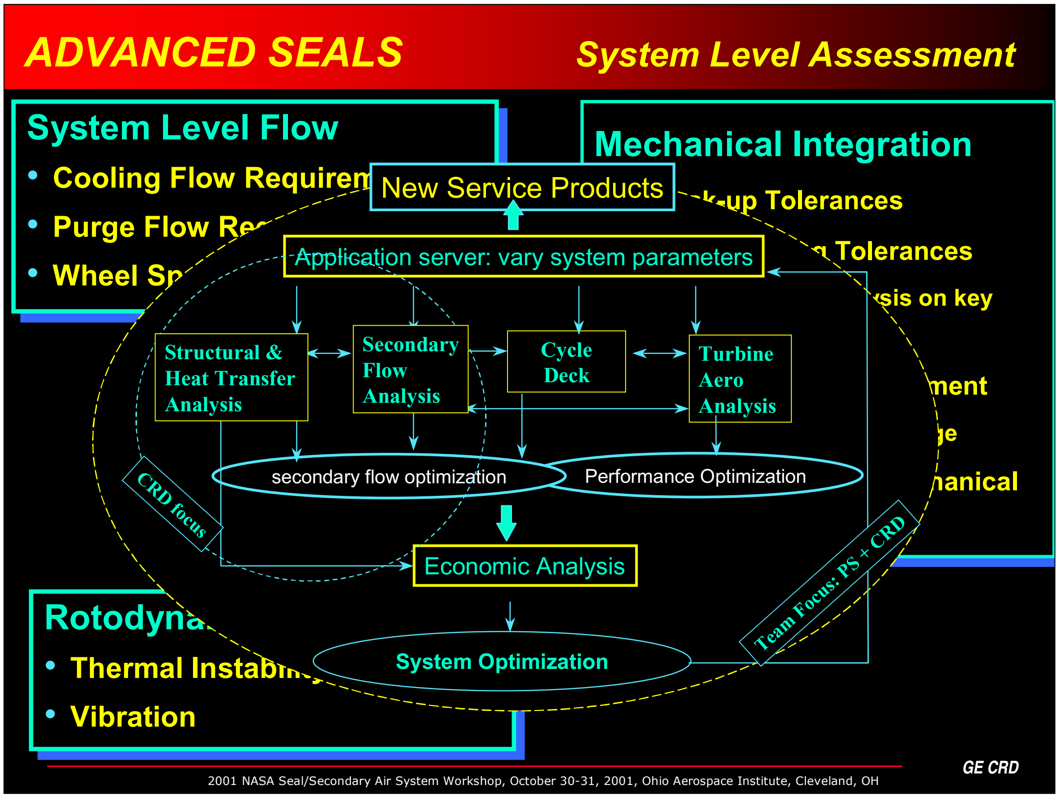
This chart shows representative sealing areas that have been addressed in industrial gas turbines. **Static cloth seals** have been implemented in gas turbine hot-gas path junctions and also steam turbine packing ring segment end gaps. **Brush seals** have been developed to significantly decrease labyrinth seal leakages in several locations. **Abradable seals** are being developed for several blade tip locations to reduce operating clearances.



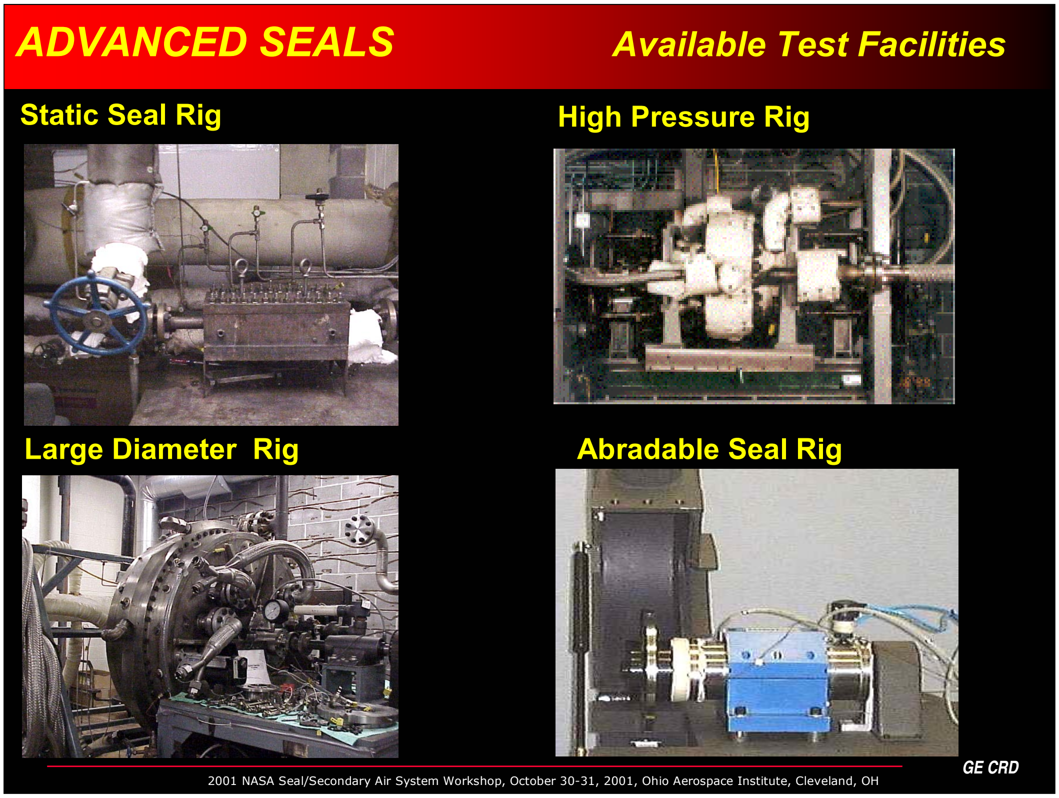
Aspirating seals have been developed in conjunction with GE Aircraft Engines and NASA as discussed in an earlier presentation today.



A systematic approach is followed in developing advanced seals based on the six-sigma methodology. A system level analysis is an important part of the effort to insure that all impacts of the improved sealing are considered and that the benefits are realistically assessed. The effort is carried through prototype engine testing to validate advanced seal designs.

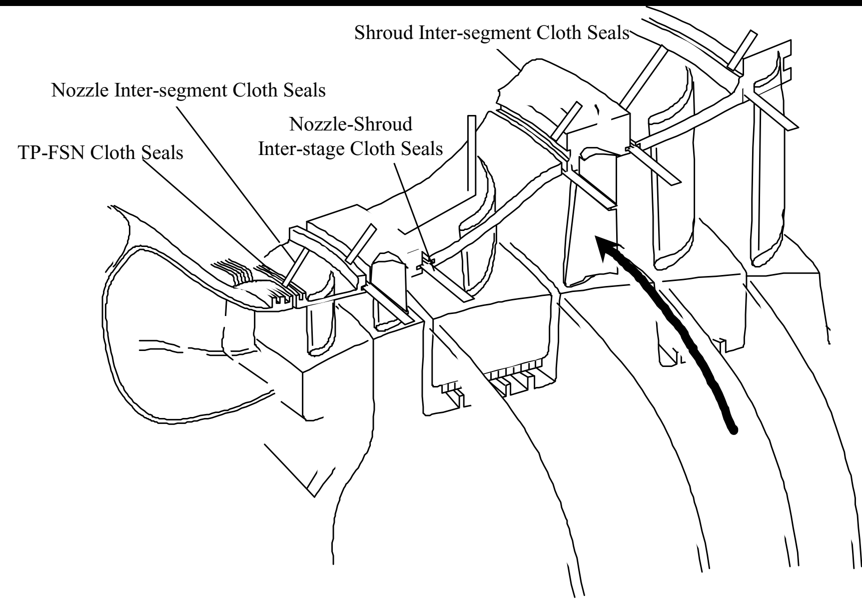


This chart gives an overview of the system level assessment for a gas turbine application. Often there is more leakage through the seals than necessary for component cooling and cavity purging of hot gas. These areas provide opportunities for improved sealing. But leakages can not be simply decreased to a minimum level possible by an advanced seal concept. The seals must be designed or the flow system modified to maintain required flow rates. Otherwise, decreased part lives or premature failures could occur.



Several experimental rigs are used to quantify performance and characteristics of advanced seals. A **static rig** is employed for testing both static and dynamic seals. The rig is shaped like a shoebox. It is a high pressure, high temperature rig that gives comparative leakage performance data for various seals types, i.e., cloth, labyrinth, brush, honeycomb, C-, E-, etc. A **smaller rotary rig** is used for testing in air or steam of dynamic seals. This rig is used to test subscale seals at full turbine conditions. A **larger rotary rig** is used for testing full-scale dynamic seals at subscale conditions. This rig is the one that has been used to test aspirating face seals as well as brush seals. An **abradable rub rig** is a versatile rig for testing candidate abradable shroud materials rubbing against tipped and untipped blades. It can simulate turbine blade-tip rotation and incursion rates, and has heating capability to operate at turbine environment temperatures. Wear characteristics are determined from measured level of shroud and blade-tip wear.

CLOTH SEALS

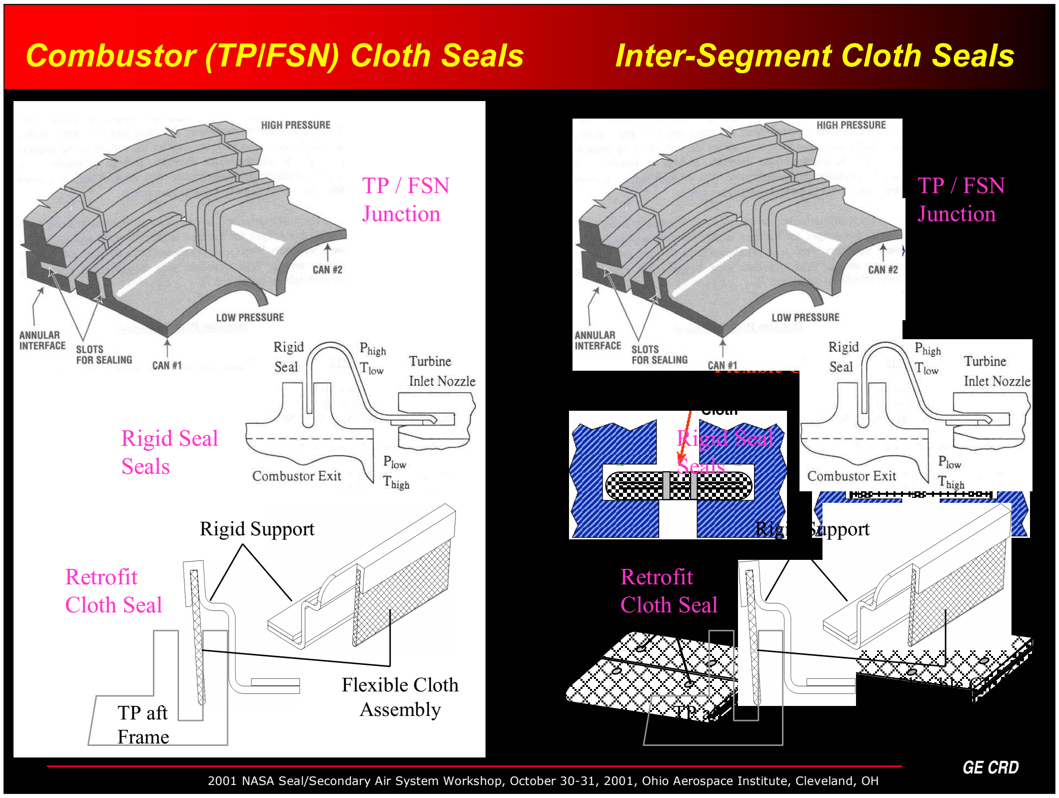


Cloth Seal Applications in a Gas Turbine

2001 NASA Seal/Secondary Air System Workshop, October 30-31, 2001, Ohio Aerospace Institute, Cleveland, OH

GE CRD

Advanced static sealing applications in gas turbines include junctions between stationary components throughout the air system flow path. Typically, adjacent members have to sustain relative vibratory motion with minimal wear or loss of sealing. They must accommodate thermal growth mismatch and misalignment. Cloth seals have been applied in combustor transition pieces and turbine nozzles and shrouds.



In gas turbine combustors (left side of this chart), cloth seals have been applied to seal the gaps between the can transition pieces (TP) and the first stage nozzles (FSN). Combustion dynamics and excessive thermal misalignments make combustor sealing very challenging. A typical application includes two TP's and FSN segments. Large axial offsets and relative skew/misalignments between neighboring TP's are common. The FSN segments experience relative misalignments causing seals to stick in the FSN slots. Jamming of the seal on the FSN side results in heavy wear. Cloth seals at this location have demonstrated reduced leakage and extended service lives.

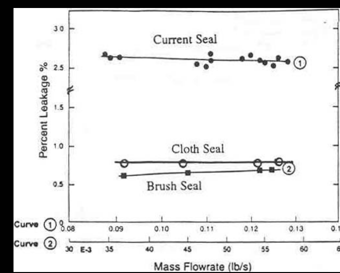
In gas turbine nozzle-shroud inter-segment seals (right side of this chart), cloth seals have been applied in many of the shroud and nozzle segments that require high temperature sealing. Typically, deep slots have been machined into mating parts and fairly stiff metal strips are used as seals. The relative motion between members can cause these seals to tip and toe, or jam against the slots. Lack of flexibility results in poor sealing and excessive wear. For smaller gap changes, conventional metal seals are adequate. Braided rope seals are used for demanding cases. For large gap changes, cloth seals have been replacing rigid metal seal strips. These seals have demonstrated improve turbine performance.

CLOTH SEALS

Status

Business Impact

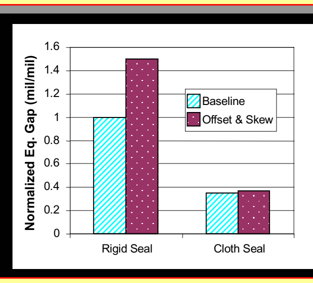
- HGP Cloth Seals commercialized for
  - E-Class: 3J, MS5N, MS5P, 6B, 7EA, 9E
  - F-Class: 7FA/FA+e, 9FA, 7FB
  - H-class
- Combustor Cloth Seals commercialized for
  - E-Class: 6B
  - F-Class: 6FA, 7FA/FA+e, 9FA



- 35-60% leakage reduction for combustors

Benefits

- 2:1 Leakage Reduction
  - 35-60% leakage decrease in combustor; 65-75% decrease for nozzle-shroud-segments
  - 0.40% MW output increase in 9FA; 1.0% MW increase in 6B (S1S's only)
- 1-2 ppm NOx reduction for combustor applications
- 3:1 Improvement in life and inspection intervals
- 2:1 Reduction in combustor assembly time
- Improves hot-gas path temperature radial profile

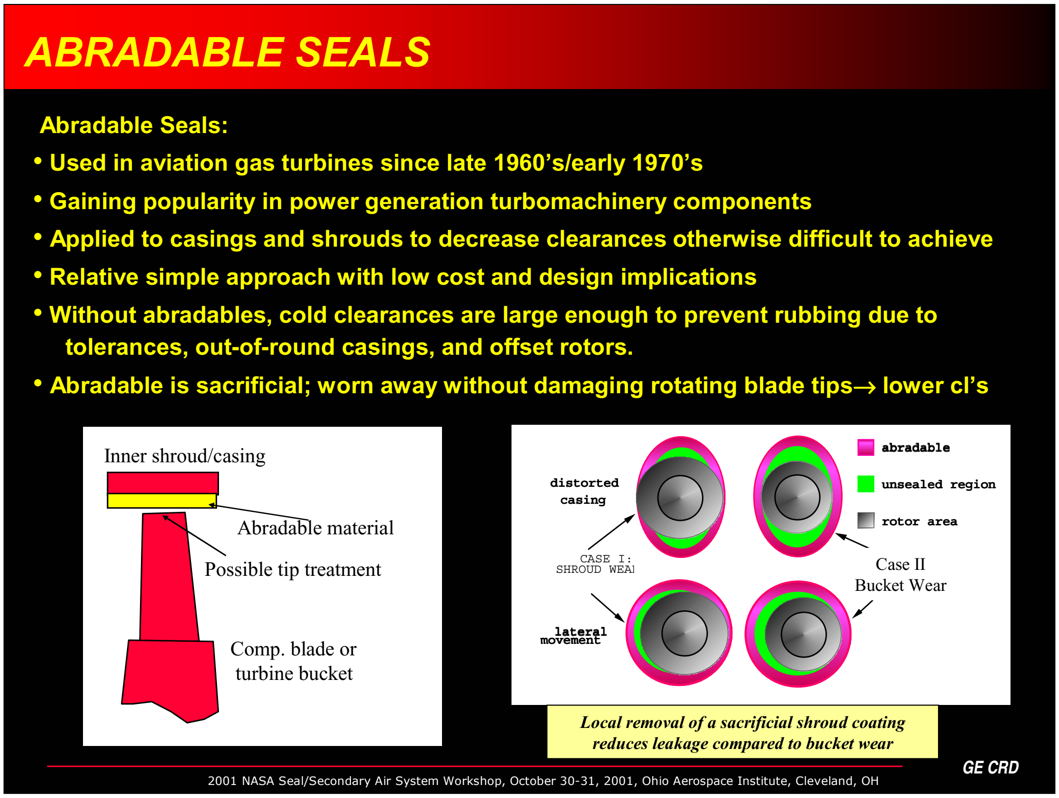


- 65-75% leakage reduction for Nozzles&Shrouds

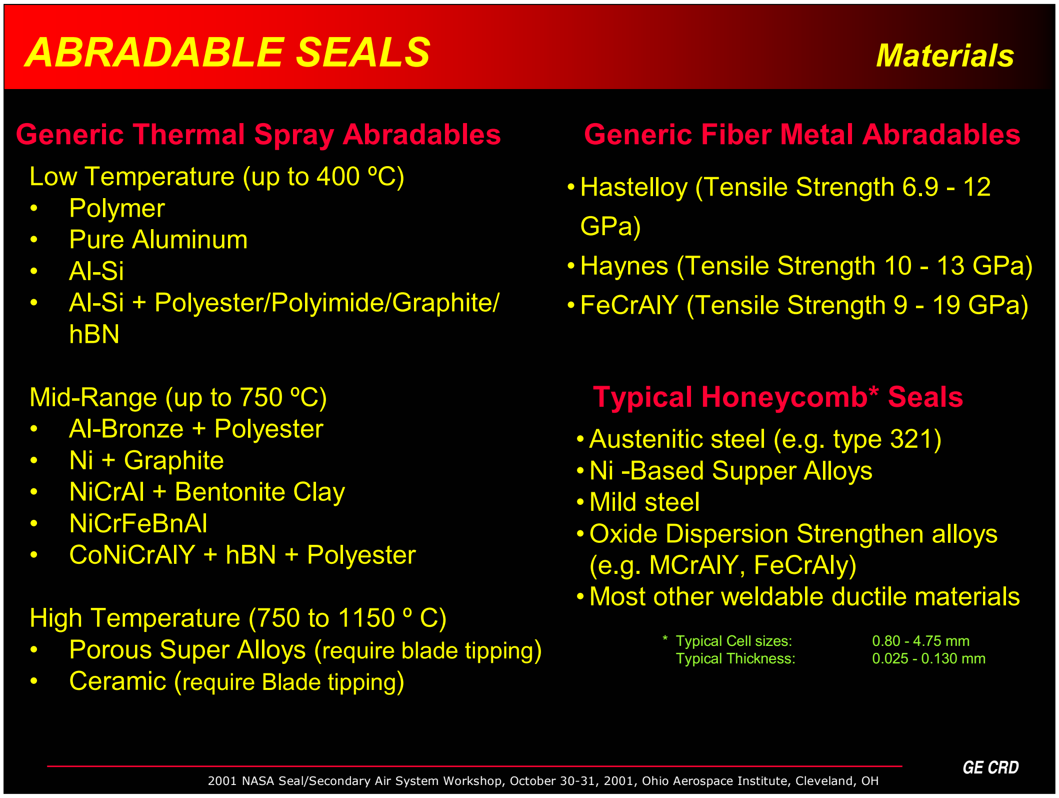
2001 NASA Seal/Secondary Air System Workshop, October 30-31, 2001, Ohio Aerospace Institute, Cleveland, OH

GE CRD

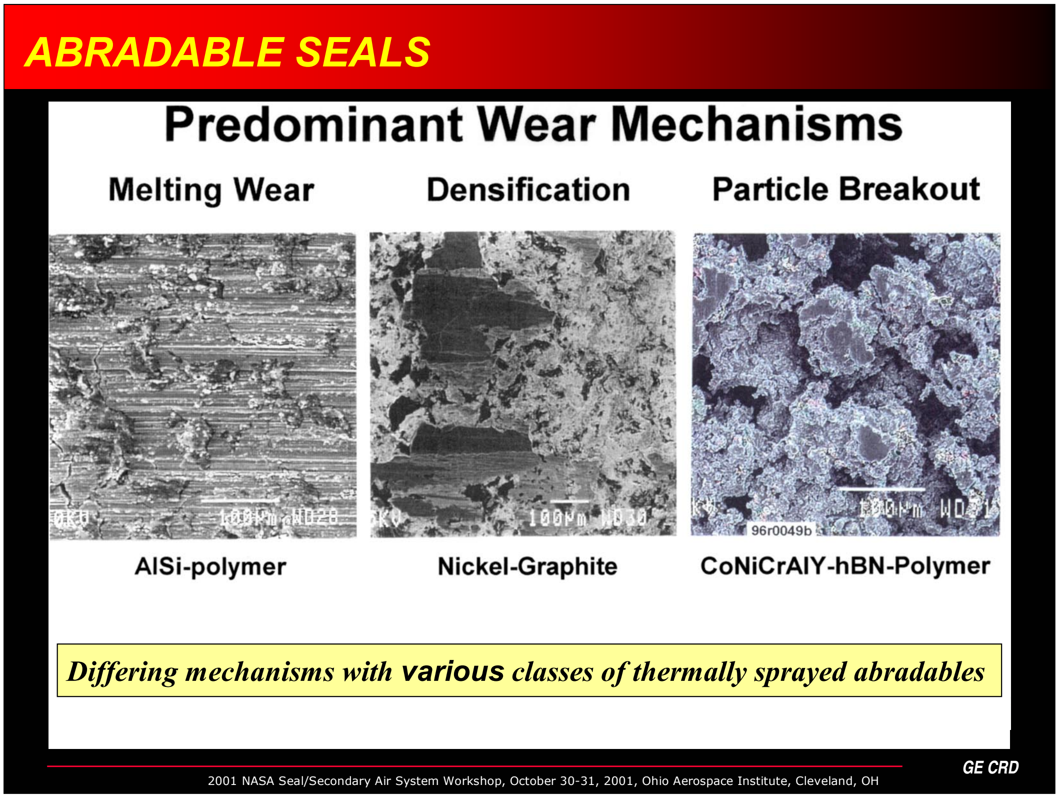
This chart summarizes the current status of applying cloth seals to turbine inter-segments and between the combustors and the first stage nozzles. The performance gains and extended life of cloth seals are significant.



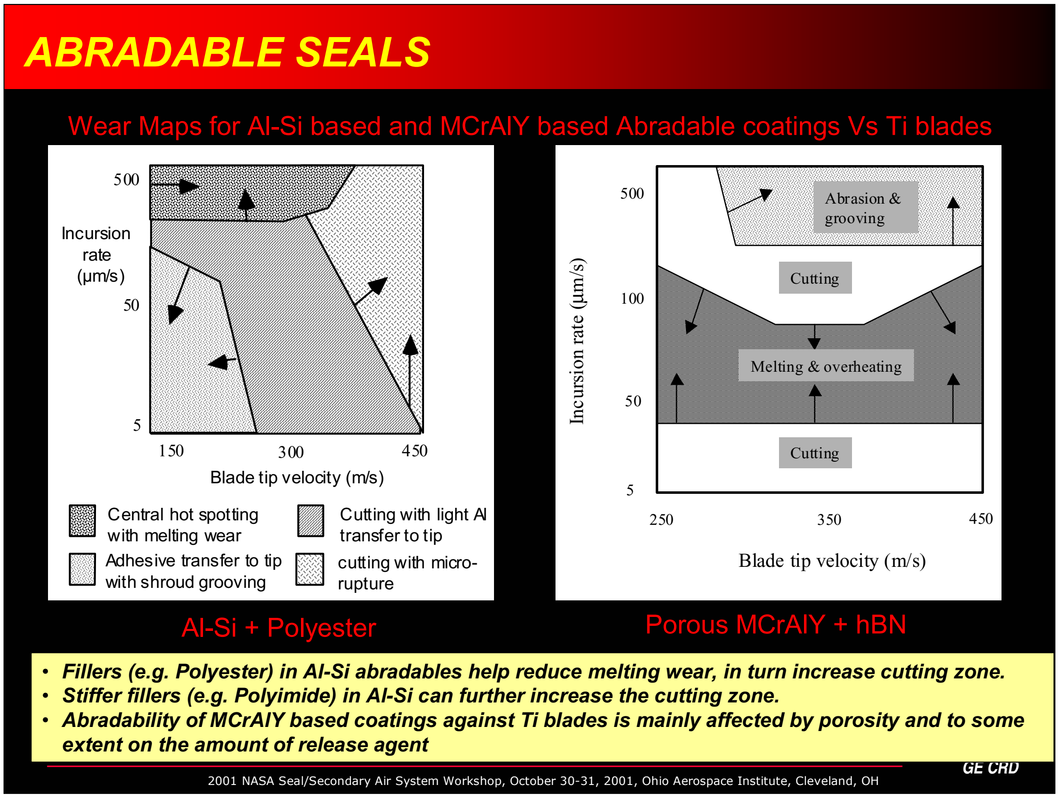
Abradable seals offer significant performance gains for turbines by decreasing the operating clearances of the compressor and turbine blade tips. Abradable seal materials are applied to the casings of gas or steam turbines. These seals are worn-in by the rotating blade during service with little wear of the blade tips. The seals can reduce operating clearances by allowing tighter cold-build clearances without fear of damaging blade tips by tip/shroud closures during turbine transients and at steady state. They also minimize the effect of casing out-of-roundness and rotor misalignment.



Abradable seal development is materials centered. These type materials can be classified into three categories according to their temperature capability. They can also be classified by how they are applied, i.e., (1) castings for polymer based abradables, (2) brazing or diffusion bonding for fibermetal (discussed in a presentation later today) and honeycomb structures, and (3) thermal spray coatings for a large range of powdered composite materials.

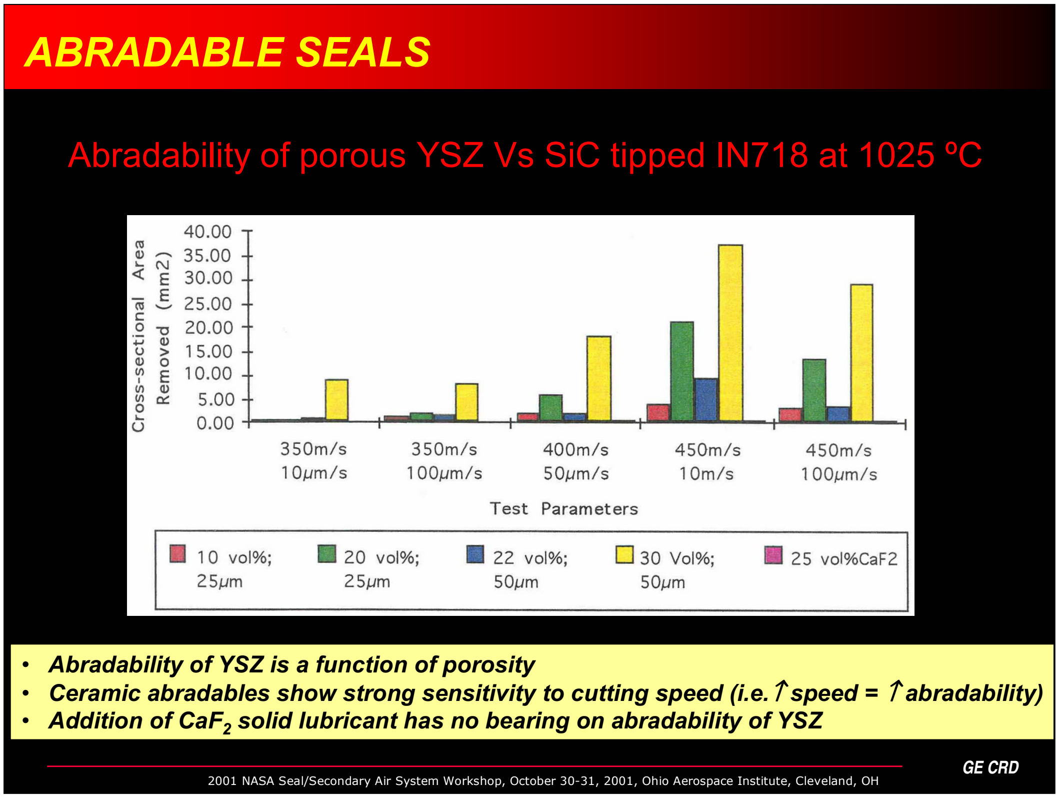


For thermally sprayed abradables, there are different wear mechanisms for different types of materials. The mechanism affects the depth of incursion without blade tip wear. For the third mechanism, a "lubricant" material, e.g., hBN, is often introduced into the coating to facilitate particle breakout.



This chart shows wear maps for low and mid-temperature abradable seals. For low temperature abradables (left side of chart), a second phase is often added. This phase usually consists of a polymeric material or release agent, i.e., solid lubricant. For Aluminum-Silicon based abradables, the second phase primarily promotes crack initiation. The type of second phase added determines the wear mechanism and abradability under various tribological conditions. The left-hand side of this chart shows a typical wear map for an Aluminum-Silicon-polyester coating for a 3 mm thick titanium blade at ambient temperature. The arrows indicate the movement of wear mechanism boundaries when a stiffer polymer than polyester is used as the second phase.

The right-hand side of this chart shows a wear map of a mid-temperature coating system abraded at 500 C (930 F) using titanium blades. This plot also shows the wear mechanism domains vs. blade-tip velocity and incursion rate. Again for this temperature range, additional phases are added to the base metal powder to make the material abradable. The arrows on the plot indicate the movement of the wear regime boundaries as the polyester level increases.

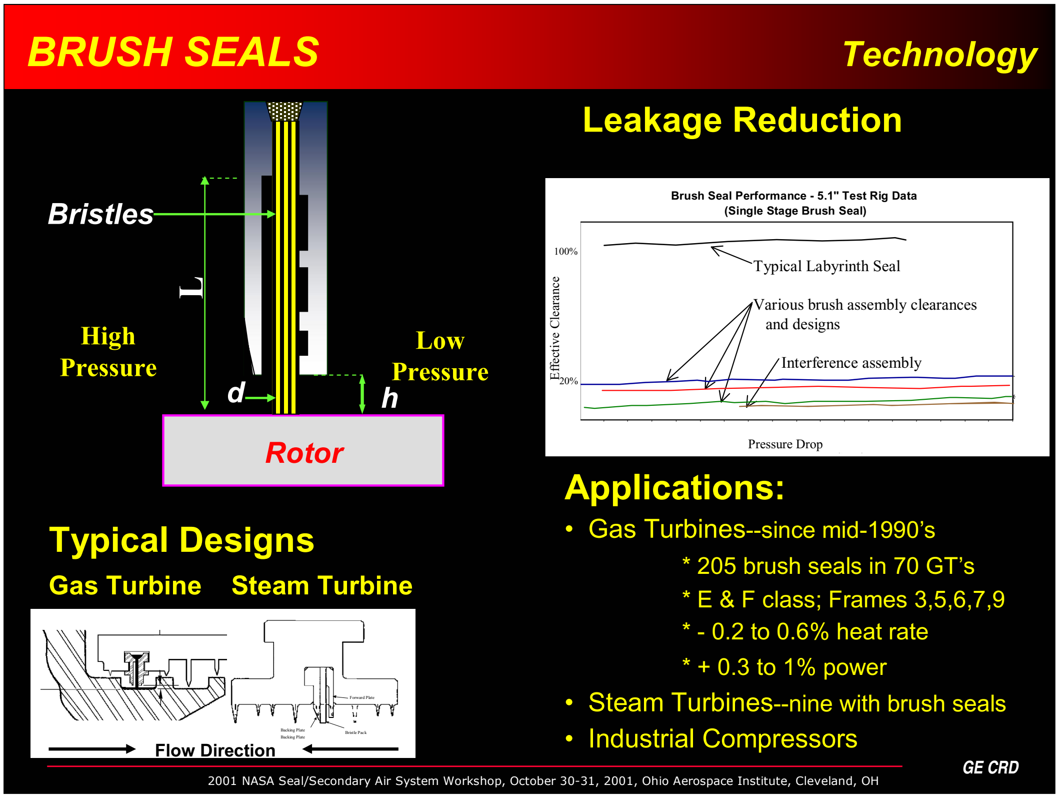


For temperatures above 760 C (1400 F), porous ceramics are generally used as the abradable material. The most widely used material is yttria-stabilized zirconia (YSZ). A fugitive polymeric phase is usually added to produce the desired level of porosity. To prevent blade tip wear, a cutting element is generally added on the blade tips, e.g., hard grits. Choosing the grits and processes to apply them has been investigated extensively and numerous patents issued. Most common grits are cBN, silicon carbide, aluminum oxide, and zirconium oxide. cBN is the best abrasive material against YSZ. But it has a relatively low oxidation temperature (850 C, 1560 F) so it only functions for a short time at elevated temperatures.

The ceramic coating microstructure and porosity are also important for abradability. The more porous the coating is, the higher its abradability but the lower its erosion resistance.

Thermally sprayed YSZ coatings display different tribological behavior compared to metallic abradables. Wear of ceramics is strongly influenced by blade-tip velocity with abradability improving with increasing velocity. Also, they tend to show poorer abradability at very low incursions rates (typical of power generation turbines), thus requiring blade tips.

The design considerations on this chart make the abradable system unique. The abradable seal must be design to fit the particular application. Thus, even though there are many off-the-shelf abradable seal materials, these materials usually have to be modified or redesigned to fit the particular design constraints.



Brush seals can significantly reduce leakage flows in rotating machinery vs. labyrinth seals. They have been under development by GE, other OEM's, seal vendors, Air Force, and NASA. GE's application of brush seals in their power generation turbines is summarized on this chart. Technology development continues to leverage aircraft engine applications. Typical applications put a brush seals in series with labyrinth seal teeth in current seal locations. This reduces the risk when applying a newer technology while providing a means of measuring brush seal performance and any long term deterioration.

BRUSH SEALS — Business Impact

HPP Brush Seals

Performance Improvement	
(Output/Heat Rate)	
HPP	
32G	+0.7%/-0.5%
32J	+0.7%/-0.5%
51P	+0.6%/-0.45%
61B	+1.0%/-0.5%
71E,EA	+1.0%/-0.5%
91E	+1.0%/-0.5%

#2 Bearing Brush

Performance Improvement	
(Output/Heat Rate)	
BRG2*	
71E	+0.3%/-0.2%
91E	+0.3%/-0.2%
HPP and BRG2**	
52C	+0.7%/-0.5%
52D	+0.9%/-0.6%
71B	+1.0%/-0.5%
91B	+1.0%/-0.5%

Brush Seals for Steam Turbine

Efficiency Benefit Compared to New Labyrinth Seals	
Large Steam Turbines (HP Section)	
End Packings	0.1-0.2% unit heat rate
Interstage Packing	0.5-1.2% HP section efficiency
	0.1-0.2% unit heat rate
Industrial Steam Turbines	
End Packings	0.4 - 0.8% efficiency
Interstage Packing	0.2 - 0.4% efficiency

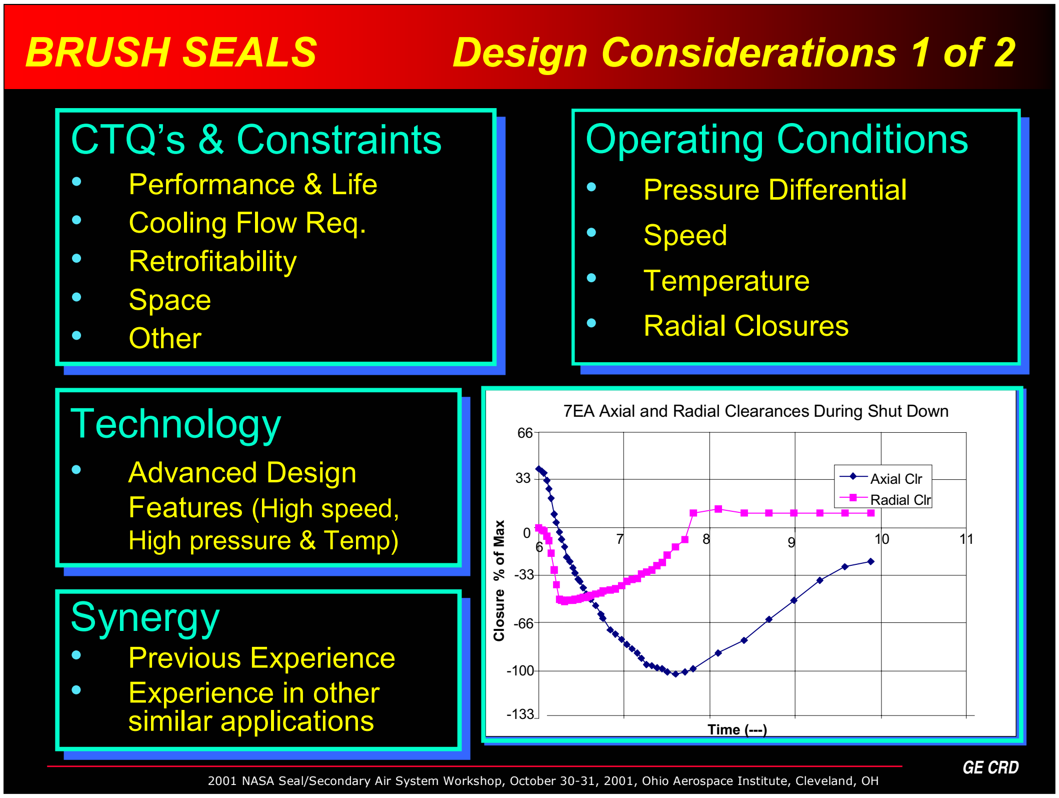
Interstage Brush Seals

Performance Improvement	
(Output/Heat Rate)	
ISTG	
51N	+1.0%/-0.5%
51P	+1.0%/-0.5%
61B	+1.0%/-0.5%
71E,EA	+1.0%/-0.5%
91E	+1.0%/-0.5%

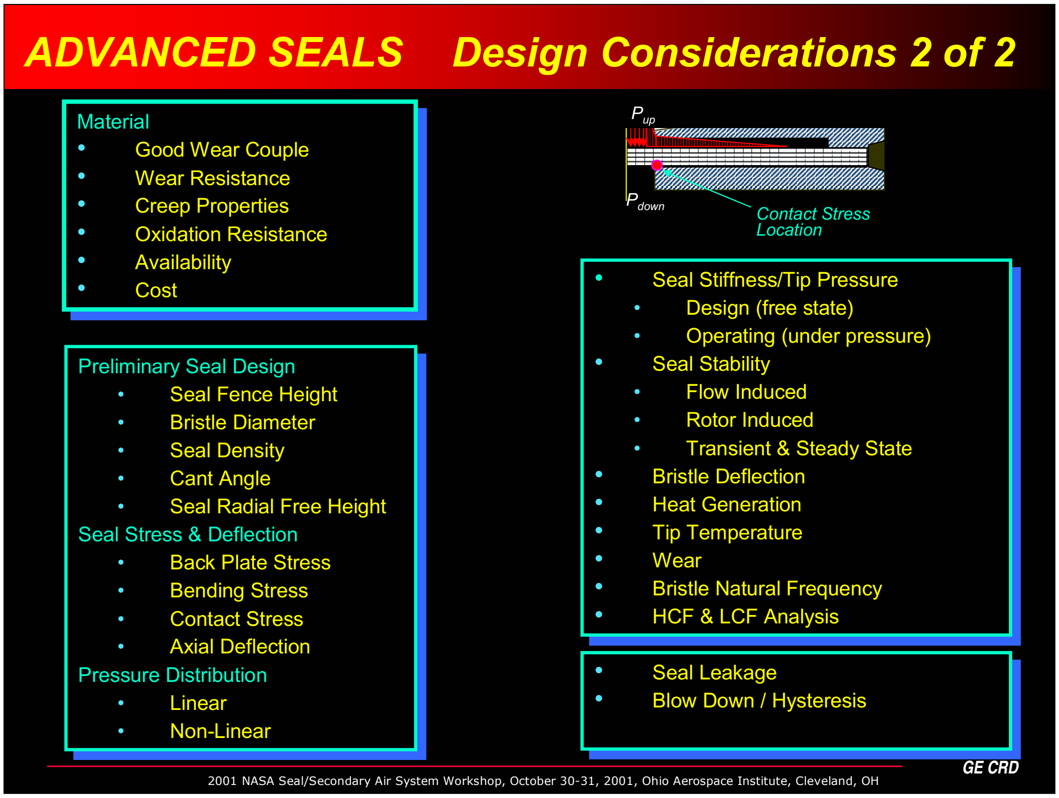
2001 NASA Seal/Secondary Air System Workshop, October 30-31, 2001, Ohio Aerospace Institute, Cleveland, OH

GE CRD

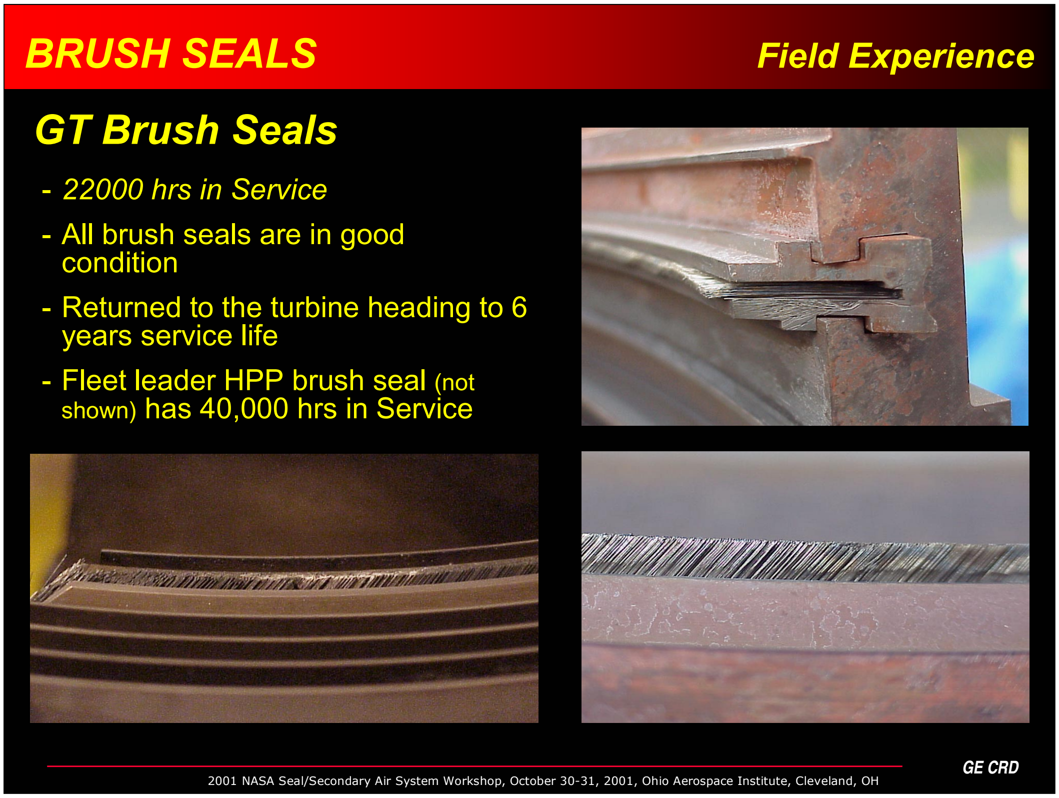
These performance benefits of applying brush seals to GE turbines were taken from a recent company brochure. These gains are significant and the resulting financial benefits for turbine customers far exceed the cost of implementing brush seals into their machines.



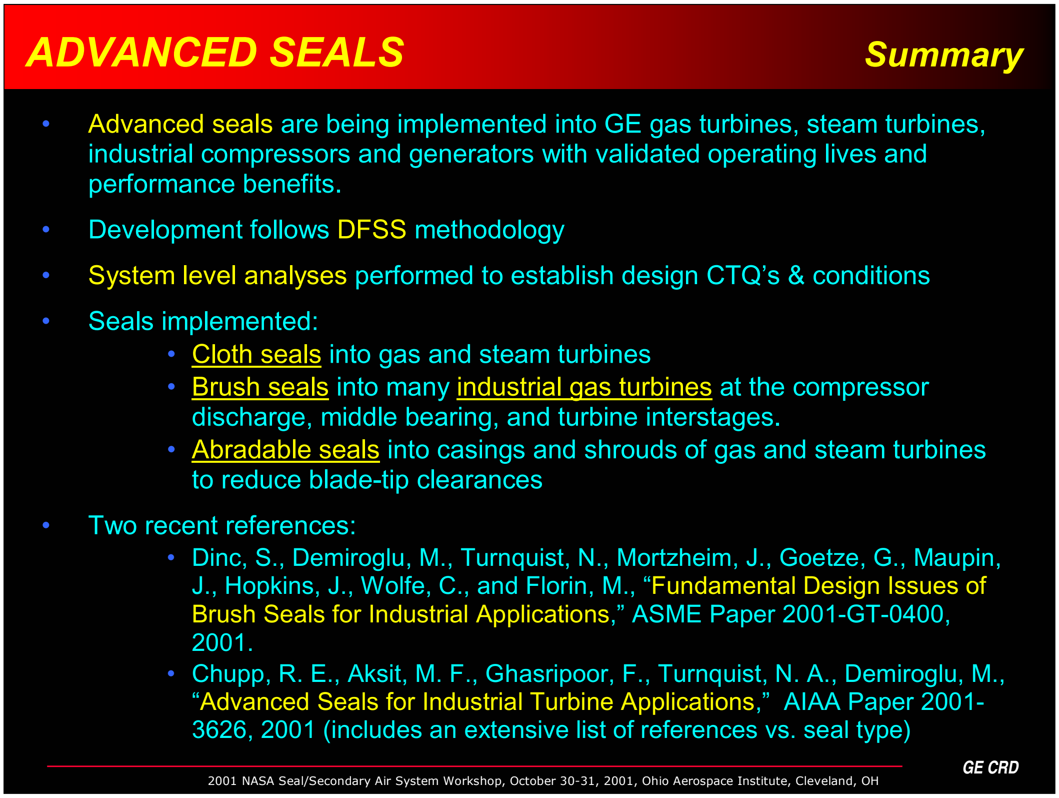
This first of two charts listing brush seal design considerations shows the top level CTQ's and issues to consider. A system level analysis has previously been performed to define many of these considerations.



This second chart gives a detailed list of the next level down design considerations. These are thoroughly addressed following company design practices. Detailed analyses and experimentally derived transfer functions are used in this process. Following this approach insures the brush seals are designed properly so that it meets the system requirements, the desired leakage reduction, and the desired operating life.



This chart gives a brief summary of field experience in applying brush seals to GE industrial gas turbines. The long life seal experience realized validates the seal design technology and practices in place.



In summary, advanced seals are well underway of being incorporated into GE industrial turbines. These include cloth seals, brush seals, and abradable seals. In the next part of this presentation, brush seals as applied to steam turbine will be discussed. More details of the application of advanced seals is given in two recent publications.

IMPROVED STEAM TURBINE LEAKAGE CONTROL WITH A BRUSH SEAL DESIGN

Norman Turnquist and Raymond E. Chupp
General Electric Corporate Research and Development
Niskayuna, New York

Ryan Pastrana
General Electric Energy Services
Atlanta, Georgia

Chris Wolfe and Mark Burnett
General Electric Power Systems
Schenectady, New York

Modified version of a presentation given by Ryan Pastrana at the recent Texas A&M Turbomachinery Symposium, September, 2001.

GE has installed approximately 70 brush seals in the field (in 9 machines).

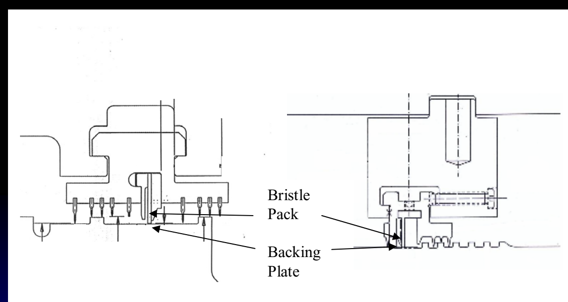
Being designed into new units as well as retrofits.

INTRODUCTION

- Performance Benefits
- Design Parameters
- System Considerations
- Laboratory Testing
- Field Experience
- Conclusion

Typical Design Characteristics

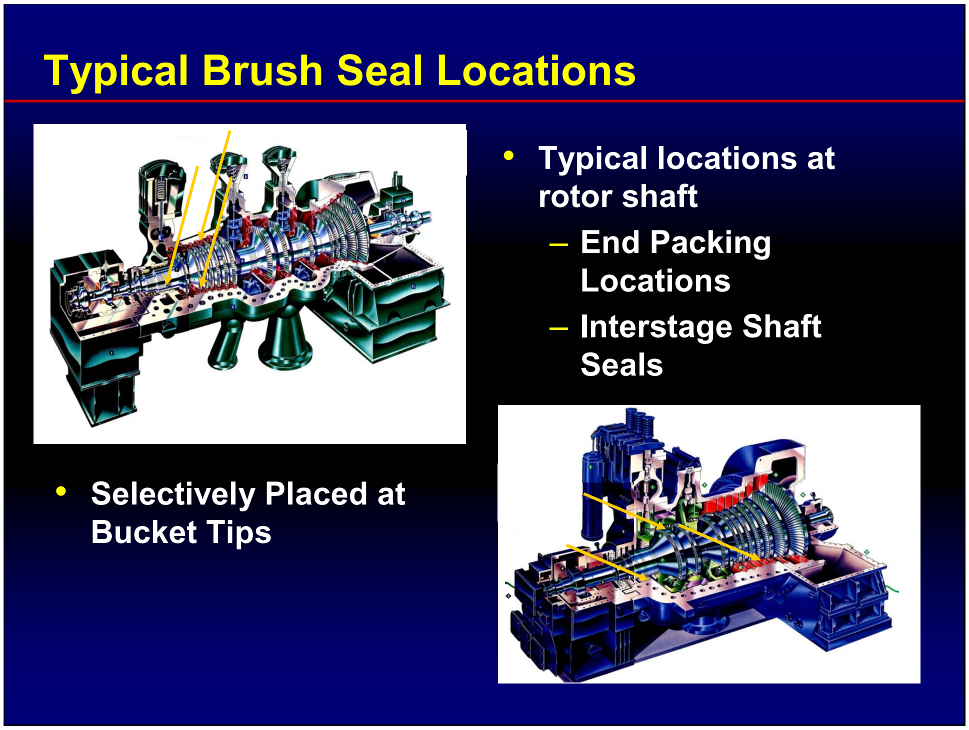
- Standard Labyrinth Seal Ring is Machined to Fit Brush Seal
- Insert Design Comprised of Bristle Strip – Groove in Labyrinth Ring serves as Backing Plate



Two configurations:

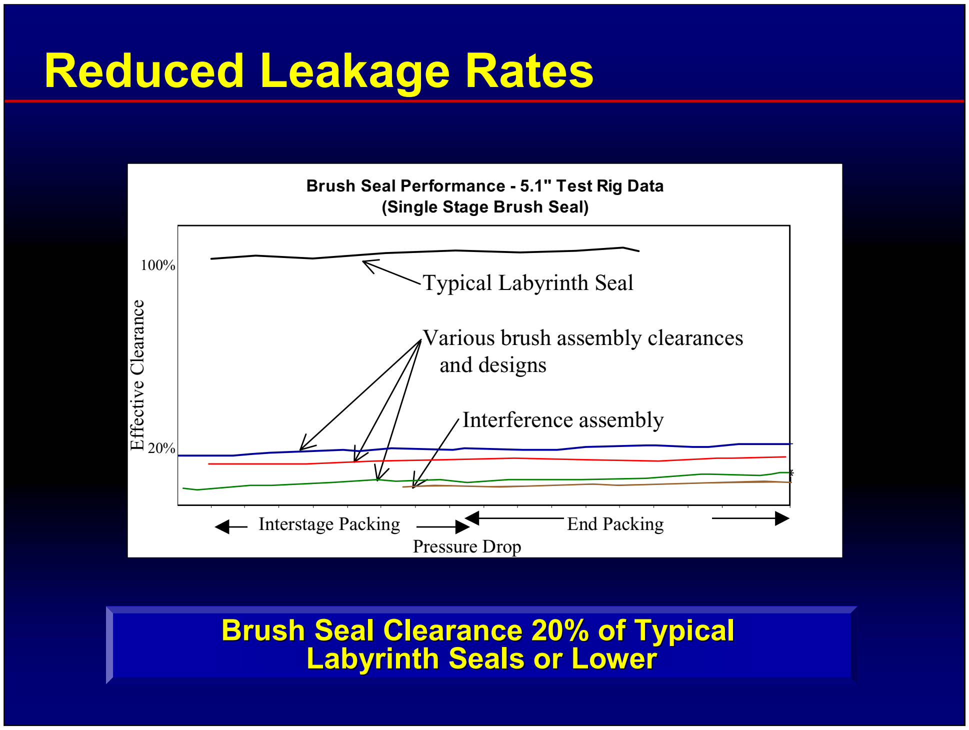
-Conventional brush seal fitted into existing labyrinth packing ring.

- New design - the pack is welded to side rails and the strip is slid into a slot in the packing ring. The side of the slot serves as the backplate. Can be rolled to diameter for cycle time savings.



Typical High Pressure section may have 8-12 turbine stages.

Typical brush seal application would be one brush at each interstage location, and 3-6 brush seals at end packing locations.


Reduced Leakage Rates
Brush Seal Performance - 5.1" Test Rig Data
(Single Stage Brush Seal)
100%
20%
Effective Clearance
Typical Labyrinth Seal
Various brush assembly clearances
and designs
Interference assembly
Interstage Packing
End Packing
Pressure Drop
Brush Seal Clearance 20% of Typical
Labyrinth Seals or Lower

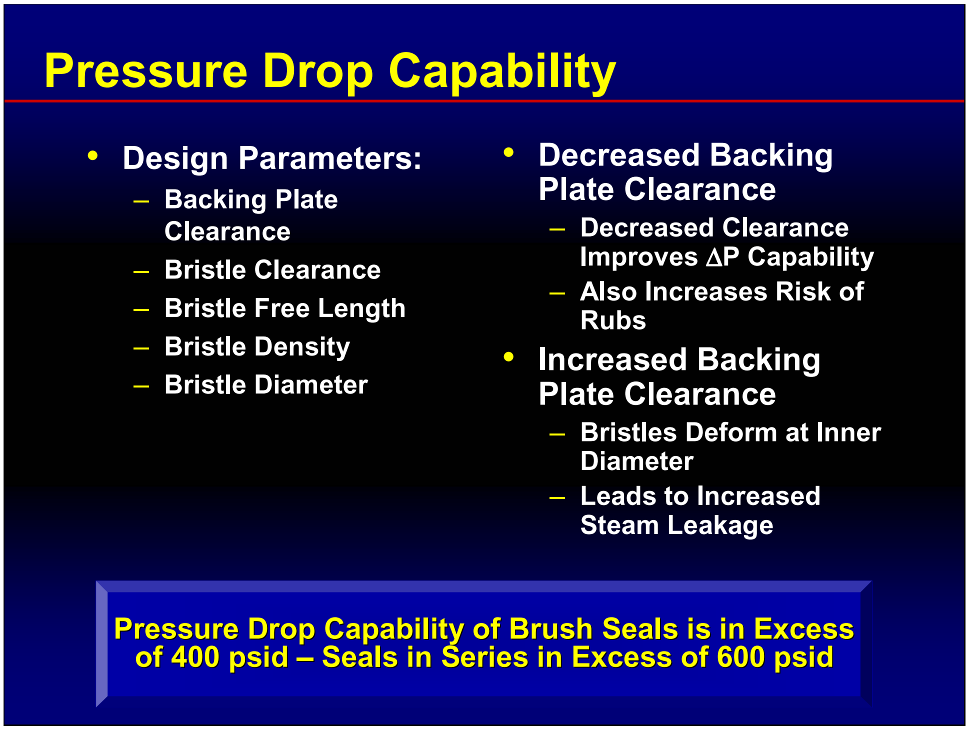
Performance Benefits

	Utility ST	Industrial ST
Interstage	0.5-1.2% HP section efficiency; 0.1-0.2% unit heat rate	0.2-0.4% efficiency
End Packing	0.1-0.2% unit heat rate	0.4-0.8% efficiency
Bucket Tip	0.5-1.0% HP section efficiency; 0.1-0.2% unit heat rate	0.7-1.1% efficiency

Utility Steam Turbine is typically rated at 400-800 MW.

Industrial ST is typically 50-150 MW.

The performance benefit of brush seals in ST's makes them a <u>significantly</u> worthwhile investment in the majority of Utility and Industrial units.

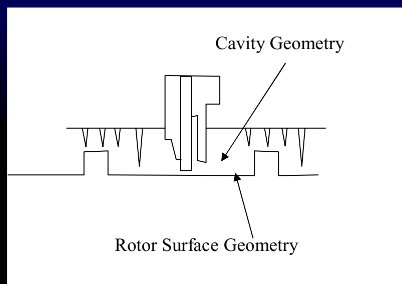


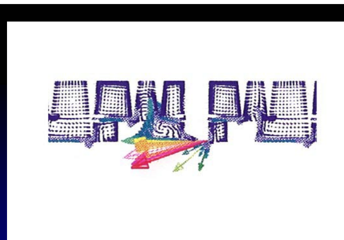
Typical pressure drop across interstage seal is 100-400 psid.

End packing seals typically up to 600 psid.

Can be up to 2000 psid at inlet end of ST; currently working on ways to handle this.

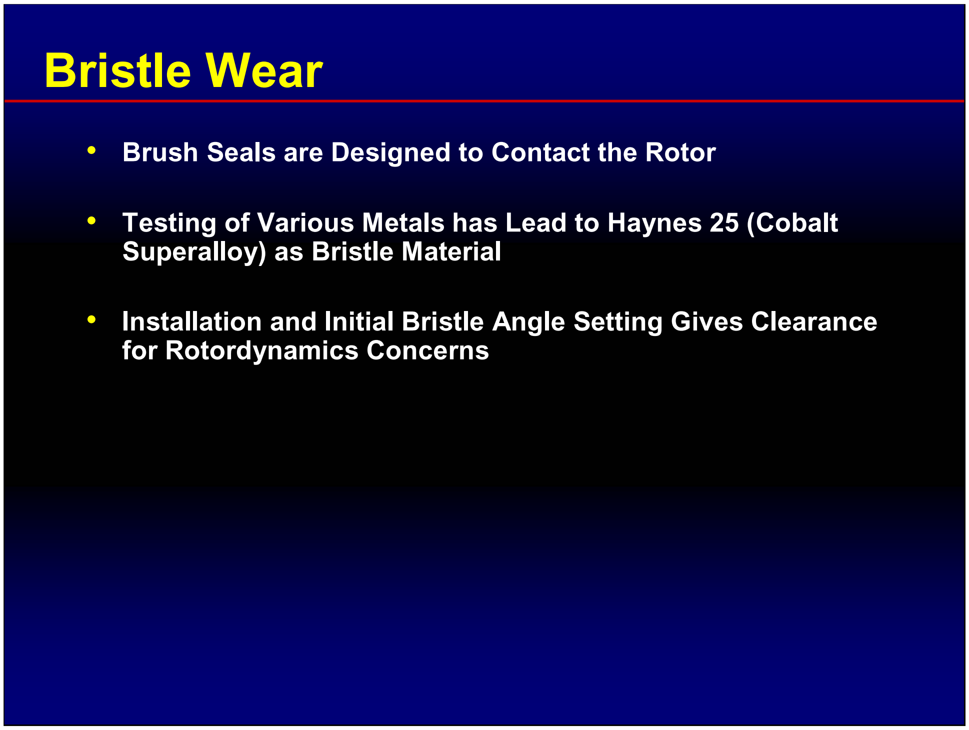
Bristle Stability





- CFD Model of Brush Seal with Velocity Vectors
- Design of Upstream Cavity Key to Reducing Bristle Flutter
- Poor Designs Lead to High Cycle Fatigue of Bristles

Bristle aerodynamic stability is an important design consideration.

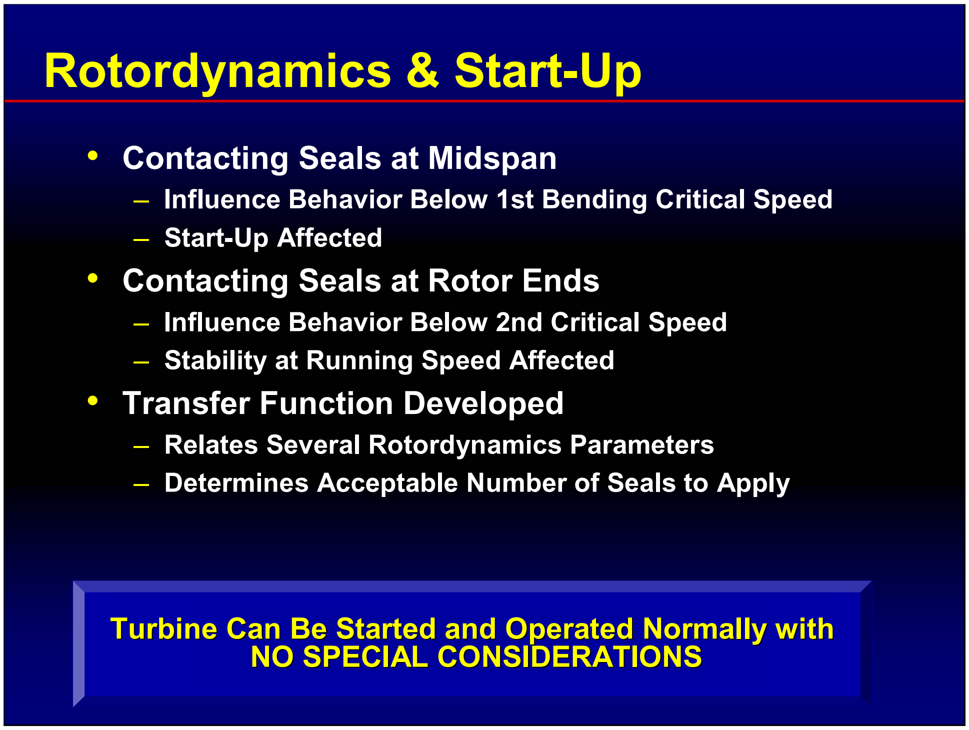


Haynes 25 is standard bristle material for ST applications.

Used on uncoated CrMoV rotor.

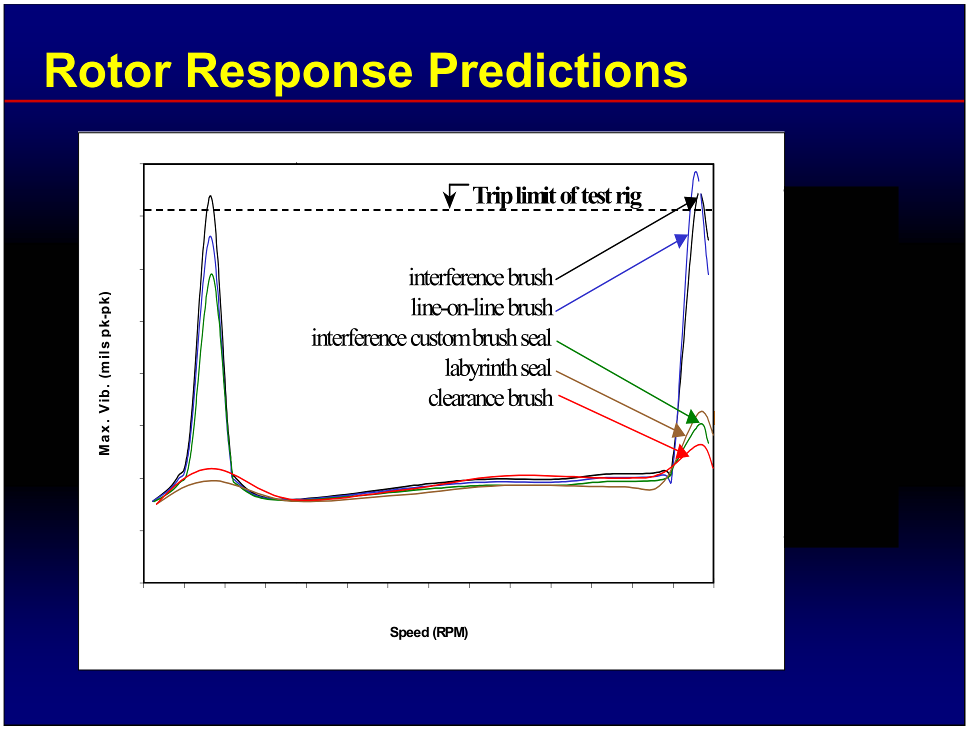
Temperatures range from 500-1050 F in high pressure turbine section.

Initial Angle Setting Allows for Clearance During Start-Up, and At Normal Operation, Steam Blow Down Pushes Bristles into Contact.



Rotordynamics is a very important consideration in how many seals are applied, at which locations, and with what level of assembly clearance/interference.

GE has developed a tool to assess rotordynamic impact; validated through lab testing and field experience.

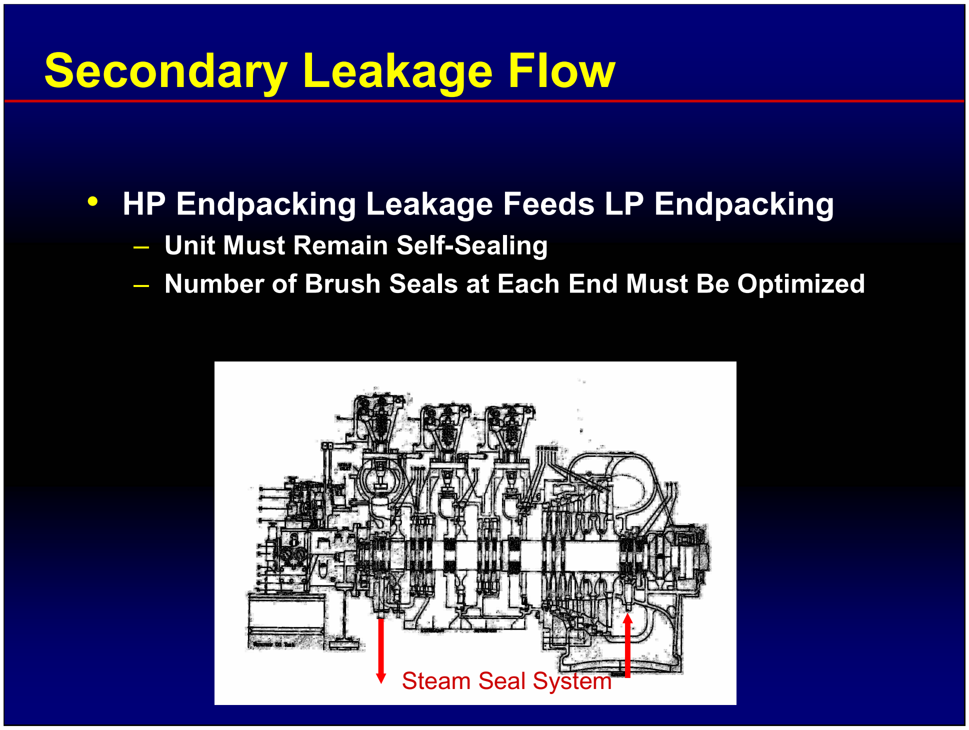


Steam Turbine solid, flexible shaft is sensitive to rub-induced heating and possibility of resultant rotor ‘bow”, which results in rotor vibrations.

Seals concentrated near rotor midspan affect rotor during startup (passing through critical speed). Seals near rotor ends tend to affect rotor at speeds just below 2nd critical speed. (ST’s typically run between the 1st and 2nd critical speeds.

Impact on rotordynamic response is reduced with increasing assembly clearance.

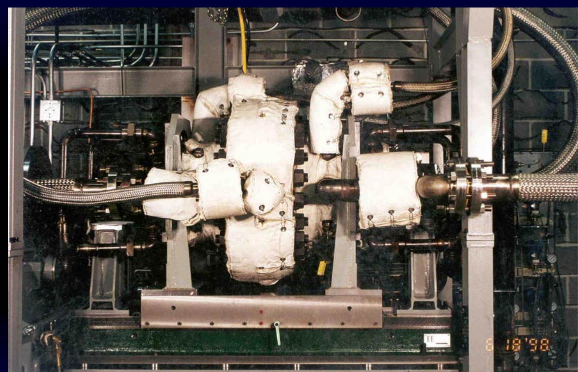
Brush seals assembled with clearance; blowdown results in minimal contact of bristles to rotor, but significant performance improvement.



End packing brush seals must be integrated into the overall unit sealing system.

High Pressure end leakage is used to seal Low Pressure end; need to apply brush seals selectively to balance the system.

Seals Test Rig at GE CRD

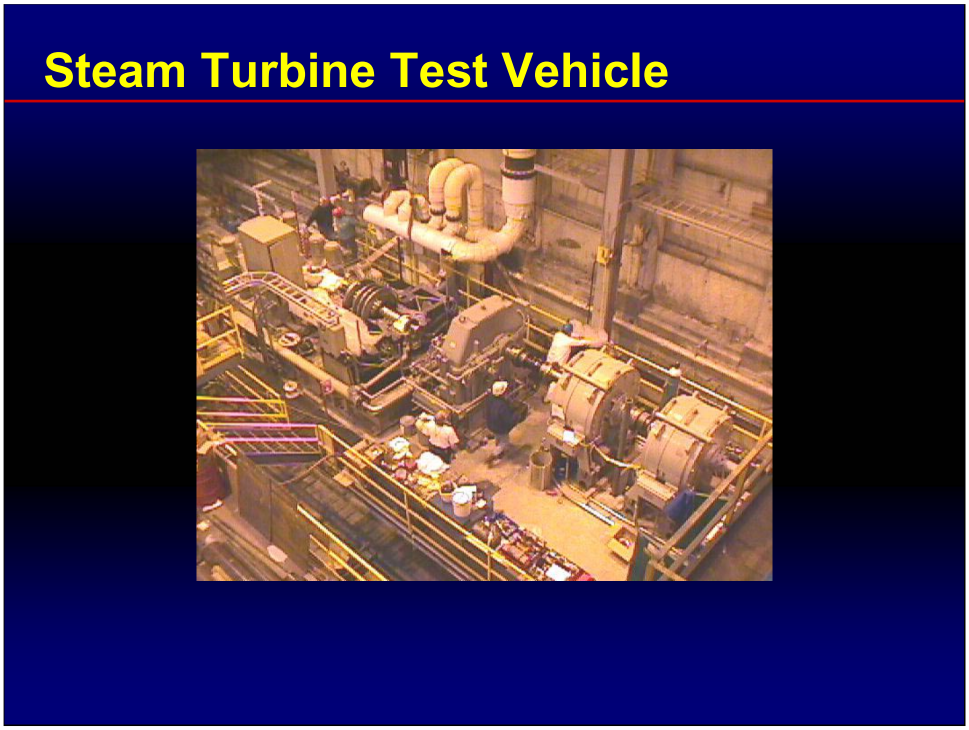


Rig capable of testing in 1200 psi, 750 F Steam
or 450 psi, 1000 F Air

Capable of 800 ft/s surface speed (36000 RPM).

5.1” shaft supported on tilting pad journal bearings; can be run above 1st and 2nd critical speeds to evaluate rotordynamics.

Rig is used for leakage and wear testing of ST, GT, and AE brush and labyrinth seals.



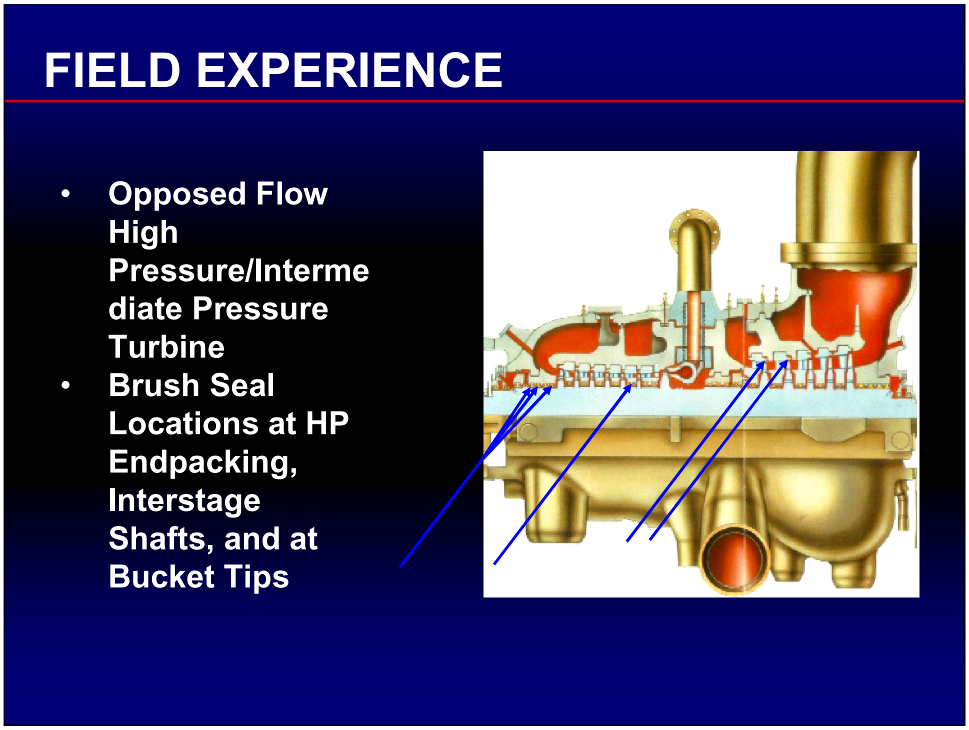
Located in Lynn, MA.

Fully Instrumented Test Vehicle Allows for Pressures, Temperatures to be Measured at Discrete Radial Positions at each stage.

Velocity profiles at specified locations measured.

Back to back performance testing with brush seals in a STEAM ENVIRONMENT validates predictive methods.

Used for validation testing of brush seal performance predictions.



9 machines in the field with approximately 70 brush seals.

Fleet leader has 32000 hours.

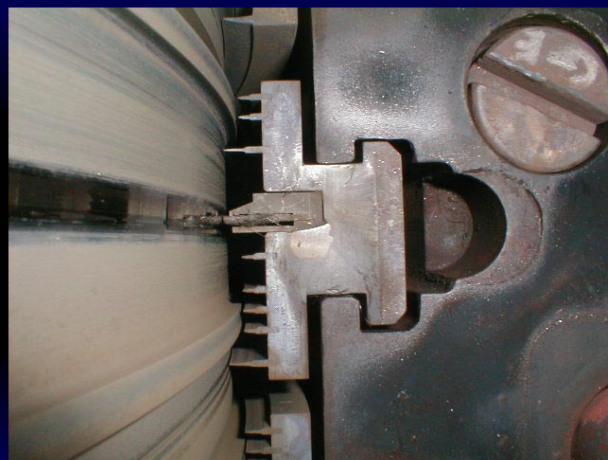
Two unit inspections this year:
- One unit after 3 years (10 seals – all seals looked good, but replaced)
- One unit after 1.5 years (Seals looked good and returned to service)

End packing seals (3 brushes shown).

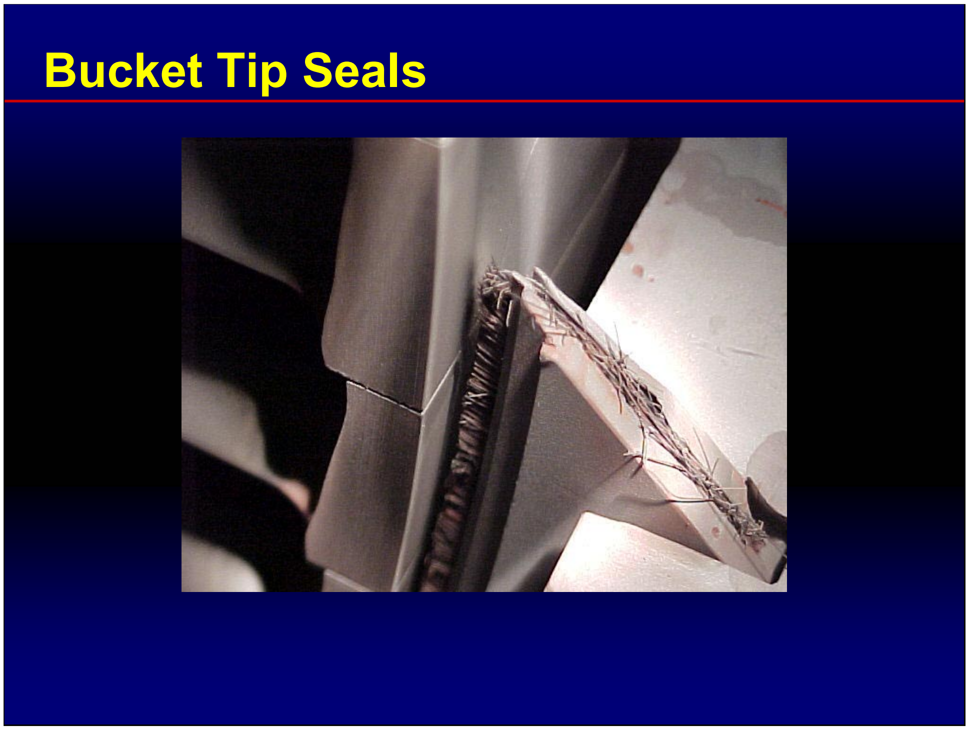
Polishing of rotor surface.

Minimal brush wear observed.

HP Shaft Seals



Note the polished rotor. Not only in this view, but throughout the circumference, the bristles survived. Bristle density is good and clearance (no wear) maintained. These were reinstalled after the outage.



Tip seal in this unit looked very good. This end segment is slightly gnarled at the end, but along the circumference, the bristles survived. Note that over bucket tips, gaps between cover sections or radial steps at the junction of adjacent cover sections are important design considerations.

CONCLUSION

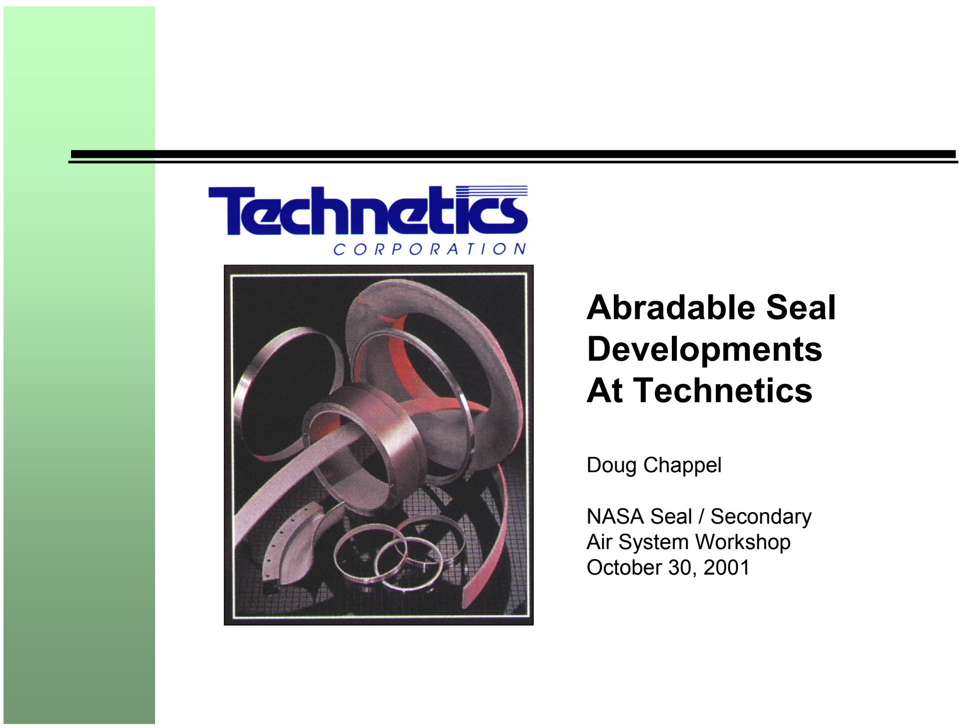
- Performance Benefits Up to 1.2% on Total Output Due to Reduced Leakage Rates for Industrial Sized Machines
- Design Characteristics Well Understood
- Consideration of the Turbine as a System is Very Important
- Analytical Predictions and Extensive Lab Testing Have Been Verified with Field Experience

Latest Inspections Show Excellent Results

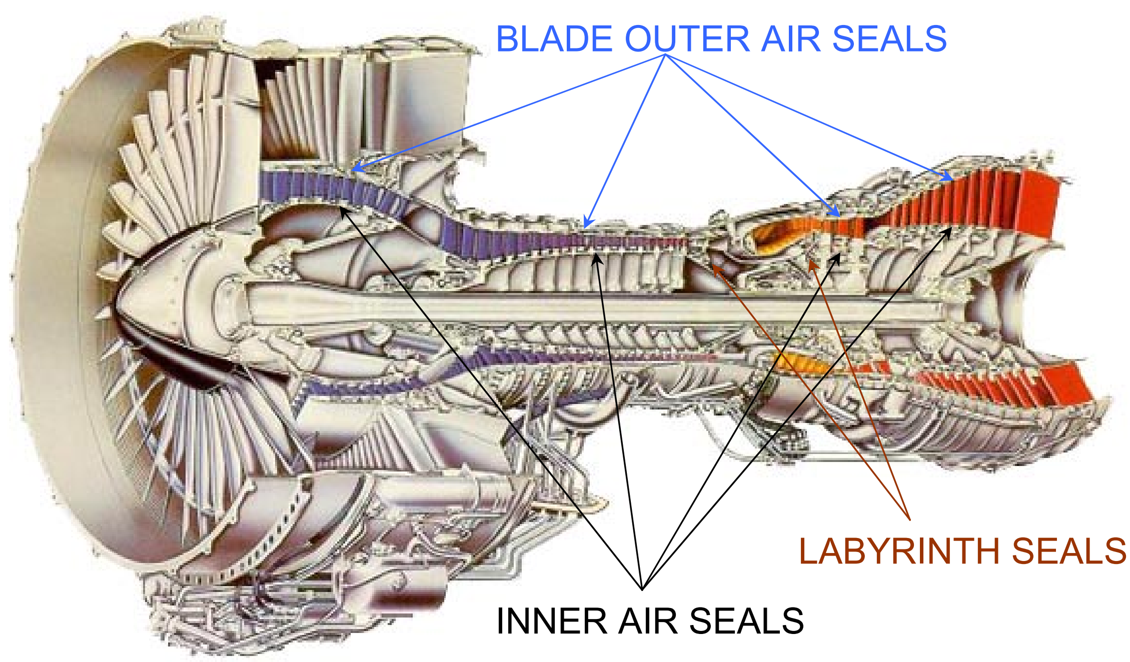
STATUS OF SEAL DEVELOPMENT AT TECHNETICS

Doug Chappel
Technetics Corporation
Indianapolis, Indiana

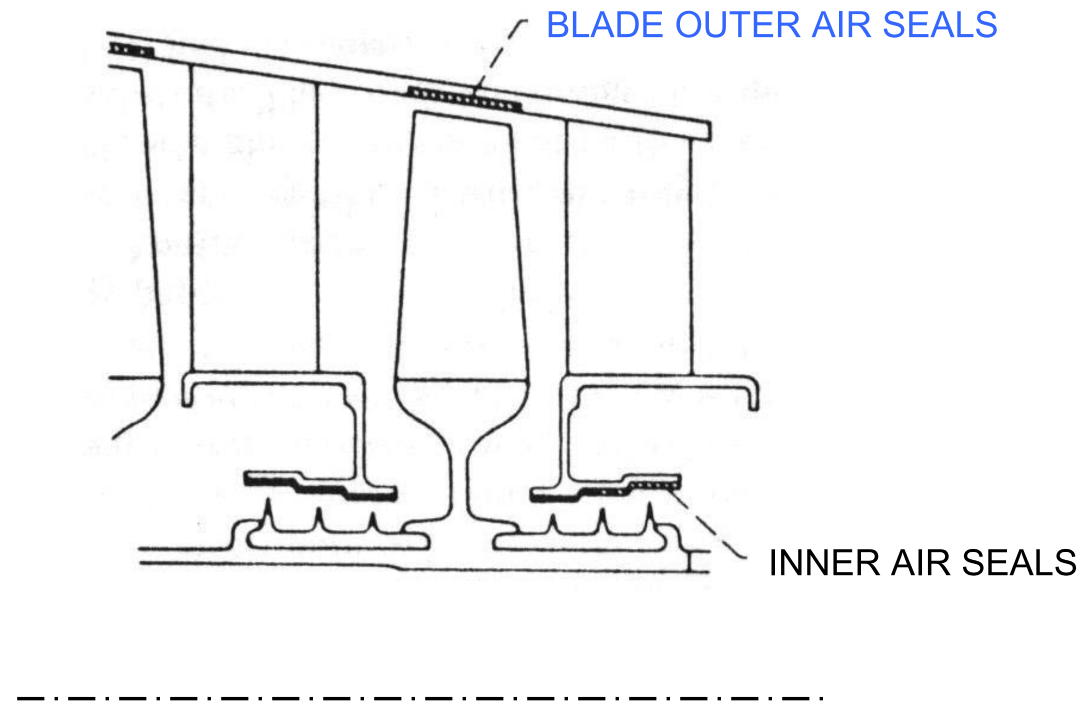
Technetics has recently reported results for blade tip seal rub characteristics. Expanding on this work, Technetics will share rub characteristics for knife edge abradable seal systems typical of those found at vane inner air seal and shaft seal locations.



Typical Abradable Seal Applications

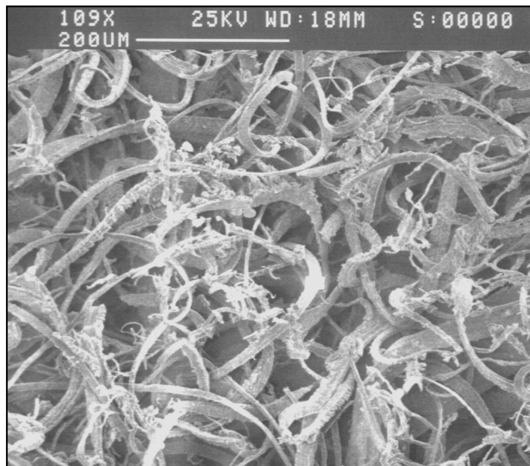


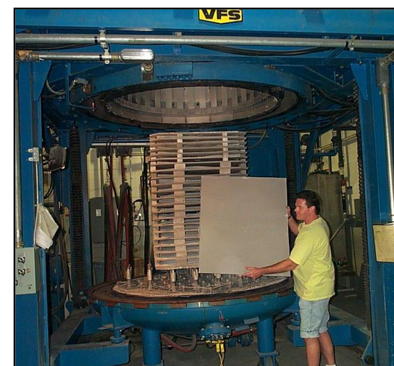
Typical Abradable Seal Applications



What Is Feltmetal®?

Micron Size Fiber Sinter Bonded Into A Continuous Felt





- Typically Hast-X or FeCrAlY
- Density Range 10 – 50%
- UTS Range 500 – 3000 psi
- Temperatures Up To 1400 F

Feltmetal® Compressor Abradable Materials Have Well Over 250 Million Hours Of Successful Operation

Manufacturer	Engine	Aircraft	Engines In Service	Total Engine Hours	
Pratt & Whitney	JT9D	B747, B767, A300, A310, DC-10	2,700	150 Million	
	PW2000	B757, IL-96, C-17	1,100	16 Million	
	PW4000	B747, B767, A300, A310, A330, MD-11	2,000	35 Million	
	F-100	F-15, F-16	6,500	-?-	
P&W Canada	Various	Various	0	0	Enters Service 2000
Rolls-Royce	RB211-524	B747, B767	1700	-?-	
	RB211-535	B757, Tu204	1300	18 Million	
	Trent 500	A340-500, 600	0	0	Enters Service 2001
	Trent 700	A330	60	-?-	
	Trent 800	B777	200	-?-	
	Trent 900	A3XX, B747-X	0	0	Enters Service 2004
	Industrial RB211	n/a	-?-	5 Million	Power Generation
	Industrial Trent	n/a	-?-	-?-	Power Generation
IAE	V2500	A319, A320, A321, MD-90	1300	3 Million	
Honeywell	AGT1500	M1 Abrams Battle Tank	10,000	-?-	

Key Requirements For Abradable Seal Materials

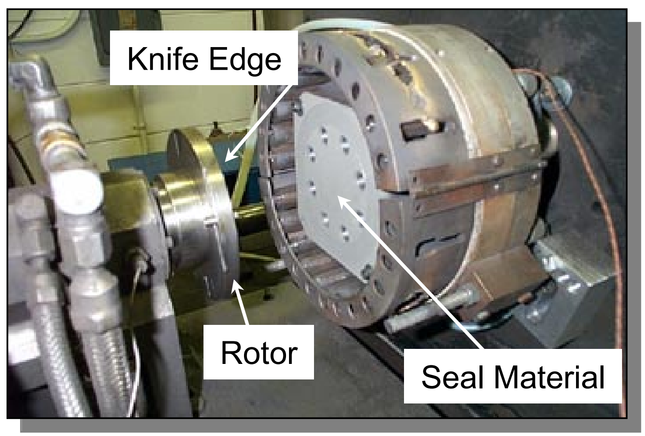
- Clean Cutting With Minimal Blade Wear
- Erosion Resistance
- Operating Life

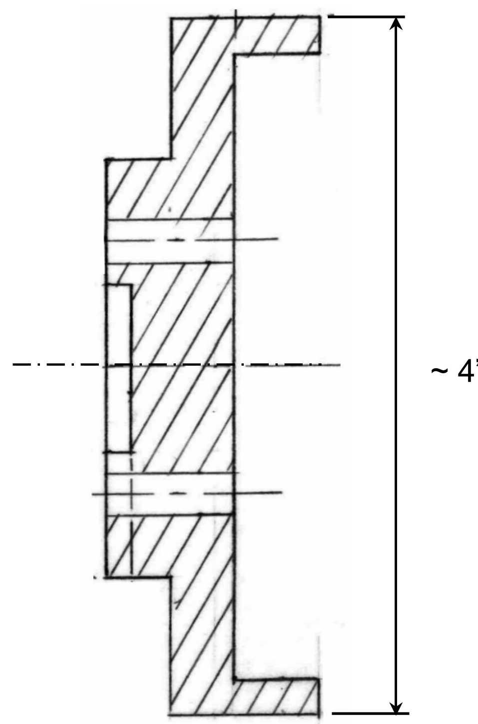
➔ *Performance Is Application Specific*

Typical GT Compressor	AERO	UTILITY
Max Tip Speed	1400 fps	1200 fps
Max Temp	1300 F	1200 F
Incursion Rate	10 mil/sec	0.1 mil / sec
Incursion Depth	20 mils	40+ mils
Knife Edge Material	Ni, Ti	Steel
Knife Edge Thickness	25 mils	Up to 300 mils

Face Configuration Abradability Rig

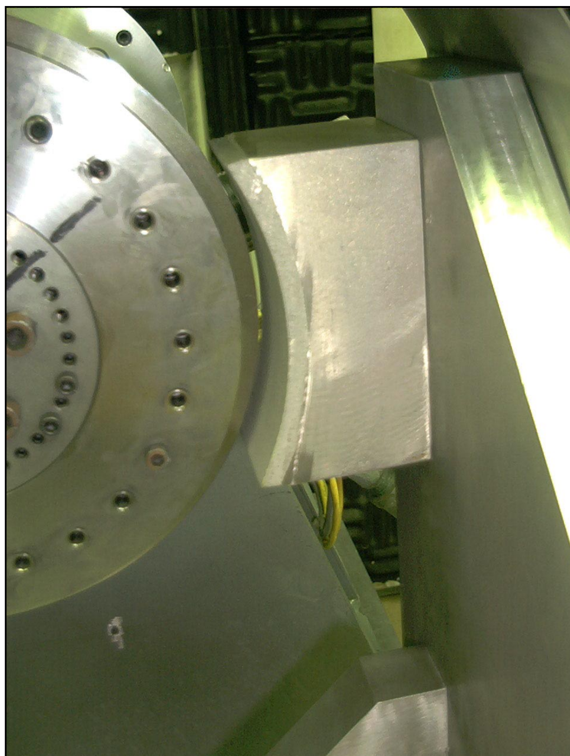
Motion Limited To Plunge Direction

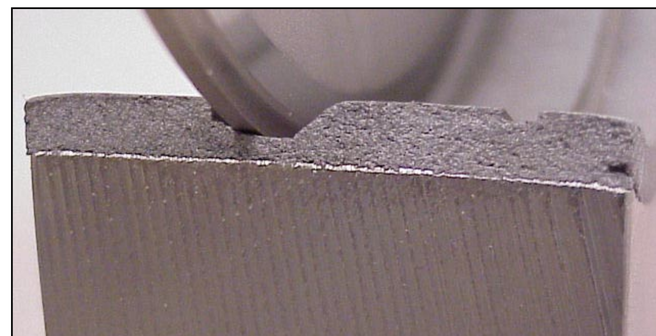




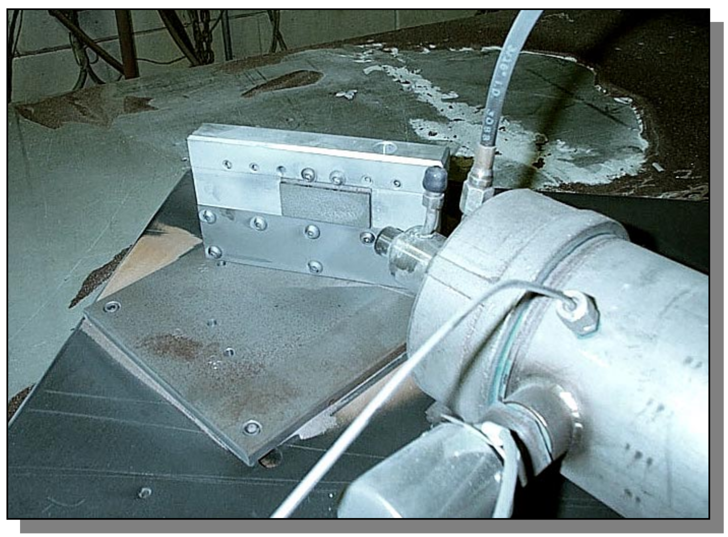
Radial Configuration Abradability Rig

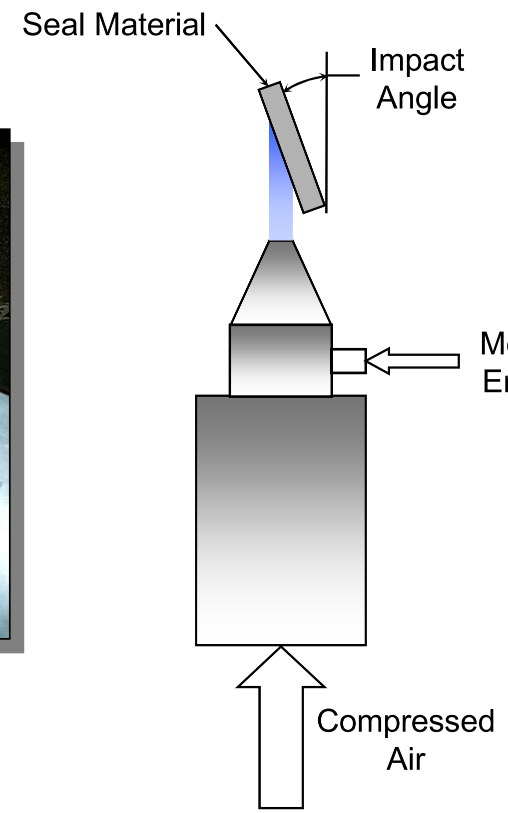
Can Move In Plunge And Sweep Directions





Erosion Test Rig



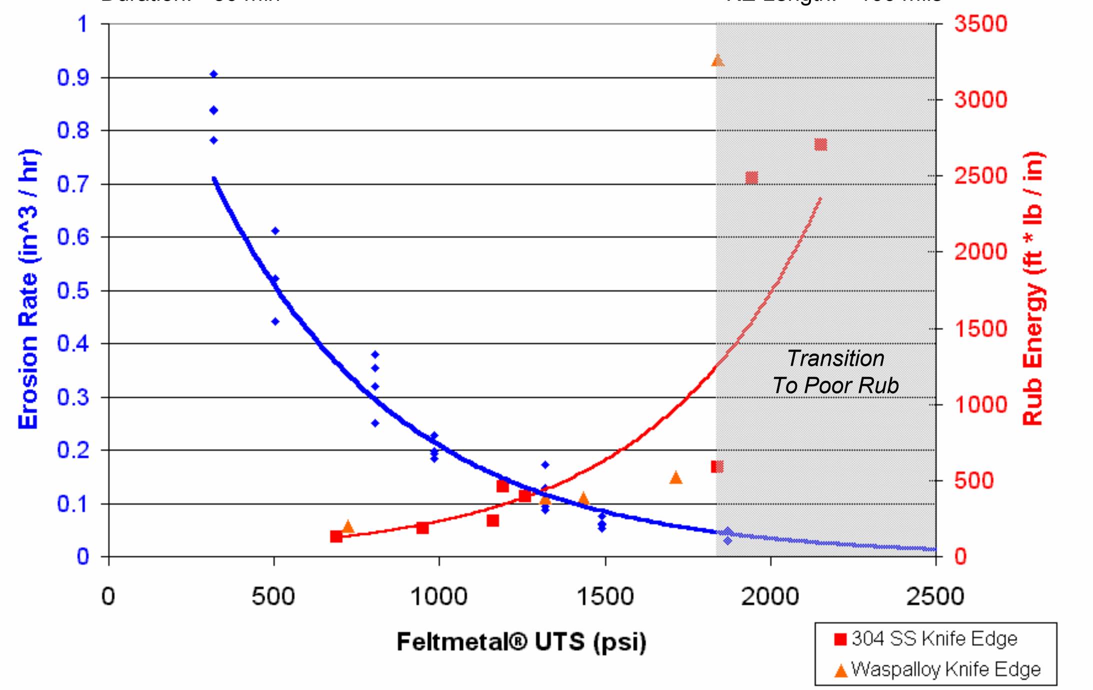


Plunge Data For “Aero” Conditions

Felt Tensile Strength Is The Driving Material Property

Temp:	70F
Erodent::	180u Al2O3
Gas Vel:	425 ft/min
Angle:	20 deg
Feed Rate:	10 g/min
Duration:	30 min

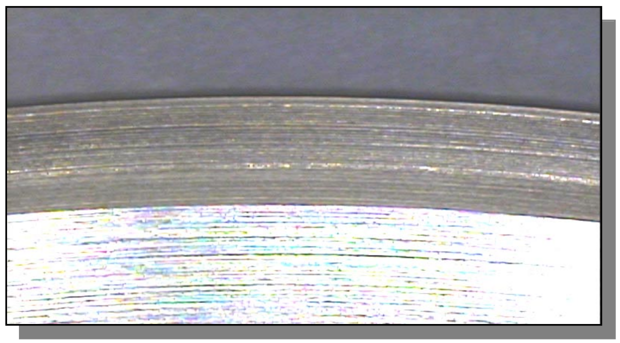
Temp:	70F
Rim Speed:	800 ft/s
Incur. Rate:	5 mil/s
Incur. Depth:	20 mils
KE Width:	20 mils
KE Length:	100 mils

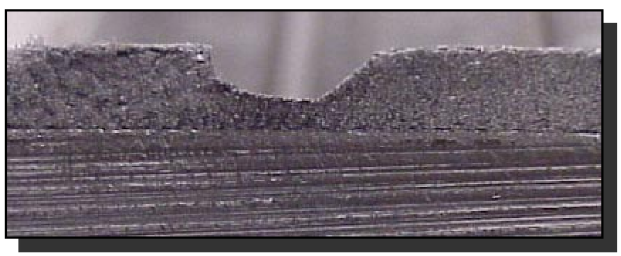


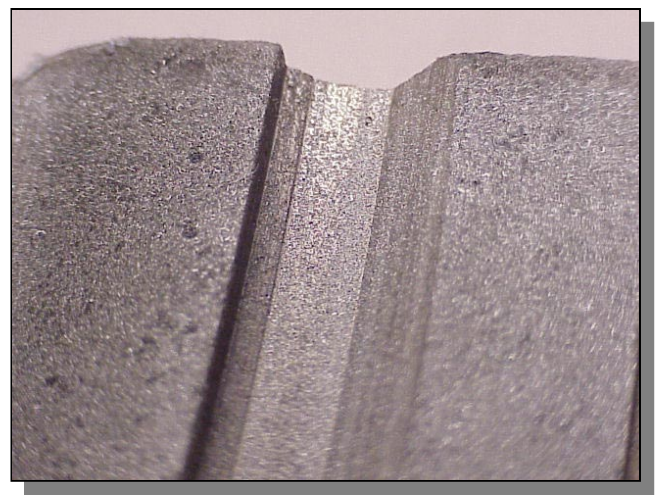
Plunge And Sweep Results For "Utility" Conditions

Clean-Cut Groove, No Blade Wear Or Thermal Distress

Temp:	70F
Rim Speed:	800 ft/s
Incur. Rates:	up to 0.4 mil/s
Axial Travel:	~ 400 mils
Radial Travel:	~ 160 mils
KE Width:	~ 80 mils



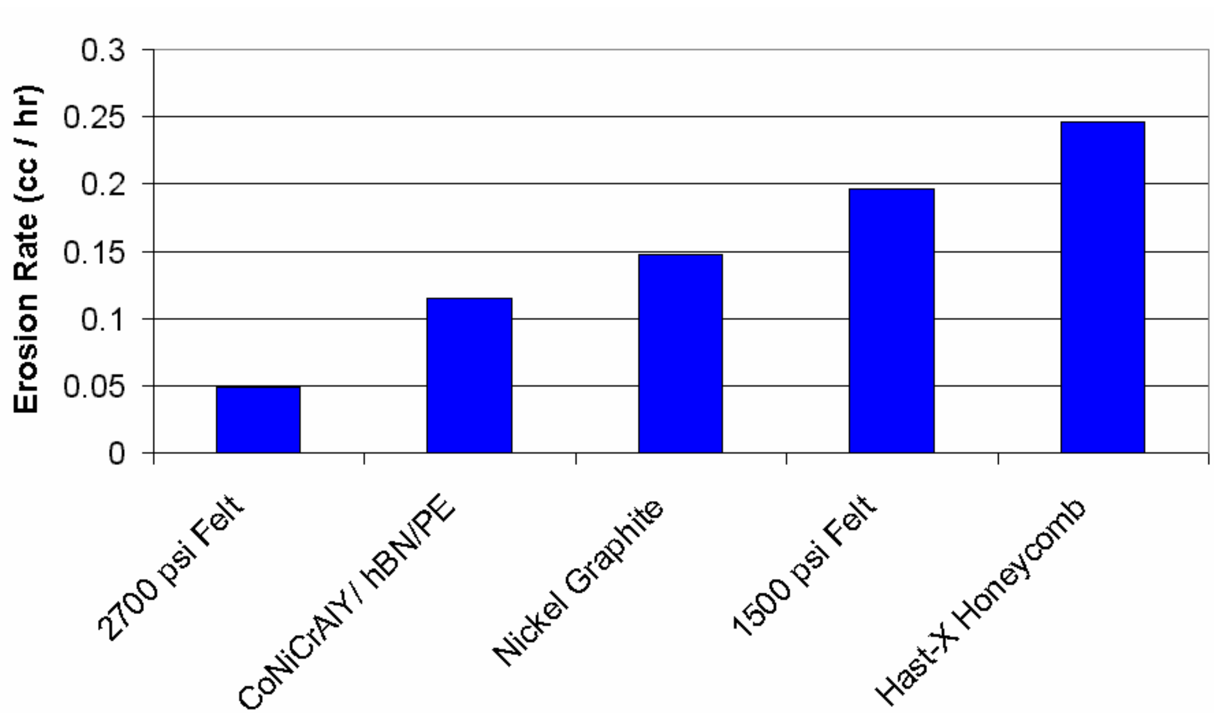




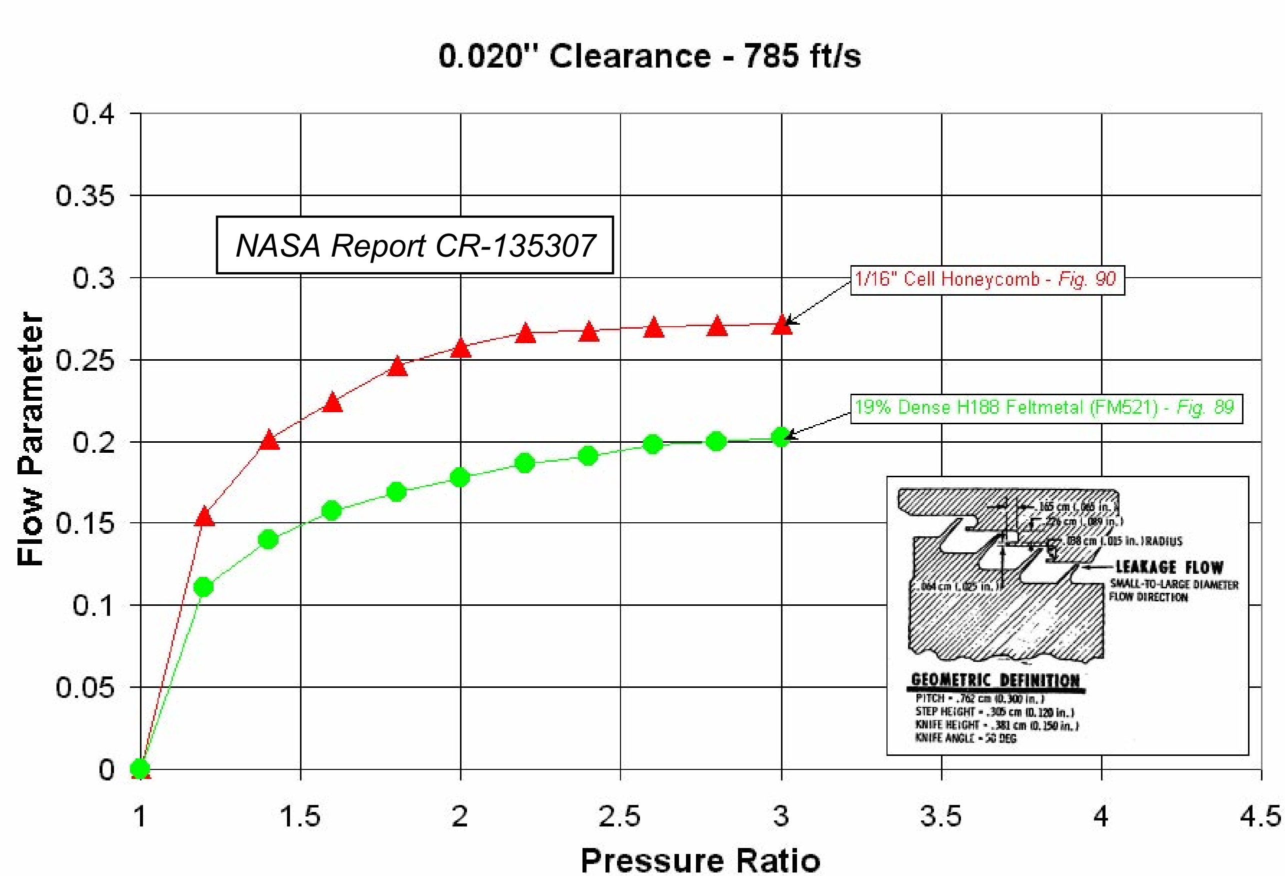
Erosion Test Results

Temp:	70F
Erodent::	60u, Al2O3
Gas Vel:	425 ft/min
Angle:	20 deg
Feed Rate:	10 g/min
Duration:	30 min

Erosion Not As Significant A Concern At Many KE Seal Locations



Potential Benefit: Leakage Flow Reduction

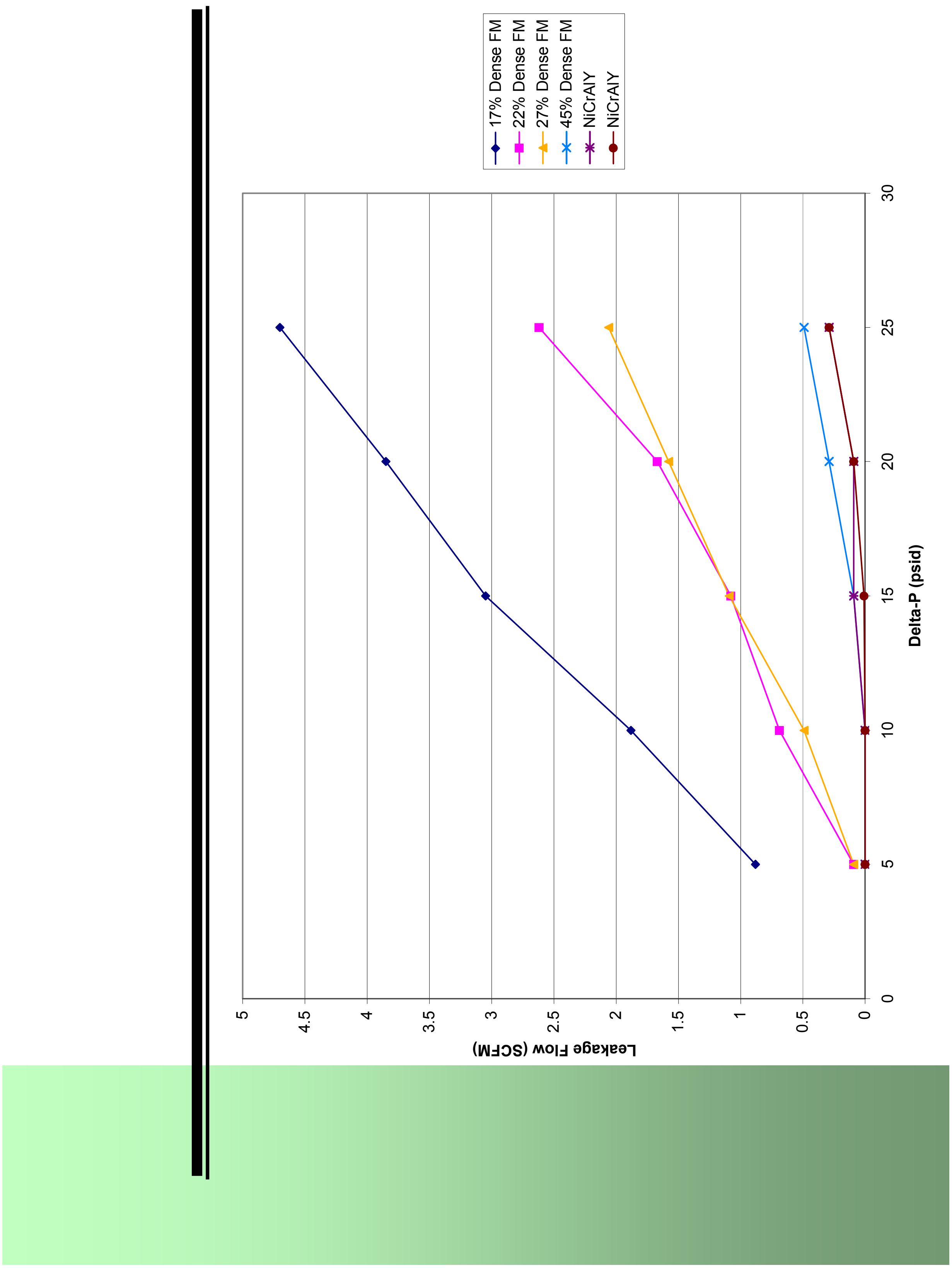


Conclusions

- Like Prior Blade Tip Seal Testing, Knife Edge Seal Abradability Driven By Feltmetal® Tensile Strength.
- Feltmetal® Can Be Tailored To Meet Specific Application Requirement
- Initial Testing Indicates Simultaneous Plunge And Sweep Cutting Is No Problem

Future Work

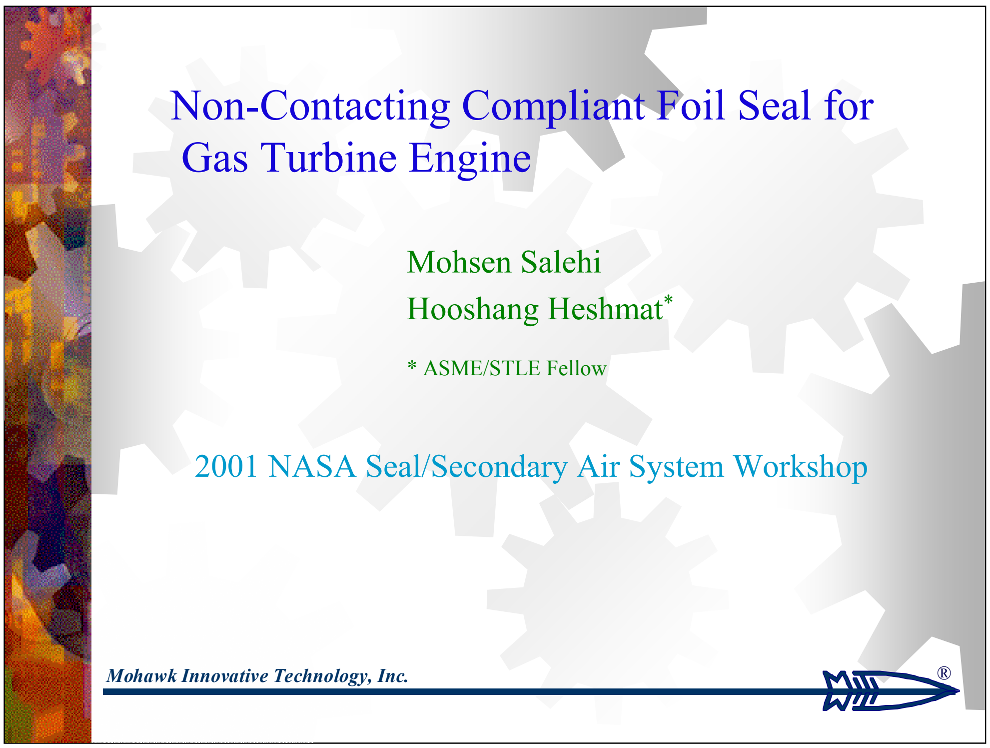
- Titanium Knife Edge Data
- Mapping Limits At Low Interaction Rates
- Benchmark Against Competing Materials
  (Honeycomb, Thermal Spray)
- Leakage Flow Testing
- Establish Industry Standards For Erosion And Abradability Testing



17% Dense FM
22% Dense FM
27% Dense FM
45% Dense FM
NiCrAlY
NiCrAlY
Leakage Flow (SCFM)
Delta-P (psid)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
5
10
15
20
25
30

NON-CONTACTING COMPLIANT FOIL SEAL FOR GAS TURBINE ENGINE

Mohsen Salehi and Hooshang Heshmat
Mohawk Innovative Technology, Inc.
Albany, New York



Acknowledgment

- The authors would like to thank NASA GRC, especially Margaret Proctor and Dr. Bruce M. Steinetz for their guidance and sustained interest in our work

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Overview
• Objectives
• Test Facilities
• Analysis Enhancements
• Accomplishments/Status
• Materials Study
• Conclusions/Remarks
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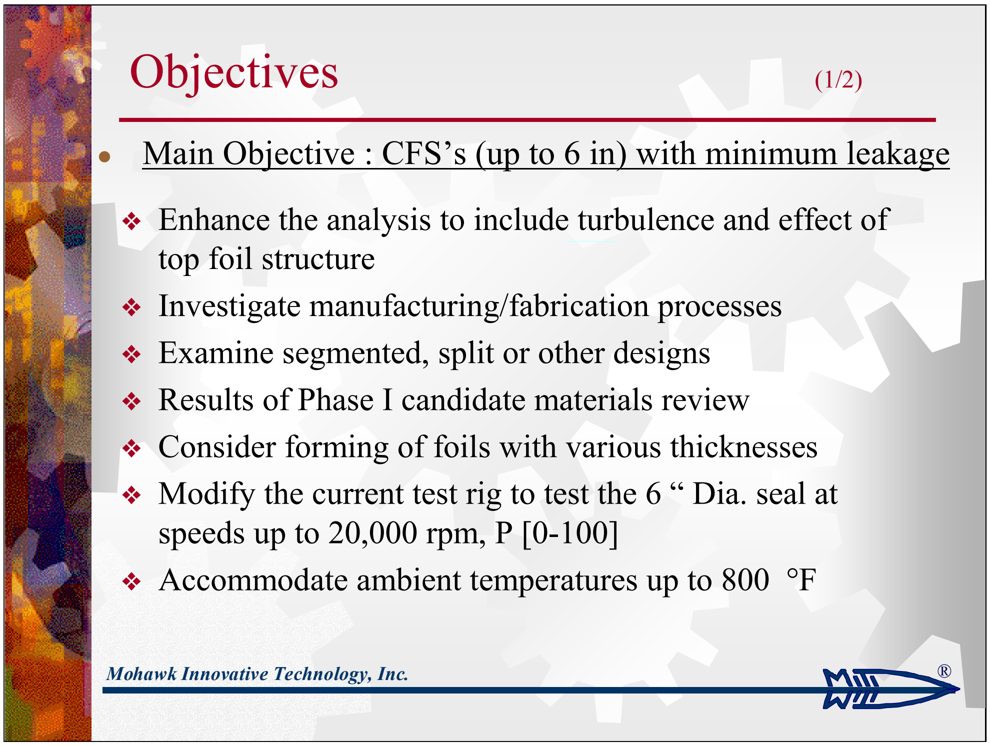
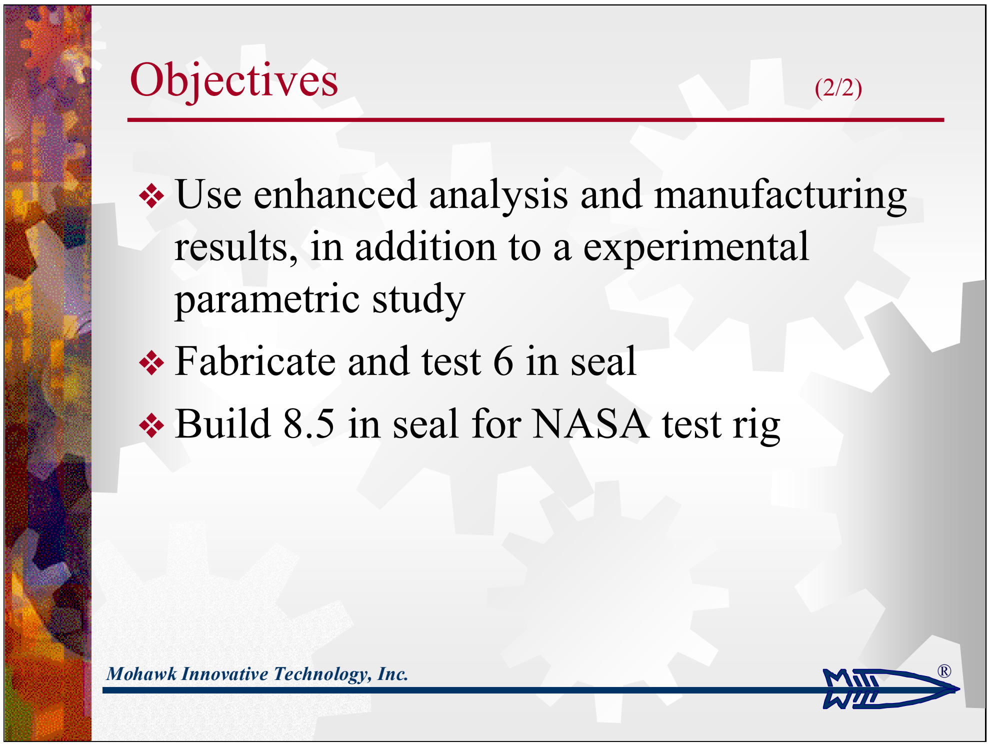


The program aimed at enhancing the existing analysis to include the turbulence effect. Several manufacturing methods are being investigated in order to apply our know-how in building the seal hardware.


Objectives
(2/2)
Use enhanced analysis and manufacturing results, in addition to a experimental parametric study
Fabricate and test 6 in seal
Build 8.5 in seal for NASA test rig
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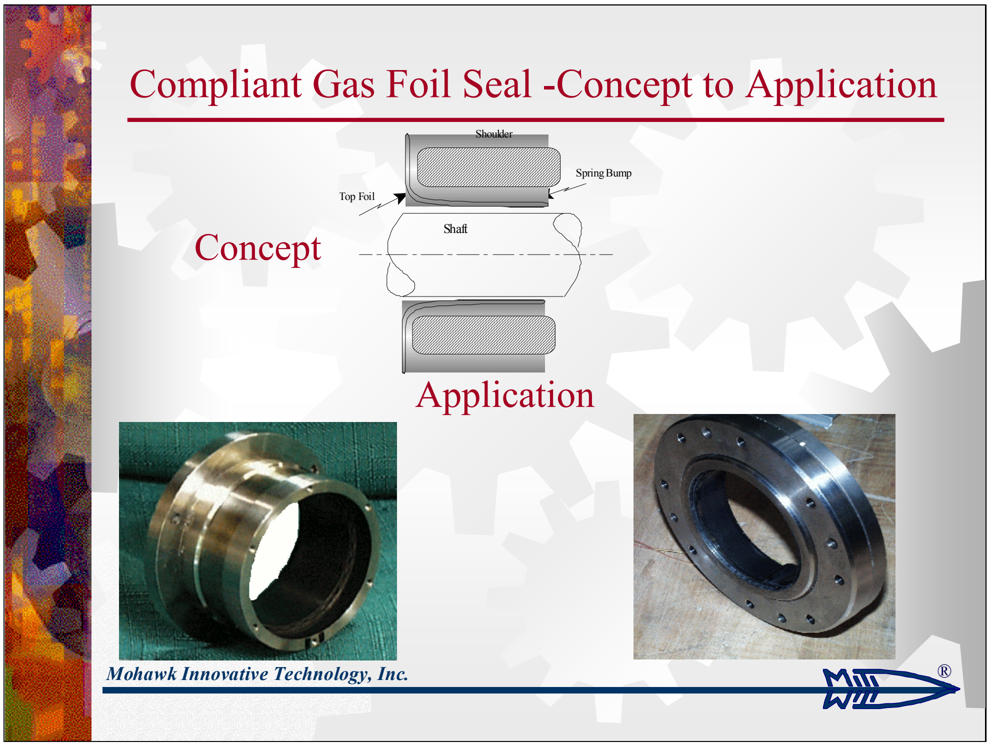
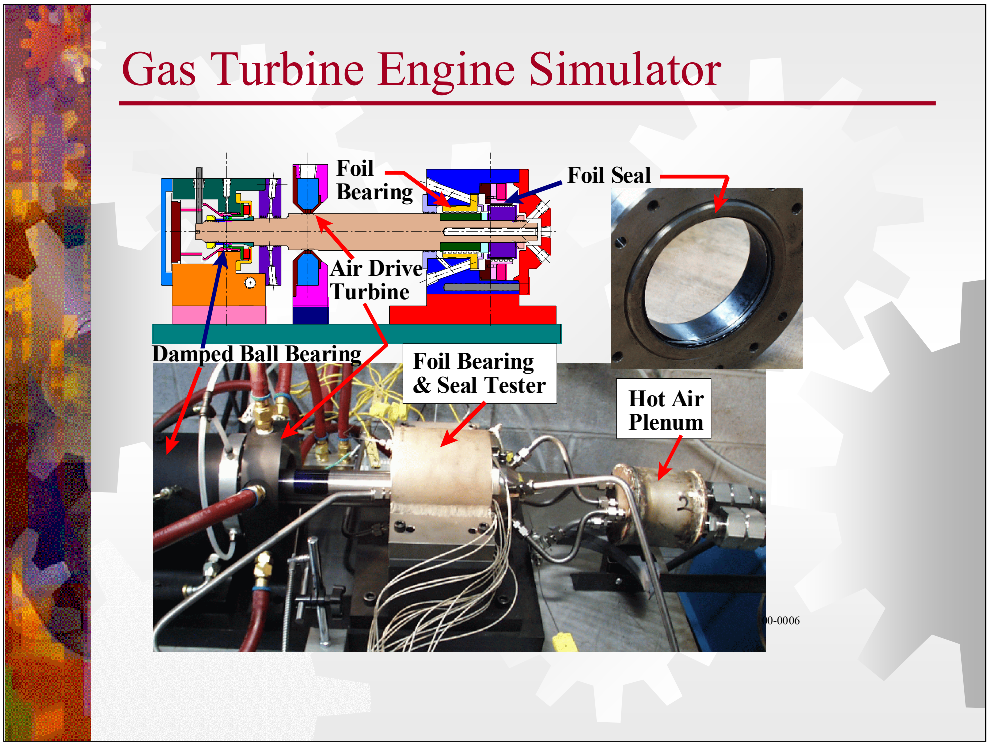
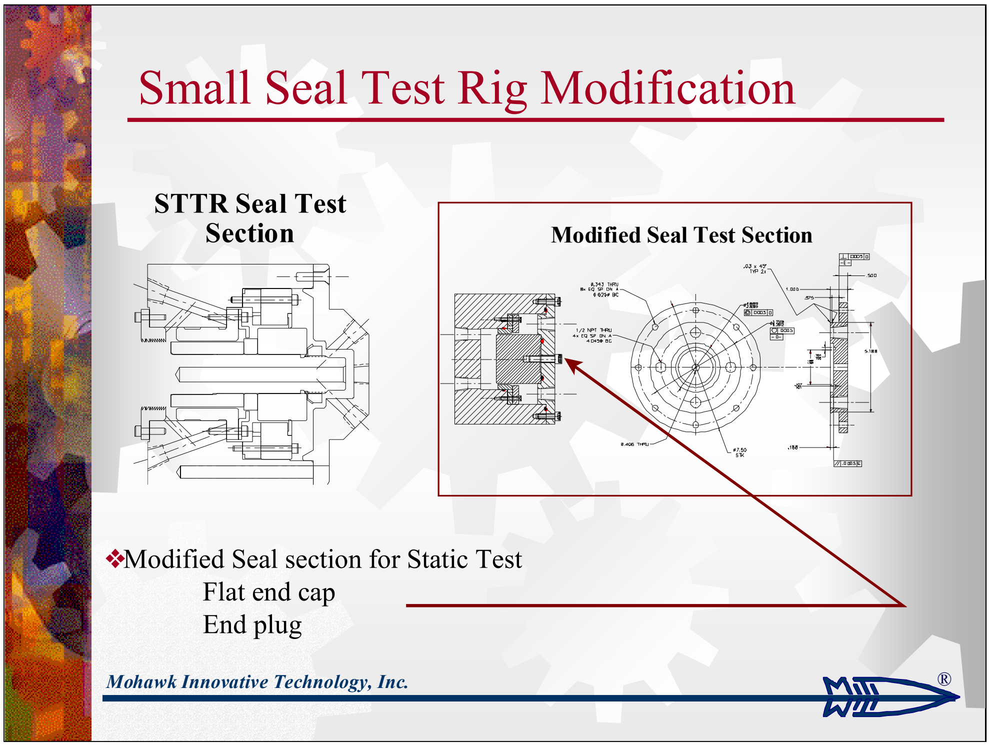


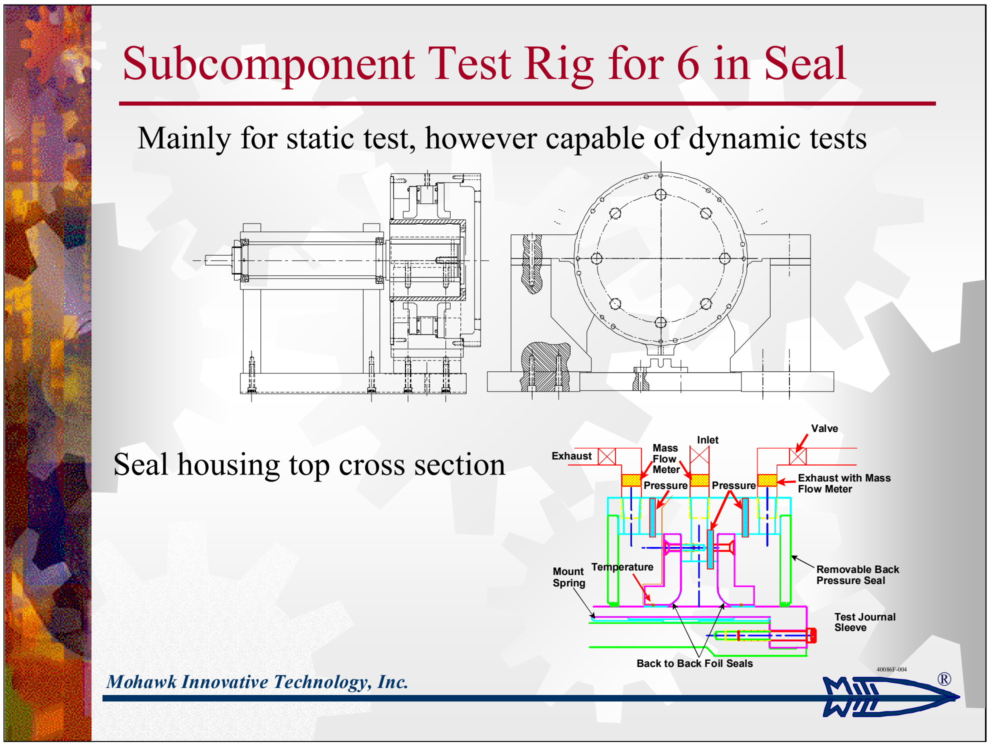
The basic concept of the seal is shown here. The two initial seal hardware built are also shown. The seal on the left side has 1.5 in diameter and the seal right side has 2.84 in diameter.



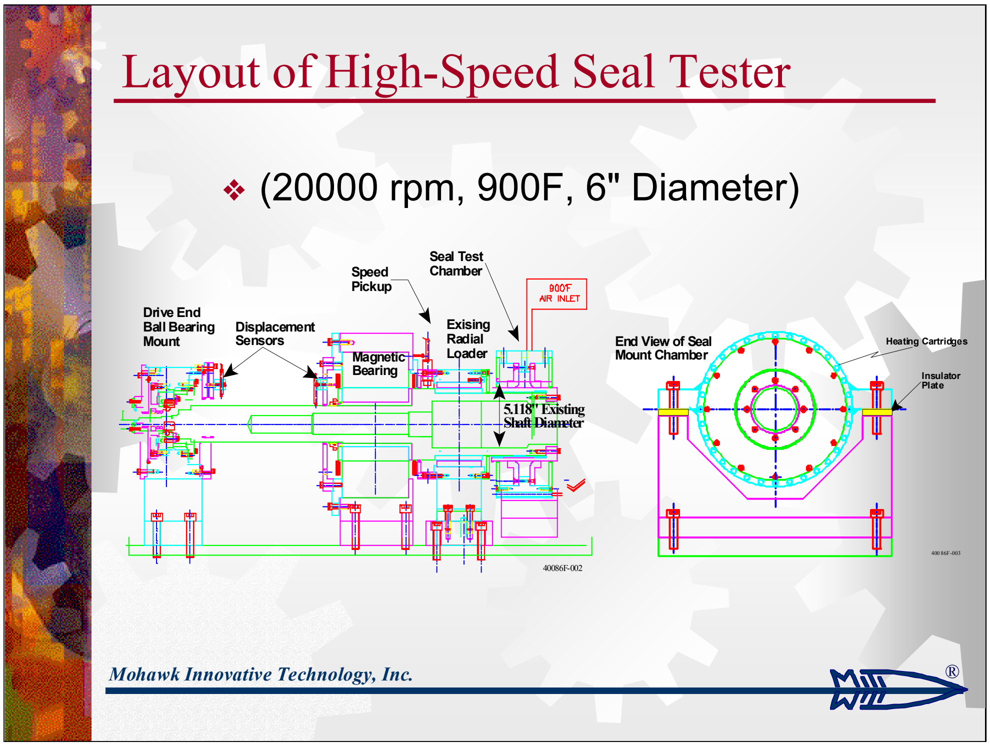
The small gas turbine engine simulator is shown here. The hybrid system included ball bearing and compliant foil bearing for support. The compliant foil seal and foil bearing were taken to speed as high as 56,000 rpm and temperature as high as 1100 F.



The hybrid system compliant foil seal housing (shown in previous page) was modified for quick static tests.



The subcomponent test rig will be used to test the 6 in seal. Most test will be static test. However the test rig can accommodate for some limited dynamic conditions.



The main dynamic test rig is shown here. This seal tester consists of rolling element bearing and magnetic bearing for main support.

A compliant radial loader is used for control of rotor orbit. The magnetic bearing also provides testing with controlled eccentricity introduced to the seal.

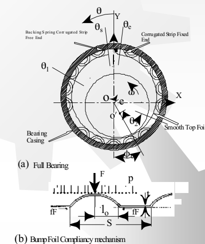
Reynolds – Compliance Equations for Laminar Flow

Reynolds Equation:

Velocity & Inertia

$$\frac{\partial}{\partial\theta}\left[\bar{P}\bar{h}^3\frac{\partial\bar{p}}{\partial\theta}\right]+\frac{\partial}{\partial\bar{z}}\left[\bar{P}\bar{h}^3\frac{\partial\bar{p}}{\partial z}\right]=\Lambda\frac{\partial}{\partial\theta}(\bar{P}\bar{h})$$

$\bar{z} = (Z/R)$ $\bar{p} = (P/P_L)$ $\bar{h} = (h/C)$



Film Thickness :

Compliancy

$$\mathbf{h = C + e\,Cos\,(\theta - \theta_0) + \sum K_{ij}\,(p_{eff} - P_N)}$$

K_{ij} : The combined compliancy coefficeint

P_N: Normalized pressure behind foils

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Governing equations of pressure and film thickness combined with structural compliance is presented. The above equations were applied to the laminar flow conditions.

Modified Reynolds Equation for Turbulent Conditions

$$\frac{\partial}{\partial\theta}\left[G_x p^*(h^*)^3\frac{\partial p^*}{\partial\theta}\right]+\frac{\partial}{\partial z^*}\left[G_z p^*(h^*)^3\frac{\partial p^*}{\partial z^*}\right]=\Lambda\frac{\partial}{\partial\theta}\left(p^* h^*\right)$$

$$h^*=\left(\frac{h}{C}\right)=1+e\ \cos(\theta-\phi)+\sum\alpha_{i,j}(p^*-1)$$

$$|\nabla p|^*=\left((\frac{\partial p^*}{\partial\theta})^2+(\frac{\partial p^*}{\partial z^*})^2\right)^{1/2},\qquad \mathrm{Re}^*=\mathrm{Re}_r{}^*(h/C)^3|\nabla p|^*$$

$$G_z=Min\left[G_z(\mathrm{Re}),G_p(\mathrm{Re}_p)\right]\qquad \frac{1}{G}=\frac{1}{G_x}=\frac{1}{G_z}=1.471\left(\mathrm{Re}_p\right)^{0.681}$$

$$G_x=Min\left[G_x(\mathrm{Re}),G_p(\mathrm{Re}_p)\right]\qquad \frac{1}{G_x}=0.0687\mathrm{Re}^{0.75}$$

$$\mathrm{Re}_p=\frac{h^3}{\mu\nu}\nabla p\qquad \frac{1}{G_z}=0.0392\mathrm{Re}^{0.75}$$

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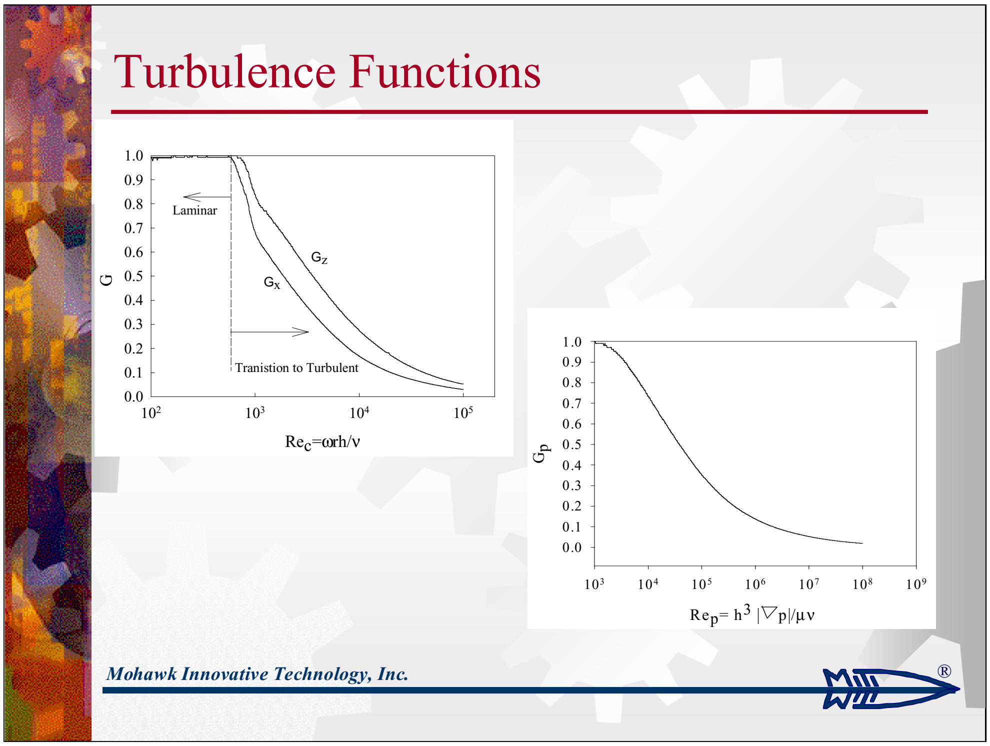
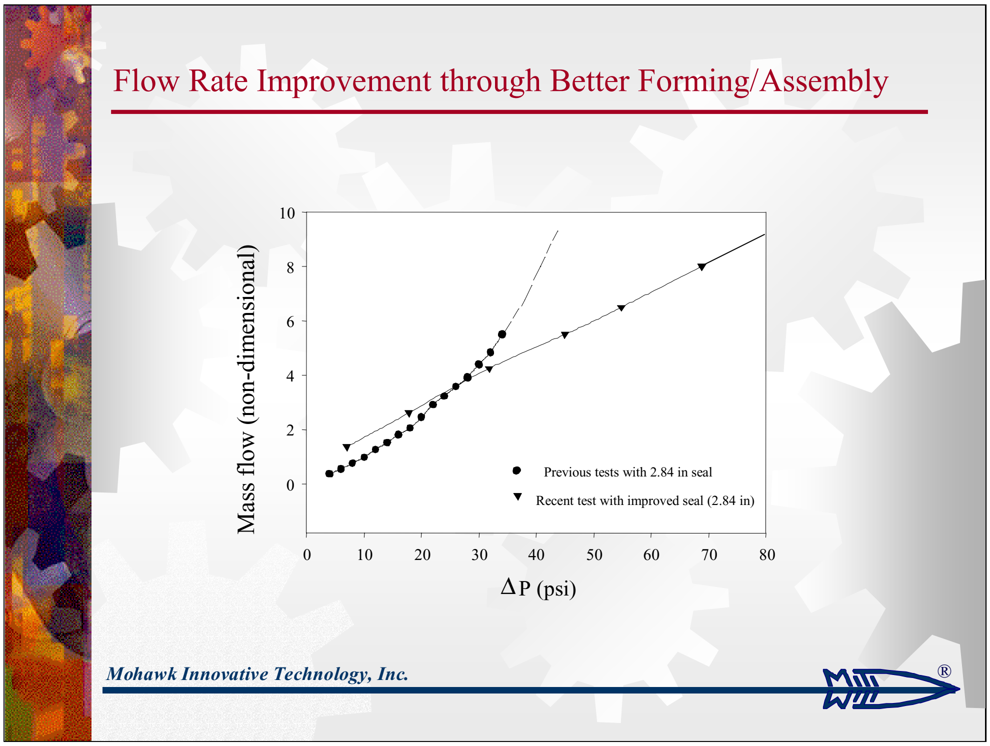
The turbulence influence was introduced via some turbulent functions (G’s). These G’s were calculated based on the circumferential Reynolds and pressure Reynolds numbers.



Plots of G functions vs. Reynolds numbers.



Static test showing the performance of the improved seal against the existing seal. The trend in improved seal is more linear at high pressure.

Accomplishments/Status

- Analysis enhancements is completed
- Seal manufacturing enhancement is partially fulfilled
- Materials testing matrix is finalized and preparation for testing is in process
- Small scale tested to ΔP = 80 Psi conducted
- Large scale static test rig is in manufacturing/parts -delivery process
- Fabrication of high speed test rig is in process
- Implement fabrication/know-how to large size seal

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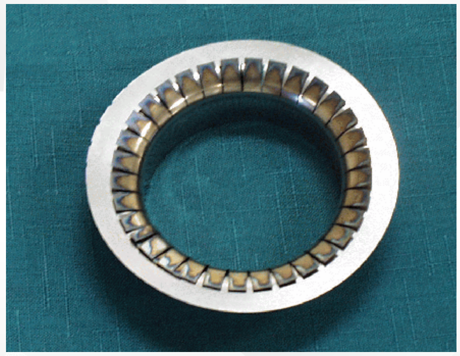
Photo of Enhanced CFS



Additional foil ring is incorporated in the enhanced seal

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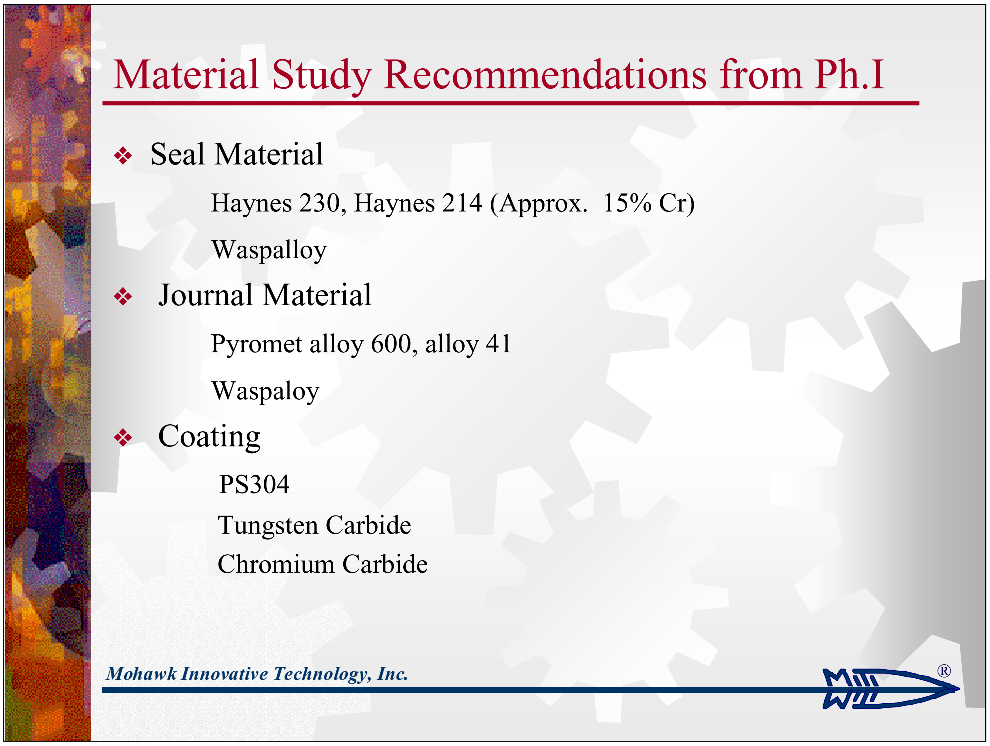
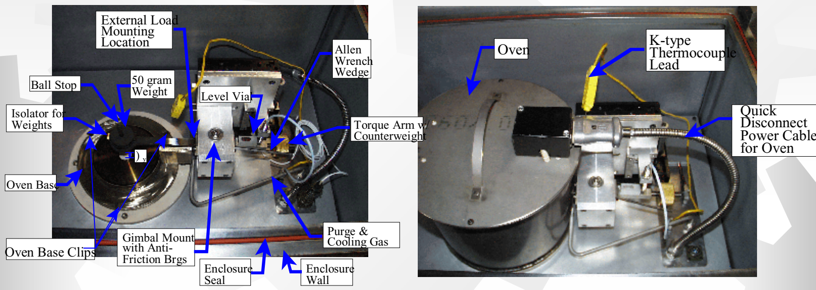


Material study from Phase I was revisited.

High Temperature Tribometer



<u>Specifications</u>
Test Configuration -Pin on disc / Pad on disc set-up
Temperature - 1500^{o}F
Speed - 10,000rpm
Load Range - 0.22 - 1.1lb
Multi-track disc range from 0.125 to 3.135in

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The in-house high temperature tribometer is used for testing trobological characteristics of the materials to be used in seal hardware.

Test Procedures

Material Characterization
Foil Material - for top pad on HT Tribometer- Waspalloy
Disc Material - for HT Tribometer - Heat Treated Inconel X718

Test Matrix

Test No.	Test Condition	Load, psi	Speed, rpm	Test Duration, mins	
				Start-up	Shut-down
1	Ambient	2	5000	25	2
2	Ambient	2	10000	25	2
3	Ambient	3	5000	25	2
4	Ambient	3	10000	25	2
5	H/ Temp - 1200°F	2	5000	25	2
6	H/ Temp - 1200°F	2	10000	25	2
7	H/ Temp - 1200°F	3	5000	25	2
8	H/ Temp - 1200°F	3	10000	25	2

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The selected materials and test conditions are shown here.

Test Procedures

- Foil seal simulation

  Foil Material - for top pad on HT Tribometer- Waspalloy

  Disc Material - for HT Tribometer - Heat Treated Inconel X718

- Tribomaterial

  Surface will be examined to characterize the type of wear using a High Powered Zeiss MC63 Microscope

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Conclusions/Remarks

- Non-Contact compliant foil seal is under development for structural integrity and performance evaluation
- Analysis included the turbulence effects
- Differential pressure up to 80 Psi was statically tested
- Dynamic and static test rigs are under development
- Material study aims at addressing the tribological concerns
- Manufacturing process and forming techniques are applied for better performance of the seal
- Structural integrity of the large seal should be address in future

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NUMERICAL SIMULATION OF FLOW, PRESSURE AND MOTION OF FRONT BACK FINGERS IN A TWO ROWS FINGER SEAL

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Numerical Simulation of Flow, Pressure and Motion of Front Back Fingers in a Two Rows Finger Seal

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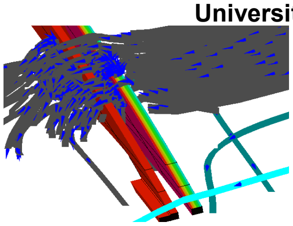
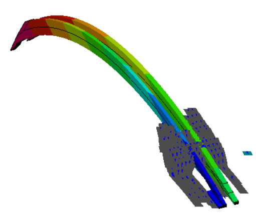




ABSTRACT

- This proposal fits within the programmatic long-term development direction for turbine engine seals of the Seal Team of the Mechanical Component Branch.

- The intended work concerns the further development of the Finger Seal concept which is a compliant passive-adaptive seal meant to mitigate (and eventually replace) the shortcomings of the entire class of rigid seals used today (labyrinth, honeycomb, mechanical face seals) in the gas turbines and compressors.

GOALS

- **First**,

  we are aiming at developing a fully integrated numerical 3-D model, which couples the hydrodynamic fluid model (Navier-Stokes based) to the solid mechanics code that models the compliance of the fingers.

  The coupled codes that feedback in an iterative mode, will allow the full simulation of the passive-adaptive properties of this innovative seal.

- **Secondly**,

  experimentally, we shall test alternative models of finger seals in an effort to better understand their sealing and lifting properties, as well as guide and validate the code numerical development.

In Year II, in collaboration with the Seal Team of the Mechanical Components Branch, we shall extend the University of Akron based experimental program to the High Temperature Test Rig at NASA Glenn Research Center. This will allow moving our technology readiness level from a room temperature laboratory environment (TRL-4) to the high temperature, engine relevant environment (TRL-5).

NUMERICAL SIMULATION COMPONENT MODULES

⇨**<u>Mechanical model of the single finger and assembly of fingers</u>.** This model will entail the generation of a finite element based code that will simulate the stiffness and damping of the element as it is subject to engine environment pressures (high and low side), hydrodynamic pressures at the finger foot/shaft interface, and Coulomb friction between the two rows of fingers.

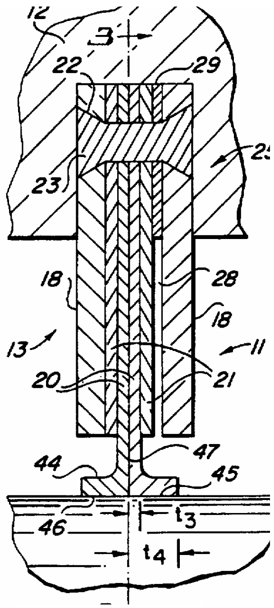
⇨**)<u>Hydrodynamic fluid model</u>.** This model has to simulate the hydrodynamic lifting effects on the finger seal, as well as the primary and secondary leakages as they occur between the fingers and at the shaft/finger foot interface. We intend to use an already existing numerical package and tailor it to the particular needs of the project.

NUMERICAL SIMULATION COMPONENT MODULES

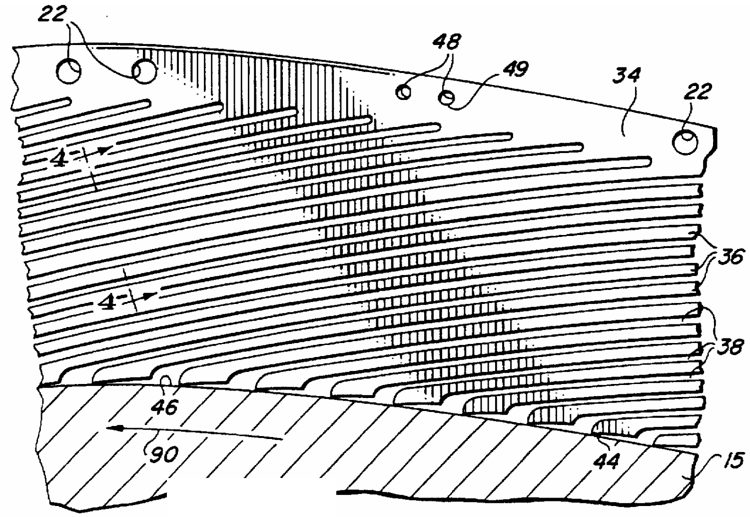
⇨)**Solid/fluid Interaction with the Dynamics module.** Through the implementation of a) and b) we shall obtain a fully interactive model that will model the interaction between finger mechanics and the 3-D fluid hydrodynamic behavior In this context we shall generate a complete pressure map of the hydrodynamic pressures ensuing under the finger pad footprint. All external body forces acting on the finger will be accounted for, in this model.

⇨)**Simplified spreadsheet design.** With a), b) and c) implemented we project the possibility that a detailed parametric run will allow creation of a database that can be used for the creation of a simplified calculation methodology that will use a spreadsheet format, without any further need of 3-D calculations.

GEOMETRY OF THE FINGER



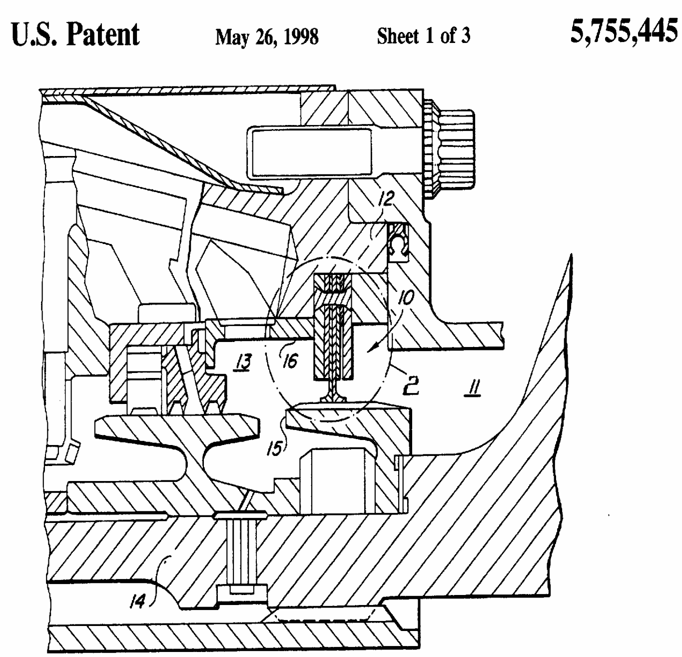
4a)



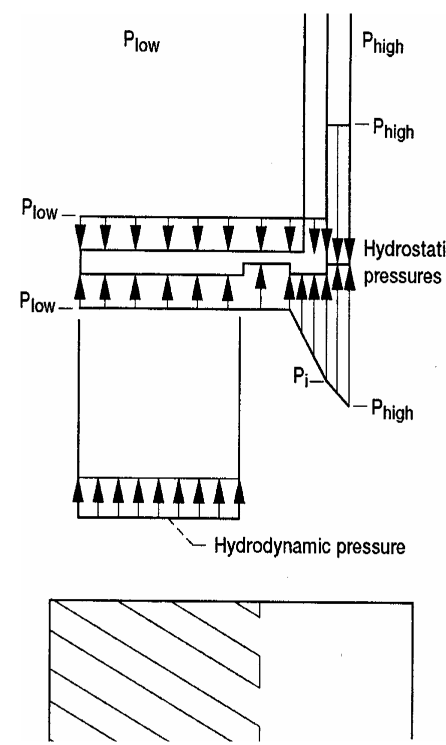
4b)

Seal Two row Configuration with Wide Finger Pads. Cross Section and Side View of the Seal (U.S. Patent No. 5,755,445)

Typical application and Free Body Diagram



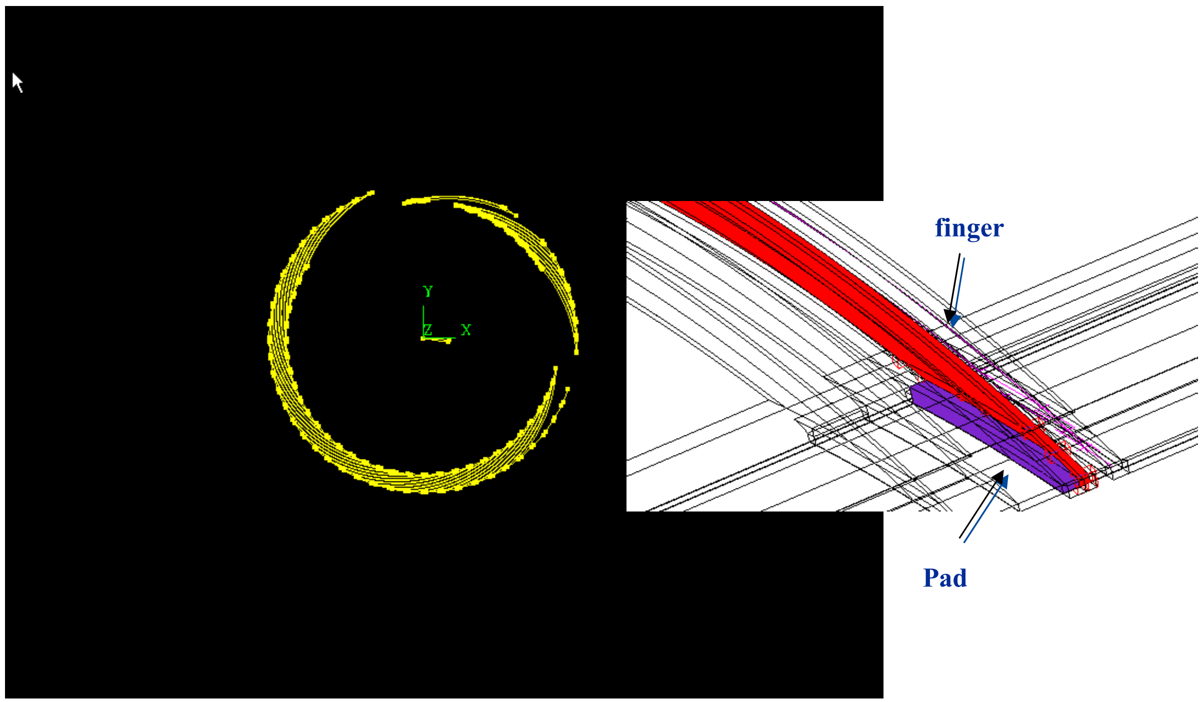
Typical Application of the Finger Seal presented on previous slide (U.S. Patent No. 5,755,445)



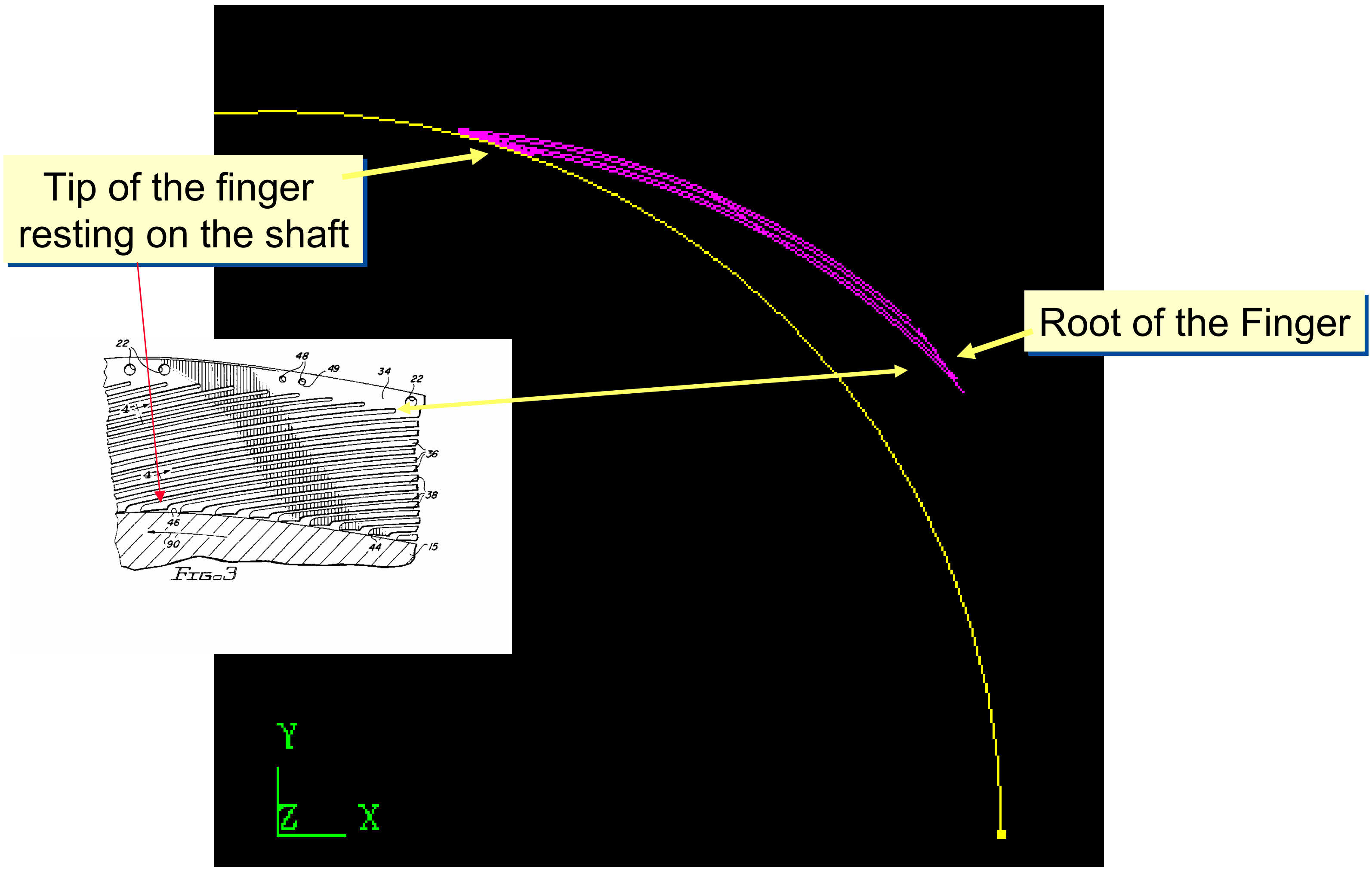
Single Finger as a Free Body Diagram and Geometrical Changes Proposed For Better Wear Behavior

Compliant Fingers Discretization

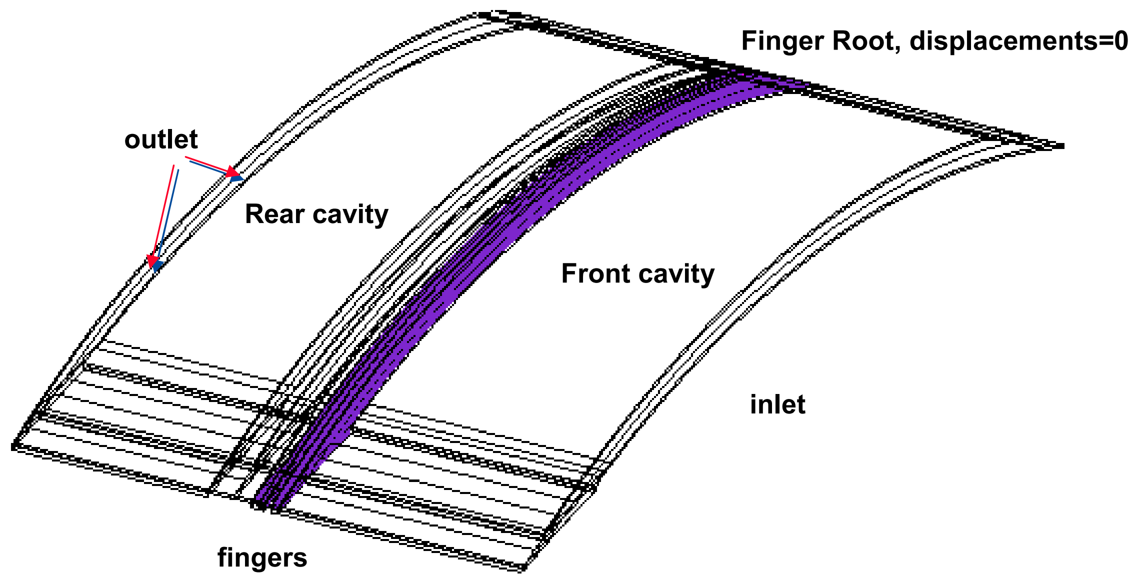
Assembly of 72
fingers along the
circumference



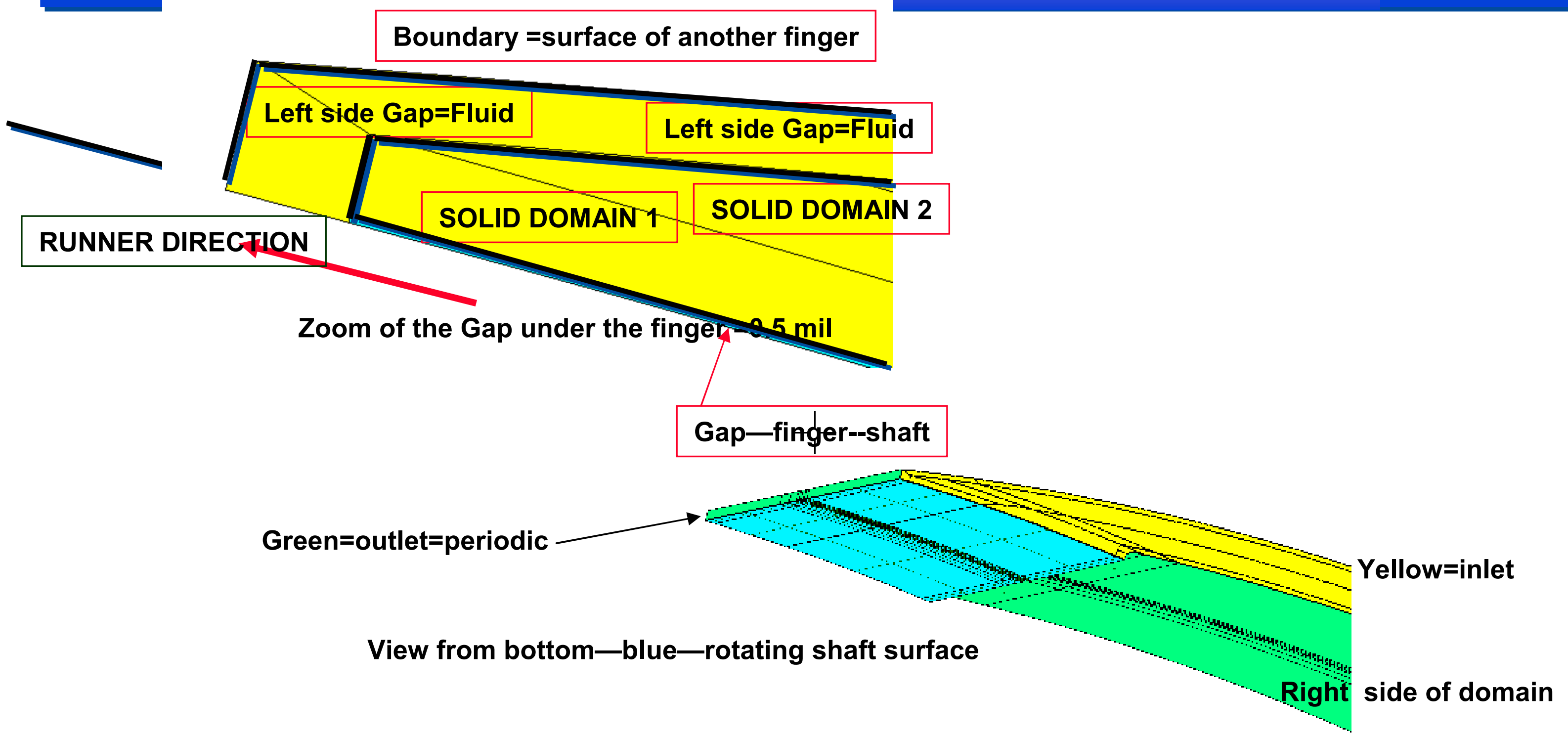
Single Finger Resting on the Shaft



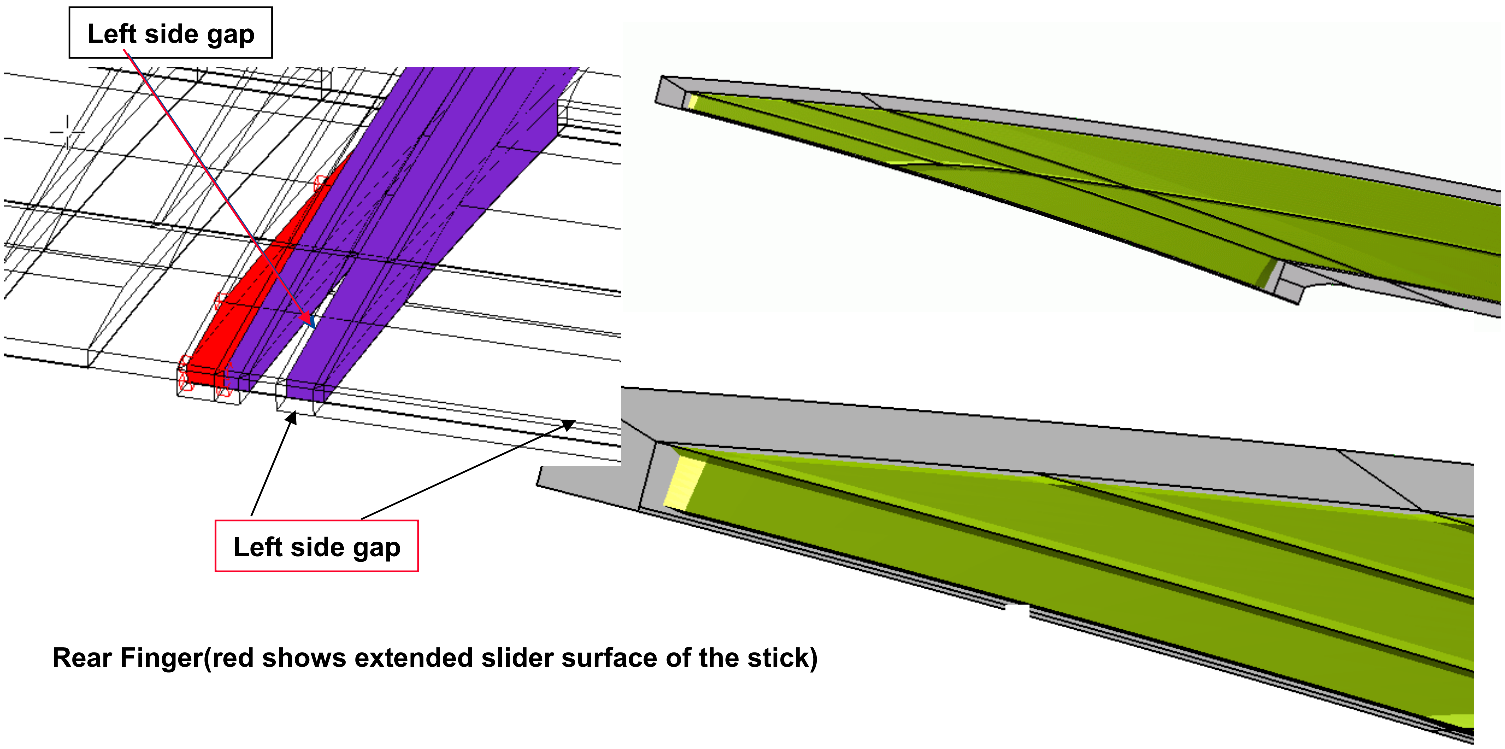
3d of computational domain



Domains identification and 3d view of the runner



Details of the computational grid



Rear Finger(red shows extended slider surface of the stick)

FEMSTRESS--for FINGER DEFORMATION

- **)<u>Mechanical model of the single finger and assembly of fingers</u>**.. FEMSTRESS is used for static and transient structural analysis, for both linear and nonlinear problems. The module is coupled with the other modules of CFD-ACE+ (flow, thermal, electrostatics, etc.) for multidisciplinary analyses. It uses a Fast and Efficient Vector Sparse Solver (VSS).

- In the fluid solid interaction proposed by this study a two-way coupling will be utilized to proliferate shape changes due to deformation into computational flow domain. In this case for the flow within the finger seal domain, grid deformation and stress modules will be simultaneously activated, pressure forces integrated on all fingers, finger deflections will be calculated on each iteration and corresponding geometry/grid changes will be implemented.

CFD-ACE+ for Fluid Simulation

⇨ **<u>Hydrodynamic fluid model</u>. <u>The computational engine used is CFD-ACE+, which is a product of CFD Research Corporation of Huntsville/Alabama.</u>** CFD-ACE+ supports structured, unstructured polyhedral, hybrid (structured/unstructured) moving grids and non-matching grid interfaces. It consists of pre-processor for grid generation (CFD-GEOM), GUI Module for model setup (CFD-GUI) and post-processor CFD-VIEW.

⇨**Special features** that make CFD-ACE+ and FEMSTRESS especially suitable for our purposes are:

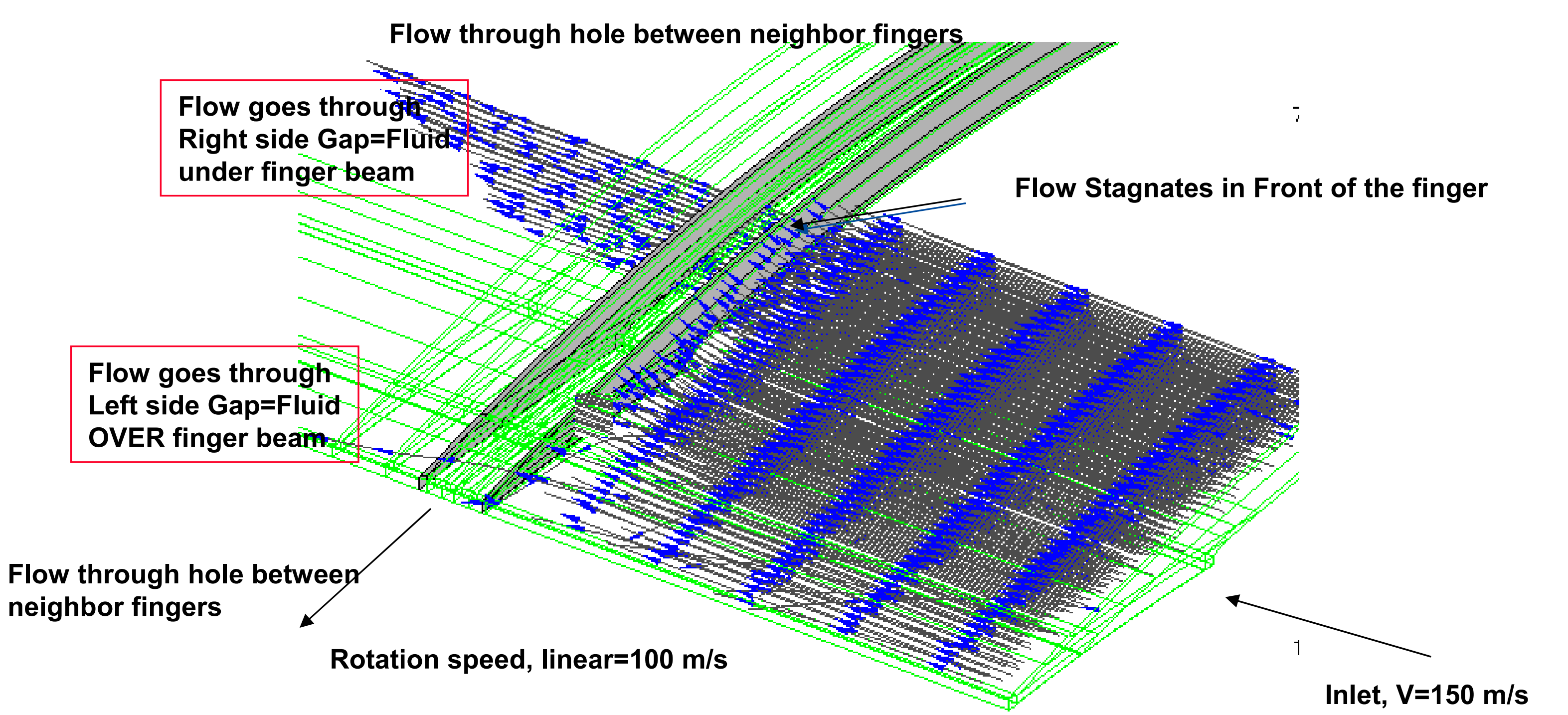
- coupled flow-structure interaction for steady-state and transient flow regimes
- solver stability which allow highly stretched nodes required for thin-film resolution
- ability to solve leakage flows in full Navier-Stokes formulation
- configurable GUI which allows creation of application specific templates/tools

RESULTS

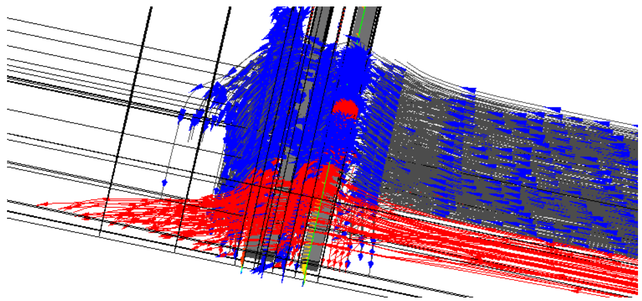
- Flow in the Front Cavity
- Flow About the First Finger
- Flow in the Inter-Cavity First/Second Finger
- Flow Past The Second Finger (2nd Cavity) and Under the Pad
- Pad Motion
- Pressure Maps

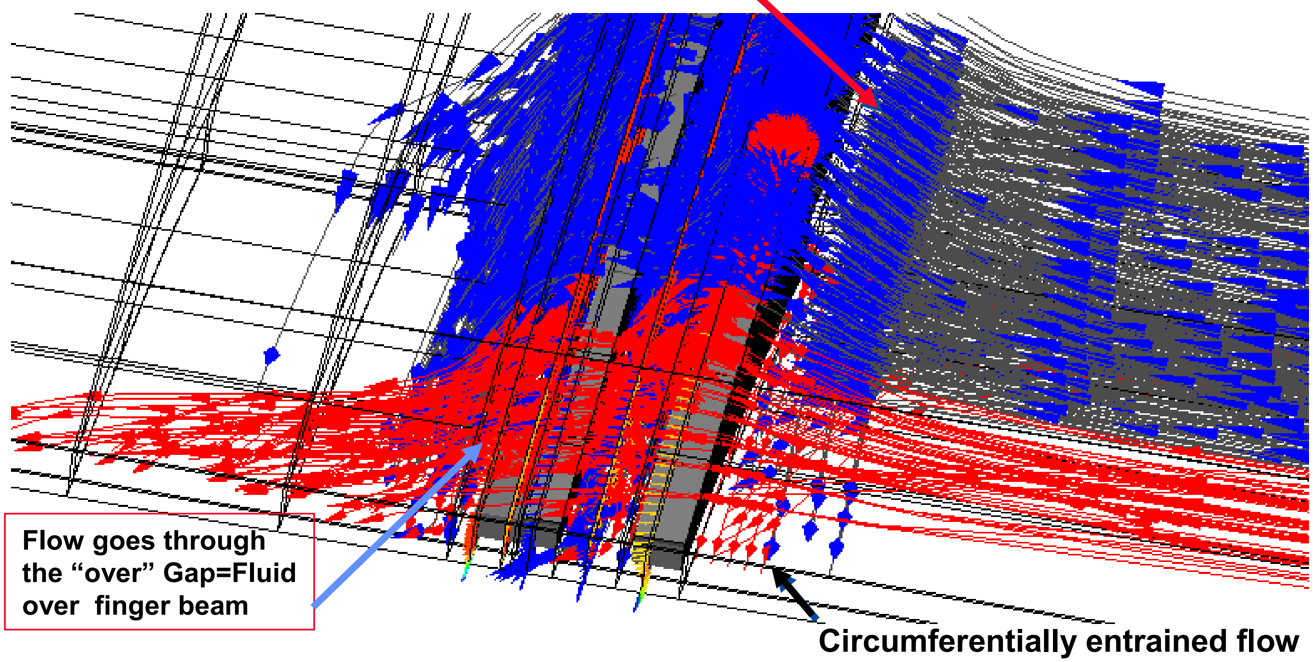
3D Example Solution (no deformation)

HIGH VELOCITY CASE –rotational flow is swung by axial

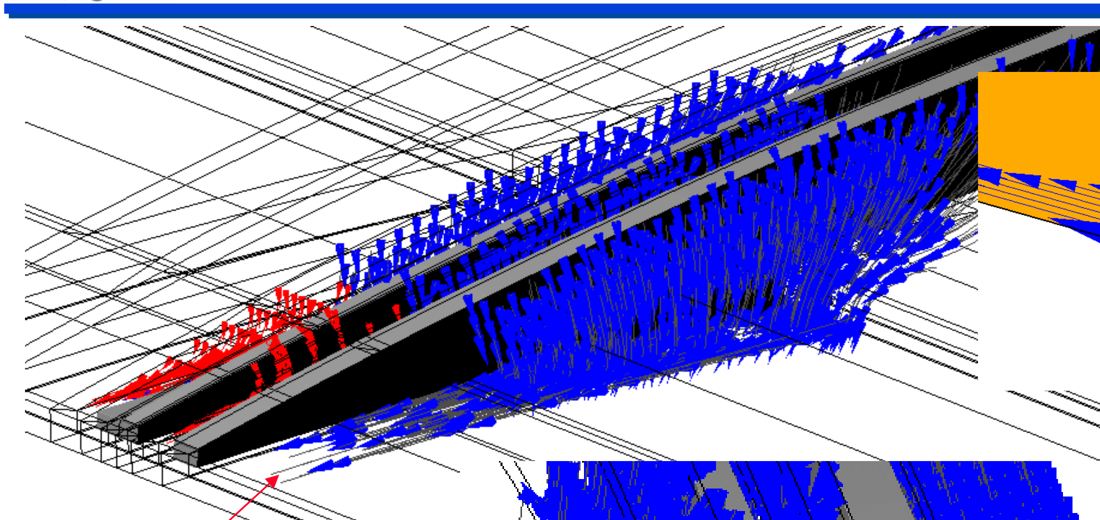


3-D flows, Vshaft=125 m/s, V inlet= 50 ms no finger deformation

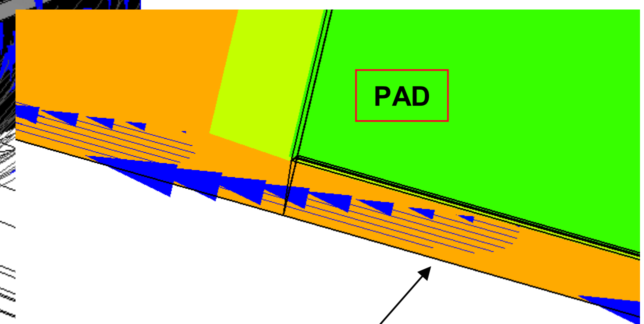




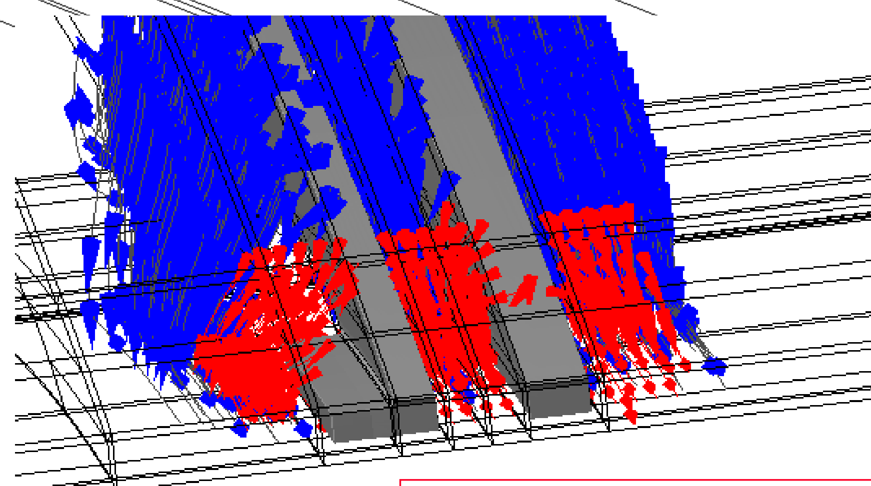
Rotational Dominated Flow
Vshaft=100 m/s, V inlet= 1 m/s, no def



Strong Flow in the circumferential direction
Side view

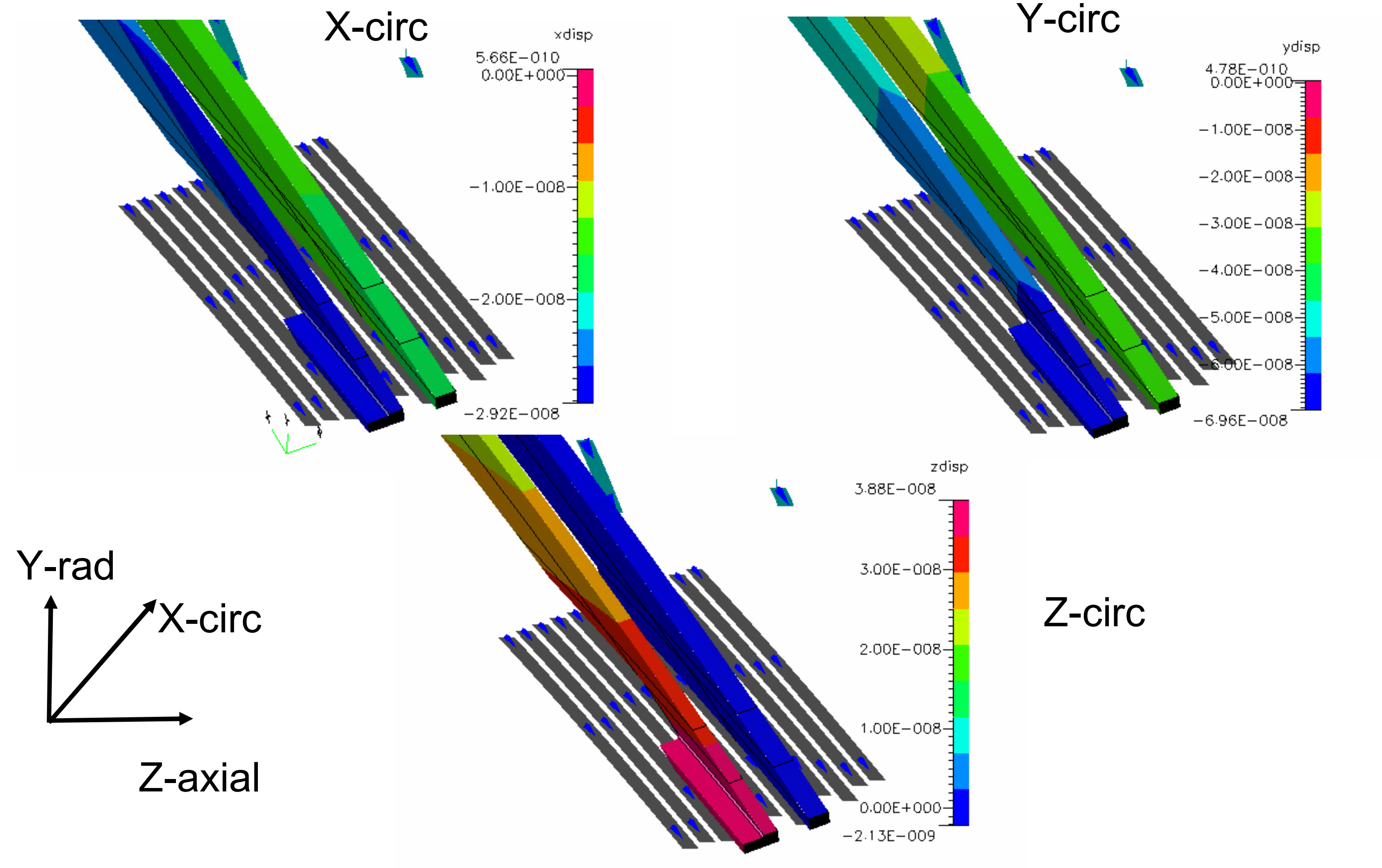


Flow in the Gap

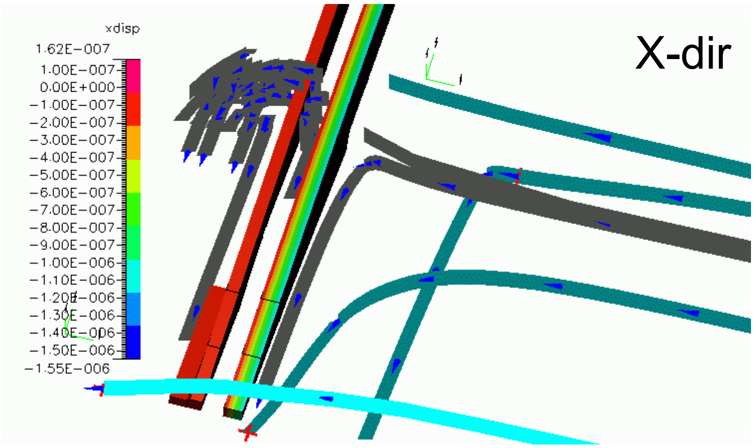


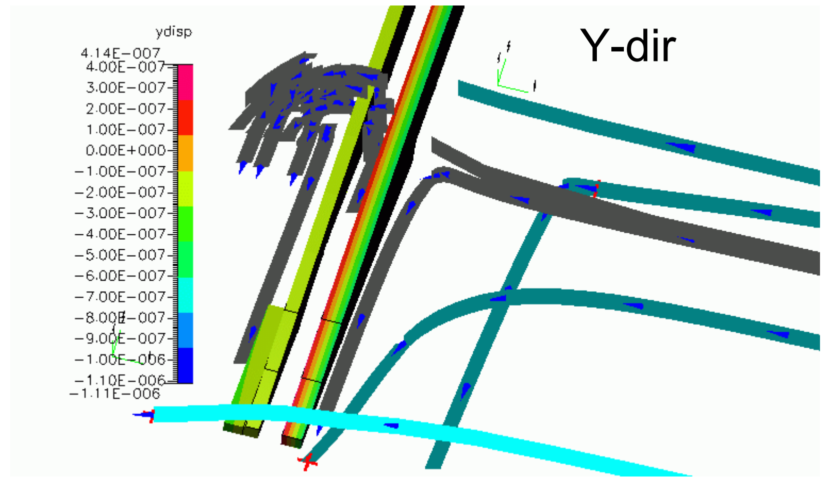
Fingers Assembly and Flow Front View
Arrows pointing at us showing strong rotational (circumferential) flow

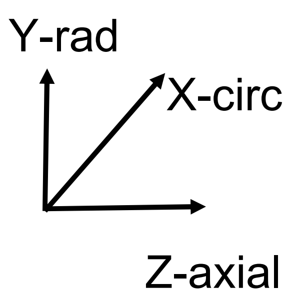
Color Coded displacements and Streamlines Vshaft=100 m/s, V inlet= 1 m/s

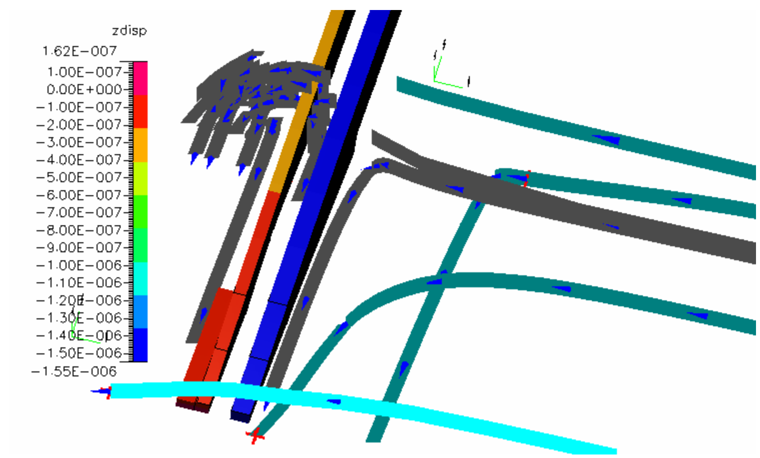


Color Coded displacements and Streamlines
Vshaft=100 m/s, V inlet= 50 ms

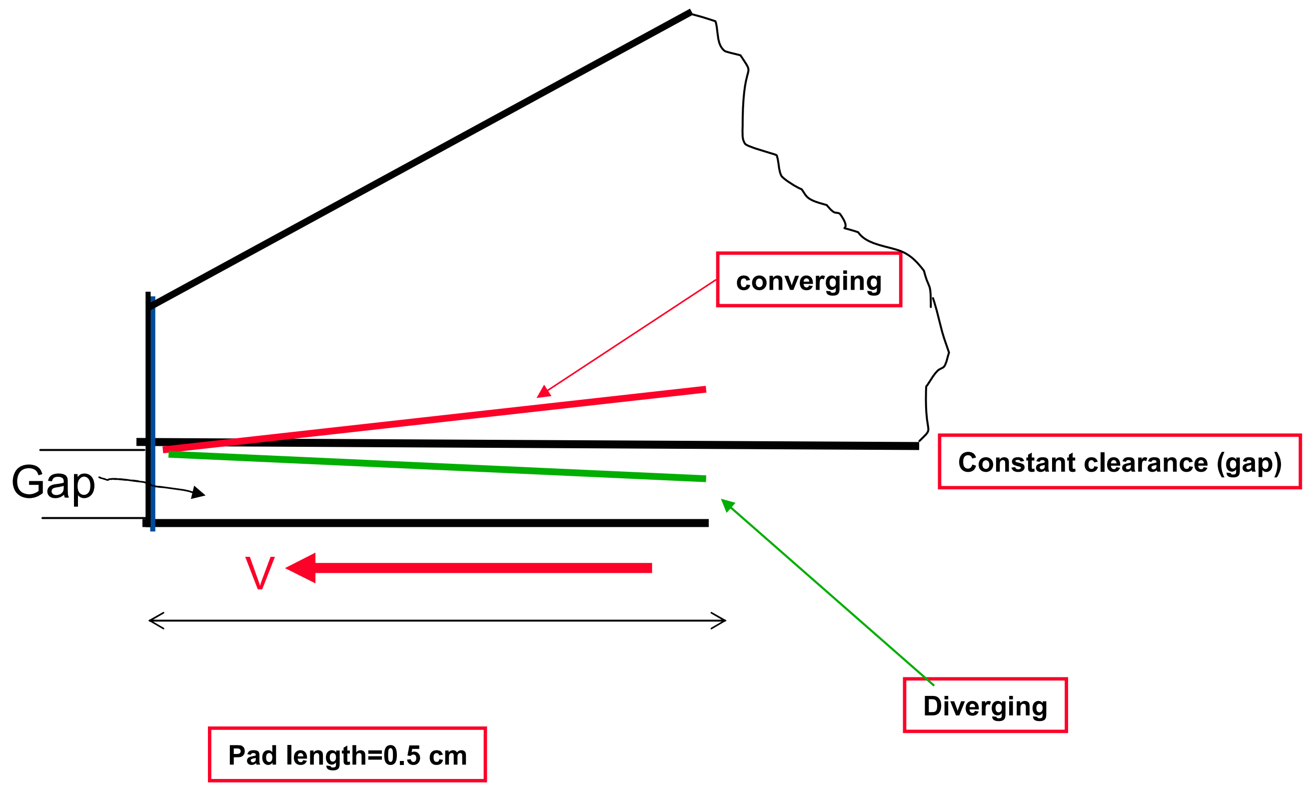




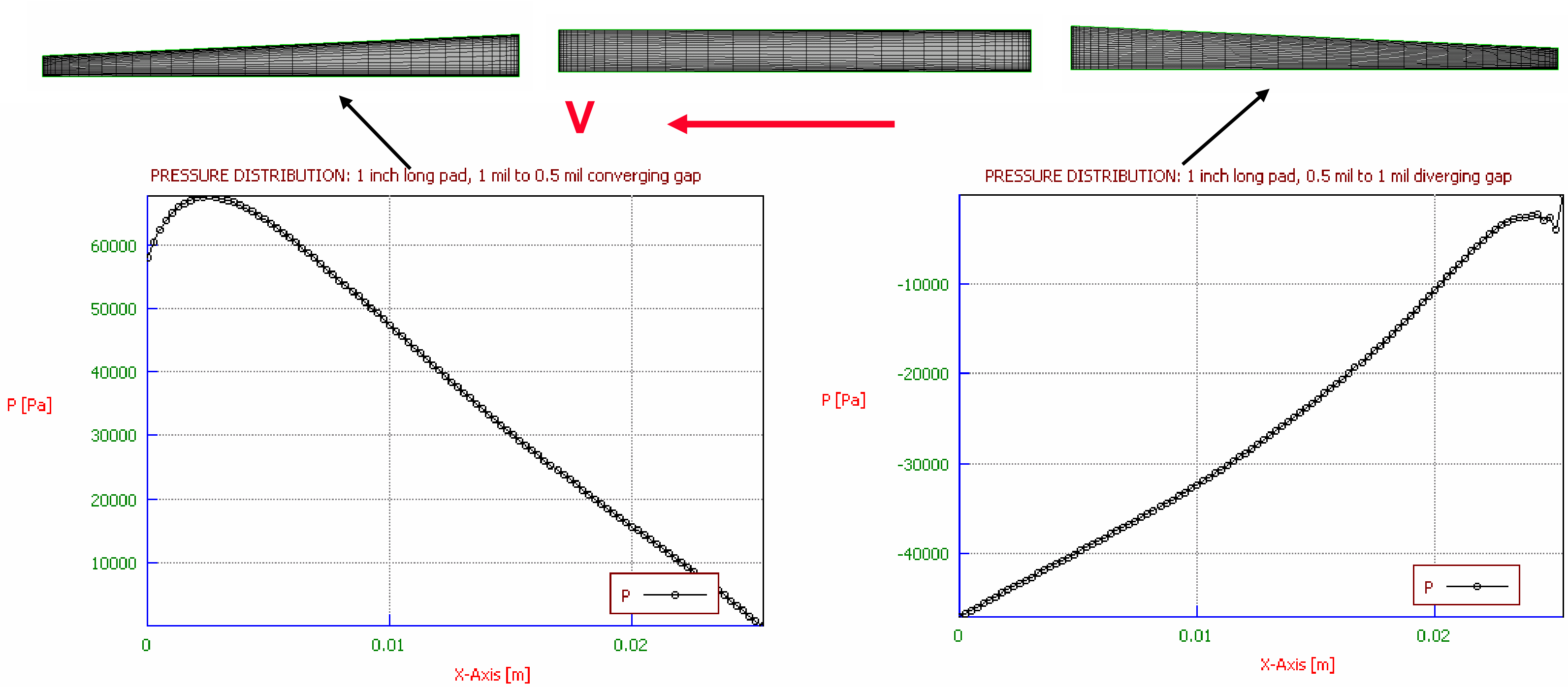




2-D Pressure Distributions for Characteristic Gap



Pressure profiles in the Finger gap



Conclusions

- Good insights into flow formation, finger motion, pressure development.
- Proper software well chosen. FEMSTRESS + CFD ACE+
- A LOT MORE WORK TO DO.

HIGH TEMPERATURE METALLIC SEAL DEVELOPMENT

Amit Datta
Advanced Components & Materials, Inc.
E. Greenwich, Connecticut

D. Greg More
The Advanced Products Company
North Haven, Connecticut

Objective

- Develop a high temperature static seal capable of long term operation at temperatures ranging from 1400°F to 1800°F

Advanced

Outline

- Development approach
- Stress relaxation curves
- High temperature seal test rig
- High temperature seal design
- High temperature seal testing

Advanced

Development Approach

- Screen Metallic Alloys Using ASTM E-328 Stress Relaxation Tests in the 1600-1800 °F Range

- Fabricate and Evaluate Seals in the 1400-1800 °F Range

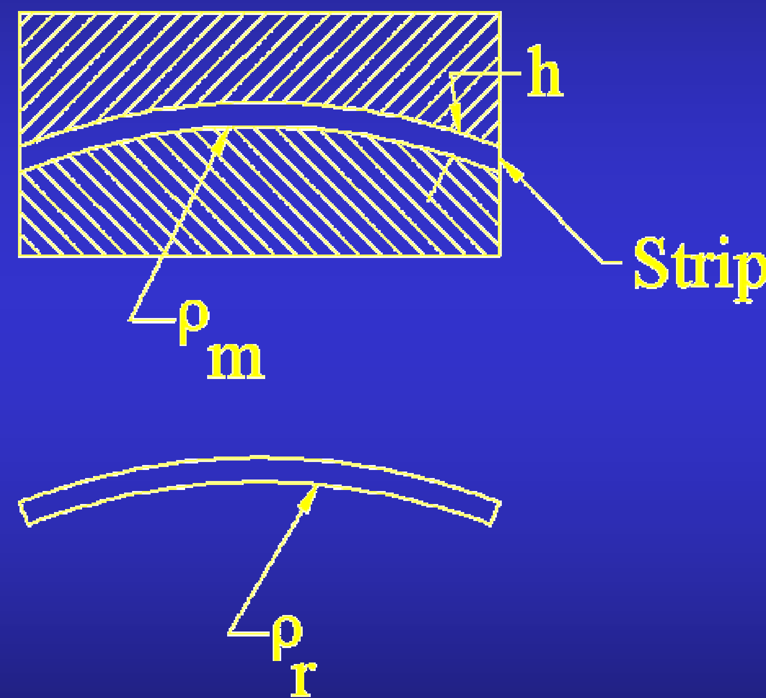
Advanced

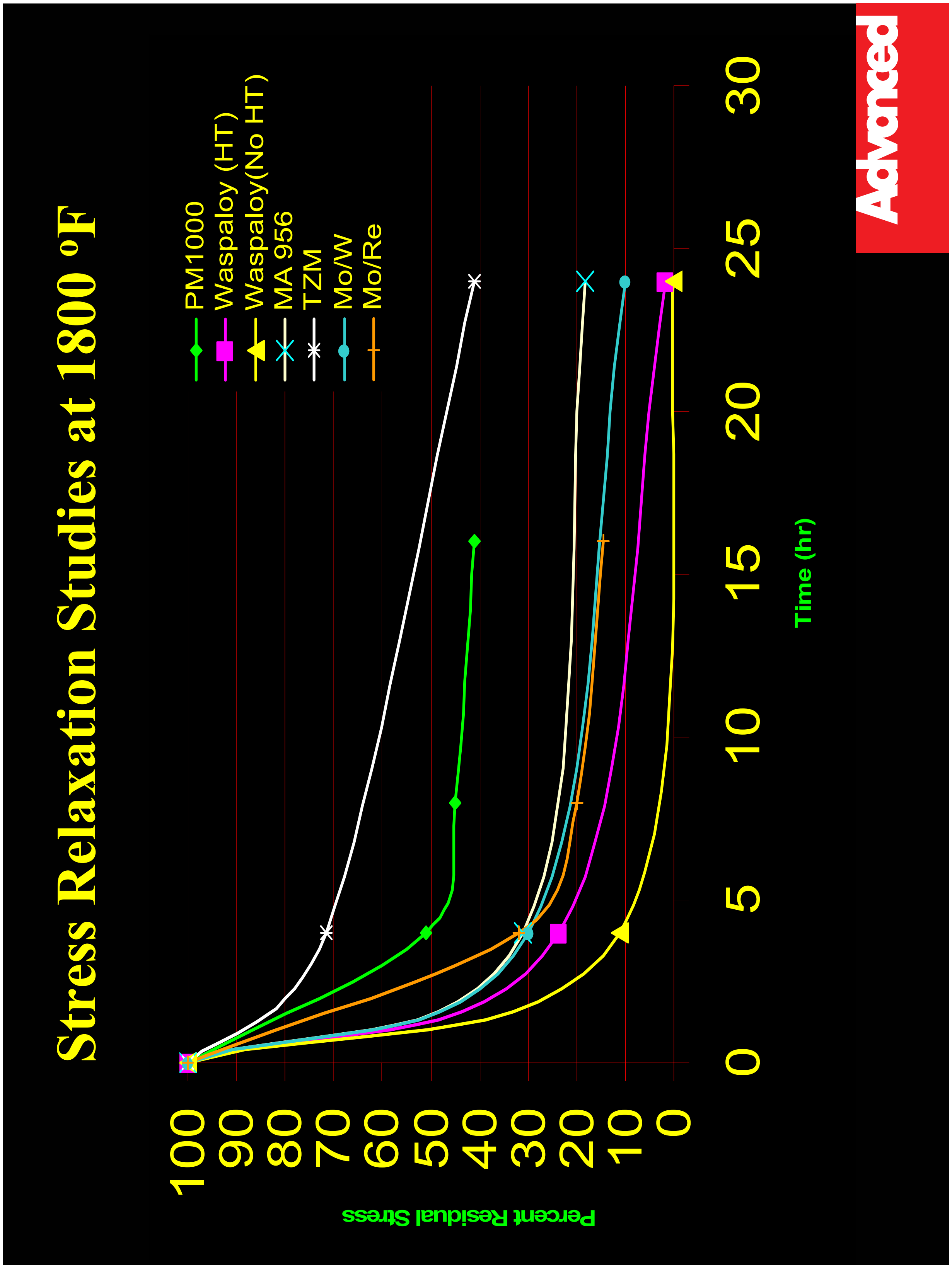
Stress Relaxation Studies

- ASTM E-328 Test:

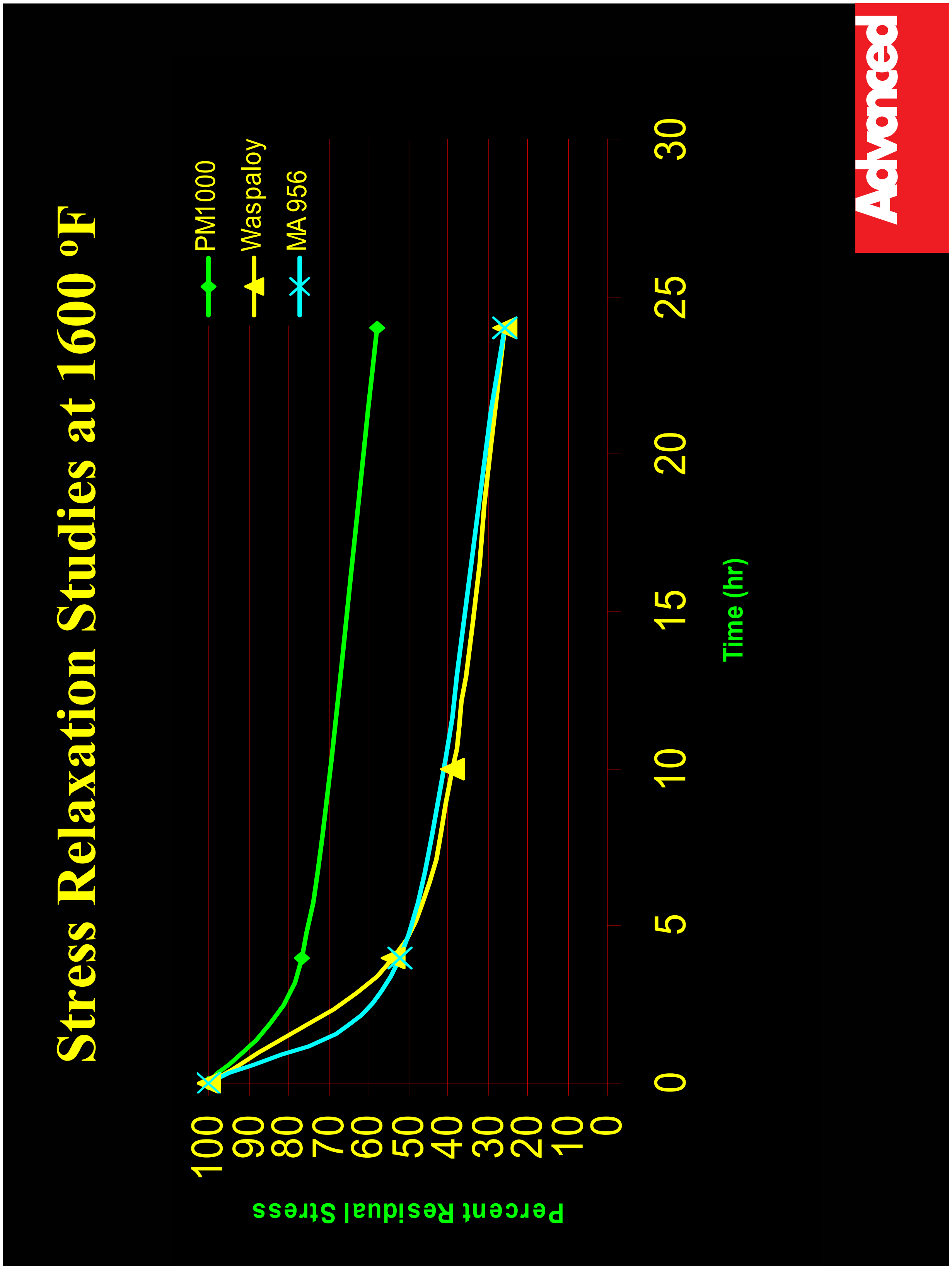
ρ_m - mandrel radius
ρ_r - relaxed radius

Residual Stress:
$\sigma_{El} = E.h/2\ (1/\rho_m - 1/\rho_r)$





Stress Relaxation Studies at 1800 °F
PM1000
Waspaloy (HT)
Waspaloy(No HT)
MA 956
TZM
Mo/W
Mo/Re
Percent Residual Stress
100
90
80
70
60
50
40
30
20
10
0
Time (hr)
0
5
10
15
20
25
30
Advanced


Stress Relaxation Studies at 1600 °F
Percent Residual Stress
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Time (hr)
PM1000
Waspaloy
MA 956
Advanced

Stress Relaxation Studies

- ASTM Style Testing
  – Continuing to perform testing of currently used and new seal alloys at temperatures ranging from 1000°F to 1800°F
  – This testing is necessary to properly select materials for specific temperature ranges

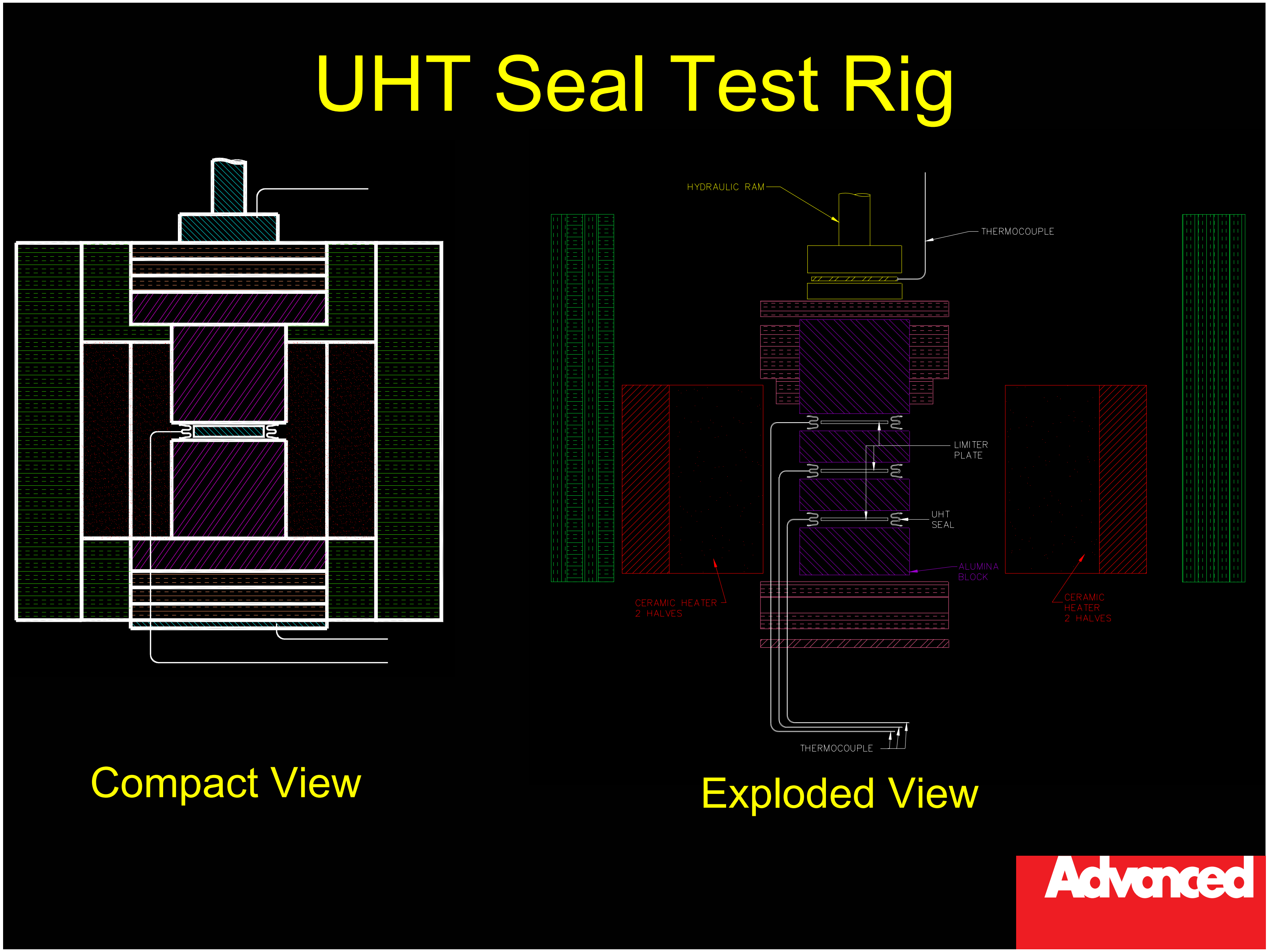
Advanced

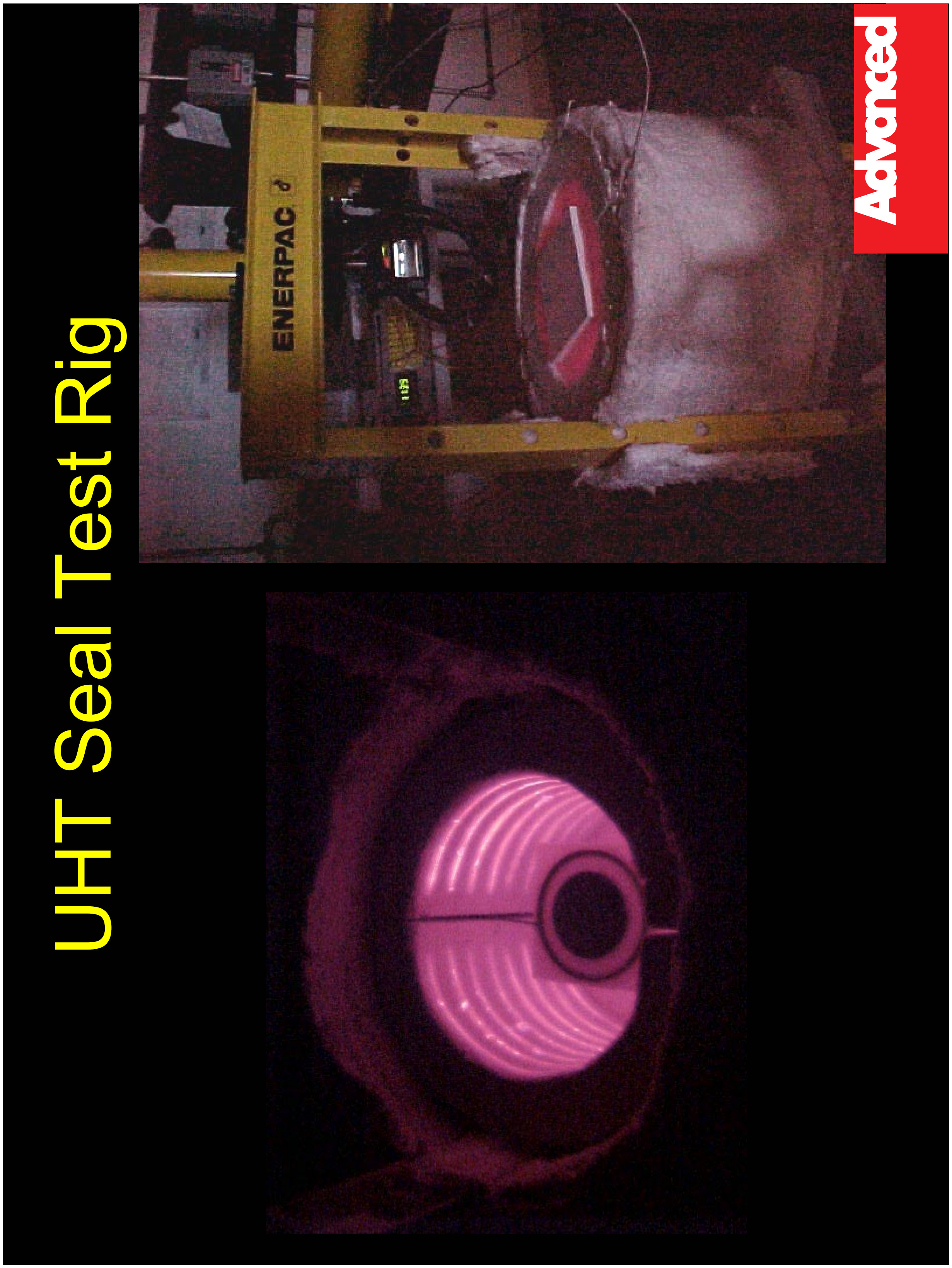
UHT Seal Test Rig

Performance Requirements

- Room Temperature through 1800°F continuous test temperature
- PLC controls with built in safety mechanisms
- Multiple thermocouple locations for accurate seal temperature monitoring
- Capable of extended test duration's to examine long term seal performance

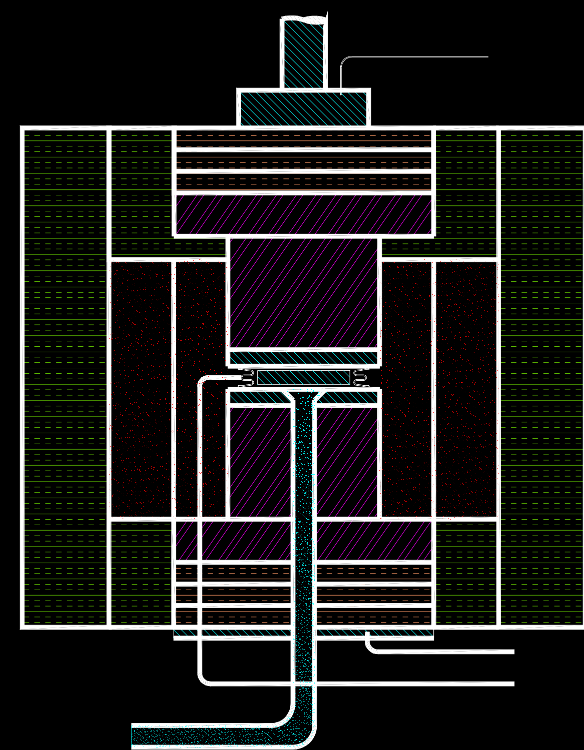
Advanced


UHT Seal Test Rig
HYDRAULIC RAM
THERMOCOUPLE
LIMITER PLATE
UHT SEAL
ALUMINA BLOCK
CERAMIC HEATER 2 HALVES
CERAMIC HEATER 2 HALVES
THERMOCOUPLE
Compact View
Exploded View
Advanced

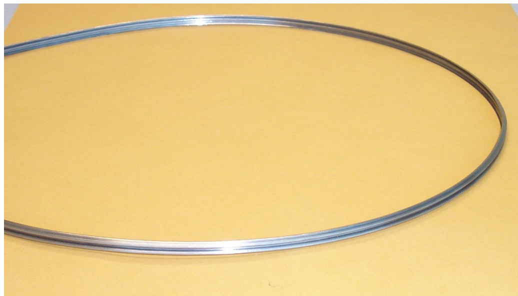

UHT Seal Test Rig
Advanced
ENERPAC

UHT Seal Test Rig

- Seal leak testing at temperature
  - Rig will be modified to determine leakage
  - Inconel 718 plates will be used a seal seat
  - Mass flow meters will be used to measure leakage



Advanced

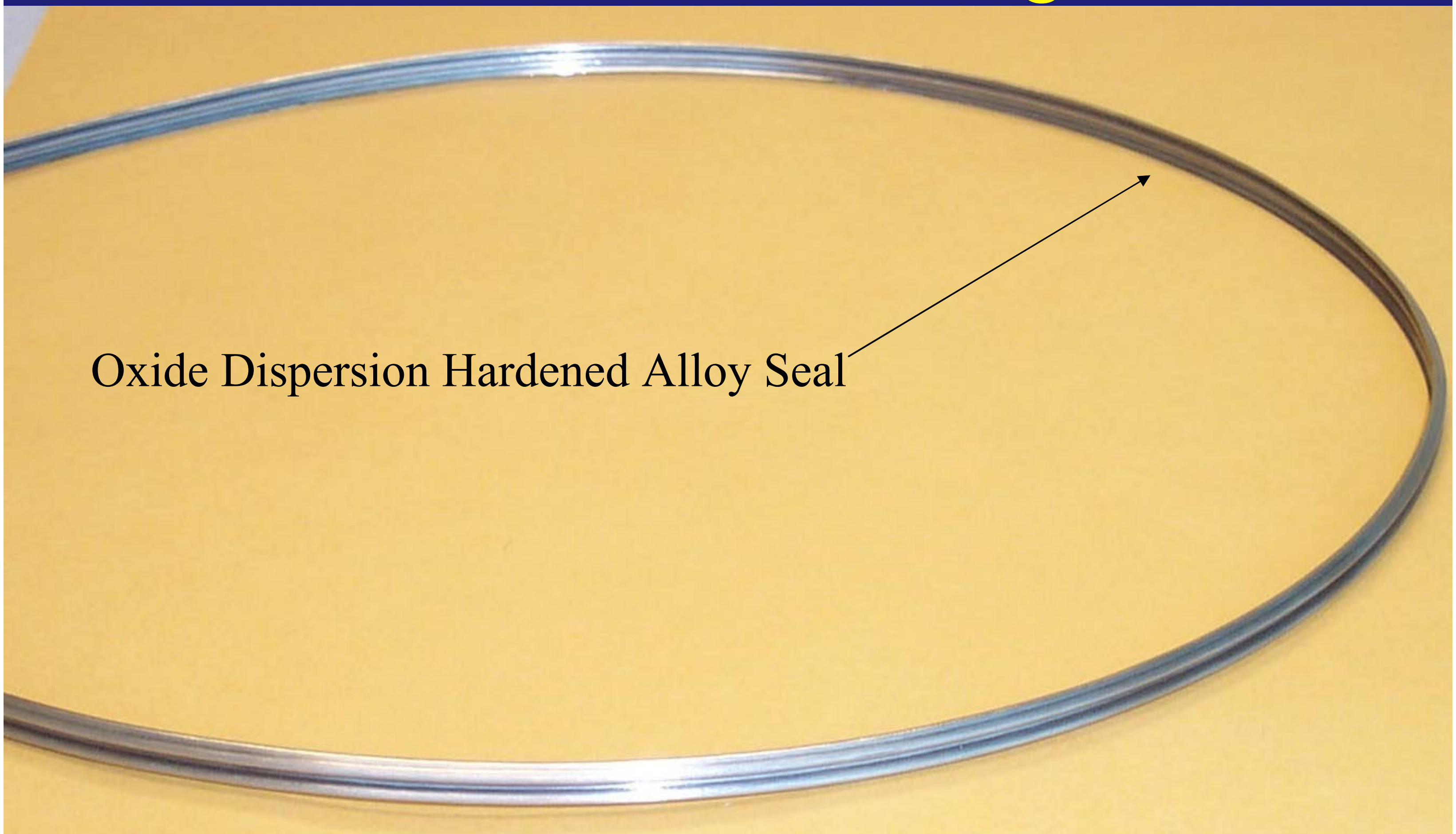


UHT Seal Design

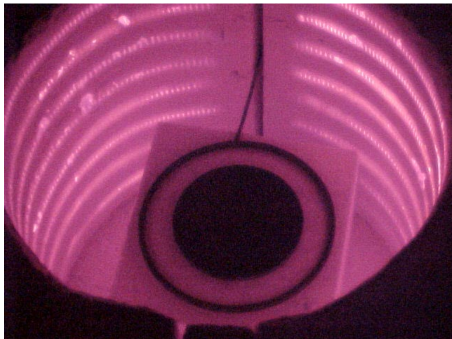
- Seal cross section designed to minimize stress levels
- Manufactured seals from
  - Waspaloy - Baseline
  - Precipitation hardenable alloy with a higher precipitation temperature than Waspaloy
  - Solid solution hardened alloy
  - Oxide Dispersion Hardened Alloy(1800 ^{o}F)

Advanced

UHT Seal Design



Advanced



UHT Seal Testing

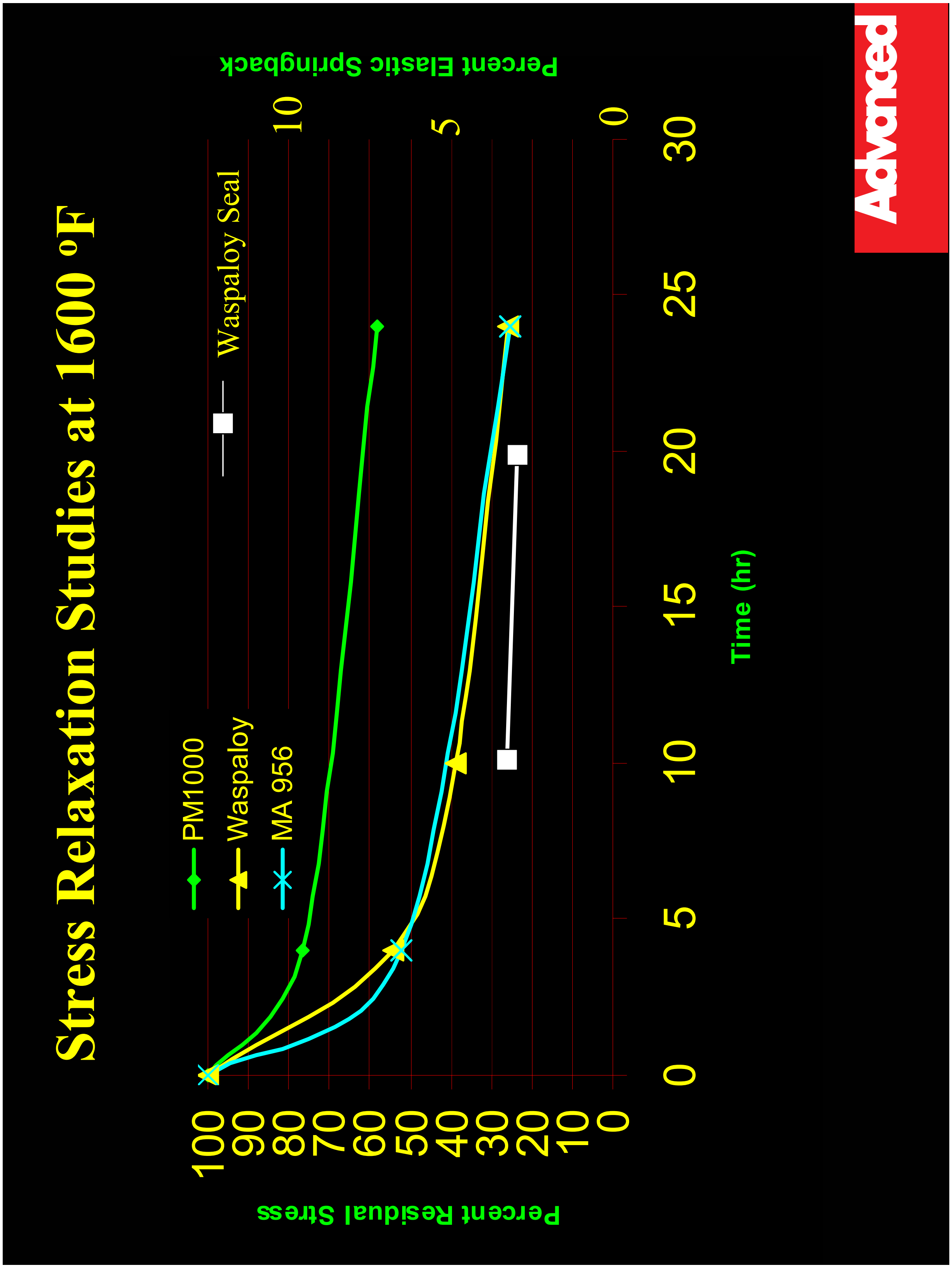
- Performed preliminary testing on baseline(Waspaloy) material
- Over the next several months tests of additional material and seal cross section configurations will undergo basic stress relaxation testing
- Additional phases to include high temperature leakage testing

Advanced

UHT Seal Testing

- Seal testing procedure
  - Measure seal free height prior to test
  - Compress seal 15% in UHT rig
  - Hold at temperature for a controlled time
  - Cool and measure seal height
  - Calculate percent loss in seal free height

Advanced


Stress Relaxation Studies at 1600 °F
Percent Residual Stress
100
90
80
70
60
50
40
30
20
10
0
Percent Elastic Springback
10
5
0
Time (hr)
0
5
10
15
20
25
30
PM1000
Waspaloy
MA 956
Waspaloy Seal
Advanced

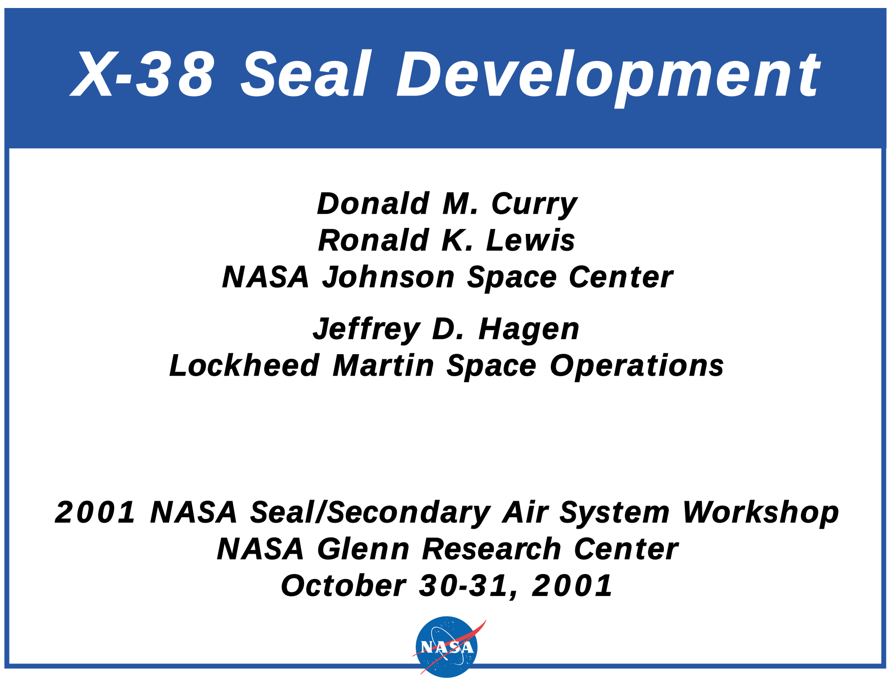
Summary

- ASTM Style testing continues for basic material screening
- UHT test rig is completed and is operational
- UHT Seal testing underway and will continue over the following months

X-38 SEAL DEVELOPMENT

Donald M. Curry and Ronald K. Lewis
National Aeronautics and Space Administration
Johnson Space Center
Houston, Texas

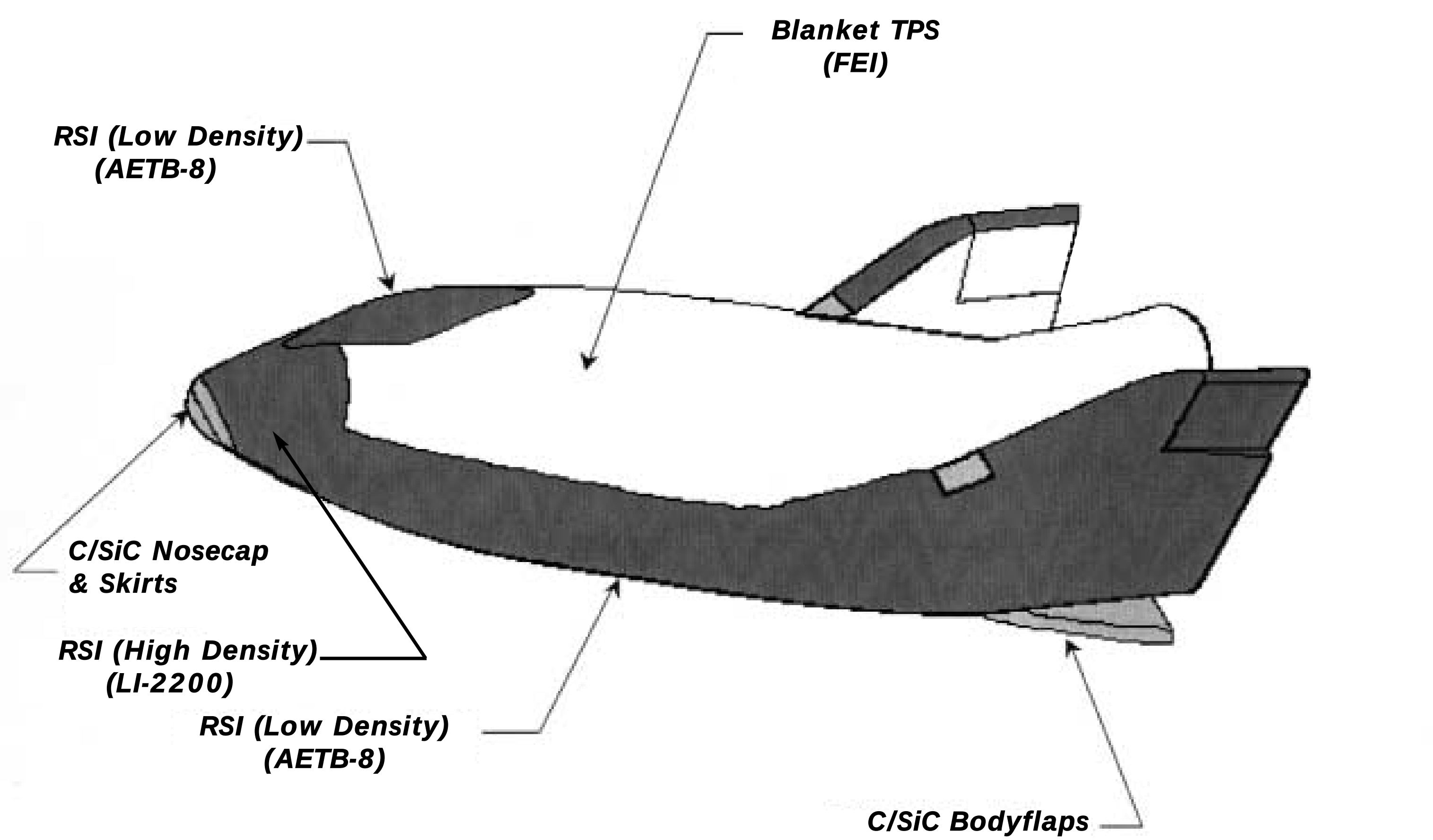
Jeffrey D. Hagen
Lockheed Martin Space Operations
Houston, Texas



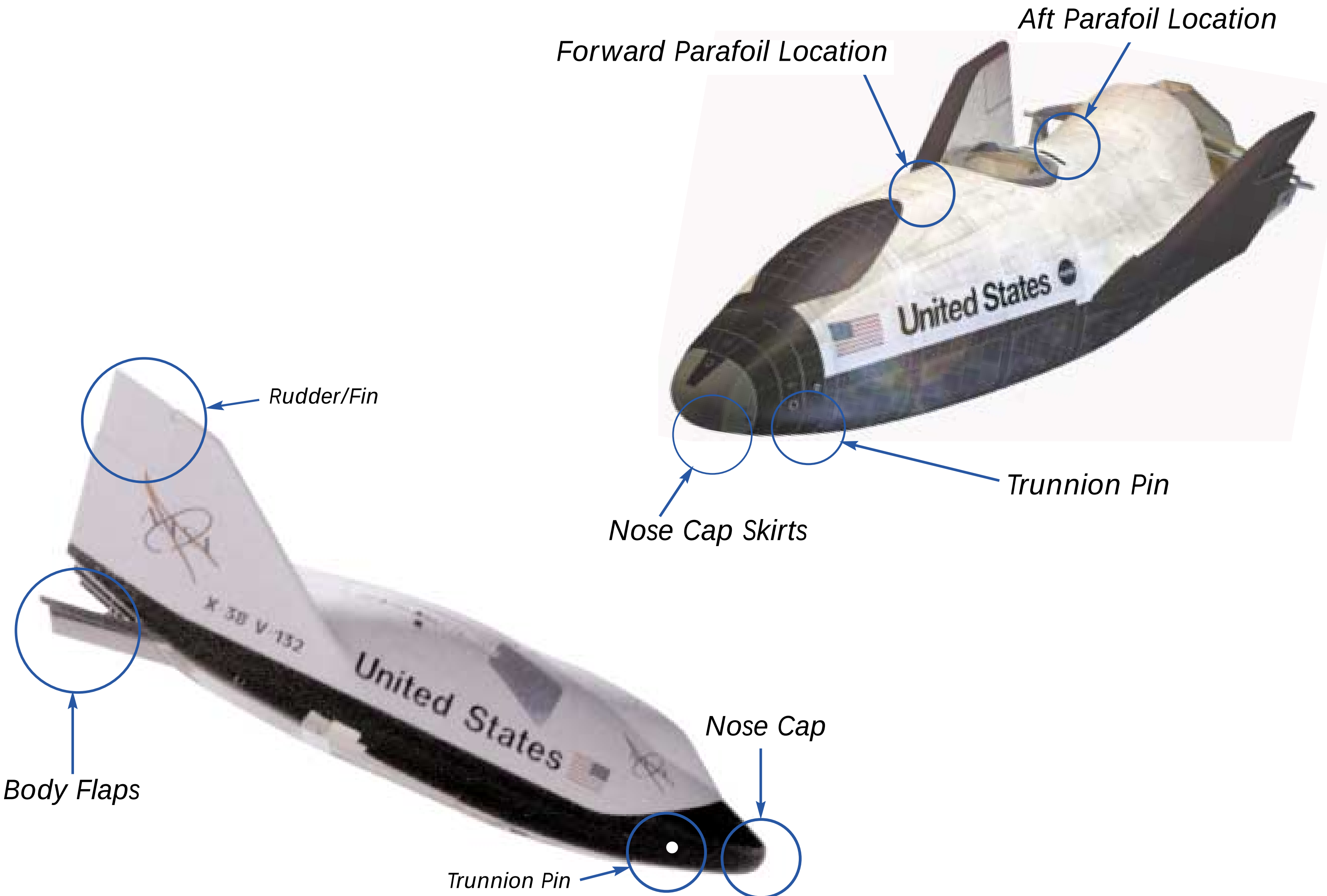
X-38 – Crew Return Vehicle

- *An element of the International Space Station (ISS)*
- *Three Scenarios*
  - *ISS castastrope*
  - *Emergency medical evacuation*
  - *Period of Space Shuttle unavailability*
- *X-38 Program Purpose:*
  - *To greatly reduce the costs and schedule for the development of crew Return Vehicles (CRVs) and Crew Transfer Vehicles (CTVs) through the use of the rapid development methodology associated with an X-project*
    - *Ground Testing*
    - *Atmospheric Testing*
    - *Space Flight Testing*

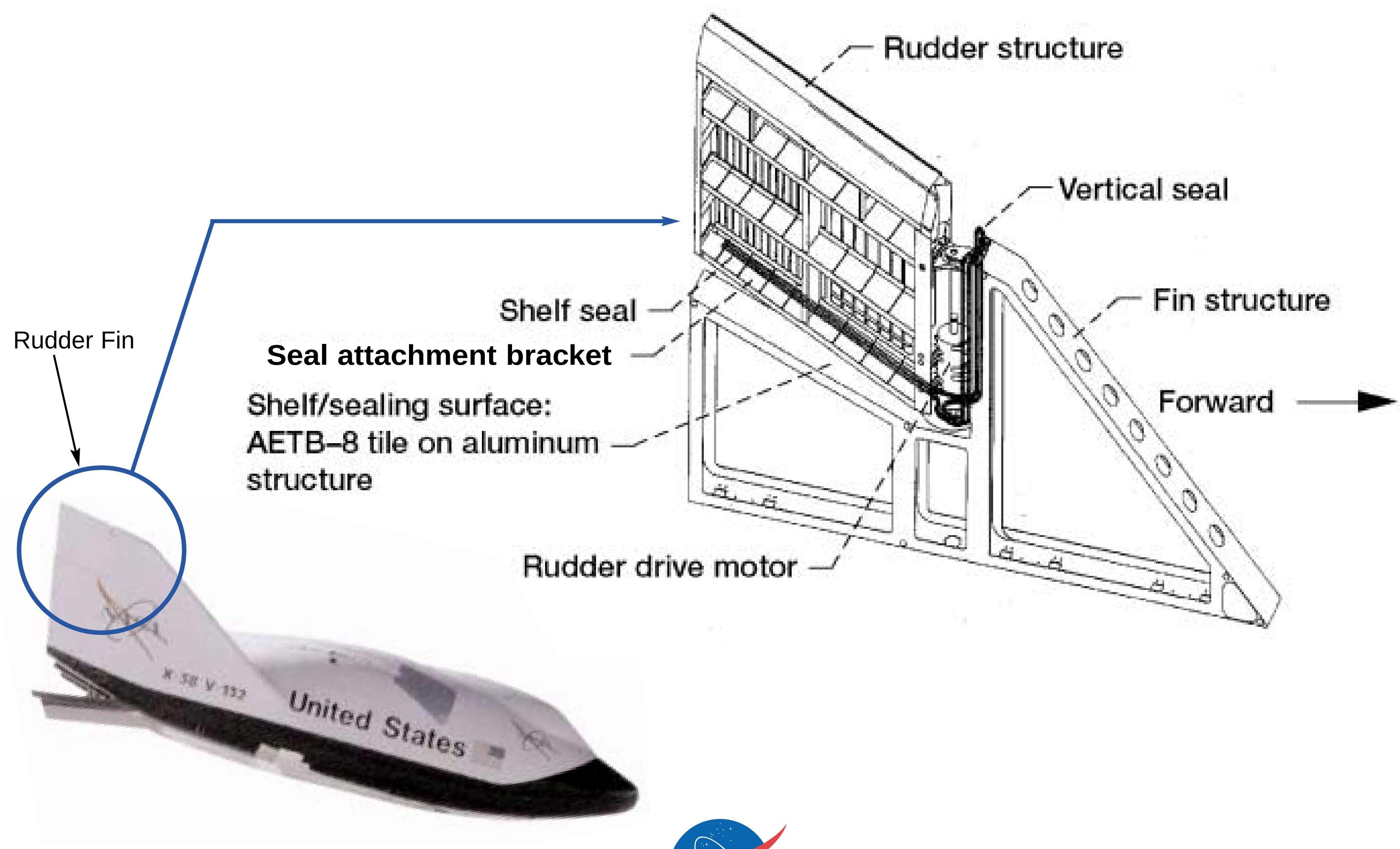
X-38 TPS Configuration



X-38 Seal Locations

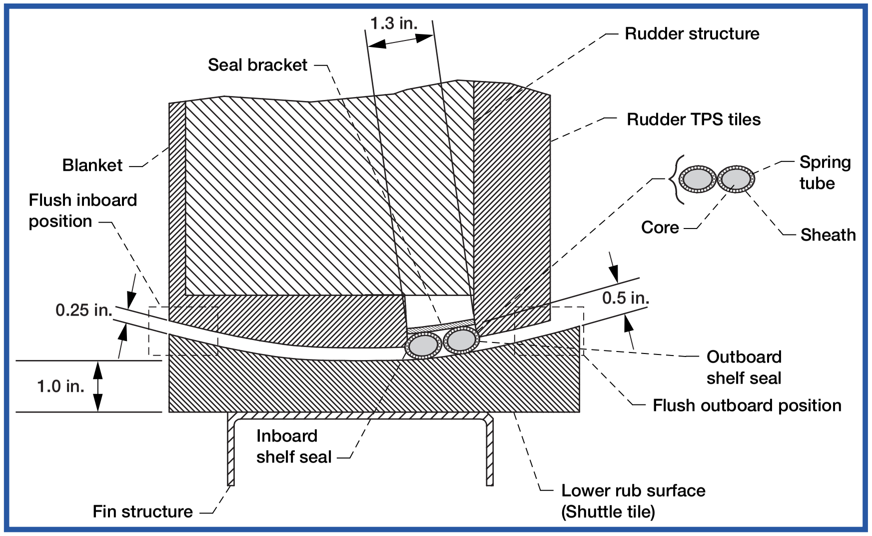


X-38 Rudder/Fin Seal Assembly

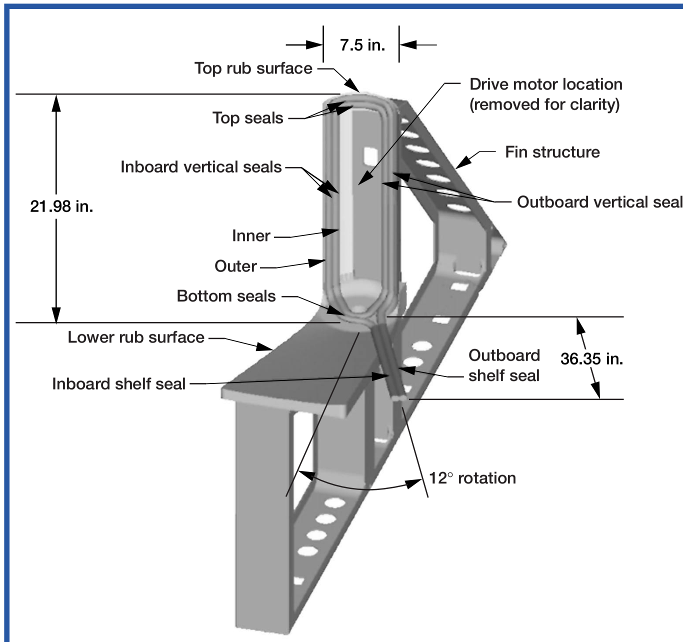


Baseline X-38 Rudder/Fin Seal Design

Cross Section of Rudder/Fin Seal Shelf Location



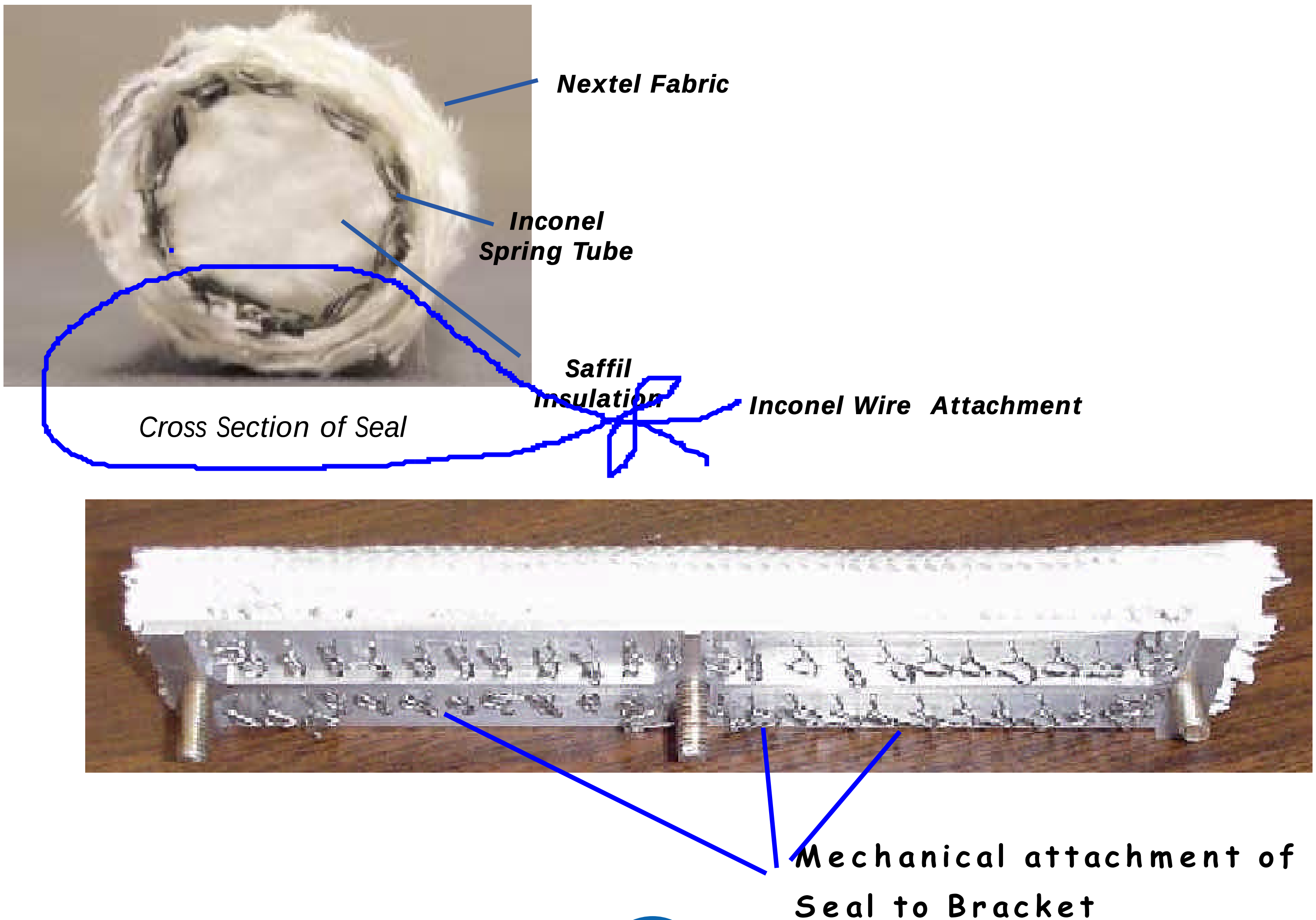
Rudder Shown at Flush Inboard Position



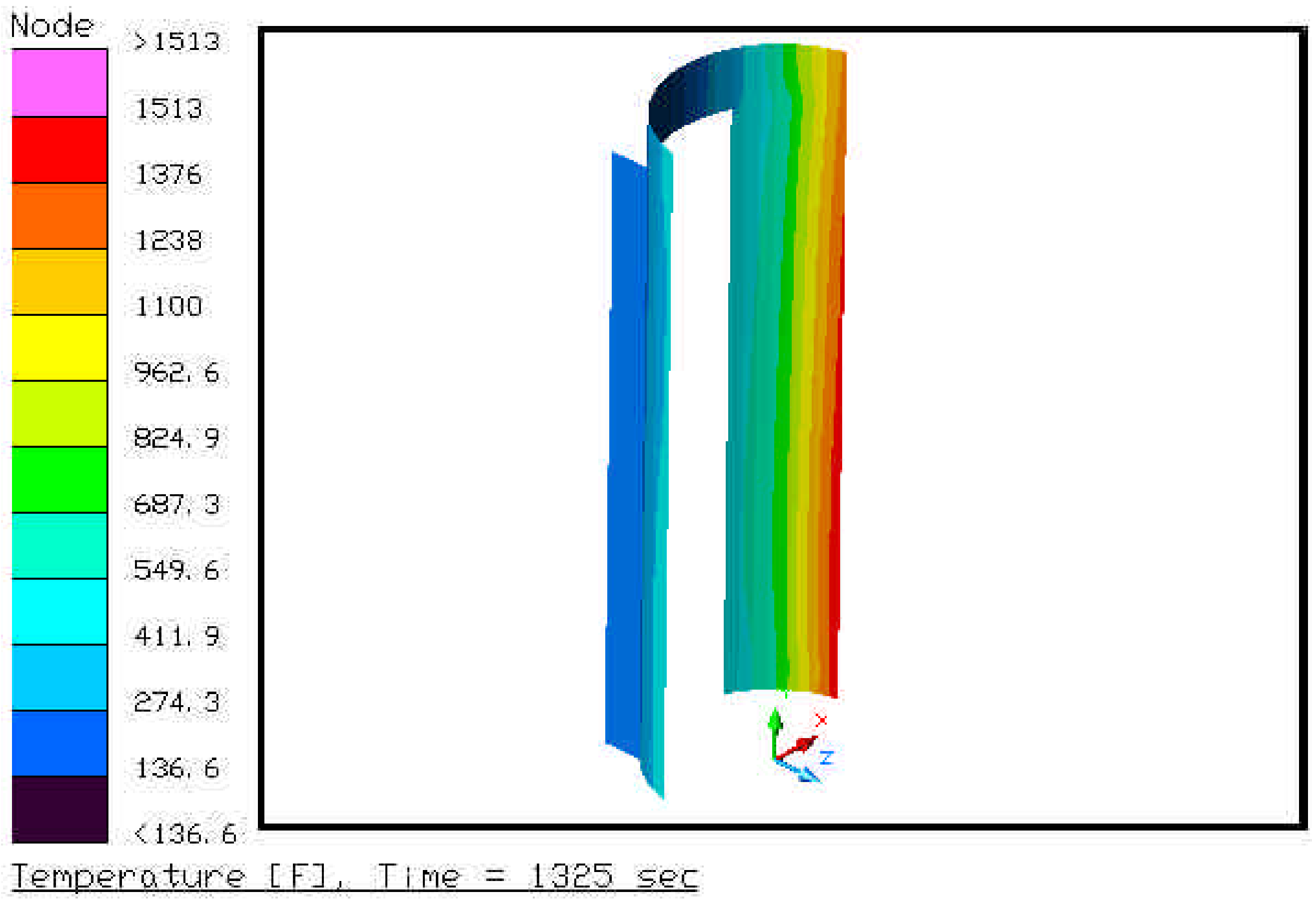
❖ *Main Seal Components*
- *Core: 6 pcf Saffil Insulation*
- *Spring Tube: Inconel X-750*
- *Sheath: Two Layers of Nextel 312 Fabric*

❖ *Nominal 20% Compression and 0.25-in. Gap*

Rudder / Fin Seal to Bracket Assembly



X-38 Rudder / Fin Vertical Rub Surface Inconel – 0.10 in.



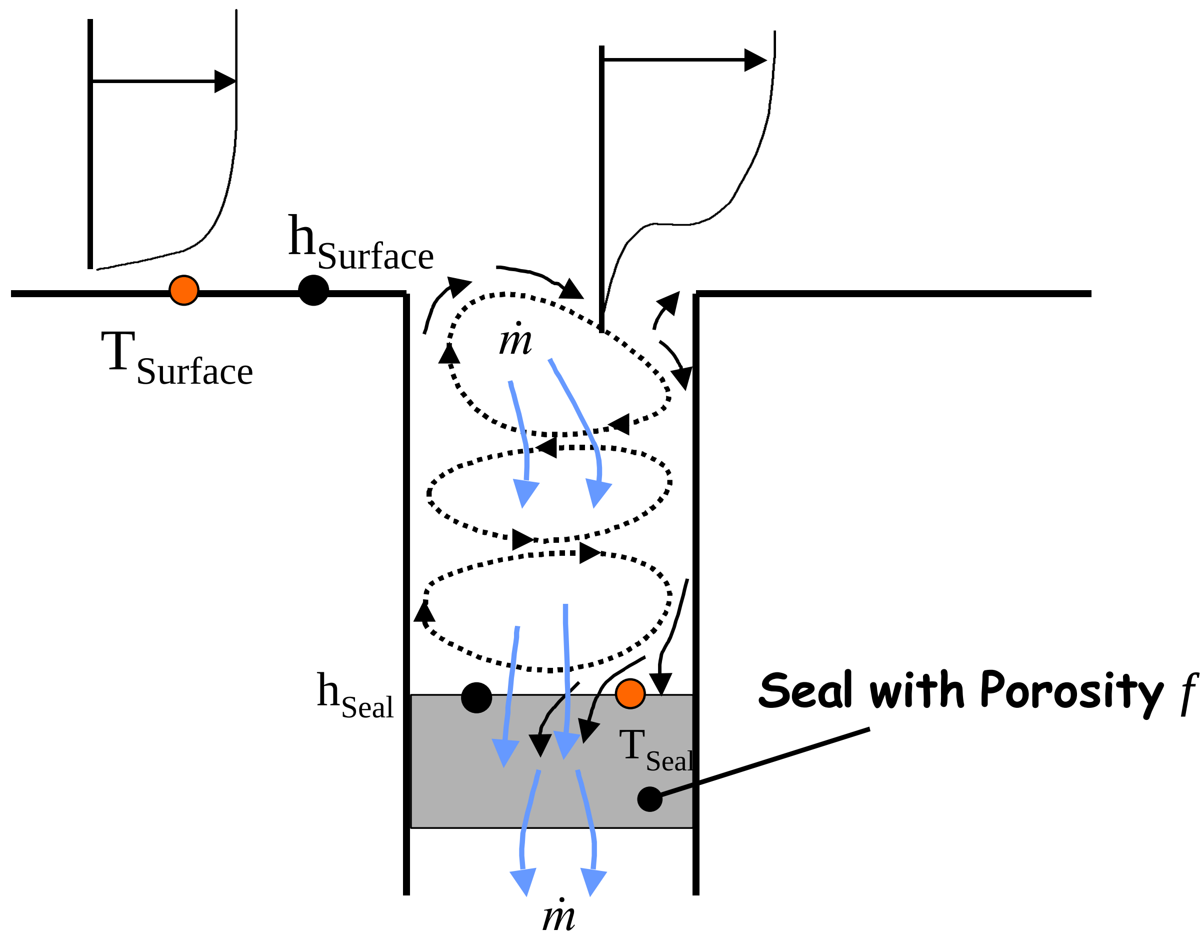
X-38 Rudder / Fin Seal Analysis

- **Flow Characteristics**
  - **20% Seal Compression**
  - **Permeability = 1.0 E-09 Ft^2**
  - **Mass Flux Computed using Darcy Relation:**

$$m_{dot} = \frac{r * A * K * DP}{m * L}$$

- **Thermal Analysis**
  - **Thermal Equilibrium Assumed between Seal/Structure and Gas Flow**
  - **Heat Transfer to Seal Surface Modeled using Nestler Correlation**
  - **Influx Gas Temperature Assumed to be Equal to External Wall Temperature**

Seal Analysis Model



Governing Differential Equations for Equilibrium Thermal Assumption

Composite Fluid – Solid Energy Equation

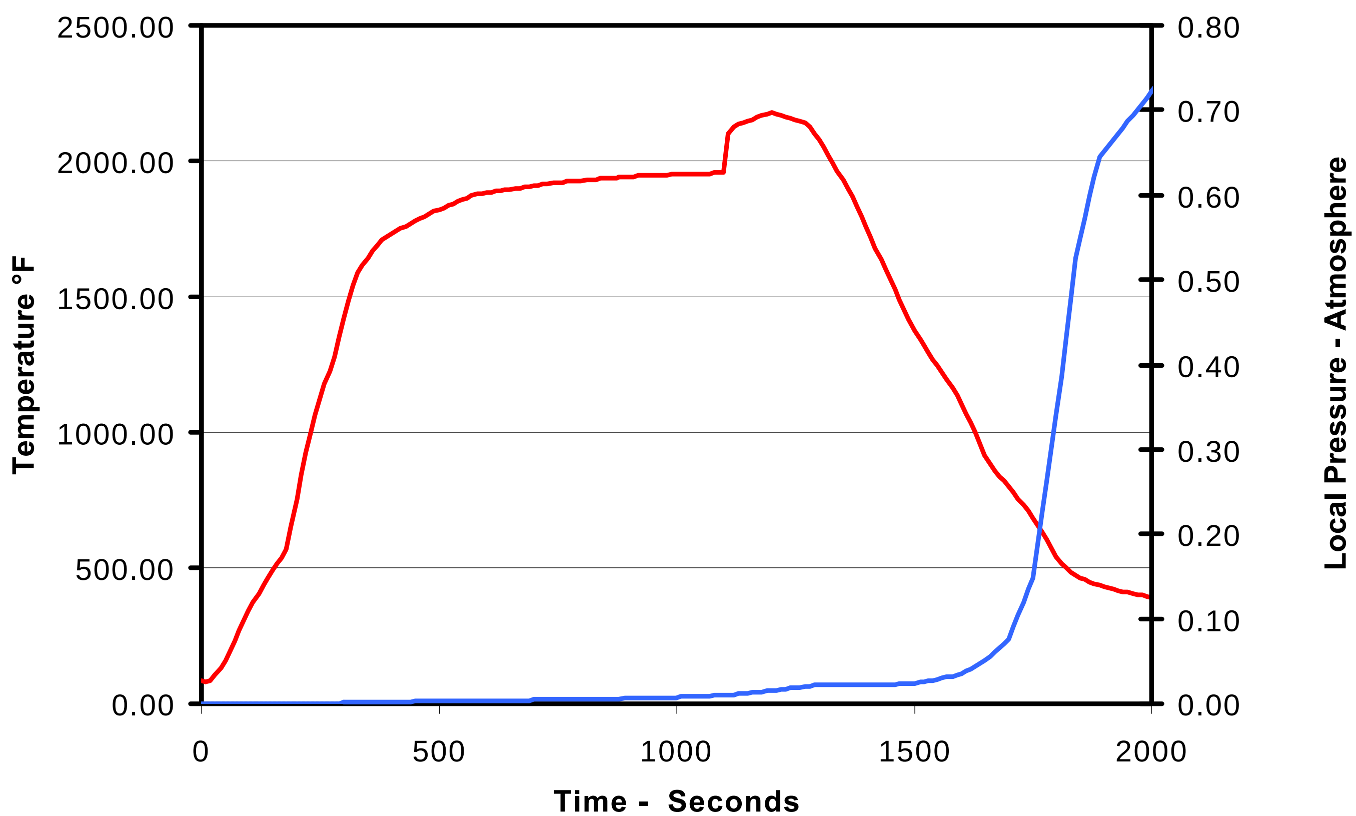
$$r\, C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K \frac{\partial T}{\partial x}\right) + \dot{m}''\, C_{p_f} f\, \frac{\partial T}{\partial x}$$

ρ, C_P & K are Composite Properties
C_{Pf} is a Fluid Property
$T_s = T_f\ ^{o}\ T$ (Thermal Equilibrium)

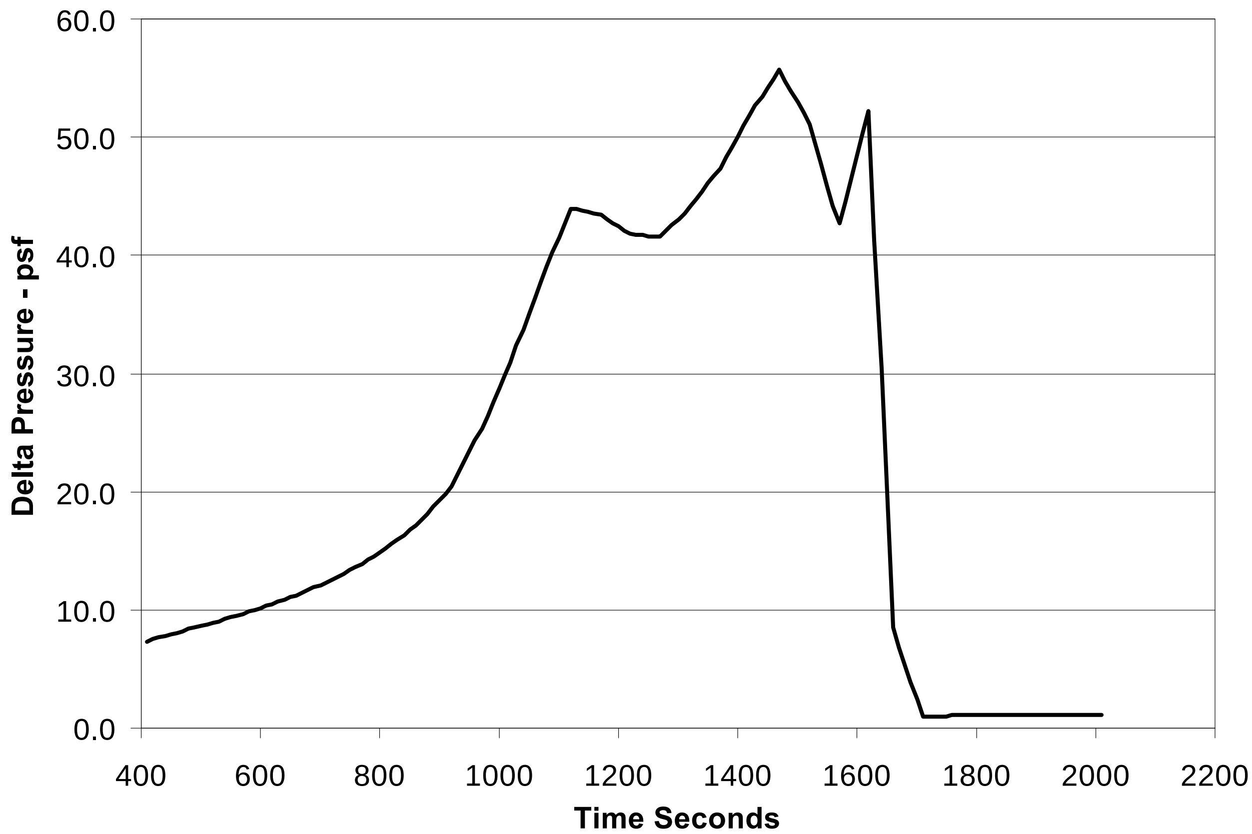
Darcy's Momentum Equation

$$-\frac{dP}{dx} = amn + brn^{2}$$

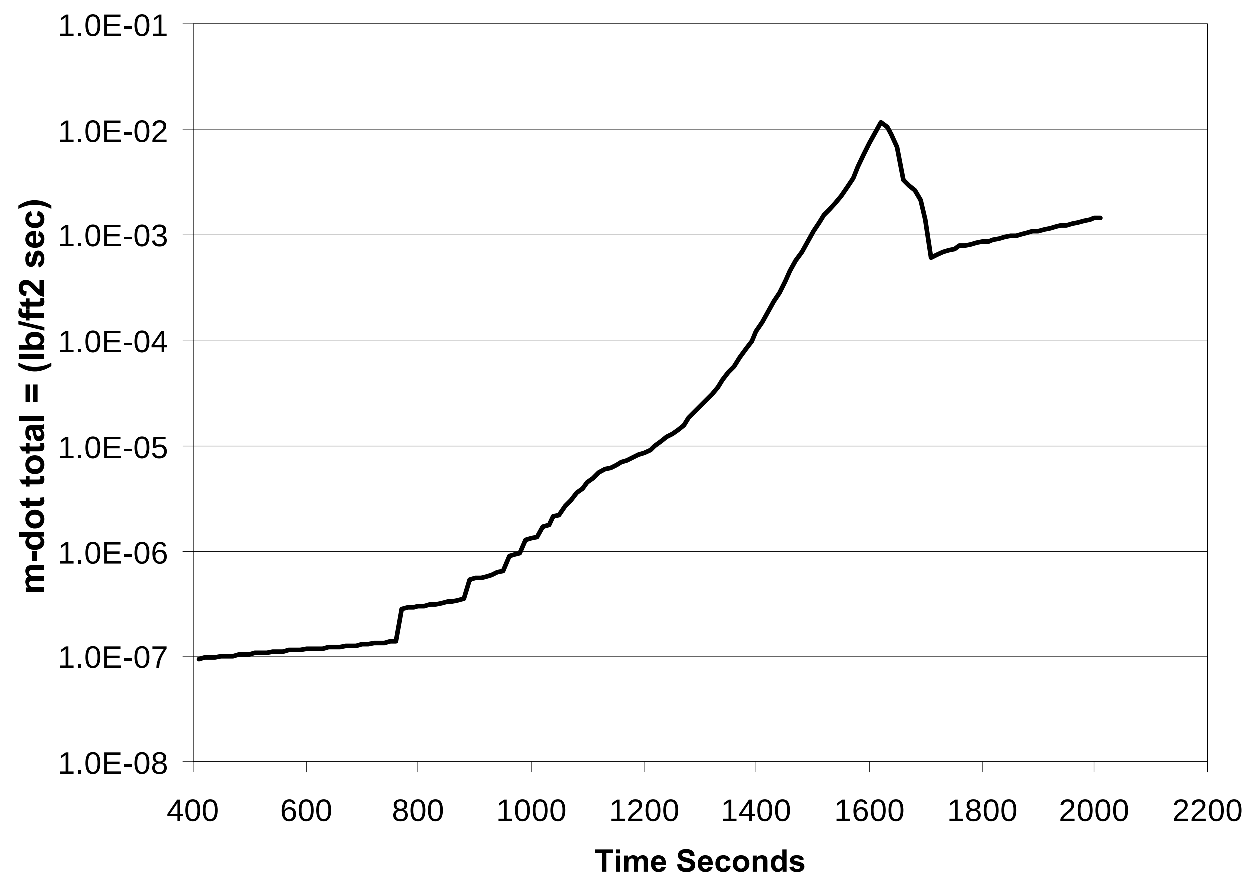
X-38 Rudder / Fin Seal Windward Surface Air Bulk Temperature and Pressure for Cycle 8 Trajectory



X-38 Rudder / Fin Seal Pressure Across the Gap Filler Seal Cycle 8 Trajectory

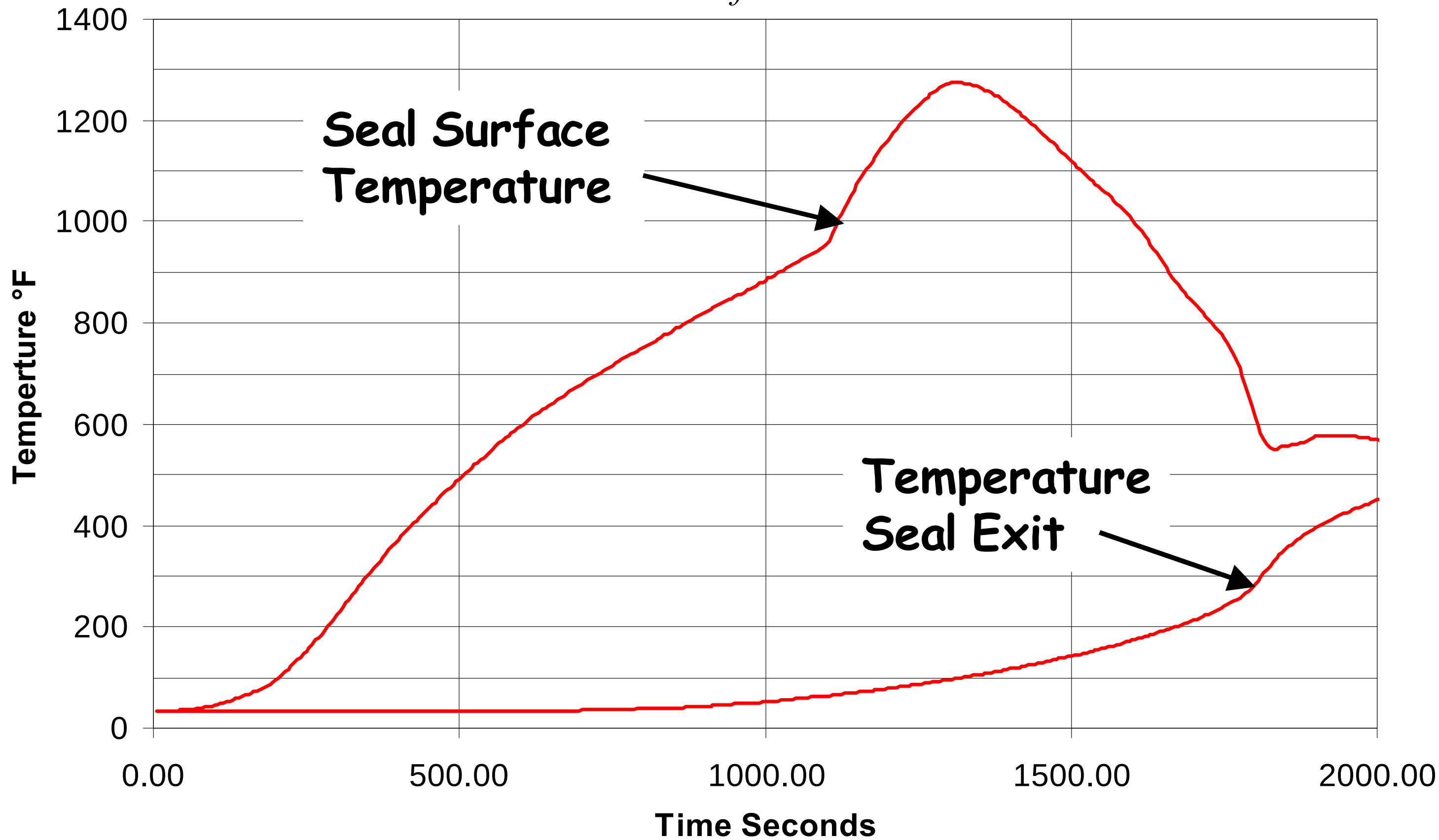


X-38 Rudder / Fin Seal Mass Flow Cycle 8 Trajectory

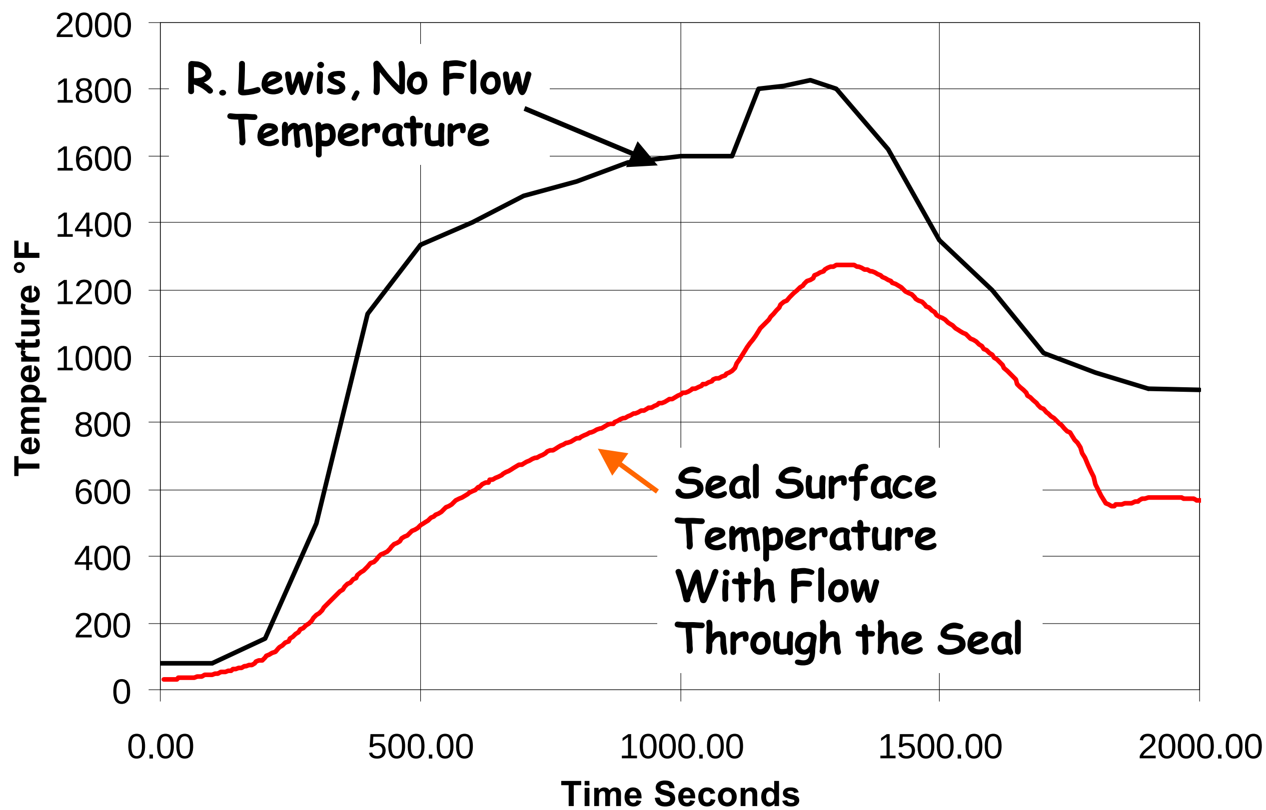


X-38 Rudder / Fin Seal Temperature and Pressure Cycle 8 Trajectory

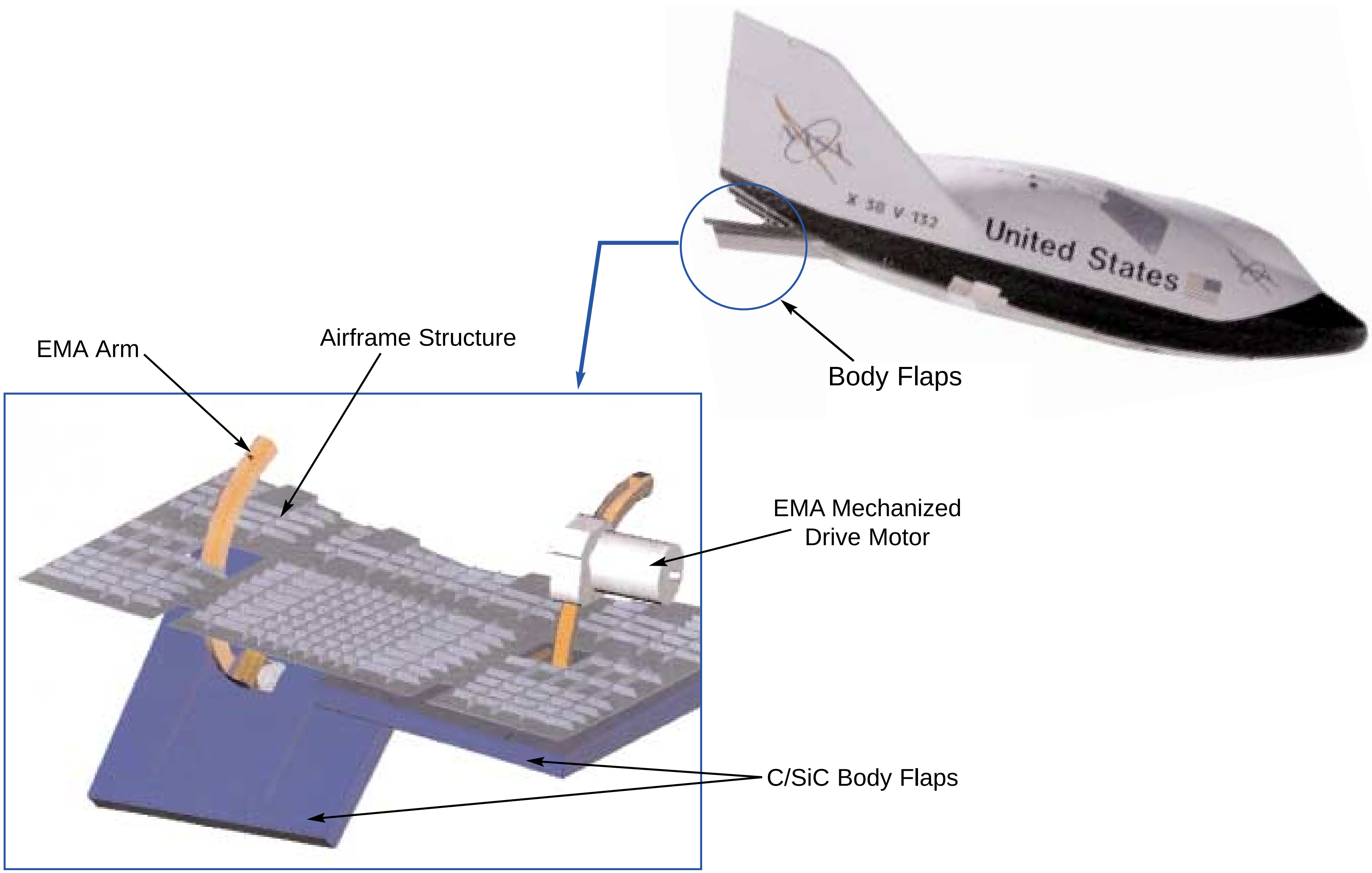
$$\dot{q}_{seal} = \dot{q}_{surface} * 0.04$$



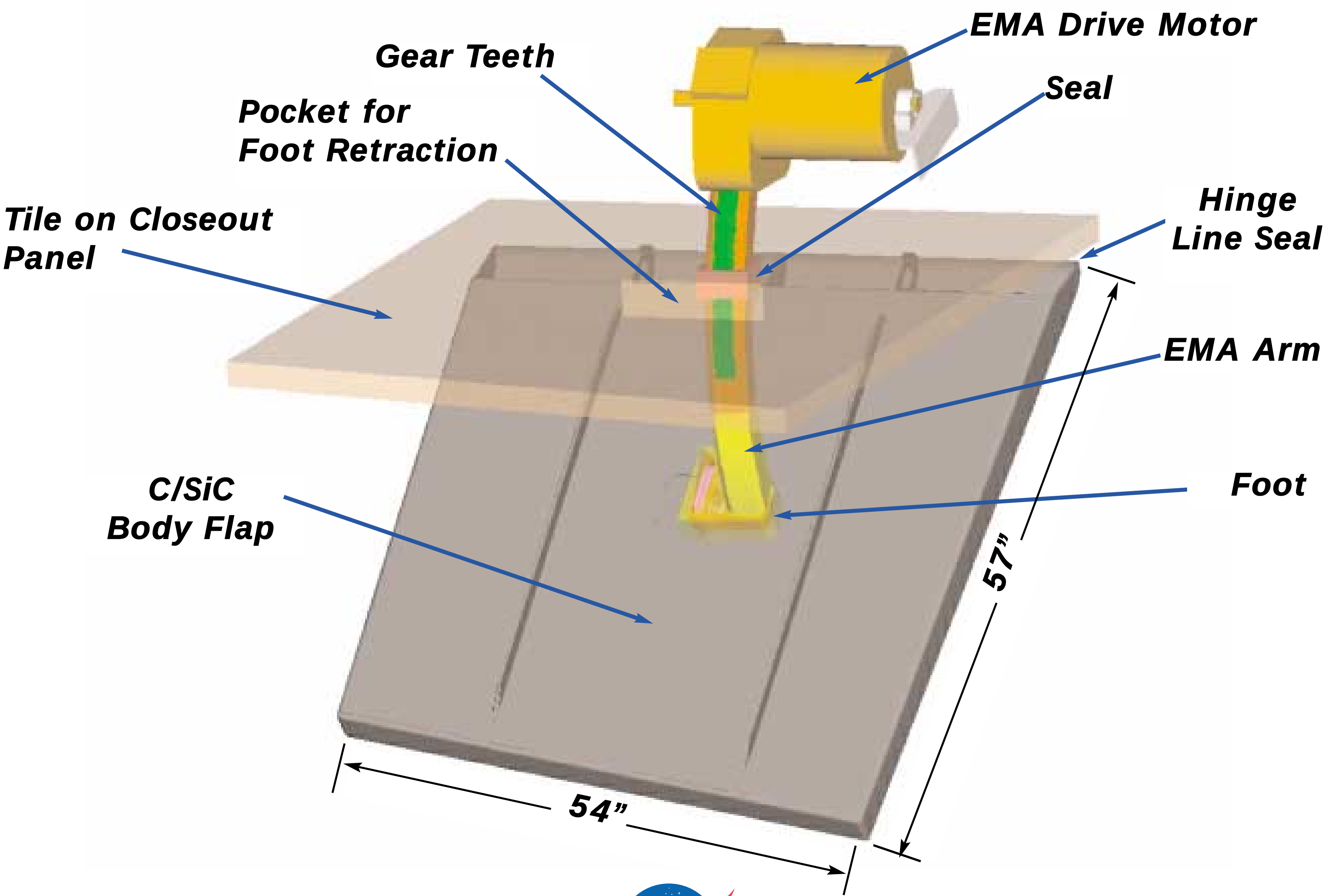
X-38 Rudder / Fin Seal Cycle 8 Seal Surface Temperature Comparison



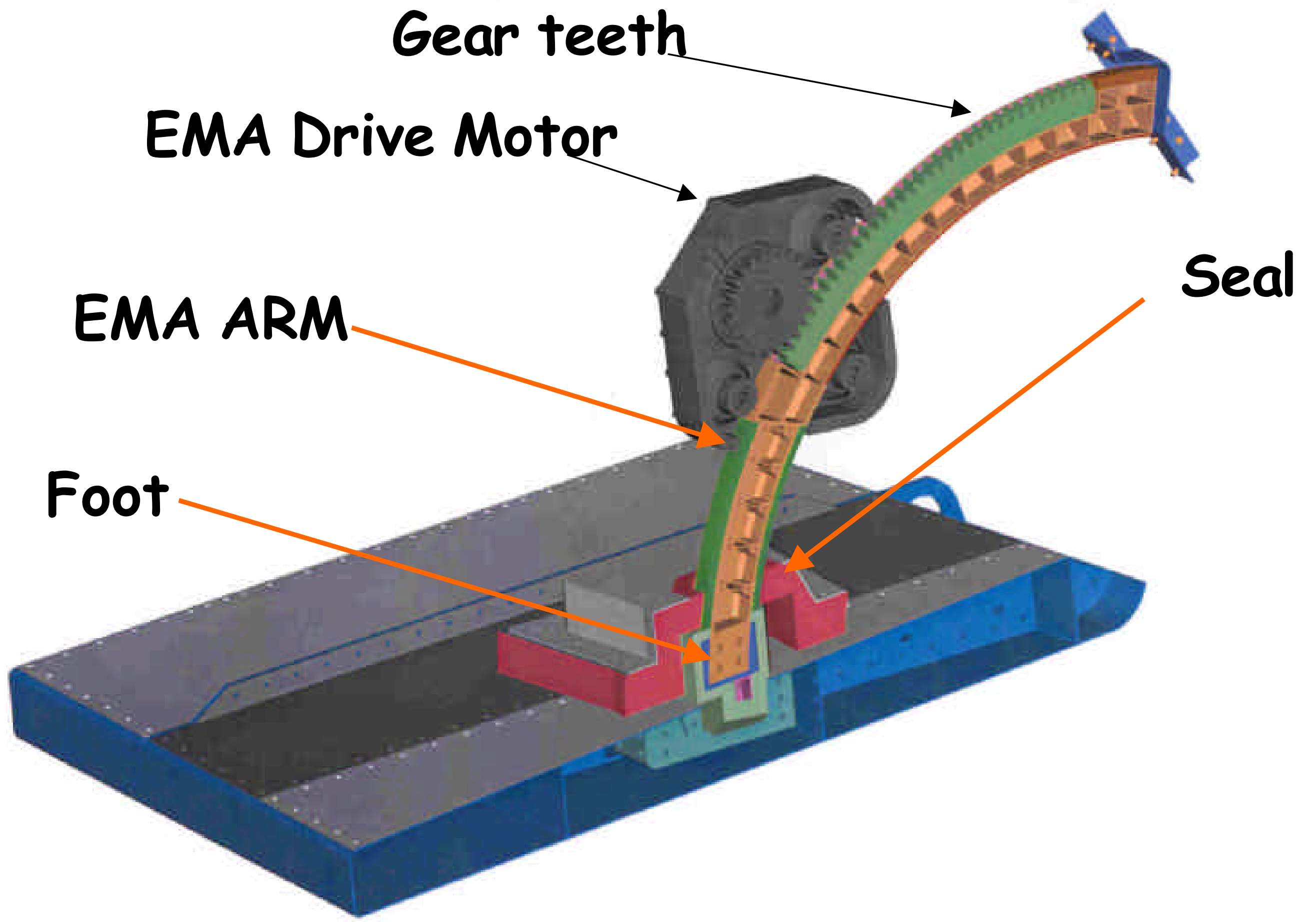
X-38 Body Flap Assembly



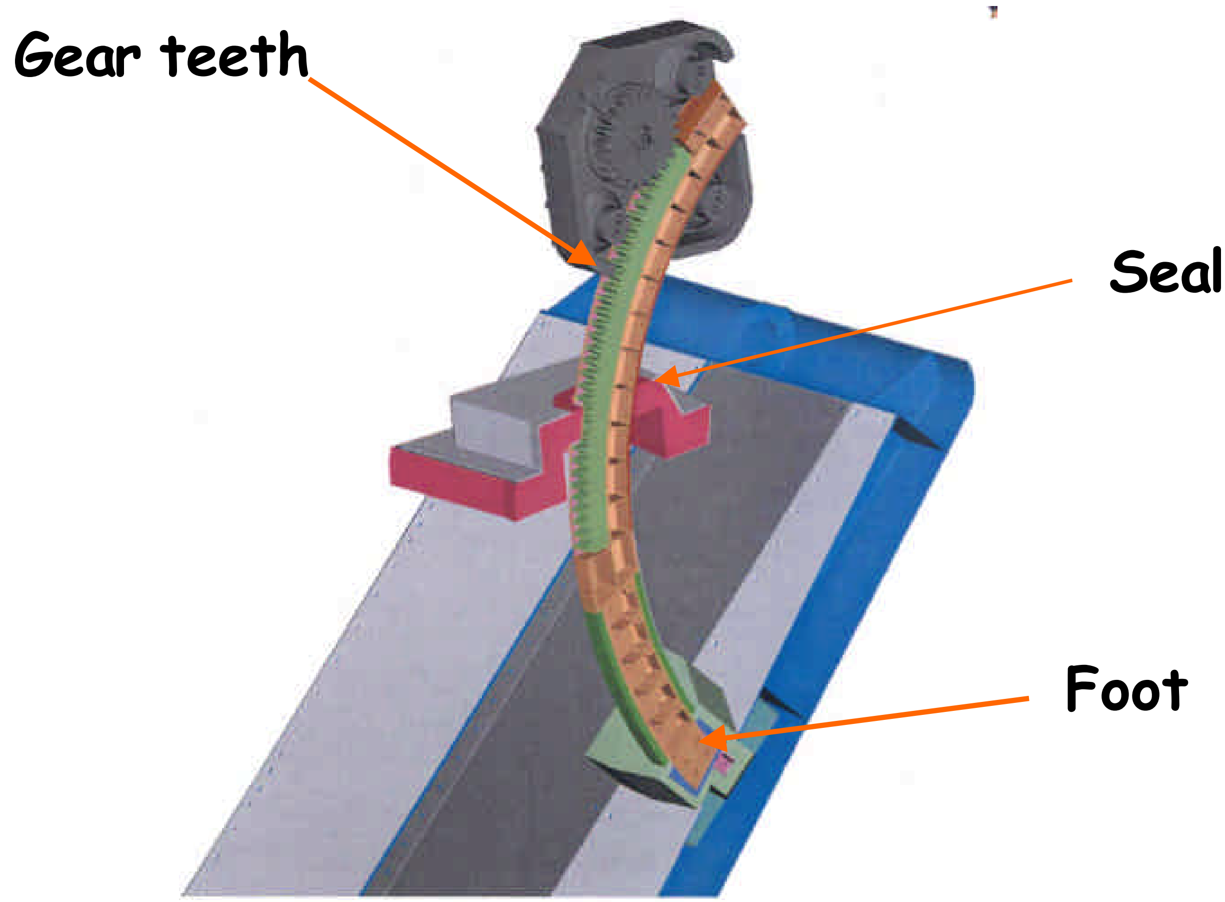
Baseline X-38 Bodyflap Seal Design



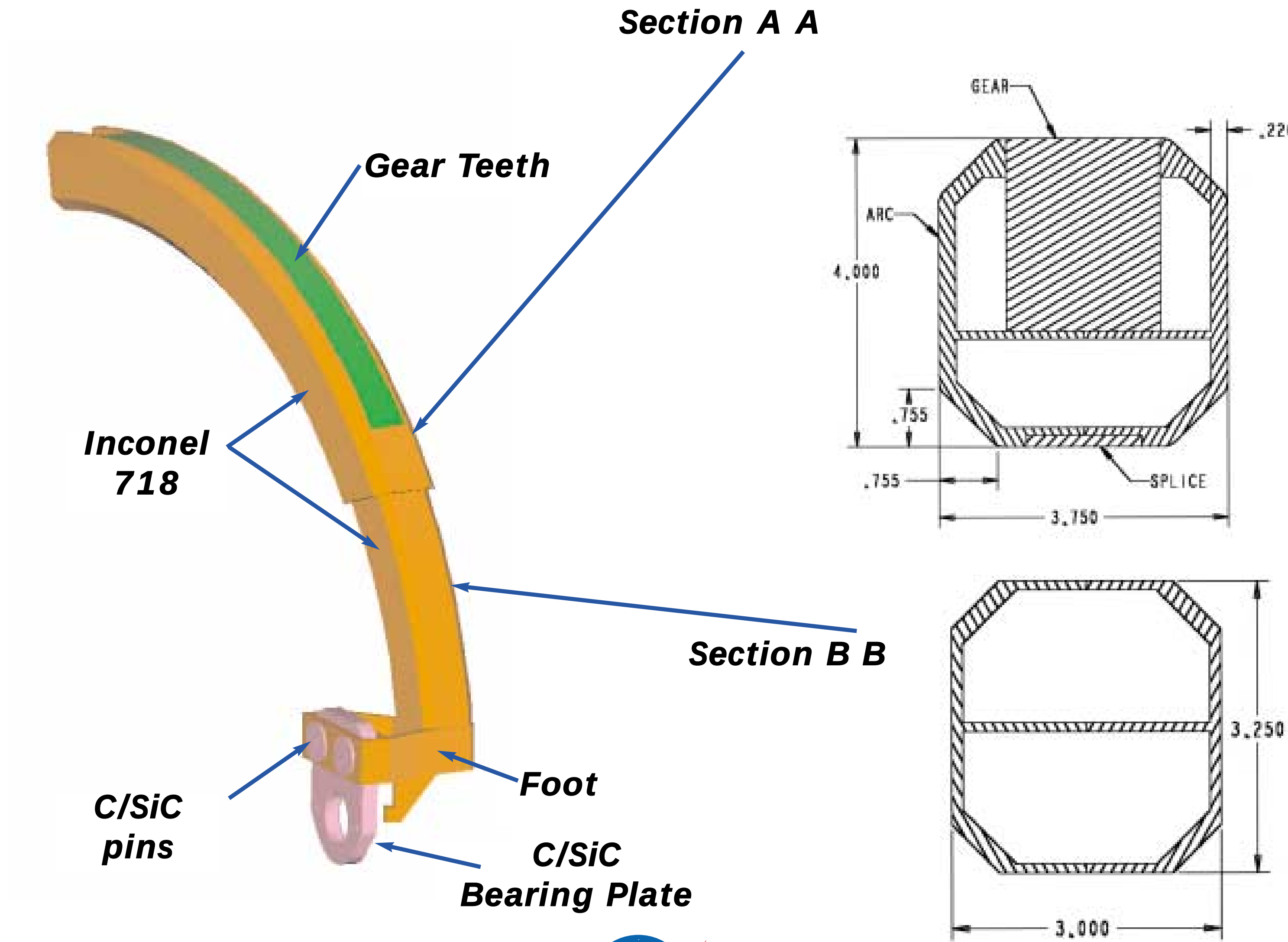
X-38 Bodyflap Seal Design (Undeflected)



X-38 Bodyflap Seal Design (45° Deflection)



EMA Arm Without Thermal Shield



X-38 Body Flap EMA TPS Concept Evaluation

- **Problem:**

  Conventional TPS do not meet the requirements for the X-38 Body Flap Electro Mechanical Actuator (EMA) Arm

- **Requirements:**

  High temperature, low conductivity, durable, and rub resistant TPS

X-38 Body Flap EMA TPS Concept Evaluation

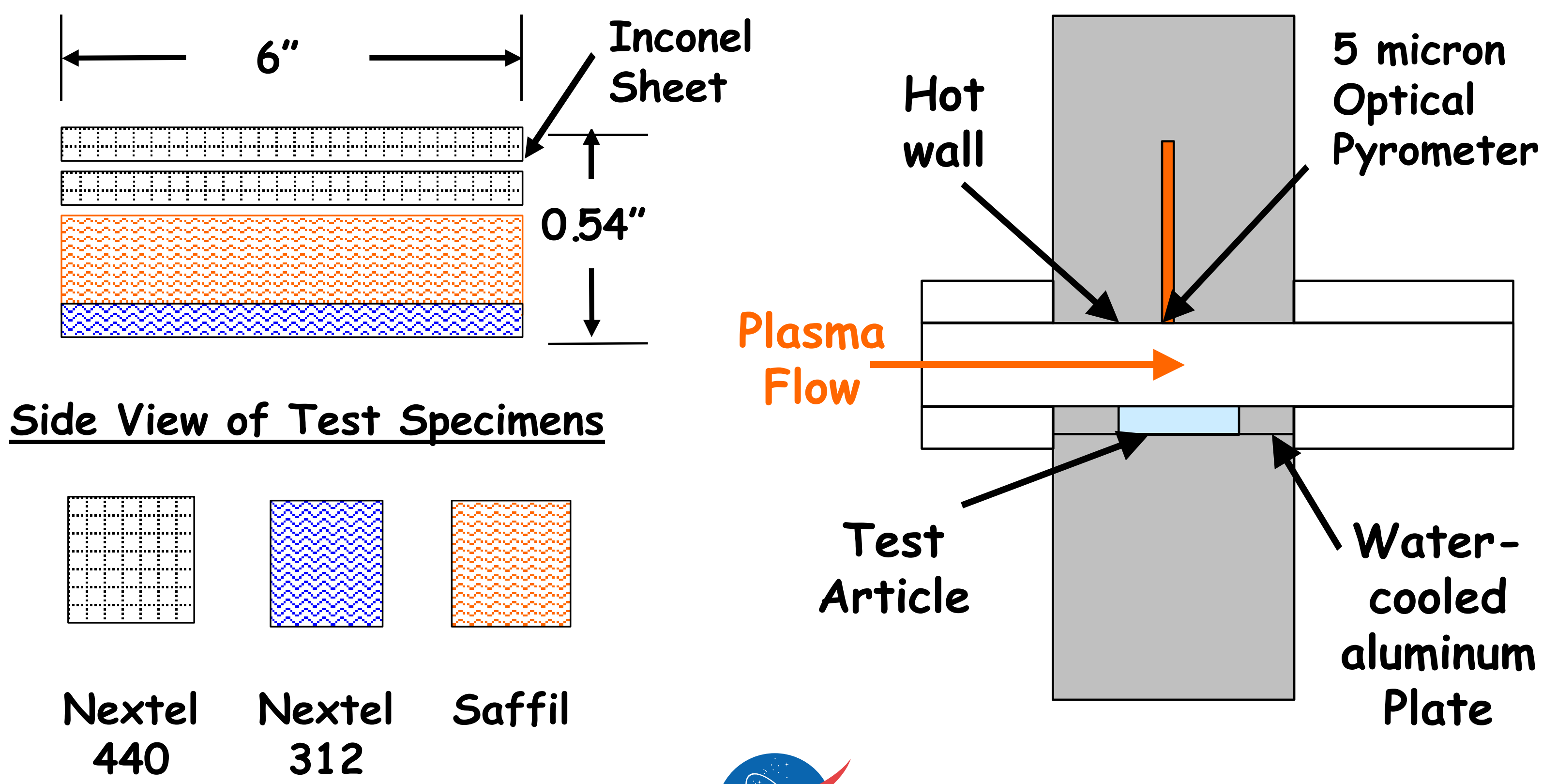
- **New Concept:**

  Two layers of Nextel 440 with a thin sheet of Inconel between them

- **Purpose:**

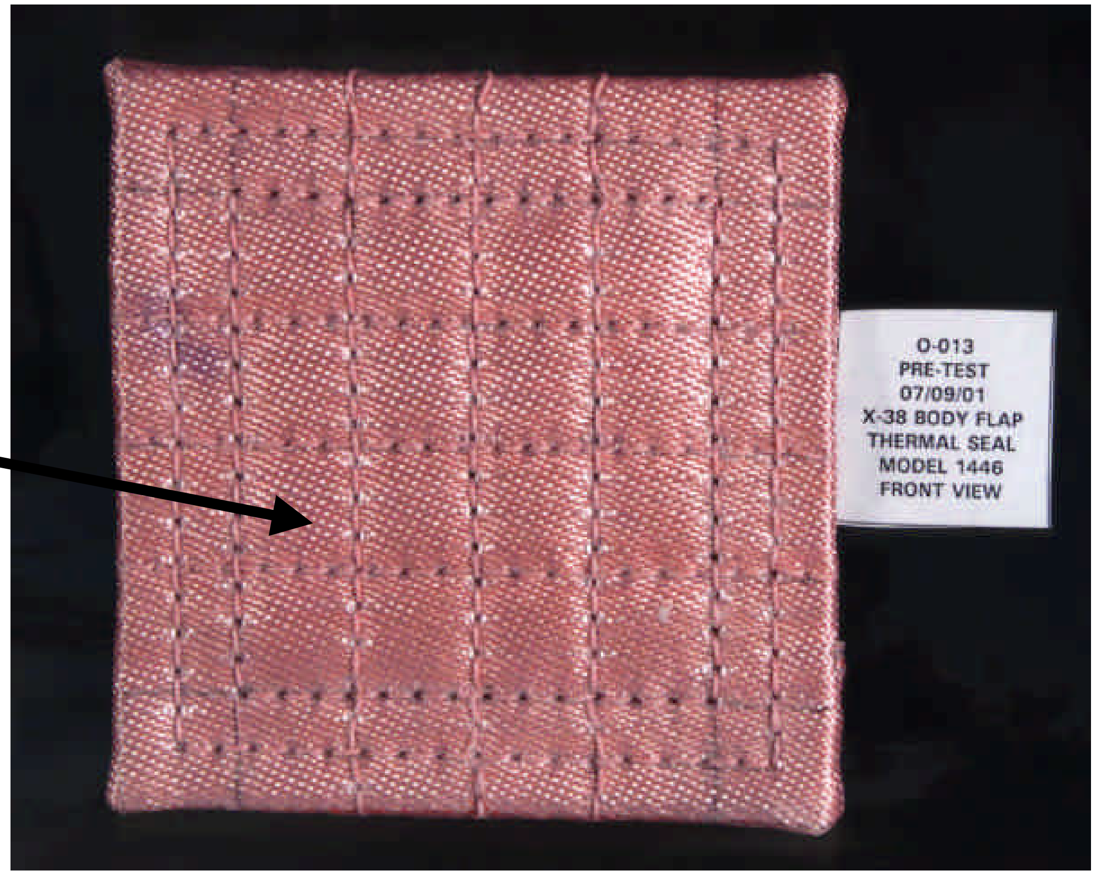
  Evaluate a new TPS concept for the X-38 Body Flap Electro Mechanical Actuator (EMA) Arm

X-38 Body Flap EMA TPS Concept Evaluation Test Setup Top View of Cross Section of Channel Nozzle (Schematic)



X-38 Pre – Test Photograph

Nextel
440



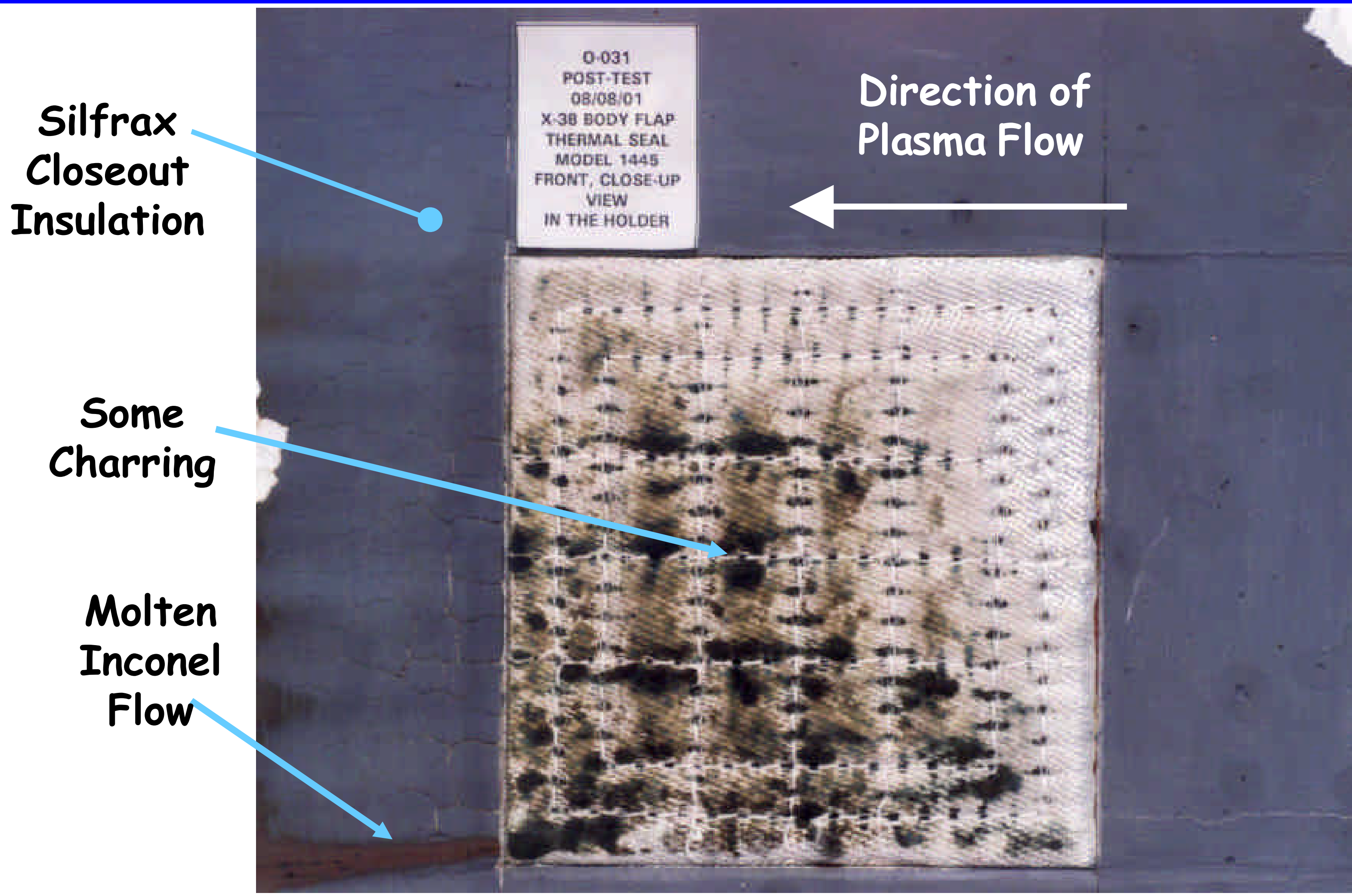
X-38 Body Flap Thermal Shield Concept Evaluation

- **Results:**

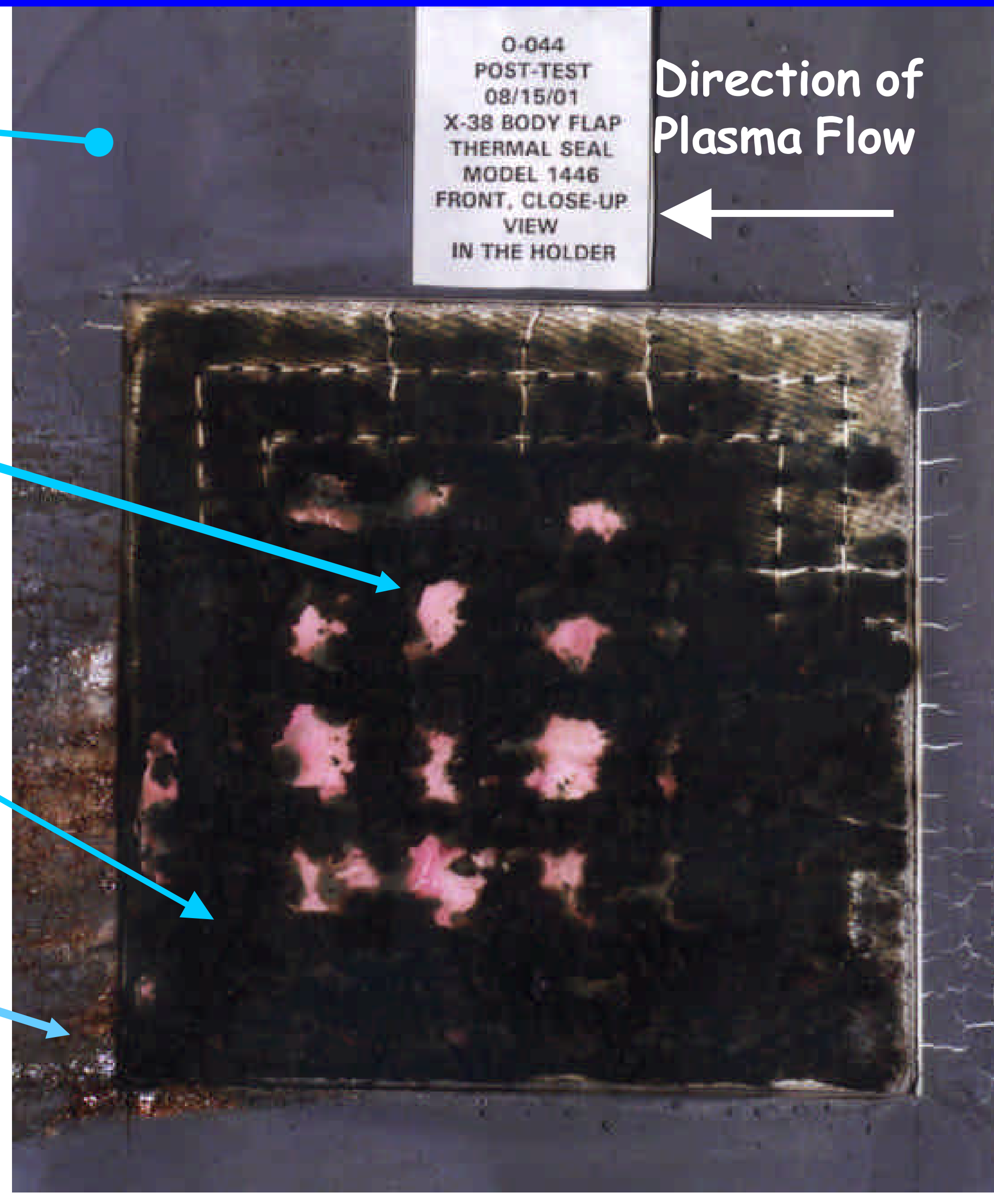
  New TPS concept failed due to severe surface degradation and easy fragmentation from the force of a pressure seal

- **Possible Solutions:**
  - **Coated Niobium (C-103) Heat Shield (Baseline)**
  - **Reusable Surface Insulation (RSI) "Donut" Rings**

X-38 Post – Test Photograph 2500°F



X-38 Post – Test Photograph 2800°F



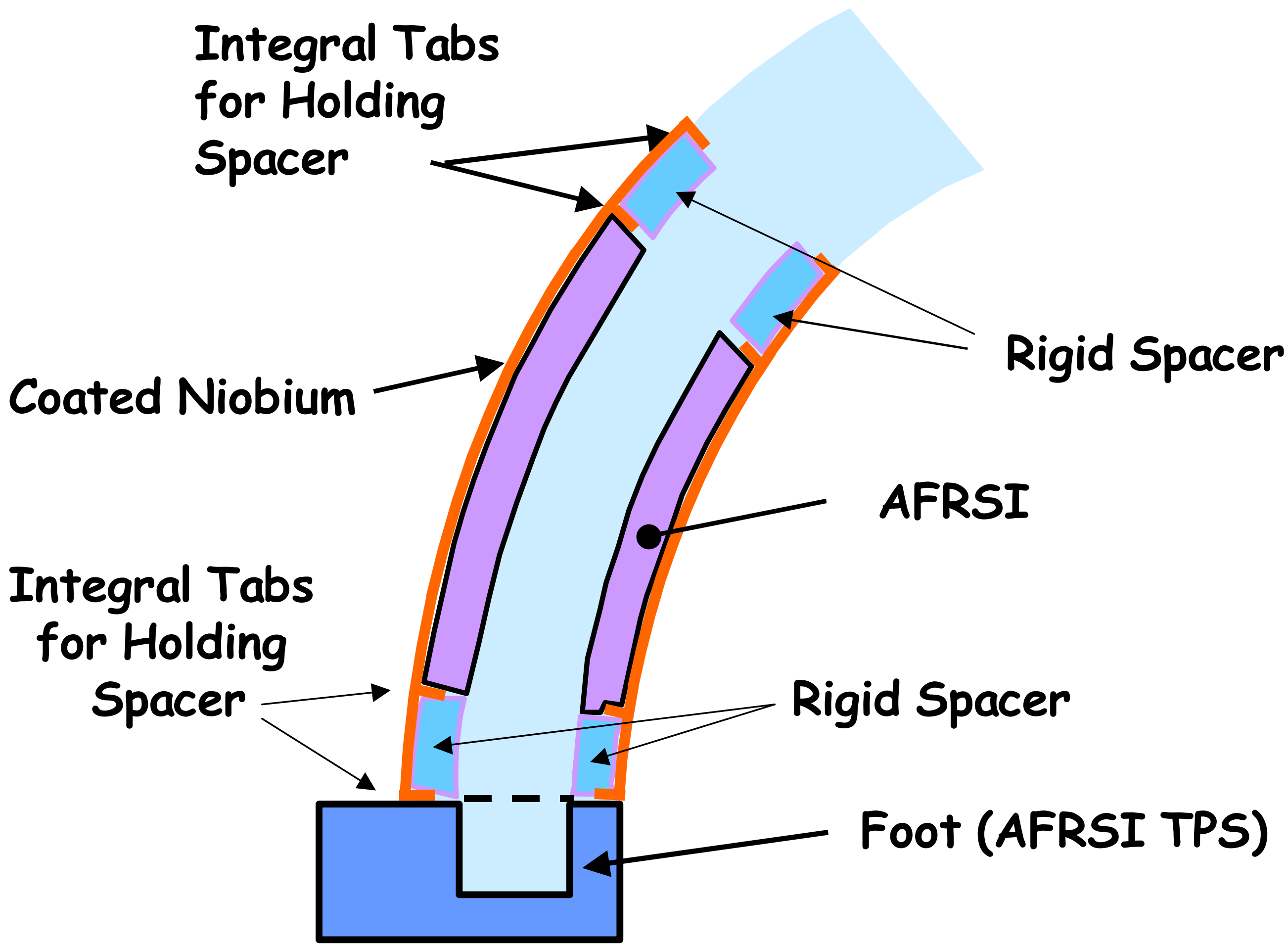
Silfrax Closeout Insulation

Fused Nextel 440 and Inconel

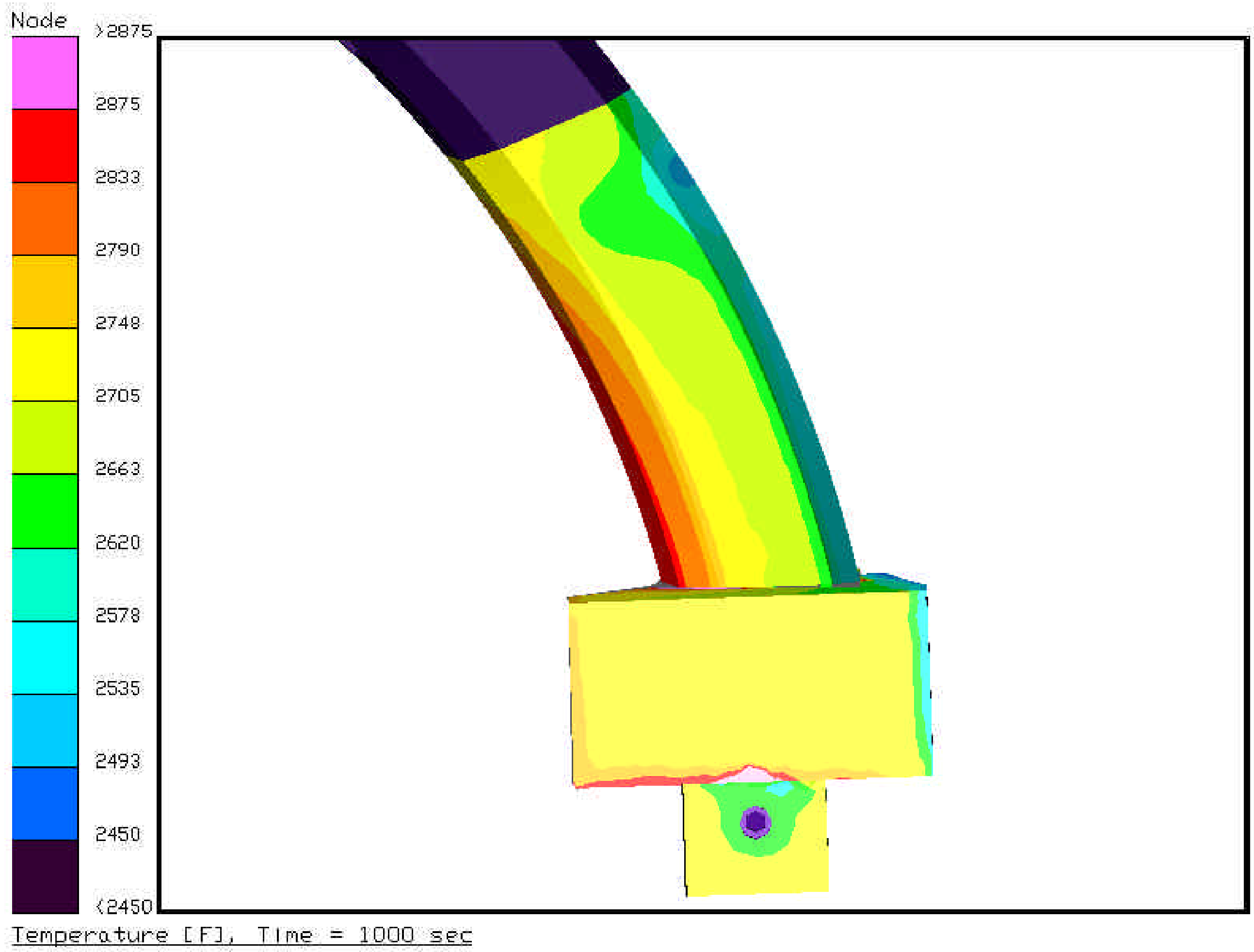
Severe Charring

Molten Inconel Flow

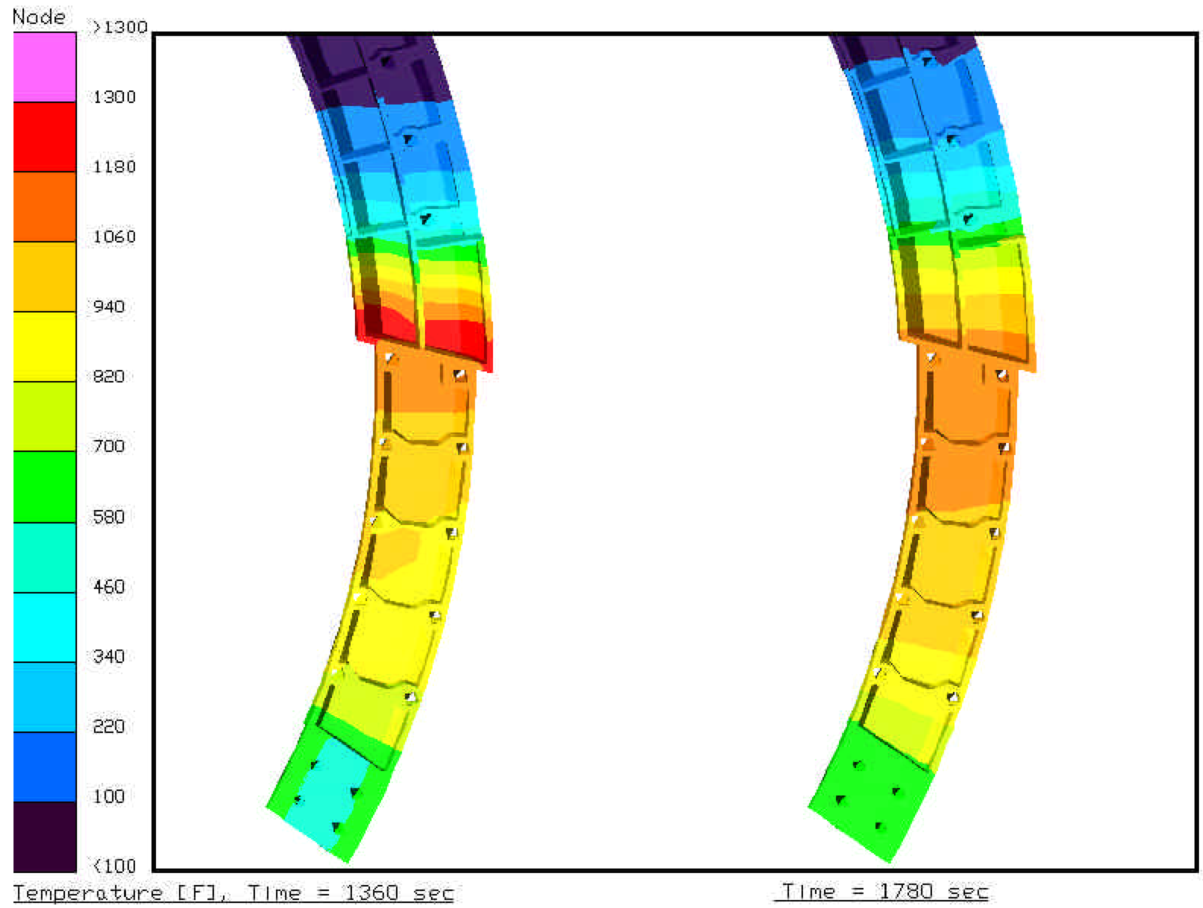
EMA Arc Niobium TPS



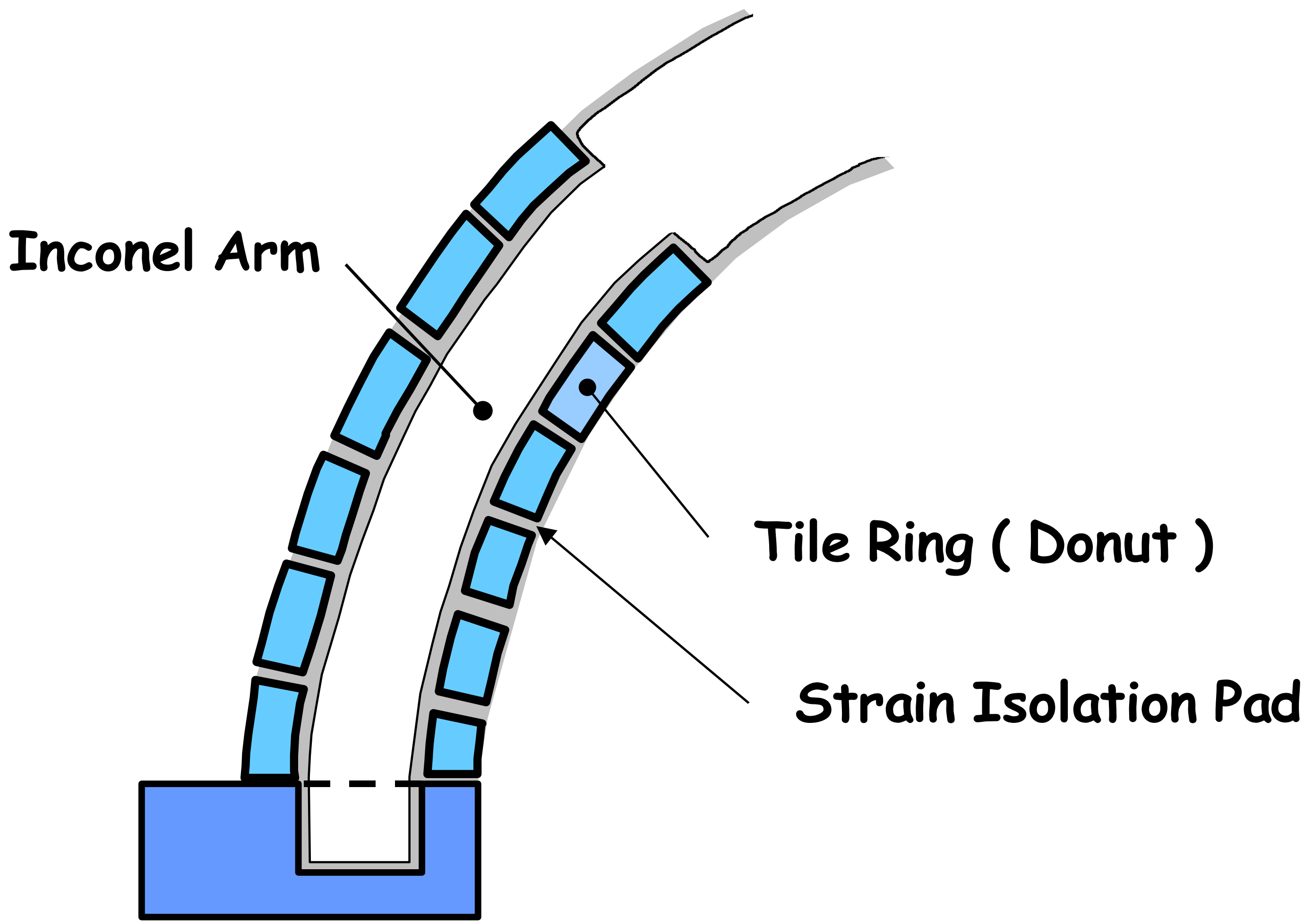
EMA Niobium Surface Temperature



EMA Actuator Arm Temperature



EMA Arc Tile Donut TPS



Current Activities Rudder / Fin Seal

Rudder / Fin Seal

- Thermal / Structural Analysis / Design of Vertical Rub Surface
- Modification of Seal Rub Test Fixture
- Mechanically Attaching Seal to Bracket for Rub Testing
    - Horizontal Tile Surface
    - Vertical Rub Surface
- Horizontal Rub Surface
    - Requires Smooth Tiles

Current Activities (Continued)
Body Flap – EMA Arm Seal

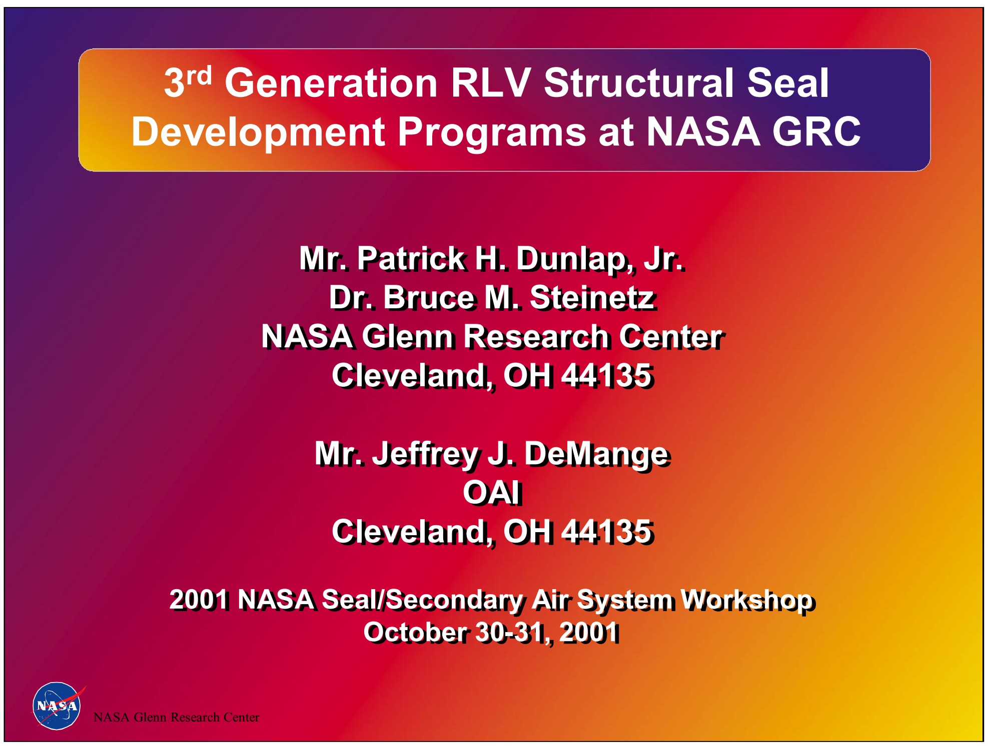
Body Flap – EMA Arm Seal

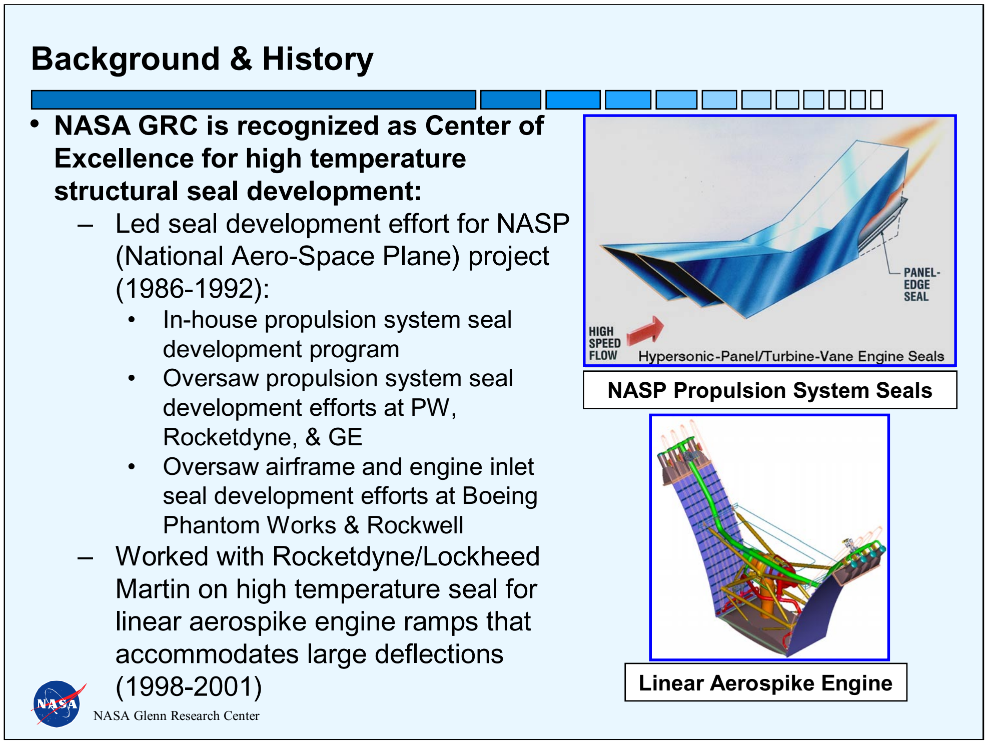
- Perform Rub Tests
  - EMA Arm TPS w / Inconel Spring Seal
    - Coated Niobium
    - Tile Ring (Donut)
  - EMA Arm Gear Teeth
    - Spring Tube Seal
    - Inconel Spring Seal

THIRD GENERATION RLV STRUCTURAL SEAL DEVELOPMENT PROGRAMS AT NASA GRC

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

Jeffrey J. DeMange
Ohio Aerospace Institute
Brook Park, Ohio



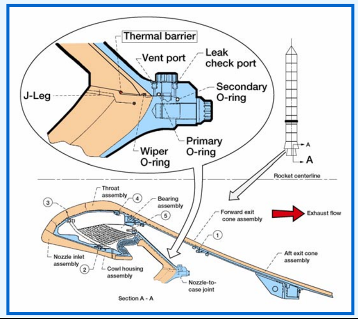


NASA GRC's work on high temperature structural seal development began in the late 1980's and early 1990's under the NASP (National Aero-Space Plane) project. Bruce Steinetz led the in-house propulsion system seal development program and oversaw industry efforts for propulsion system and airframe seal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

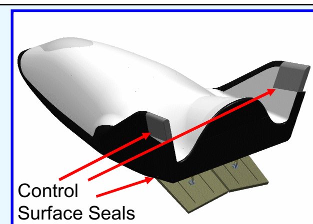
More recently, we worked with Rocketdyne on high temperature seals for the linear aerospike engine ramps. In applications such as the former X-33 program, multiple aerospike engine modules would be installed side by side on the vehicle. Seals are required in between adjacent engine modules along the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

Background & History (cont.)

- Working with Thiokol/NASA Marshall to improve nozzle joint designs in Space Shuttle RSRM's. Thiokol is implementing more reliable J-Leg design and NASA GRC thermal barrier and eliminating joint-fill compound that can develop potentially damaging gas paths (1998-2001)
- Working with NASA JSC to develop and evaluate control surface seals (e.g., rudder/fin seals) for X-38/ Crew Return Vehicle (1999-2001)



Thermal Barrier for Shuttle RSRM



X-38 Seals

NASA Glenn Research Center

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

We are also working with Don Curry and his group at JSC to develop and evaluate control surface seals for the X-38/Crew Return Vehicle. Don briefed these seal development activities earlier in the workshop.

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**

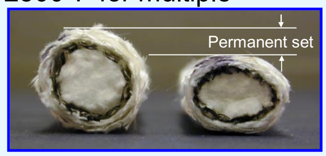
Goal: Develop long life, high temperature control surface and propulsion system seals and analysis methods and demonstrate through laboratory tests.

NASA Glenn Research Center

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

Control Surface Seal Challenges and Requirements

- **X-38 case study used to define seal requirements:**
  - Limit hot gas ingestion and leakage
  - Limit transfer of heat to underlying low-temperature structures
  - Withstand temperatures as high as 2000-2500°F for multiple heating cycles
  - Maintain resiliency (spring back) for multiple heating cycles
  - Limit loads against opposing sealing surfaces
  - Resist scrubbing damage against opposing sealing surfaces
  - Perform all functions for >10X increase in service life over current Shuttle seals



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

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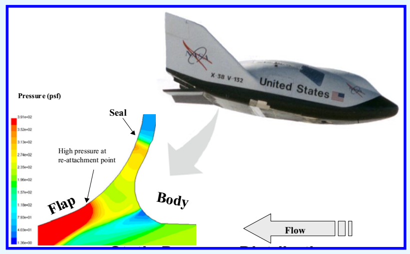
Now focusing specifically on control surface seals, this chart shows the challenges and requirements that new seal designs must meet. Because we have done a good deal of work in testing control surface seals for X-38, we are using these seals as a baseline upon which to improve. We are also using the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

Control Surface Seal Development Plans

- **Evaluate new control surface seal concepts under representative conditions (temperatures, pressures, scrubbing)**
- **New NASA GRC test rigs under development include:**
  - Hot compression rig (stroke rate: as low as 0.001 in/sec at 3000°F)
  - Hot scrub rig (stroke rate: up to 8 in/sec at 3000°F)
  - Cold flow/scrub test rig (ΔP: 0 to 2 psid)
- **Seal environmental exposure tests will be performed in other facilities:**
  - Arc jet tests to evaluate control surface seals (NASA Ames Panel Test Facility)
  - Thermal acoustic tests (NASA LaRC or WPAFB)
- **Aero-thermal-structural analyses of seals using tightly integrated CFD-FEA analysis tools**



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This chart shows how we are planning to develop our advanced control surface seals. We are coming up with new seal designs and plan to evaluate them in several new test rigs under representative conditions of temperature, pressure, and scrubbing. We are designing three new test rigs that we are going to install in our labs at GRC. The first two rigs listed, our hot compression test rig and hot scrub test rig, will actually use the same load frame and furnace with different test fixturing inside the furnace to perform the different tests. We have purchased a load frame from MTS and a box furnace from ATS. The furnace will be installed between the columns of the load frame and will be able to be heated to temperatures up to 3000°F. Test fixturing made of SiC will be used in different configurations inside the furnace to perform either compression or scrub tests.

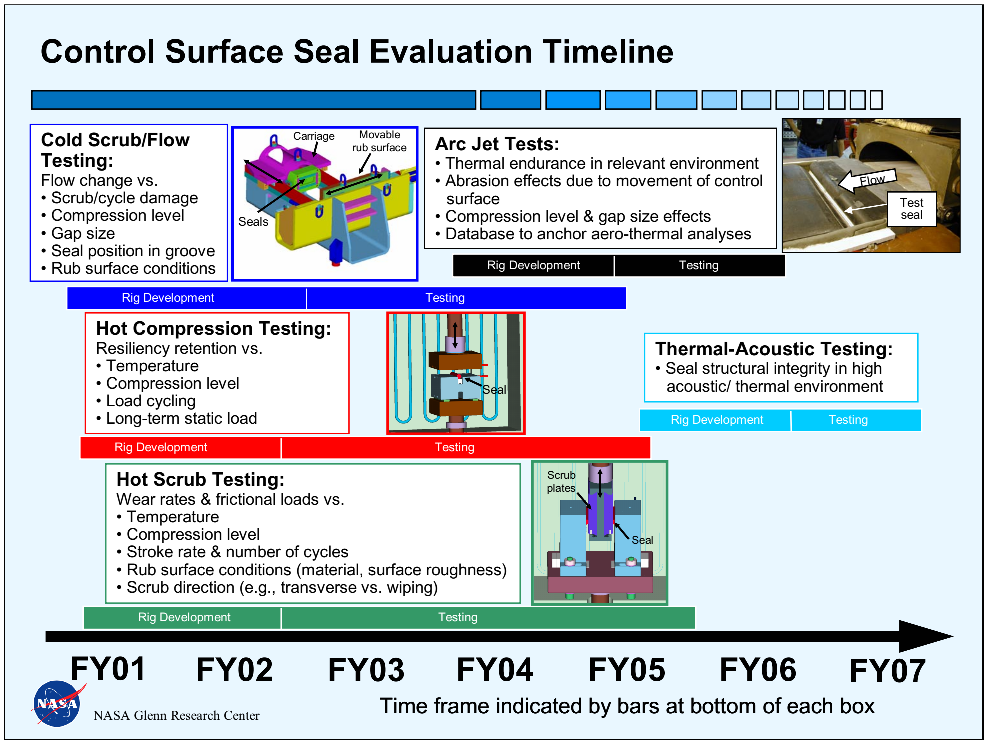
For the compression tests, the seals will be compressed between two plates and will be subjected to multiple compressive load cycles to generate load versus displacement curves for each cycle. We will be able to measure the resiliency, or spring back, of the seals at different temperatures for many load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

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

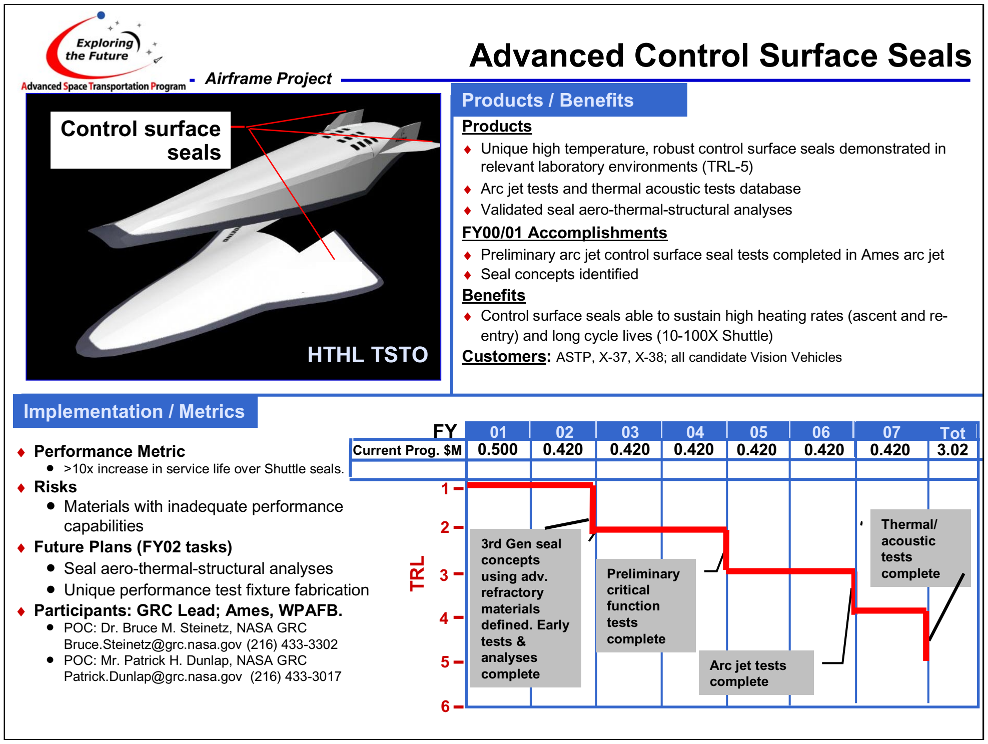
The other test rig we are developing will allow us to perform simultaneous flow and scrub tests on the seals at room temperature. We will be able to pass flow through the seals at the same time that they are being scrubbed against a moving rub surface to see how the flow blocking performance of the seals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

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

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



This chart shows a timeline for how and when we plan to have our rig development and testing occur during this program. Each rig and series of tests is color-coded so that an overall description and image of each test rig are shown above a bar indicating the time frame for rig development and testing. We are currently in the rig development stage for our new cold flow/scrub, hot compression, and hot scrub test rigs. We plan to begin hot compression and hot scrub testing by the summer of 2002, and we plan to have our cold flow/scrub test rig ready for testing by the fall of 2002. Further out on the schedule are the arc jet tests that we would do around FY05-06 and the thermal-acoustic tests that we plan to perform in FY06-07.



This is the quad chart for our advanced control surface seal development task. The lower right hand corner of the chart shows our plan for TRL advancement over the course of this program. We are beginning at a TRL of one for the task and working up to a TRL of five by the end of FY07. At this point we will have tested the seals in a relevant laboratory environment.

Propulsion System Seal Challenges and Requirements

- **NASA and I^{STAR} case studies used to define seal requirements:**
  - Withstand very high engine temperatures, as hot as 6000°F in combustor during scramjet operation
  - Limit leakage of hot gases and unburned propellant into backside cavities
  - Withstand chemically hostile environment
    - Oxidizing environment limits material selection
    - Hydrogen embrittlement can occur
  - Seal distorted sidewalls and remain resilient for multiple heating cycles ➨ flexible seals required
  - Survive hot scrub environment with acceptable change in flow rates
  - Utilize high temperature materials to minimize cooling requirements. Cooling schemes can be complex and heavy
  - Engine operation and mission safety demand highly reliable seals

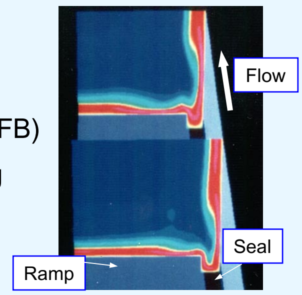
Challenge: Design hot, flexible seals that require minimal coolant and meet engine life goals

NASA Glenn Research Center

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

Propulsion System Seal Development Plans

- **Evaluate new propulsion system seal concepts under representative conditions (temperatures, pressures, scrubbing)**
- **New NASA GRC test rigs under development include:**
  - Hot compression rig (stroke rate: as low as 0.001 in/sec at 3000°F)
  - Hot scrub rig (stroke rate: up to 4.5 in/sec at 3000°F)
  - Cold flow/scrub test rig (ΔP: 0 to 120 psid)
- **Seal environmental exposure tests will be performed in other facilities:**
  - Rocket heating/thermal survival tests to evaluate propulsion system seals (NASA GRC C-22 Rocket Facility)
  - Thermal acoustic tests (NASA LaRC or WPAFB)
- **Aero-thermal-structural analyses of seals using tightly integrated CFD-FEA analysis tools**



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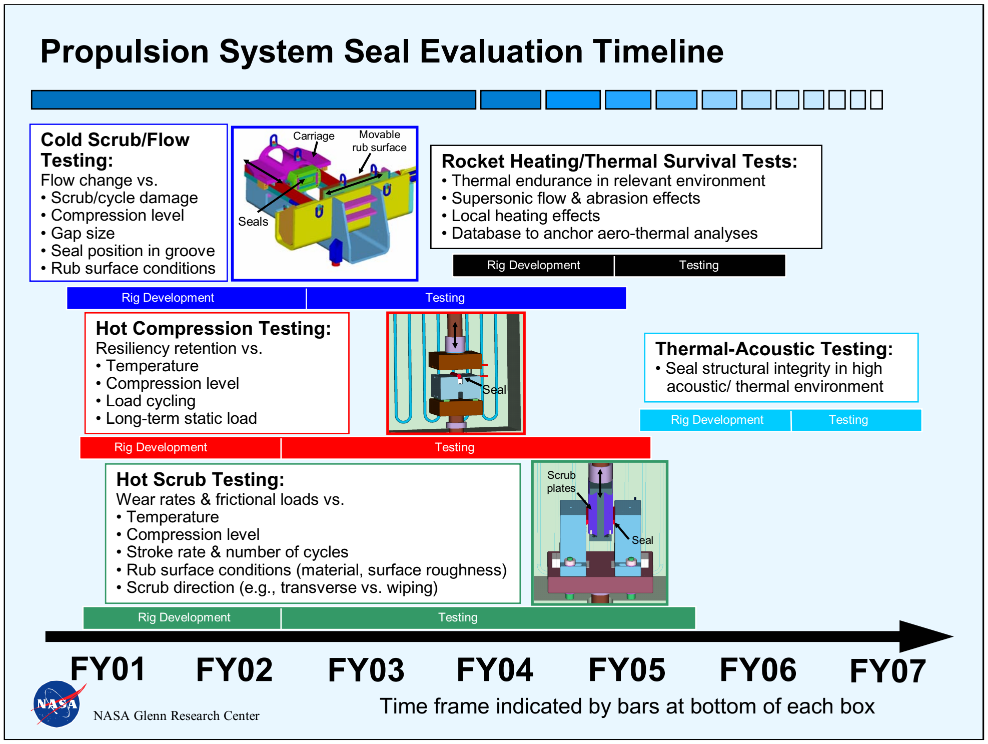
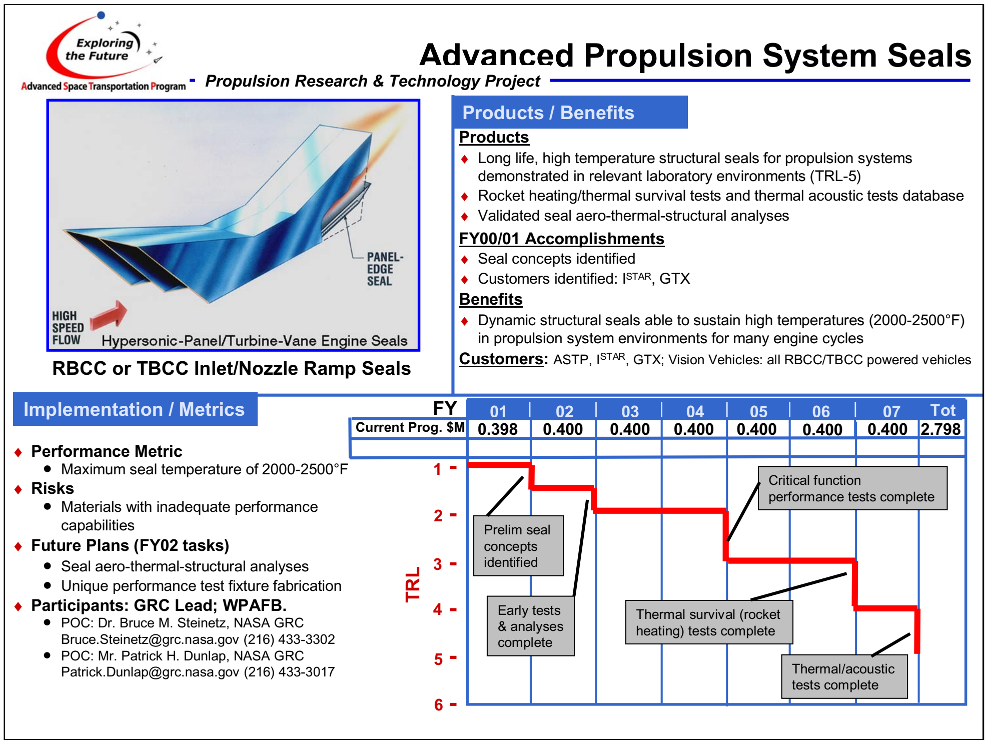
Like the control surface seals, we plan to come up with new propulsion system seal designs and evaluate them in our new test rigs. We plan to test these seals in the same test rigs but with different test fixturing than what is used for the control surface seals and under somewhat different pressure,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



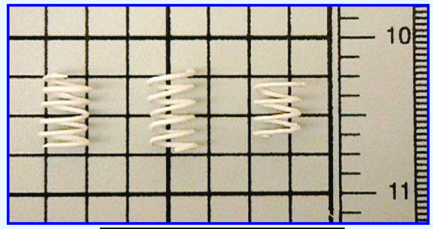
This chart is very similar to the one shown earlier for the control surface seals. The main difference is that the rocket heating/thermal survival tests are shown here in place of the arc jet tests that were shown for the control surface seals.



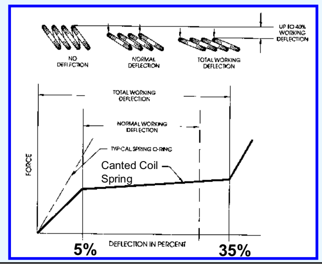
This is the quad chart for our advanced propulsion system seal development task. Like the quad chart shown earlier, the lower right hand corner of this chart shows our plan for TRL advancement over the course of this program. We are beginning at a TRL of one for the task and working up to a TRL of five by the end of FY07. At this point we will have tested the seals in a relevant laboratory environment.

Ceramic Canted Coil Spring Development: Seal Preload Device

- **Established grant/cooperative agreement with Case Western Reserve University to develop high temperature (up to 2500°F) seal preload methods (i.e., ceramic canted coil spring)**
- **FY01 Accomplishments**
  - Formulated extrudable mixture of raw materials to create YAG ceramic prototype springs (material not fully dense)
  - Currently pursuing alternative methods of producing YAG to improve density/reduce porosity of parts
  - Fabricated laboratory-scale extruder
  - Setting up equipment for winding mechanism
- **Phase I of multi-phase program**



Prototype YAG springs



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

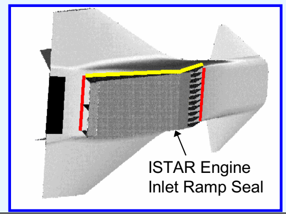
NASA Glenn Research Center

This chart highlights one of our accomplishments for our seal development tasks over the past year. In an effort to develop a new method of preloading our seals, we established a cooperative agreement with Case Western Reserve University to have them develop canted coil springs out of ceramic materials. Ceramic tension and compression springs do exist, but we are not aware of any ceramic canted coil springs that are being produced. Canted coil springs are different from regular tension or compression springs in the direction that they are loaded. Tension and compression springs are typically loaded in a direction parallel to a line down the center of the spring. Canted coil springs, though, are loaded across the coils as shown in the figure on the bottom right of this chart. They can be produced in long lengths that would be laid in a groove behind a seal to provide additional resiliency, or spring back, to the seals. Another unique feature of these springs is that as the coils of the spring deflect under a load, the force produced by the spring on the opposing surface stays rather constant over a broad range of deflections. This produces a force vs. deflection curve that is close to flat as shown in the figure at the lower right. This would be a beneficial feature for the seals because it would provide resiliency to the seals without producing excessive loads against the opposing sealing surface.

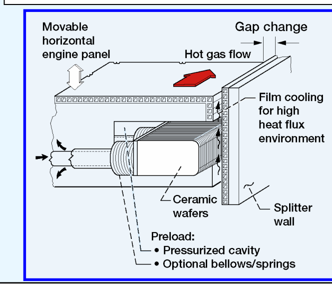
Over the past year CWRU has formulated an extrudable mixture of raw materials to produce YAG filaments that can be wound into prototype springs, as shown in the figure at the upper right. The material that they are producing is not fully dense, though, so they are pursuing alternative methods of producing YAG to improve the density and reduce the porosity of the parts. They have fabricated a laboratory-scale extruder to extrude this material and are currently setting up the equipment for a winding mechanism. This is all part of Phase I of a multi-phase program.

Summary of Significant FY01 Accomplishments

- **Identified customers for both programs**
  - Control surface seals: X-38/Crew Return Vehicle, X-37
  - Propulsion system seals: I^{STAR}, GTX, other RBCC/TBCC-powered vehicles
- **Baseline Shuttle seals evaluated for X-38 control surface seal applications**
  - Performed baseline compression, flow, scrub, and arc jet tests
  - Arc jet database to be used to validate aero-thermal-structural analyses codes to predict seal loads for future mission conditions
  - Lessons learned form basis for advanced control surface seal development program
- **New control surface and propulsion system seal concepts identified**



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



Propulsion system seal concept

NASA Glenn Research Center

In addition to setting up the cooperative agreement with CWRU, we have had many other accomplishments over the past year. We have identified customers for both programs: X-38/Crew Return Vehicle and X-37 for the control surface seals task and ISTAR, GTX, and other RBCC/TBCC-powered vehicles for the propulsion system seals task. We evaluated control surface seals for the X-38 through compression, flow, scrub, and arc jet testing and are using the results of these tests as a baseline upon which to improve in our advanced control surface seal development task. Data from the arc jet tests will be used to validate aero-thermal-structural analyses codes to predict seal performance for future mission conditions. Finally, we have come up with new control surface and propulsion system seal concepts that we plan to evaluate in the new test rigs that we are developing. A drawing of one of the propulsion system seal concepts is shown at the lower right of this chart.

Summary of Significant FY01 Accomplishments (cont.)

- **New performance test fixture acquisition/fabrication:**
  - Test cell cleared out in preparation for new rig installations
  - Hot compression/hot scrub test rig:
    - Main elements of test rig (load frame, furnace, and laser extensometer) ordered and being delivered
    - Preliminary designs for high temperature test fixturing complete
  - Cold flow/scrub test rig:
    - Ordered and received many commercial parts for test rig (e.g., drive mechanism, instrumentation)
    - Preliminary design of fabricated parts (e.g., weldments, seal cartridges) complete. Detailed design underway.
- **Contracted with CFD Research Corp. to perform aero-thermal-structural analyses of gap seals operating in high Mach environment. Currently calibrating models including porous seals using data recorded in arc jet tests at Ames**

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We have also been working on the new test rigs that we are planning to use to evaluate our new seal designs. For our hot compression/hot scrub test rig, we have ordered the main elements of the test rig (load frame, furnace, and laser extensometer) and are assembling and installing them as they are delivered. We have completed preliminary designs for the high temperature test fixturing that we are going to use inside the furnace for these tests. For the cold flow/scrub test rig, we have ordered and received most of the commercial parts for the rig. The preliminary design of the fabricated parts for the rig is complete, and we are currently working on the detailed drawings for these parts.

We contracted with CFD Research Corp. to perform the aero-thermal-structural analyses on the seals that were discussed earlier. Alton Reich from CFD RC will be briefing the progress on these analyses in a later presentation.

DEVELOPMENT AND CAPABILITIES OF UNIQUE STRUCTURAL SEAL TEST RIGS

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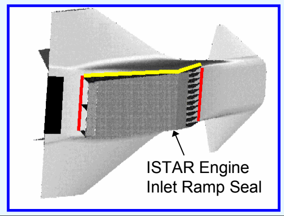
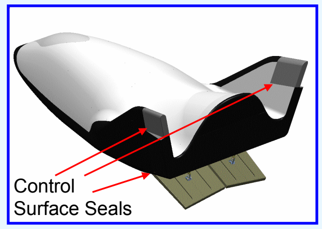
Brook Park, Ohio

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

NASA Glenn Research Center

CD-01-81812

High temperature structural seals are necessary in many aerospace and aeronautical applications to minimize any detrimental effects originating from undesired leakage. The NASA Glenn Research Center has been and continues to be a pioneer in the development and evaluation of these types of seals. The current focus for the development of structural seals is for the 3rd Generation Reusable Launch Vehicle (RLV), which is scheduled to replace the current space shuttle system around 2025. Specific areas of development under this program include seals for propulsion systems (such as the hypersonic air-breathing ISTAR engine concept based upon Rocket Based Combined Cycle technology) and control surface seals for spacecraft including the autonomous rescue X-38 Crew Return Vehicle and the X-37 Space Maneuver Vehicle.

Performance Criteria for High Temperature Seals

Primary Role of High Temperature Structural Seals:

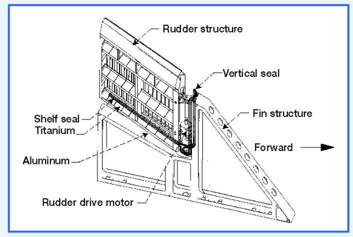
- Minimize leakage
  - Propulsion System Seals: Prevent unburned fuel from leaking into backside cavities
  - Control Surface Seals: Block excessive heat flow

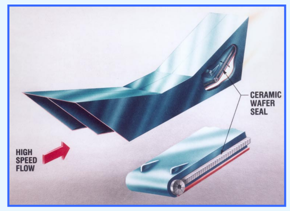
✓ Good insulatory properties → block heat flow

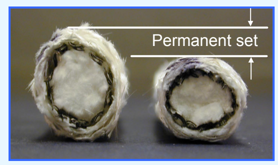
✓ Good flexibility → conform to complex airframe and propulsion system geometries

✓ 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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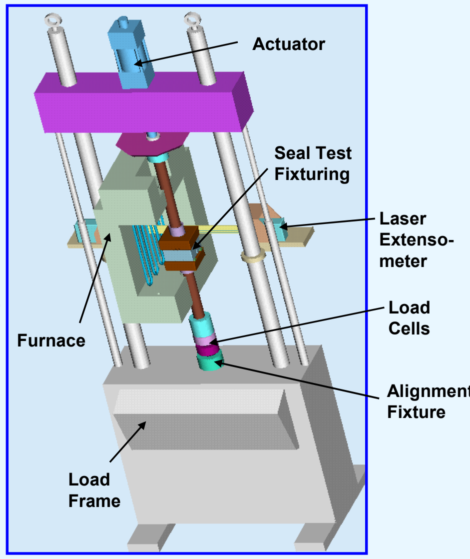
The primary role of structural seals is to minimize the leakage of elevated temperature fluids and/or gases. These hot fluids or gases could damage or destroy critical flight components if not properly sealed and could result in loss of the aircraft or even loss of life. As an example, consider the potential failure of the rudder/fin seal in the X-38 craft which could severely damage the rudder drive motor and render the craft nearly inoperable. In order to function properly, structural seals must meet or exceed certain performance criteria, including good insulatory properties, excellent flexibility, consistent and effective resiliency, and superior wear resistance. The primary focus of this presentation is on the development of testing rigs to evaluate these last two properties.

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 (14.5 kW)
  - Kanthal Super 33 $MoSi_2$ heating elements
  - Large working volume (9” W x 14” D x 18” H)
  - Front and back loading doors & top port
  - Adjustable laser alignment fixturing and 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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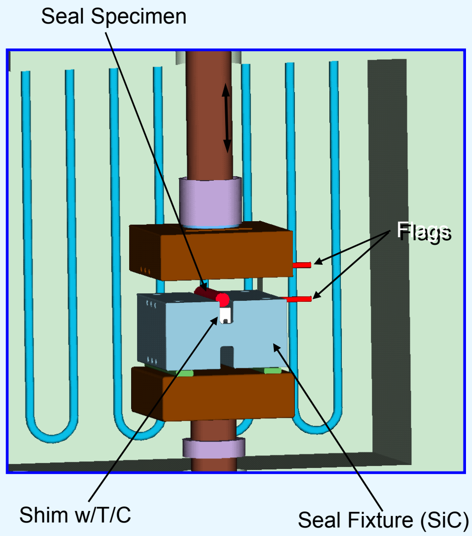
CD-01-81812

One of the rigs that the NASA Glenn Research Center is assembling for the structural seals area will consist of three main components: an MTS servohydraulic load frame, an ATS high temperature air furnace, and a Beta LaserMike non-contact laser extensometer. The rig will be designed to perform two different types of tests: compression tests to evaluate seal resiliency characteristics and seal scrub tests to evaluate wear performance. Both tests will be conducted at temperatures up to 3000 °F (1650 °C). This one-of-a-kind equipment will have many unique capabilities for testing of numerous seal configurations, including dual load cells (with multi-ranging capabilities) for accurate measurement of load application, dual servovalves to permit precise testing at multiple stroke rates, a large capacity high temperature air furnace, and a non-contact laser extensometer system to accurately measure displacements.

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

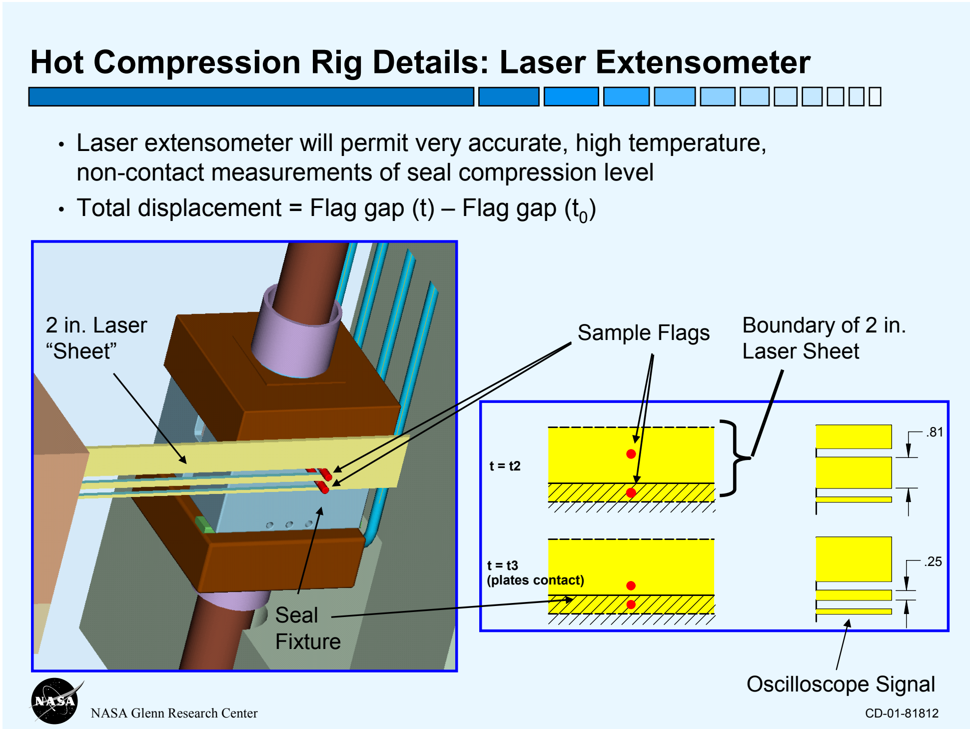


Capabilities

- ✓ 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

NASA Glenn Research Center CD-01-81812

One of the primary tests to be conducted with the new rig will be high temperature (up to 3000°F) compression tests to assess seal resiliency and stiffness. A number of parameters will be varied for these tests including temperature, loading rate, amount of compression, and mode of application (single load application vs. cycling). The setup will consist of upper and lower SiC platens which compress a seal specimen residing in the groove of a stationary seal holder. Small pins (called sample flags) will be inserted into both the upper platen and seal fixture and will be used in concert with the laser extensometer system previously mentioned to accurately measure compression level as a function of time.



The laser extensometer system (Beta LaserMike Intelliscan 50) essentially consists of a transmitter and receiver. A small motor inside the transmitter unit spins a mirror at high speed as laser light is emitted and causes a laser "sheet" to be transmitted. This sheet of laser light is detected by the receiver unit. Blockage of any part of the laser sheet results in dark areas as seen by the receiver unit. For the current setup, small SiC flags (rods) attached to the upper platen and sample fixture will be used to block part of the laser sheet. As the sample platen moves downward (compresses the seal specimen), the gap of light between the two flags will change and the displacement at any time *t* can be determined.

Hot Scrub Rig Details

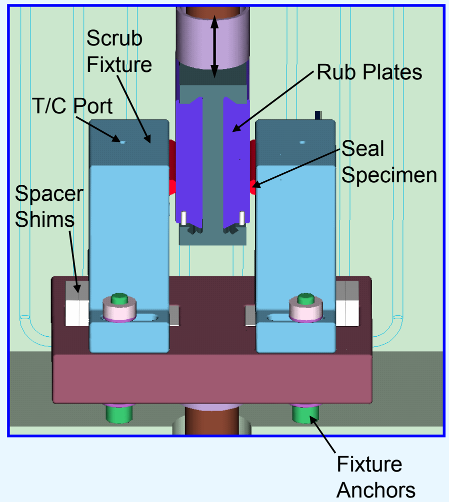
Purpose

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



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CD-01-81812

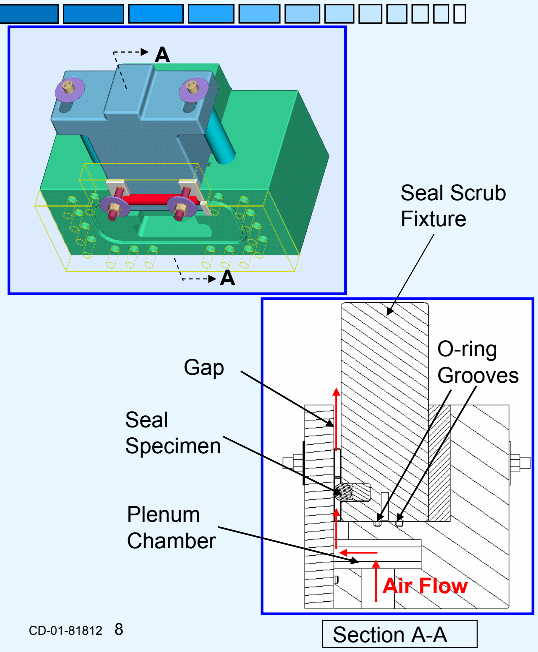
A second setup using the same MTS rig will be used to assess high temperature wear characteristics of structural seal candidates. In this setup, a SiC seal holder containing a seal specimen will flank each side of a scrubbing saber assembly. The seal holders will be held in place by a novel high temperature anchoring system and spacer shims. A load cell mounted at the bottom of the lower platen will permit monitoring of the friction loads. Numerous combinations of testing parameters will be possible with this test setup, including various temperature ranges, seal compression levels, scrubbing rates and profiles, etc. This design will also facilitate post-scrubbing flow tests, as described on the following slide.

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.



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Room temperature leakage tests will also be performed on seal candidates using the same seal holder described for the high temperature scrubbing test. The design of the seal holder will allow a seal specimen to be flow tested before and after scrub testing with minimal handling of the seal between tests. Because the seal holder "drops into" this flow fixture, a seal which has just completed a scrubbing evaluation can be flow tested without disturbing the seal during secondary handling. Seal leakage as a function of wear damage can then be easily evaluated.

Hot Compression/Scrub Rig: Design Challenges

Testing of seals at high temperature presents numerous design challenges!

Challenge	Solution
Sample accessibility	Furnace designed with front & back doors & split top plug
High temperature limits material selection for fixturing	Use fine grained dense alpha SiC (Hexoloy from Saint Gobain)
SiC sticks at high temperatures	Minimize contact area, use shims
Fixturing attachment difficult	No threaded fasteners: use connection pins, use shims to create tight fit
Dynamic loads may dislodge connecting pins	Use collar (with “lockable” feature)

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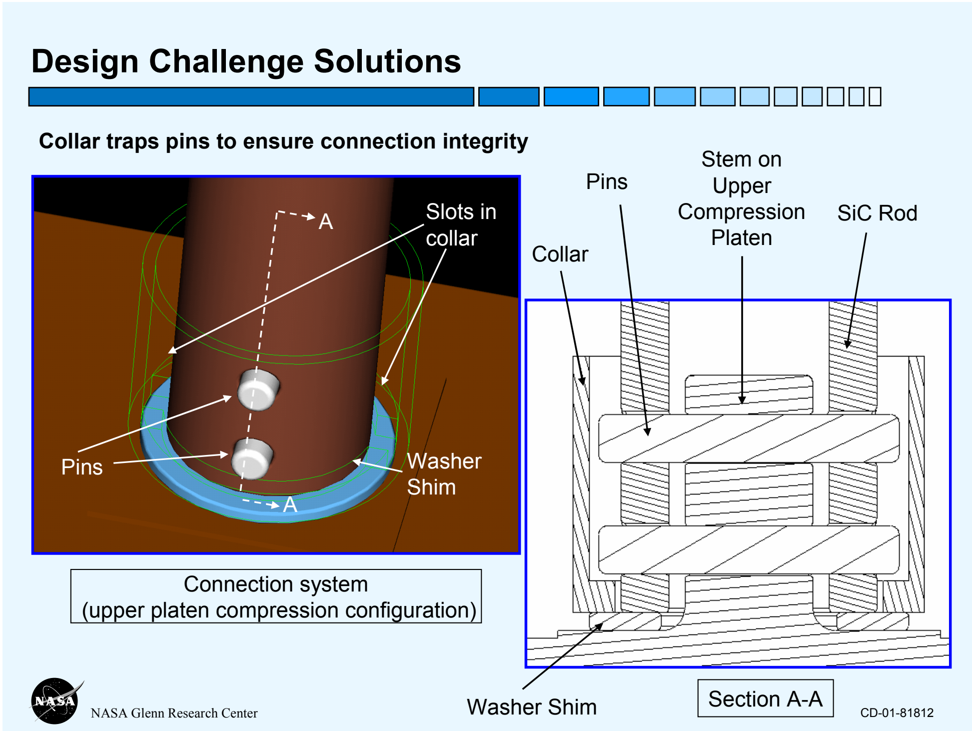
Testing at extreme temperatures (up to 3000°F) presents numerous design challenges. At the NASA Glenn Research Center, there are several material testing rigs that approach these temperatures. However, most, if not all of these rigs test only in compression. The scrub testing that we plan to perform requires design of equipment fixturing that will permit testing of relatively large specimens in both cyclic compression and tension. The need to test in tension creates many design challenges to overcome. Several approaches to solving these issues include designing a furnace with multiple access points, using the most advanced commercially available fixturing materials (Hexoloy from St. Gobain), and employing multiple pinning connection systems with lockable collars to prevent dislodging of the pins during testing.



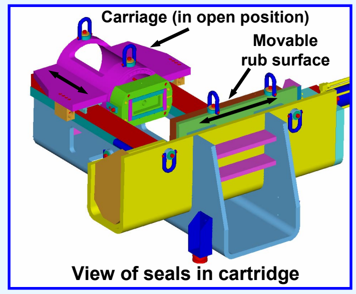
One of the many solutions proposed to solve fixturing connection issues was the use of multiple pins. In this setup, dual pins are used to securely attach the upper compression platen to the SiC rod. The rod is designed to have slightly oversized holes so that when a washer shim is used, the pins become “pinched” between the rod and stem of the compression platen. The pins are held in place through use of a lockable collar which uses a bottom lip on the collar to prevent it from dislodging. Slots cut in the lip allow initial placement of the collar around the rod and pins. This design minimizes any slop which may occur during compression testing. Similar designs will be used in other rig/fixturing components.

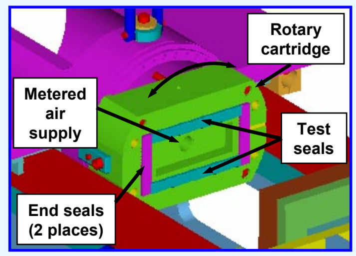
Ambient Scrub & Flow Testing Rig Overview

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)





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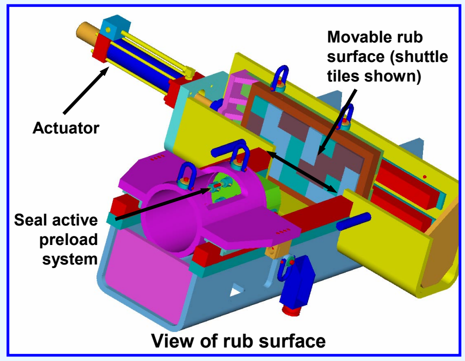
CD-01-81812

A second rig being designed at the NASA Glenn Research Center will permit simultaneous evaluation of room temperature seal leakage and wear. For this rig, a carriage containing a rotation-adjustable seal cartridge will be placed such that the seal specimens are in contact with a scrubbing surface. A servohydraulic actuator would then cycle the scrub surface across the seals according to a user-defined cycling profile. A number of different test parameters can be adjusted to mimic actual service environments, including compression level, rub surface conditions, and orientation of the seal with respect to the scrubbing direction.

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



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The scrub and flow rig being designed at NASA GRC will have numerous capabilities, including different seal configurations, multiple scrubbing speeds/profiles, measurement of frictional loads, user-controlled seal preloading, etc. These capabilities and the modularity of the design will permit evaluation of numerous seal candidates.

Conclusions and Timeline

- NASA GRC is developing and acquiring several unique high temperature seal test rigs to evaluate current and future seal designs
  - Hot Compression / Scrub Rig
  - Ambient Simultaneous Scrub & Flow Rig
  - Proposed initial seal fixture configurations:
    - X-38 rope seals (0.62 in. diam)
    - Ceramic wafer seals (1 in. x 0.5 in. x 0.25 in.)
    - Other seal configurations to be machined at a later date
    - Custom configurations as mutually arranged

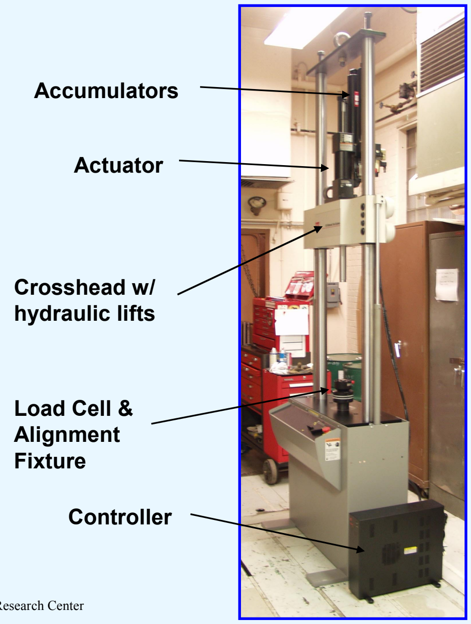
	Hot Compression / Scrub Rig	Ambient Scrub & Flow Rig
Fabrication Complete	Q2 FY02	Q2 FY02
Installation Complete	Q2 FY02	Q3 FY02
Checkout Complete	Q3 FY02	Q4 FY02
Ready for Tests	Q4 FY02	Q1 FY03

NASA Glenn Research Center

CD-01-81812

NASA Glenn's structural seal research facilities are in the process of being significantly upgraded. The acquisition of an integrated hot compression / scrub rig and an ambient simultaneous scrub and flow rig will drastically enhance the evaluation and development of current and future high temperature structural seals.

Servohydraulic Load Frame – Received 10/22/01



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The load frame portion of the Hot Compression / Scrub rig was recently received. Delivery and installation of the high temperature box furnace will occur by the end of 2001 calendar year.

ANALYSES OF CONTROL SURFACE SEAL TESTED IN THE AMES ARC JET TUNNEL (PANEL TEST FACILITY)

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National Aeronautics and Space Administration
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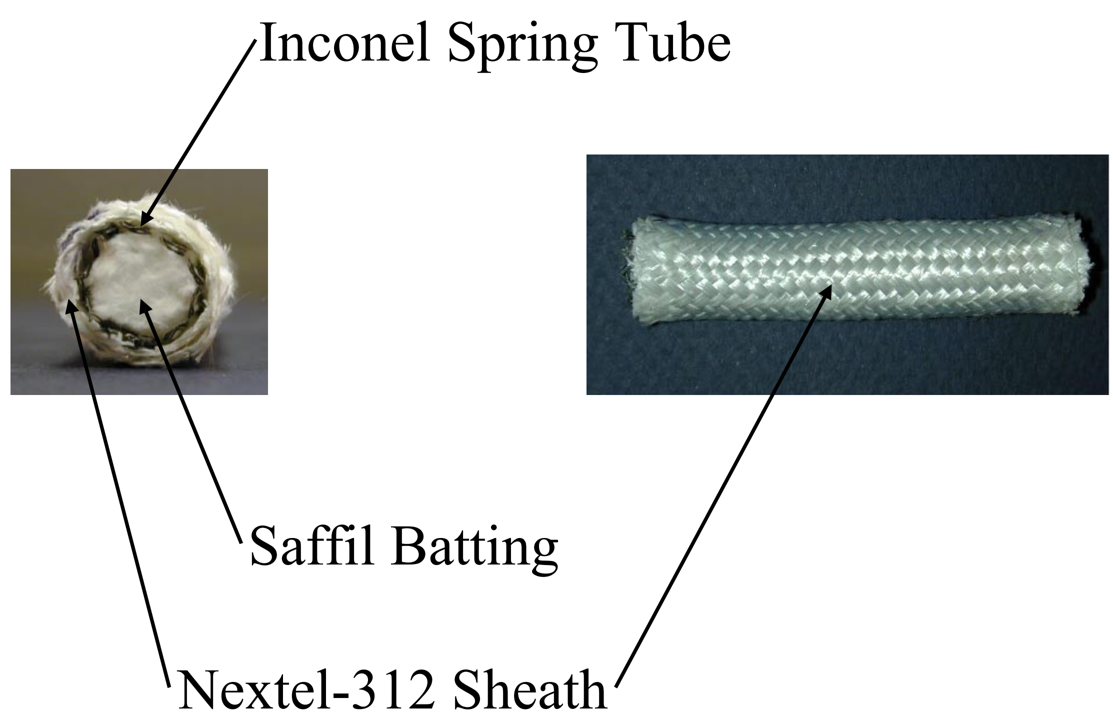
Analyses of Control Surface Seal Tested in the AMES Arc Jet Tunnel (PTF)

Presented by:
Alton J. Reich, P.E.
CFD Research Corporation
31 October 2001

Topics

- Rope seal
- Improvements to porous media simulation in CFD-ACE+
- Porous media heat transfer validation case – steady-state and transient flat plate
- Simulation of GRC cold flow seal test fixture
- Simulation of calibration plate in the Panel Test Facility (PTF)
- Simulation of rope seal test in the PTF

Rope Seal



Porous Media Improvements

- CFD-ACE+ had the capability to model porous media via a distributed resistance
  - Difficult to use in practical situations
  - User had to determine linear and quadratic resistance coefficients which have no physical analogue
- Improved porous media model uses physical material properties as inputs
  - Porosity (fraction of volume occupied by the solid)

Porous Media Improvements (con't)

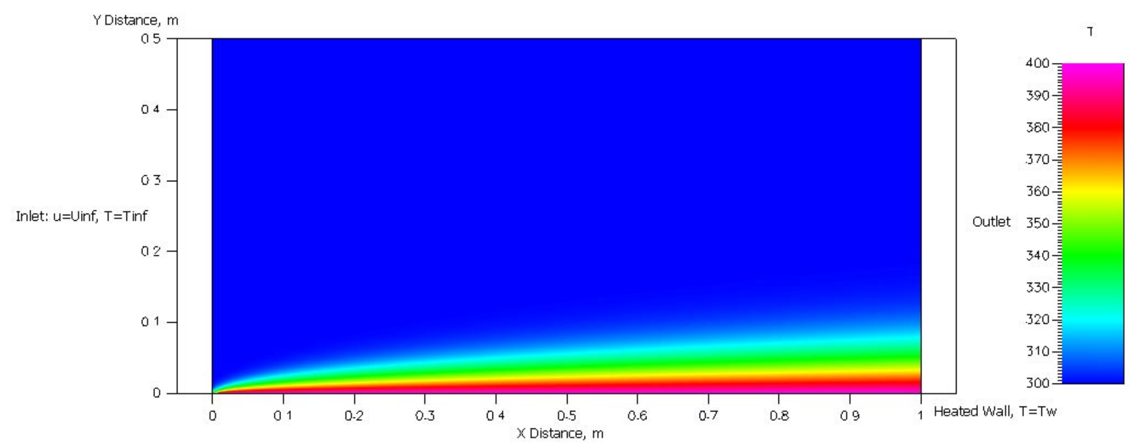
- Permeability (relates to the pressure drop per unit of nominal path length through the media)
  - Several semi-empirical correlations exist for estimating permeability
  - Best obtained from experimental data
- Second order (quadratic) effects may be considered

- Darcy's Law: $\nabla P = -\frac{\mu}{K}\mathrm{v}$

- Forchheimer Drag: $\nabla P = -\frac{\mu}{K}\mathrm{v} - \mathrm{c_F} K^{-1/2} \rho_f |\mathrm{v}| \mathrm{v}$

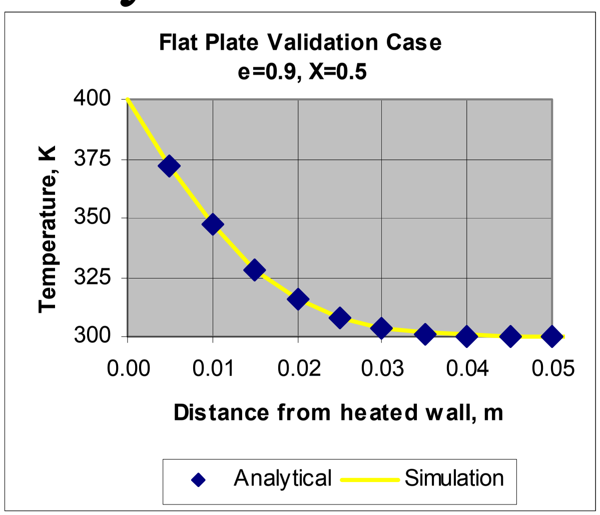
Porous Media Validation

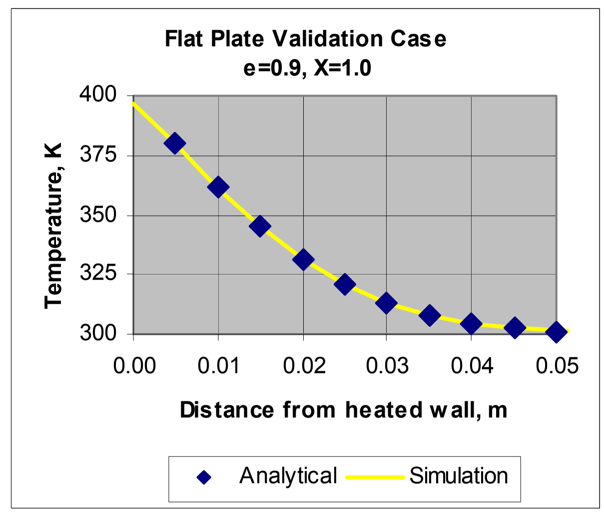
- CFDRC performed a steady-state and transient validation of the improved porous media model with heat transfer
- The geometry is a semi-infinite porous media, bounded by a flat plate
  - Wall temp. is 400K
  - Gas enters at 300K



Porous Media Validation (con't)

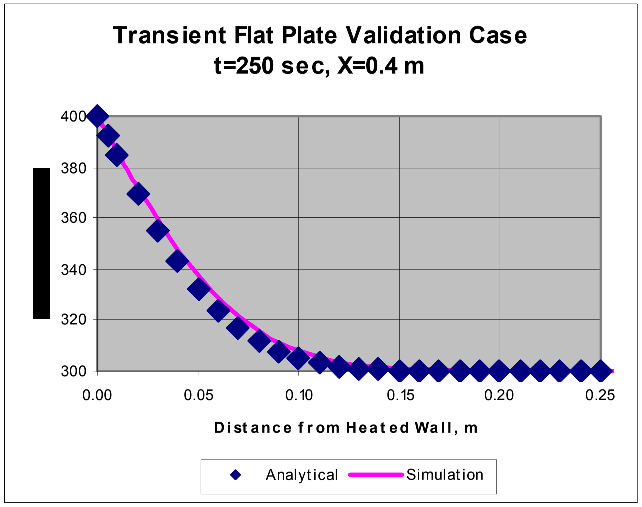
- Both steady-state and transient cases have an analytical solution
- CFDRC compared simulation results to the analytical solutions

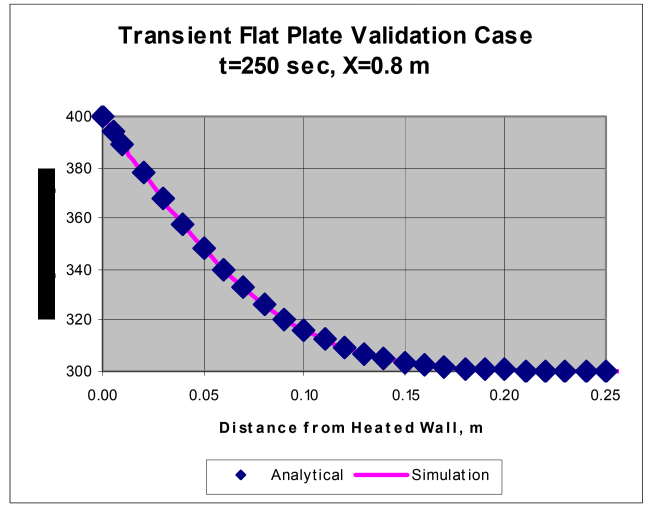




Steady-State Comparison

Porous Media Validation (con't)



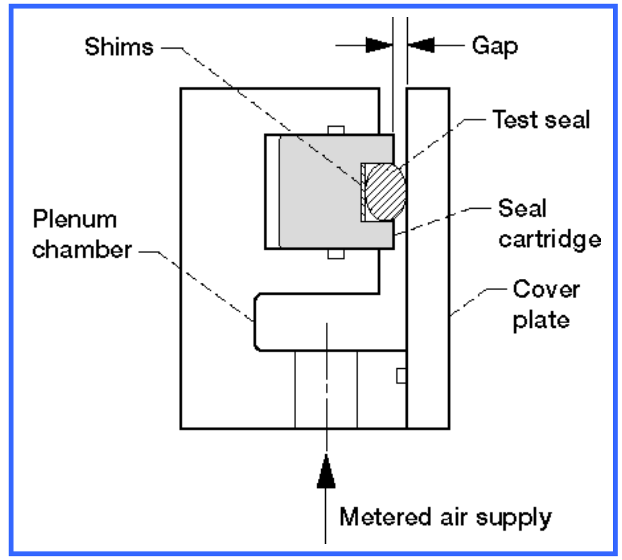


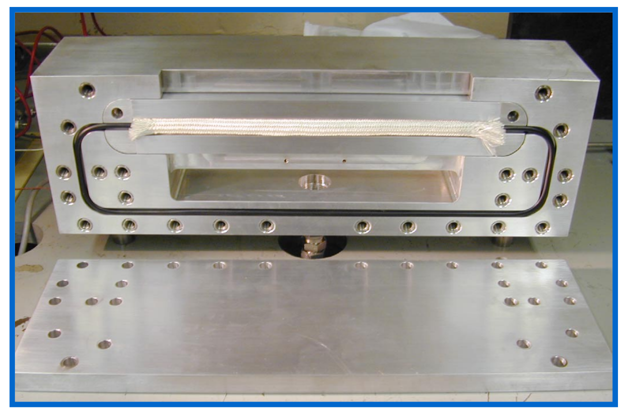
Transient Comparison

- Simulation results compare well with the analytical solutions

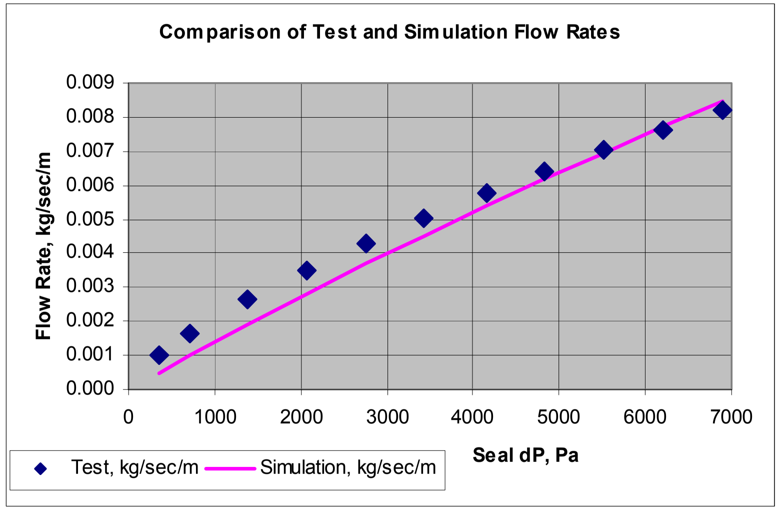
GRC Cold Flow Seal Test

- GRC measured the flow rate through a compressed seal
- CFDRC was provided mass flow rate vs. dP data
- A set of simulations were performed and results were compared using:
  - Porosity = 0.85
  - Permeability = 3.7E-11 m^2



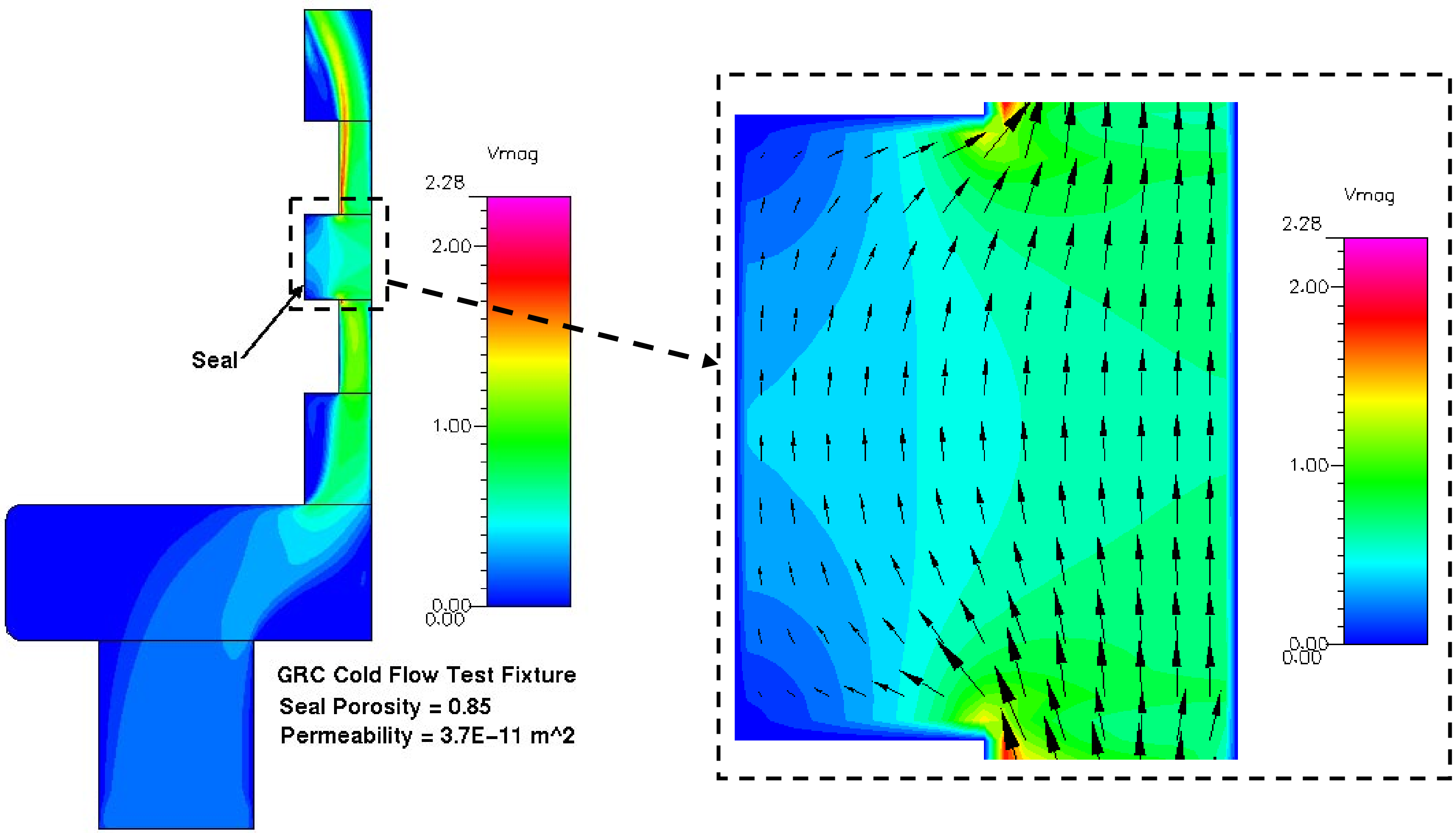


GRC Cold Flow Seal Test (con't)



- The simulation and test results compare well
- Lessons learned:
  - Semi-empirical equations predicted a permeability that was ~2 OOM too low (~1E-13 m^2)
  - When using test data to compute permeability, the cross sectional area of the seal should be considered, not the flow area upstream

GRC Cold Flow Seal Test (con't)

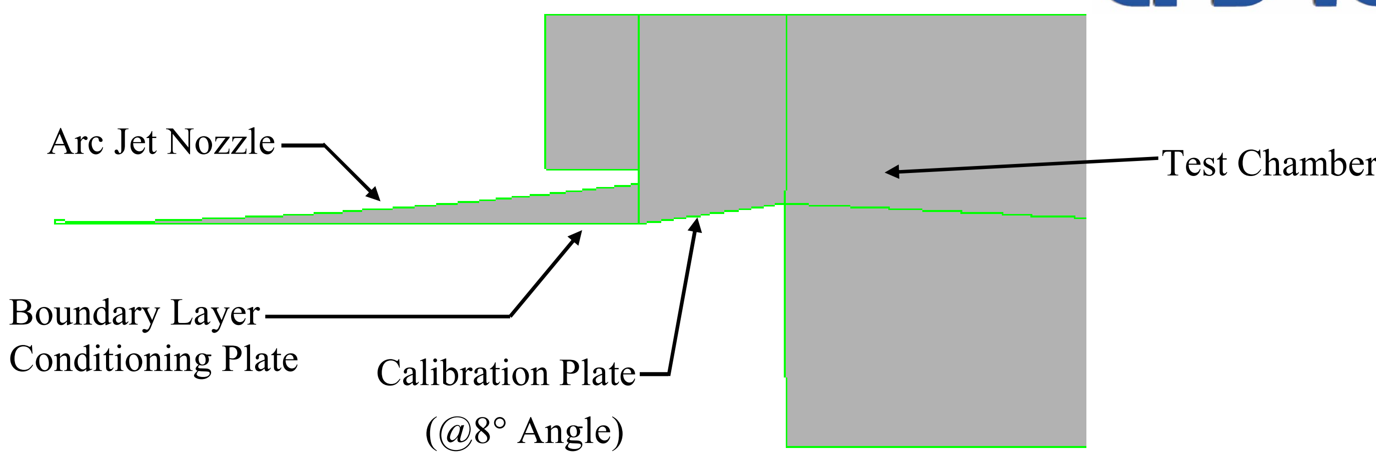


Velocity Magnitude Within the Seal

Simulation of Calibration Plate

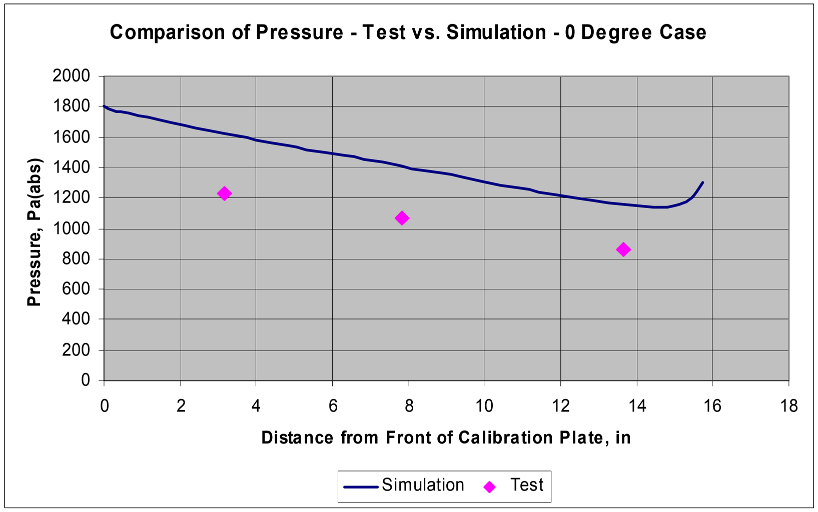
- The Panel Test Facility (PTF) uses an instrumented calibration plate to measure arc heater enthalpy and chamber pressure
- GRC provided CFDRC with a data set from recent PTF runs with the calibration plate installed
- CFDRC developed a 2D model of the PTF nozzle section and the calibration plate installed in the test chamber

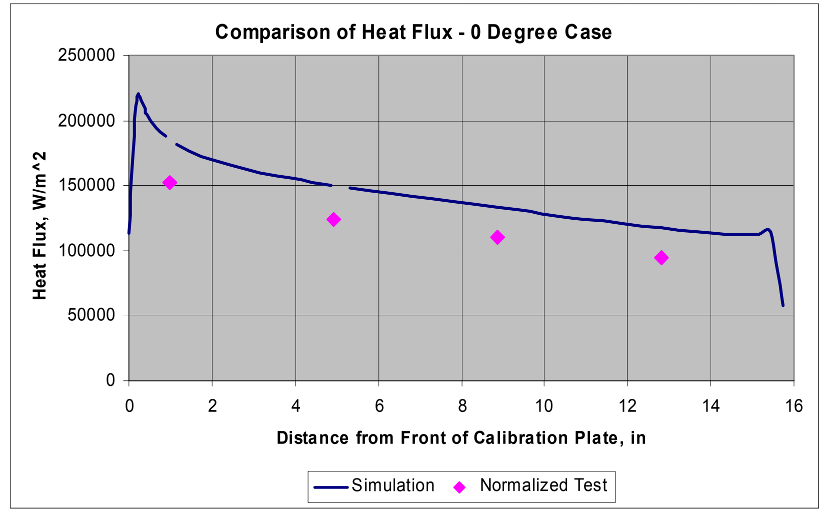
Calibration Plate Model

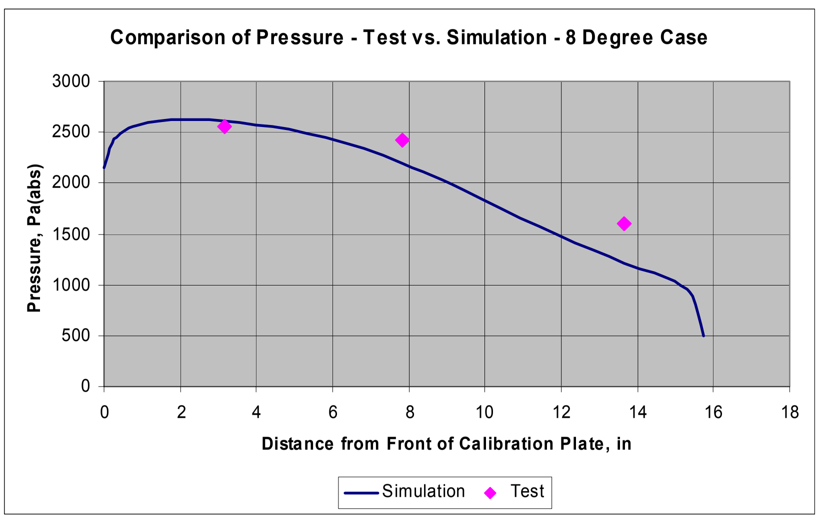


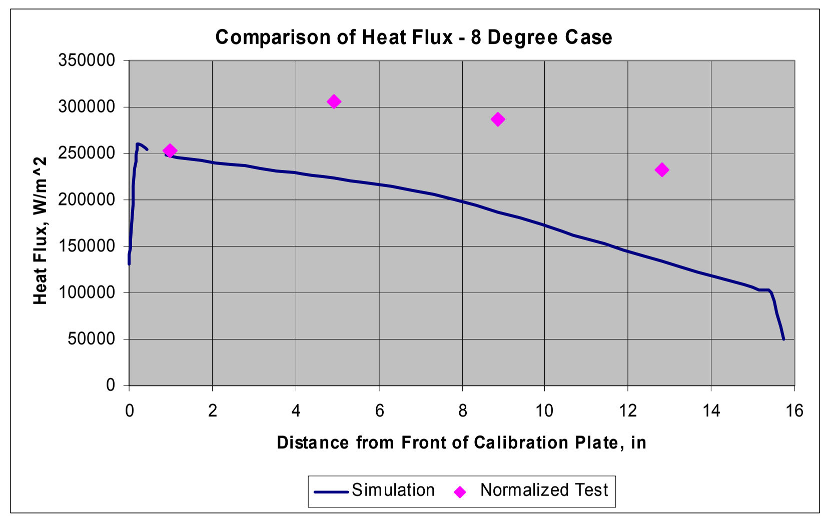
- Model Size: ~16,000 Cells
- Inlet: Air / Argon mixture, Oxygen fully dissociated
- Outlet: Low pressure, ~300Pa (abs)
- Nozzle Walls: Cooled to 600K
- Calibration Plate: Cooled to 300K

Calibration Plate Results









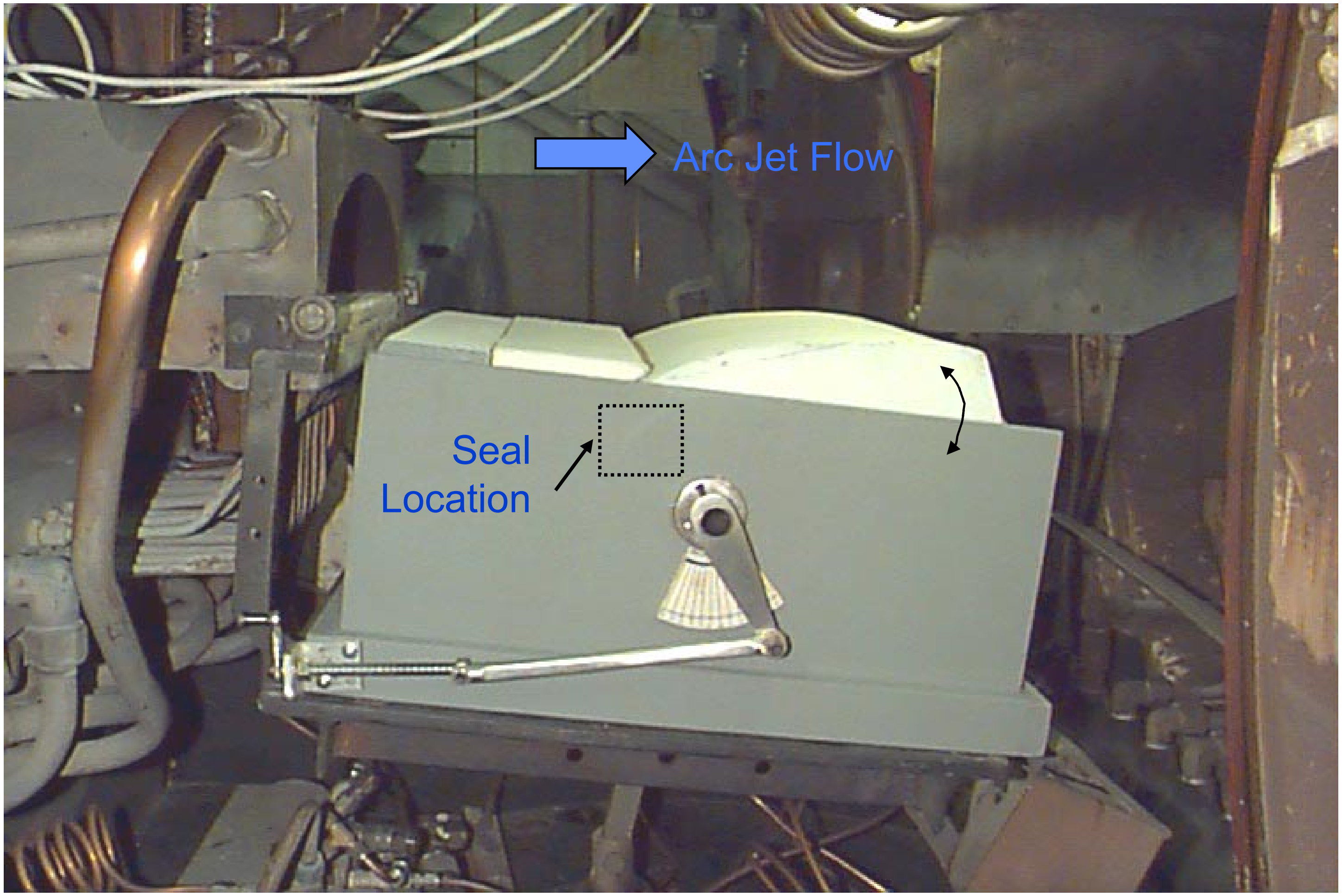
Calibration Plate Result Comments

- Pressure results show fairly good agreement in both shape and magnitude
  - CFD-ACE+ simulation over predicts the surface pressure at 0° angle of attack
- Wall heat flux is under predicted by ~40% at both 0° and 8° angles of attack
  - CFDRC is still investigating this discrepancy

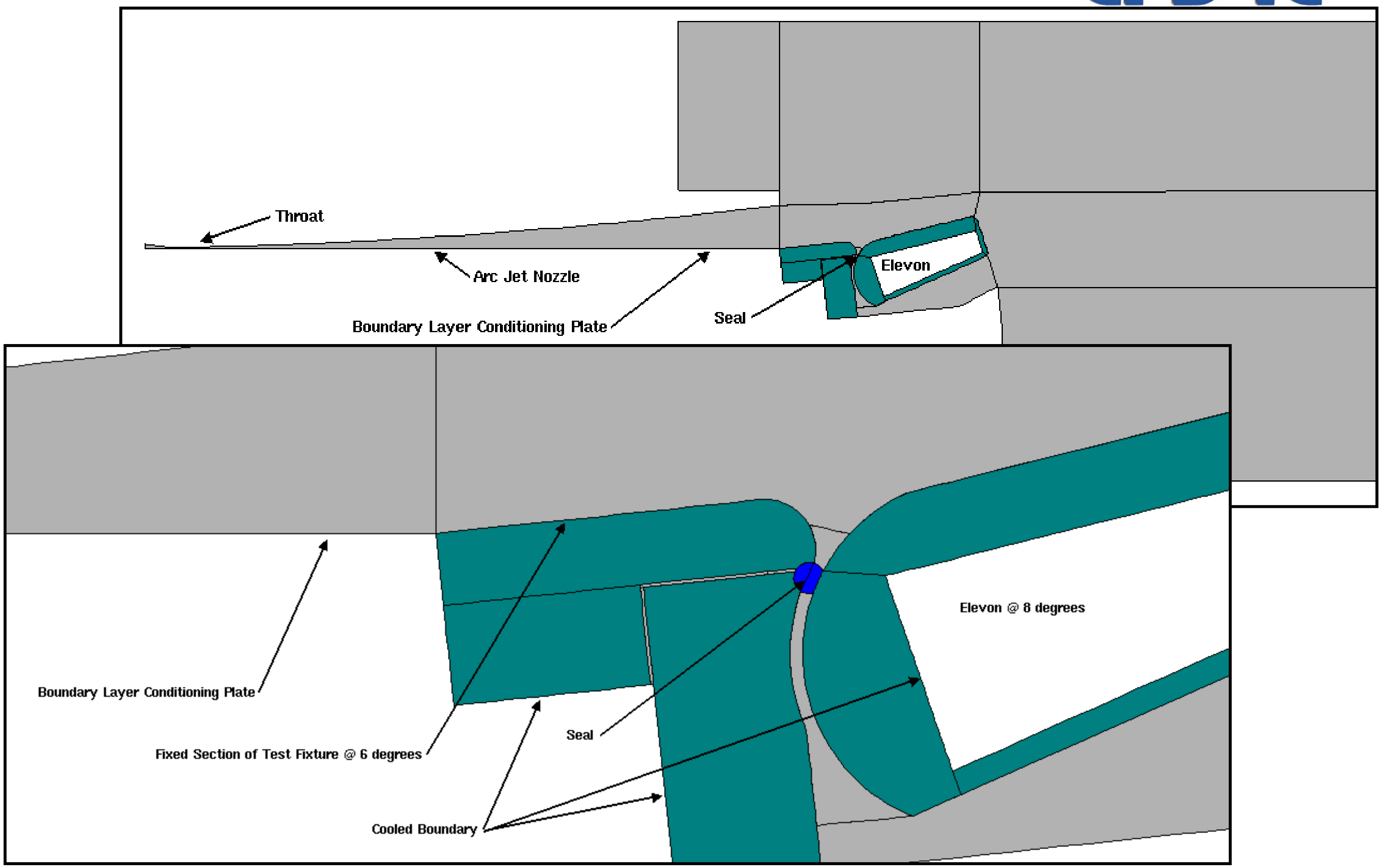
Simulation of Arc Jet Test

- Performed to show that simulation could predict the steady state temperature of the rope seal
- Data for comparison is from a test performed at the Panel Test Facility (PTF) at ARC
- CFDRC developed a 2D model of the arc jet nozzle, test chamber and test fixture
- Inlet species composition and nozzle wall temperature was the same as for the calibration plate

Seal Test Fixture



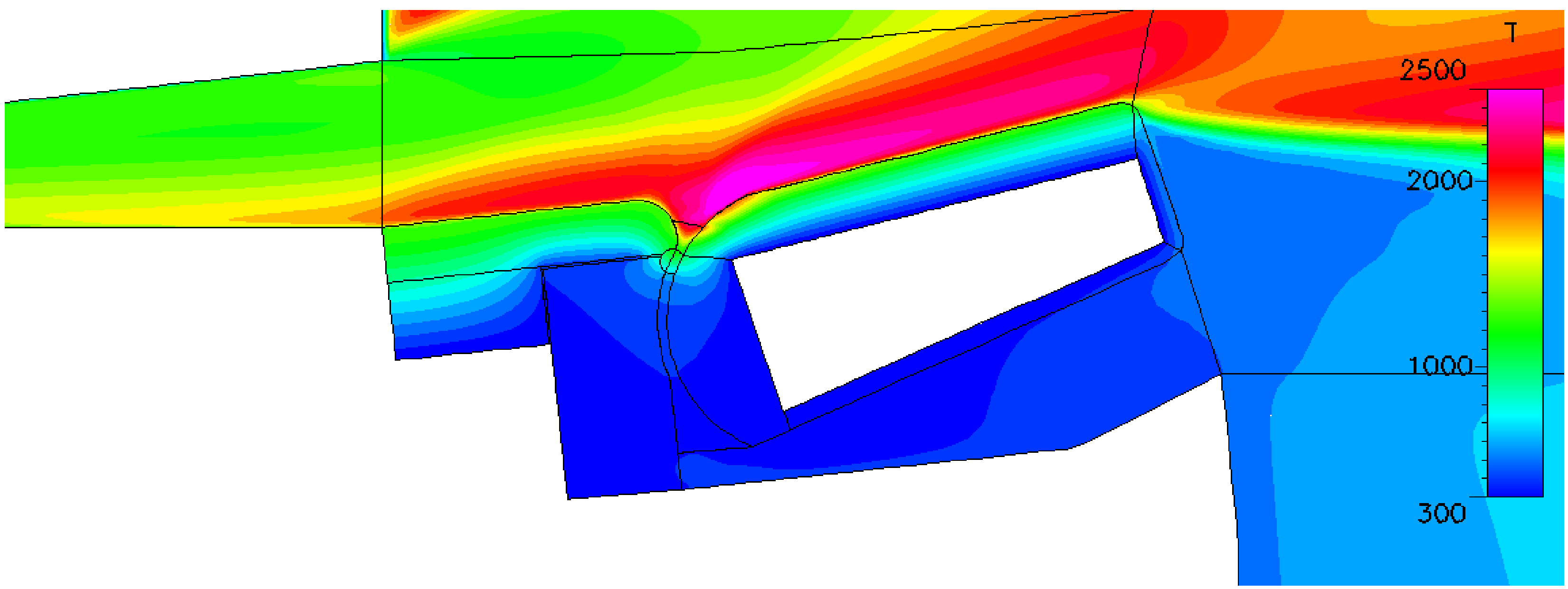
Seal Simulation Model Geometry



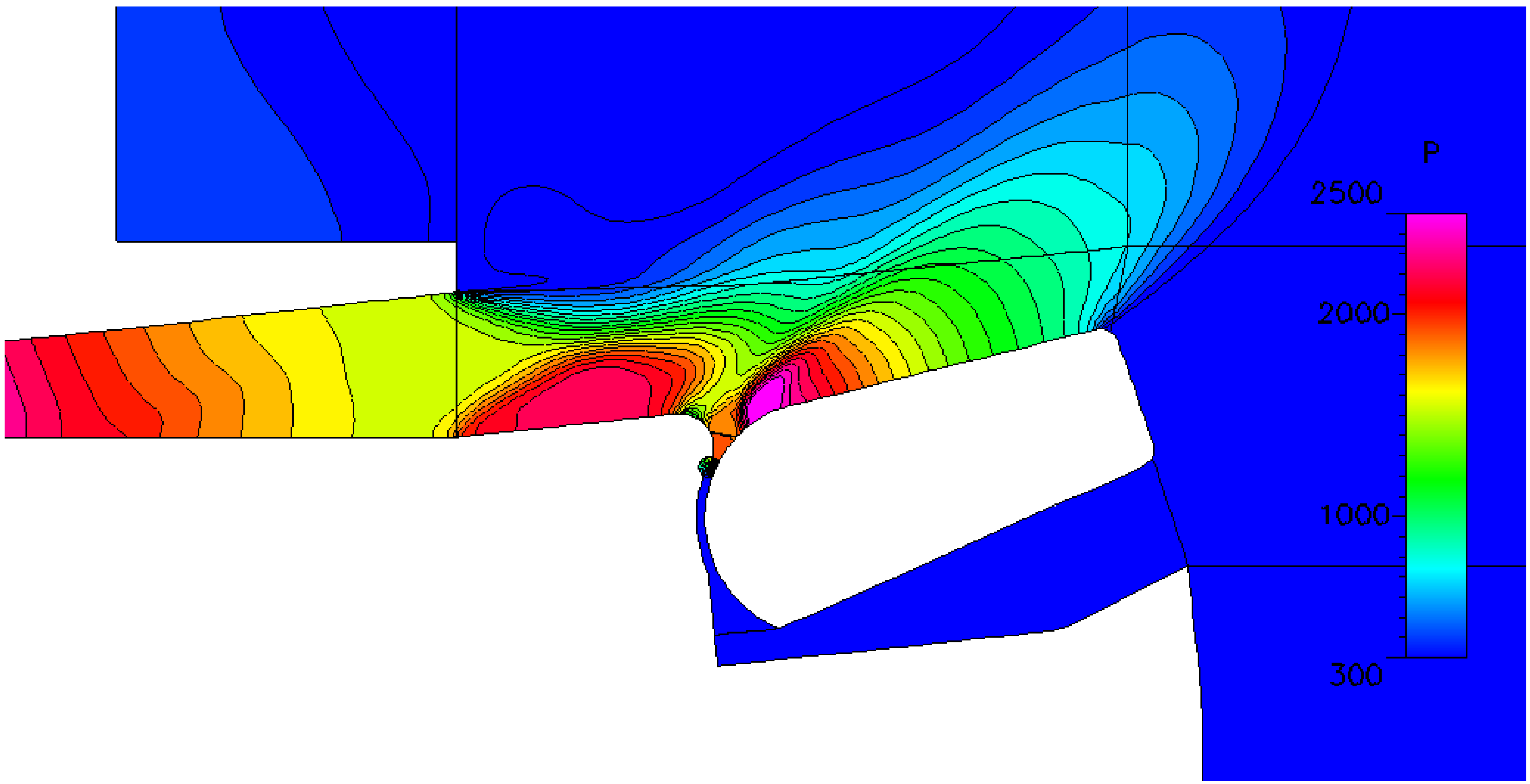
Seal Simulation Challenges

- Test data provides ample time-dependent information about the areas of interest (i.e.: temperature on hot surfaces of test fixture)
- Data is lacking for specification of CFD analysis boundary conditions
  - Nozzle wall temperature
  - Fixture cold side cooling water temperature
- Inlet temperature is inferred from calibration plate test data

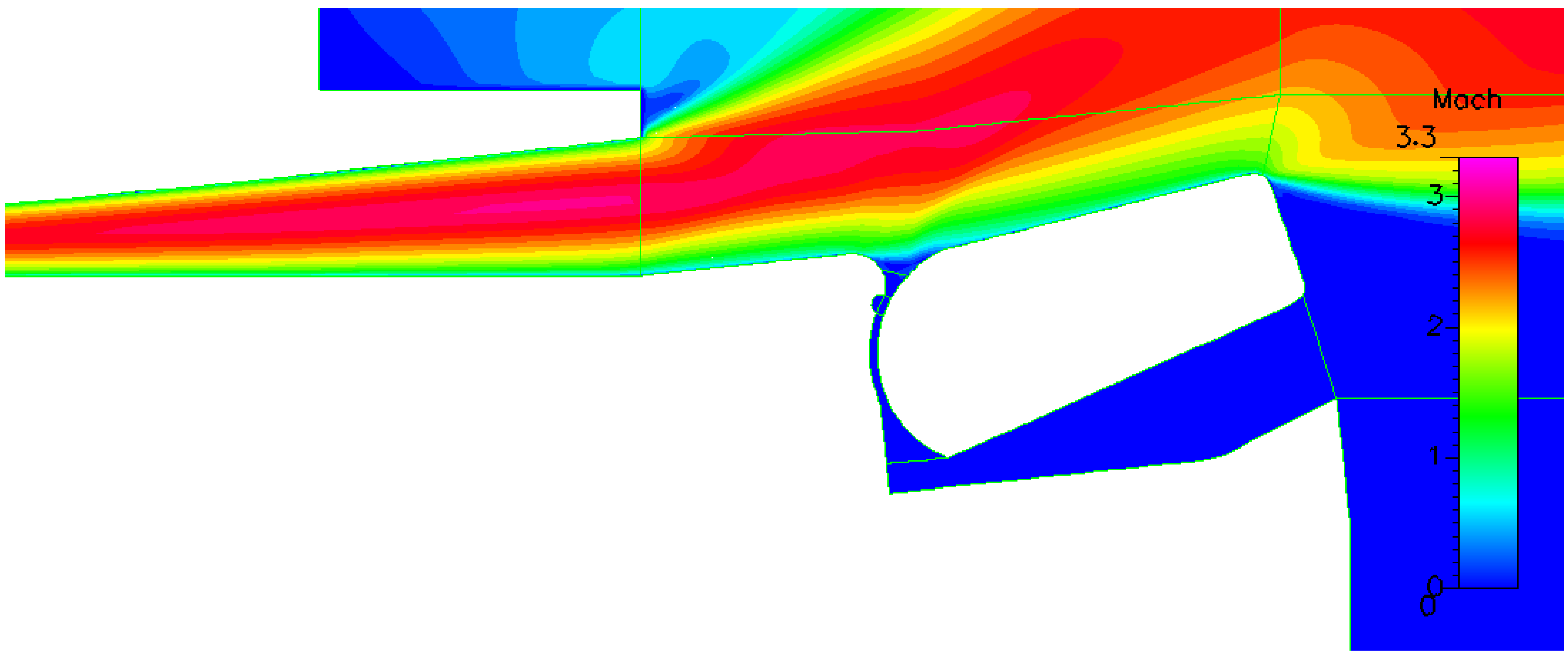
Simulation Results - Temperature



Simulation Results - Pressure



Simulation Results – Mach



Seal Simulation – Temperatures

Arc Jet Test vs. Simulation Result Comparison

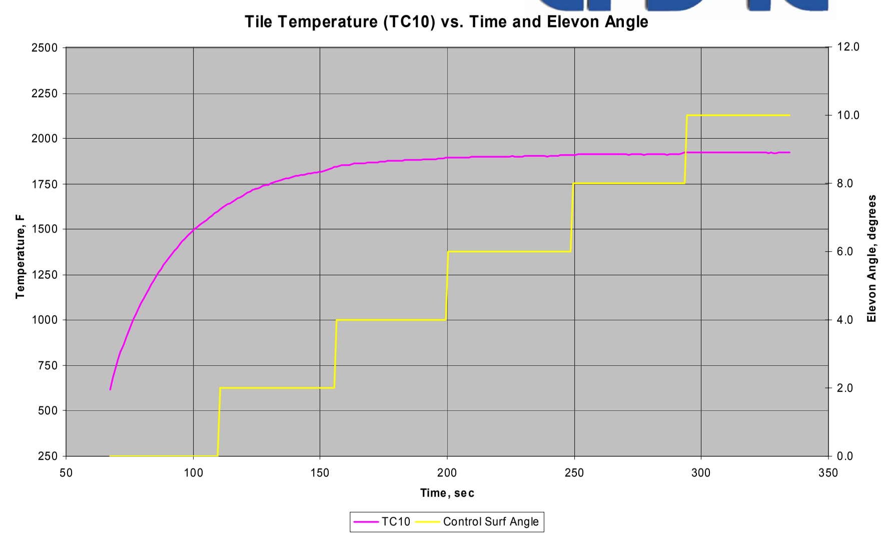
Fixture Angle:	6 deg
Elevon Angle:	8 deg

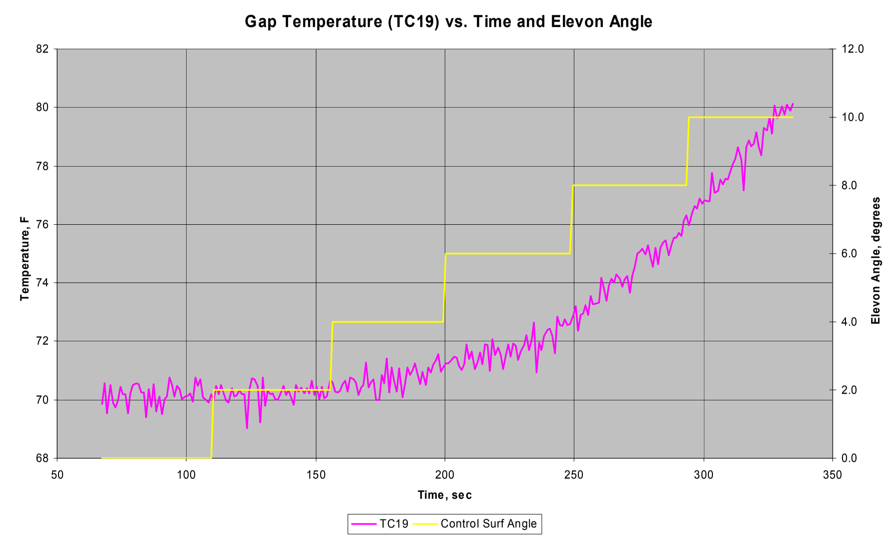
Thermocouple Location #	Test T, F	Test T, K	ACE T, K	X, m	Y, m	Location Notes
4	2227	1493	1621	0.164	0.017	"Fixed" surface, 6.5" from nozzle lip
10	1916	1320	1582	0.192	-0.002	Cove entrance surface, 0.5" above seal
16	158	343	529	0.181	-0.041	Cove gap surface, 0.5" below seal
19	76	298	444	0.179	-0.067	Cove gap surface, 1.5" below seal
20	157	343	388	0.195	-0.167	Cove gap surface, 5.5" below seal
23	930	772	1123	0.198	-0.015	Elevon nose surface, 45 deg above 0
28	107	315	517	0.187	-0.044	Elevon nose surface, 25 deg above 0

- Simulation predicts temperatures greater than measured during test
  - Does the model provide enough cooling downstream of the seal?
  - Are the test temperatures really steady state?

Test Data – Temperature vs. Time

- Test data indicates:
  - Temperature of tile on fixed surface has reached steady state at 8° elevon angle
  - Temperature below seal has NOT reached steady state during test



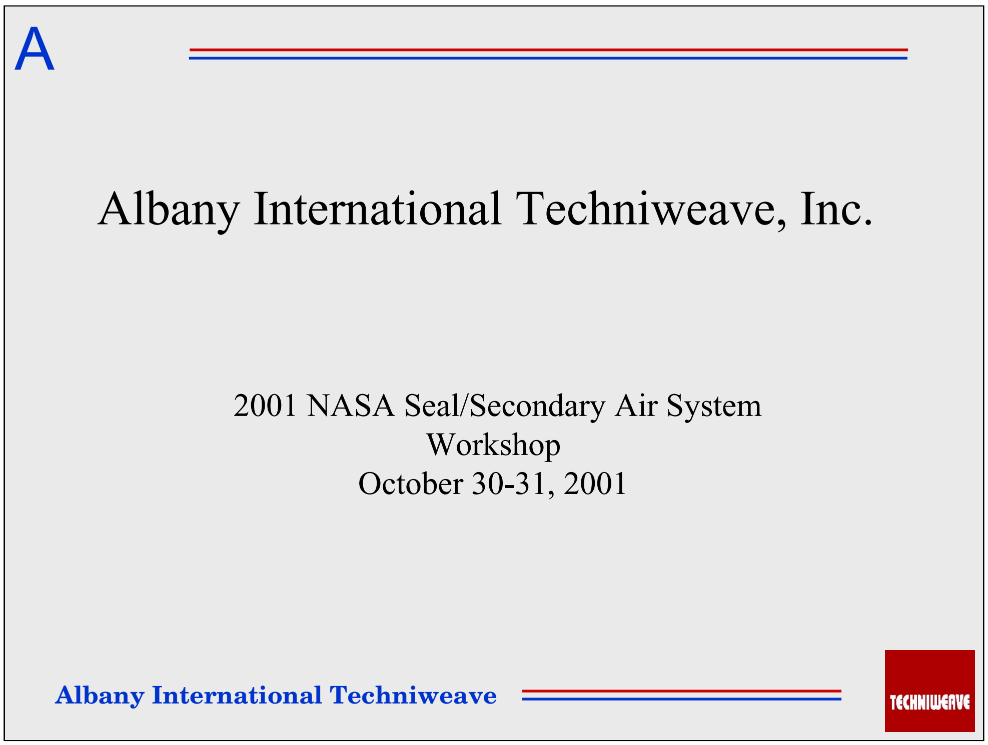


Seal Simulations – Future Steps

- Wrap up runs
- Write report on this phase of project
- Planned follow-on work:
  - 3D simulations of control surface seals with X-38 boundary layer flow
  - Simulations of ceramic ram jet ramp seals
  - Explore active cooling of seals by gap-side gas injection

OVERVIEW OF SEAL DEVELOPMENT AT ALBANY INTERNATIONAL TECHNIWEAVE

Bruce Bond
Albany International Techniweave
Rochester, New Hampshire



A

The Ideal High Temperature Seal

- An elastomeric o-ring with:
  - No leakage
  - Infinitely compressible
  - Unlimited spring back
  - Not limited to 600 o F

Albany International Techniweave

TECHNIWEAVE

The ideal high temperature seal would have the same properties as an elastomeric O-ring but without the temperature limitations.

A

Reality of State of the Art Rope Seals

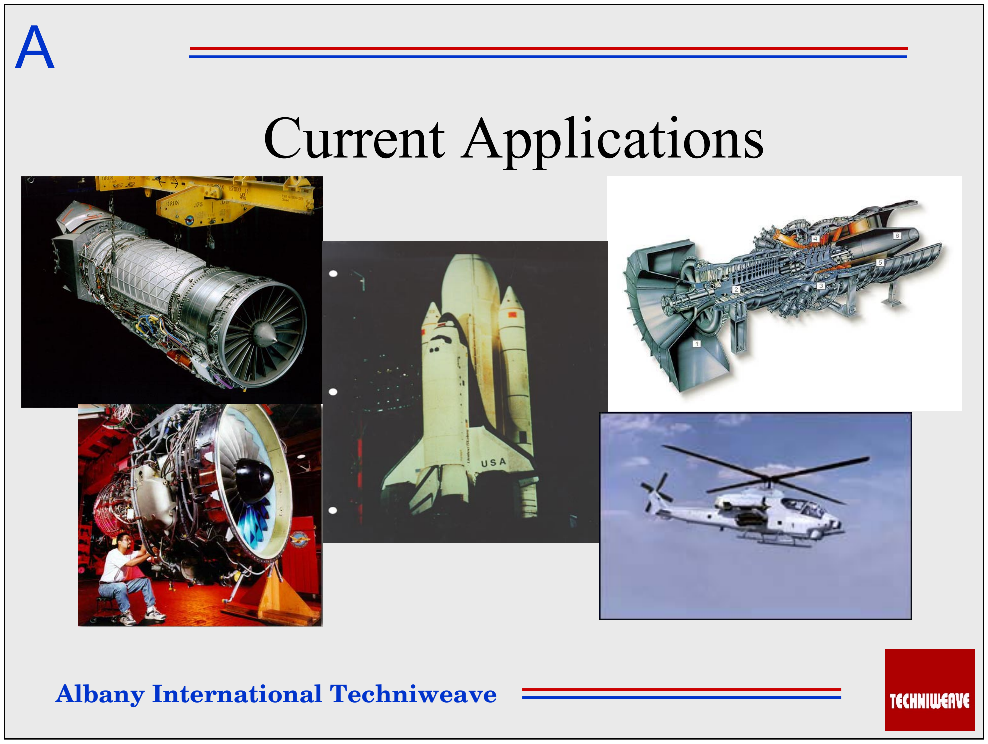
- The seal will leak
- If the seal is compressed too far the fiber turns to powder
- Only limited spring back is realistic
- There are temperature limitations and the higher the temperature the more difficult the fiber is to work with
- The chemical environment affects performance and life

Albany International Techniweave

TECHNIWEAVE

The reality of high temperature seals is often far from the ideal. Engineers are forced to find innovative methods for utilizing ceramic seals.

Our most popular seal combines the high temperature resistance and insulating properties of the relatively resilient ceramic fiber core with an overbraid of Haynes 188 wire for wear and vibration resistance.



Currently our rope seals are used in three major applications

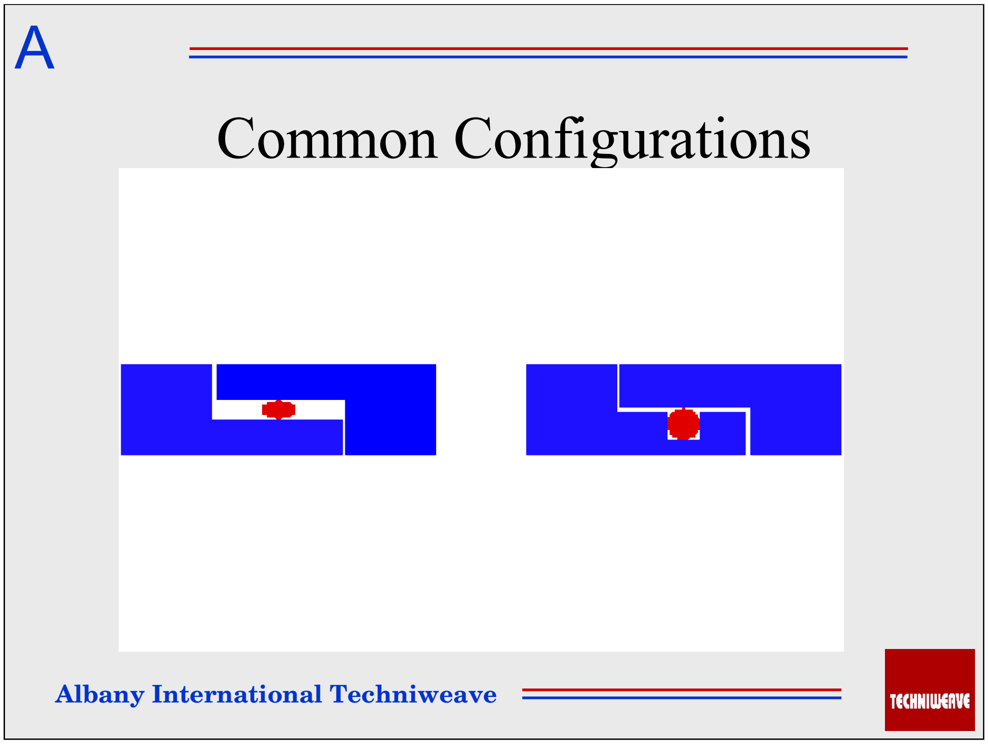
•Advanced aircraft engines such as the P&W F-119 (upper left)

•Land based gas turbines such as the Siemens Westinghouse 501G (upper right)

•Space Shuttle solid rocket booster manufactured by Thiokol (carbon rope seal)

•New commercial aircraft engines, P&W 6000 (lower left)

•High temperature exhaust gasketing, Bell Helicopters Cobra



Rope seals are typically used in two basic configurations.

•The left diagram shows a seal captured between two surfaces with no distinct O-ring groove. In this application the rope seal may carry the entire compressive load. This configuration can be used to isolate ceramic components for metal support fixtures and hence mitigate the effects of widely varying CTE's

•The more conventional looking O-ring grove on the right allows the seal to reduce the leakage between two surfaces by expanding upward to follow the irregularities of the mating part. The seal is an adjunct to joint and only servers to further reduce the flow between two closely mated surfaces. Typically the seal does not carry all of the compressive forces in this configuration.

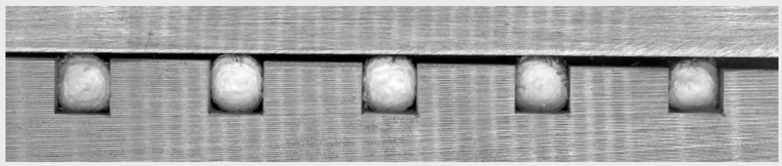
Rope Seal Styles

Style	Diameter [in]	Core	Sheath
9032	.125	Nextel 312	HS-188
9021	.157	Nextel 312	HS-188
9046	.25	Nextel 312	HS-188
9024	.375	Nextel 312	HS-188

Albany International Techniweave

We offer several standard rope seal styles as readily available products. A large portion of our business is fabricating custom seal to meet our customers specific needs. Please feel free to contact us with your requirements.

Compression with Changing Volume (Constant Width)

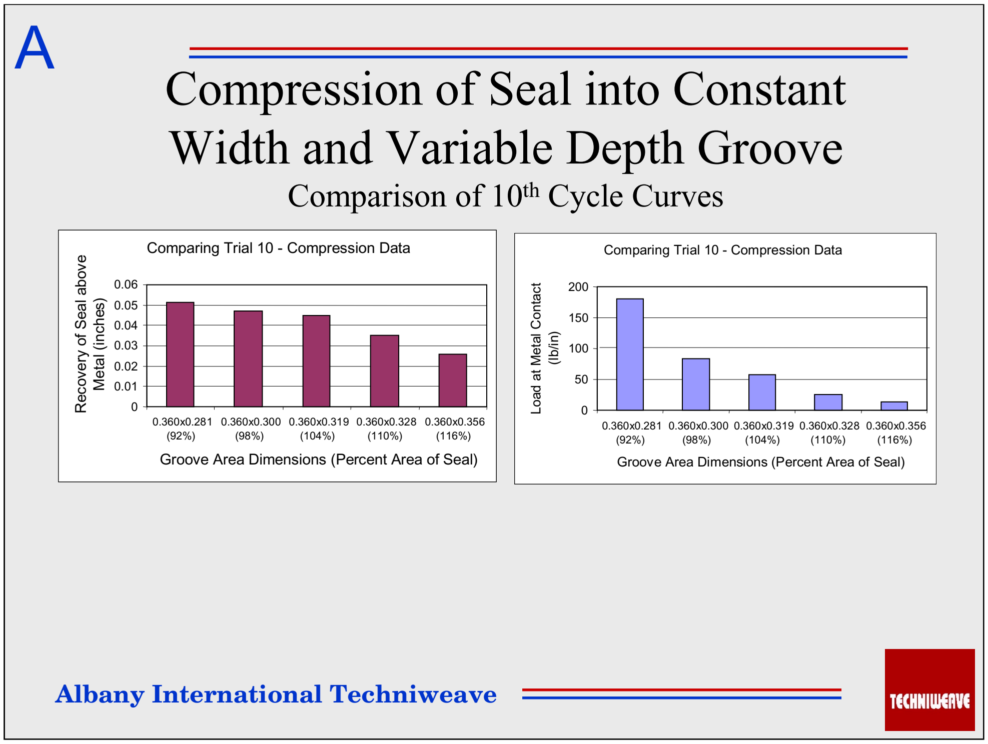


Width: 0.360” 0.360” 0.360” 0.360 0.360”
Depth: 0.356” 0.338” 0.319” 0.300”
0.281” Area: 0.128 in^2 0.122 in^2 0.115 in^2 0.108 in^2
0.101 in^2

*Note, photos are for demonstration purposes only; testing was performed one seal at a time

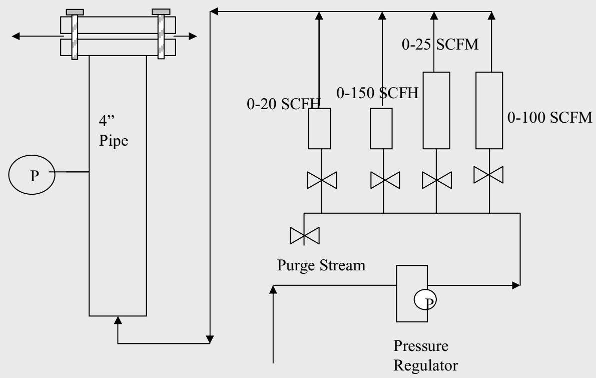
Albany International Techniweave

In certain applications it is desirable to place the seal in a groove which is slightly narrower than the diameter of the seal to facilitate installation and retention during assembly. A family of curves can be established using different loads per linear inch and various groove depths..



In some instances the anticipated loads would be sufficient to ensure metal to metal contact. The graphs above show the recovery of the seal and the loads required to make metal to metal contact for various groove depths where the width is held to a 0.360 inches.

Leakage Testing



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This apparatus was built over 5 years ago to conduct internal leakage tests on high temperature candle filters. The apparatus was modified to allow room temperature leakage testing of rope seals.

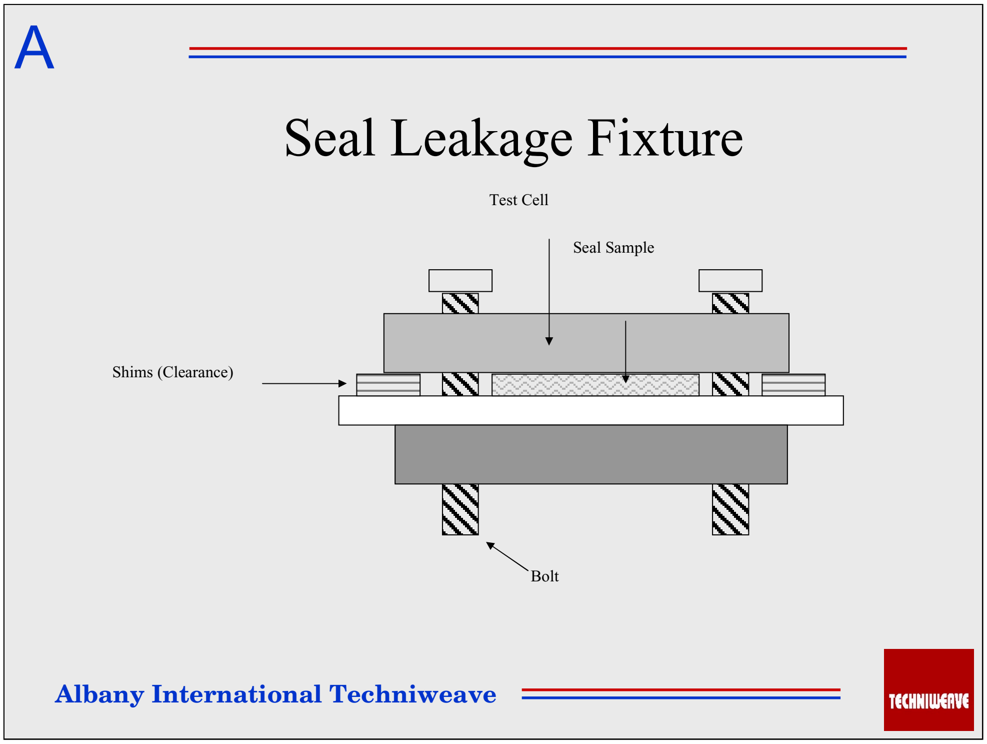
A

Test Apparatus

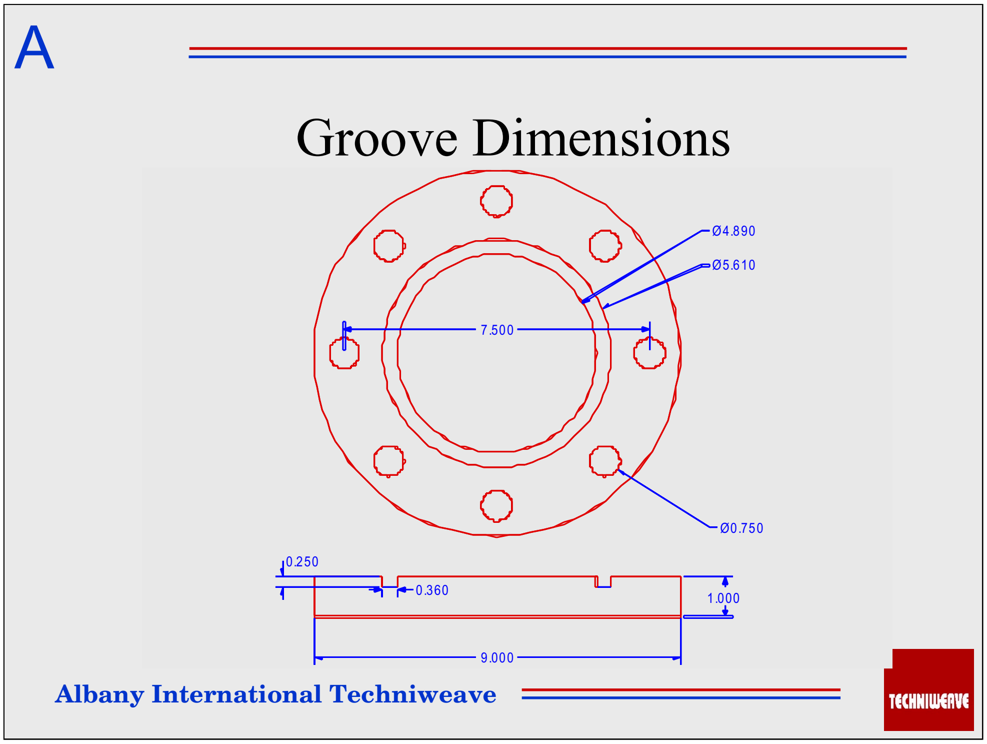
Albany International Techniweave

TECHNIWEAVE

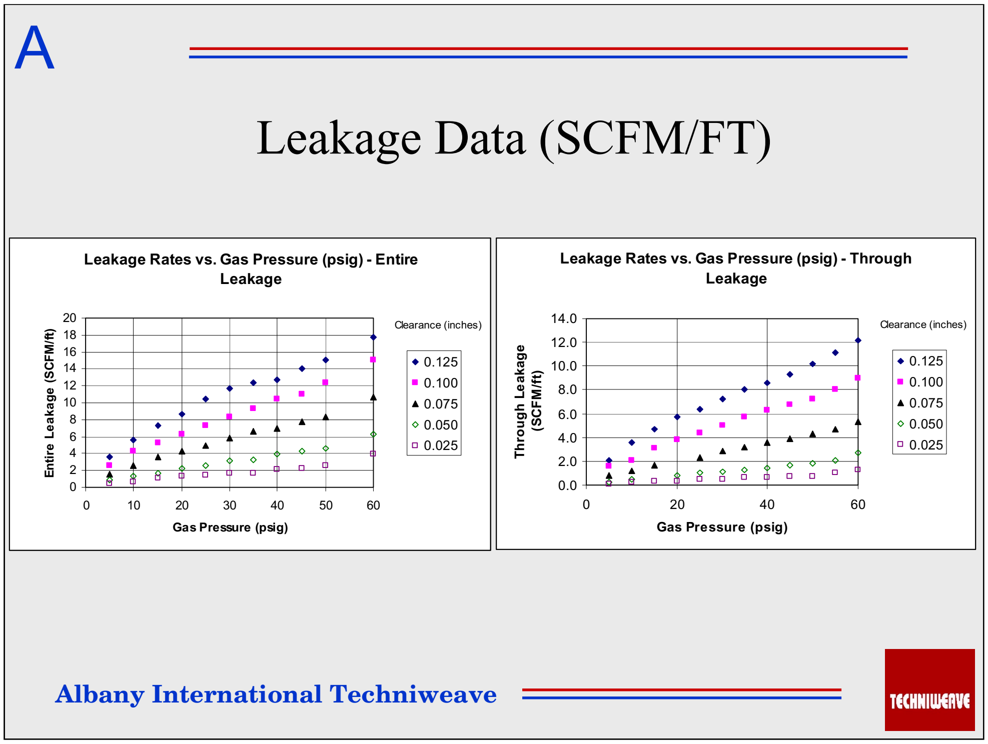
Four flowometers provide measurements from 2 SCFH to 100 SCFM.



The fixture utilized shims at four points to ensure uniform and accurate compression of the seal in the leakage fixture.



A plastic cap was machined as indicated. The mating surface was smooth steel.



The ends of the seal were butted and glued with RTV. The fixture was tightened down to various shim heights. The clearance is the distance between the top plate of the grooved fixture and an smooth steel plate. The use of shims provided a method for ensuring uniform alignment. The data is presented in units of SCFM/FT. The data on the right was generated after the top and bottom surfaces were coated with a thin layer of silicone rubber. This eliminated leakage in that area. In this case roughly 1/3 of all leakage occurred on the top and bottom surfaces of the seal highlighting the importance of architecture and surface finish.

A

New Work

- Shape and fiber volumes of seals in grooves
- Lot to lot leakage variation
- Effect of architecture on leakage
- Effect of fiber volume on leakage

Albany International Techniweave

TECHNIWEAVE

OVERVIEW OF GRC’S ADVANCED SENSOR AND INSTRUMENTATION DEVELOPMENT

Carolyn Mercer
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

National Aeronautics and
Space Administration
Glenn Research Center

Overview of GRC’s Advanced Sensor and Instrumentation Development

Carolyn Mercer
Instrumentation and Controls Division
Glenn Research Center

October 31, 2001

National Aeronautics and
Space Administration
Glenn Research Center

Overview

Glenn Research Center develops advanced diagnostic techniques to measure surface and flow properties in research facilities.

We support a variety of aerospace propulsion applications: Shuttle, X-33, X-43, ISS, and research engine components: inlets, compressors, combustors, nozzles.

We are developing a suite of instrumentation specifically for 3rd Generation Reusable Launch Vehicle testing.

Today's presentation:

- Overview
- 3rd Generation Technologies
- Additional flow and surface measurement technologies
- Summary

3rd Gen Instrumentation Objectives

GOALS

- Increase safety by understanding operating conditions and component capabilities
- Reduce development and operating costs by:
  - Reducing testing and design cycle times and
  - Reducing engine weight and increasing component life

OBJECTIVES

- Determine cooling system effectiveness
- Determine structural loads

•**TECHNICAL CHALLENGES**

- 2000 deg F surfaces; 8000 deg F flows; up to Mach 11
- Remote signal extraction
- Ultra-low intrusive measurements

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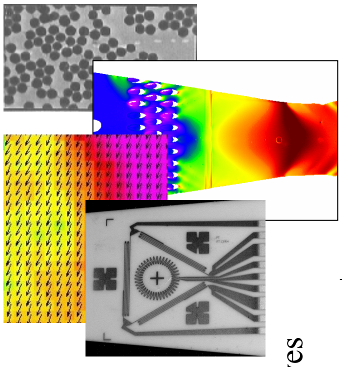
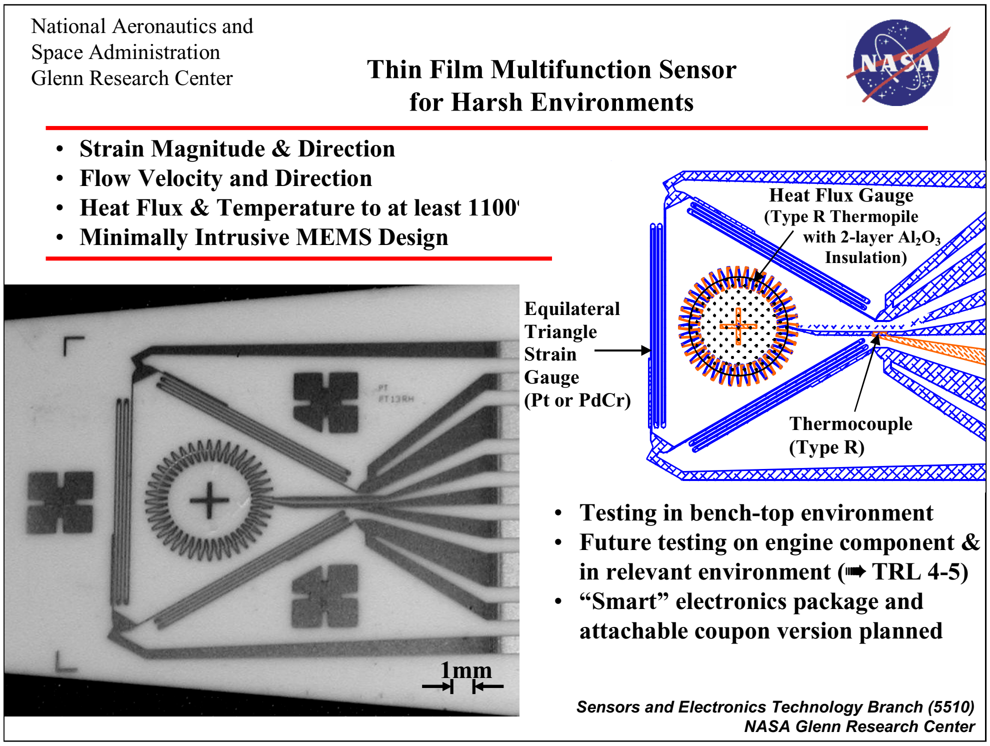
Technologies selected to address objectives



Objectives	Technologies: Thin Films/MEMS	Phosphor Paints	Velocimetry
Cooling System			
Surface Temp	●	●	
Surface Heat Flux	●		
Gas Temp			
Combustion	●		
Weight			
Surface strain	●		
CFD validation			
Velocity			●
Temperature	●	●	



High-temperature MEMS sensors to measure temperature, strain, vibration and heat flux, integrated into a single array.

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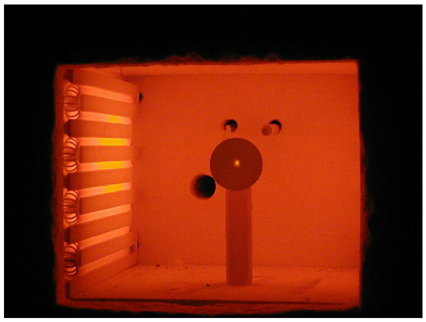
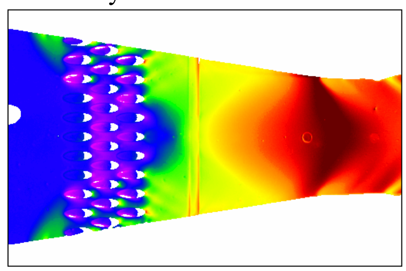
Thermographic Phosphors for Surface Temperature and Heat Flux Measurements

Paint surfaces using temperature sensitive paint
1000C operation demonstrated; new target is 1600C
Borescope inspection – no wires
Optically measure 2D heat transfer using paints survivable to 1000C



Phosphor temperature-indicating emission at about 700 C

Optical data acquisition for minimally intrusive full-surface data



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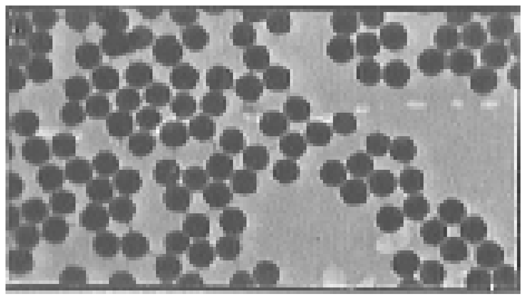
Thermographic phosphors for gas temperature measurements

•Continuously measure gas temperature using small seed particles entrained in the flow.
•Planar gas temperature measurements – flow temperature profiling
•Uniform nano particles fabricated for 250C operation



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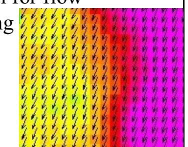
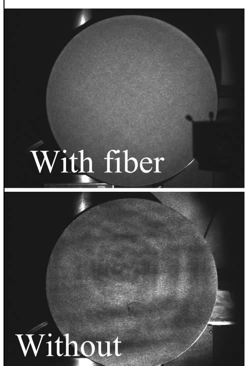
Multi-planar dynamic velocity measurements

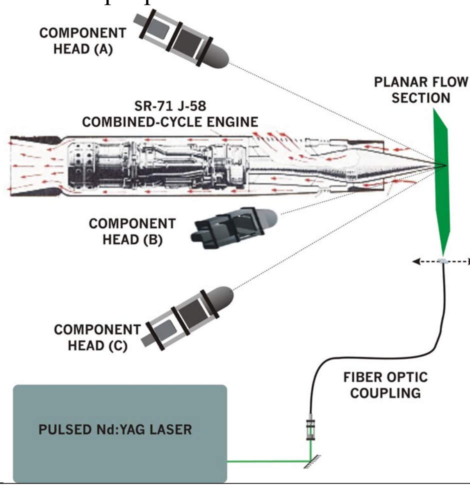
- Develop unsteady, 3-component flow measurement compatible with the confined space encountered in advanced propulsion system inlets and flow paths.
- Fiber optic light delivery and collection minimizes optical access requirements
- MHz data capture at multiple planes for volumetric measurements

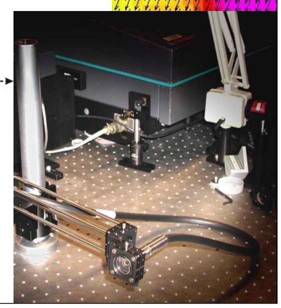
Planar velocity map essential for flow modeling





Fiber illumination improves signal uniformity





Additional Flow and Surface Measurement Technologies

In addition to our Space Transportation work, we are developing and using the following technologies as well:

Thin Films – surface strain, temperature, heat flux
Pressure sensitive paint – surface pressure
Particle imaging velocimetry – gas velocity
MEMS sensors – velocity, gas leak detection, pressure
Fiber optic Bragg sensors – strain, temperature, pressure
Spectroscopy - Combustion diagnostics
Rayleigh scattering – dynamic gas density, temperature, velocity
Schlieren – flow visualization, leak detection

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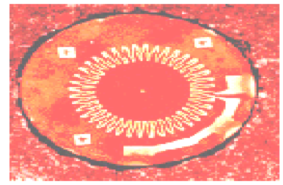
Thin Film Sensor Technology for minimally-intrusive, high temperature strain, temperature, and heat flux measurements.

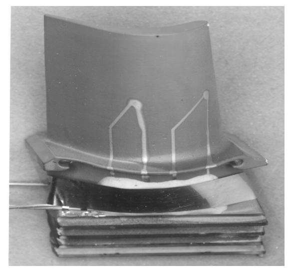
1995 & 1998 R&D 100 Award Winner

PdCr thin-film strain gauge applied on Allied-Signal Engines' ceramic turbine blade.



Heat flux gage on Silicon Nitride plug.

Thin film thermocouples on ceramic matrix composite hoop.



Thin film thermocouples on Space Shuttle Main Engine turbine blades.

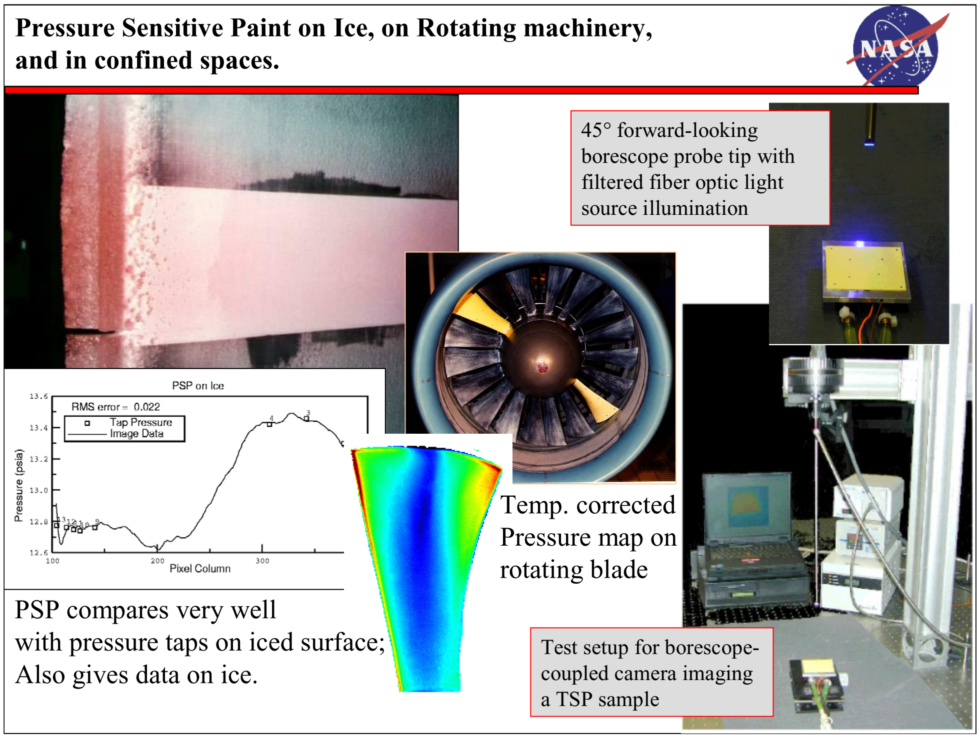
Very thin, minimally intrusive sensors provide high temperature data without disturbing flow.

Fabricate directly onto ceramic and metal engine parts; no need to cut into the part.

Apply on metals, ceramics, and ceramic matrix composites.

Recent achievements:

- Received 1995 R&D 100 Award for thin film strain gauge
- Received 1998 R&D 100 Award for improved durability of wire connections to thin film gages
- PdCr strain gauge applied on Allied-Signal ceramic turbine blade
- Thermocouples applied to SSME turbine blades and CMC hoop
- Heat flux gauge applied on SiN plug
- High temperature survivability



Reduce testing time by measuring pressure across entire surfaces rather than at discrete points in complex geometries including confined flow passages and ice accretions.

Recent Achievements:

Full-view, high-speed rotating temperature and pressure measurements demonstrated on fan blades.

Application of PSP on ice accretions in IRT.

Developed 3D portable PSP system integrating multiple cameras/computers for multiple views, developing borescope system for windowless measurement.

Incorporated Temperature Sensitive Paint for temperature compensation. Generalized compensation algorithm

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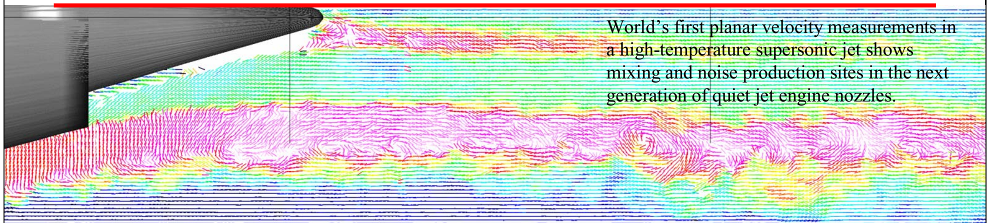
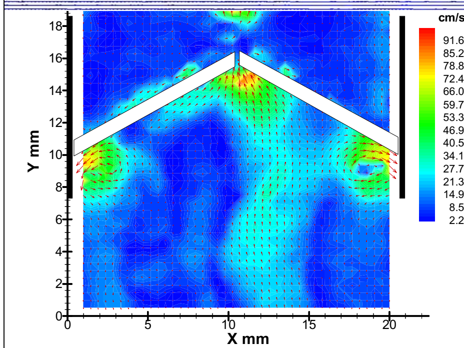
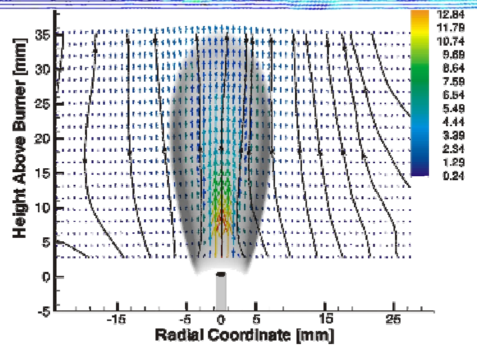
Particle Imaging Velocimetry for instantaneous planar velocity measurements





Detailed velocity measurements in an artificial heart valve, showing regions of stagnation potentially leading to blood clotting.



Planar velocity measurements in "microgravity" combustion flows. PIV system packaged for drop in the 2.2 second drop tower simulating weightlessness.

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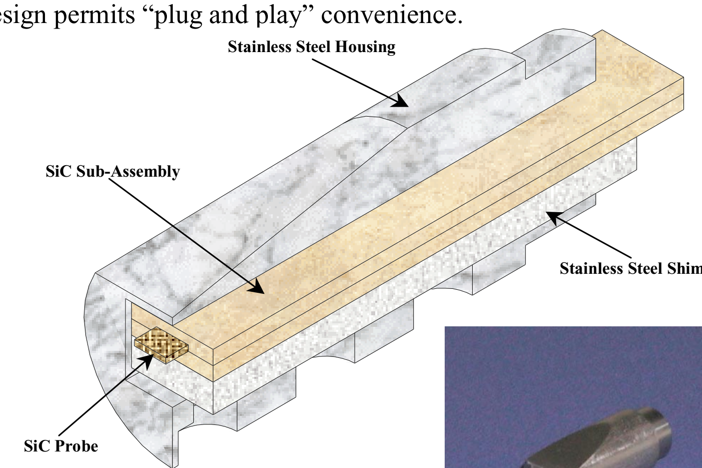
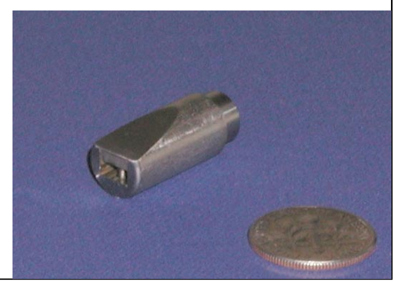
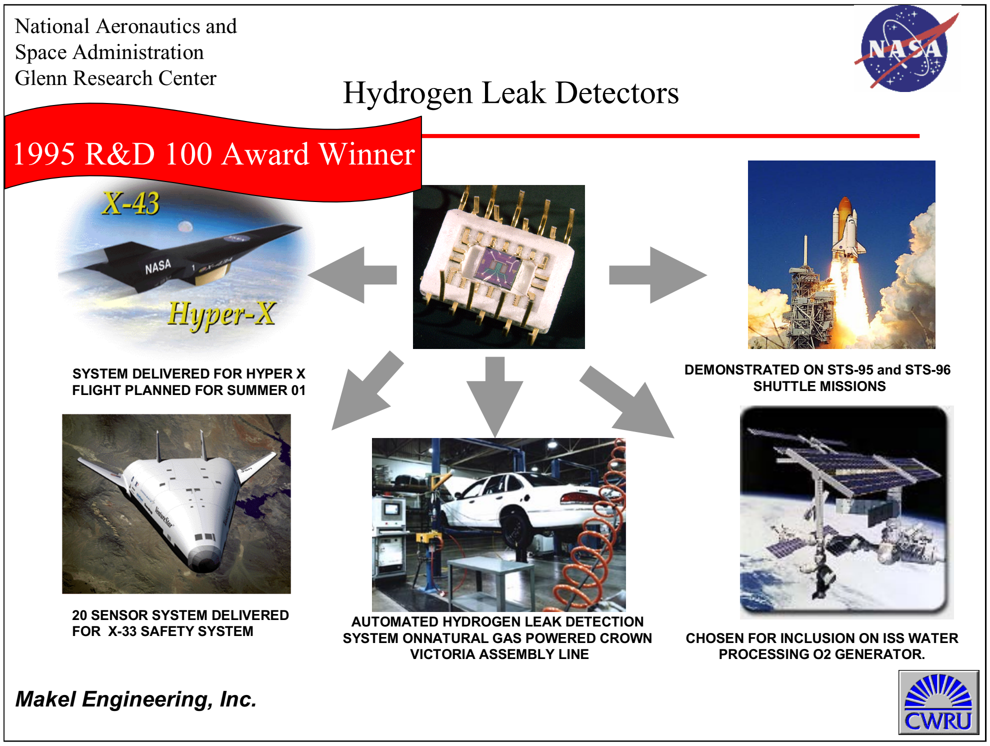
Turbulence Beam Probe

Silicon-Carbide fabrication enables velocity measurements at 600C.
Modular design permits “plug and play” convenience.





Sensors and Electronics Technology Branch - 5510



Microfabricated using MEMS-based technology for minimal size, weight, and power consumption.

Highly sensitive in inert or O2-bearing environments; wide concentration range detection.

Integrated with smart electronics for signal processing and temperature control.

Recent achievements:

- Demonstrated combined hydrogen and oxygen sensing integrated with electronics. Hydrocarbon sensor being developed.
- Flew on Space Shuttle STS-95 and STS-96 missions
- Selected for use on International Space Station
- 20 sensor system delivered to X-33
- Included on Chrysler's Crown Victoria assembly line

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SiC-based Pressure Sensors

Excellent mechanical properties for use as a harsh environment sensor: strong, large piezoresistive coefficients.

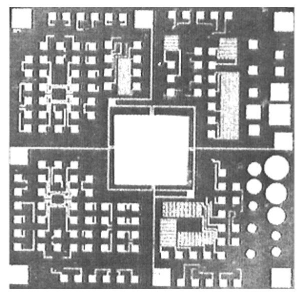
Form diaphragm of SiC and integrate with electronics.

Micro-devices reduce size, weight and power consumption.

Integrated electronics and sensors provide “smart” solutions for harsh environments.

Recent achievements:

- Demonstrated operation at 500C in an engine
- Micromachining methods for harsh environment
  - MEMS developed



SiC Pressure Sensor with Electronics

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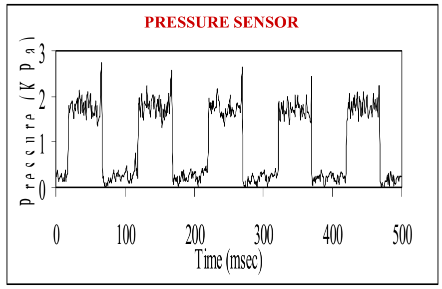
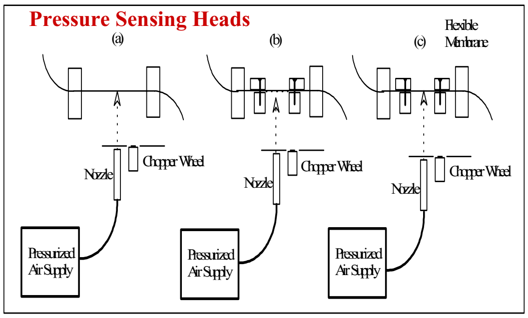
Fiber optic dynamic pressure detectors

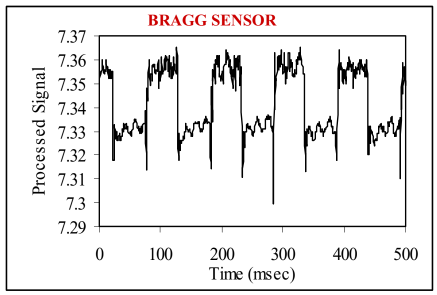
Fiber optic Bragg gratings detect strain – relate to pressure based on mounting geometry.

Interferometric spectrometer enables dynamic data readout – tracks pressure transducer well.

We've embedded these sensors into PMC plates, surviving up to 300C.







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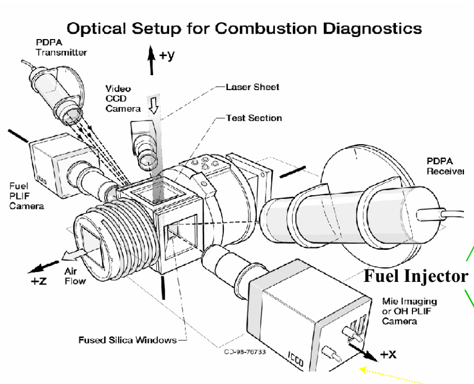
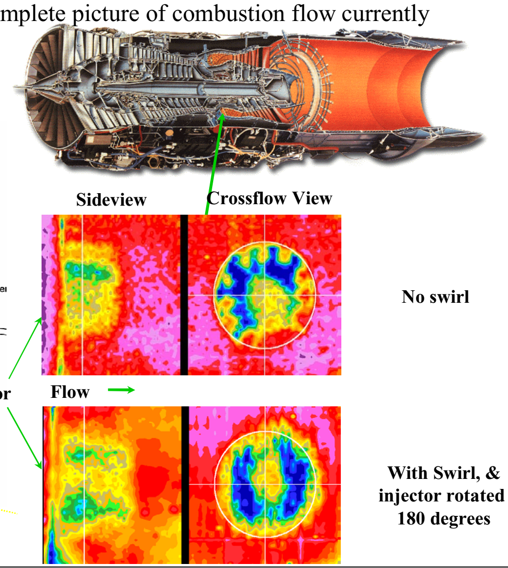
Combustion Diagnostics

Planar laser induced fluorescence and Mie scattering, chemiluminescent imaging, and phase doppler particle sizing yields most complete picture of combustion flow currently available.





Optical accessibility allows first ever direct visual observation of the effect of combustor configuration changes leading to informed next step alternatives in combustor and sub-component design modifications for improved performance and emissions reduction.

Mie data combined with PLIF data shows gas/liquid fuel distribution, may yield planar particle size distribution.

Planar data combined with PDPA yields most complete picture of combustion flow currently available.

Particle size distribution, spray angle, species distribution.

- Provide previously unavailable observations of combustor flows.
- Get data to understand effect of design changes to reduce emissions.
- Support code validation.

Recent Achievements:

•Demonstrated integrated suite of measurements in high-pressure (42 atmospheres) jet-fueled combustors:

OH, NO, and fuel PLIF; Mie scattering; PDPA; chemi-luminescence.

•Integrated PLIF and particle scattering measurements to quantify fuel-air ratio under certain conditions.

•Volumetric data processing permits virtual cross-flow views.

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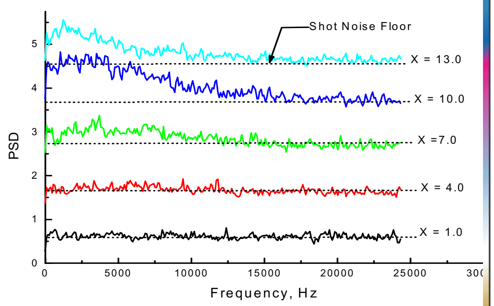
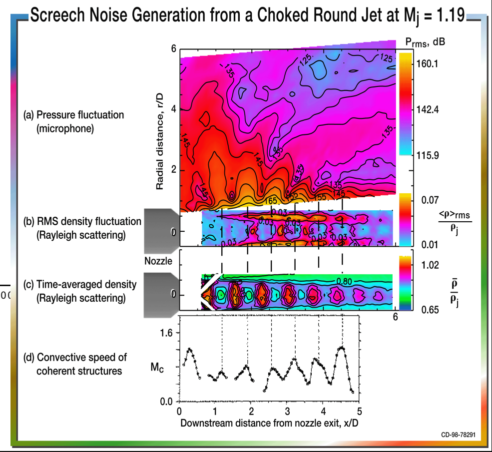
Dynamic Rayleigh Scattering

Optical technique to dynamically measure gas density, velocity and temperature.

Density power spectra measurements in a supersonic free jet.





Point Rayleigh measurements scanned through out supersonic nozzle flow to measure time average density and density fluctuations.

Rayleigh data correlates to microphone noise measurements.

- Provide previously unavailable real-time data by making time-resolved density and velocity measurements in a free-jet
- Get data to understand physics of noise generation
- Support Unsteady NPARC Validation Experiment

Recent Achievements:

- Demonstrated simultaneous density, velocity, and temperature measurements in supersonic nozzle flow.
- Made first density measurements showing growth and decay of turbulent fluctuations in a supersonic free jet.
- Added fiber optic delivery system for use in high-noise environment.

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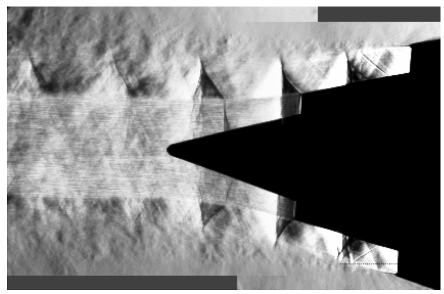
Focused Schlieren

- Ability to focus on a particular plane.
- Get data to understand effect of design changes for noise reduction.
- Real time test validation.

Recent Achievements:

- Added digital data acquisition, enabling post-test image processing



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Summary

Advanced Instrumentation Development for Aerospace Propulsion Test Facilities

- Reduce project risk and vehicle/engine weight by using measurements to narrow uncertainty in operating and capability ranges.
- Reduce design cycle times by extracting maximum information from minimum testing
  - Characterize operating and capability ranges
  - Understand physics
  - Improve models
- Use advanced optical and MEMS technology to make measurements faster, more reliably, or where never before possible.
- Use integrated sensors/electronics and advanced data processing to extract maximum information.

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13. ABSTRACT ***(Maximum 200 words)***

The 2001 NASA Seal/Secondary Air System Workshop covered the following topics: (i) overview of NASA's Vision for 21st Century Aircraft; (ii) overview of NASA-sponsored Ultra-Efficient Engine Technology (UEET); (iii) reviews of sealing concepts, test results, experimental facilities, and numerical predictions; and (iv) reviews of material development programs relevant to advanced seals development. The NASA UEET overview illustrates for the reader the importance of advanced technologies, including seals, in meeting future turbine engine system efficiency and emission goals. The NASA UEET program goals include an 8- to 15-percent reduction in fuel burn, a 15-percent reduction in CO_2, a 70-percent reduction in NO_x, CO, and unburned hydrocarbons, and a 30-dB noise reduction relative to program baselines. The workshop also covered several programs NASA is funding to investigate advanced reusable space vehicle technologies (X–38) and advanced space ram/scramjet propulsion systems. Seal challenges posed by these advanced systems include high-temperature operation, resiliency at the operating temperature to accommodate sidewall flexing, and durability to last many missions.

14. SUBJECT TERMS
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