NASA/CP—2003-212458/VOL1

2002 NASA Seal/Secondary Air System Workshop

September 2003

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/CP—2003-212458/VOL1

2002 NASA Seal/Secondary Air System Workshop

Proceedings of a conference held at Ohio Aerospace Institute
sponsored by -NASA Glenn Research Center
Cleveland, Ohio
October 23–24, 2002

National Aeronautics and
Space Administration

Glenn Research Center

September 2003

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

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

Executive Summary
Volume 1

The 2002 NASA Seal/Secondary Air System Workshop covered the following topics

(i) Overview of NASA's perspective of aeronautics and space technology for the 21st century
(ii) Overview of NASA-sponsored Ultra-Efficient Engine Technology (UEET), Turbine-Based Combined-Cycle (TBCC), and Revolutionary Turbine Accelerator (RTA) programs
(iii) Overview of NASA Glenn's seal program aimed at developing advanced seals for NASA's turbomachinery, space propulsion, and reentry vehicle needs
(iv) Reviews of sealing concepts, test results, experimental facilities, and numerical predictions
(v) 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. The TBCC/RTA program mission is to develop, demonstrate, and transition enabling turbine technologies for future turbine-based combined-cycle propulsion systems for commercial and military applications including access-to-space and hypersonic cruise. These advanced turbine technologies will be demonstrated in subscale ground-based engine tests (fiscal years 2006 and 2009) and future X–43 flight tests. The need to reach high speeds (Mach = 4) high thrust-to-weight (10:1) and acceptable life (500 hours) pose temperature and life challenges to all elements within the engine including rotating seals and engine duct/ramp seals.

Cikanek presented NASA's Integrated Space Transportation development plan covering near-term rocket-based launch systems, future airbreathing/rocket launch systems, and reentry vehicle systems. Advanced low-leakage cryogenic turbomachinery seals are required for the rocket systems. High-temperature, resilient, long-life engine ramp and control surface seals are required for future airbreathing propulsion and reentry vehicle systems, respectively.

Lattime, Chupp, and Bloch each presented approaches for controlling/mitigating blade tip leakage. Lattime presented NASA/OAI's program of developing active clearance control techniques to reduce blade tip clearances to reduce specific fuel consumption, slow exhaust gas temperature rise, and increase engine time-on-wing. Chupp presented how abradable seals work, locations within turbine engines, and current research focus areas. Bloch presented preliminary results of brush seals applied as a compliant casing for transonic axial compressors.

Braun, et al., presented numerical simulations of finger seal elements of a noncontacting seal currently under development, sponsored by NASA GRC. Mohawk presented a foil seal arrangement that applies foil-bearing technology to arrive at a noncontacting seal. This foil seal is being developed by Mohawk under an NASA SBIR contract and exploits NASA Glenn's advanced solid film lubricant developments. Shapiro presented preliminary investigations of a film riding brush seal concept. 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.

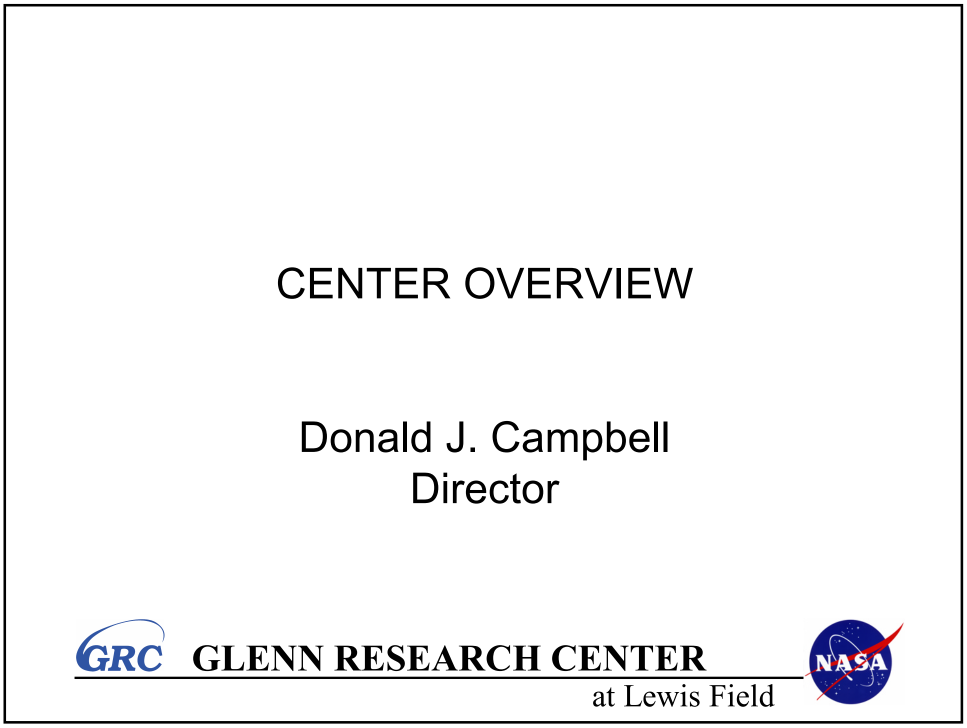
Space Seal Developments: NASA is funding several programs to investigate advanced reusable space vehicle technologies (X–38) and advanced space ram/scramjet propulsion systems. Future highly reusable launch vehicles pose challenging control surface seal demands that require new seal concepts made from 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. Dunlap also reviewed plans and status of efforts to develop high-temperature (2000+°F) seal preloaders, essential to ensuring seal resiliency over many missions. Glenn is installing high-temperature seal scrub and compression test rigs capable of up to 3000 °F operation. DeMange presented an overview of the unique features of these state-of-the-art high-temperature test rigs. Bond of Albany Techniweave presented techniques for braiding ceramic fiber and carbon fiber seals to meet NASA's needs. Owens of Saint-Gobain presented an overview of silicon carbide (SiC) ceramic properties and applications where SiC's strength-at-temperature and wear resistance are being utilized.

TABLE OF CONTENTS
Volume 1

NASA GLENN RESEARCH CENTER OVERVIEW

Donald J. Campbell
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio



CENTER OVERVIEW

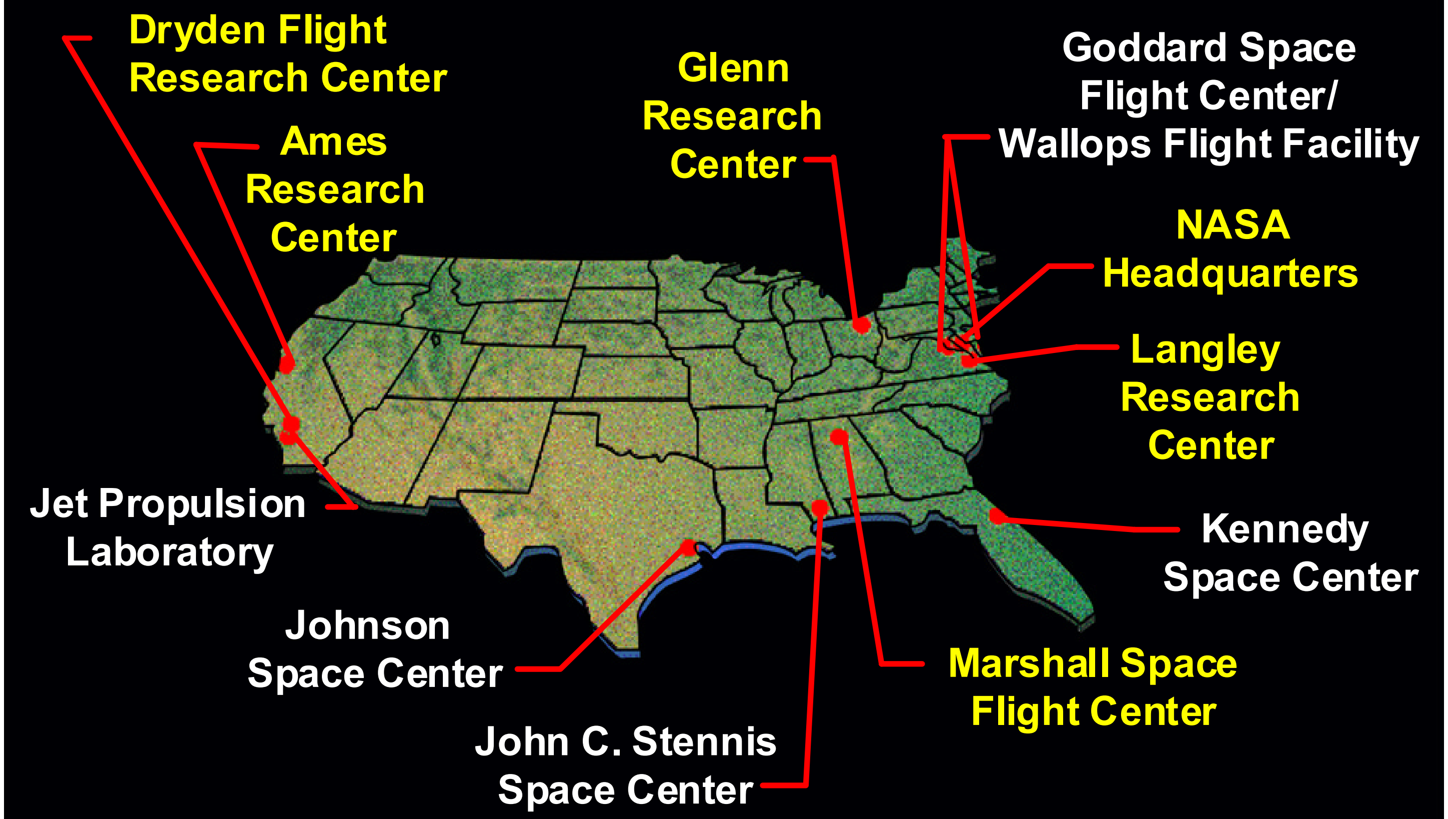
Donald J. Campbell
Director

GLENN RESEARCH CENTER
at Lewis Field

Welcome

GRC GLENN RESEARCH CENTER
at Lewis Field

NASA Installations



Dryden Flight Research Center

Ames Research Center

Glenn Research Center

Goddard Space Flight Center/ Wallops Flight Facility

NASA Headquarters

Langley Research Center

Jet Propulsion Laboratory

Kennedy Space Center

Johnson Space Center

Marshall Space Flight Center

John C. Stennis Space Center

GRC GLENN RESEARCH CENTER
at Lewis Field

NASA's Vision

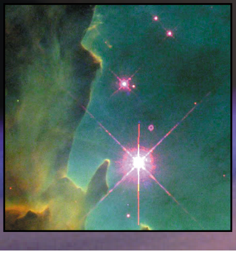
- To improve life here
- To extend life to there
- To find life beyond

NASA's Mission

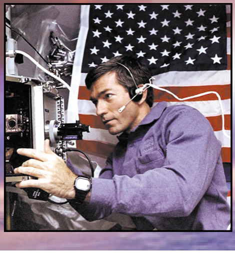
- To understand and protect our home planet
- To explore the universe and search for life
- To inspire the next generation of explorers

…as only NASA can

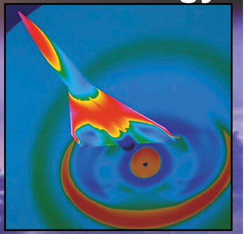
5 Strategic Enterprises


Space Science


Earth Science


Biological & Physical Research


HEDS


Aerospace Technology

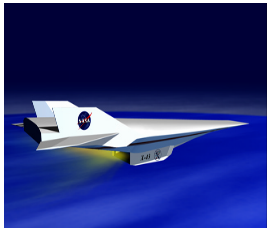
One NASA

GRC **GLENN RESEARCH CENTER**
at Lewis Field

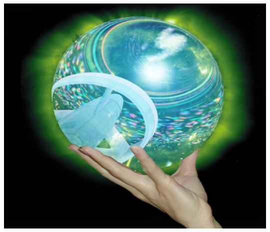
NASA Aerospace Technology - Themes

Revolutionize Aviation

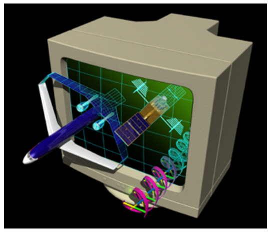
Space Launch Initiative



Advanced Space Transportation Technology



Fundamental Technology



Commercial Technology

GRC GLENN RESEARCH CENTER
at Lewis Field

GRC Roles and Responsibilities

Primary Responsibility

- Aeropropulsion

Additional Responsibilities

- Space Propulsion
- Space Power
- Space Communications

Transformational Responsibilities

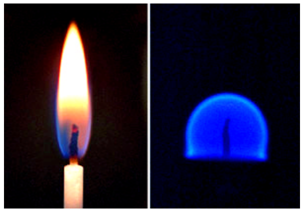
- Microgravity

GRC GLENN RESEARCH CENTER
at Lewis Field

GRC Mission Areas

Aerospace Power

Microgravity Science



Aeropropulsion

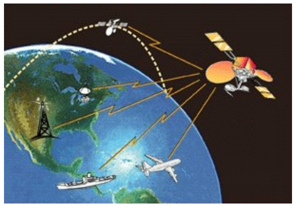
Hypersonic

Supersonic

Subsonic

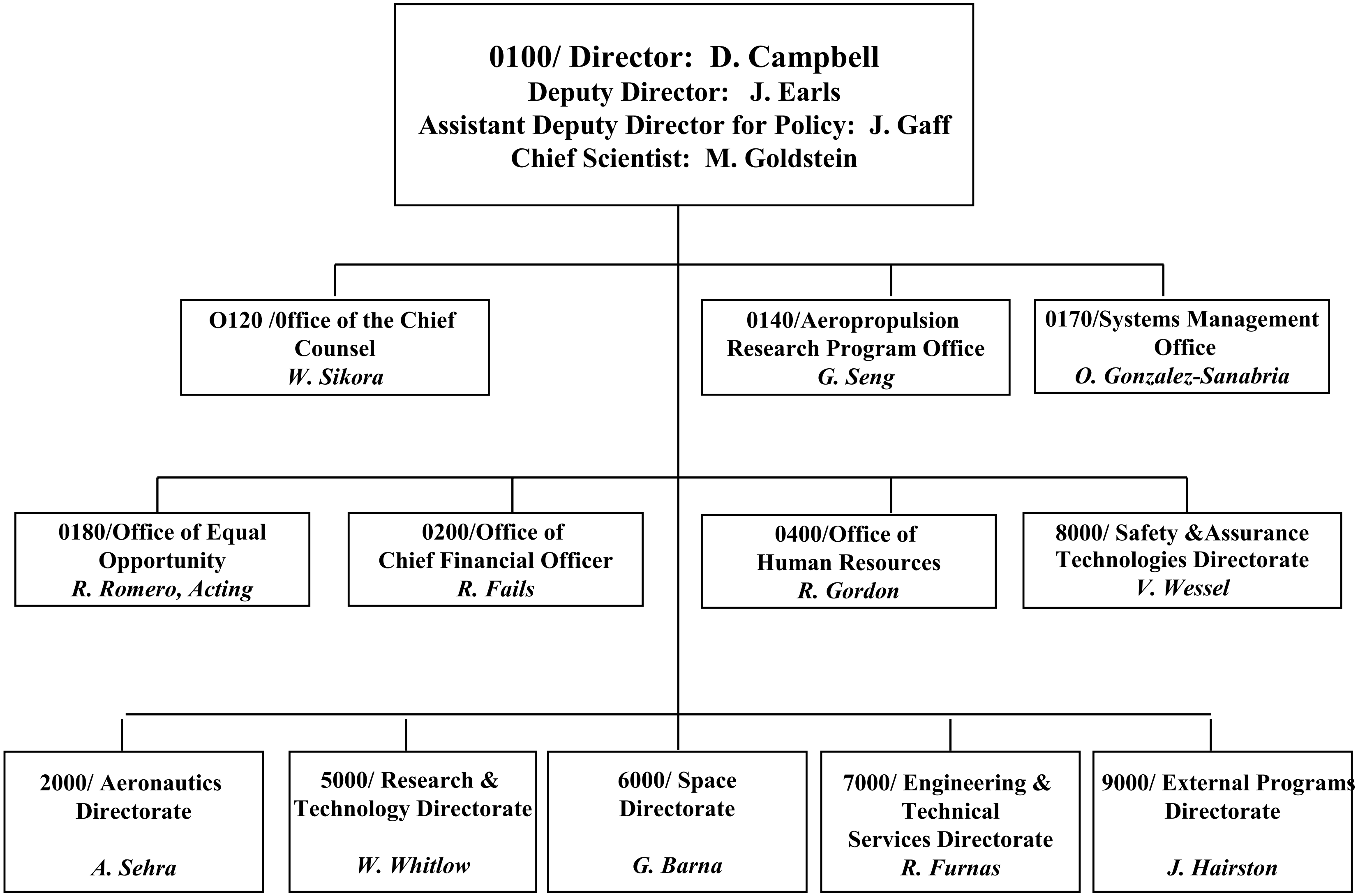
Space Propulsion

Aerospace Communication



GRC GLENN RESEARCH CENTER
at Lewis Field

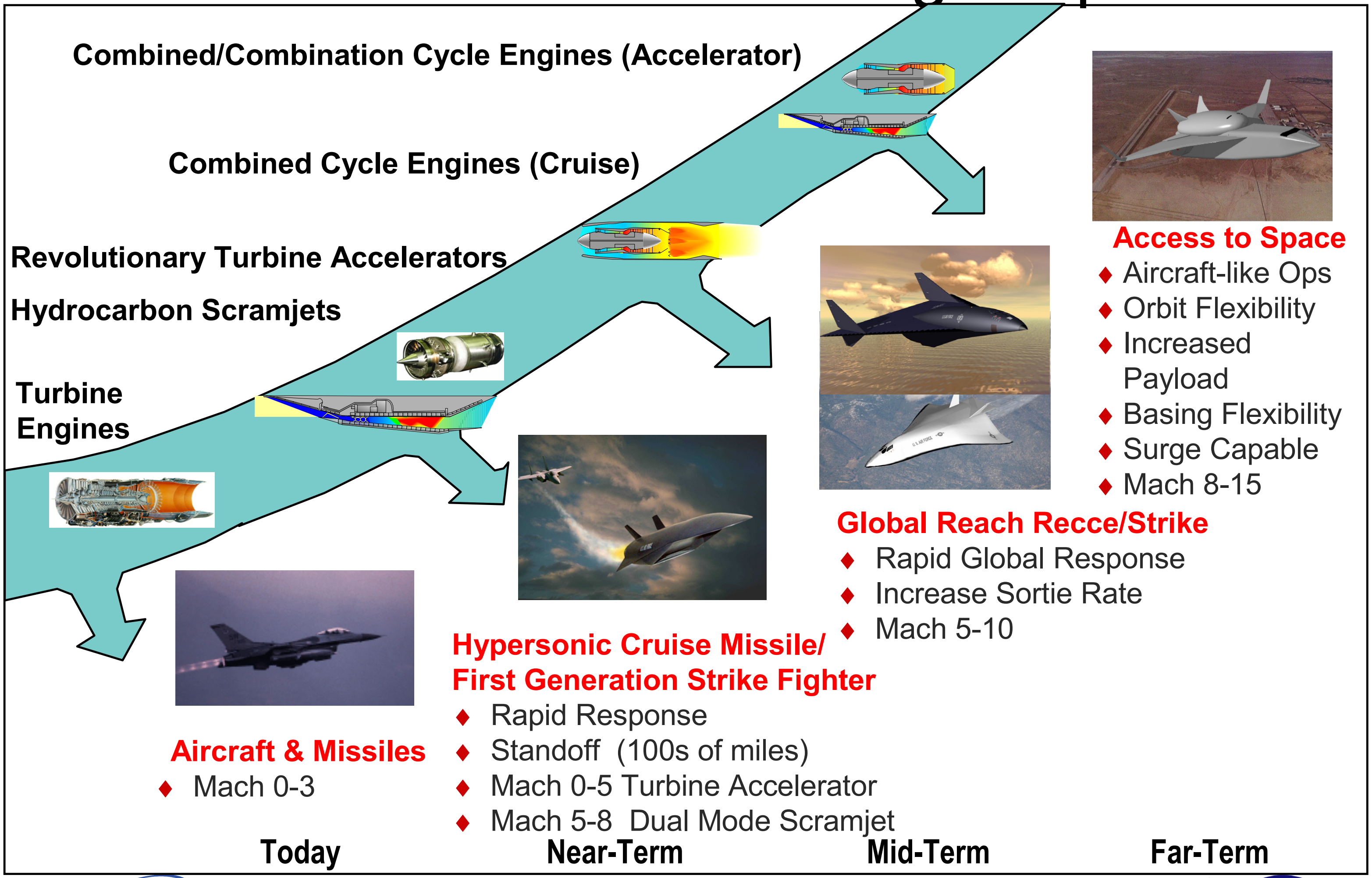
NASA



GRC **GLENN RESEARCH CENTER**

at Lewis Field

Potential Uses of Airbreathing Propulsion



Aircraft & Missiles

- Mach 0-3

Hypersonic Cruise Missile/ First Generation Strike Fighter

- Rapid Response
- Standoff (100s of miles)
- Mach 0-5 Turbine Accelerator
- Mach 5-8 Dual Mode Scramjet

Global Reach Recce/Strike

- Rapid Global Response
- Increase Sortie Rate
- Mach 5-10

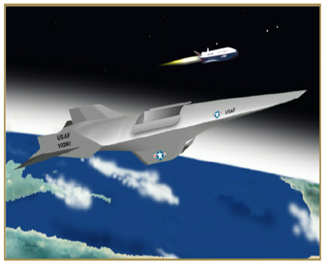
Access to Space

- Aircraft-like Ops
- Orbit Flexibility
- Increased Payload
- Basing Flexibility
- Surge Capable
- Mach 8-15

GRC GLENN RESEARCH CENTER
at Lewis Field

GRC Space

Communications
Modeling/Analyses
Antennas
Solid-state devices
Digital communications
Vacuum electronics
Satellite/terrestrial networks
Spectrum Management



Space Transportation
Advanced Concepts/Analyses
Airbreathing Propulsion
Propulsion Materials/Structures
Subsystems (Power, Actuators)
Propellants
Vehicle Health Management

Microgravity Science

Fluid Physics
Combustion science
BioScience and Engineering
Acceleration measurements
Flight exp. development & operations
Space Station utilization

Power
Architecture/Analyses
Generation
Storage
Distribution/Control
Environmental durability
Space Station support

Space Propulsion
Modeling/Analyses
Electric
Chemical
Thrusters/Controls & Electronics/Feed Sys.

GRC GLENN RESEARCH CENTER
at Lewis Field

NASA

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

GRC **GLENN RESEARCH CENTER**
at Lewis Field

TECHNOLOGY REQUIREMENTS FOR THE 21ST CENTURY—A NASA PERSPECTIVE

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

Technology Requirements for the 21st Century – A NASA Perspective

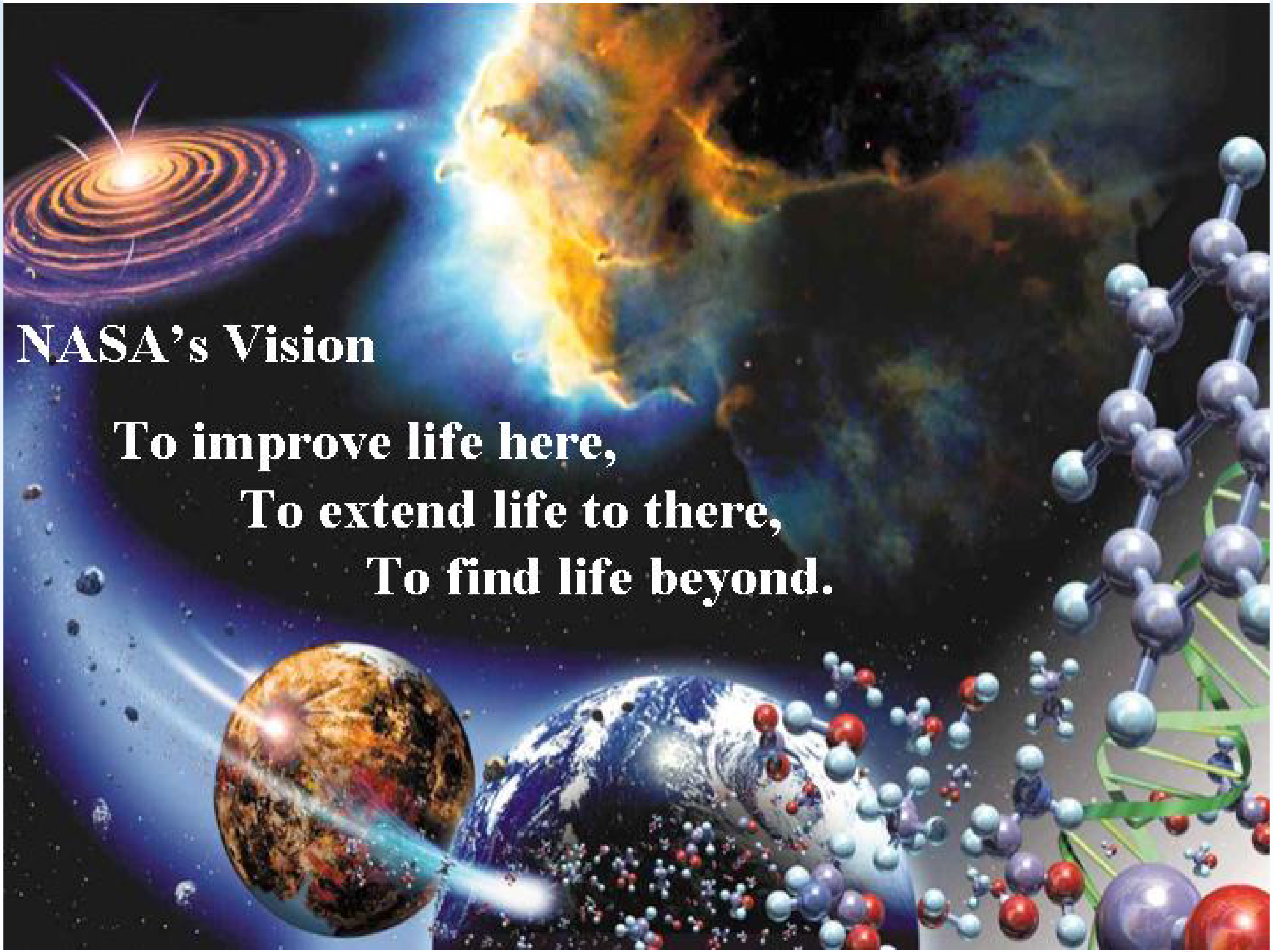
Dr. Woodrow Whitlow, Jr.
October 23, 2002

Glenn Research Center
at Lewis Field

8/14/2003

Outline

- NASA Vision and Mission
- Aeronautics Technology
- Space Technology
- Education Programs
- Conclusions



NASA's Vision

To improve life here,
To extend life to there,
To find life beyond.

Glenn Research Center

at Lewis Field

The NASA Mission

To understand and protect our home planet

To explore the universe and search for life

To inspire the next generation of explorers

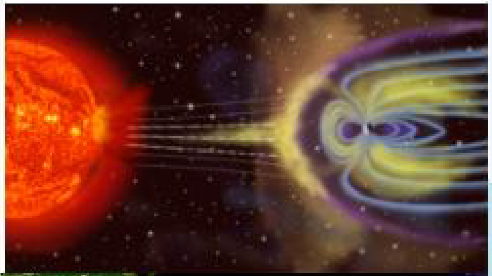
… as only NASA can.

Glenn Research Center

at Lewis Field

To Understand and Protect Our Home Planet

- Understanding the Earth's system and its response to natural and human-induced changes
- Enabling a safe, secure, efficient, and environmentally friendly air transportation system
- Investing in technologies and collaborating with others to improve the quality of life and to create a more secure world



Glenn Research Center

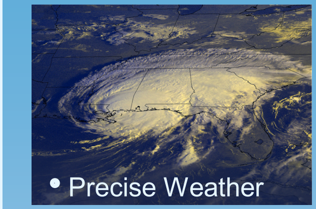
at Lewis Field

The Airspace System

Today’s Challenges:

- **Overcome reduced throughput in bad weather**
- **Eliminate en route congestion and the “domino effect” throughout the system**
- **Keep pace with demand for arrival and departures at benchmark airports***
- **Increase situational awareness in the system**

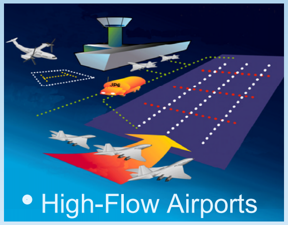
Technology Solutions:


• Precise Weather

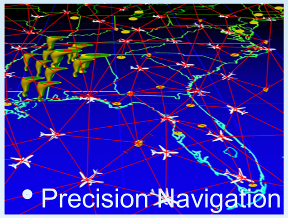
- **High-resolution weather**
  - **Precise forecasts**
  - **Precise wake vortex knowledge**


• Traffic Optimization

- **System-level traffic flows optimization**
  - **Separation assurance for complex traffic flows**


• High-Flow Airports

- **High-flow airports**
  - **No gaps in arrival and departure streams**
  - **Efficient surface movement and rapid reconfiguration**


• Precision Navigation

- **Communication, navigation, and surveillance**
  - **High-bandwidth and reliable data transmission**
  - **Precision navigation**
  - **System wide coverage**

Airspace System of the Future

Glenn Research Center

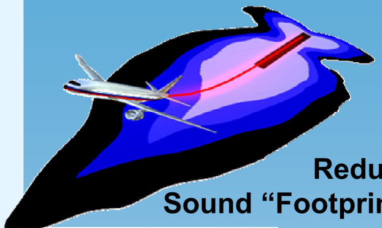
at Lewis Field

Revolutionary Vehicles

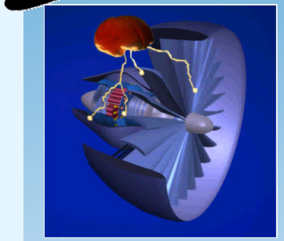
Today's Challenges:

- Reduce noise
  - Eliminate airport restrictions
- Lower emissions
  - Reduce greenhouse gases
  - Improve local air quality
- Improve safety
  - Reduce the accident rate
- Enhance capabilities–advance technology
  - Autonomous operation
  - Supersonic overland flight
  - Runway independence

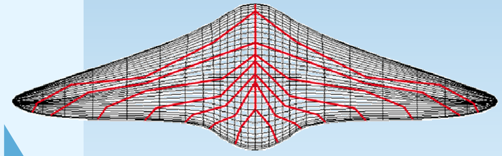
Technology Solutions:



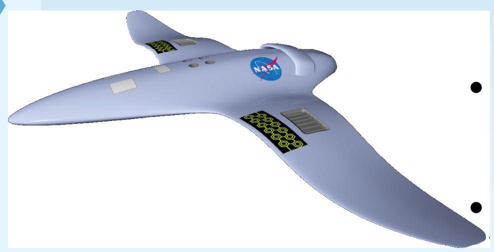
Reduce Sound "Footprint"



Intelligent Propulsion System

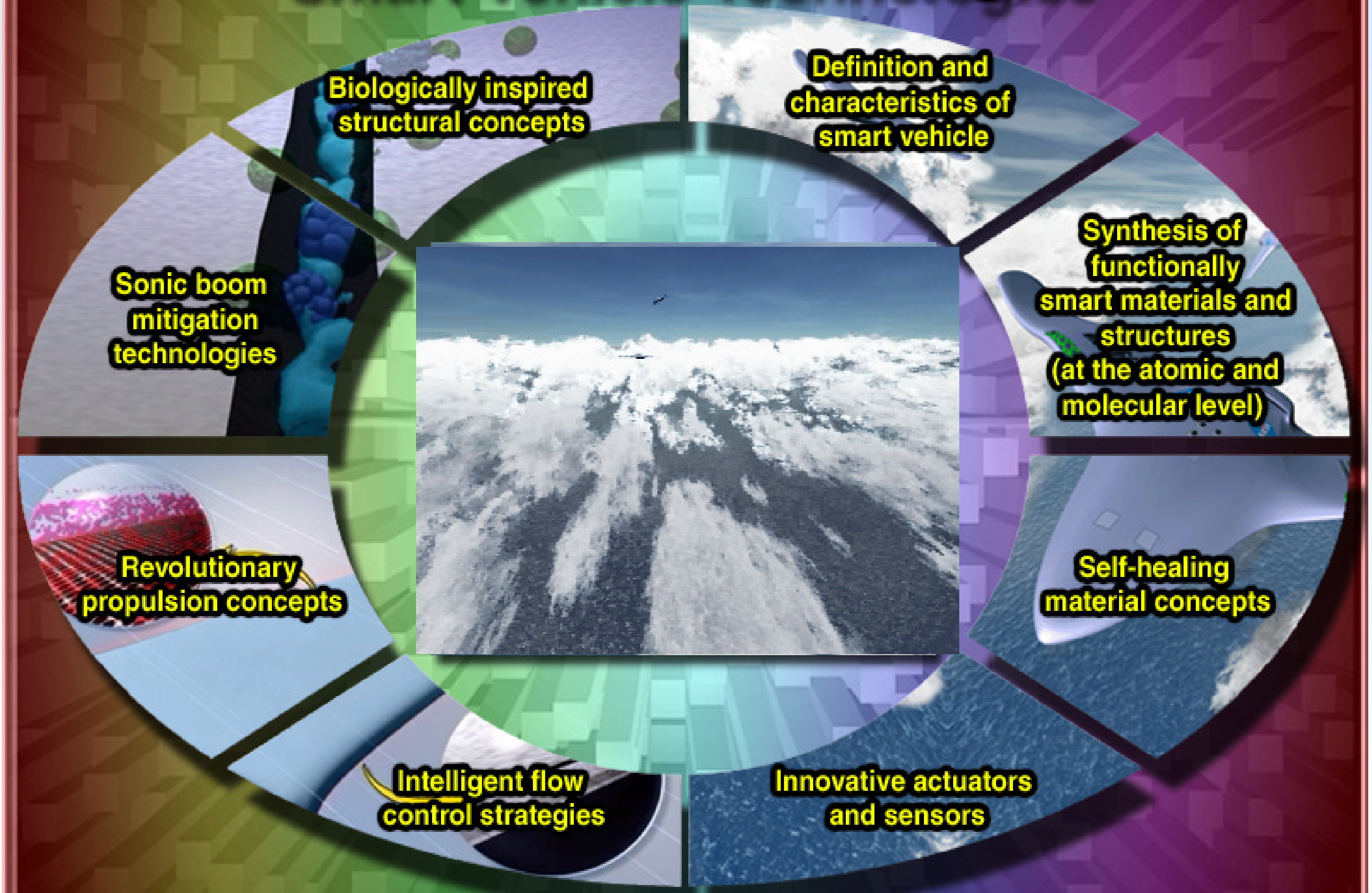


Intelligent Sensors



- Integrated airframe and propulsion systems
- Active flow and noise control
- Intelligent propulsion systems
- Fuel-efficient vehicles
- Robust flight control
  - Reconfigurable control laws
- Integrated vehicle health monitoring
- Automated decision aids
- Advanced vehicle concepts

Smart Vehicle Technologies



Definition and characteristics of smart vehicle

Synthesis of functionally smart materials and structures (at the atomic and molecular level)

Self-healing material concepts

Innovative actuators and sensors

Intelligent flow control strategies

Revolutionary propulsion concepts

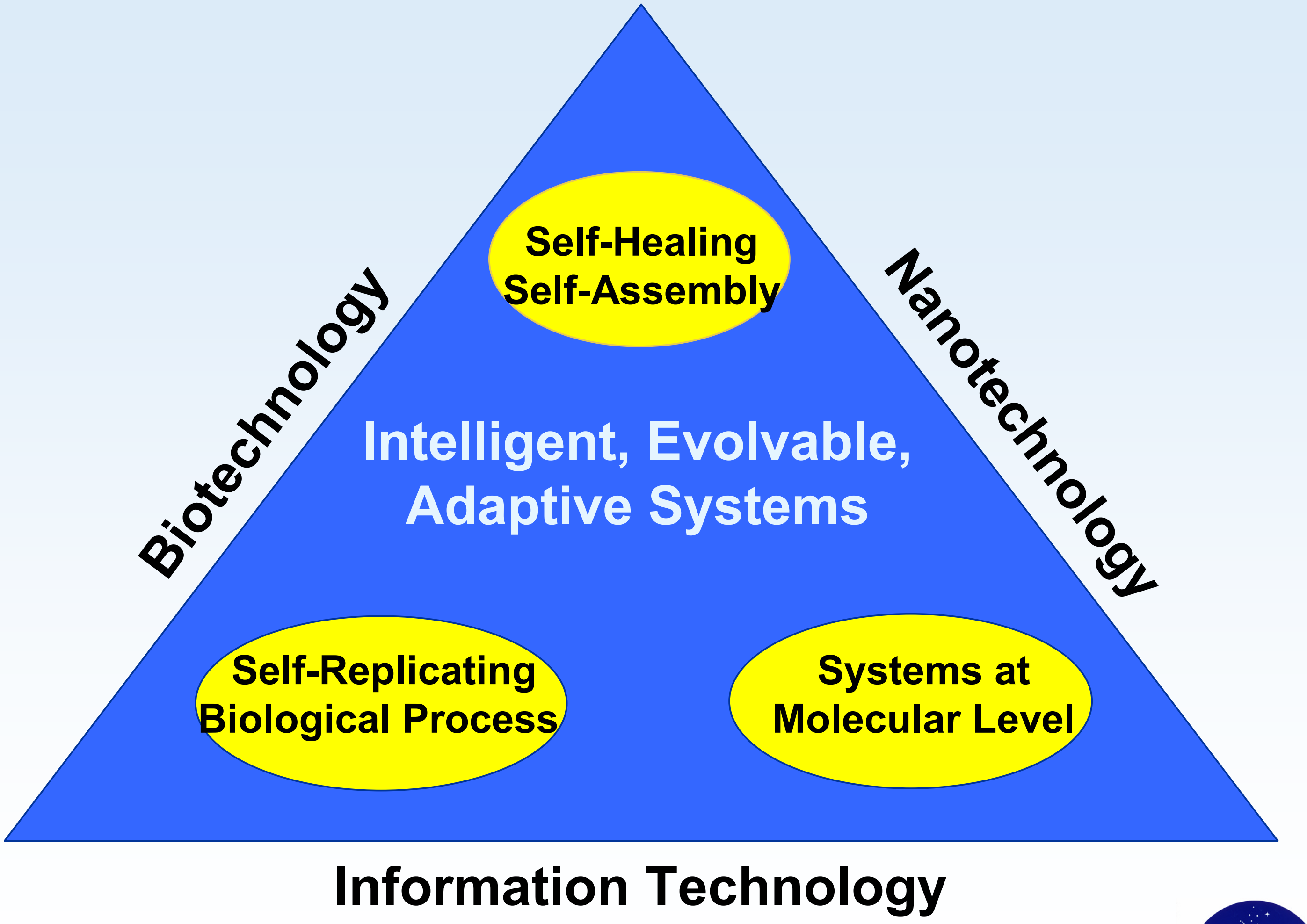
Sonic boom mitigation technologies

Biologically inspired structural concepts

Glenn Research Center

at Lewis Field

Revolutionary Technology Vision



Self-Healing
Self-Assembly

Biotechnology

Nanotechnology

Intelligent, Evolvable,
Adaptive Systems

Self-Replicating
Biological Process

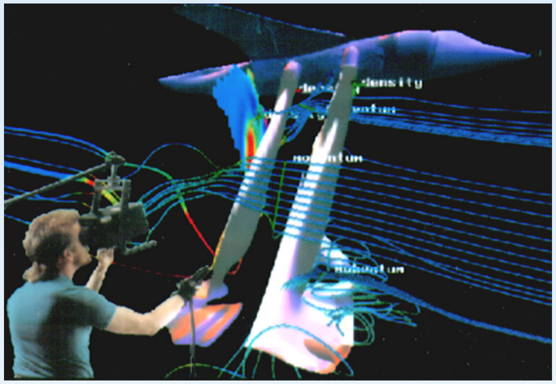
Systems at
Molecular Level

Information Technology

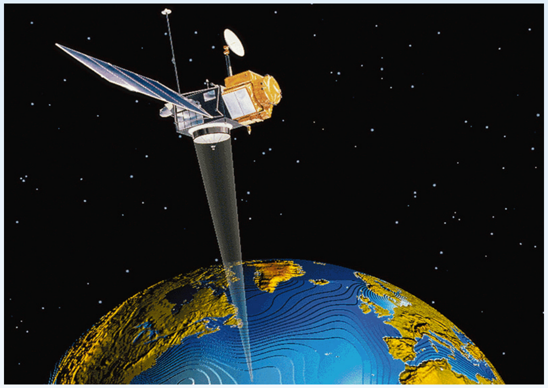
Glenn Research Center

at Lewis Field

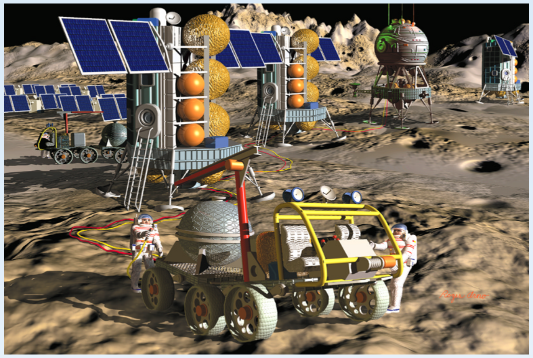
Information Technology



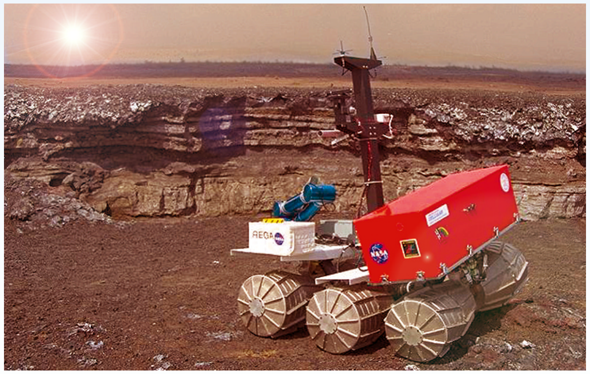
**Intelligent Design Synthesis
In the Virtual Environment**



Science Understanding



**Human Exploration
of Space**



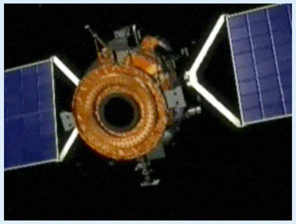
Robotic Exploration of Space

Aircraft Operations

Glenn Research Center

at Lewis Field

Intelligent Systems



Automated Reasoning

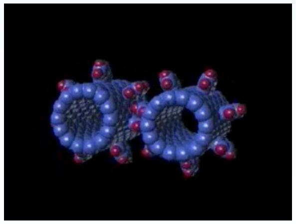
Systems that reliably make and execute decisions which traditionally require human intervention

Human Centered Computing

Tools that amplify both human and machine performance

Intelligent Data Understanding

Autonomous techniques that transform data into information, information into knowledge, and knowledge into understanding



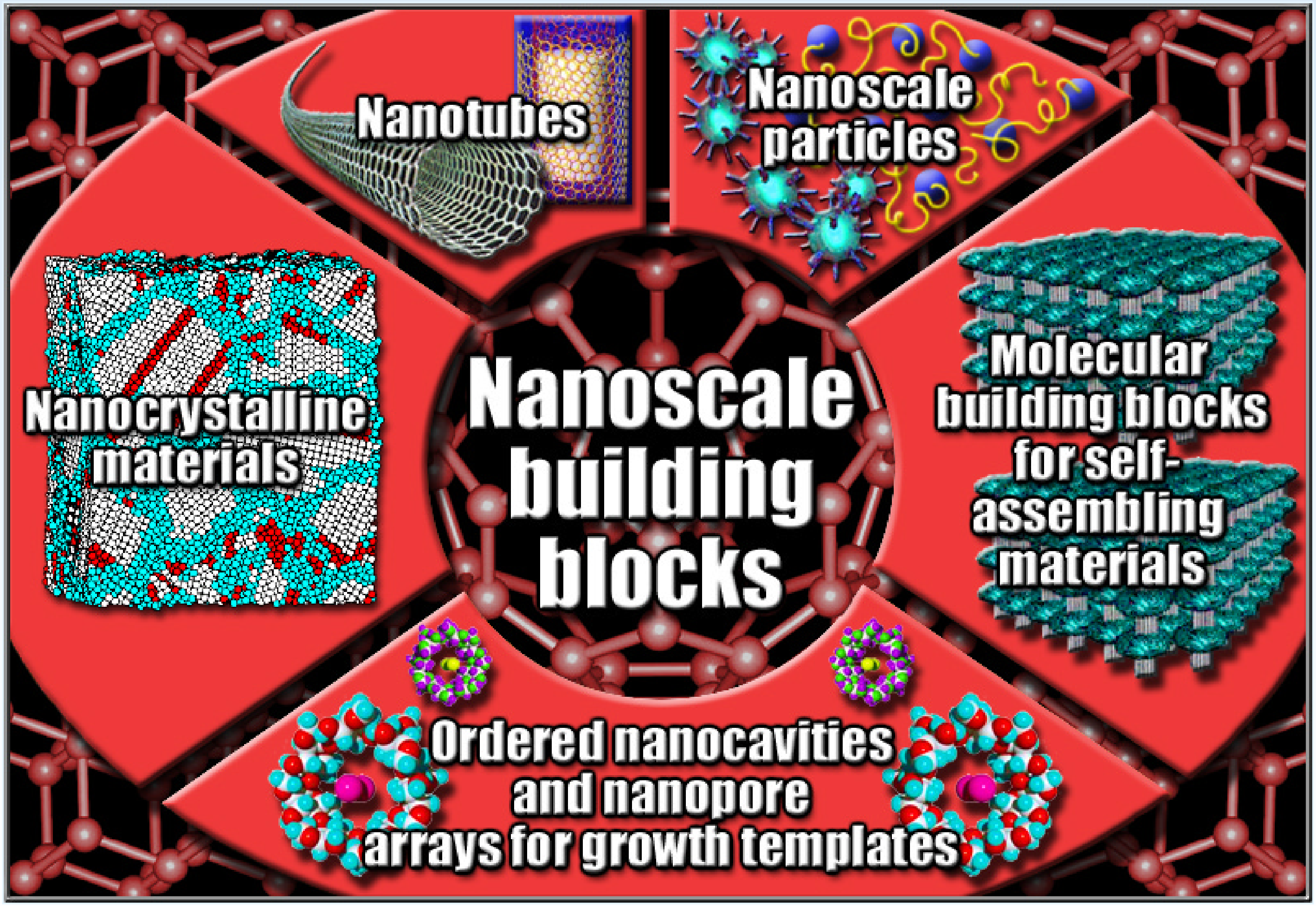
Revolutionary Computing

Advanced technologies that provide a platform for future Intelligent Systems

Glenn Research Center

at Lewis Field

Nanoscale Technologies

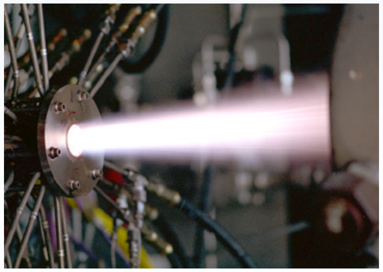


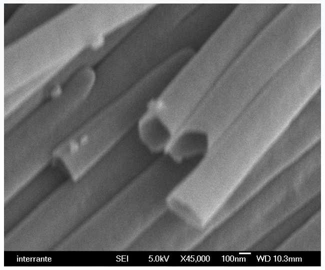
Glenn Research Center

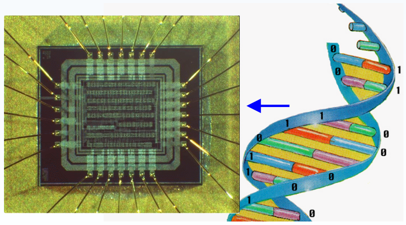
at Lewis Field

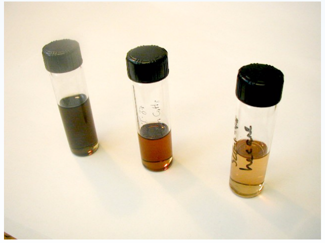
Nanotechnology Research for Propulsion & Power

- Materials 100x stronger than Steel
- Electronics processing 100x faster
- Fuel Cell with 10x greater power density
- In-vivo biosensors 1000X smaller





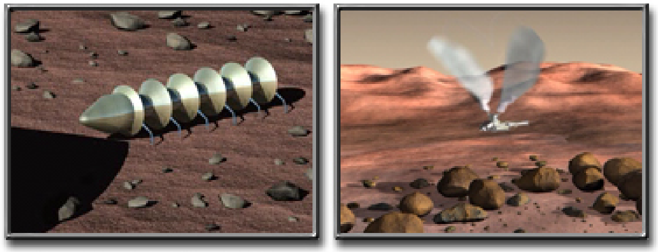




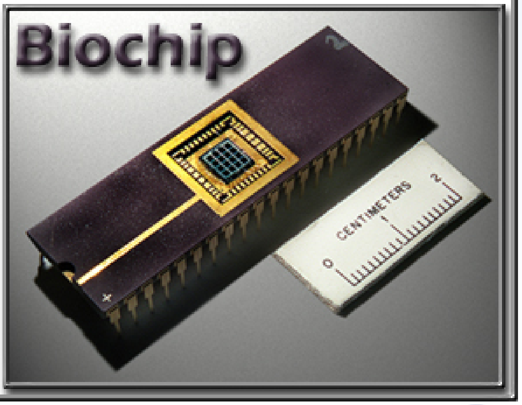
Glenn Research Center

at Lewis Field

Biotechnology Applications



- Mimic biological systems
- Embed biological elements to create hybrid systems (e.g., hybrid nanomechanical devices - integration of biological motors with NEMS)
- Create fully biological and life-like systems. Examples:
  - Embryological electronics, with reproduction, adaptation and evolution
  - Highly intelligent structures that design themselves

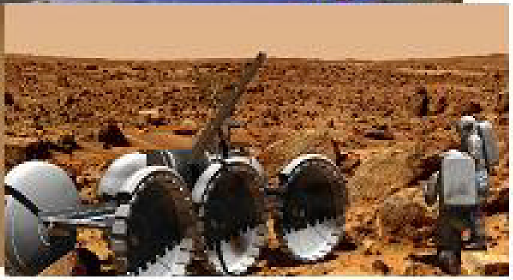


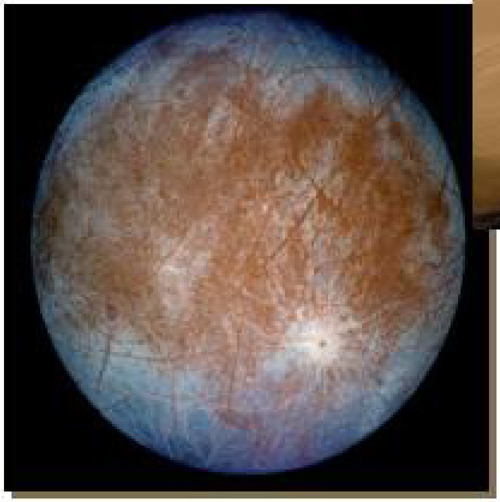
Glenn Research Center

at Lewis Field

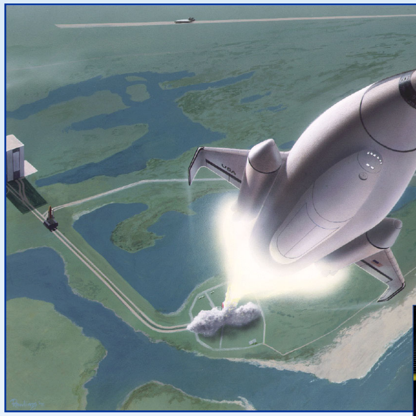
To Explore the Universe and Search for Life

- Exploring the Universe and the life within it… enabled by technology, first with robotic trailblazers, and eventually humans… as driven by these compelling scientific questions:
    - How did we get here?
    - Where are we going?
    - Are we alone?

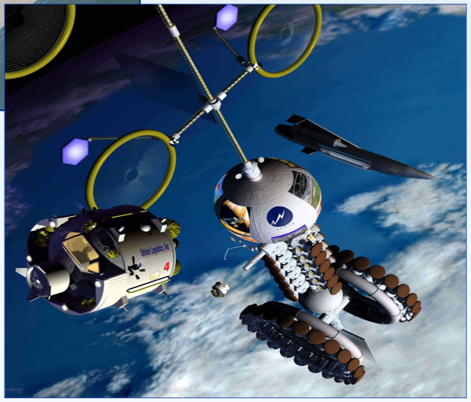




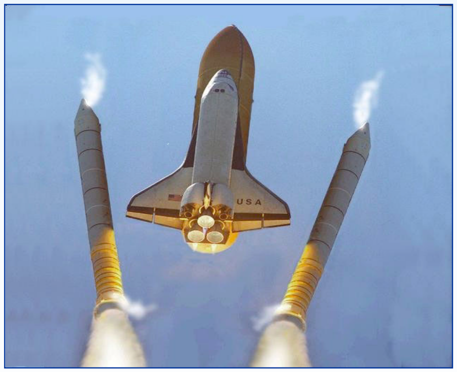
Integrated Space Transportation Plan



3rd Generation and In-Space Technologies



Risk Reduction for 2nd Generation RLV and NASA Unique Systems (Human-rated)

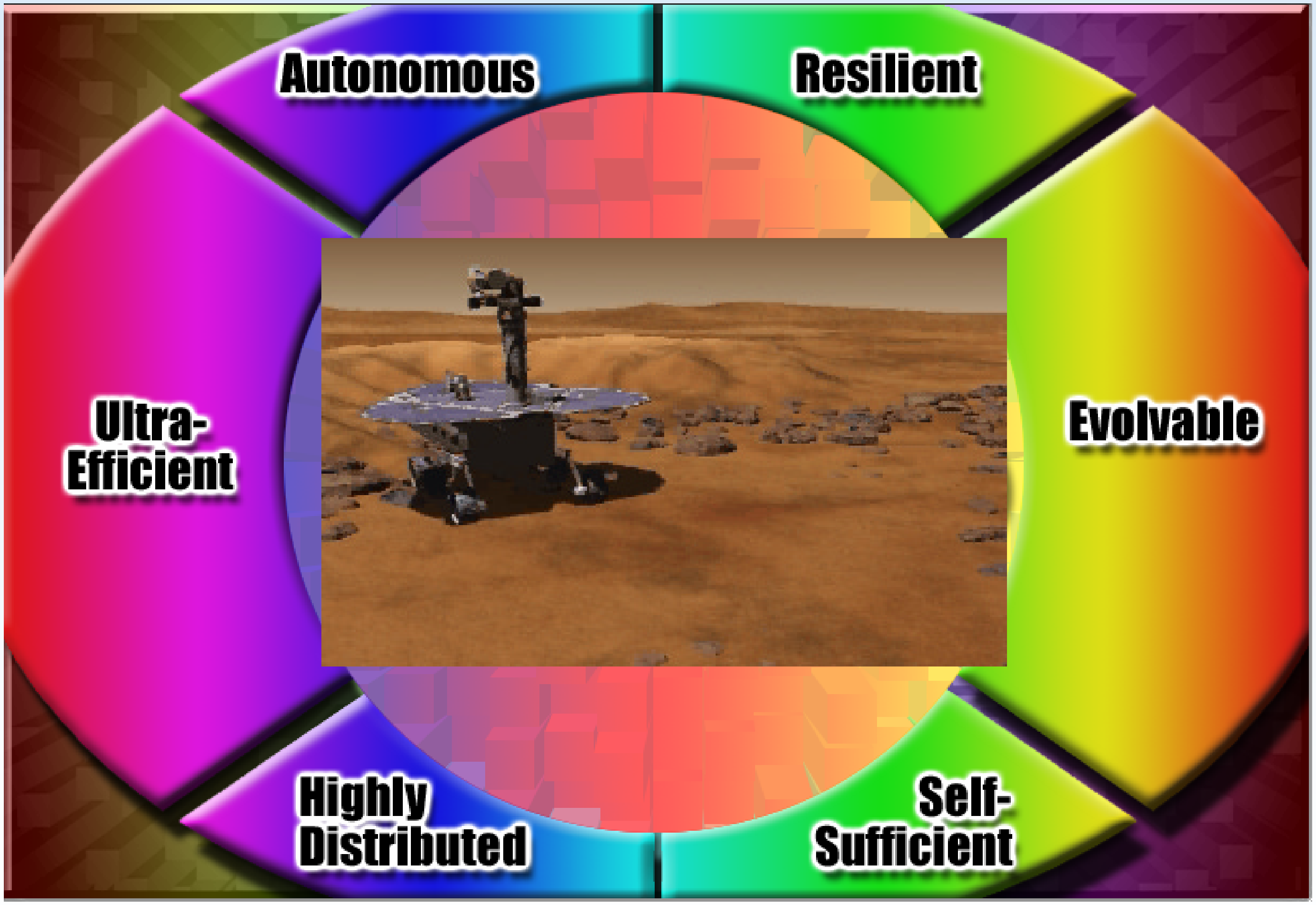


Space Shuttle Safety Upgrades (1st Generation RLV)

Glenn Research Center

at Lewis Field

Space Systems of the Future



Autonomous

Resilient

Ultra-
Efficient

Evolvable

Highly
Distributed

Self-
Sufficient

Glenn Research Center

at Lewis Field

To Inspire the Next Generation of Explorers

- Motivating students to pursue careers in science, math, and engineering
- Providing educators with unique teaching tools and compelling teaching experiences
- Improving our Nation's scientific literacy
- Engaging the public in shaping and sharing the experience of exploration and discovery

Educated Workforce–Approach to Education

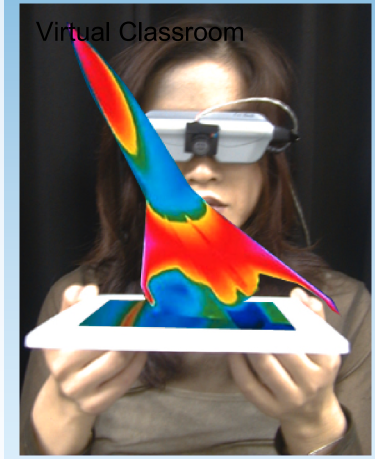
Today's Challenges:

- Raise the interest in science and engineering in elementary, middle, and high schools.
- Prepare future graduates for a world of rapid technological change, complex systems, and advancements around the world.
- Maintain the high-tech workforce on par with the continuously advancing state of technology.

Technology Solutions:


K-12 Engagement

- Foster interest and excitement in aerospace–establish an exciting vision for aeronautics


Virtual Classroom

- Stimulate curriculum change and virtual and collaborative learning environments that will enhance educational relevance and scope


Distributed Learning

- Create life-long learning system that links classrooms to laboratories and on-the-job experiences

Glenn Research Center

at Lewis Field

Conclusions

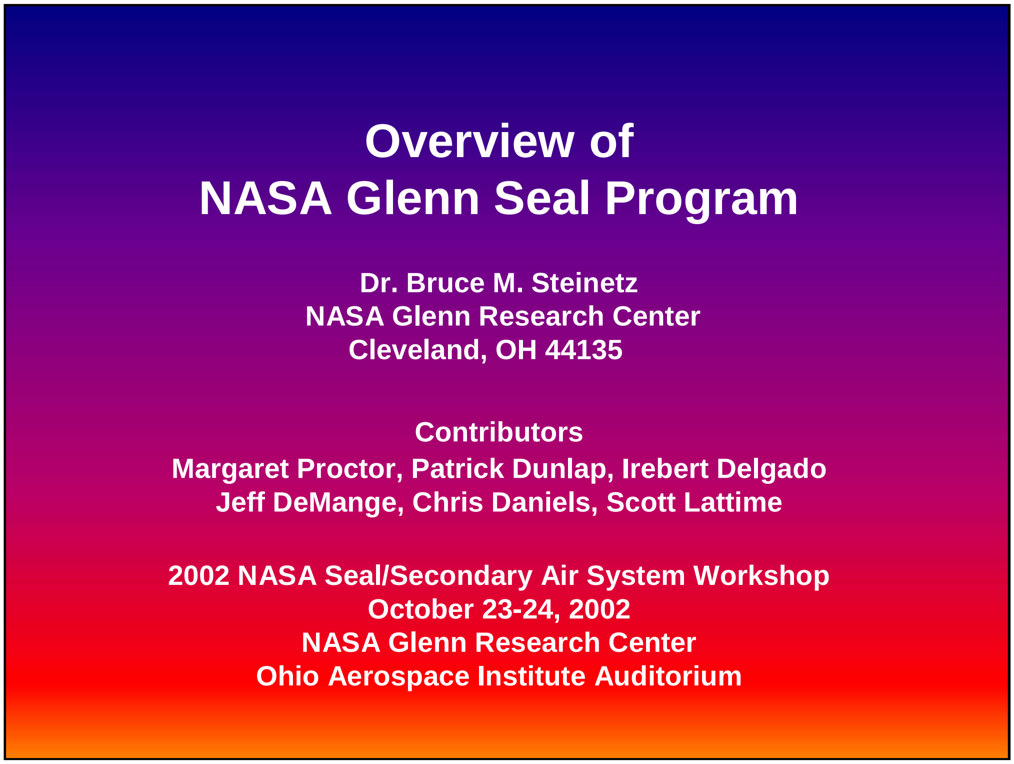
- Advanced technology is essential to the Nation's future
- NASA has established very challenging technology goals for meeting future challenges
- Innovative research programs are in place to help obtain those goals
- NASA plays a significant role in ensuring a well-trained technology workforce and is increasing its emphasis in this area

OVERVIEW OF NASA GLENN SEAL PROGRAM

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

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

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



Overview of
NASA Glenn Seal Program

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

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

2002 NASA Seal/Secondary Air System Workshop
October 23-24, 2002
NASA Glenn Research Center
Ohio Aerospace Institute Auditorium

NASA Glenn hosted the Seals/Secondary Air System Workshop on October 23-24, 2002. At this workshop 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 Export Administration Regulations (E.A.R.).

Workshop Agenda

Wednesday, Oct. 23, Morning

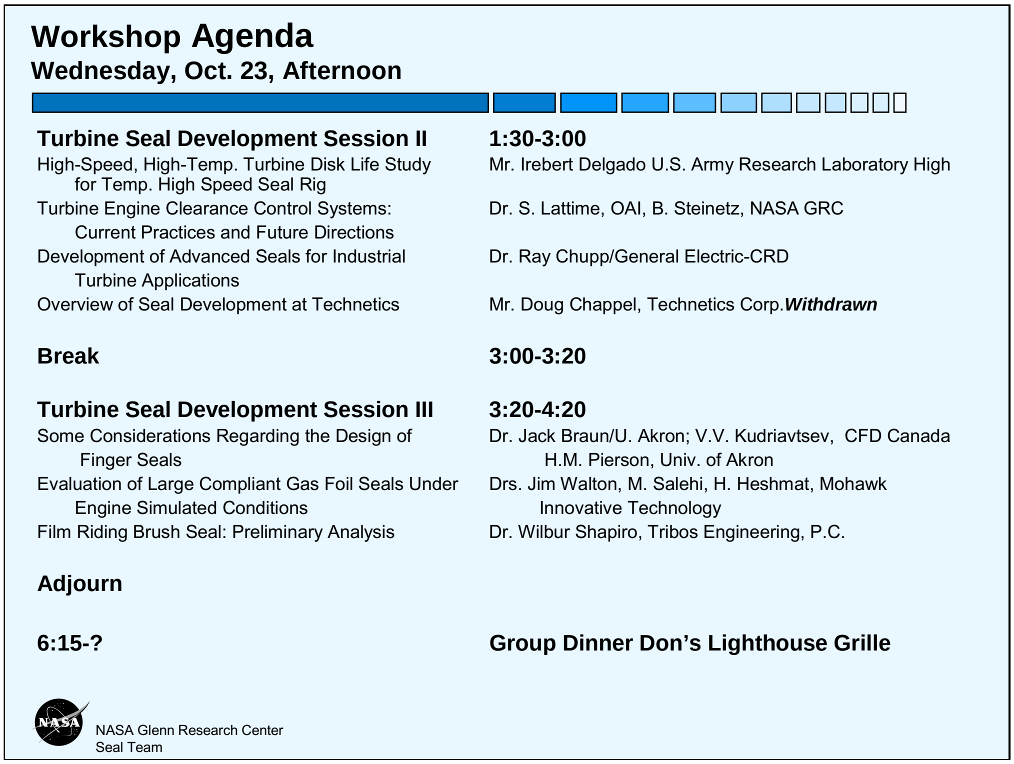
Registration	**8:00 a.m.–8:30 a.m.**
Introductions	**8:30 a.m.–9:30 a.m.**
Introduction	Dr. Bruce Steinetz, R. Hendricks/NASA GRC
Welcome to NASA Glenn	Mr. Donald Campbell, Director, NASA GRC
NASA Technology Requirements	Dr. Woodrow Whitlow, Director of R&T at NASA GRC
Overview of NASA Glenn Seal Program	Dr. Bruce Steinetz/NASA GRC
Program Overviews and Requirements	**9:30 a.m.–11:00 a.m.**
Air Force Turbine Engine Development + Seal Needs	Dr, Lewis Rosado, WPAFB
Overview of NASA's UEET and TBCC/RTA Programs	Dr. Joe Shaw, C. Peddie/NASA GRC
Overview of NASA's Access to Space Programs	Mr. Harry Cikanek/NASA GRC
Revolutionary Turbine Accelerator (RTA) Engine Dev.	Dr. Ken Suder, Paul Bartolotta, N. McNelis/NASA GRC
Break	**11:00-11:15**
Turbine Seal Development Session I	**11:15-12:15**
Overview of Aspirating Seal Final Preparations for GE90 Test	Ms. Marcia Boyle, B. Albers; GE Aircraft Engines
Foil Face Seal Proof-of-Concept Demo. Testing	Mr. John Munson, Rolls Royce Allison ***Withdrawn*** Mr. Darrell Grant, Navy; Dr. Giri Agrawal, R&D Dynamics
Overview of Turbine Seal Testing at GRC	Ms. M.P. Proctor, NASA GRC; I.R. Delgado, US Army Research Lab
Lunch OAI Sun Room	**12:30-1:30**

NASA Glenn Research Center
Seal Team

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

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

Dr. Steinetz presented an overview of the NASA seal development program. Representatives from GE provided insight into their advanced seal development program. Ms. Proctor of NASA Glenn presented an overview of turbine testing at NASA GRC.



Workshop Agenda

Wednesday, Oct. 23, Afternoon

Turbine Seal Development Session II	**1:30-3:00**
High-Speed, High-Temp. Turbine Disk Life Study for Temp. High Speed Seal Rig	Mr. Irebert Delgado U.S. Army Research Laboratory High
Turbine Engine Clearance Control Systems: Current Practices and Future Directions	Dr. S. Lattime, OAI, B. Steinetz, NASA GRC
Development of Advanced Seals for Industrial Turbine Applications	Dr. Ray Chupp/General Electric-CRD
Overview of Seal Development at Technetics	Mr. Doug Chappel, Technetics Corp.***Withdrawn***
Break	**3:00-3:20**
Turbine Seal Development Session III	**3:20-4:20**
Some Considerations Regarding the Design of Finger Seals	Dr. Jack Braun/U. Akron; V.V. Kudriavtsev, CFD Canada H.M. Pierson, Univ. of Akron
Evaluation of Large Compliant Gas Foil Seals Under Engine Simulated Conditions	Drs. Jim Walton, M. Salehi, H. Heshmat, Mohawk Innovative Technology
Film Riding Brush Seal: Preliminary Analysis	Dr. Wilbur Shapiro, Tribos Engineering, P.C.
Adjourn	
6:15-?	**Group Dinner Don’s Lighthouse Grille**

NASA Glenn Research Center
Seal Team

Mr. Delgado presented results of fatigue life and crack growth tests performed on material taken from a test rotor of the high speed seal test rig. Dr. Lattime gave an overview of current practices and future directions in turbine tip clearance control systems. Dr. Chupp of GE-Global Research Center (formerly GE-Corporate Research Center) presented industrial turbine seal developments.

Dr. Braun presented preliminary investigations into metallic non-contacting finger seals. Dr. Walton of Mohawk Innovative Technology presented their company’s progress in developing and assessing a new compliant foil seal. Dr. Shapiro presented a preliminary analysis performed on a film-riding brush seal concept.

Workshop Agenda

Thursday, Oct. 24, Morning

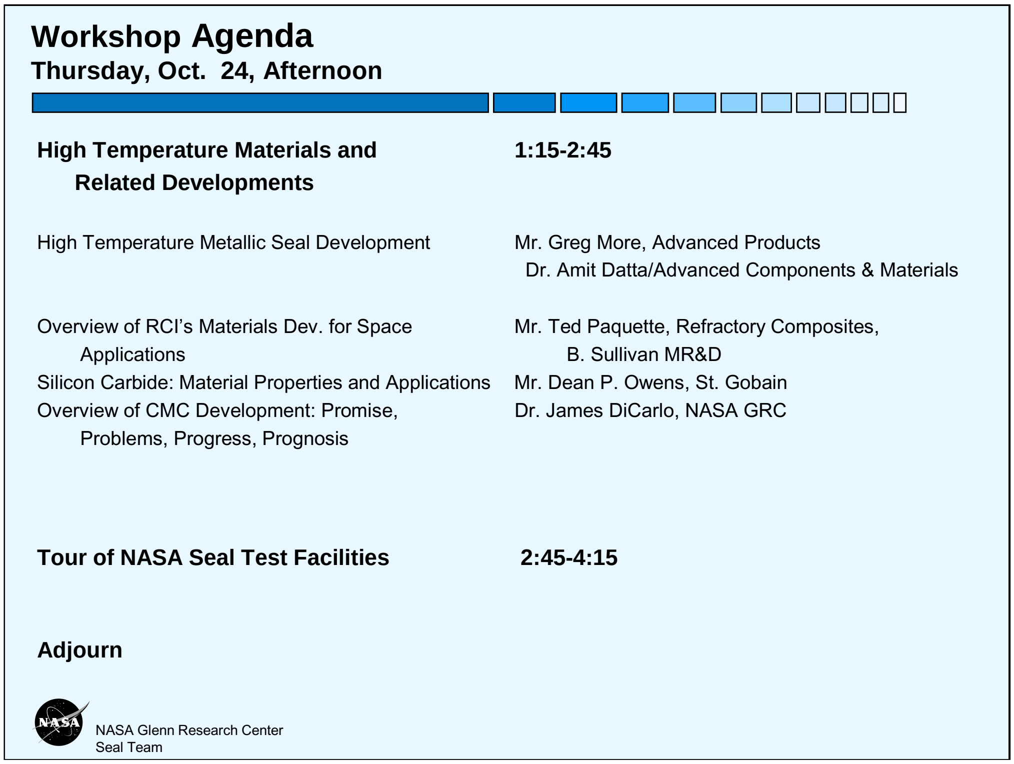
Registration at OAI	**8:00-8:30**
Space Vehicle Development	**8:30-9:45**
Overview of Air Force Space Operations Vehicle Development Plans	Dr. Jeff Zweber, Space Operations Vehicle, WPAFB
Overview of Boeing Advanced Space Vehicles and Seal Needs	Dr. Todd Steyer, Boeing Space and Comm.
Overview of ISTAR Engine Dev. and Seal Needs	Mr. Ravi Nigam, R. Kreidler, P&W
Break	**9:45 -10:00**
Structural Seal Development	**10:00-12:15**
3rd Generation RLV Structural Seal Dev. Program	Mr. Pat Dunlap, B. Steinetz/NASA GRC
Develop. and Capabilities of Unique Structural Seal Test Rigs	Mr. Jeff DeMange/OAI; P. Dunlap, B. Steinetz/NASA GRC
CFD Analyses of ISTAR Engine Seals	Mr. Alton Reich, M. Athavale/CFD-RC, R. Kreidler P&W P. Dunlap, B. Steinetz/NASA GRC
Atlas V SRM Gap Analysis with Carbon Fiber Rope	Dr. Gary Luke, Aerojet, Mr. Bob Prozan, CEA
Overview of Seal Development at Albany-Techniweave	Mr. Bruce Bond/Albany Techniweave
Lunch OAI Sun Room	**12:15-1:15**

NASA Glenn Research Center
Seal Team

Dr. Zweber presented an Overview of the Air Force’s Space Operations Vehicle. Dr. Steyer of Boeing Space and Communications presented Boeing’s plans for future space vehicles and seal lesson’s learned from the Shuttle Orbiter.

NASA is investigating hybrid rocket/air-breathing systems to increase propulsion system specific impulse. Mr. Nigam presented an overview of the ISTAR (Integrated System Test of an Air-breathing Rocket) program and engine seal challenges. Mr. Reich presented plans for CFD/thermal analyses of the ISTAR engine ramp seals. Mr. Dunlap and Mr. DeMange presented overviews of NASA Glenn’s 3rd generation RLV structural seal development program and unique test rigs under development, respectively.

Dr. Luke and Mr. Prozan presented results of a program investigating the feasibility of using the GRC-developed thermal barrier in the nozzle joint of the solid rocket motors for the Atlas 5 Rocket. Mr. Bond presented an overview of the seal developments at Albany-Techniweave.



Workshop Agenda

Thursday, Oct. 24, Afternoon

High Temperature Materials and Related Developments	**1:15-2:45**
High Temperature Metallic Seal Development	Mr. Greg More, Advanced Products Dr. Amit Datta/Advanced Components & Materials
Overview of RCI's Materials Dev. for Space Applications	Mr. Ted Paquette, Refractory Composites, B. Sullivan MR&D
Silicon Carbide: Material Properties and Applications	Mr. Dean P. Owens, St. Gobain
Overview of CMC Development: Promise, Problems, Progress, Prognosis	Dr. James DiCarlo, NASA GRC
Tour of NASA Seal Test Facilities	**2:45-4:15**
Adjourn	

NASA Glenn Research Center
Seal Team

Advanced structural seals require application of advanced high temperature materials. The closing session of the conference presented seal concepts and materials being developed at several locations. Mr. More (Advanced Products) and Dr. Datta (Advanced Components and Materials) presented an overview of the high temperature metallic seal development. Mr. Paquette presented an Overview of Refractory Composites Co. materials development for space applications including development of an advanced composite (hot-structure) control surface for a future re-usable launch vehicle.

Mr. Owens described silicon carbide developments at St. Gobain, Niagra Falls, NY.
Dr. DiCarlo of NASA GRC provided an overview of ceramic matrix composites development: promise, problems, progress and prognosis.

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

Structural Seal Development
Principal Investigator: **Pat Dunlap**
Sr. Researcher: **Jeff DeMange**
Design Eng: **Dan Breen**

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

Acoustic Seal Development
Principal Investigators: **Chris Daniels/B. Steinetz**

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

Adaptive Seal Development
Principal Investigators: **Scott Lattime/B. Steinetz**

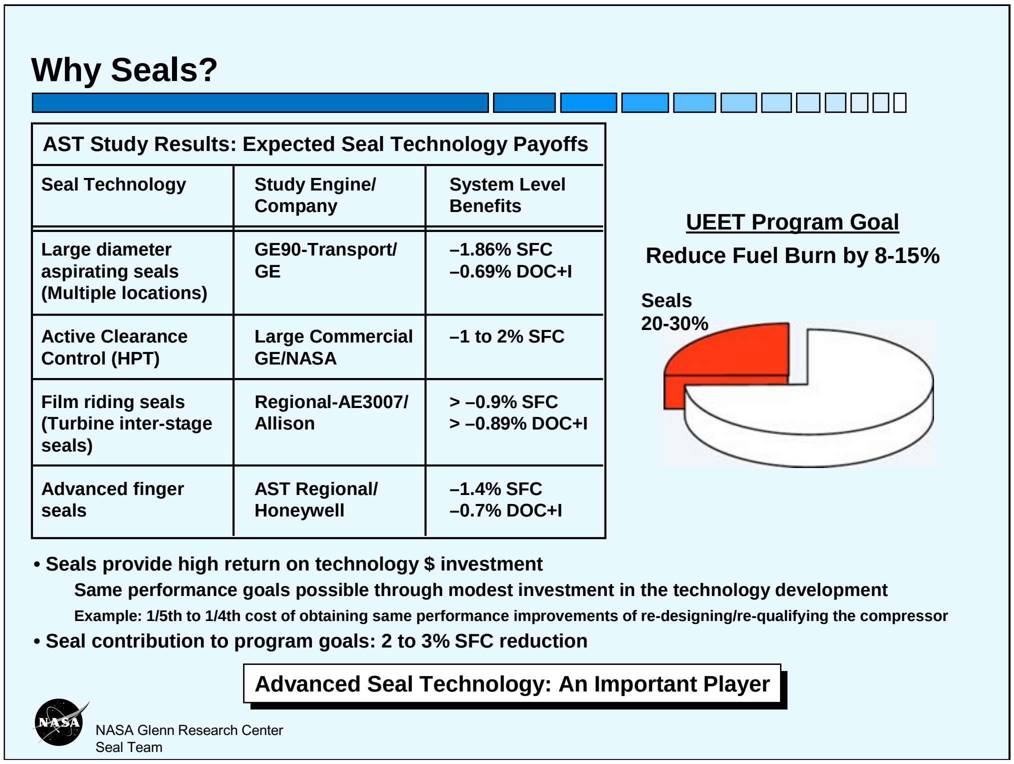
Develop novel adaptive blade-tip/inter-stage seals

NASA Glenn Research Center
Seal Team

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.

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 acoustic standing pressure waves to form an effective air-barrier/seal.

Our goal in the adaptive seal 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.



Why Seals?

AST Study Results: Expected Seal Technology Payoffs

Seal Technology	Study Engine/ Company	System Level Benefits
Large diameter aspirating seals (Multiple locations)	GE90-Transport/ GE	–1.86% SFC –0.69% DOC+I
Active Clearance Control (HPT)	Large Commercial GE/NASA	–1 to 2% SFC
Film riding seals (Turbine inter-stage seals)	Regional-AE3007/ Allison	> –0.9% SFC > –0.89% DOC+I
Advanced finger seals	AST Regional/ Honeywell	–1.4% SFC –0.7% DOC+I

UEET Program Goal

Reduce Fuel Burn by 8-15%

- Seals provide high return on technology $ investment
  - Same performance goals possible through modest investment in the technology development
  - Example: 1/5th 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

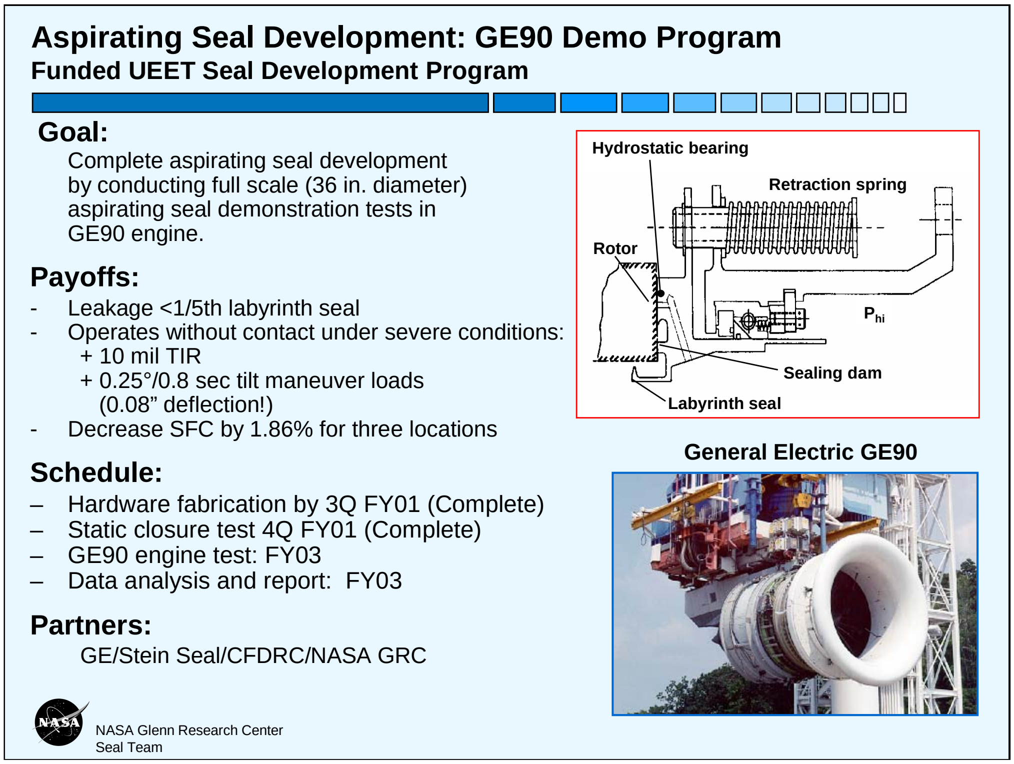
Advanced Seal Technology: An Important Player

NASA Glenn Research Center
Seal Team

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 2 or 3 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:

- Hardware fabrication by 3Q FY01 (Complete)
- Static closure test 4Q FY01 (Complete)
- GE90 engine test: FY03
- Data analysis and report: FY03

Partners:

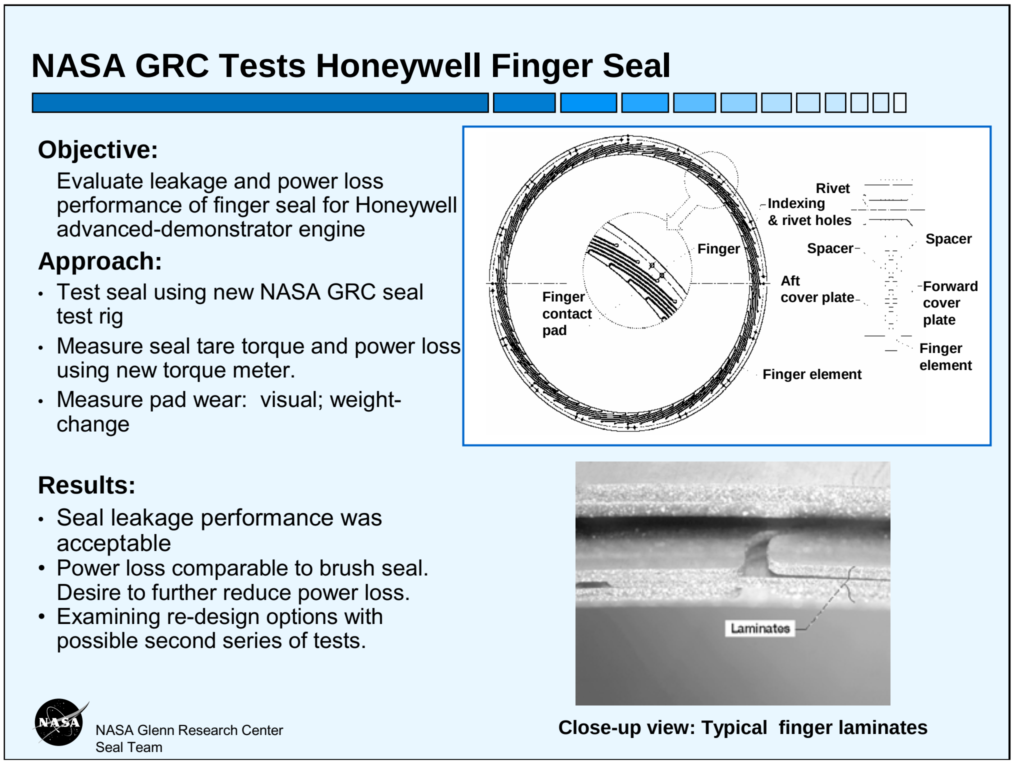
GE/Stein Seal/CFDRC/NASA GRC

General Electric GE90

NASA Glenn Research Center
Seal Team

General Electric is developing a low leakage aspirating face seal for a number of locations within modern turbine applications. This seal shows promise both for compressor discharge and balance piston locations.

The seal consists of an axially translating mechanical face that seals the face of a high speed rotor. The face rides on a hydrostatic cushion of air supplied through ports on the seal face connected to the high pressure side of the seal. The small clearance (0.001-0.002 in.) between the seal and rotor results in low leakage (1/5th 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. More details can be found in Boyle and Albers, 2003 in this Seal Workshop Proceedings and Turnquist, et al 1999. The NASA GRC Ultra Efficient Engine Technology (UEET) Program is funding GE to demonstrate this seal in a ground-based GE-90 demonstrator engine in 2003.



NASA GRC Tests Honeywell Finger Seal

Objective:

Evaluate leakage and power loss performance of finger seal for Honeywell advanced-demonstrator engine

Approach:

- Test seal using new NASA GRC seal test rig
- Measure seal tare torque and power loss using new torque meter.
- Measure pad wear: visual; weight-change

Results:

- Seal leakage performance was acceptable
- Power loss comparable to brush seal. Desire to further reduce power loss.
- Examining re-design options with possible second series of tests.

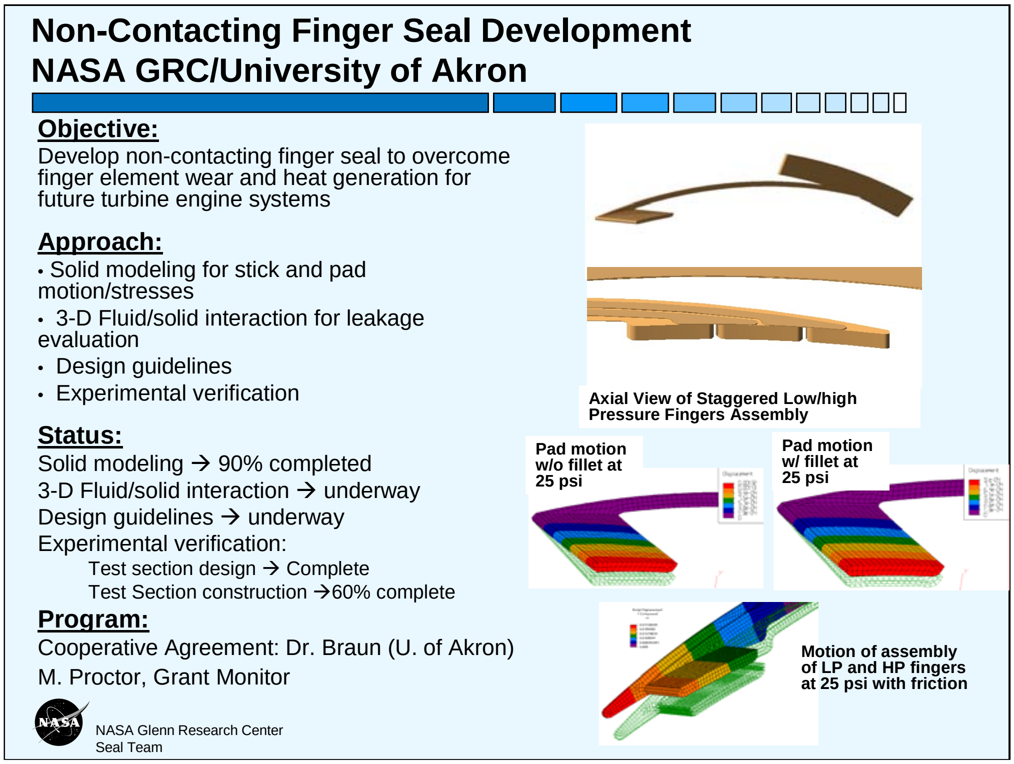
Close-up view: Typical finger laminates

NASA Glenn Research Center
Seal Team

NASA GRC recently completed a series of tests to evaluate the performance of a finger seal being considered by Honeywell for an advanced demonstrator-engine.

Finger seals are constructed of a series of laminates deriving radial flexibility through slots between adjacent fingers. Several laminates are stacked on top of each other and indexed so as to block the flow through successive laminates. Finger seals exhibit low leakage comparable to brush seals but can be produced at a fraction of the cost of brush seals.

The NASA GRC tests showed the seal exhibited acceptable leakage. The measured seal power loss was acceptable for certain applications but was high for other applications. For further details, please see Proctor et al, 2002 and Proctor et al, 2003 in this Seal Workshop Proceedings.



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

Objective:

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

Approach:

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

Status:

Solid modeling → 90% completed
3-D Fluid/solid interaction → underway
Design guidelines → underway
Experimental verification:
    Test section design → Complete
    Test Section construction →60% complete

Program:

Cooperative Agreement: Dr. Braun (U. of Akron)
M. Proctor, Grant Monitor

Axial View of Staggered Low/high Pressure Fingers Assembly

Pad motion w/o fillet at 25 psi

Pad motion w/ fillet at 25 psi

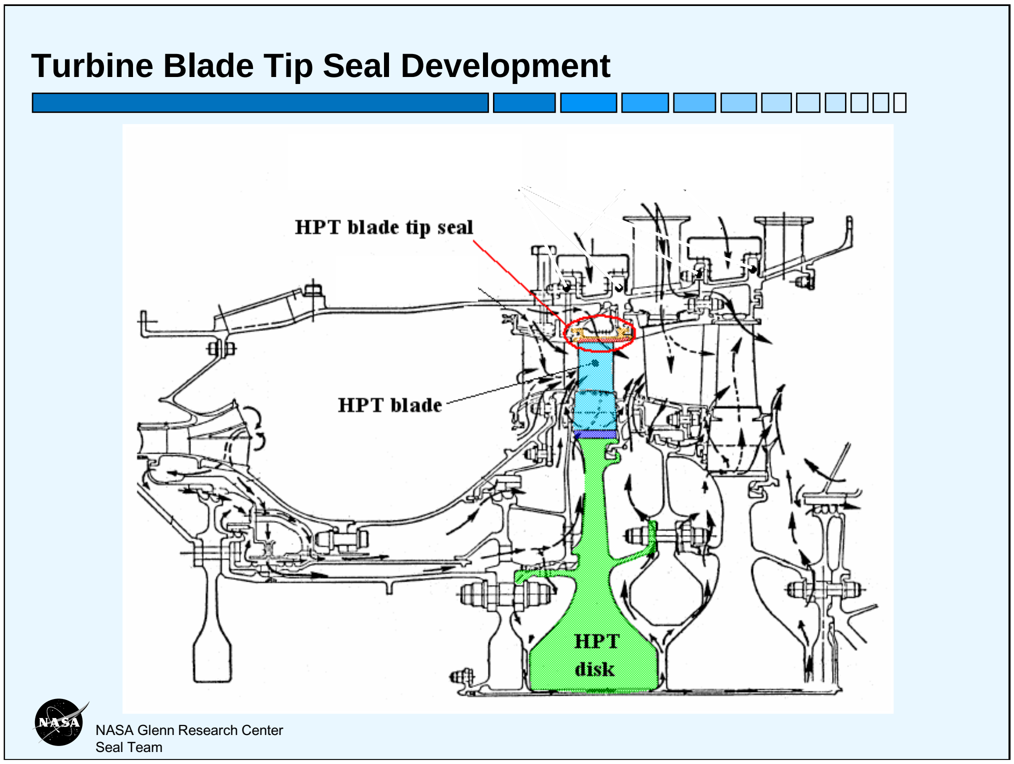
Motion of assembly of LP and HP fingers at 25 psi with friction

NASA Glenn Research Center
Seal Team

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

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

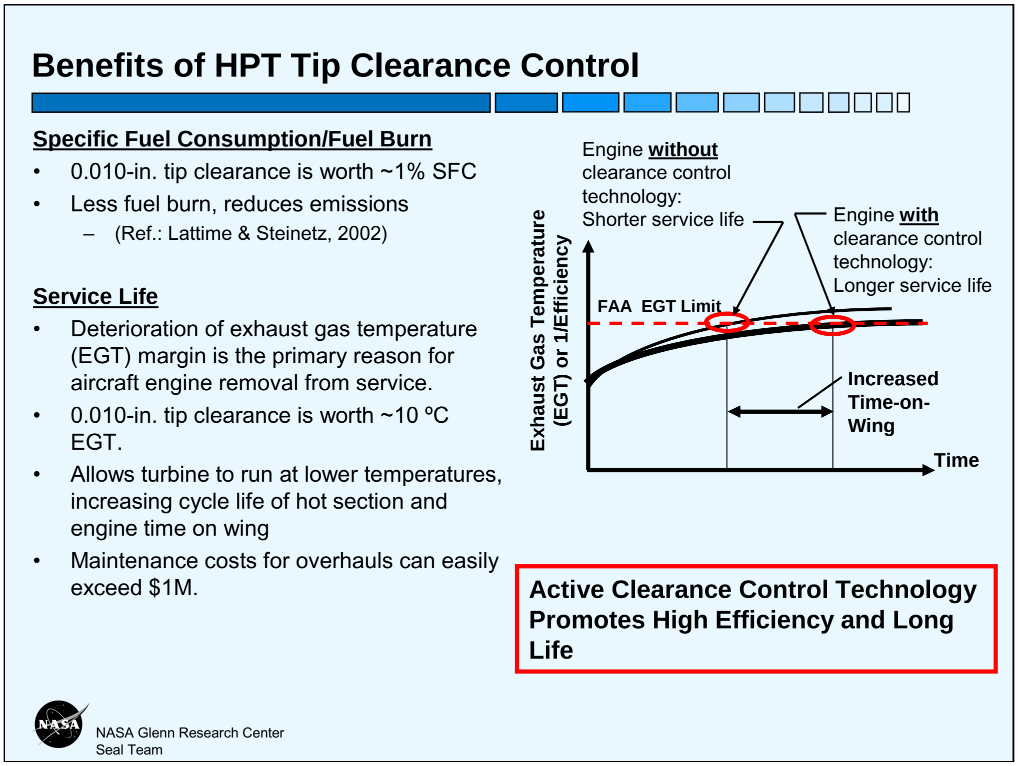
Through a grant with University of Akron, NASA Glenn is working with Dr. J. Braun of University of Akron to perform analyses and tests of this GRC concept. Preliminary finite element analysis results of the finger movements subjected to various pressures are shown. More details can be found in Braun et al, 2003 in this Seal Workshop Proceedings.



Turbine Blade Tip Seal Development

NASA Glenn Research Center
Seal Team

Current commercial jet engines control the high pressure turbine (HPT) blade tip clearances using active thermal control. Based on a model based schedule involving a variety of engine operating parameters (e.g. RPM, temperatures, pressures, etc) air is directed to cool the HPT case structure and keep cruise clearances at their minimum practical level. Though effective for current engines, future engines require tighter, faster control to improve turbine stage efficiency, to delay or slow the growth of exhaust gas temperature (EGT), and increase engine time-on-wing.



Benefits of HPT Tip Clearance Control

Specific Fuel Consumption/Fuel Burn

- 0.010-in. tip clearance is worth ~1% SFC
- Less fuel burn, reduces emissions
  - (Ref.: Lattime & Steinetz, 2002)

Service Life

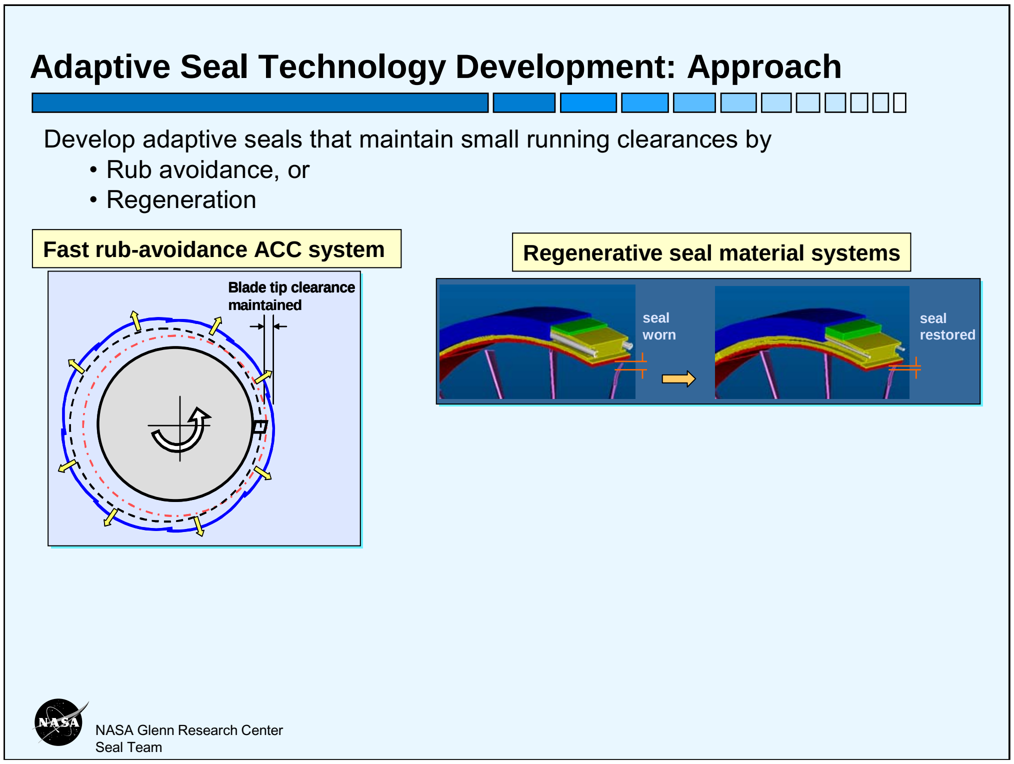
- Deterioration of exhaust gas temperature (EGT) margin is the primary reason for aircraft engine removal from service.
- 0.010-in. tip clearance is worth ~10 ºC EGT.
- Allows turbine to run at lower temperatures, increasing cycle life of hot section and engine time on wing
- Maintenance costs for overhauls can easily exceed $1M.

Active Clearance Control Technology Promotes High Efficiency and Long Life

NASA Glenn Research Center
Seal Team

Blade tip clearance opening is a primary reason for turbine engines reaching their FAA certified exhaust gas temperature (EGT) limit and subsequent required refurbishment. NASA GRC has embarked on a program to overcome or greatly mitigate this clearance opening problem.

Benefits of clearance control in the turbine section include retained EGT margins, 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.



Adaptive Seal Technology Development: Approach

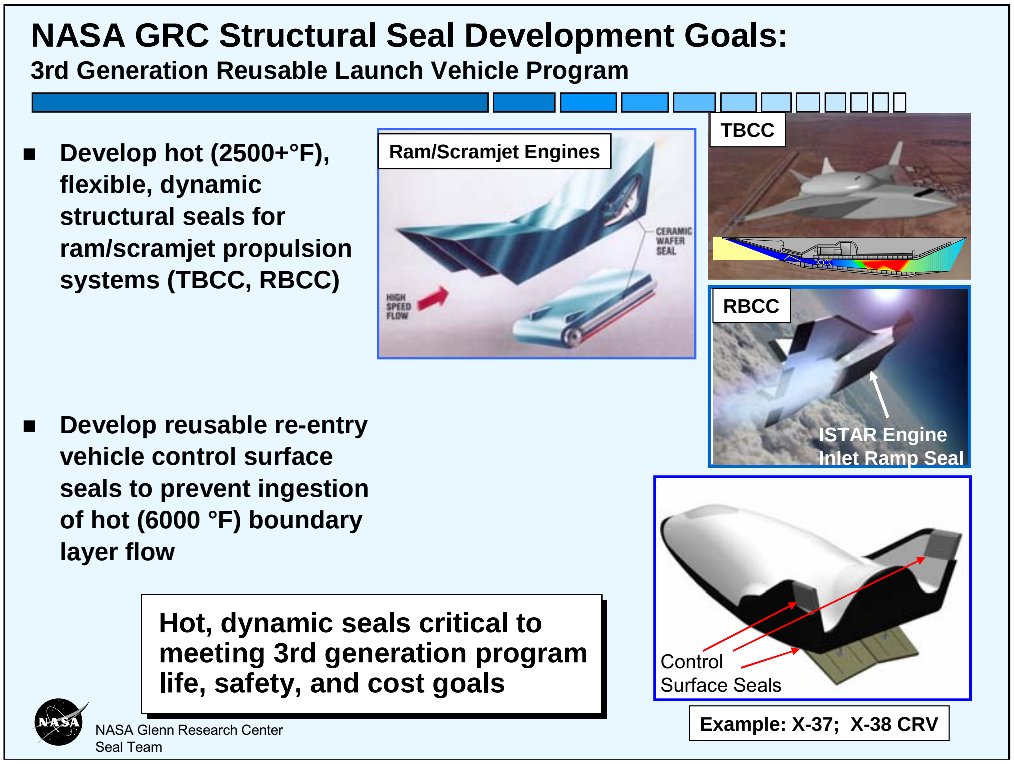
Develop adaptive seals that maintain small running clearances by
- Rub avoidance, or
- Regeneration

Fast rub-avoidance ACC system

Regenerative seal material systems

NASA Glenn Research Center
Seal Team

NASA Glenn is pursuing two approaches. The first is rub-avoidance in which an active clearance control system would actively move the seal segments out of the way during the transient event to avoid blade rubs. 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 using specially engineered materials. More details regarding this program can be found in Lattime and Steinetz 2003 in this Seal Workshop Proceedings, and Lattime and Steinetz, 2002.



NASA GRC Structural Seal Development Goals:

3rd Generation Reusable Launch Vehicle Program

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

Ram/Scramjet Engines

TBCC

RBCC

ISTAR Engine Inlet Ramp Seal

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

Control Surface Seals

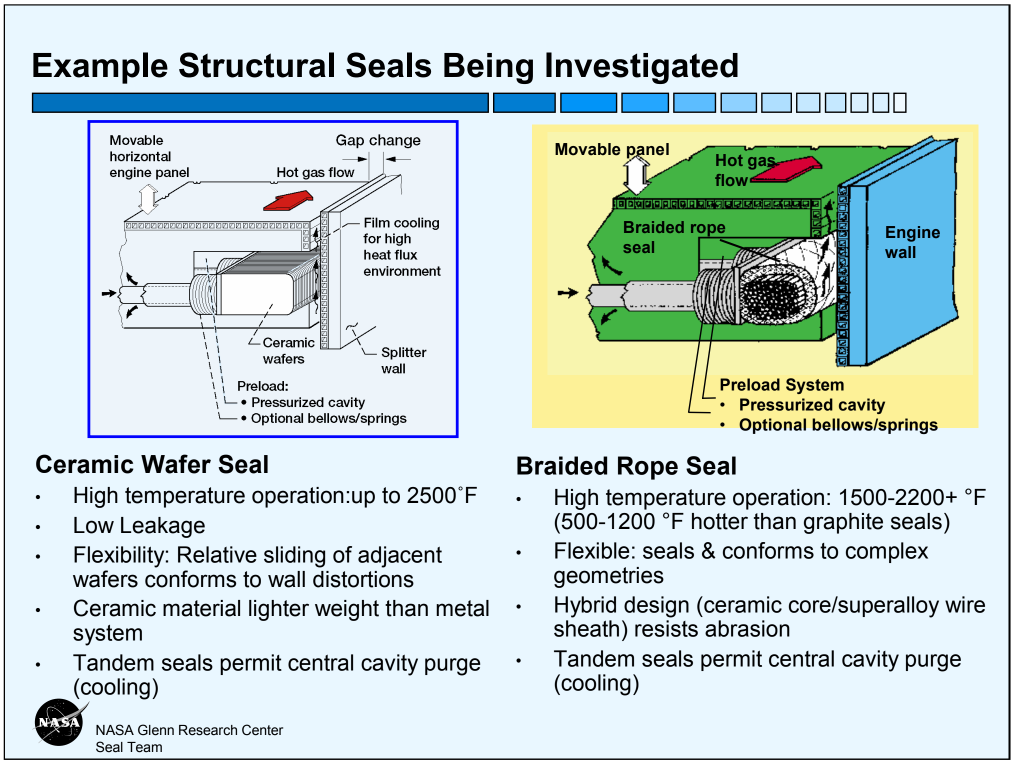
Example: X-37; X-38 CRV

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

NASA Glenn Research Center
Seal Team

NASA is currently funding research on advanced technologies that could greatly increase the reusability, safety, and performance of future Reusable Launch Vehicles (RLV). Research work is being performed under NASA's 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 propulsion and vehicle needs by applying advanced design concepts made from emerging high temperature ceramic materials and testing them in advanced test rigs that are under development. See Dunlap, et al, 2003 in this Seal Workshop Proceedings for further details.



Example Structural Seals Being Investigated

Ceramic Wafer Seal

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

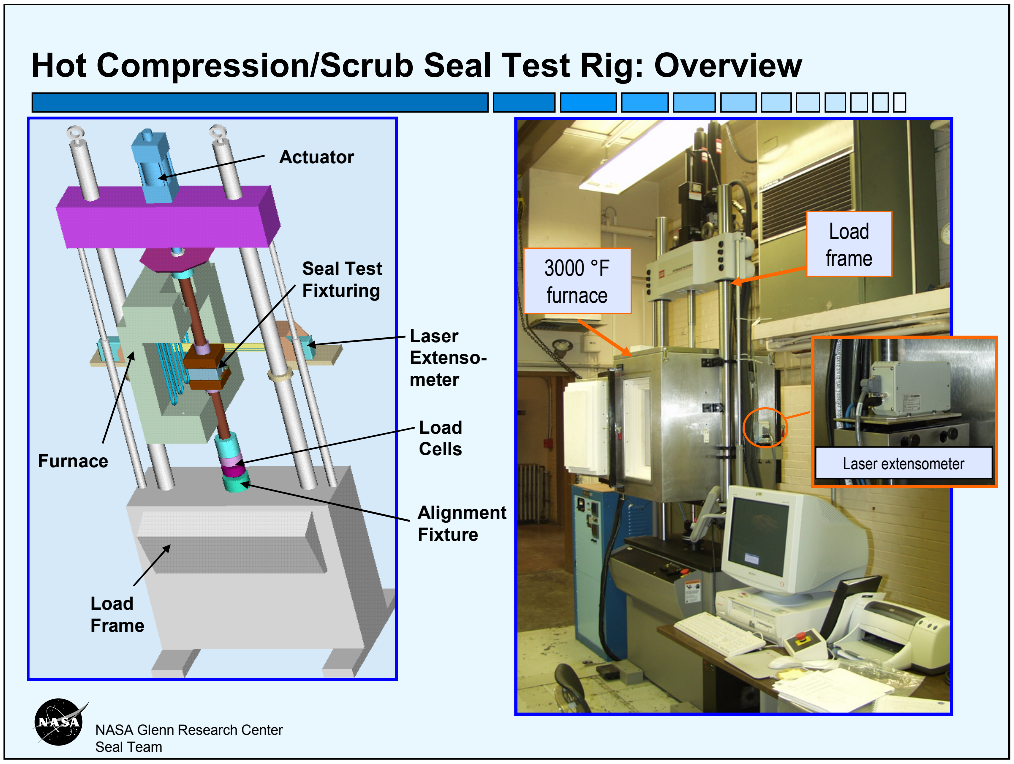
Braided Rope Seal

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

NASA Glenn Research Center
Seal Team

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

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

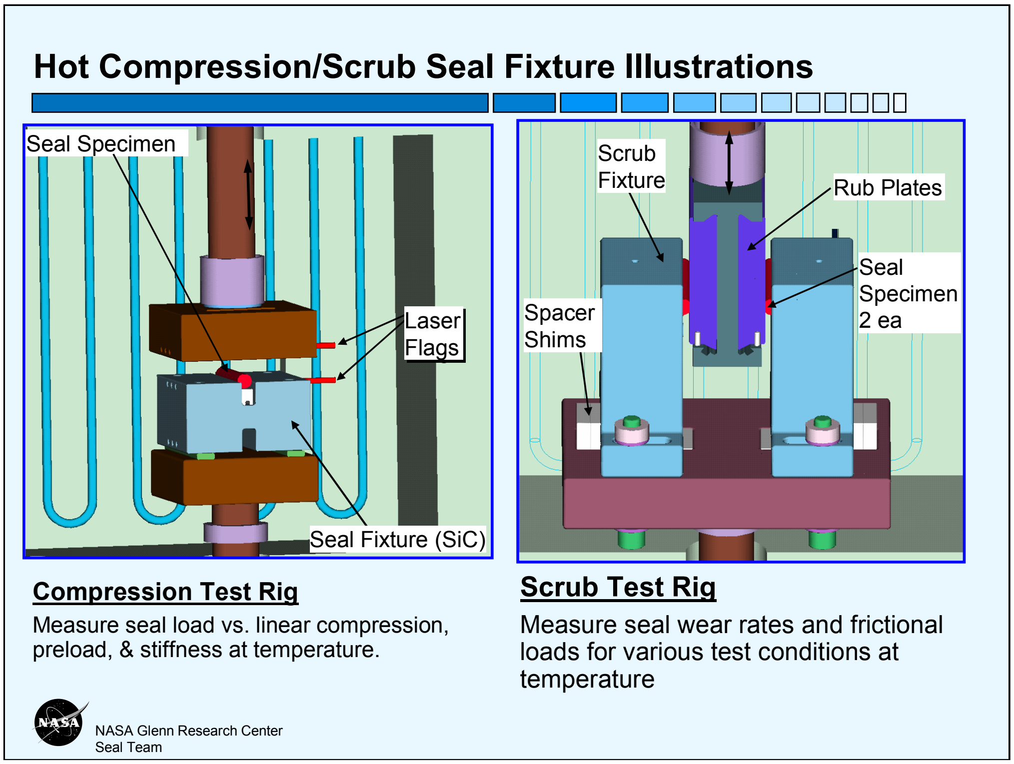


Hot Compression/Scrub Seal Test Rig: Overview

NASA Glenn Research Center
Seal Team

One of the rigs that NASA Glenn Research Center is assembling for the structural seals area consists 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 permit independent (i.e. non-simultaneous) testing of both seal resiliency characteristics (compression test) and seal wear performance (scrub test) 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.

As shown in the photograph on the right, the load frame, furnace, laser extensometer, data system and considerable test fixture hardware has been delivered. We are currently assembling elements together and performing initial check-out tests.



Hot Compression/Scrub Seal Fixture Illustrations

Compression Test Rig

Measure seal load vs. linear compression, preload, & stiffness at temperature.

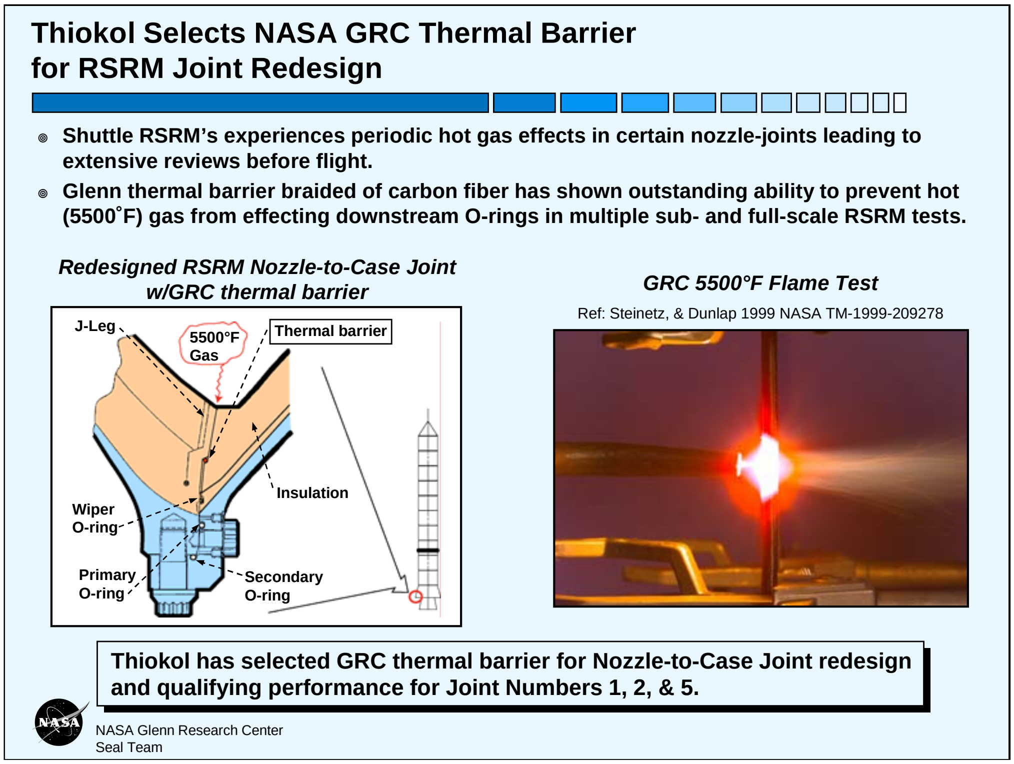
Scrub Test Rig

Measure seal wear rates and frictional loads for various test conditions at temperature

NASA Glenn Research Center
Seal Team

One of the primary tests to be conducted with the new rig will be high temperature compression tests to assess seal resiliency. These evaluations will be carried out by employing a number of user-defined parameters including temperature, loading rate, amount of compression, and mode of application (single load application vs. cycling). The setup will consist of upper and lower silicon carbide (SiC) platens which compress a seal specimen residing in the groove of a seal holder. Small pins (laser 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 measure compression level as a function of time. See DeMange, et al, 2003 in this Seal Workshop Proceedings for further details.

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 (rub plate) assembly. The seal holders will be held in place through a novel high temperature anchoring system. 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.



Thiokol Selects NASA GRC Thermal Barrier for RSRM Joint Redesign

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

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

GRC 5500°F Flame Test

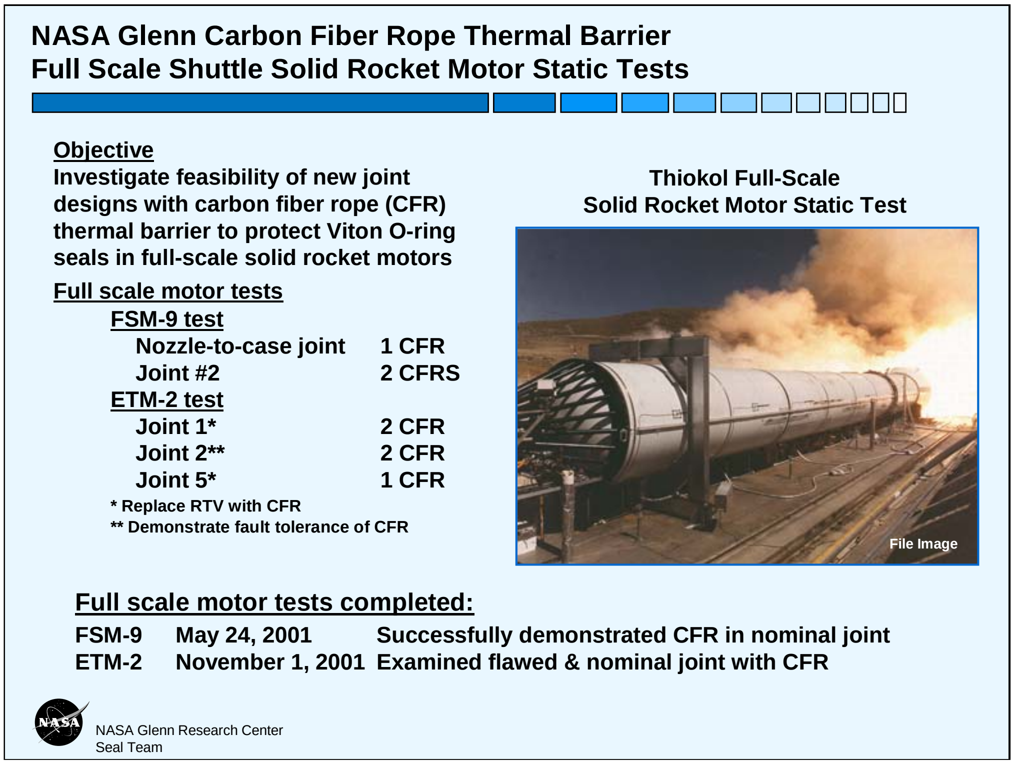
Ref: Steinetz, & Dunlap 1999 NASA TM-1999-209278

Thiokol has selected GRC thermal barrier for Nozzle-to-Case Joint redesign and qualifying performance for Joint Numbers 1, 2, & 5.

NASA Glenn Research Center
Seal Team

Periodically several of the Shuttle’s solid rocket motor nozzle joints experience hot gas effects. Over the past several years, engineers from NASA Glenn, Marshall Space Flight Center, Thiokol, and Albany-Techniweave have been investigating the feasibility of applying the NASA GRC developed carbon fiber rope to overcome this issue. More details of this program can be found in Steinetz and Dunlap, 2001, Steinetz and Dunlap, 2002, and U.S. Patent # 6,446,979 B1.

The braided carbon fiber thermal barrier is the primary candidate being considered for the redesign of nozzle-to-case joint and for nozzle joints 1-5. Incorporation of the thermal barrier into the nozzle joints of the Space Shuttle RSRMs eliminates hot gas penetration to nozzle joint Viton O-rings. 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 Tests

Objective

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

Full scale motor tests

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

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

Thiokol Full-Scale Solid Rocket Motor Static Test

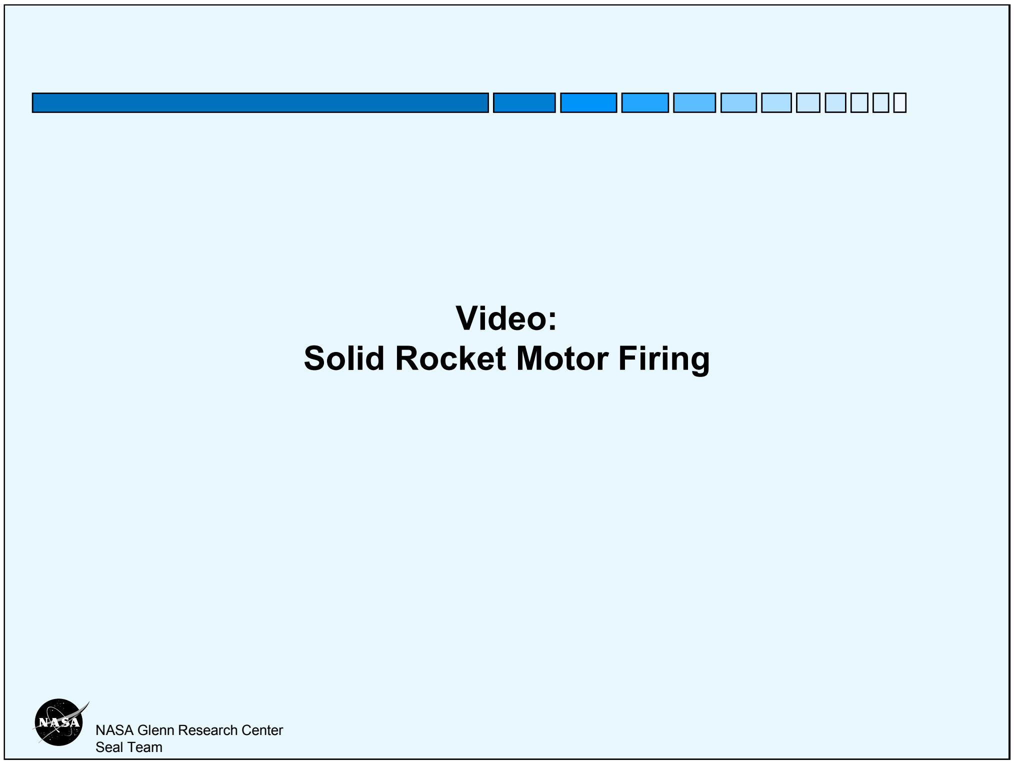
Full scale motor tests completed:

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

NASA Glenn Research Center
Seal Team

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.

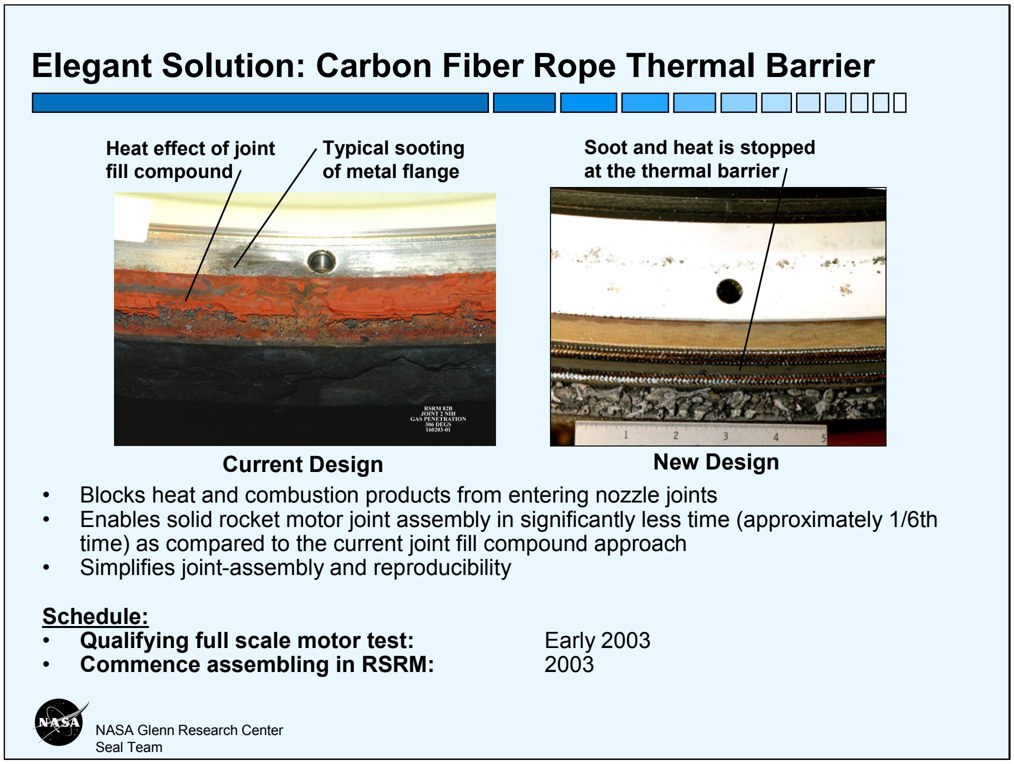
On November 1, 2001, the CFR was tested in joints 1, 2, and 5 in a full-scale solid-rocket motor test designated ETM-2. In joints 1 and 5 CFRs was used in place of the RTV joint compound. RTV often cures with voids that can lead to rocket gas impingement on the Viton O-rings. Replacing the RTV with the CFR eliminates the focusing of the hot rocket gas, reduces the temperature of the gas impinging on the Viton O-rings, and significantly reduces assembly time.



Video:
Solid Rocket Motor Firing

NASA Glenn Research Center
Seal Team

During the workshop presentation, a video was shown of the full scale static motor test-firing that included the thermal barrier.



Elegant Solution: Carbon Fiber Rope Thermal Barrier

Heat effect of joint fill compound

Typical sooting of metal flange

Soot and heat is stopped at the thermal barrier

Current Design

New Design

- Blocks heat and combustion products from entering nozzle joints
- Enables solid rocket motor joint assembly in significantly less time (approximately 1/6th time) as compared to the current joint fill compound approach
- Simplifies joint-assembly and reproducibility

Schedule:

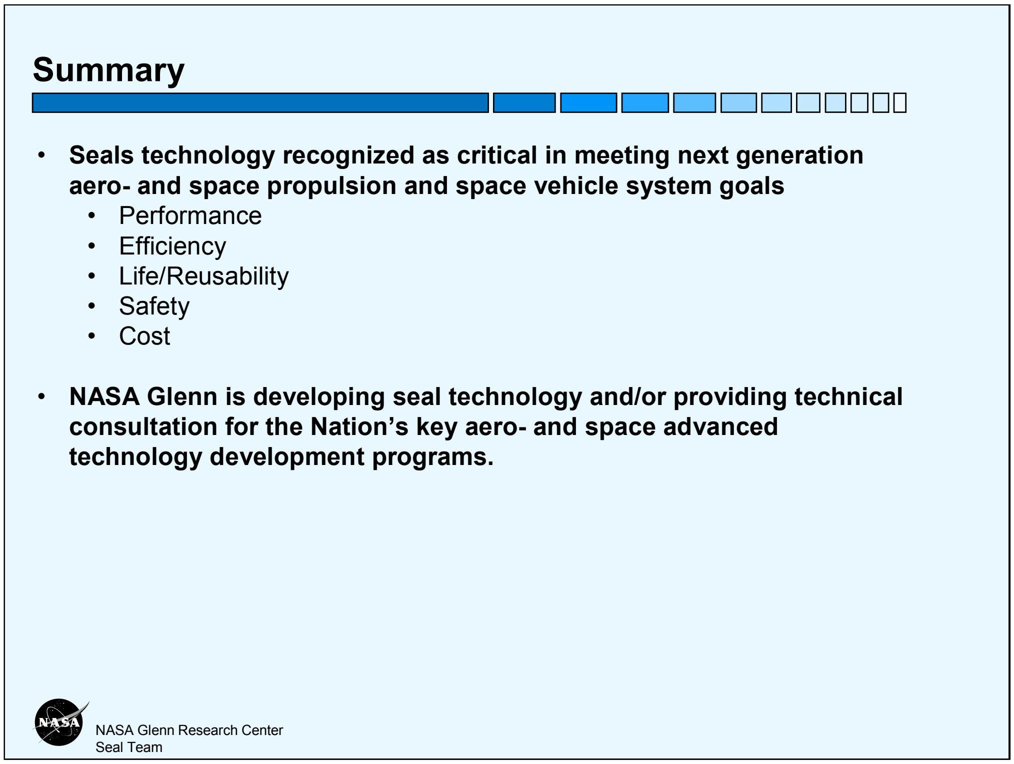
Qualifying full scale motor test:	Early 2003
Commence assembling in RSRM:	2003

NASA Glenn Research Center
Seal Team

This slide shows the benefits of incorporating the thermal barrier.

Shown here for comparison purposes, is the condition of Joint 2 before and after implementation of the thermal barrier design. The left image shows the poor condition of the joint after flight before the thermal barriers were added. The right image shows the excellent condition of the joint after the full-scale test with the thermal barriers showing no heat effect of any elements in the joint.

Schedule: After a final qualifying full scale motor test scheduled in early 2003, it is anticipated that the boosters will be assembled with the thermal barriers later that year. 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
  - Life/Reusability
  - Safety
  - Cost

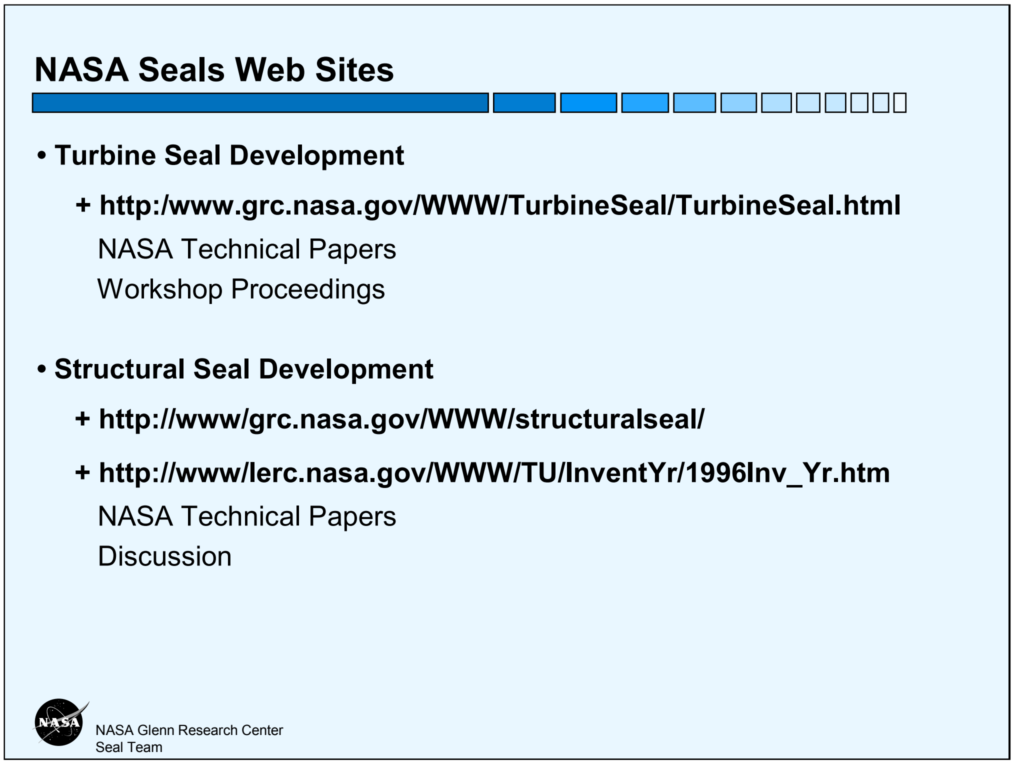
- **NASA Glenn is developing seal technology and/or providing technical consultation for the Nation's key aero- and space advanced technology development programs.**

NASA Glenn Research Center
Seal Team

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**

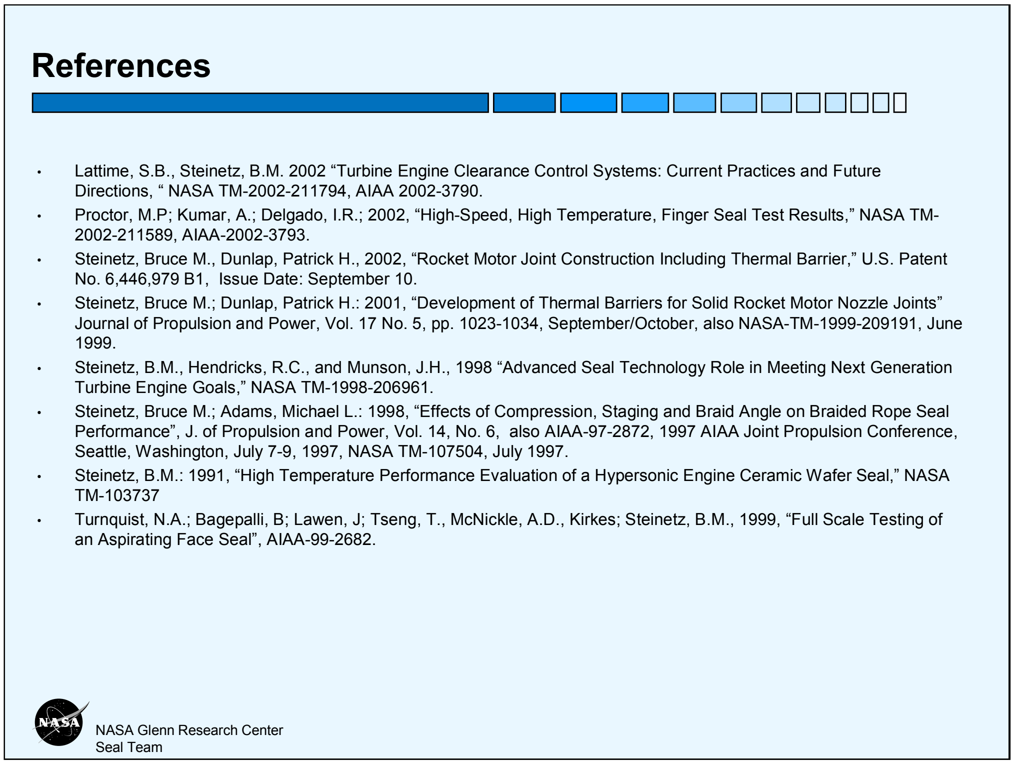
    NASA Technical Papers
    Workshop Proceedings

- **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

NASA Glenn Research Center
Seal Team

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



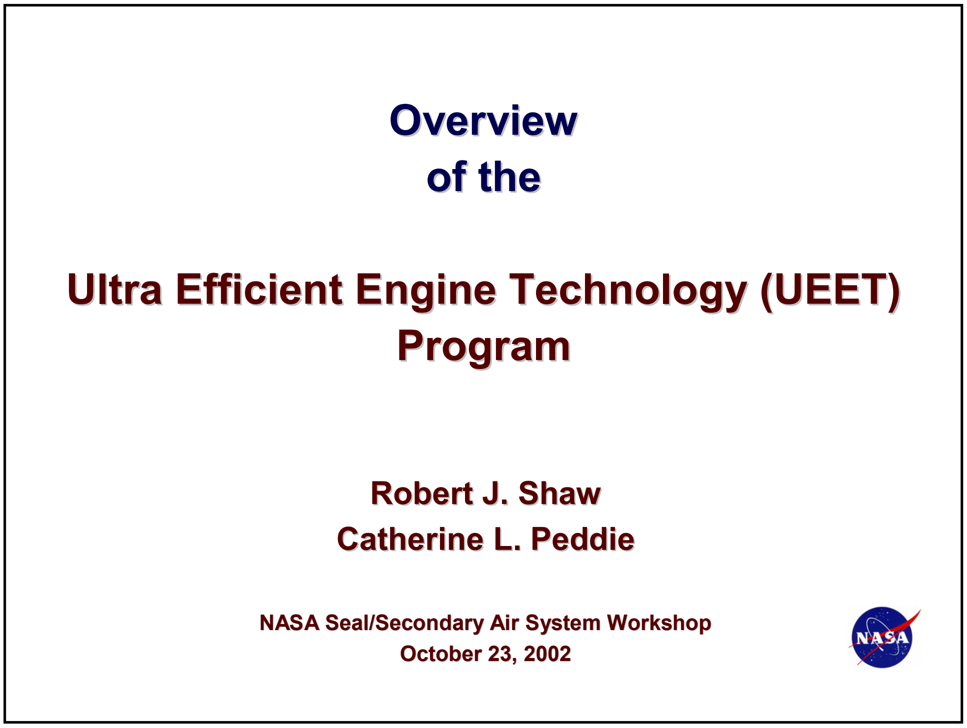
References

- Lattime, S.B., Steinetz, B.M. 2002 “Turbine Engine Clearance Control Systems: Current Practices and Future Directions, “ NASA TM-2002-211794, AIAA 2002-3790.
- Proctor, M.P; Kumar, A.; Delgado, I.R.; 2002, “High-Speed, High Temperature, Finger Seal Test Results,” NASA TM-2002-211589, AIAA-2002-3793.
- Steinetz, Bruce M., Dunlap, Patrick H., 2002, “Rocket Motor Joint Construction Including Thermal Barrier,” U.S. Patent No. 6,446,979 B1, Issue Date: September 10.
- Steinetz, Bruce M.; Dunlap, Patrick H.: 2001, “Development of Thermal Barriers for Solid Rocket Motor Nozzle Joints” Journal of Propulsion and Power, Vol. 17 No. 5, pp. 1023-1034, September/October, also NASA-TM-1999-209191, June 1999.
- Steinetz, B.M., Hendricks, R.C., and Munson, J.H., 1998 “Advanced Seal Technology Role in Meeting Next Generation Turbine Engine Goals,” NASA TM-1998-206961.
- Steinetz, Bruce M.; Adams, Michael L.: 1998, “Effects of Compression, Staging and Braid Angle on Braided Rope Seal Performance”, J. of Propulsion and Power, Vol. 14, No. 6, also AIAA-97-2872, 1997 AIAA Joint Propulsion Conference, Seattle, Washington, July 7-9, 1997, NASA TM-107504, July 1997.
- Steinetz, B.M.: 1991, “High Temperature Performance Evaluation of a Hypersonic Engine Ceramic Wafer Seal,” NASA TM-103737
- Turnquist, N.A.; Bagepalli, B; Lawen, J; Tseng, T., McNickle, A.D., Kirkes; Steinetz, B.M., 1999, “Full Scale Testing of an Aspirating Face Seal”, AIAA-99-2682.

NASA Glenn Research Center
Seal Team

OVERVIEW OF NASA'S UEET AND TBCC/RTA PROGRAMS

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



Overview
of the

Ultra Efficient Engine Technology (UEET) Program

Robert J. Shaw
Catherine L. Peddie

NASA Seal/Secondary Air System Workshop
October 23, 2002

Revolutionize Aviation Goal Emissions Objective

UEET Ultra Efficient Engine Technology

Reduce emissions of future aircraft by a factor of three within 10 years (2007), and by a factor of five within 20 years.

NASA Three Pillars for Success-1997

Reduce NOx emissions of future aircraft by 70 percent within 10 years, and by 80 percent within 25 years (using the 1996 ICAO Standard for NO_x as the baseline. Reduce CO_2 emissions of future aircraft by 25 percent and by 50 percent In the same timeframes (using 1997 subsonic aircraft technology as the baseline).

NASA Aerospace Technology Enterprise Strategic Plan-2001

UEET will be the responsible propulsion program for delivering on this objective!

Commercial Turbine
Engine Technology
Leadership for the
21st Century

NASA Glenn Research Center

UEET

Ultra-Efficient Engine Technology Program

The UEET Program will develop and transfer to the U. S. industry critical gas turbine engine technologies which will contribute to "enabling a safe, secure, and environmentally friendly air transportation system".

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***

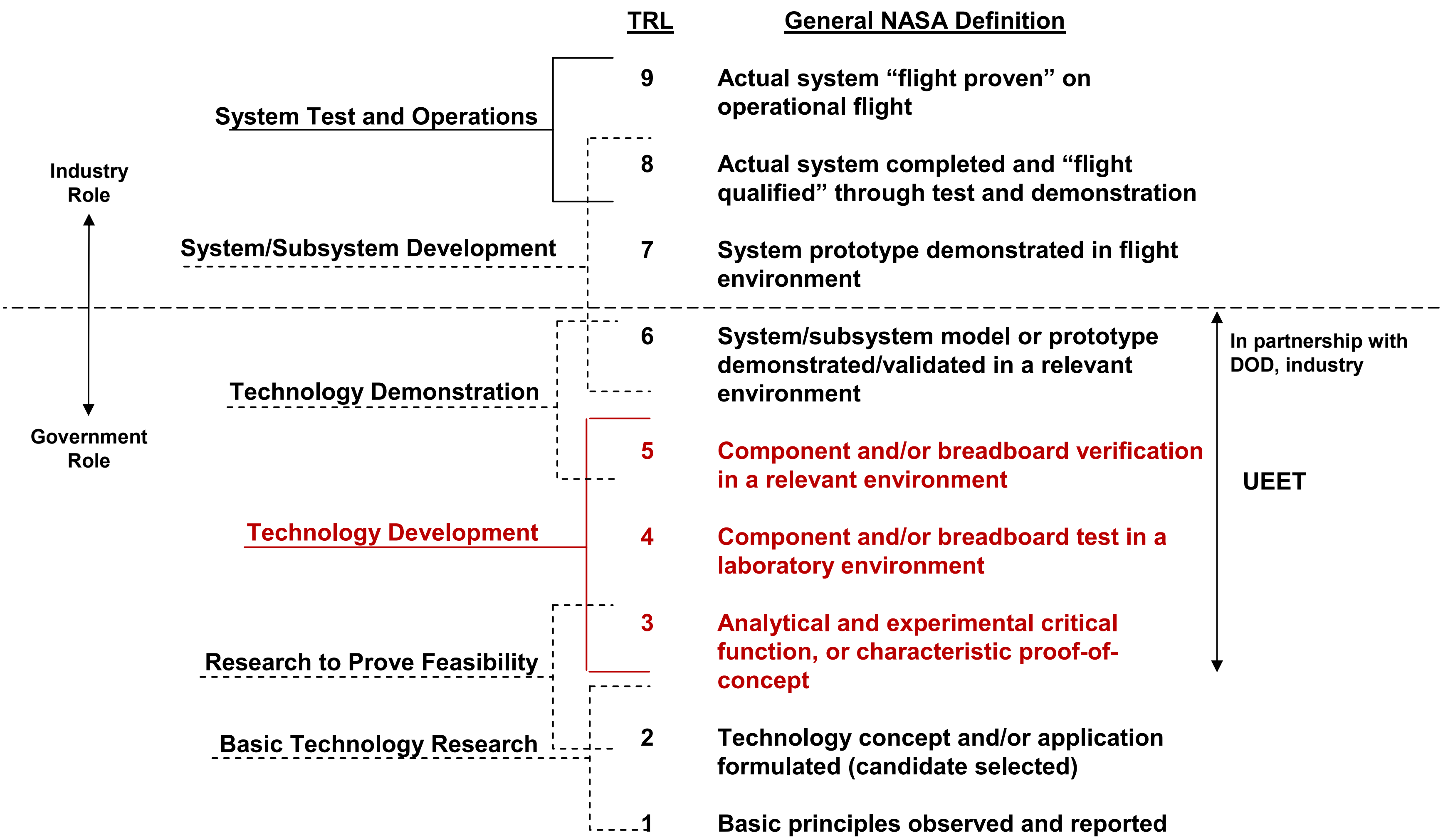
Program Technical Objectives

UEET Ultra Efficient Engine Technology

	Goal	Minimum Success Criteria
CO_2 Goal	15% fuel burn reduction for large subsonic aircraft	12% fuel burn reduction for large subsonic aircraft
	8% fuel burn reduction for small subsonic, small / large supersonic	4% fuel burn reduction for small subsonic, small / large supersonic
NO_x Goal	70% N0x reduction (below ICAO 96) for subsonic (large/ regional) combustors over the LTO cycle	65% N0x reduction (below ICAO 96) for subsonic (large/ regional) combustors over the LTO cycle

NASA’s Technology Readiness Level (TRL) Scale

UEET Ultra Efficient Engine Technology



TRL	General NASA Definition
9	Actual system “flight proven” on operational flight
8	Actual system completed and “flight qualified” through test and demonstration
7	System prototype demonstrated in flight environment
6	System/subsystem model or prototype demonstrated/validated in a relevant environment
5	Component and/or breadboard verification in a relevant environment
4	Component and/or breadboard test in a laboratory environment
3	Analytical and experimental critical function, or characteristic proof-of-concept
2	Technology concept and/or application formulated (candidate selected)
1	Basic principles observed and reported

System Test and Operations

System/Subsystem Development

Technology Demonstration

Technology Development

Research to Prove Feasibility

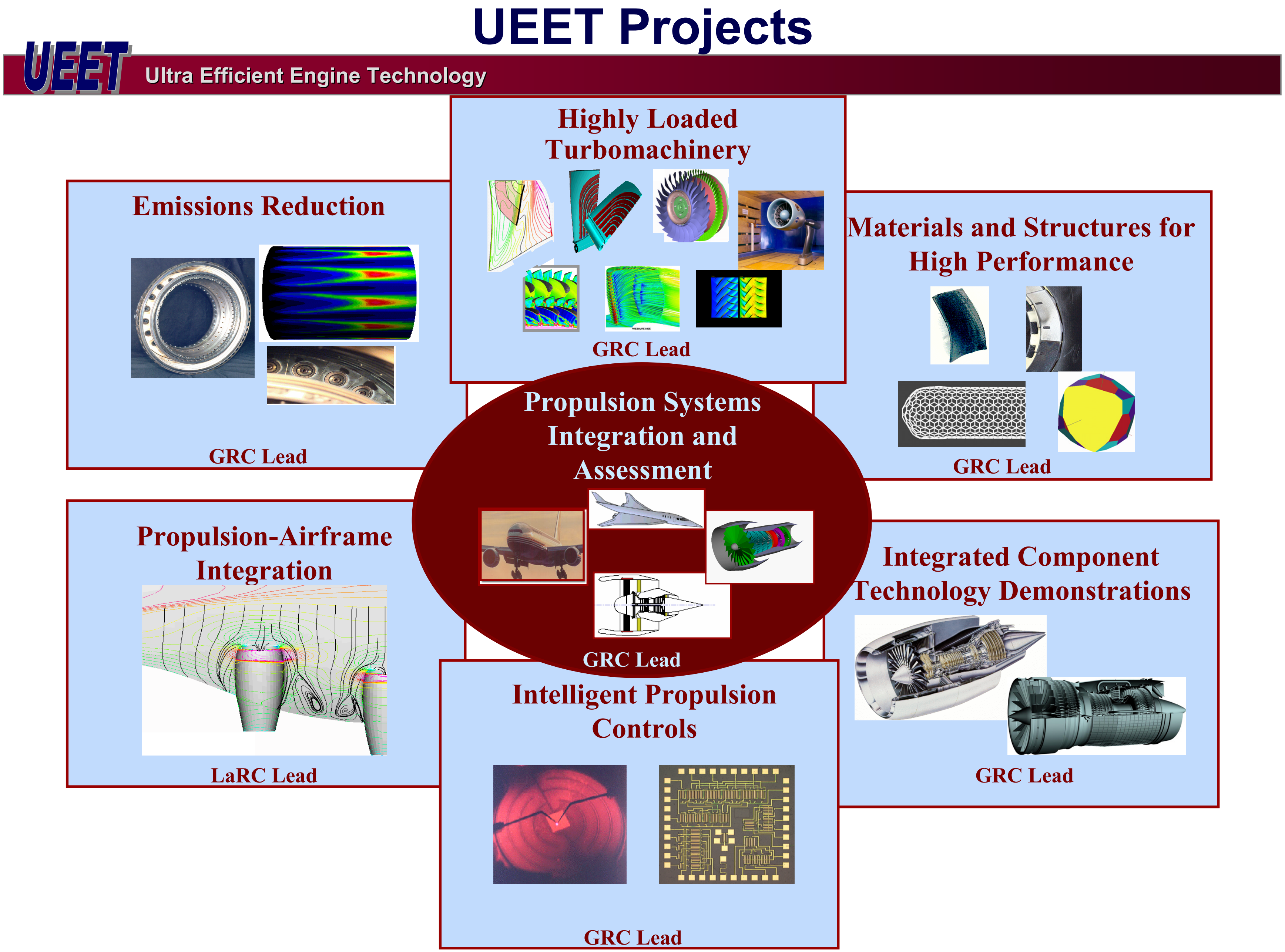
Basic Technology Research

Industry Role

Government Role

In partnership with DOD, industry

UEET



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

Baseline Vehicles for UEETP Technology Application Studies

UEET Ultra Efficient Engine Technology

Commercial Vehicles

Subsonic

300 PAX
Large Subsonic Transport

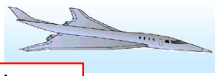
50 PAX
Regional Jet Transport

500-600 PAX
Blended Wing Body (BWB)

Supersonic

300 PAX
High Speed Civil Transport (HSCT)

10 PAX
Supersonic Business Jet (SBJ)



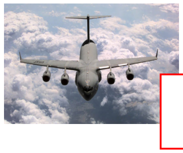
Hypersonic

These vehicles drive the technology investment strategy

Non-Commercial Vehicles

4 PAX

General Aviation Aircraft (GA)



Military Transport (C-17)

Unmanned Aerial Vehicle (UAV)

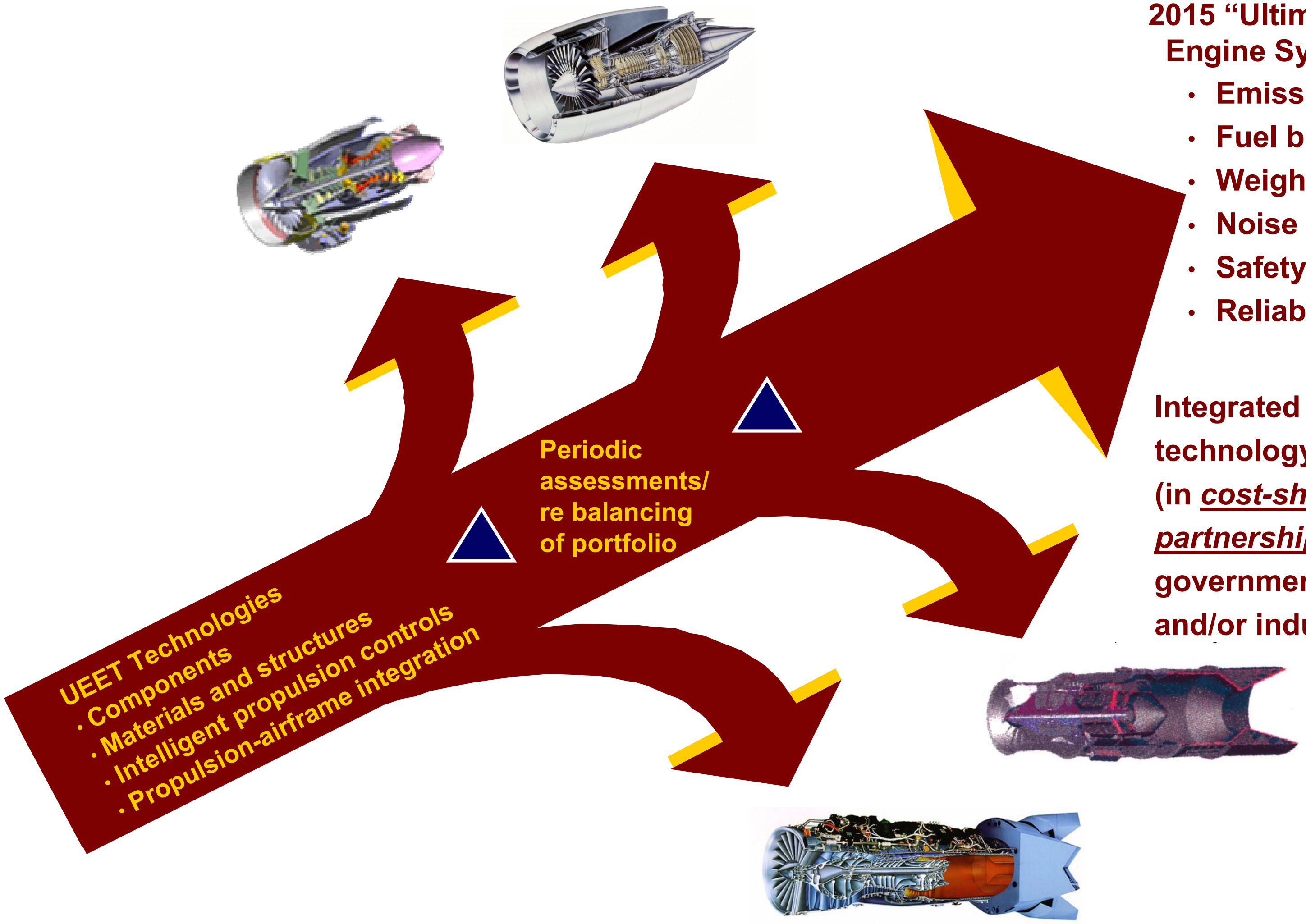
Advanced Fighter

Access-to-Space/High Mach Platform

These vehicles determine the technology synergies

The UEET “Roadmap”

UEET Ultra Efficient Engine Technology



UEET Technologies
- Components
- Materials and structures
- Intelligent propulsion controls
- Propulsion-airframe integration

Periodic assessments/ re balancing of portfolio

2015 “Ultimate” Turbine Engine Systems
- Emissions
- Fuel burn
- Weight
- Noise
- Safety
- Reliability

Integrated component technology validations (in ***cost-sharing partnership*** with other government agencies and/or industry)

UEET Ultra Efficient Engine Technology

Vision

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

Richard Hill, Air Force Research Laboratory

Gerald L. Brines

Gerald Brines, Allison-Rolls Royce

Mahmood Naimi

Mahmood Naimi, Boeing Commercial Airplane Company

Fred H. Krause

Fred Krause, General Electric Aircraft Engines

Dimitri Mavris

Dimitri Mavris, Georgia Tech

Vinod Nangia

Vinod Nangia, Honeywell

Tom Hartmann, Lockheed-Martin

Robert J. Shaw

Robert J. Shaw, NASA Glenn Research Center

Robert D Southwick

Robert D. Southwick, Pratt & Whitney

Scott Cruzen, Williams International

UEET Partnerships

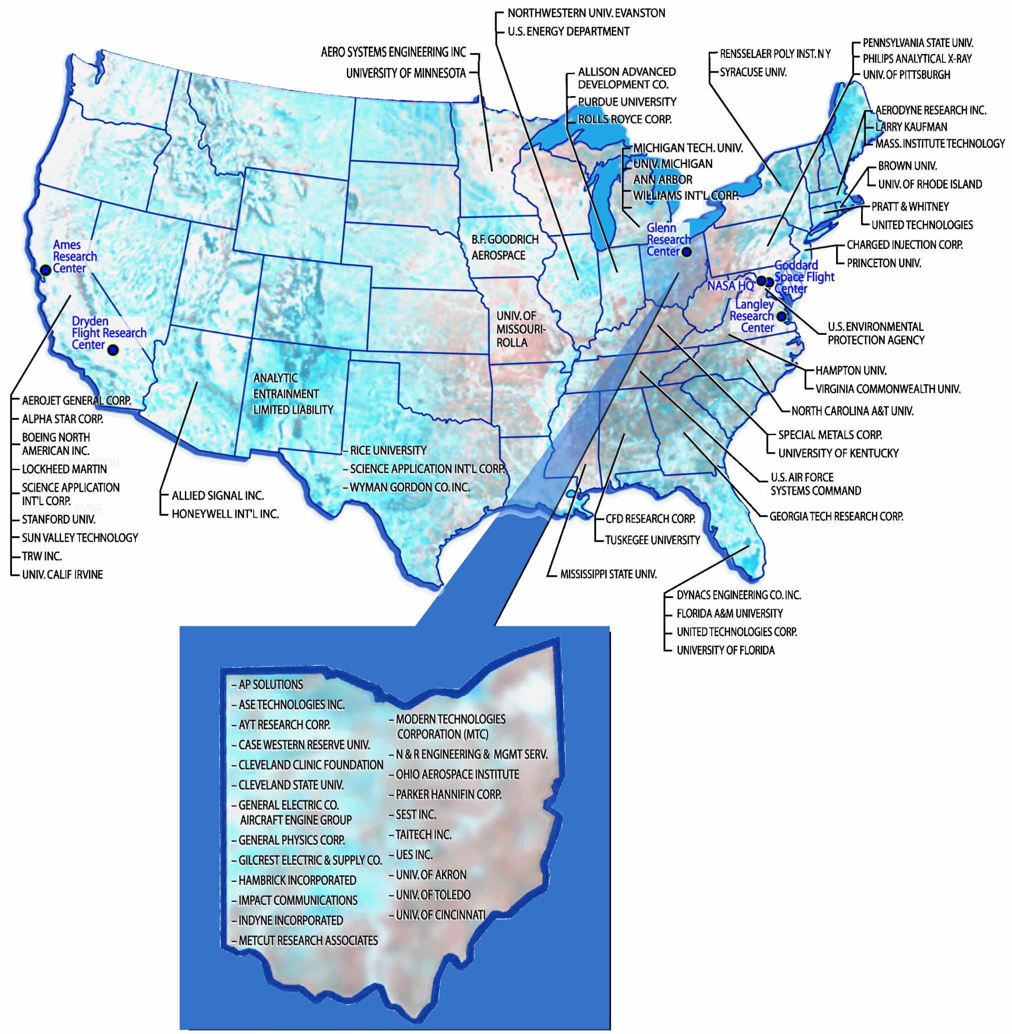
UEET Ultra Efficient Engine Technology

Partner	Comments
Boeing, Lockheed-Martin, GE, P&W, Honeywell, AAD/RR, Williams, Georgia Tech	On track to provide >$50M of direct in kind contributions to overall UEET Program
NASA Quiet Aircraft Technology (QAT) Program	Shared development of fan technologies
NASA Advanced Space Transportation Program (ASTP)	Technology insertion opportunities on TBCC/RTA demonstrators
NASA Propulsion and Power Program (APP)	Shared responsibility in simulation tool development; revolutionary lower TRL technologies
EPA	Environmental compatibility of technologies
FAA	Pre certification “issues” of technologies
DOD (IHPTET/VAATE)	Technology insertion on IHPTET/VAATE demos; collaboration on materials development/studies; support for Dual Spool Turbine facility (DSTF)
DOE	Technology insertion on ground power demos
National Technology Transfer Center (NTTC)	Technology transfer to non aerospace community
QinetiQ (UK)	Emissions modeling validation data sets

UEET is all about partnerships!

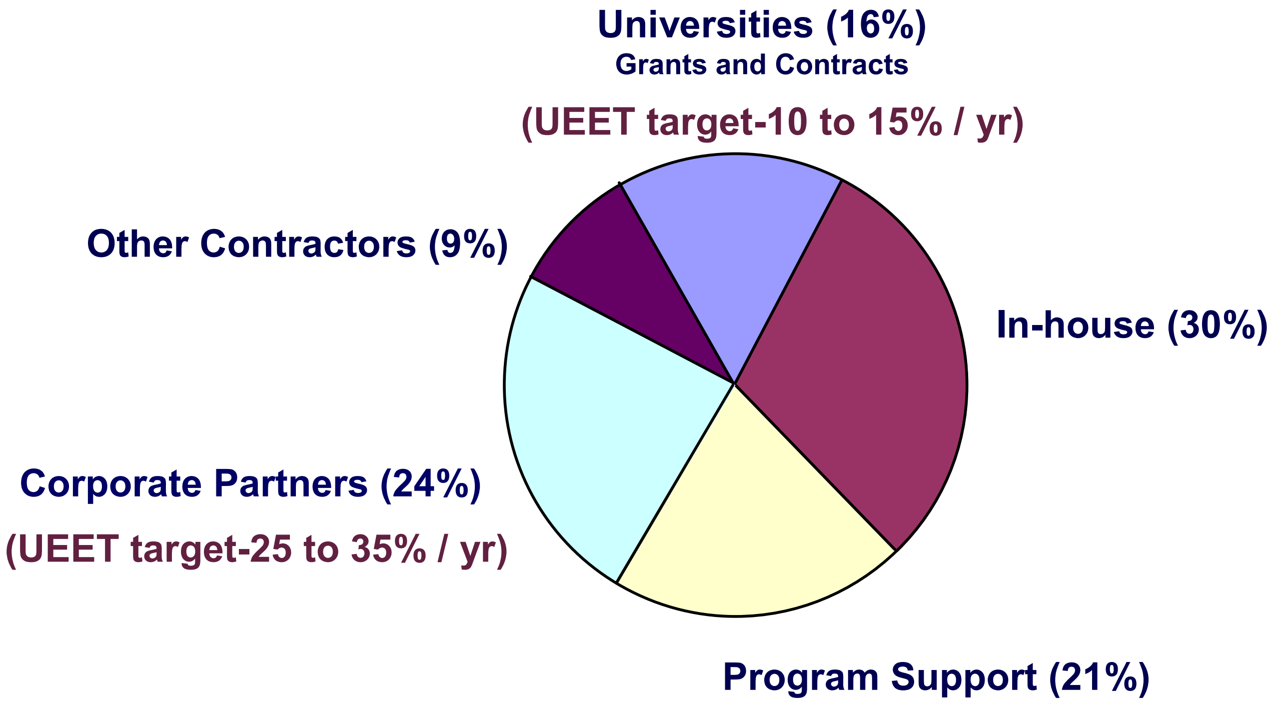
The UEET Team

UEET Ultra Efficient Engine Technology



UEET Investment Portfolio (FY00-02)

Ultra Efficient Engine Technology



Program Status

Ultra Efficient Engine Technology

October 2002

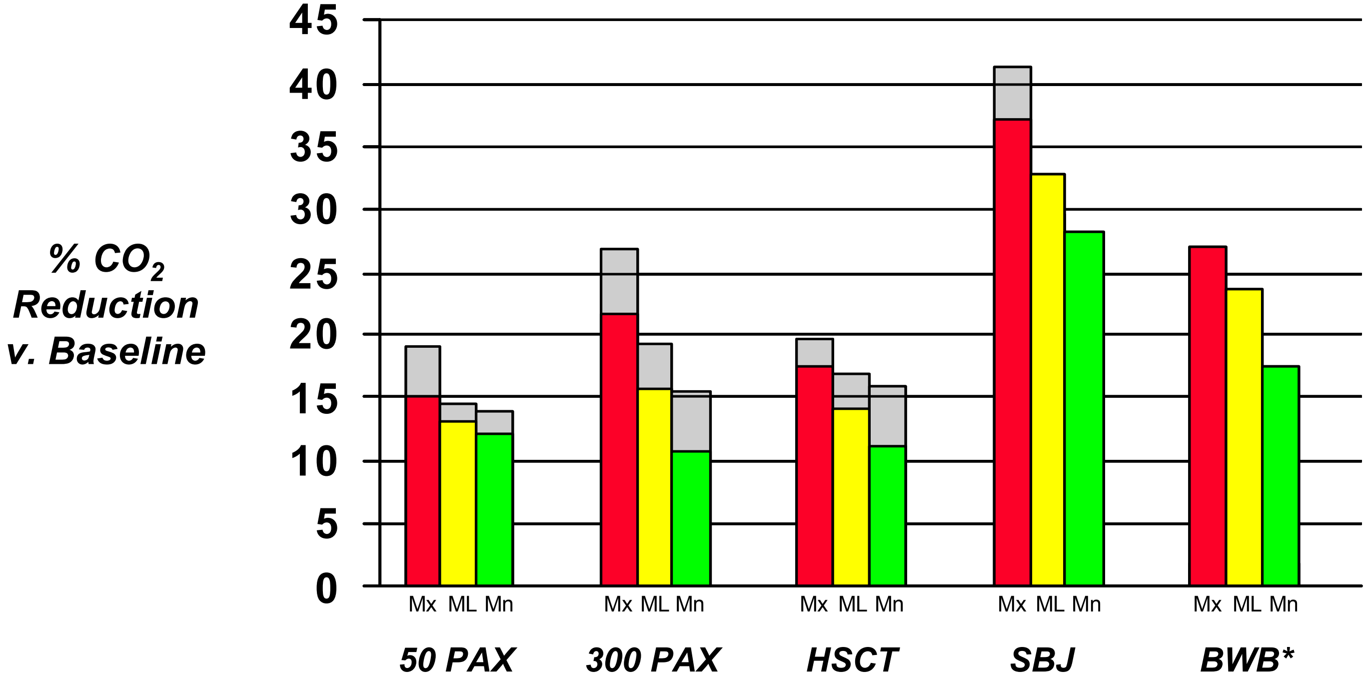
Goal	Status	Remarks
15% fuel burn reduction for large subsonic	22% projected for 300 PAX	Systems studies projections of combined impacts of UEET technologies.
8% fuel burn reduction for small subsonic, small / large supersonic	15% for 50 PAX 17% for 300 PAX HSCT 37% for 10 PAX SSBJ	Limited test data (TRL2-3+ range)
70% N0x reduction (below ICAO 96) for subsonic (large regional) combustors over the LTO cycle	Initial industrial sector tests give confidence that at least the min success will be achieved (TRL = 3+)	Initial sector tests completed

UEET Ultra Efficient Engine Technology

Potential CO_2 Reduction

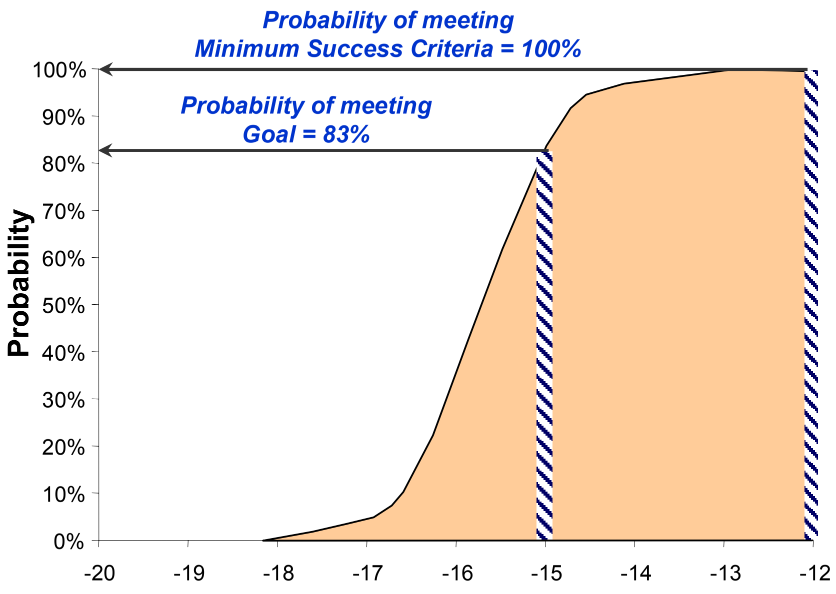
(Using “Core” Set of Technologies)

▨ *- represents FY01 results*

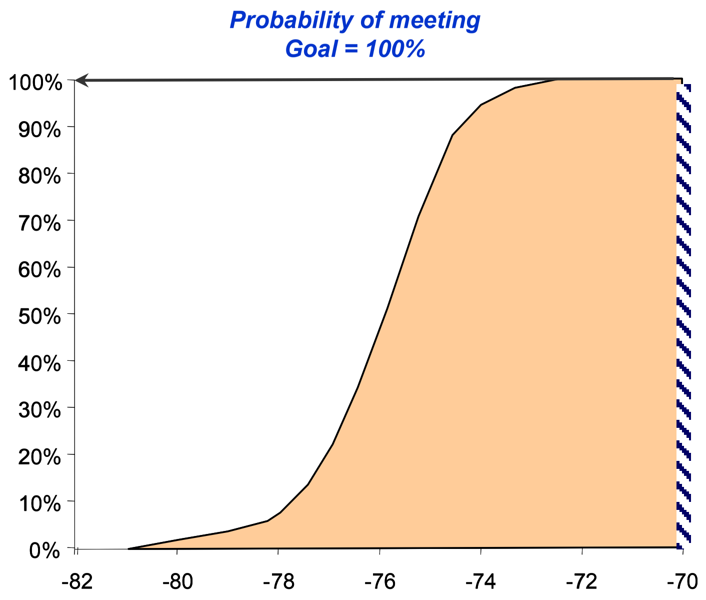


* Same engine for all cases only Active Flow Control benefit varied

Probability Distribution for Meeting UEET Program Goals



% Change in CO_2/ASM from Baseline for GT Best



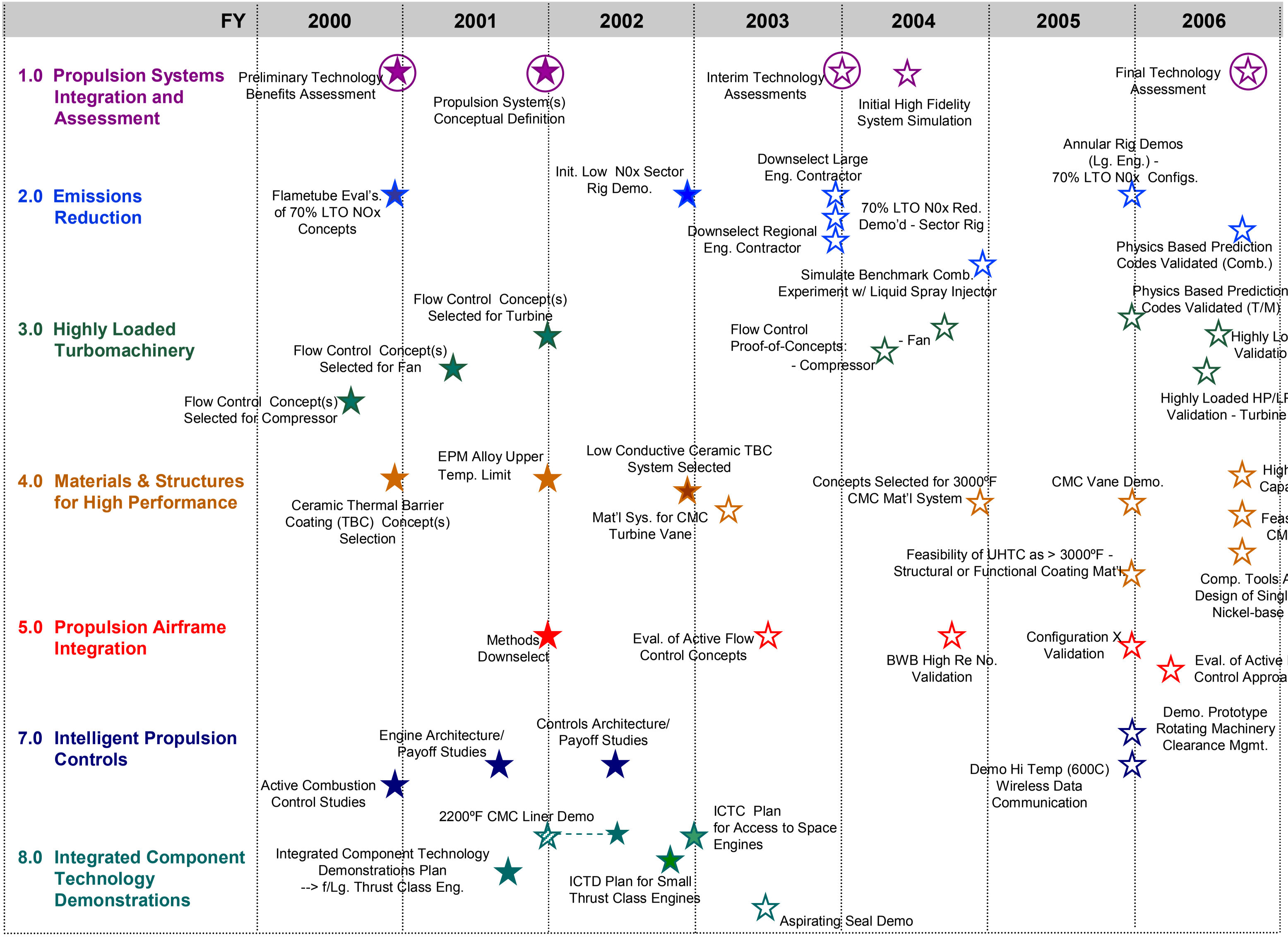
% Below LTO NO_x Rule for GT Best

- UEET Program Goal of -70% LTO NO_x can be achieved with a 100% confidence with the identified best set of technologies
- UEET Program Goal of -15% CO_2 can be achieved with a 83% confidence

Preliminary results

UEET Level I Milestone Schedule

May 2002 Rebaseline



Notes: 1) PCA milestones are denoted by ✪

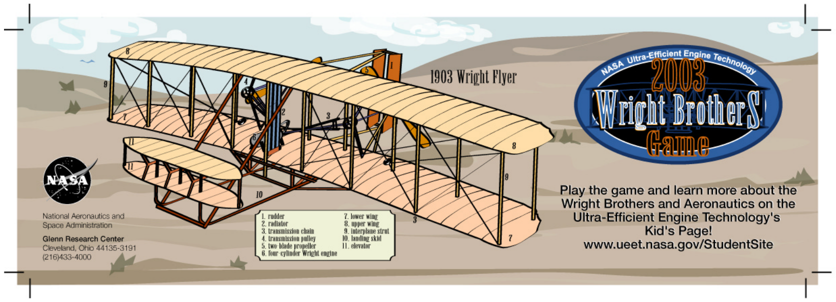
2) WBS 6.0 reserved for Program Mgmt. functions

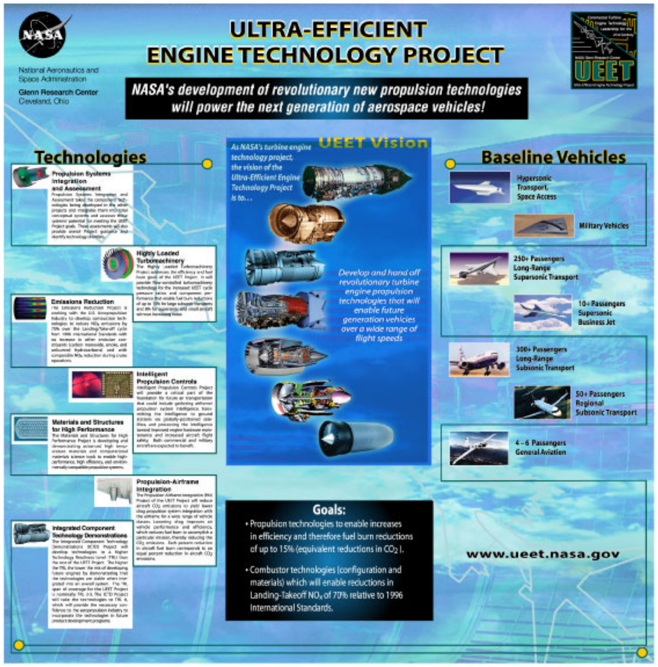
Education/Outreach Activities

UEET Ultra Efficient Engine Technology

Wright Brothers Game for the Web

Targeted to grades 5-8, this educational game encourages students to browse the museum and learn facts about the Wright Brothers and their journey to discover the secret of powered flight, then answer questions for points on Kill Devil Hills near Kitty Hawk. The game has been posted to the UEET Website:
http://www.ueet.nasa.gov/StudentSite





National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

ULTRA-EFFICIENT
ENGINE TECHNOLOGY PROJECT

NASA's development of revolutionary new propulsion technologies will power the next generation of aerospace vehicles!

Technologies

Propulsion Systems Integration and Assessment

Highly Loaded Turbomachinery

Emissions Reduction

Intelligent Propulsion Controls

Materials and Structures for High Performance

Propulsion-Airframe Integration

Integrated Component Technology Demonstrations

UEET Vision

As NASA's turbine engine technology project, the vision of the Ultra-Efficient Engine Technology Project is to…

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

Baseline Vehicles

Hypersonic Transport, Space Access

Military Vehicles

250+ Passengers Long-Range Supersonic Transport

10+ Passengers Supersonic Business Jet

300+ Passengers Long-Range Subsonic Transport

50+ Passengers Regional Subsonic Transport

4 – 6 Passengers General Aviation

Goals:

- Propulsion technologies to enable increases in 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 Landing-Takeoff NO_x of 70% relative to 1996 International Standards.

www.ueet.nasa.gov

UEET Outreach Display

This 8ft x 10ft display was created to represent UEET to the technical community and the general public. It was debuted at the Integrated High Performance Turbine Engine Technology (IHPTET) Symposium in Dayton, Ohio on September 9, 2002.

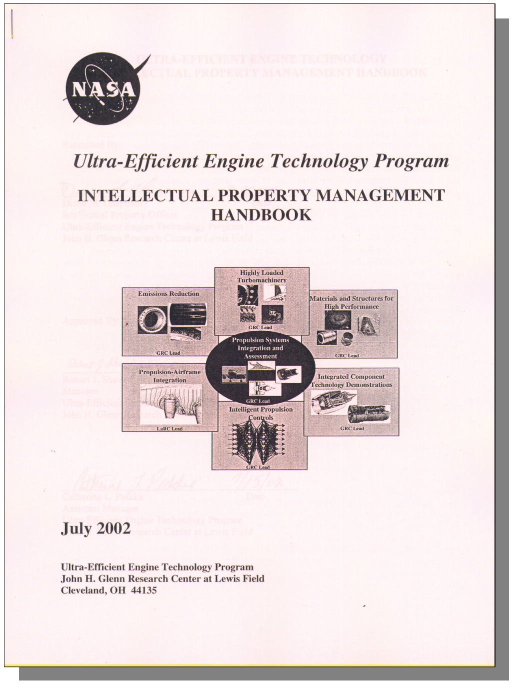
Intellectual Property Management Handbook

UEET Ultra Efficient Engine Technology

- Handbook signed July 2002 after extensive interactions with industry

- Training module has been developed in co-operation with National Technology Transfer Center (NTTC) for NASA employees (including on site PBC's)

- Training module (and trainers) have been offered to corporate partners



NASA

Ultra-Efficient Engine Technology Program

INTELLECTUAL PROPERTY MANAGEMENT
HANDBOOK

July 2002

Ultra-Efficient Engine Technology Program
John H. Glenn Research Center at Lewis Field
Cleveland, OH 44135

Technology Transfer Partnership

UEET Ultra Efficient Engine Technology

We are committed to working together in partnership to actively seek out non aerospace opportunities for transfer and commercialization of all appropriate technologies being developed through programs and projects being managed by the Ultra Efficient Engine Technology (UEET) Office.

Joseph C Allen

Joseph Allen
President, National Technology Transfer Center
Wheeling Jesuit University

Robert J. Shaw

Robert J. Shaw
Chief, UEET Office
NASA Glenn Research Center

Larry A Viterna

Larry Viterna
Chief, Commercial Technology Office
NASA Glenn Research Center

Robert C. Byrd National Technology Transfer Center

Final Major Technology Deliverables (1)

Propulsion Systems Assessment and Integration:

Systems studies assessment of impact of UEET technologies towards meeting NO_X and CO_2 goals.

Emissions:

Annular rig validation test (TRL5) of combustor configurations that will meet or exceed 70 % Landing Take-Off NOx goal.

Validated physics based simulation tools. (TRL4)

Highly Loaded Turbomachinery

Wind tunnel validation of wake flow control concept for efficient, low noise fan. (TRL4) Done in partnership with QAT.

Test rig validation of compressor flow control/management concept. (TRL4)

Test rig validation of turbine flow control/management techniques. (TRL4)

Validated physics based simulation tools. (TRL4)

Material and Structures

Rig test validation of high temperature turbine airfoil materials systems. (TRL3)

Rig test validation of 2700 deg F Ceramic Matrix Composite material system. (TRL3)

Develop and validate computational materials tools. (TRL2)

Final Major Technology Deliverables (2)

UEET Ultra Efficient Engine Technology

Propulsion-Airframe Integration

Wind tunnel validation of advanced flow and shape control technologies for propulsion system application. (TRL3)

Validated advanced CFD based design methods. (TRL4)

Intelligent Propulsion Controls:

Validated approaches for propulsion system active clearance management. (TRL3-6?)

Determine through laboratory tests attractive approaches for high temperature wireless data communications for propulsion system applications. (TRL3)

Integrated Component Technology Demonstrations

Demonstrate through engine tests (TRL6) in partnership with industry technology readiness for 2200°F Ceramic Matrix Composite Combustor liner and aspirating seal.

Concluding Remarks

- The UEET Program is comprised of a portfolio of technologies which are matured to a TRL of 3-6 and transitioned to industry for their use in future aerospace vehicles designs.

- The program goals/objectives are satisfied through systems studies assessments of the combined impact of the technologies on four vehicle classes.
    - Large subsonic transports
    - Regional subsonic transports
    - Large commercial supersonic transport
    - Supersonic business jet

- The ultimate measure of success of the UEET Program will be the impact of the technologies.

Overview
of the

Turbine Based Combined Cycle (TBCC) Program

Robert J. Shaw
Catherine L. Peddie

NASA Seal/Secondary Air System Workshop
October 23, 2002

Vision and Mission

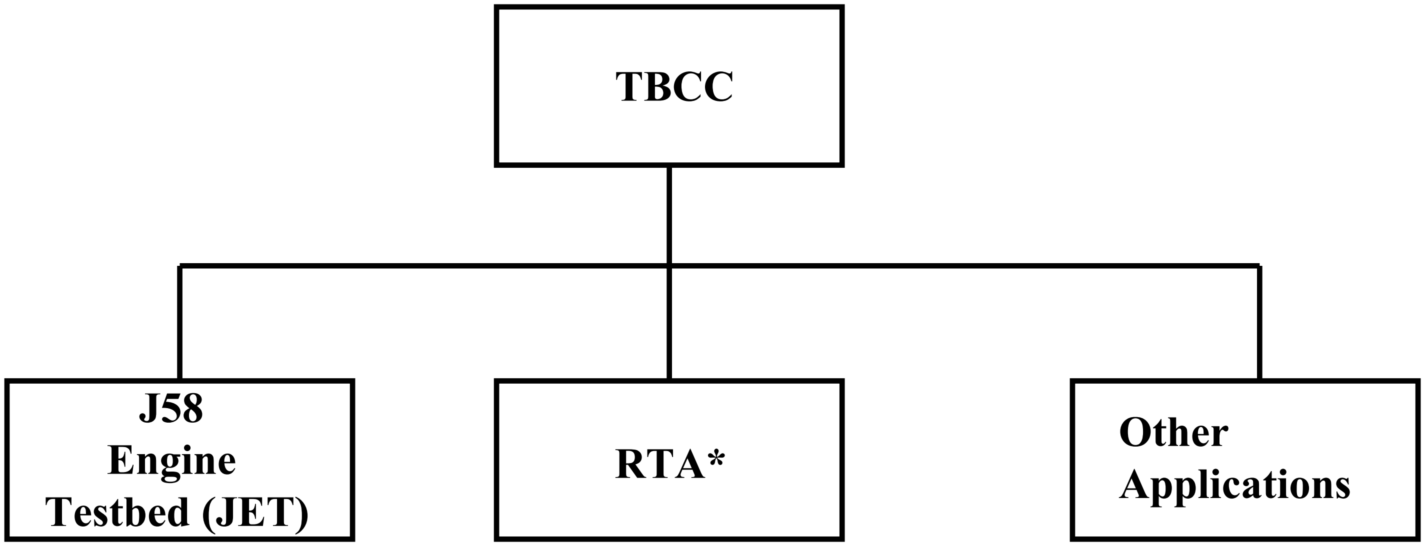
Vision:

Forging high mach turbine technologies for future transportation systems.

Mission:

Develop, demonstrate, and transition the enabling technologies required for future turbine based combined cycle propulsion systems for commercial and military applications including access-to-space and hypersonic cruise.

Project Organization



TBCC

J58
Engine
Testbed (JET)

RTA*

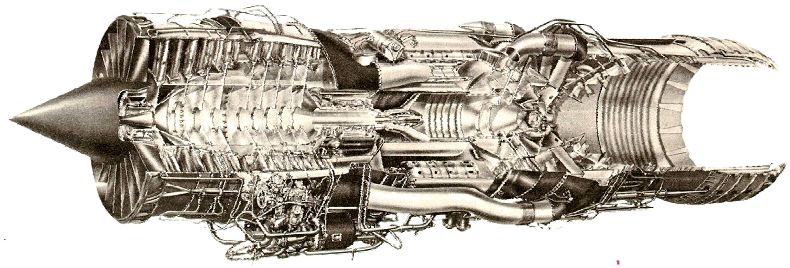
Other
Applications

RTA-revolutionary turbine accelerator project
(funded by NASA ASTP)

State of the Art High Speed Turbine Application

Strategic Reconnaissance Aircraft
(High Speed Recon.)

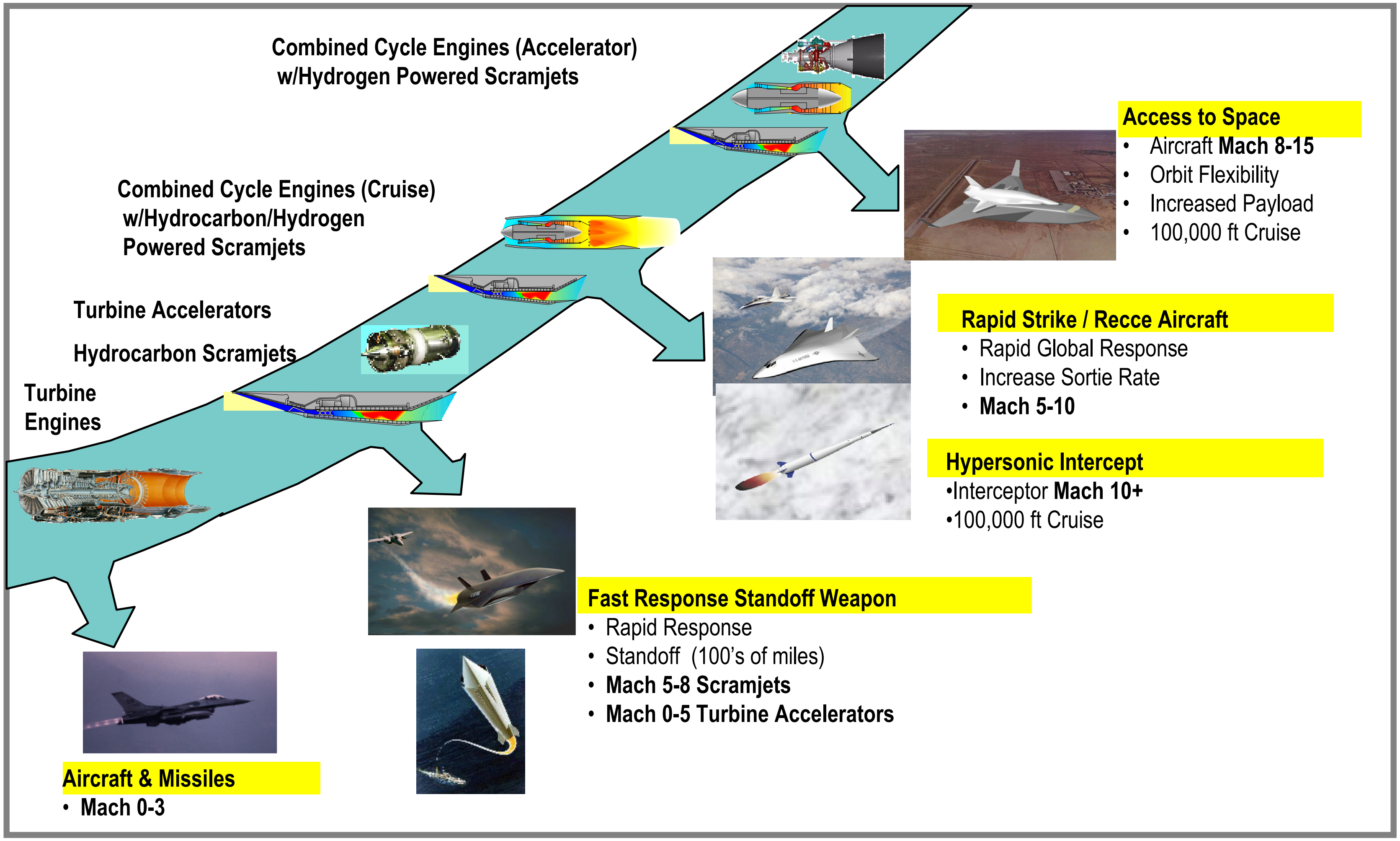
JT11D-20 (J58)



Variable Cycle 'Turbine Bypass' Turbojet

- ***Mach 3+ Cruise Applications***
- ***40+ year old technologies (some materials no longer made)***
- ***Requires frequent engine overhauls (every ~100 hrs)***
- ***T/W ~4:1***

RTA Bridges the Gap Between Mach 3 & Mach 5



Combined Cycle Engines (Accelerator) w/Hydrogen Powered Scramjets

Combined Cycle Engines (Cruise) w/Hydrocarbon/Hydrogen Powered Scramjets

Turbine Accelerators

Hydrocarbon Scramjets

Turbine Engines

Access to Space
- Aircraft **Mach 8-15**
- Orbit Flexibility
- Increased Payload
- 100,000 ft Cruise

Rapid Strike / Recce Aircraft
- Rapid Global Response
- Increase Sortie Rate
- **Mach 5-10**

Hypersonic Intercept
- Interceptor **Mach 10+**
- 100,000 ft Cruise

Fast Response Standoff Weapon
- Rapid Response
- Standoff (100's of miles)
- **Mach 5-8 Scramjets**
- **Mach 0-5 Turbine Accelerators**

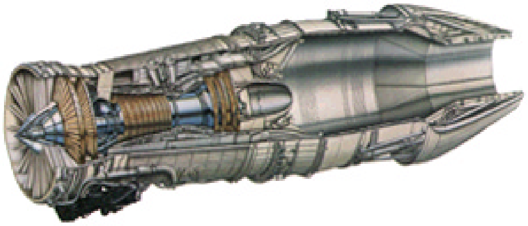
Aircraft & Missiles
- Mach 0-3

Today Near-Term Mid-Term Far-Term

RTA Project Areas of Emphasis

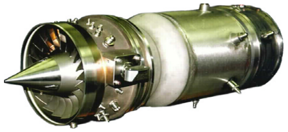
Subscale Ground Based Testbed (GBT) Demonstrator (2001-2008)

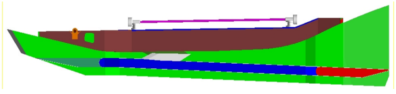
- Develop & Demonstrate enabling turbine technologies required to meet ASTP objectives
- Demonstrate technologies on a proper scaled ground based testbed (GBT)
- Utilize GBT as a system to evaluate
  - Advanced Turbine Technologies
  - High Mach Operability (I.e., Thermal management)
  - The "ilities" (I.e.,Reliability, Durability, etc..)

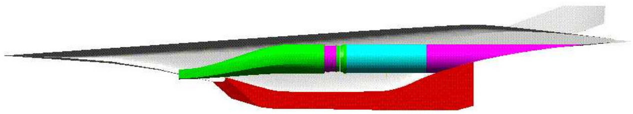

Ground Based Testbed (GBT)

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

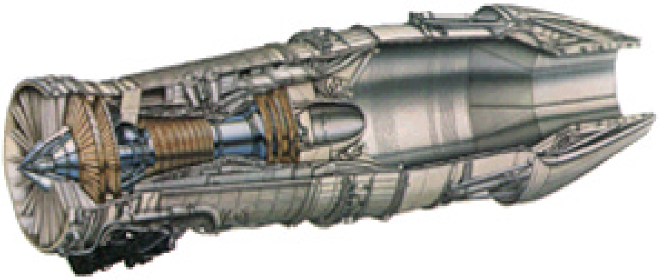
RTAFY03 POP.14

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.

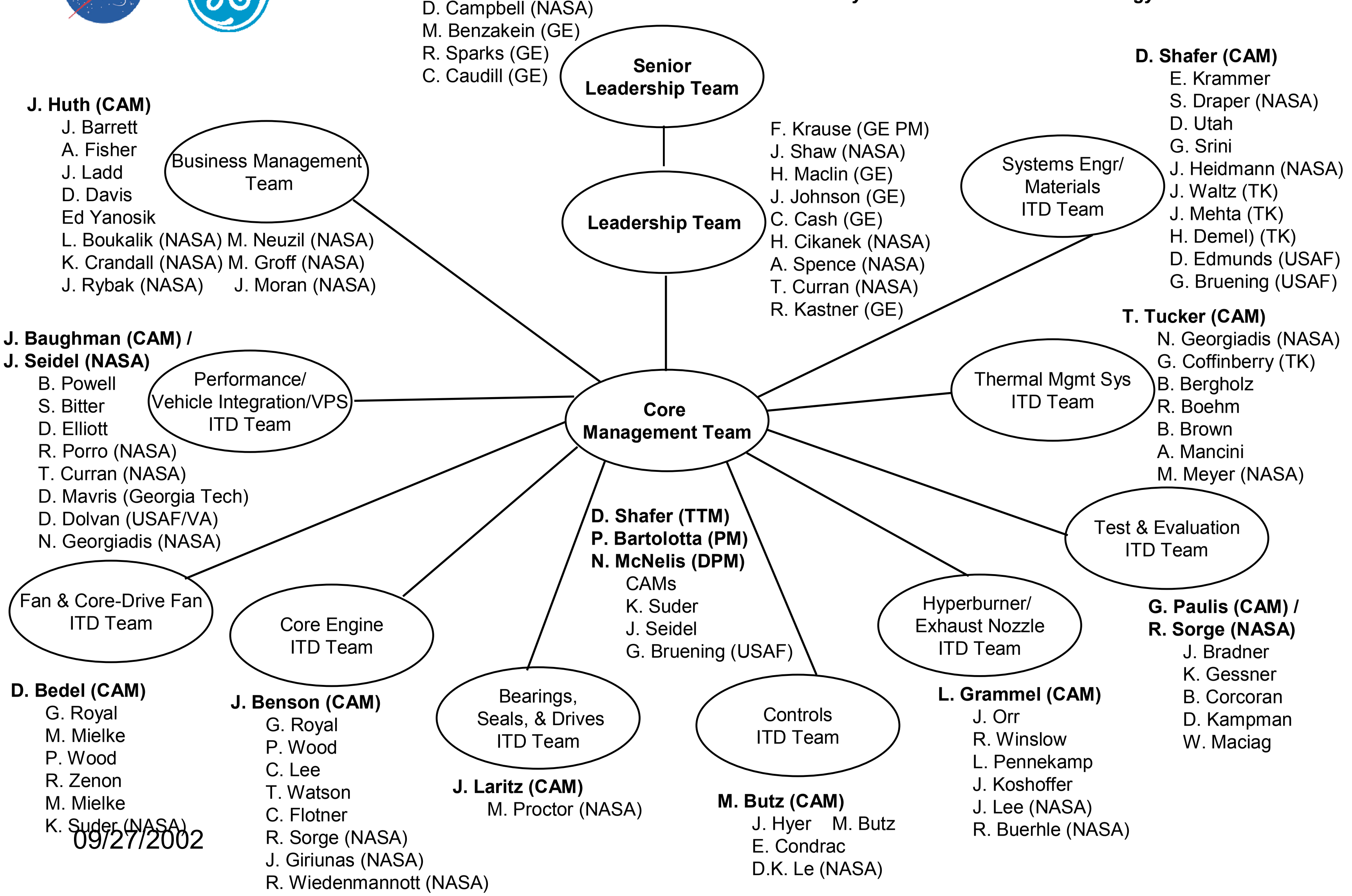
- ☐ **Approach:**
  1. Develop & evaluate enabling technologies to improve performance above SOA.
  2. Incorporate and evaluate new advanced technologies (from ASTP as well as UEET, IHPTET, and VAATE) as they mature.
  3. Conduct investment studies for enabling technologies specific to RTA propulsion systems and use as key input to technology selection process
  4. Design and build a sub 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 Performance Turbine Engine Technology program***
VAATE: ***Versatile Affordable Advanced Turbine Engine program***

Team Structure

Revolutionary Turbine Accelerator Technology Demonstration



Senior Leadership Team

D. Campbell (NASA)
M. Benzakein (GE)
R. Sparks (GE)
C. Caudill (GE)

Leadership Team

F. Krause (GE PM)
J. Shaw (NASA)
H. Maclin (GE)
J. Johnson (GE)
C. Cash (GE)
H. Cikanek (NASA)
A. Spence (NASA)
T. Curran (NASA)
R. Kastner (GE)

Core Management Team

D. Shafer (TTM)
P. Bartolotta (PM)
N. McNelis (DPM)
CAMs
K. Suder
J. Seidel
G. Bruening (USAF)

Business Management Team

J. Huth (CAM)
J. Barrett
A. Fisher
J. Ladd
D. Davis
Ed Yanosik
L. Boukalik (NASA)
K. Crandall (NASA)
J. Rybak (NASA)
M. Neuzil (NASA)
M. Groff (NASA)
J. Moran (NASA)

Performance/Vehicle Integration/VPS ITD Team

J. Baughman (CAM) /
J. Seidel (NASA)
B. Powell
S. Bitter
D. Elliott
R. Porro (NASA)
T. Curran (NASA)
D. Mavris (Georgia Tech)
D. Dolvan (USAF/VA)
N. Georgiadis (NASA)

Fan & Core-Drive Fan ITD Team

D. Bedel (CAM)
G. Royal
M. Mielke
P. Wood
R. Zenon
M. Mielke
K. Suder (NASA)

Core Engine ITD Team

J. Benson (CAM)
G. Royal
P. Wood
C. Lee
T. Watson
C. Flotner
R. Sorge (NASA)
J. Giriunas (NASA)
R. Wiedenmannott (NASA)

Bearings, Seals, & Drives ITD Team

J. Laritz (CAM)
M. Proctor (NASA)

Controls ITD Team

M. Butz (CAM)
J. Hyer
M. Butz
E. Condrac
D.K. Le (NASA)

Hyperburner/Exhaust Nozzle ITD Team

L. Grammel (CAM)
J. Orr
R. Winslow
L. Pennekamp
J. Koshoffer
J. Lee (NASA)
R. Buerhle (NASA)

Test & Evaluation ITD Team

G. Paulis (CAM) /
R. Sorge (NASA)
J. Bradner
K. Gessner
B. Corcoran
D. Kampman
W. Maciag

Thermal Mgmt Sys ITD Team

T. Tucker (CAM)
N. Georgiadis (NASA)
G. Coffinberry (TK)
B. Bergholz
R. Boehm
B. Brown
A. Mancini
M. Meyer (NASA)

Systems Engr/Materials ITD Team

D. Shafer (CAM)
E. Krammer
S. Draper (NASA)
D. Utah
G. Srini
J. Heidmann (NASA)
J. Waltz (TK)
J. Mehta (TK)
H. Demel) (TK)
D. Edmunds (USAF)
G. Bruening (USAF)

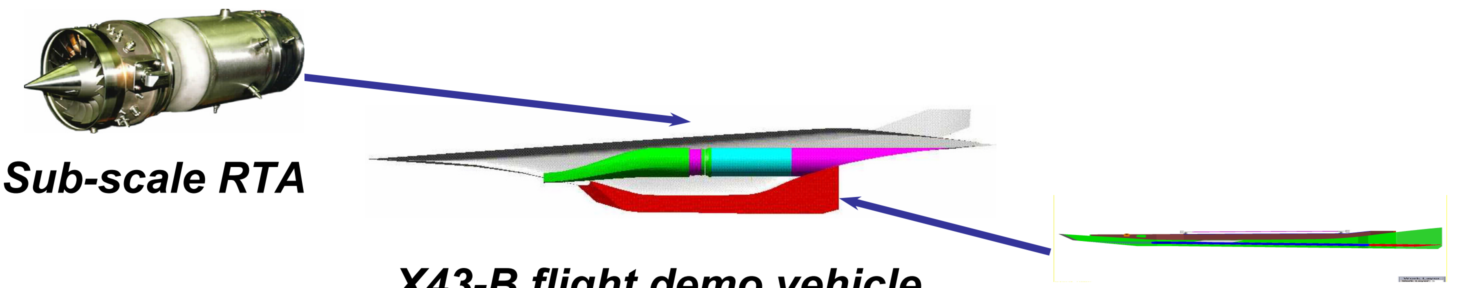
09/27/2002

X43-B Flight Demonstrator Goals & Objectives

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

Goal: Develop and demonstrate a turbine based combination cycle propulsion system for the X43-B flight vehicle to evaluate propulsion/airframe integration and mode transition between low speed and high speed flow paths.

Approach: Mature to PDR level the design of a turbine accelerator and DMSJ flow paths for the X43-B flight demonstrator for a propulsion concept down-select in FY03 (program has slipped this decision to FY06.

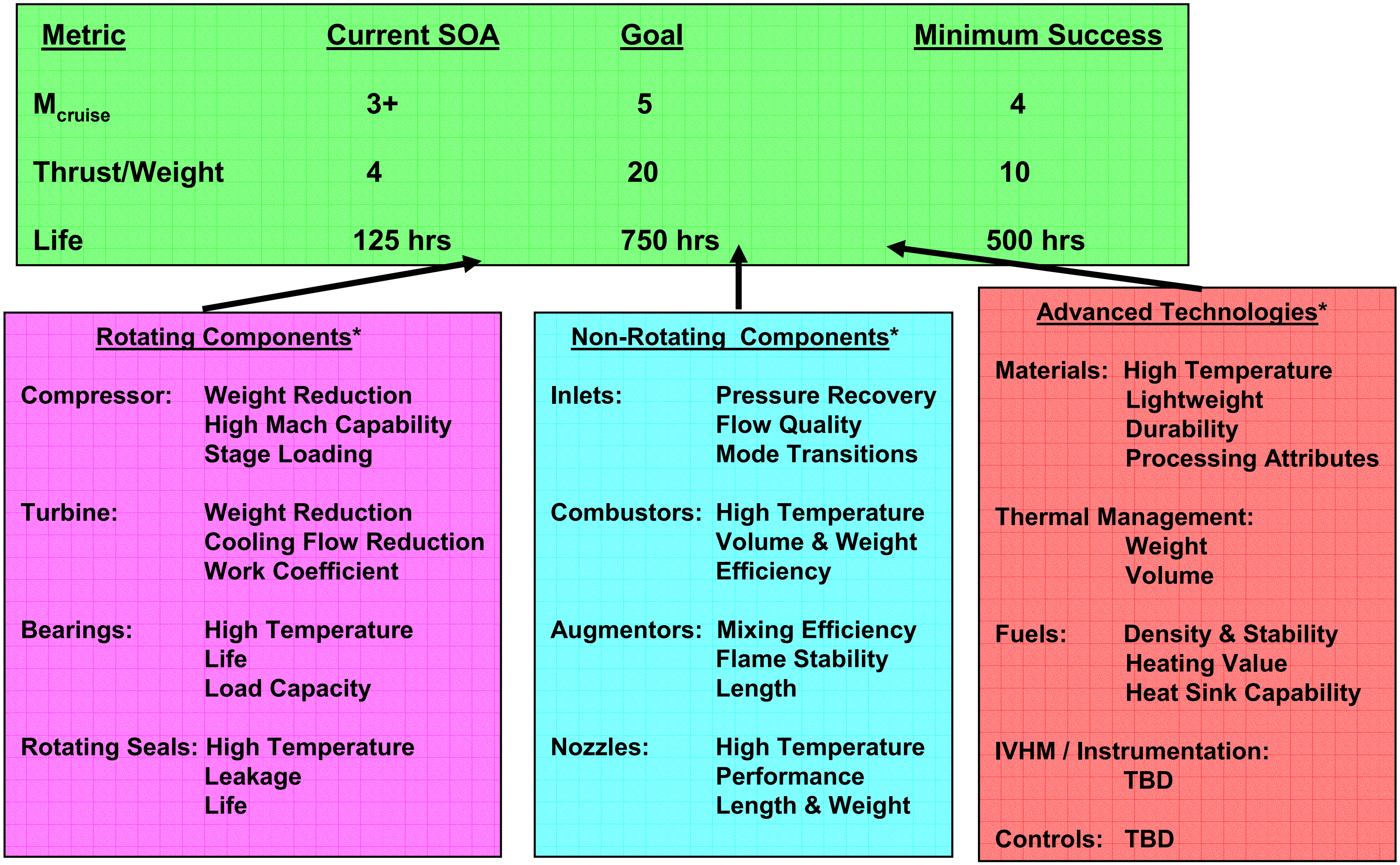


Sub-scale RTA

X43-B flight demo vehicle

Dual Mode Scramjet

RTA Technical Performance Metrics
(Ground Based Testbed)



Metric	Current SOA	Goal	Minimum Success
M_{cruise}	3+	5	4
Thrust/Weight	4	20	10
Life	125 hrs	750 hrs	500 hrs

Rotating Components*

Compressor:	Weight Reduction High Mach Capability Stage Loading
Turbine:	Weight Reduction Cooling Flow Reduction Work Coefficient
Bearings:	High Temperature Life Load Capacity
Rotating Seals:	High Temperature Leakage Life

Non-Rotating Components*

Inlets:	Pressure Recovery Flow Quality Mode Transitions
Combustors:	High Temperature Volume & Weight Efficiency
Augmentors:	Mixing Efficiency Flame Stability Length
Nozzles:	High Temperature Performance Length & Weight

Advanced Technologies*

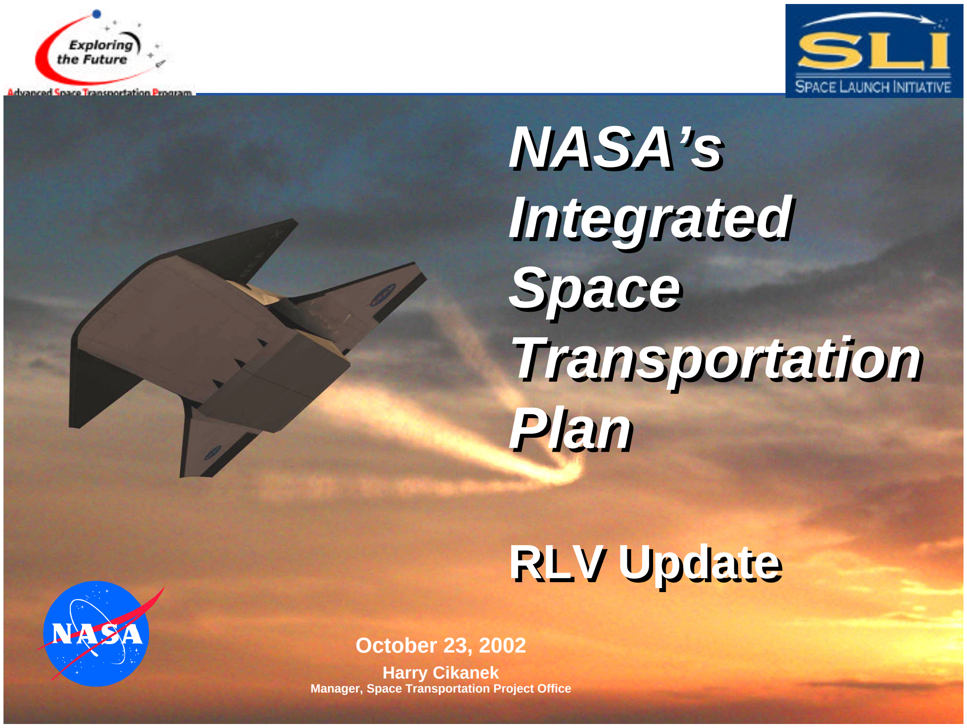
Materials:	High Temperature Lightweight Durability Processing Attributes
Thermal Management:	Weight Volume
Fuels:	Density & Stability Heating Value Heat Sink Capability
IVHM / Instrumentation:	TBD
Controls:	TBD

** All sub-element metric values are TBD until after system cycle selection is complete.*

Note: Thrust, weight, and life will be projected values based on GBT data and acceptable analytical tools

NASA'S INTEGRATED SPACE TRANSPORTATION PLAN

Harry Cikanek
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio



NASA's Integrated Space Transportation Plan

RLV Update

October 23, 2002

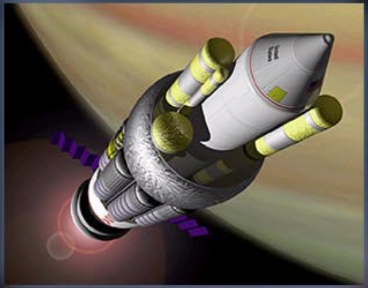
Harry Cikanek
Manager, Space Transportation Project Office

Integrated Space Transportation Plan: A National Plan

Space Shuttle Safety Upgrades

Space Launch Initiative

- 2nd Generation RLV Risk Reduction
- NASA Unique Systems
- Alternate Access to the ISS



3rd Generation RLV and In-Space Research and Technology

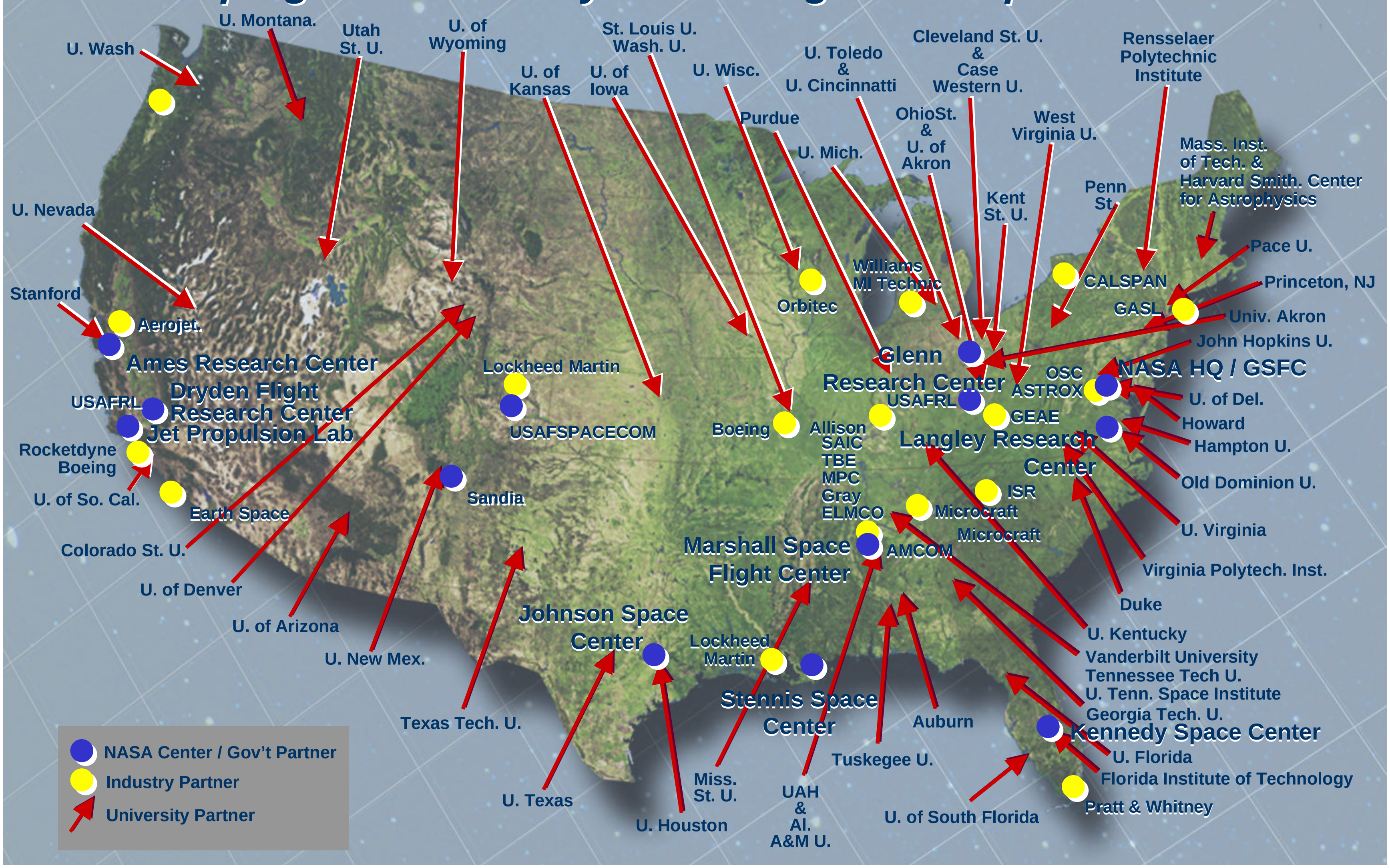
NASA's Long-Term Investment Strategy to Increase the Safety, Reliability and Reduce the Cost of Space Access

Space Transportation - A National Team Effort

Exploring the Future

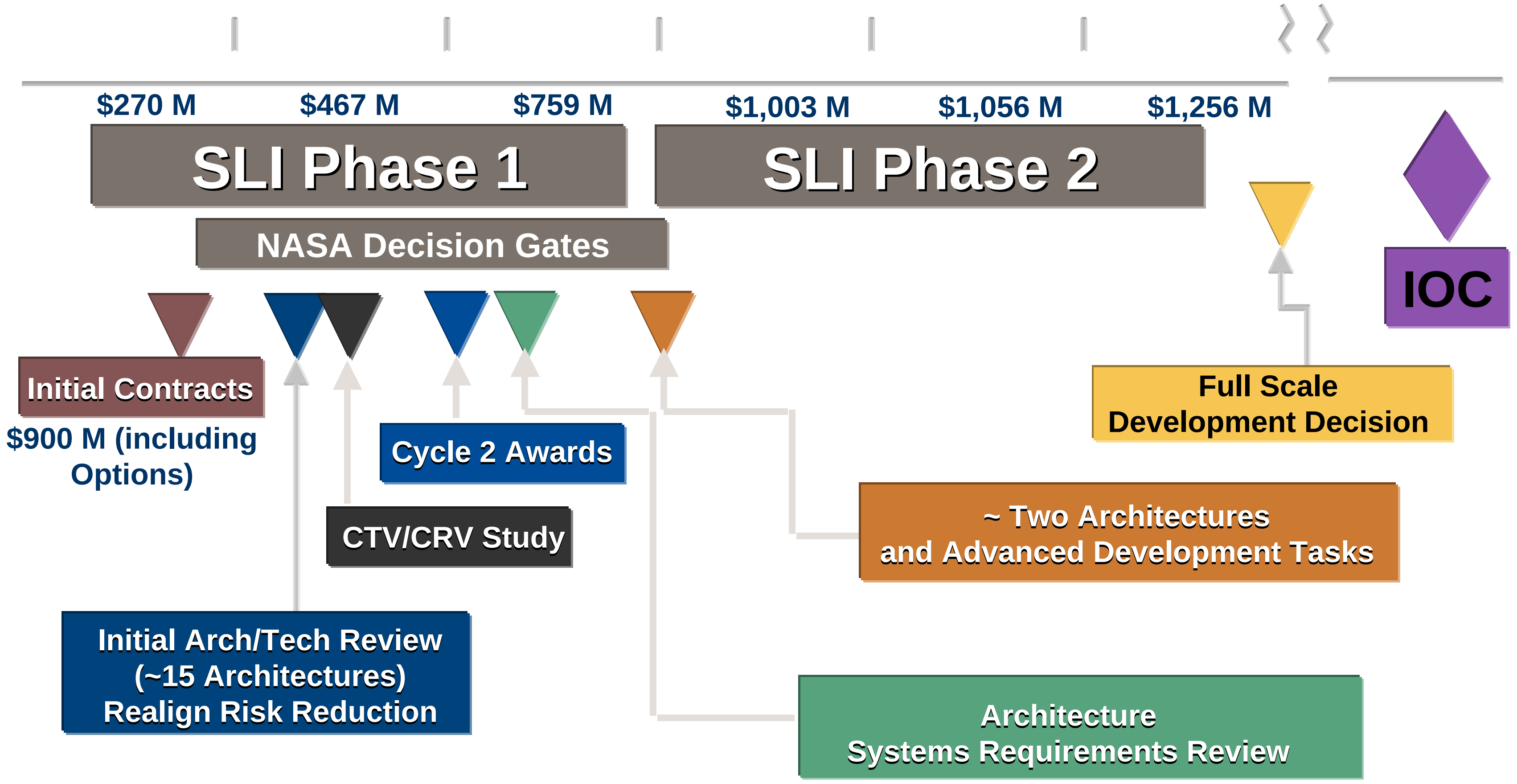
Advanced Space Transportation Program

Developing Revolutionary Technologies to Explore the Future



SLI Program Schedule

- ♦ **Mid-Decade: Full-Scale Development Decision**
- Early Next Decade: Initial Operational Capability



$270 M

$467 M

$759 M

$1,003 M

$1,056 M

$1,256 M

SLI Phase 1

SLI Phase 2

NASA Decision Gates

Initial Contracts

$900 M (including Options)

Cycle 2 Awards

CTV/CRV Study

Initial Arch/Tech Review
(~15 Architectures)
Realign Risk Reduction

~ Two Architectures
and Advanced Development Tasks

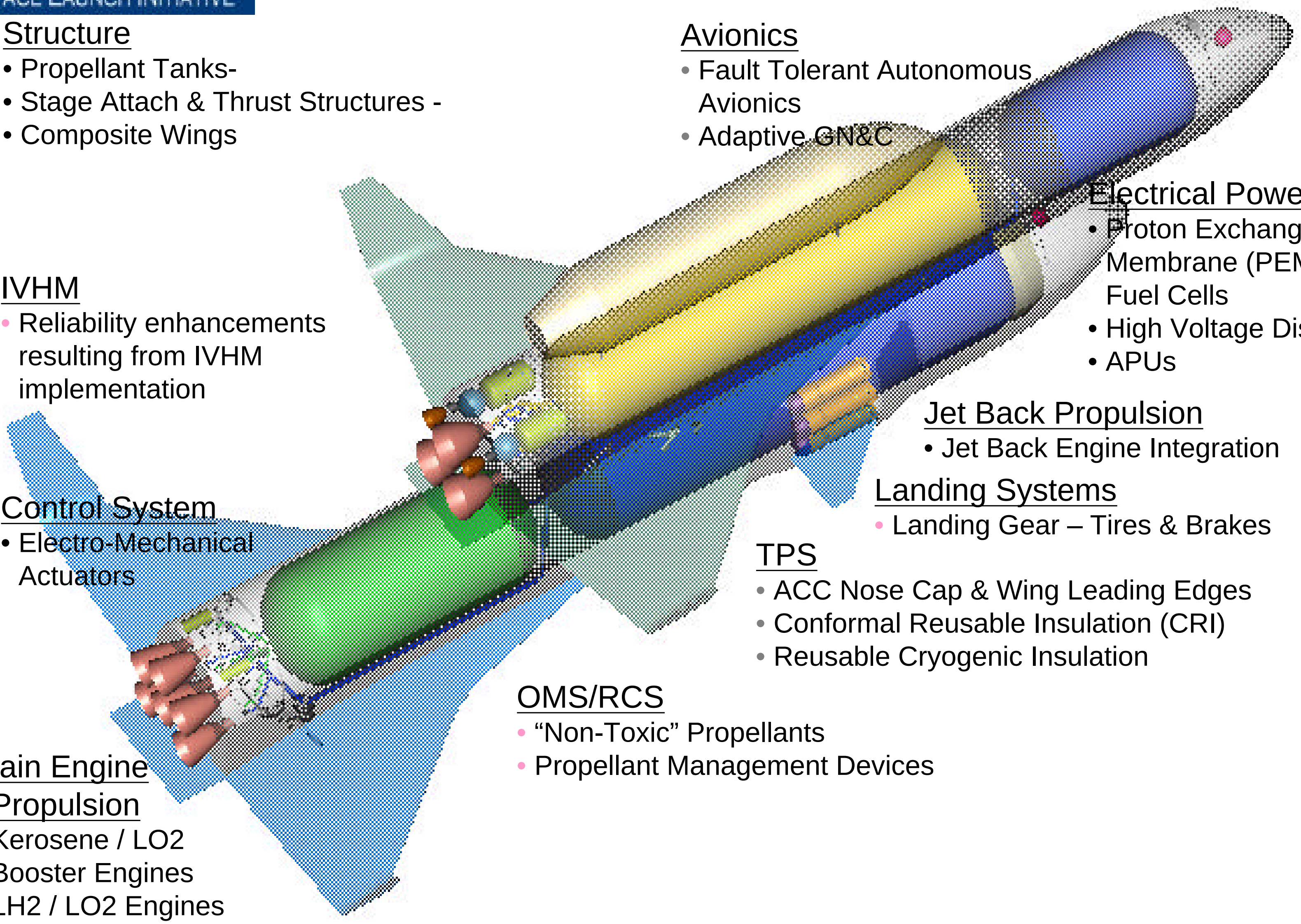
Architecture
Systems Requirements Review

Full Scale
Development Decision

IOC

6047 SLI - 4

Technology Linked To Architecture Needs



Structure
- Propellant Tanks-
- Stage Attach & Thrust Structures -
- Composite Wings

Avionics
- Fault Tolerant Autonomous Avionics
- Adaptive GN&C

Electrical Power
- Proton Exchange Membrane (PEM) Fuel Cells
- High Voltage Dist.
- APUs

IVHM
- Reliability enhancements resulting from IVHM implementation

Jet Back Propulsion
- Jet Back Engine Integration

Landing Systems
- Landing Gear – Tires & Brakes

Control System
- Electro-Mechanical Actuators

TPS
- ACC Nose Cap & Wing Leading Edges
- Conformal Reusable Insulation (CRI)
- Reusable Cryogenic Insulation

OMS/RCS
- “Non-Toxic” Propellants
- Propellant Management Devices

Main Engine Propulsion
- Kerosene / LO2 Booster Engines
- LH2 / LO2 Engines

Exploring the Future
Advanced Space Transportation Program

Air Breathing Hypersonics

Applications and Benefits

Reusable Launch Vehicles

Long-Term
Decade after Next

Hypersonic Cruiser

Mid-Term
Next Decade

Hypersonic Missiles

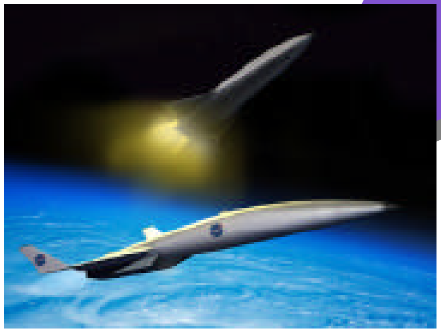
Near-Term
This Decade

Large 3rd Generation RLV Design Space


Horizontal Take-Off SSTO


Vertical Take-Off SSTO

- Over 30 concepts (primarily using airbreathing propulsion)
- Selected by aerospace community (NASA, DOD, Industry)
- Probabilistic systems analysis for key technologies

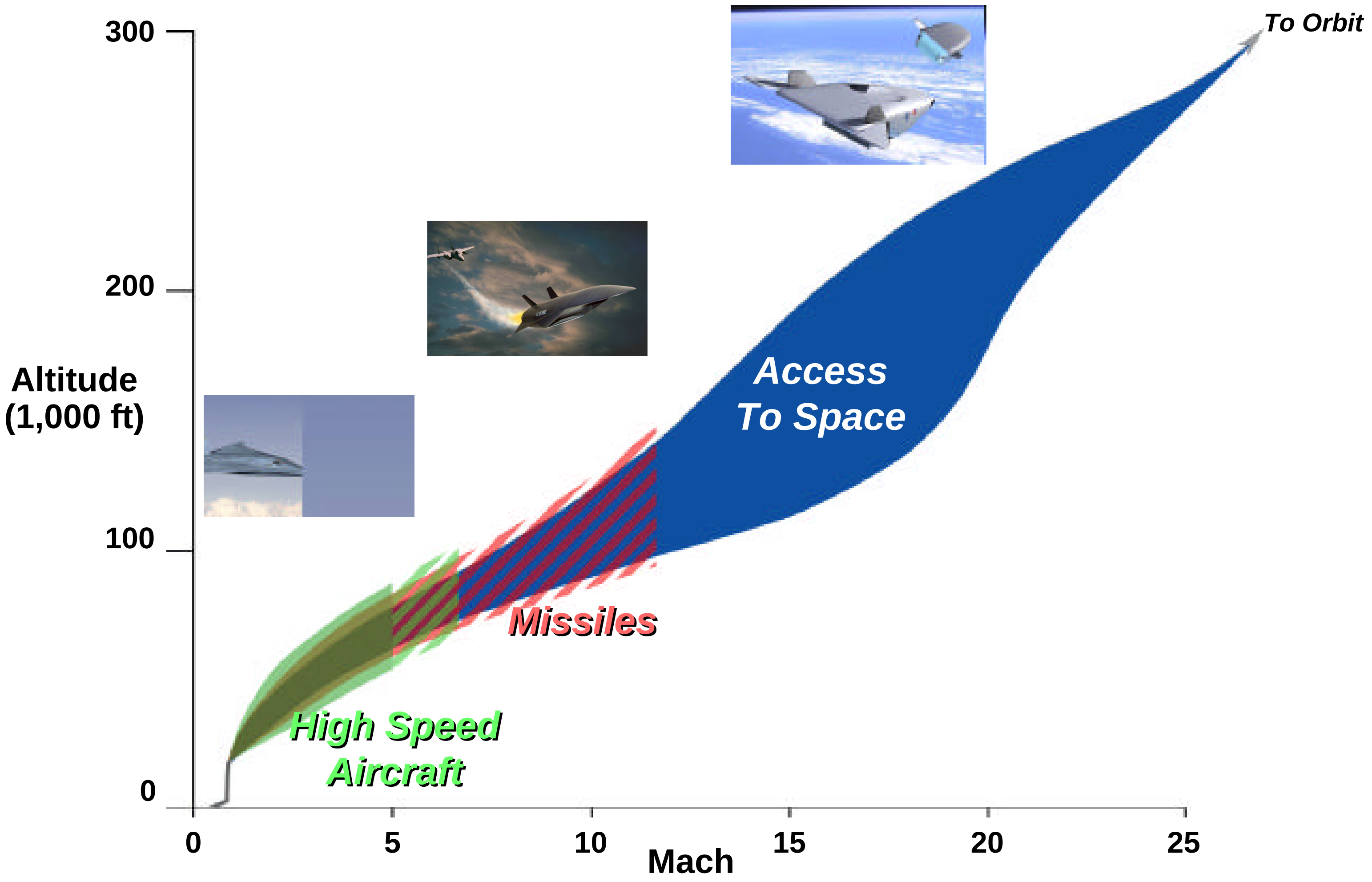

Horizontal Take-Off TSTO


Vertical Take-Off TSTO

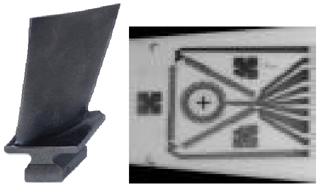
Advanced Space Transportation Program

Representative Flight Corridors

Air Breathing Hypersonic Flight



Technologies and Systems Analysis



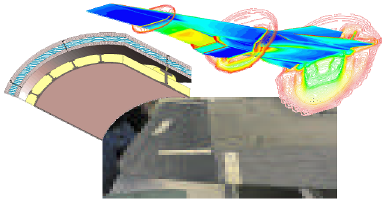
Propulsion Research and Technology Project

- ♦ Rotating Components and Seals
- ♦ Flowpath Components
- ♦ Engineering Capabilities

Pursing Enabling Propulsion and Airframe Technologies

Systems Analysis Project

- ♦ Requirements
- ♦ Synthesis
- ♦ Analysis and Assessment



Airframe Research and Technology Project

- ♦ Integrated Airframe Design
- ♦ Integrated Thermal Structures
- ♦ Thermal Protection
- ♦ Aerothermodynamics
- ♦ Propulsion Airframe Integration

Advanced Space Transportation Program

Propulsion Ground Demonstrations

Rocket Based Combined Cycle Ground Demonstration (ISTAR)

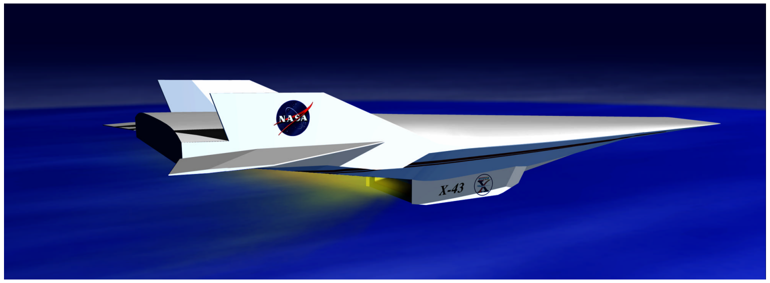
- Demonstration of a Rocket Based Combined Cycle Engine ***System***
- Testing in 2006-8
- Aerojet, Rocketdyne, P&W Consortium (RBC^3)

Pursing Parallel Paths

Turbine Based Combined Cycle Ground Demonstration (RTA)

- Development and test of a High Speed Turbine Engine
- Primary element of a Turbine Based Combined Cycle Engine
- Testing in 2006-8
- General Electric selected in July, 2002

Propulsion Flight Demonstrations



X-43A Flight Demonstrator

- Flight validation of a Ma 7 and 10 Hydrogen Ram/Scramjet
- 2nd Flight in late 2003 (Ma 7)
- 3rd Flight TBD (Ma 10)
- Microcraft/Boeing Team

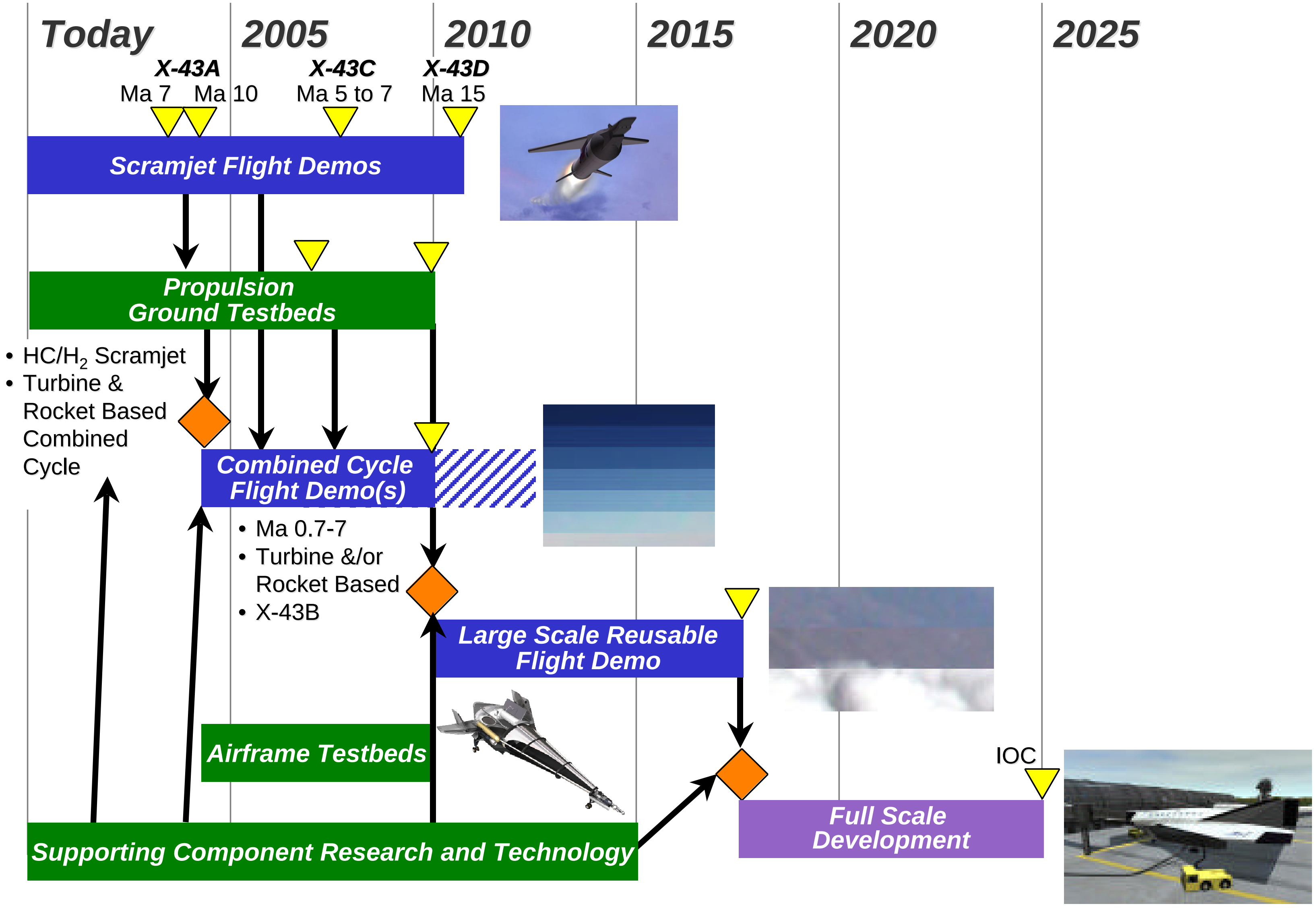
Validation of A Key Element of Any Airbreathing Propulsion System

X-43C Flight Demonstrator

- Flight validation of the USAF HyTECH Hydrocarbon Ram/Scramjet (Ma 5 – 7)
- Integrated with vehicle
- Flights in 2007-8
- Contractor selection in mid-2003

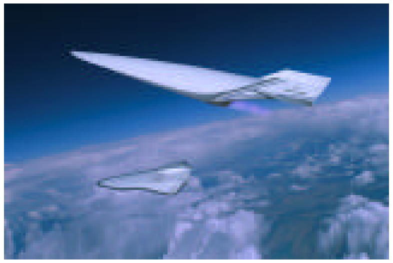
Air Breathing Hypersonics

Access to Space Roadmap

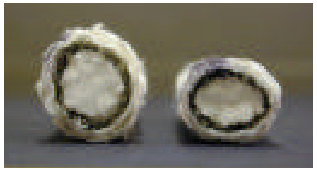


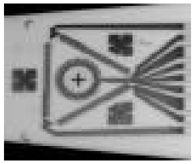
Advanced Space Transportation Program

Propulsion R&T Project Objectives

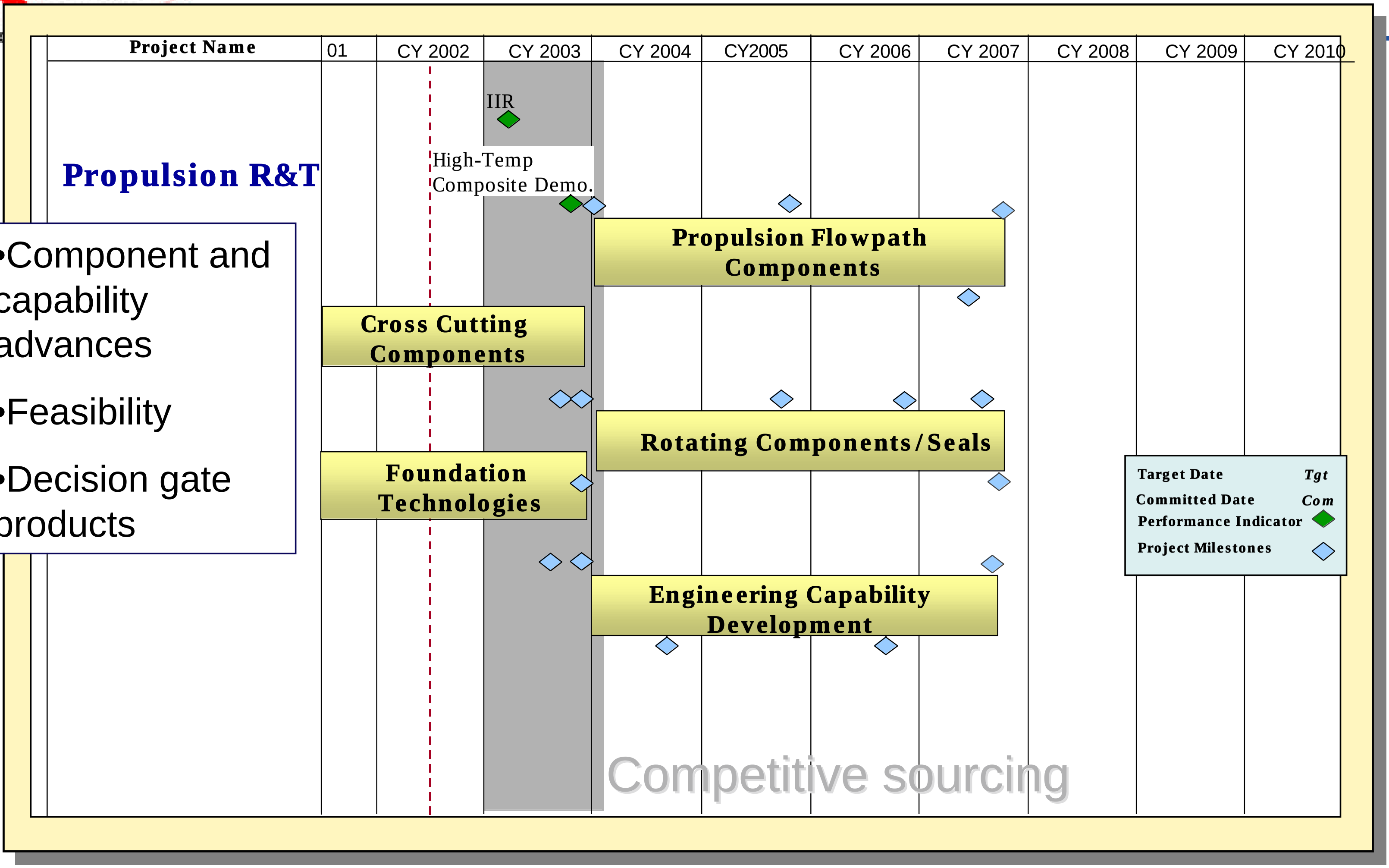


- **FY06 Data Products for Vision Propulsion Design**
  - Technology and Design Advancement
  - Feasibility information
- **Data that feeds FY06 Program Decision Gate(s)**
  - Input for Build 2 definition for Ground Based Demonstrators
  - Identification of technology insertions to flight demonstrators
  - Information for update of program goals, requirements, and vision system design
- **06 Deliverables**
  - Actively cooled panels characterization
  - Rotating component materials
  - High temperature seals
  - Instrumentation





Propulsion R&T Project Elements



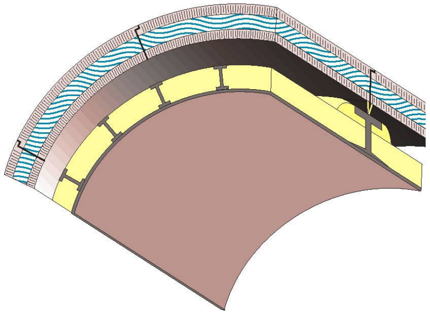
- Component and capability advances
- Feasibility
- Decision gate products

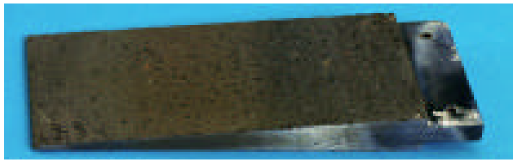
Project Overview

- **Airframe project goal**
  - Advance airframe technology providing reduced cost and increased safety through increased performance margin and reusability

- **Performance margin and reusability will be increased by focusing efforts on airframe technical challenges such as**
  - Composite tanks
  - Light weight control surfaces
  - Hot structures
  - TPS
  - Boundary layer transition
  - Transonics
  - Design and analysis tools
  - Sharp leading edges
  - Dynamic seals
  - Health monitoring

- **Customer driven objectives**
  - Increased weight margin
  - Increased combined loads margin
    - Thermal
    - Structural
    - Acoustic
    - Aero/aerothermo
  - Increased operational margin





Airframe Project Tasks

- ♦ **Integrated Airframe Design**
  - Airframe Health Monitoring
  - Analysis and Design Tools
- ♦ **Integrated Thermal Structures and Materials**
  - PMC Constituents and Processes
  - Metallic Hot Structures for Airframe
  - CMC Constituents and Processes
  - Integrated Airframe Structure Development
- ♦ **Thermal Protection Systems**
  - Ceramic Acreage TPS
  - Refractory Composite Leading Edges
  - Advanced Control Surface Seals
- ♦ **Aerothermodynamics**
  - Rapid Aerothermodynamic Environment Definition
  - Essential Aerothermodynamic Technologies
- ♦ **Propulsion Airframe Integration**
  - Scramjet Flowpath Development and Aero-Propulsive Interaction
  - Airframe/Propulsion Aerothermodynamic Technologies

Hypersonics University Research and Engineering Technology Institutes

◆ URETIs were awarded in August to University of Florida and University of Maryland consortiums

University of Florida

- Principal Investigator: Dr. Wei Shyy
- University Partners
    - Mississippi State University
    - Cornell University
    - Georgia Institute of Technology
    - Syracuse University
    - North Carolina A&T State University
    - Prairie View A&M University

- Propulsion Technologies
- Airframe Technologies
- Vehicle Life Prediction and Health Management
- Systems Integration & Design Optimization
- Educational Program Plan

University of Maryland

- Principal Investigator: Dr. Mark Lewis
- University Partners
    - University of Michigan
    - University of Washington
    - North Carolina A&T State University
    - Johns Hopkins University (APL):

- Mission Analysis
- Cost and Reliability Analysis
- Propulsion
- Aerodynamics/Configuration
- Structures and Materials
- Education Program Plan

The NASA/USAF

X-43C

Seal WBS Linkages

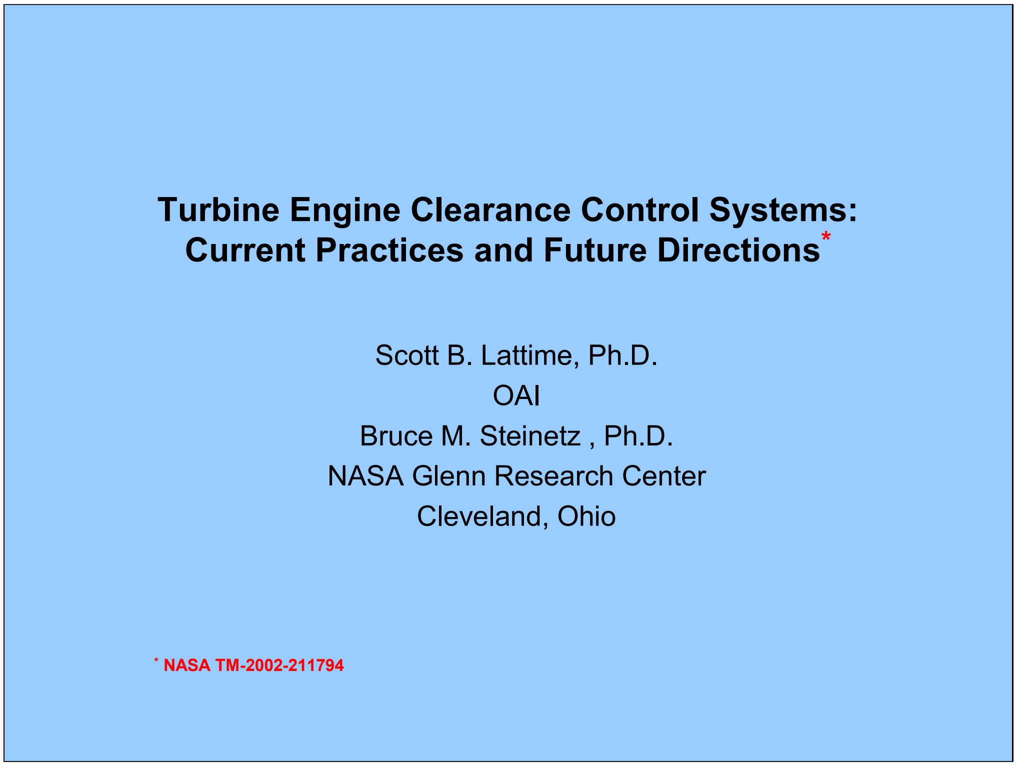
- ♦ **Propulsion System - Structural Architecture**
  - Hot Seals for the Propulsion Flowpath
    - Static
    - Dynamic

- ♦ **Airframe – Structural Architecture**
  - Airframe and Control Surface Seals
    - Static
    - Dynamic

TURBINE ENGINE CLEARANCE CONTROL SYSTEMS: CURRENT PRACTICES AND FUTURE DIRECTIONS

Scott B. Lattime
Ohio Aerospace Institute
Brook Park, Ohio

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



Turbine Engine Clearance Control Systems: Current Practices and Future Directions[*]

Scott B. Lattime, Ph.D.
OAI
Bruce M. Steinetz , Ph.D.
NASA Glenn Research Center
Cleveland, Ohio

[*] **NASA TM-2002-211794**

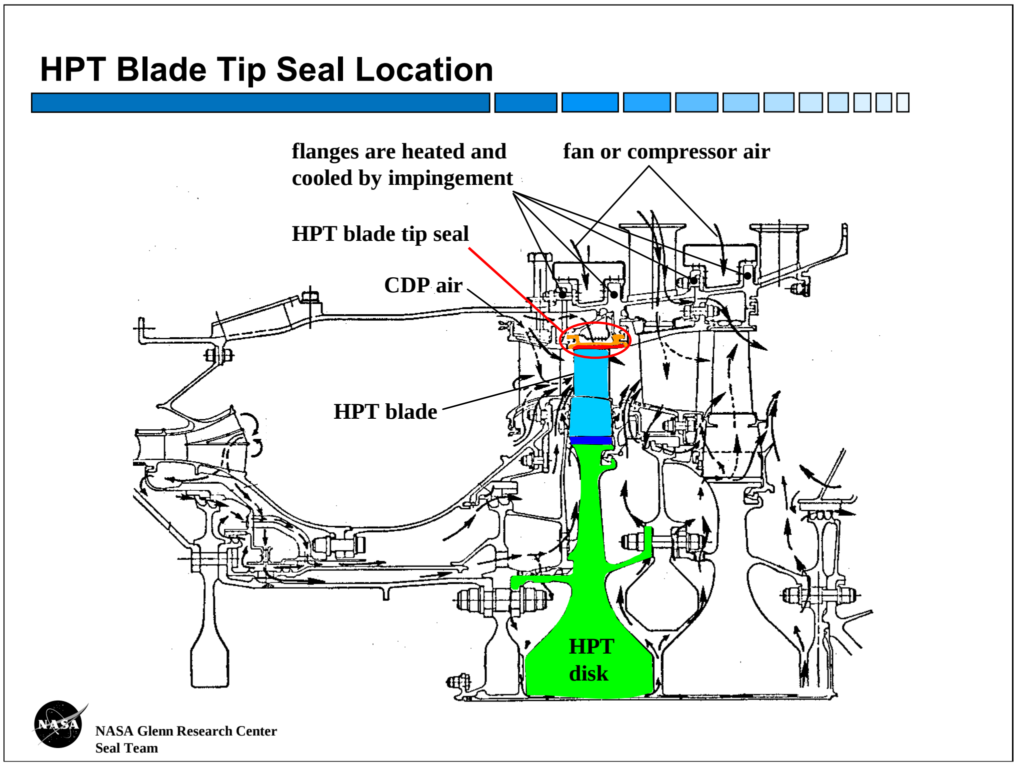
This presentation reviews the

(i) Cause and effect of gas turbine blade tip seal wear

(ii) Current clearance control practices

(iii) Present approaches under investigation at GRC

This work can be found in the recently published NASA/TM-2002-211794.



HPT Blade Tip Seal Location

NASA Glenn Research Center
Seal Team

Blade tip seal location in a modern gas turbine. Cross section combustor and 2-stage turbine.

Tip sealing is a challenging problem due to the speed (1500 fps), temp (2500F), and varying clearance. More so in aero engines due to the frequency of changes in operating points and aero and inertia loads.

Turbine engine is highly evolved. Still room for improvement.

Why HPT Tip Clearance?

Specific Fuel Consumption/Fuel Burn

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

Service Life

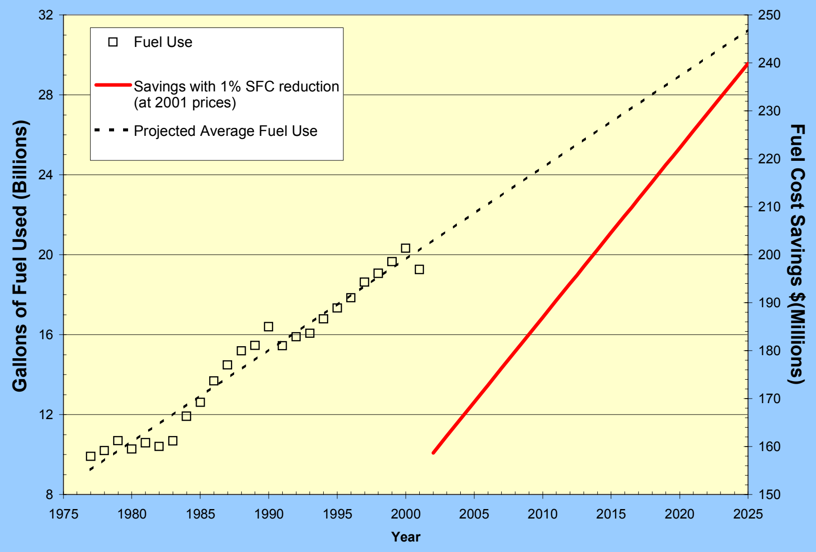
- Deterioration of exhaust gas temperature (EGT) margin is the primary reason for aircraft engine removal from service.
- 0.010-in tip clearance is worth ~10 ºC EGT.
- Allows turbine to run at lower temperatures, increasing cycle life of hot section and engine TOW (≥ 1000 cycles).
- Maintenance costs for overhauls can easily exceed $1M.

HPT Reaps the Most Benefit Due to ACC

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

NASA Glenn Research Center
Seal Team

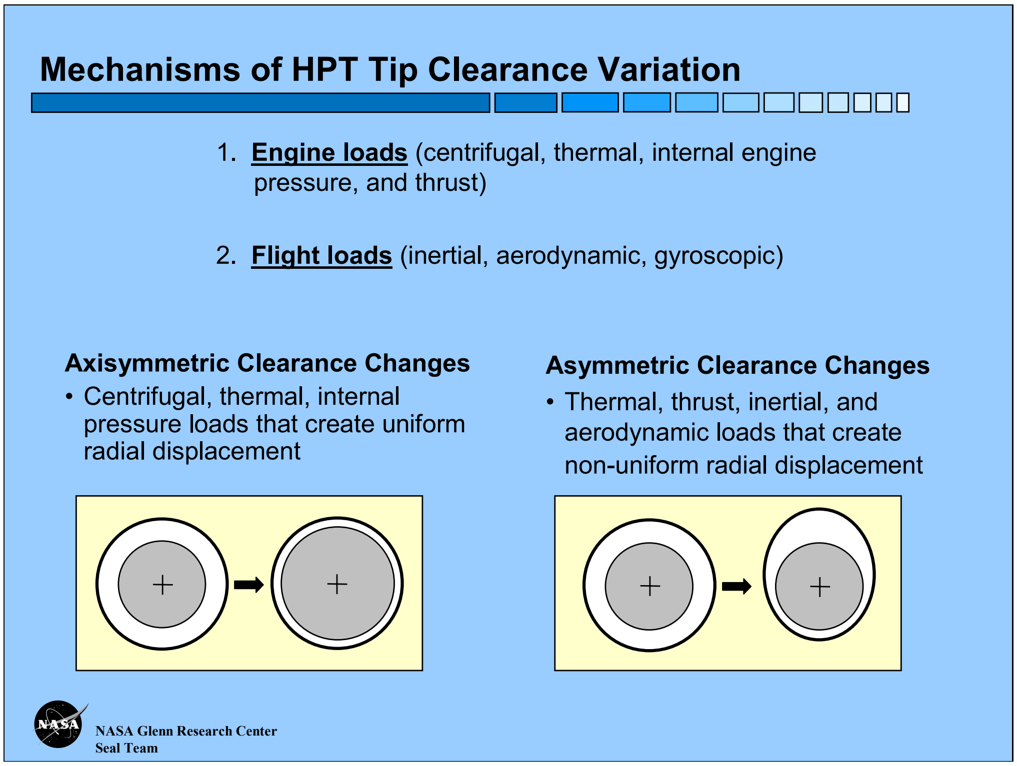
Projected Cost Savings for a 1% Reduction in SFC



NASA Glenn Research Center
Seal Team

Chart shows the projected U.S. carriers fuel use based on usage over the last 25 years and the projected cost savings for a 1% reduction in fuel use (based on 2001 fuel prices).

For this year alone, a 1% reduction in fuel use is shown to save $160M. Yearly savings are shown to grow to almost a quarter of a billion dollars in 2025.



Mechanisms of HPT Tip Clearance Variation

1. **Engine loads** (centrifugal, thermal, internal engine pressure, and thrust)
2. **Flight loads** (inertial, aerodynamic, gyroscopic)

Axisymmetric Clearance Changes

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

Asymmetric Clearance Changes

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

NASA Glenn Research Center
Seal Team

Tip clearance varies over the operating points of the engine.

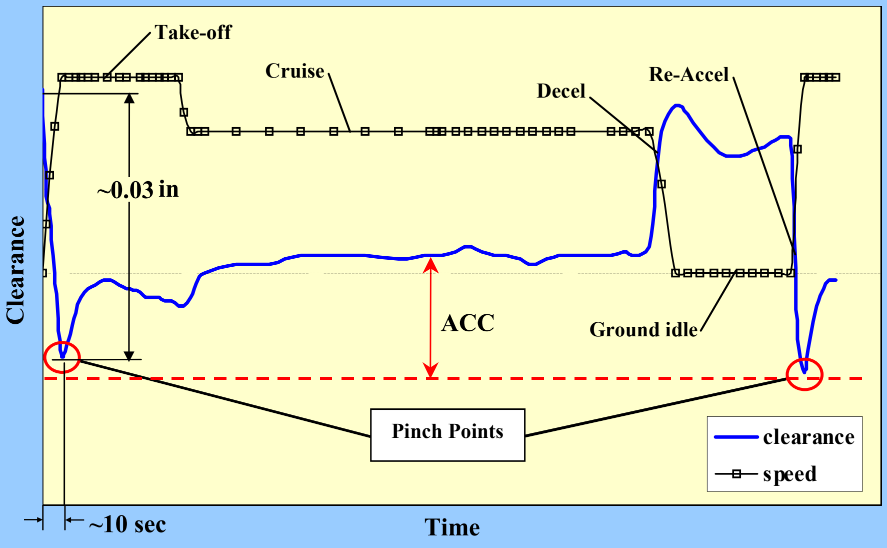
Mechanisms behind these variations comes from the displacement or distortion of both static and rotating components due to a number of loads.

Loads can be separated into 2 categories: engine and flight.

Engine loads produce both axisymmetric and asymmetric clearance changes.

flight loads produce both asymmetric clearance changes.

Axisymmetric Clearance Changes Due to Centrifugal and Thermal Loads



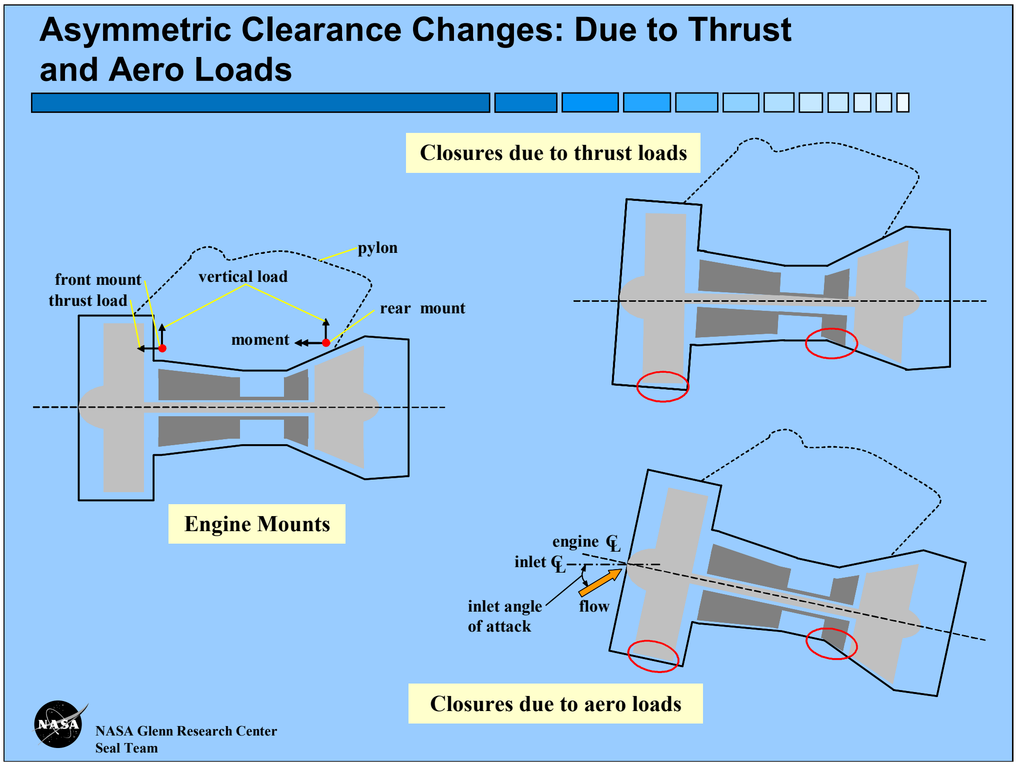
NASA Glenn Research Center
Seal Team

Shows the rotor and case response to axisymmetric centrifugal and thermal loads at various operating points for a given mission profile.

Walk through the major points of the profile: takeoff, cruise, decel, and reaccel.

Object of ACC is to bring down clearance during cruise. Current ACC is not fast enough to respond to throttle transients (step change in altitude maneuver), must maintain adequate clearance.

Fast ACC system can bring down cruise clearance and possible track throttle transients (takeoff, reaccel) to lower EGT and increase service life.



Asymmetric Clearance Changes: Due to Thrust and Aero Loads

Closures due to thrust loads

Engine Mounts

Closures due to aero loads

NASA Glenn Research Center
Seal Team

Asymmetric clearance changes are due to non-uniform loading (thermal, thrust, inertial, aero) on the stator components.

Non-uniform heating can cause ovalization of the case. Asymmetric distortion can also come from aero, thrust and maneuver loads.

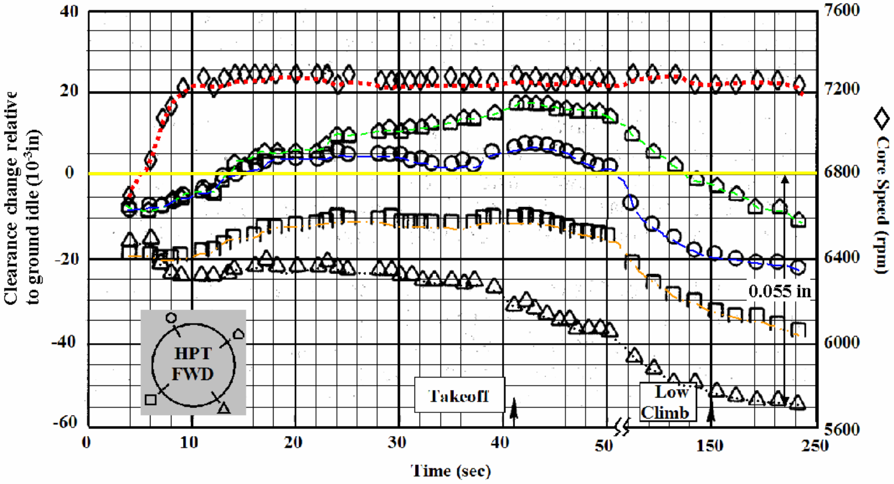
Engine not mounted on centerline, aero and thrust load reactions create an applied moment on the case, causing it to bend relative to the rotor.

Aero pressure on the inlet cowl create shear forces and bending moments on the fan case that can carry through the engine. distort the case such that closure occurs at 6 o’clock. Greatest after takeoff rotation.

During takeoff, thrust loads create a downward pitch moment causing clearances to open towards the top of the engine, while closing at the bottom (backbone bending).

The opposite is true during reverse thrust.

Engine and Flight Load Effects During Takeoff on HPT Clearance of JT9D Engine



Olsson and Martin, 1982

NASA Glenn Research Center
Seal Team

Shows actual HTP clearance change due to both engine and flight loads during takeoff for a JT9D engine.

Clearance probe locations are shown.

Minimum clearance shown to occur at the 5 o’clock position.

Closure is initially due to centrifugal forces with engine acceleration. As engine continues acceleration to takeoff power, clearances open axisymmetrically due to heating of the case.

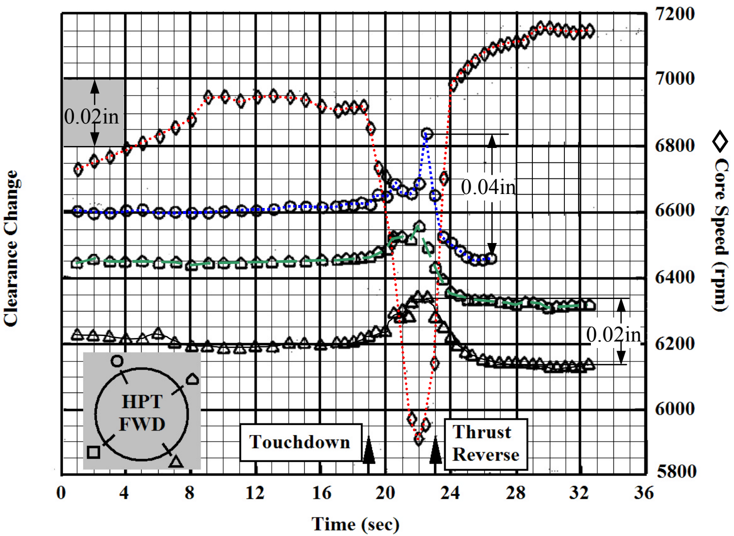
Clearances soon begin closing along the bottom half of the HPT and open along the top due to increased thrust load.

The asymmetric effect is further increased due to aero pressure loads on the inlet cowl which transmit back to the HPT during climb.

The chart shows the aero effects to be most intense just after takeoff rotation when the angle of attack is greatest and begin to decrease after low climb when this angle decreases.

We see that the maximum closure relative to ground idle is about 55 mils, occurring at the 5 o’clock position.

Engine and Flight Load Effects During Hard Landing and Reverse Thrust on HPT Clearance of JT9D Engine

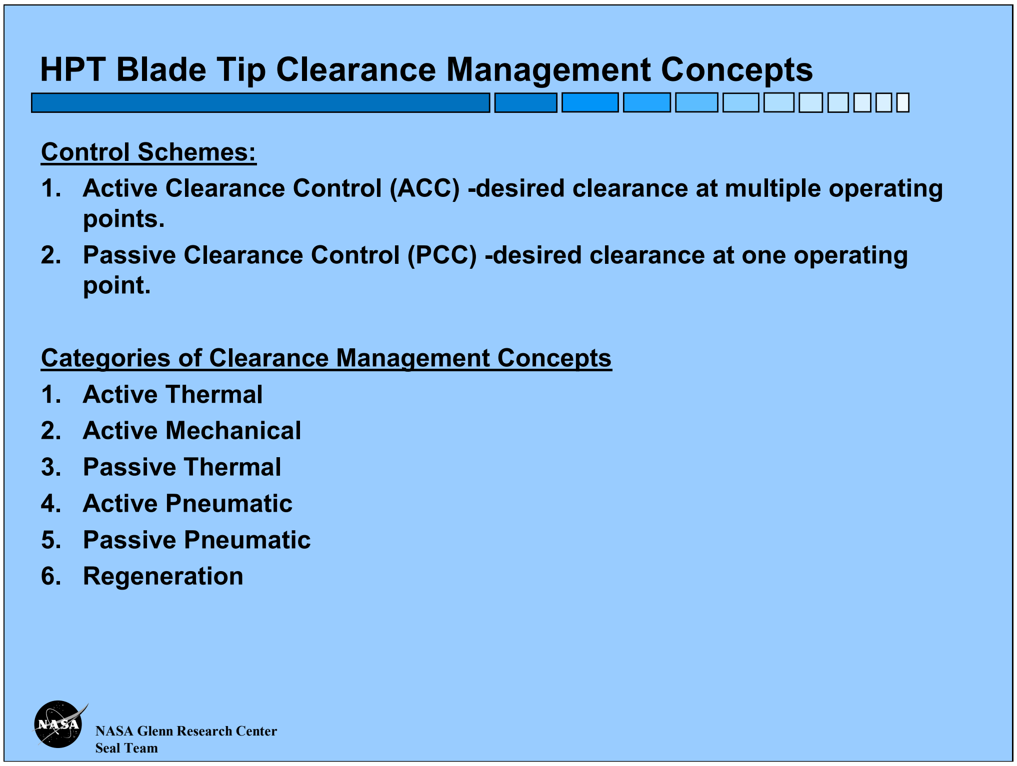


Olsson and Martin, 1982

This chart again shows clearance data for a JT9D but this time during a hard landing and thrust reverse.

The landing had a sink rate of 5 ft/s and a gross weight of 690,000 lb, which was much higher than revenue service. Chart shows that the landing had no effect on HPT clearance.

Reverse thrust, however, is shown to produce backbone bending with closure effects opposite to that during takeoff. We see that closure now occurs along the top half of the engine rather than the bottom.



HPT Blade Tip Clearance Management Concepts

Control Schemes:

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

Categories of Clearance Management Concepts

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

NASA Glenn Research Center
Seal Team

Tip clearance management categorized by 2 control schemes: active and passive.

PCC is any system that sets the desired clearance at one operating point, namely the most severe transient condition.

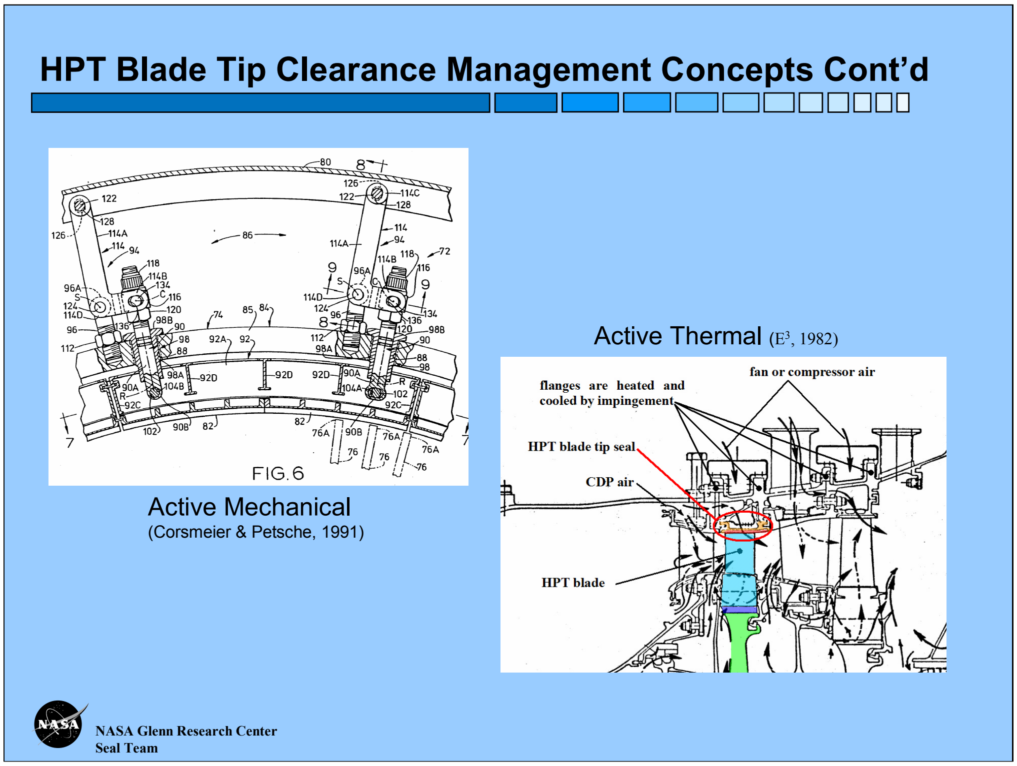
ACC is any system that sets the desired clearance at more than one operating point.

Problem with PCC is that the minimum clearance that the system must accommodate leaves an undesired larger clearance during the cruise portion of the flight where the most benefits of SFC are gained.

PCC systems include matching of rotor and stator growth, using abrabables to limit blade tip wear, using stiffer materials and applying maching techniques to limit distortion of static components to improve roundness.

Engine manufacturers began using ACC in the late 70's and early 80's. These systems utilize fan air to cool the support flanges of the HPT and LPT during cruise, and hence reducing tip seal clearance.

There have been an abundance of PCC and ACC concepts patented in the U.S. alone. Most of these concepts can be placed into 5 categories: active thermal, mechanical, and pneumatic, and passive thermal and pneumatic.



HPT Blade Tip Clearance Management Concepts Cont'd

Active Mechanical
(Corsmeier & Petsche, 1991)

Active Thermal (E^3, 1982)

NASA Glenn Research Center
Seal Team

Active thermal concepts utilize both fan and compressor stage air to respectively cool (contract) or heat (expand) the HPT shroud and hence vary tip clearance.

These concepts remain the staple technology for clearance control in modern engines.

These systems are limited by their slow thermal response and must therefore allow for adequate clearance in the event of throttle transients during cruise (step change in altitude).

Active mechanical concepts combine linkages and some actuation (hydraulic, electro-mechanical, magnetic, etc.) to vary tip clearance.

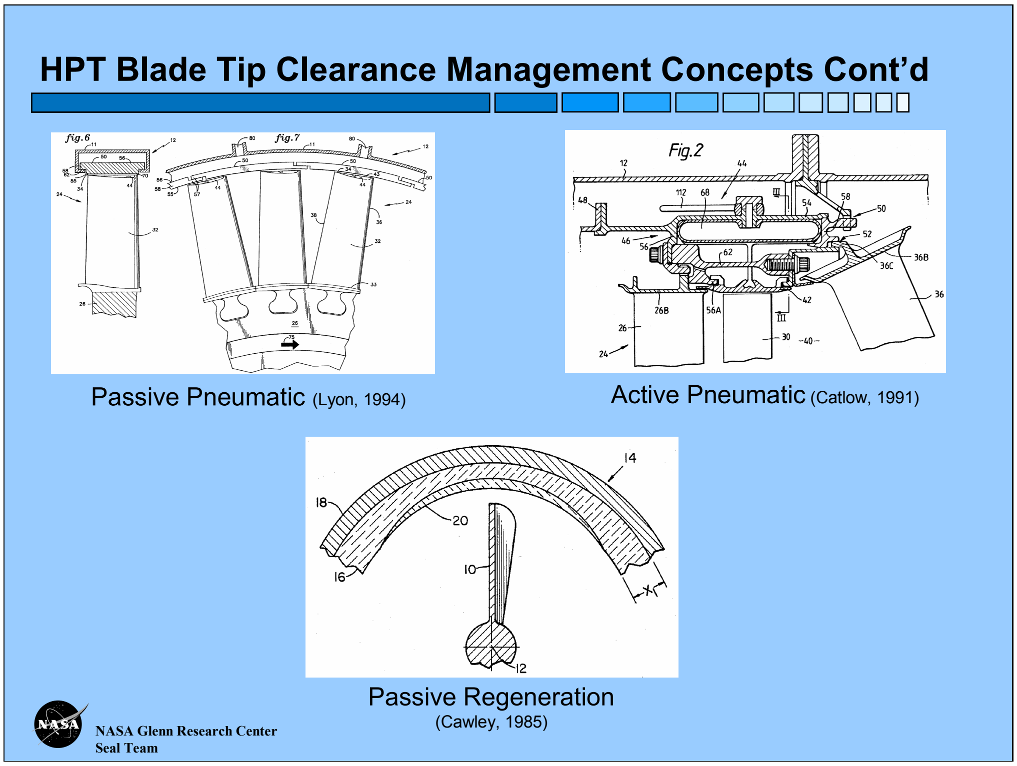
This can be done with a segmented shroud with the segments connected to a unison ring.

These concepts usually require actuation through the case due to the lack of radial space and high temperature actuators.

Mechanically active systems are subject to secondary sealing, tolerance stack-ups, as well as increased weight and complexity. While these issues may be overcome, the biggest issue is positioning control.

Currently, no clearance measuring systems exist which can reliably survive the operating temps and vibration levels at the HPT tip seal location for extended periods of time (50hrs).

Hopefully this issue will soon be resolved with on-going research in high temperature sensor electronics.



HPT Blade Tip Clearance Management Concepts Cont’d

Passive Pneumatic (Lyon, 1994)

Active Pneumatic (Catlow, 1991)

Passive Regeneration
(Cawley, 1985)

NASA Glenn Research Center
Seal Team

Active pneumatic concepts utilize internally generated engine pressures or externally generated pressures and valving to load deflectable, sealed shroud segments directly or through some bellows arrangement to radially vary tip clearance.

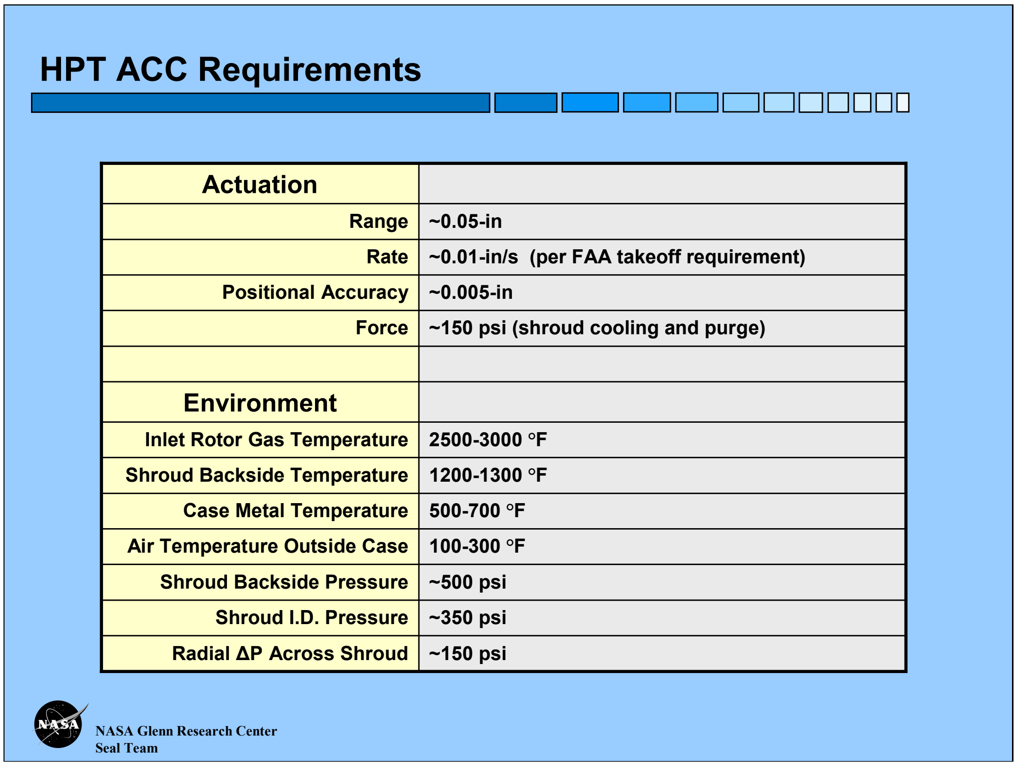
These concepts would be subject to HCF and are very sensitive to pressure balancing. They could require a great deal of system or auxiliary pressure.

Passive pneumatic systems are driven by engine generated pressures or hydrodynamic effects.

These systems are again subject to HFC, pressure balancing, and in the case of hydrodynamic, extremely high positioning and alignment tolerances.

The previous systems all dealt with passive or active variation of tip clearance with the intent of avoiding rubs. Another category exists called regeneration.

Concepts in this category utilize passive and active control to restore worn tip seals due to rubs and erosion.



HPT ACC Requirements

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

NASA Glenn Research Center
Seal Team

The largest HPT tip clearance variations are due to centrifugal and thermal growth of the rotor during takeoff and reburst conditions.

The FAA requires engines reach 95% rated takeoff power from flight idle in 5.0 seconds. this would require actuation systems that can provide radial clearance change on the order of 0.010-in/s.

Positional and dimensional accuracy is extremely important in a gas turbine engine. Sealing and rotor dynamic issues depend on high manufacturing and assembly tolerances.

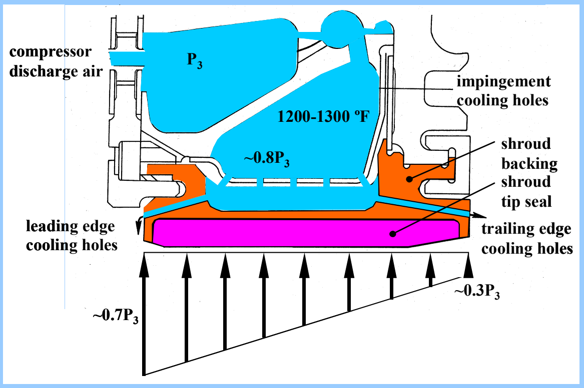
Any mechanical ACC system that is attempting to control tip clearances to within 0.010-in or better must be precisely designed.

The backside of the HPT shroud is cooled and purged with compressor discharge air (1200-1300 ºF). The radial pressure difference across the shroud creates a load inward to the shaft centerline.

An ACC system must be able to overcome this load as well as the resultant moment created by the non-uniform axial pressure distribution.

Actuator Force Due to Shroud Cooling and Purge

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

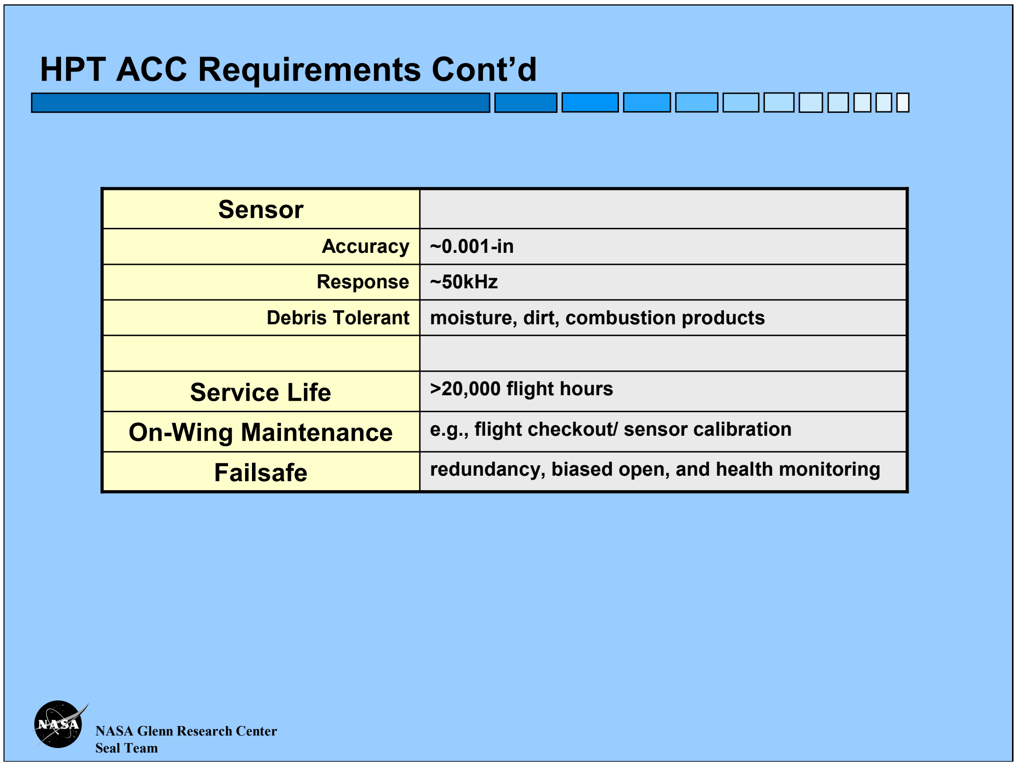


Example:

Shroud i.d: 30-in, width: 2-in
ave Δp: 120-psi
→ 240 lbf/in on the shroud diameter

no. of shroud segments: 16, ~6-in long,
→ 1,440 lbf per segment.

NASA Glenn Research Center
Seal Team



HPT ACC Requirements Cont'd

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

NASA Glenn Research Center
Seal Team

Researchers and engine manufacturers have been using blade tip sensors for over 30 years.

Many different technologies have been utilized for this purpose including x-ray, capacitive, inductive, optical, eddy-current, microwave, and acoustic.

Typical blade passage sensors provide the ability to measure blade tip clearance and time of arrival.

Tip clearance measurement may be required for any ACC systems that are to improve upon and replace the current technology.

The sensors should have accuracy on the order of 0.001-in. The sensors must have accuracies well below the inherent engine and ACC system tolerance stack ups.

For clearance measurement, sensor response should be on the order of 50kHz. This response will allow multiple clearance measurements per blade for large engines.

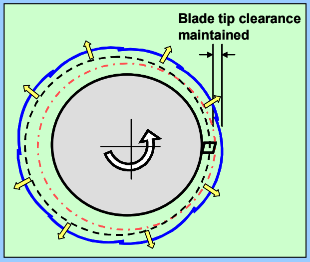
Any system that can affect the operation of the engine must be failsafe. For ACC systems, if adequate clearance is not maintained during any portion of engine operation, significant damage to shrouds and rotor components may result.

This could create an in-flight engine failure if closure is severe enough.

Sensor and actuator redundancy, biased clearance opening, and ACC system health monitoring are techniques that can be used to achieve failsafe operation.

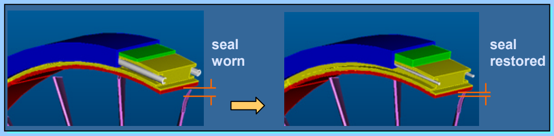
Approaches Under Investigation & Benefits

Fast rub-avoidance ACC system

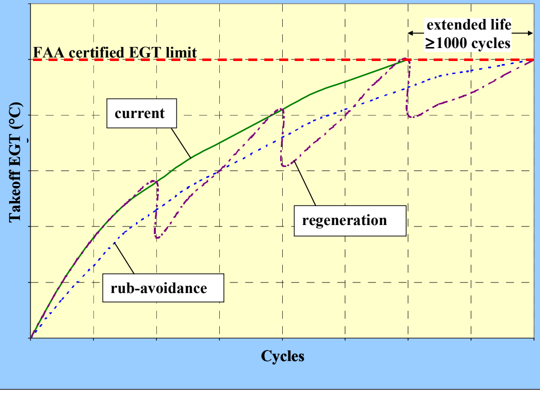


- Smart case avoids blade rubs
- 50x faster and provides 30-50% reduced clearances over current, slow-response case cooling systems

Regenerative seal material systems

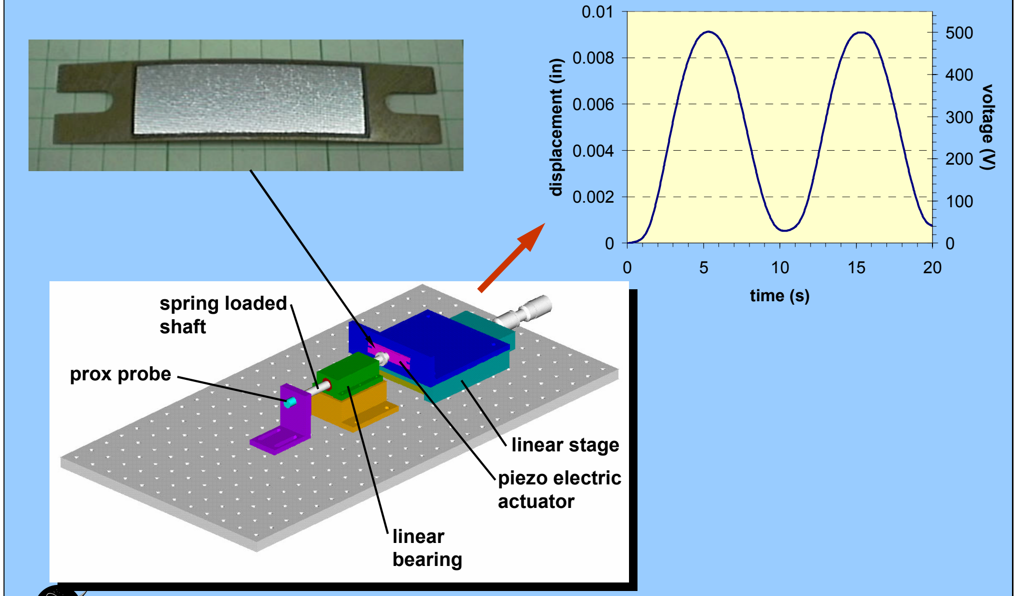


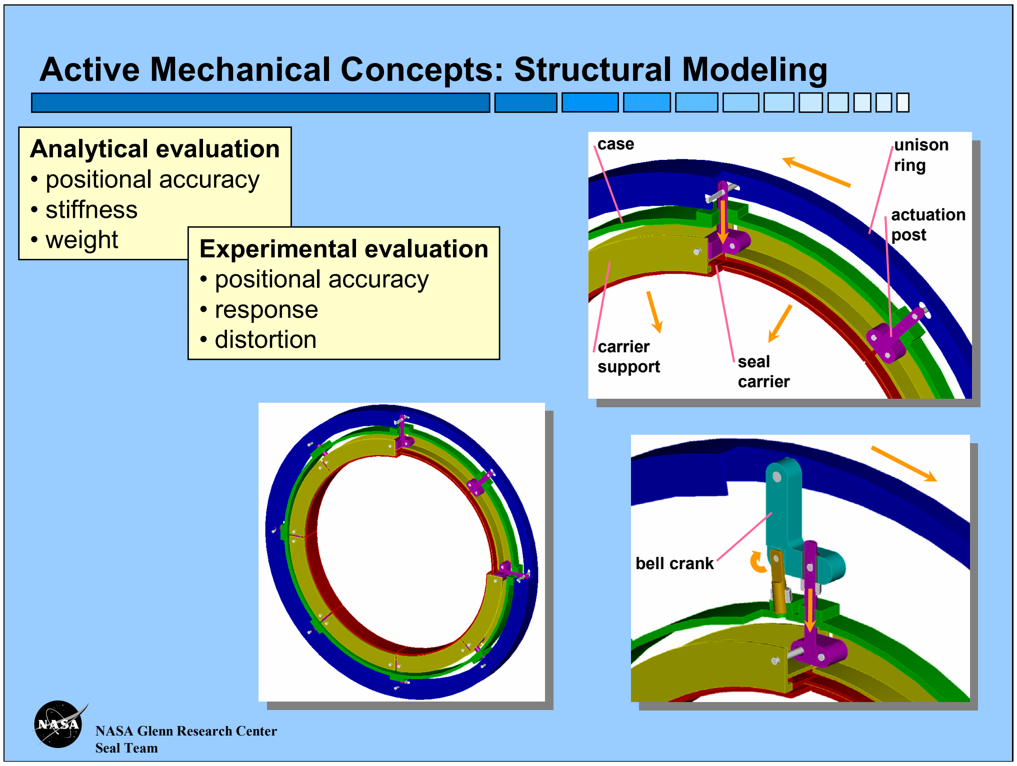
- Specially engineered materials grow to restore clearance
- Potential for operating in HPT using passive or active control



NASA Glenn Research Center
Seal Team

Smart Materials & Actuators: Piezoelectric





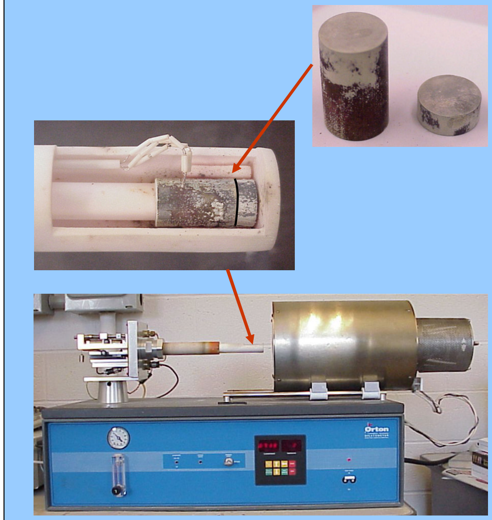
Active Mechanical Concepts: Structural Modeling

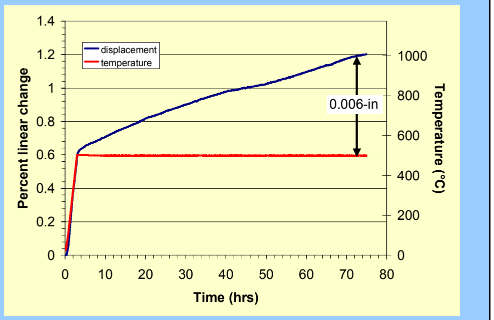
Analytical evaluation
- positional accuracy
- stiffness
- weight

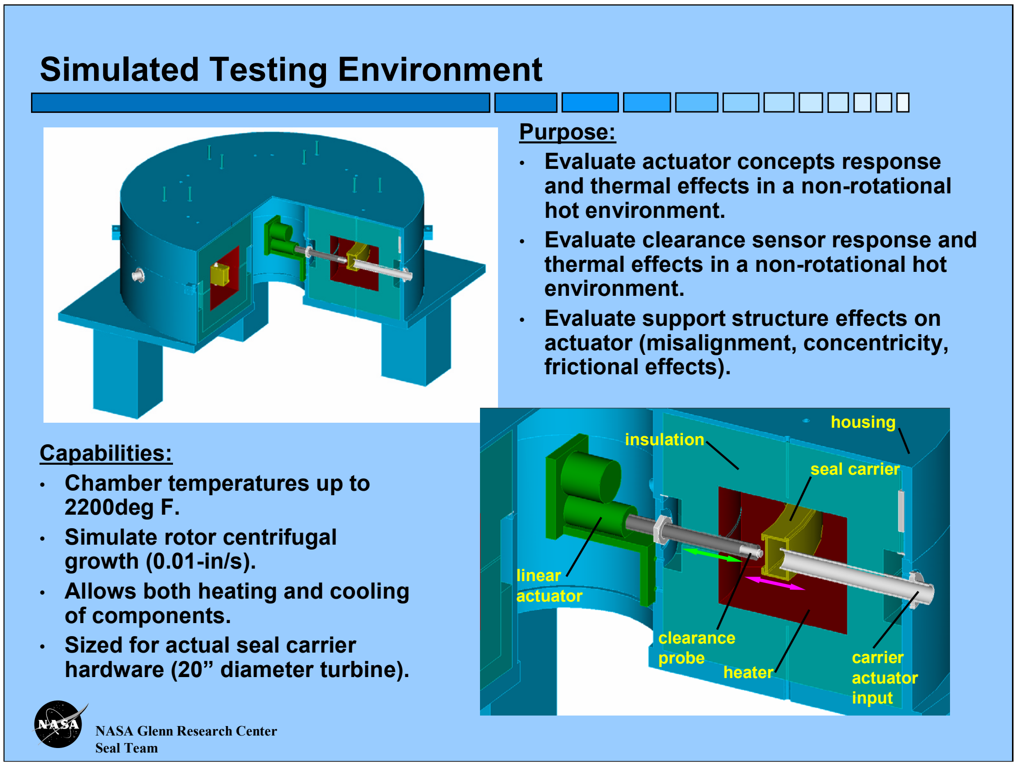
Experimental evaluation
- positional accuracy
- response
- distortion

NASA Glenn Research Center
Seal Team

Regenerative Material Systems







Simulated Testing Environment

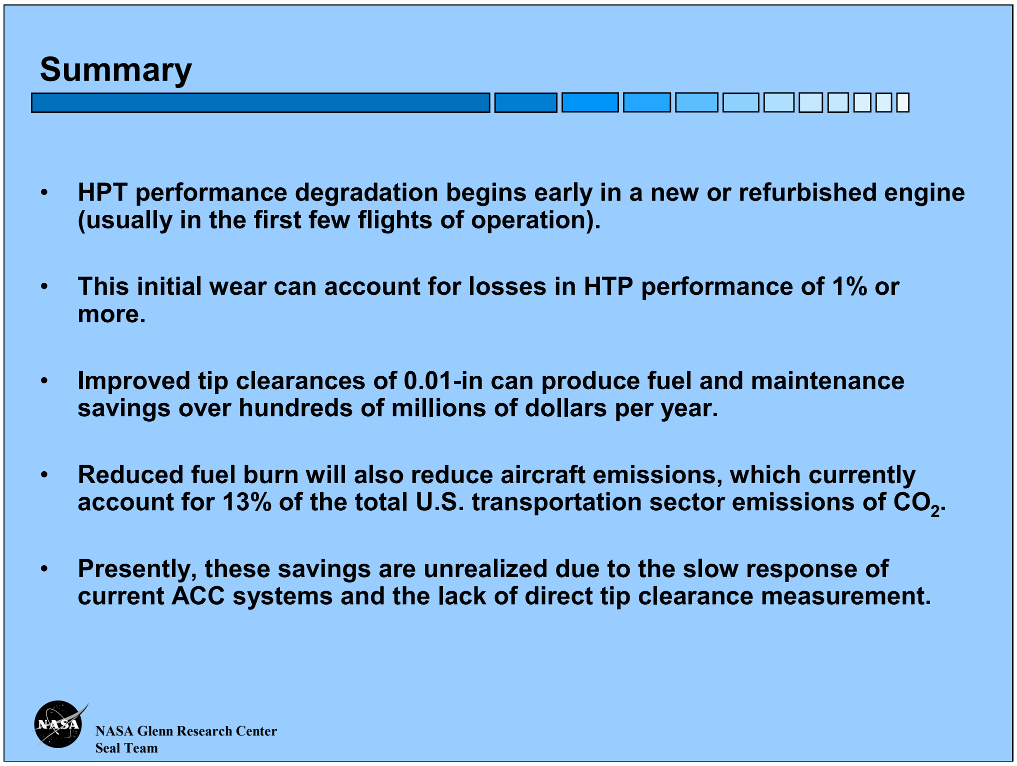
Purpose:

- Evaluate actuator concepts response and thermal effects in a non-rotational hot environment.
- Evaluate clearance sensor response and thermal effects in a non-rotational hot environment.
- Evaluate support structure effects on actuator (misalignment, concentricity, frictional effects).

Capabilities:

- Chamber temperatures up to 2200deg F.
- Simulate rotor centrifugal growth (0.01-in/s).
- Allows both heating and cooling of components.
- Sized for actual seal carrier hardware (20” diameter turbine).

NASA Glenn Research Center
Seal Team



Summary

- HPT performance degradation begins early in a new or refurbished engine (usually in the first few flights of operation).
- This initial wear can account for losses in HTP performance of 1% or more.
- Improved tip clearances of 0.01-in can produce fuel and maintenance savings over hundreds of millions of dollars per year.
- Reduced fuel burn will also reduce aircraft emissions, which currently account for 13% of the total U.S. transportation sector emissions of CO_2.
- Presently, these savings are unrealized due to the slow response of current ACC systems and the lack of direct tip clearance measurement.

NASA Glenn Research Center
Seal Team

Summary- continued

- Improved ACC systems are required to meet aggressive operating cost, life, and fuel burn goals of next generation gas turbine engines.

- It is envisioned that advanced ACC systems would provide:
  1-1.5% reduction in SFC and extended service life (≥ 1000 cycles).

- Currently investigating two parallel approaches to meet these goals:
  1) Fast Response ACC
  2) Regenerative Tip Seal Systems

NASA Glenn Research Center
Seal Team

DEVELOPMENT OF ADVANCED SEALS FOR INDUSTRIAL GAS TURBINES—ABRADABLE SEALS

Raymond E. Chupp
General Electric Global Research Center
Niskayuna, New York

Global Research

GRC team plus
GE Business
people focusing
on sealing

Development of Advanced Seals for Industrial Gas Turbines -- Abradable Seals

Raymond E. Chupp
General Electric
Global Research Center
Niskayuna, NY

Global Research Team Members:
Farshad Ghasripoor
Don Baldwin,
YC Lau
Murtuza Lokhandwalla
Norm Turnquist

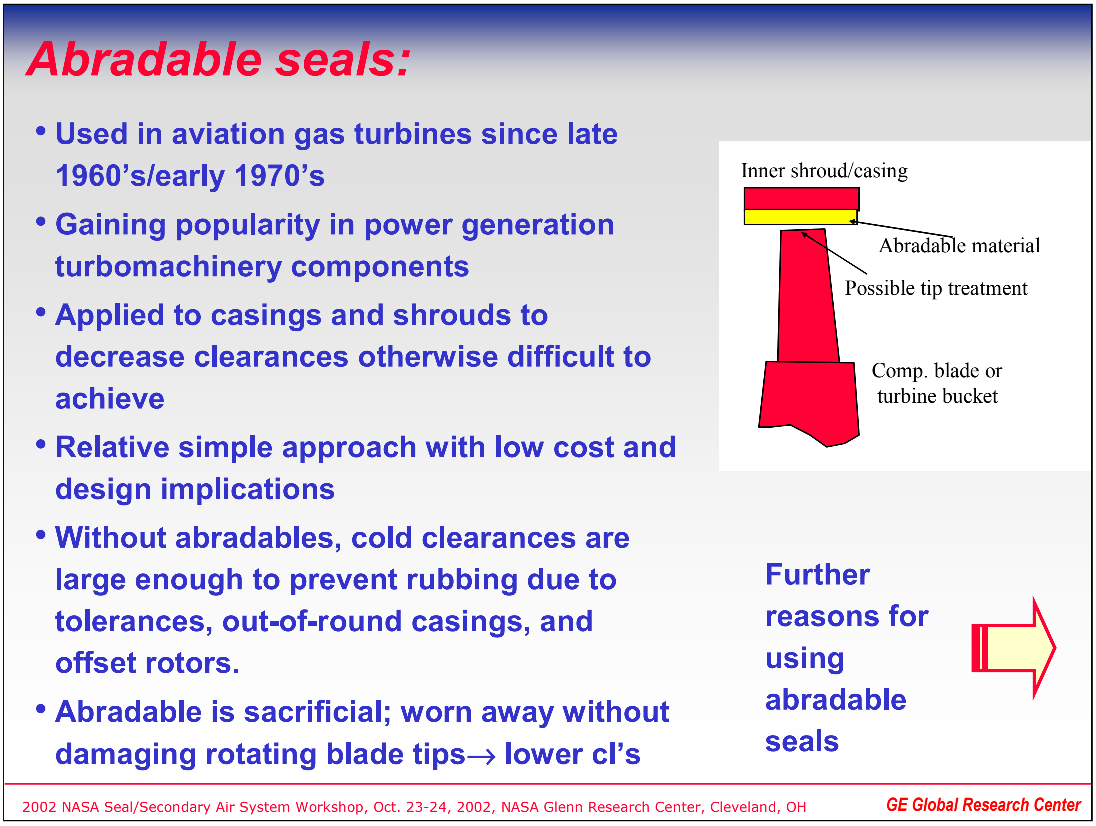
GE Power Systems Team Members:
Brian Arness
Dalero Berkeley
Jim Clare
Massimo Giannozzi
J. Robert Johnston
Lisa S. Kalv
Gerald D. Moore
Chek Ng
Surinder Pabla

For more details see:
AIAA-2002-3795, “Applying Abradable Seals to Industrial Gas Turbines,” Presented at the 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 7-10 July, 2002 in Indianapolis, IN

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 Global Research and Center in cooperation with GE Power Systems. A team of over a dozen individuals at GE-GRC focus on developing advanced seals for several turbine locations.

The focus of this presentation is the development for abradable blade tip sealing for industrial gas turbines. The presentation includes: description of how abradable seals work, where they are located in a gas turbine, types of abradable materials, method of application, and detailed information for turbine locations.

Details of the abradable seal development are given in AIAA-2002-3795 paper.

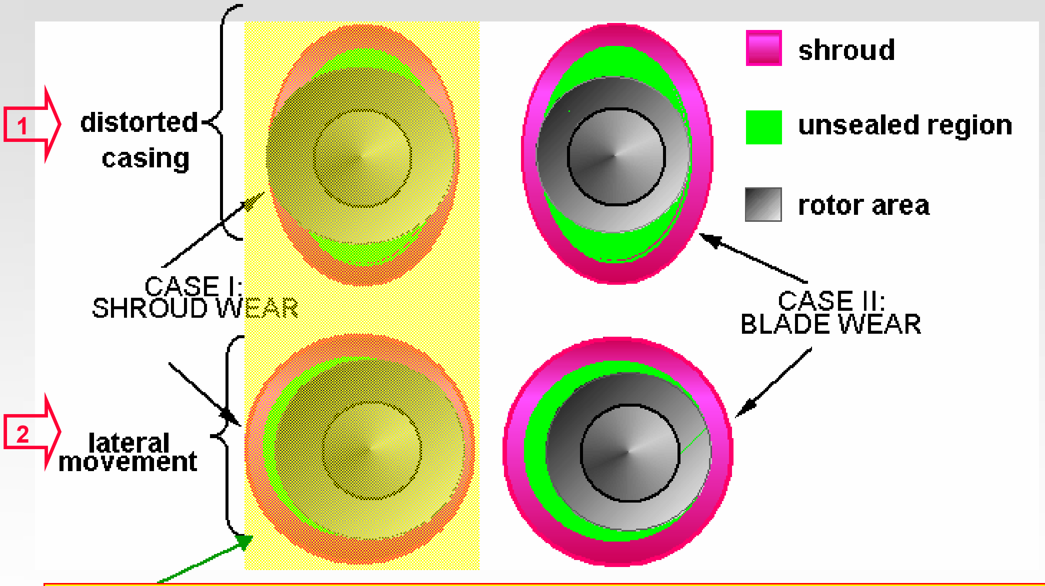


Abradable seals:

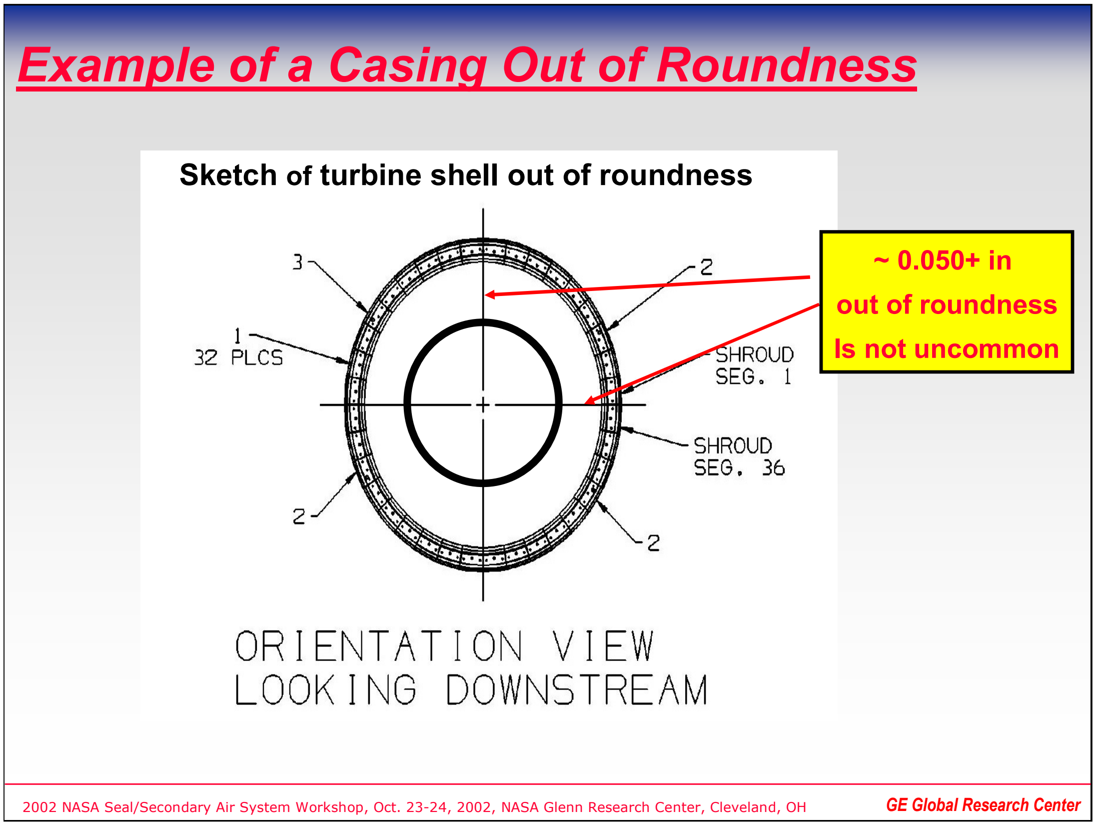
- Used in aviation gas turbines since late 1960's/early 1970's
- Gaining popularity in power generation turbomachinery components
- Applied to casings and shrouds to decrease clearances otherwise difficult to achieve
- Relative simple approach with low cost and design implications
- Without abradables, cold clearances are large enough to prevent rubbing due to tolerances, out-of-round casings, and offset rotors.
- Abradable is sacrificial; worn away without damaging rotating blade tips→ lower cl's

Further reasons for using abradable seals

Abradable sealing also reduces clearances for …



Abradable shroud case → Local removal of a sacrificial shroud coating reduces leakage compared to bucket wearing

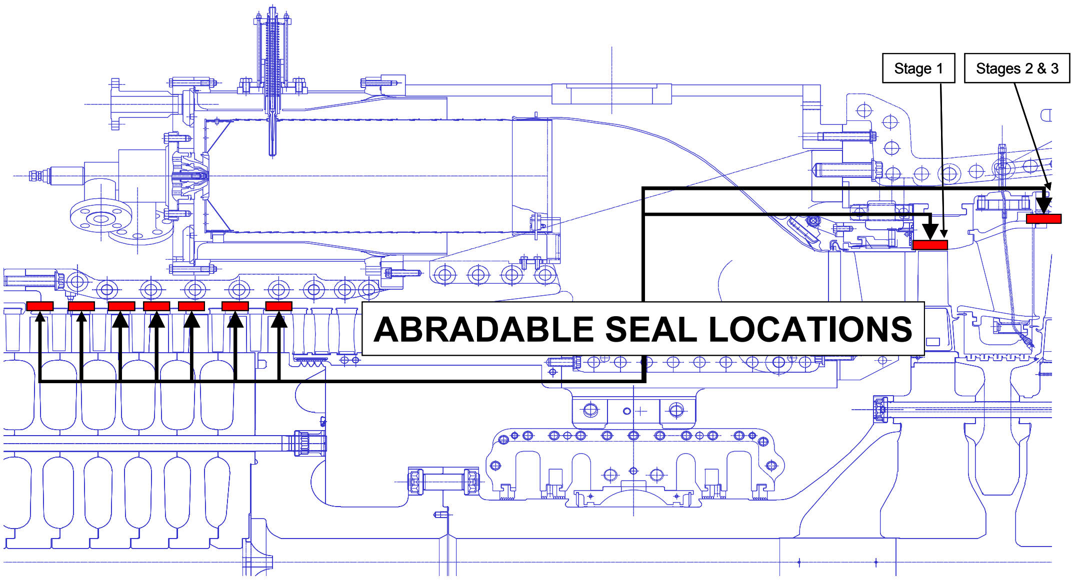


Example of a Casing Out of Roundness

Sketch of turbine shell out of roundness

~ 0.050+ in
out of roundness
Is not uncommon

ADVANCED SEALS -- Gas Turbine Focus Locations

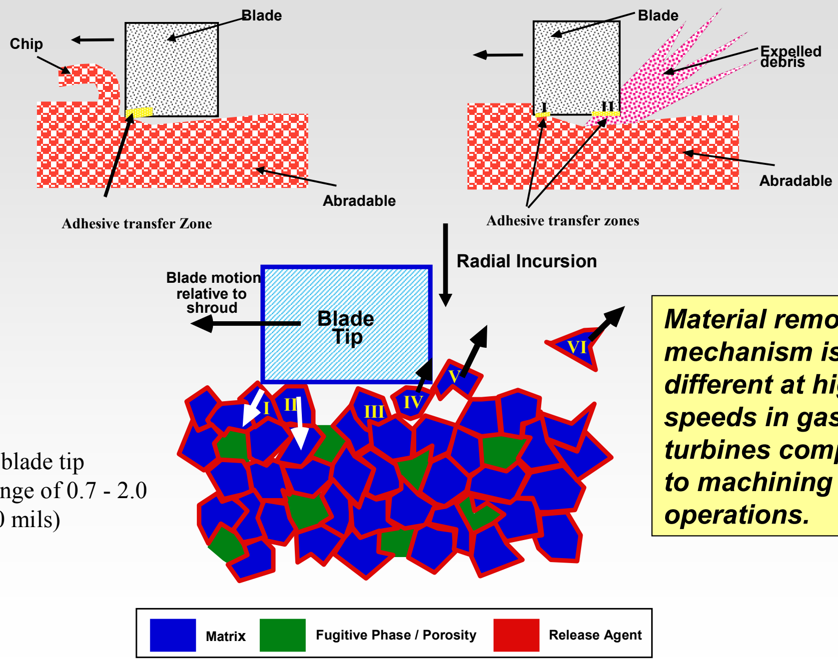


2002 NASA Seal/Secondary Air System Workshop, Oct. 23-24, 2002, NASA Glenn Research Center, Cleveland, OH

GE Global Research Center

ABRADABLE SEALS

Rub Mechanisms



*Assuming blade tip thickness range of 0.7 - 2.0 mm (20 - 80 mils)

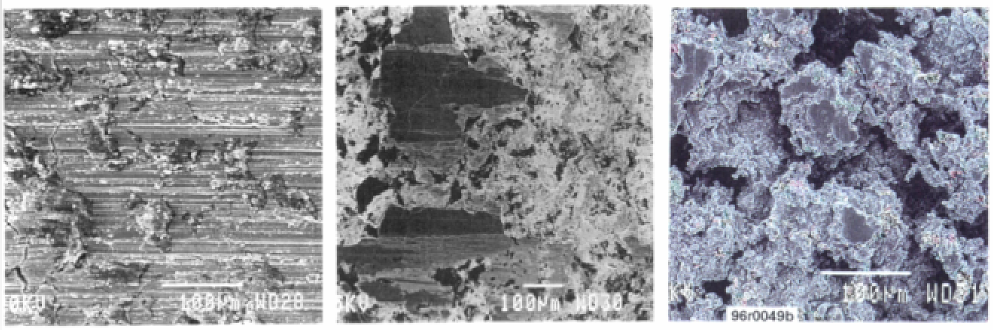
Material removal mechanism is different at high speeds in gas turbines compared to machining operations.

ABRADABLE SEALS

Rub Mechanisms

Predominant Wear Mechanisms

Melting Wear **Densification** **Particle Breakout**



AlSi-polymer Nickel-Graphite CoNiCrAlY-hBN-Polymer

Differing mechanisms with various classes of thermally sprayed abradables

ABRADABLE SEALS

Design Considerations

Abradables have:

- Low strength → susceptible to gas and particle erosion
- Inherent porosity → Prone to oxidation at higher temperatures
- Conflicting requirements → treat as a complete tribological system, i.e.,
  - Relative motions and depth of cut - blade tip speed and incursion rate
  - Environment - temperature, fluid medium and contaminants
  - Cutting element geometry and material - blade tip thickness, shrouded or unshrouded blades
  - Counter element - abradable seal material and structure

Seals must be designed to suit the particular application based on the tribo-system

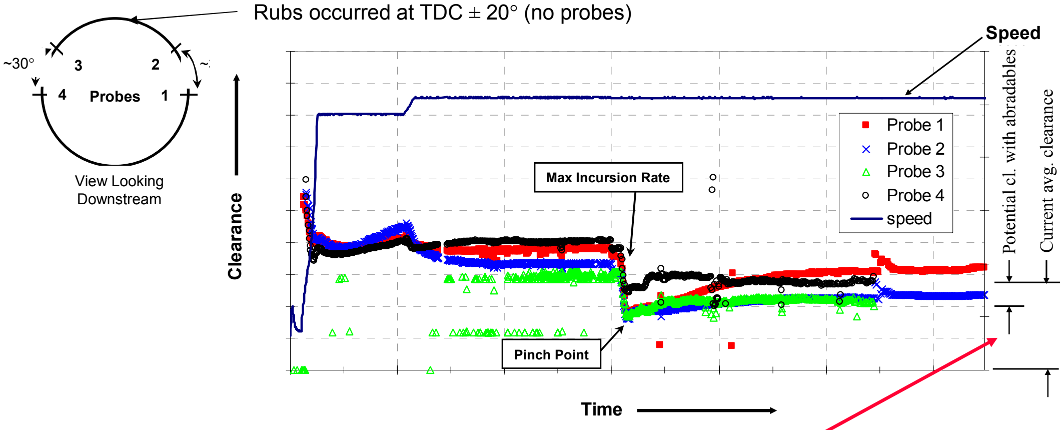
CTQ's for Abradable Development

CTQs:
- Increase power output 0.4 to 0.8%
- Reduce heat rate 0.4 to 0.7%
- Target life vs. application
- Minimum blade tip wear without any tipping
- No damage to other turbine parts if coating fails
- Etc.

Abradable (extrinsic) Requirements:
- Clearance reduction
  - ➢ coating thickness vs. application
- Abradable @ operating temperatures
- Long Service life
  - ➢ Oxidation life at operating temp's
- Erosion resistant
- Lab tests – rub rig, furnace, erosion rig
- Engine and rainbow tests

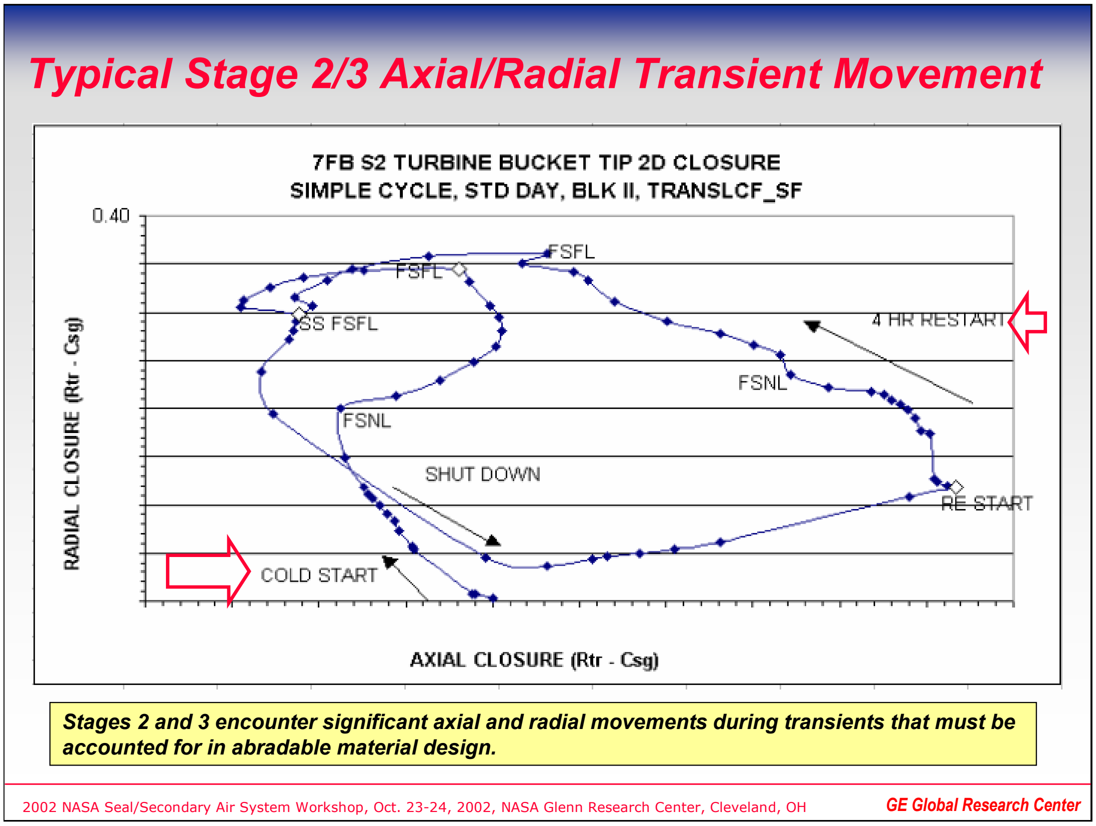
Abradable Seals Driven By Customer Requirements

Typical Transient Radial Closure Cycle



Rubs occurred at TDC ± 20° (no probes)

- Pinch point likely occurs during loading
- Desired coating thickness can be determined from radial closure data
- Significant clearance reduction possible

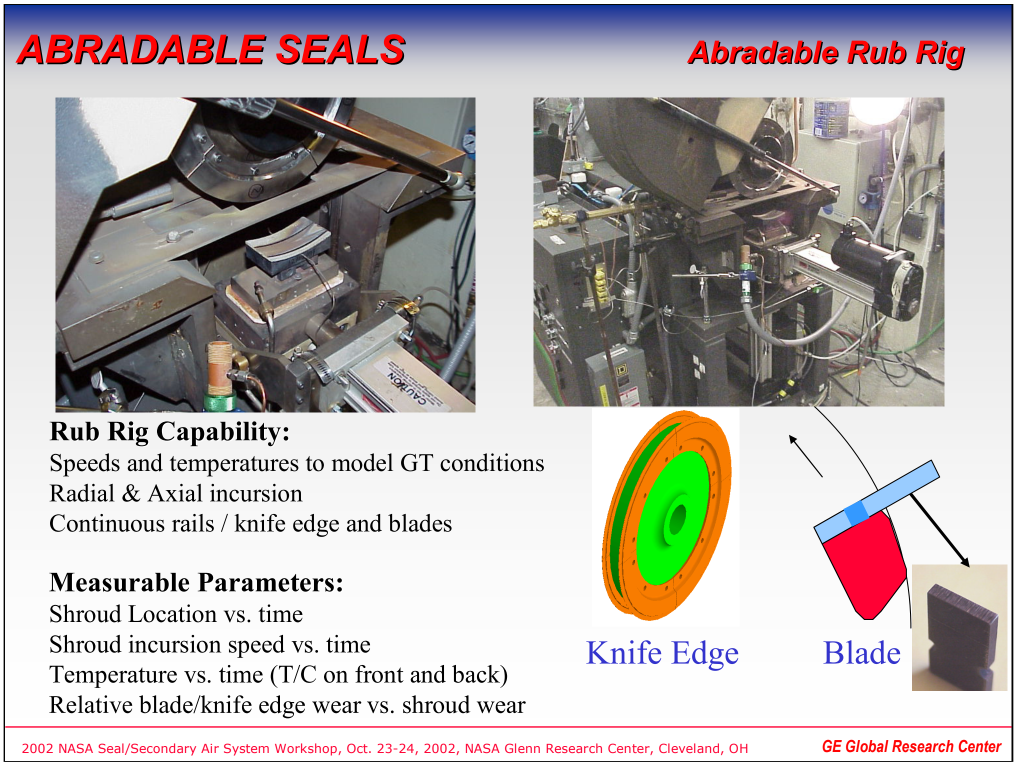


Typical Stage 2/3 Axial/Radial Transient Movement

Stages 2 and 3 encounter significant axial and radial movements during transients that must be accounted for in abradable material design.

2002 NASA Seal/Secondary Air System Workshop, Oct. 23-24, 2002, NASA Glenn Research Center, Cleveland, OH

GE Global Research Center



ABRADABLE SEALS

Abradable Rub Rig

Rub Rig Capability:
Speeds and temperatures to model GT conditions
Radial & Axial incursion
Continuous rails / knife edge and blades

Measurable Parameters:
Shroud Location vs. time
Shroud incursion speed vs. time
Temperature vs. time (T/C on front and back)
Relative blade/knife edge wear vs. shroud wear

Knife Edge

Blade

2002 NASA Seal/Secondary Air System Workshop, Oct. 23-24, 2002, NASA Glenn Research Center, Cleveland, OH

GE Global Research Center

Advanced seal testing capabilities at CRD

3 test rigs:

“Shoebox” (Static testing, Air only)

Used for static seal characterization and basic leakage testing of labyrinth, honeycomb, and brush seals.

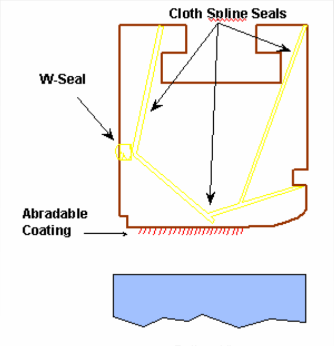
5.1” Rotary Rig (Dynamic testing, Air or Steam, up to 1200 psia)

Used for testing subscale seals at approximately full scale conditions (speed, pressure, temperature)

36” Rotary Rig (can be reconfigured to 50”) (Dynamic testing, Air only)

Used for testing full scale seals at subscale conditions.

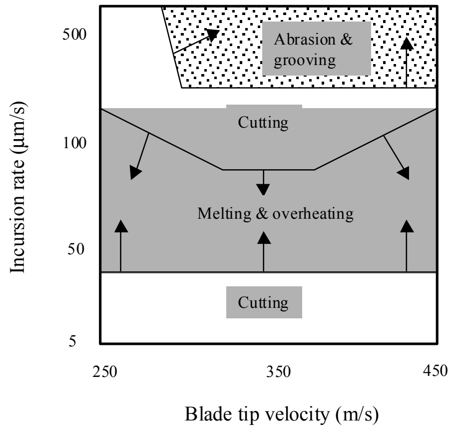
Stage 1 Turbine Shroud Abradable Seals



Uprate Shroud

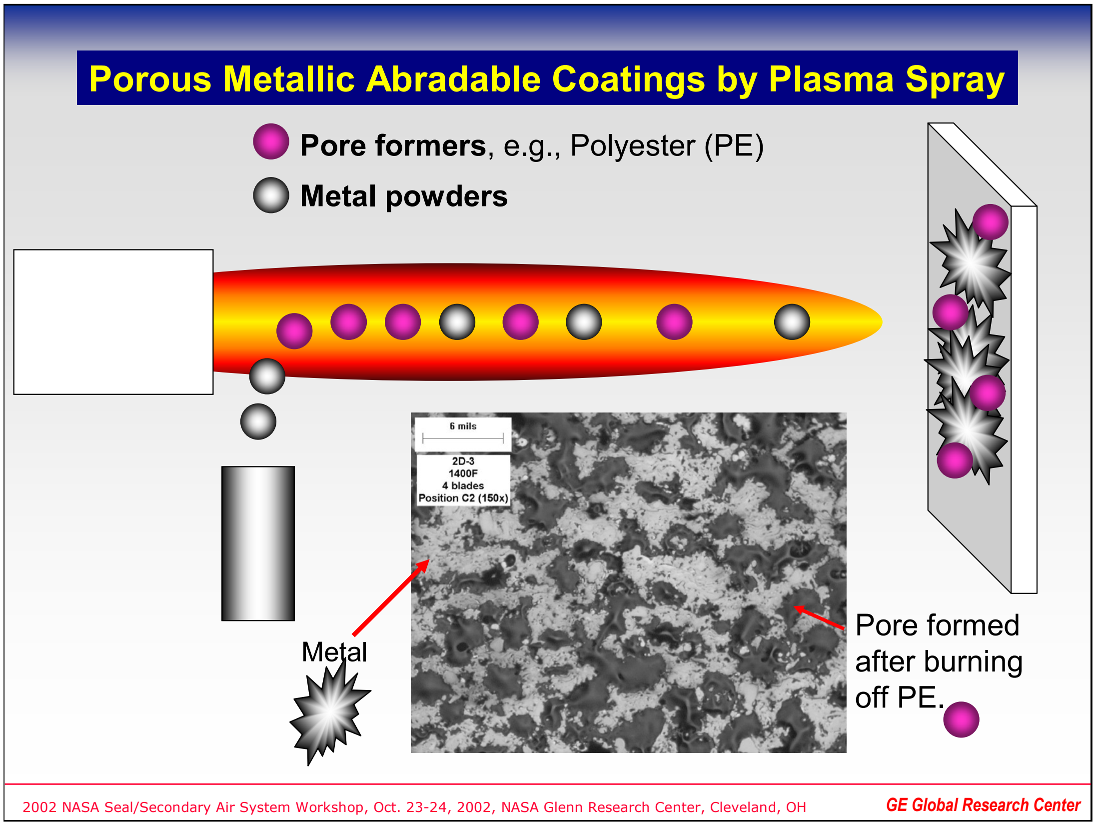
ABRADABLE SEALS

Wear Maps for MCrAlY based Abradable coatings Vs Ti blades



Porous CoNiCrAlY + hBN (500°C)

Abradability of MCrAlY based coatings against Ti blades is mainly affected by porosity and to some extent on the amount of release agent.



Porous Metallic Abradable Coatings by Plasma Spray

● **Pore formers**, e.g., Polyester (PE)

○ **Metal powders**

Metal

Pore formed after burning off PE.

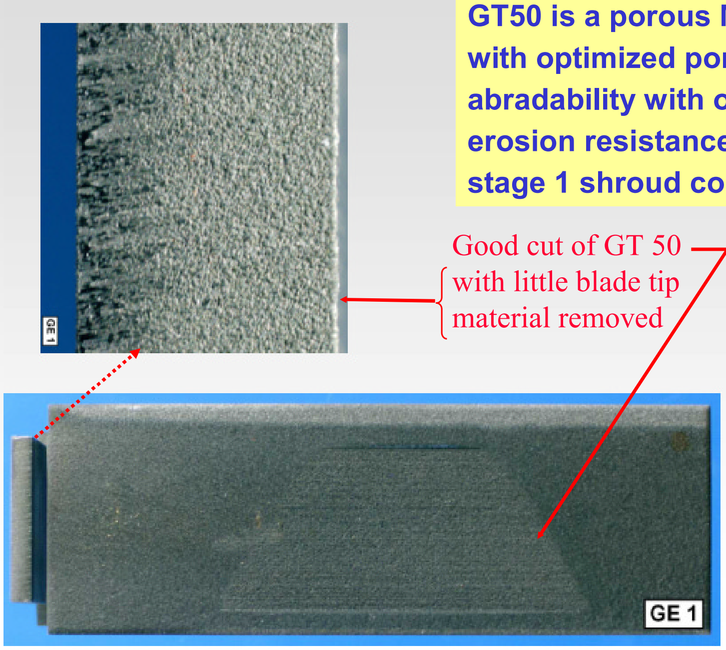
2002 NASA Seal/Secondary Air System Workshop, Oct. 23-24, 2002, NASA Glenn Research Center, Cleveland, OH

GE Global Research Center

ABRADABLE SEALS

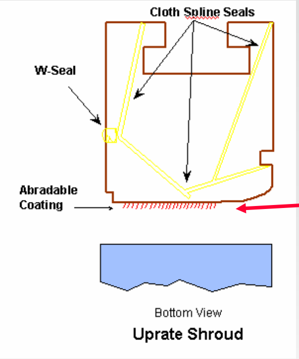
Rub Rig Test Results

GT50 is a porous MCrAlY coating with optimized porosity to balance abradability with oxidation and erosion resistance at E-Class GT stage 1 shroud conditions

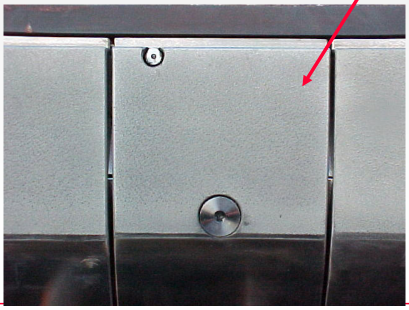


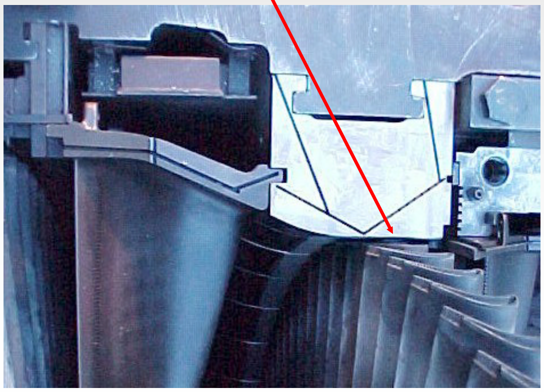
Good cut of GT 50 with little blade tip material removed

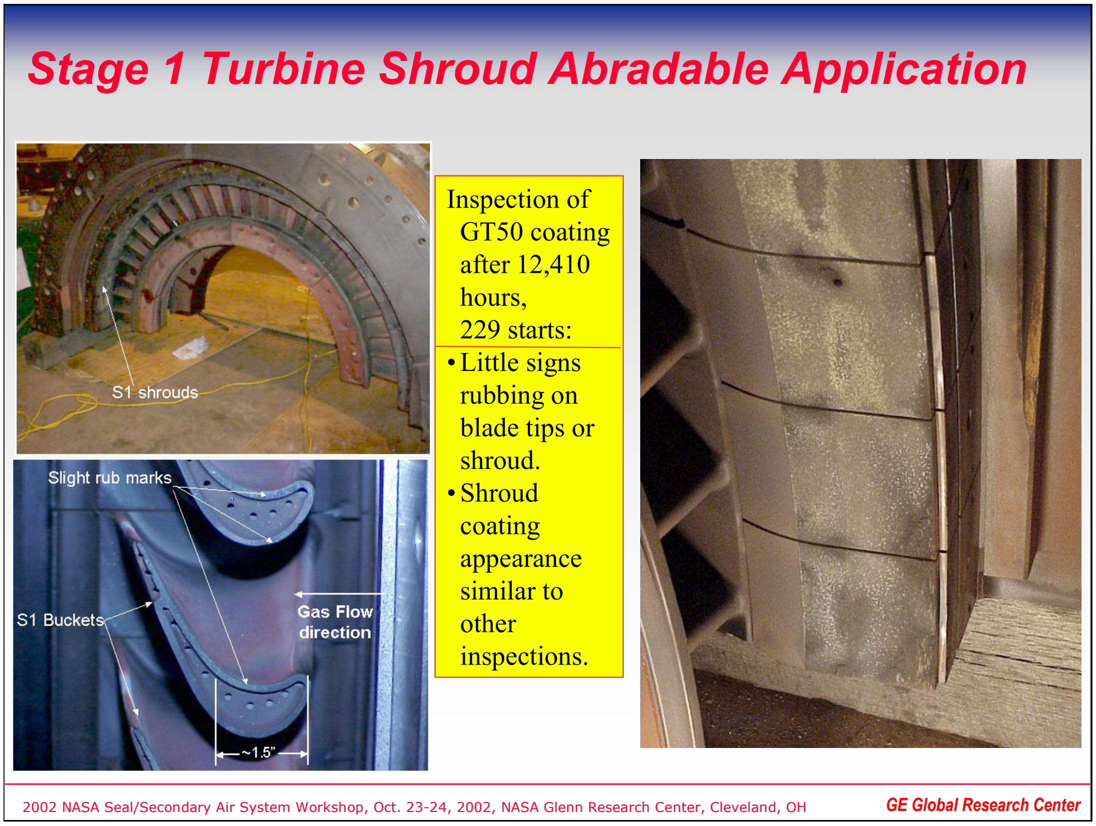
Stage 1 Shroud Abradable Seal Installation



GT50 abradable coating applied to shroud inner surface







Stage 1 Turbine Shroud Abradable Application

Inspection of GT50 coating after 12,410 hours, 229 starts:

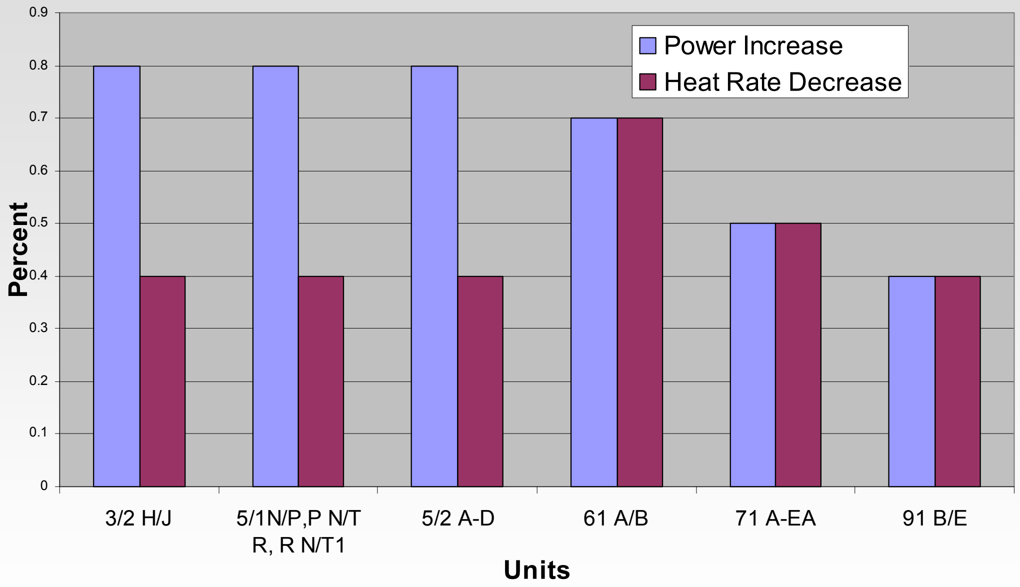
- Little signs rubbing on blade tips or shroud.
- Shroud coating appearance similar to other inspections.

2002 NASA Seal/Secondary Air System Workshop, Oct. 23-24, 2002, NASA Glenn Research Center, Cleveland, OH

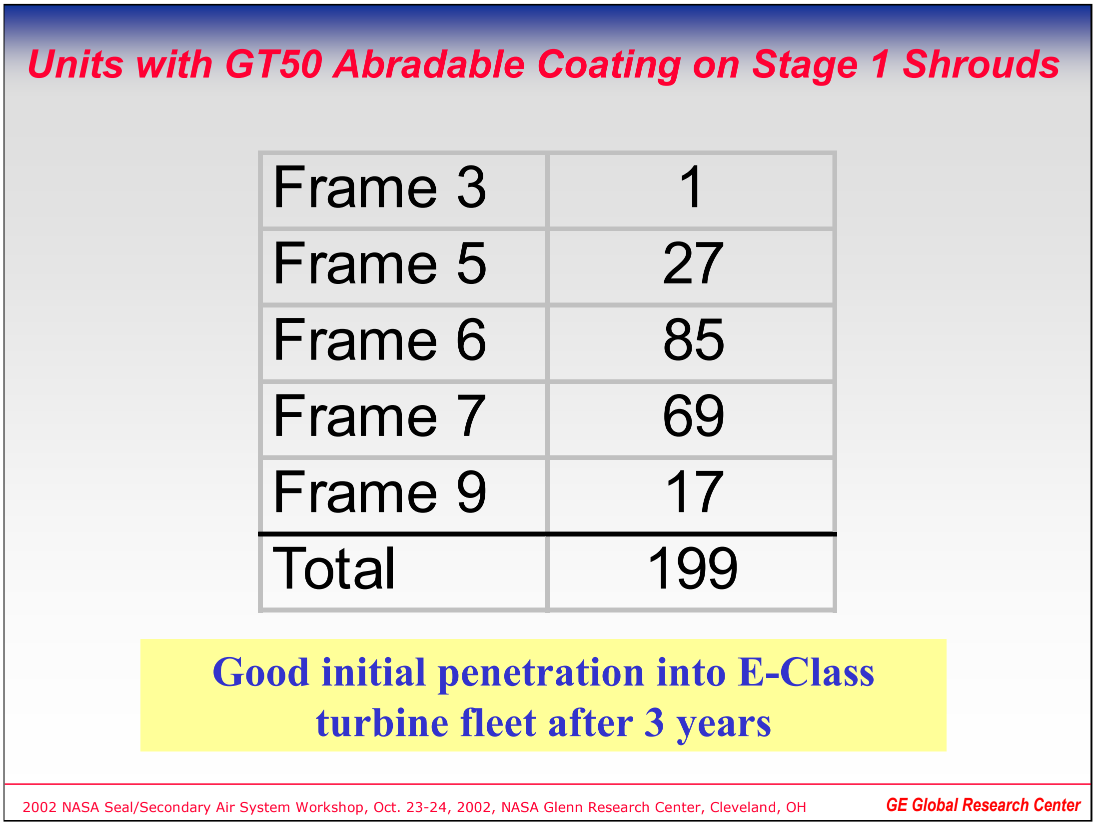
GE Global Research Center

Performance Benefits

Turbine Stage 1



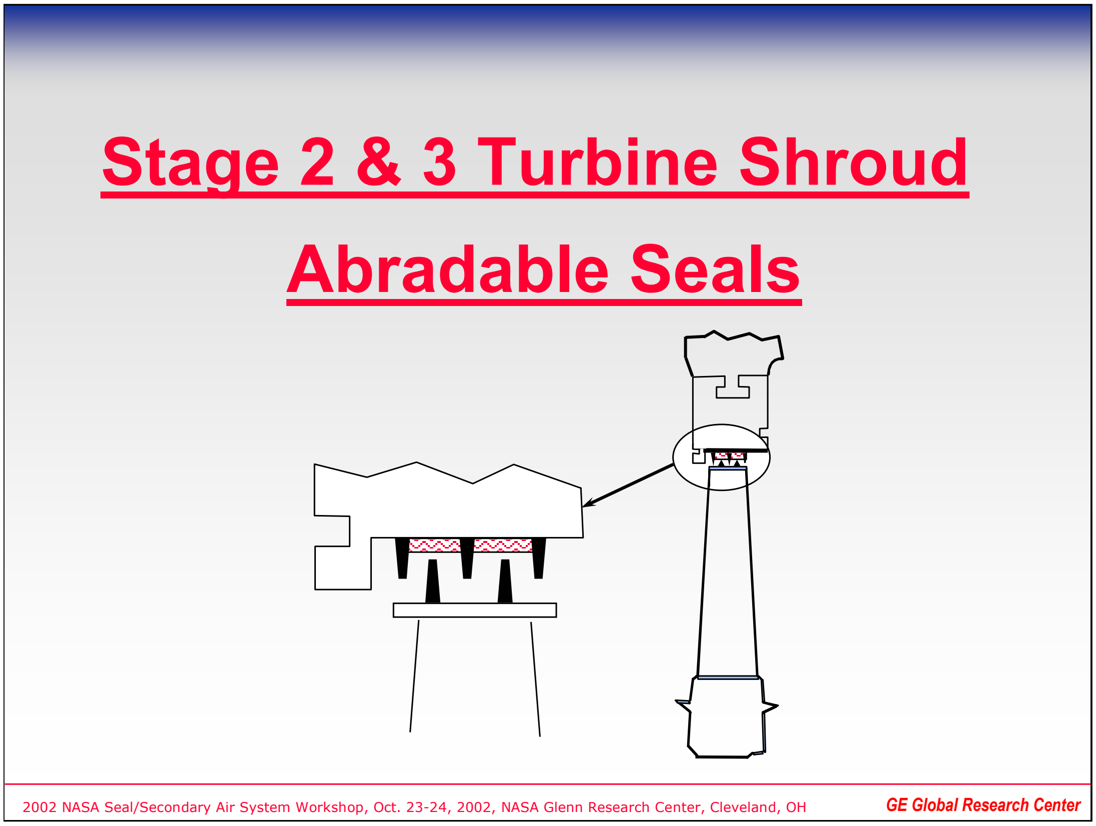
Performance gains from 0.4% to 0.8%



Units with GT50 Abradable Coating on Stage 1 Shrouds

Frame 3	1
Frame 5	27
Frame 6	85
Frame 7	69
Frame 9	17
Total	199

Good initial penetration into E-Class turbine fleet after 3 years

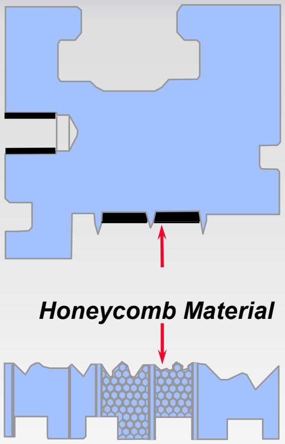


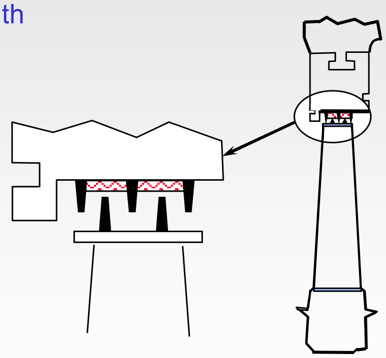
Stage 2 & 3 Turbine Shroud Abradable Seals

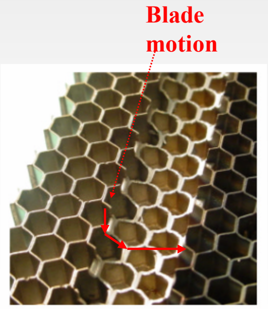
STAGE 2 & 3 ABRADABLE SEALING

Components, Feature & Benefits

- Honeycomb Material Brazed Between Casing Shroud Teeth
  - Tighter Clearance with Buckets
    - Improved performance
  - Reduced Bucket Damage Potential for Rubs
- Requires Buckets with Cutter Teeth







HC rub test sample showing radial/axial wear pattern from simulated rub testing

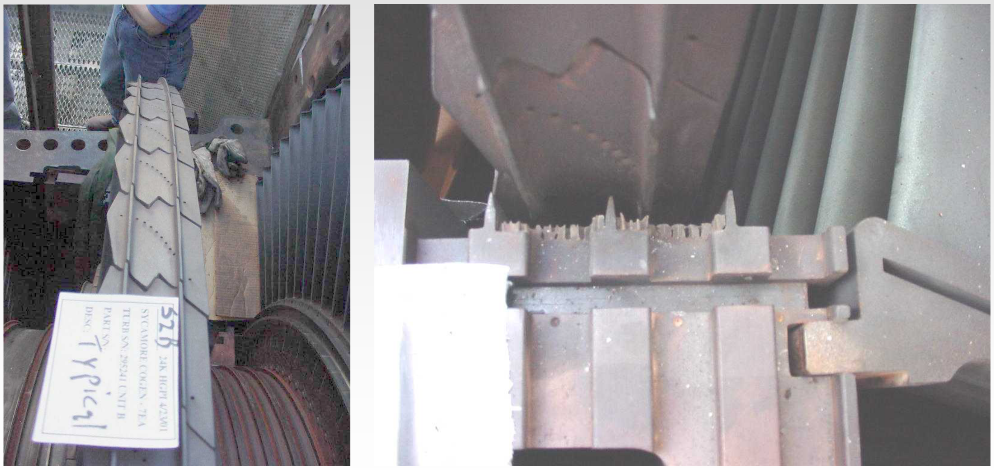
Stage 2 & 3 Abradable Sealing Application

2002 NASA Seal/Secondary Air System Workshop, Oct. 23-24, 2002, NASA Glenn Research Center, Cleveland, OH

GE Global Research Center

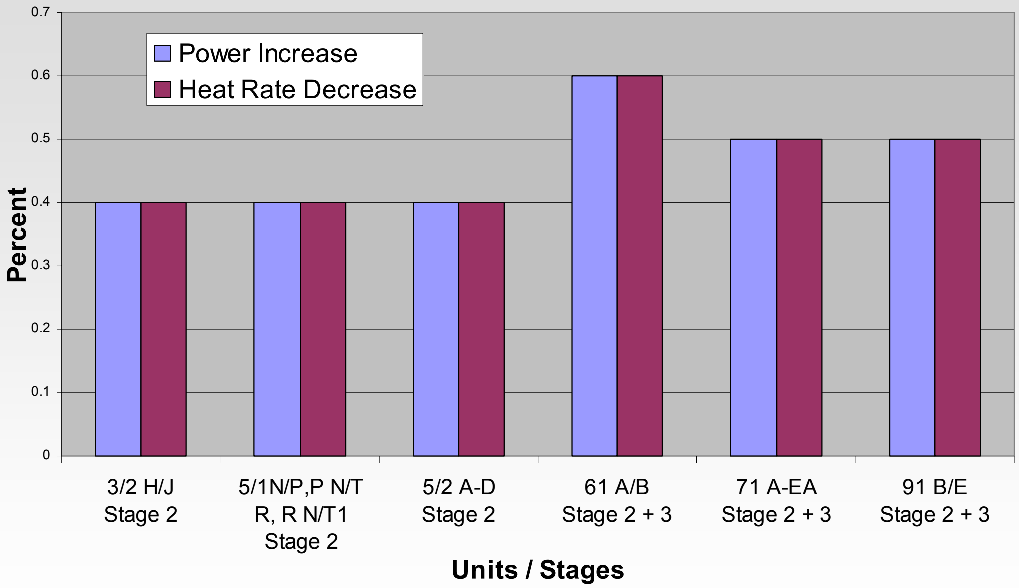
Stage 2/3 Turbine Abradable Application

Photos of installation after 24,000 hours



Performance Benefits

Turbine Stages 2 & 3

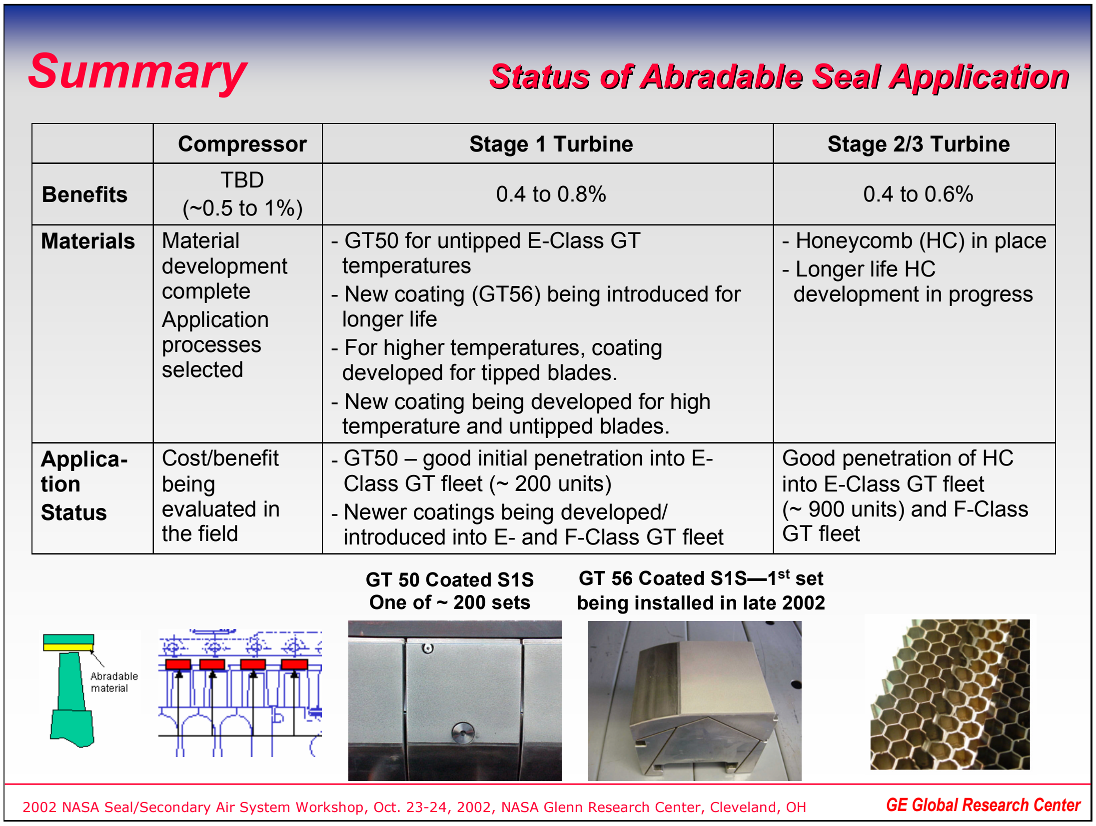


Combined performance gains from 0.4% to 0.6%

Units with Honeycomb Shrouds

	Stage 2 HC Shrouds	Stage 3 HC Shrouds
Frame 5	17	N/A
Frame 6	341	306
Frame 7	444	423
Frame 9	65	63
Total	867	792

Significant penetration into E-Class turbine fleet



Summary

Status of Abradable Seal Application

	Compressor	Stage 1 Turbine	Stage 2/3 Turbine
Benefits	TBD (~0.5 to 1%)	0.4 to 0.8%	0.4 to 0.6%
Materials	Material development complete Application processes selected	- GT50 for untipped E-Class GT temperatures - New coating (GT56) being introduced for longer life - For higher temperatures, coating developed for tipped blades. - New coating being developed for high temperature and untipped blades.	- Honeycomb (HC) in place - Longer life HC development in progress
Application Status	Cost/benefit being evaluated in the field	- GT50 – good initial penetration into E-Class GT fleet (~ 200 units) - Newer coatings being developed/ introduced into E- and F-Class GT fleet	Good penetration of HC into E-Class GT fleet (~ 900 units) and F-Class GT fleet

GT 50 Coated S1S
One of ~ 200 sets

GT 56 Coated S1S—1st set being installed in late 2002

2002 NASA Seal/Secondary Air System Workshop, Oct. 23-24, 2002, NASA Glenn Research Center, Cleveland, OH

GE Global Research Center

There is an organized, coordinated effort to develop and apply abradable seals to industrial gas turbines. E-Class turbines have been the primary focus of this presentation, but abradable seals are being considered for F-Class turbines as well. Compressor and turbine stage 2 & 3 applications are very similar for the two turbine classes. Considerable effort is being focused on the turbine stage 1 abradable tip sealing. Two generations of coatings have been introduced into E-Class turbines over the last three years. The F-Class stage 1 brings higher temperature challenges for the abradable sealing system being developed for that location.

A COMPLIANT CASING FOR TRANSONIC AXIAL COMPRESSORS

Gregory S. Bloch
Air Force Research Laboratory
Wright-Patterson Air Force Base
Dayton, Ohio

Chunill Hah
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

A COMPLIANT CASING FOR TRANSONIC AXIAL COMPRESSORS

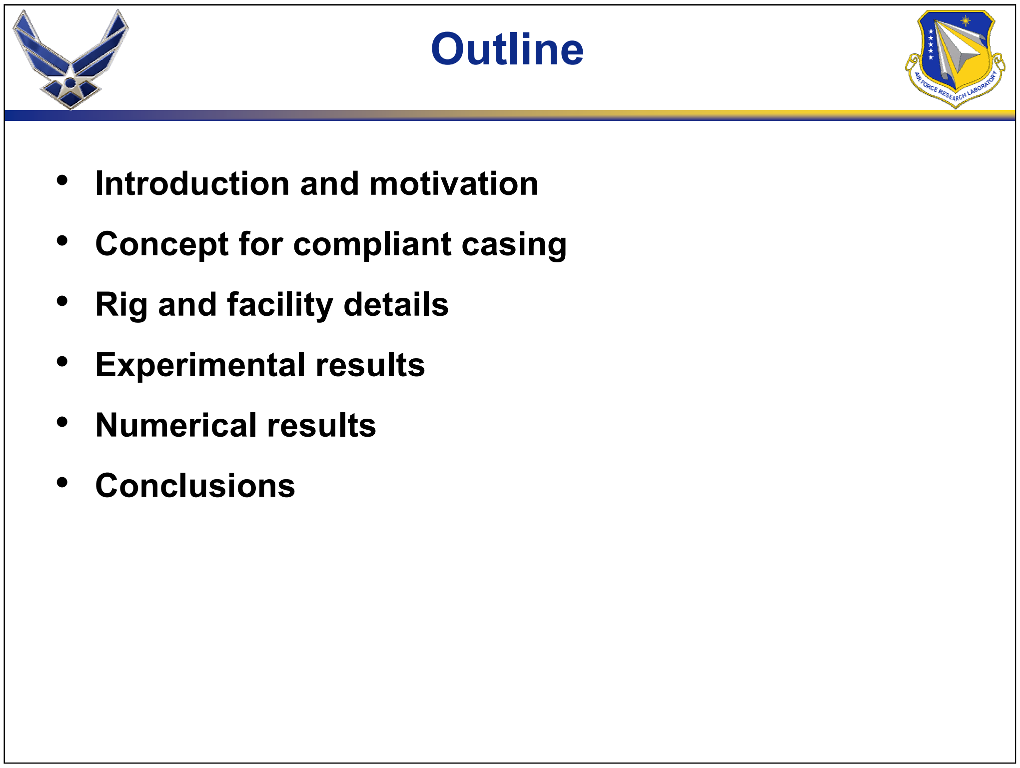
23 OCT 02

Dr. Gregory S. Bloch
Air Force Research Laboratory

Dr. Chunill Hah
NASA Glenn Research Center

Introduce Self

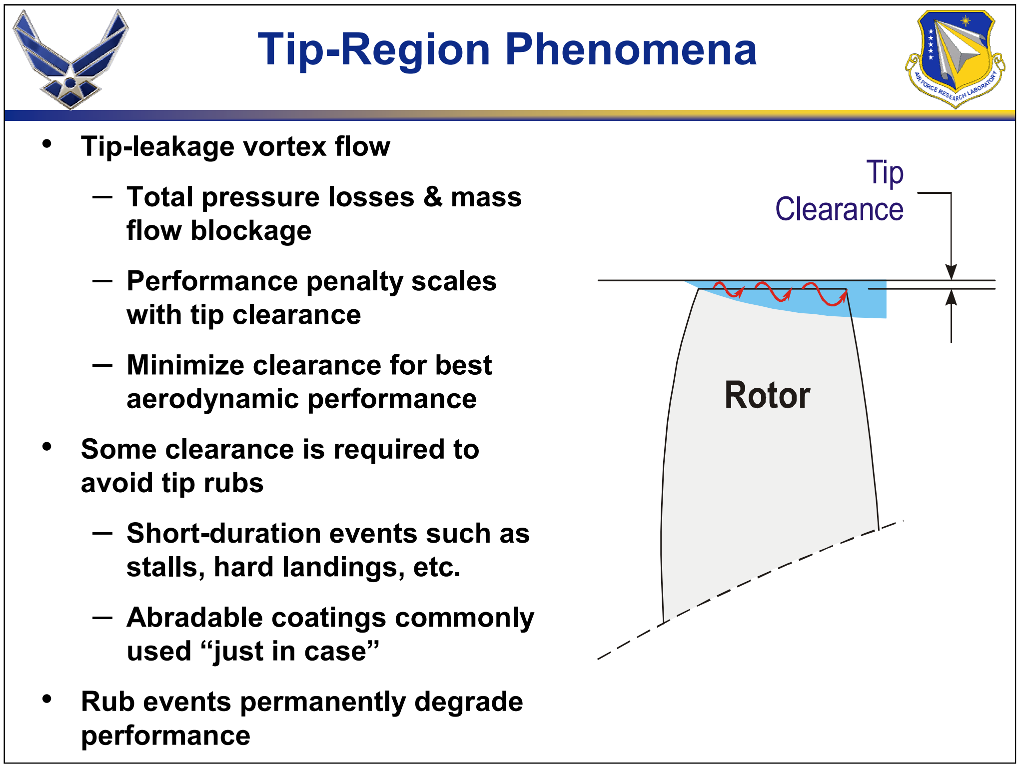
Acknowledge the contributions of my co-author, Chunill Hah



Outline

- Introduction and motivation
- Concept for compliant casing
- Rig and facility details
- Experimental results
- Numerical results
- Conclusions

Introduction and motivation
Concept for compliant casing
Rig and facility details
Experimental results
Numerical results
Conclusions



Tip-Region Phenomena

- Tip-leakage vortex flow
  - Total pressure losses & mass flow blockage
  - Performance penalty scales with tip clearance
  - Minimize clearance for best aerodynamic performance
- Some clearance is required to avoid tip rubs
  - Short-duration events such as stalls, hard landings, etc.
  - Abradable coatings commonly used “just in case”
- Rub events permanently degrade performance

In aircraft engines, some clearance exists between rotor & casing

Pressure difference drives flow through the clearance gap (shown in red)

mostly V_q relative to the rotor

relatively low Vx

produces a large blockage of the main flow (shown in blue)

this is a region of large entropy generation

results in reduced mass flow, pressure rise, and efficiency (Big 3)

Performance penalty scales with tip clearance (larger is bad)

You want to minimize the tip clearance for best aerodynamic performance, but from a practical standpoint, some clearance is required to avoid tip rubs

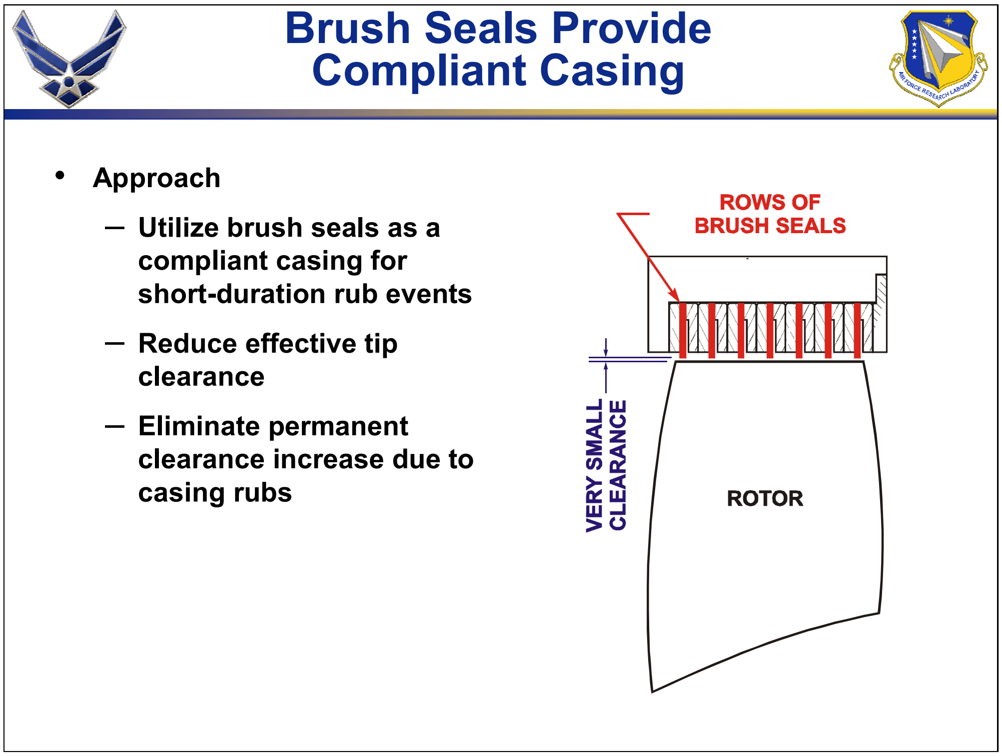
Short-duration events such as stalls, hard landings, etc.

Abradable coatings are commonly used “just in case”

The important thing to remember is that rub events remove material from casing and/or rotor

increases tip clearance

permanently reduces performance until the engine is removed from service and overhauled (***EXPENSIVE***)



Brush Seals Provide Compliant Casing

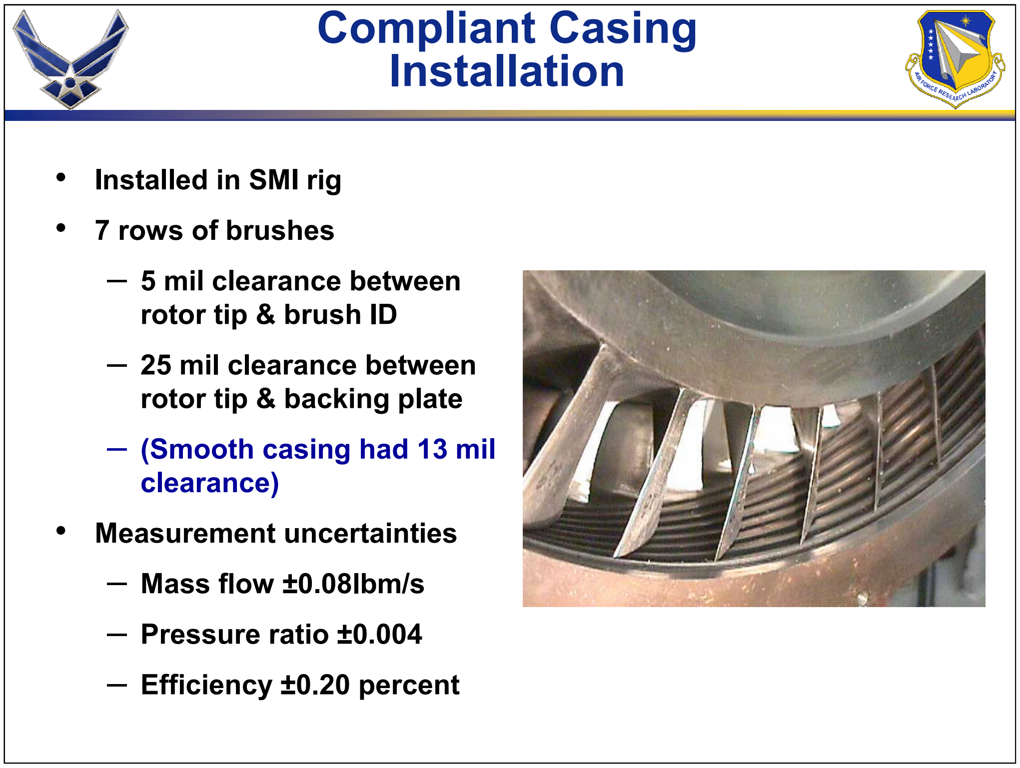
- Approach
  - Utilize brush seals as a compliant casing for short-duration rub events
  - Reduce effective tip clearance
  - Eliminate permanent clearance increase due to casing rubs

This cartoon shows the use of brush seals to provide a compliant casing for short-duration rub events … describe brushes (brush seals typical of those used for control of secondary flowpath leakage)

> Make tip clearance smaller than you would dare with a solid case
>
> In the event of a rub, the brushes will deflect and return…
>
> This eliminates the permanent performance hit that currently results from a rub event

This is not a typical brush seal application like secondary flowpath control:

> Brushes will not normally contact the rotor (only in short-duration rub event)
>
> Some small amount of tip-leakage flow will still pass between the rotor and the brushes
>
> At any given instant in time, most of the circumference of the brush is adjacent to the empty space between the blades
>
> several brush packs are placed next to each other to obtain significant coverage in the axial direction
>
> Due to the manufacturing limitations of the original brush seals, this provided a casing that is similar to circumferential-groove casing treatment, but with very shallow grooves



Compliant Casing Installation

- Installed in SMI rig
- 7 rows of brushes
  - 5 mil clearance between rotor tip & brush ID
  - 25 mil clearance between rotor tip & backing plate
  - (Smooth casing had 13 mil clearance)
- Measurement uncertainties
  - Mass flow ±0.08lbm/s
  - Pressure ratio ±0.004
  - Efficiency ±0.20 percent

Discuss SMI rig

single stage machine typical of 1st stage of modern core compressor

19”OD, 1120 ft/s tip speed

tip chord = 3.5”

tip relative Mach number = 1.19

mass flow = 34.5lbm/s

pressure ratio = 1.81

peak efficiency = 87%

Discuss brush dimensional issues

5 mil minimum clearance

25 mil clearance to brush backing plates

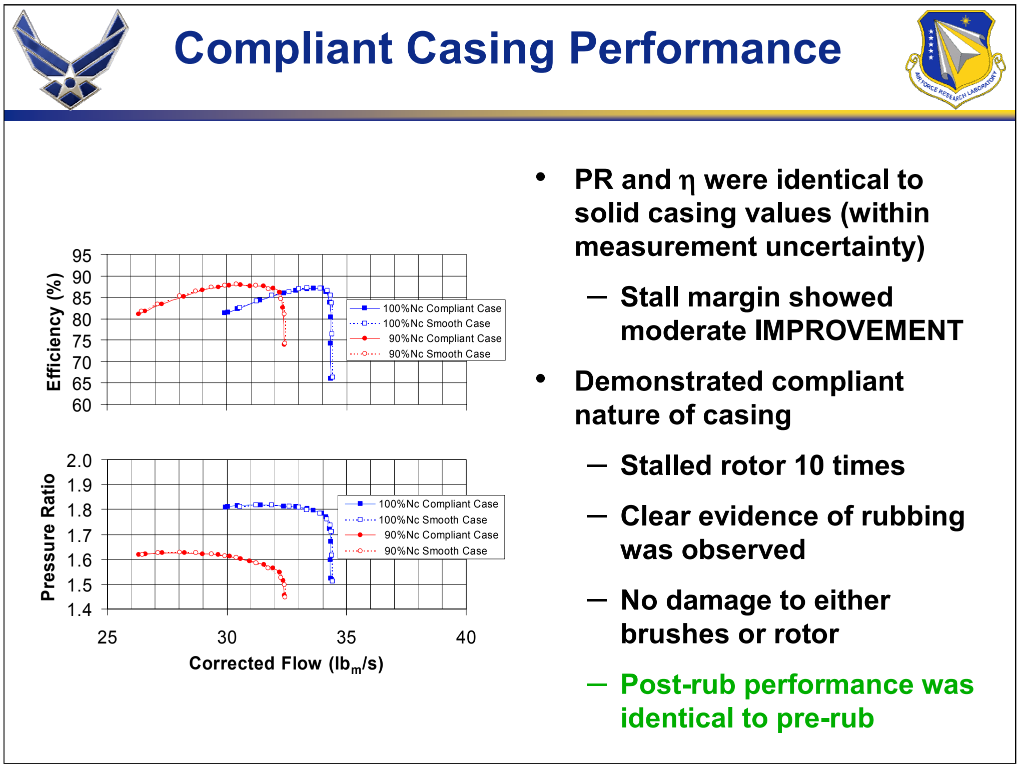
No abradable coating installed here, so gap increased for safety

13 mil clearance to smooth casing (for comparison)

The SMI rig was tested in the CARL facility, and aerodynamic performance was determined by mass-averaging an array of 80 PT probes and 80 TT probes located 2.1 stator axial chords downstream of stator TE.

mass flow uncertainty is 0.08lbm/s, PR uncertainty is 0.004, efficiency uncertainty is 0.2%

So we ran the test, and this is what we learned…



Compliant Casing Performance

- PR and η were identical to solid casing values (within measurement uncertainty)
  - Stall margin showed moderate IMPROVEMENT
- Demonstrated compliant nature of casing
  - Stalled rotor 10 times
  - Clear evidence of rubbing was observed
  - No damage to either brushes or rotor
  - Post-rub performance was identical to pre-rub

Orient the reader to the maps:

constant speed lines are same color; red=90%Nc, blue=100%Nc

solid symbols are for compliant casing; hollow symbols are for smooth casing

Pressure rise and efficiency are identical for smooth and compliant casings (within measurement uncertainty). The measurement uncertainties are approximately the size of the symbols shown here

Stall margin showed moderate IMPROVEMENT (14% increase in flow range at design speed)

The compliant nature of the casing was demonstrated

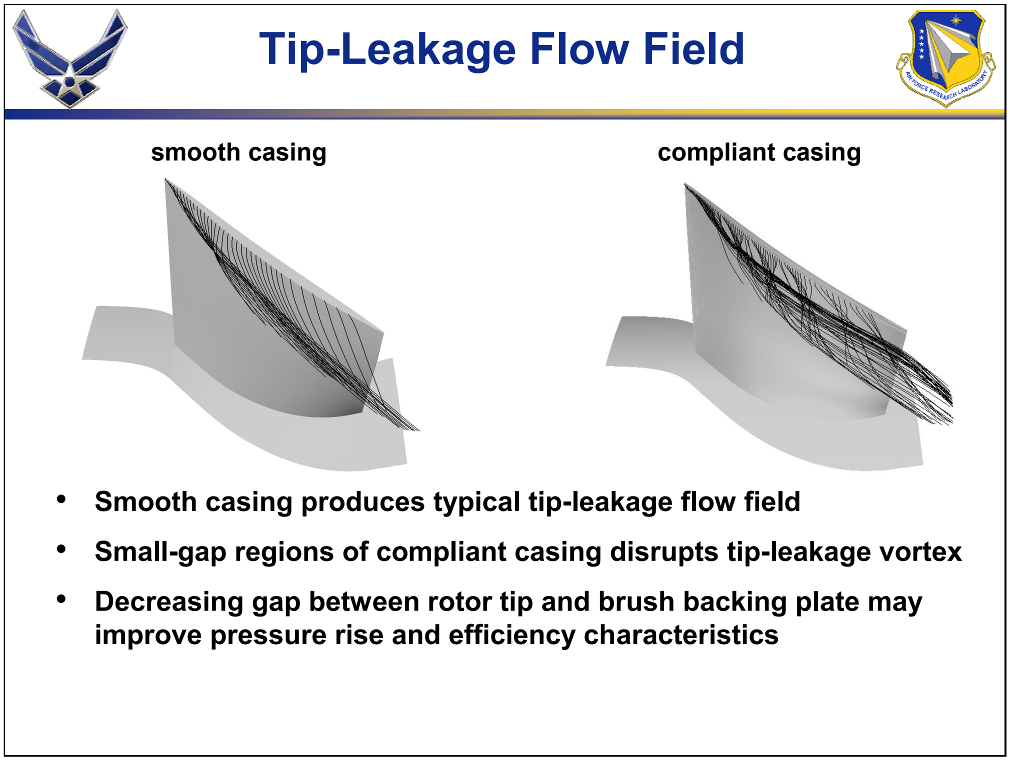
Stalled rotor 10 times

Clear evidence of rubbing was observed

prior to testing, the rotor tips were painted with a black Sharpy marker; post-test inspection revealed shiny lines where rubbing with brush seals had occurred; brush tips were shiny in some (corresponding) places

No damage to either brushes or rotor was observed

Data points repeated after stalling the rotor showed identical performance to pre-stall values (within measurement uncertainty). This is important: we beat on this rotor pretty hard. Some of the stall events lasted for several seconds before the rig recovered, but there was no post-rub performance penalty.



Tip-Leakage Flow Field

smooth casing

compliant casing

- **Smooth casing produces typical tip-leakage flow field**
- **Small-gap regions of compliant casing disrupts tip-leakage vortex**
- **Decreasing gap between rotor tip and brush backing plate may improve pressure rise and efficiency characteristics**

A brief discussion of the tip-region flow field is in order here, but I believe tip-leakage flows are fairly well understood, in general, and this paper doesn't break new ground in this area.

Orient reader to figures:

Smooth casing (left) produces typical tip-leakage flow field

> Single contiguous vortex starts at the leading edge and entrains the flow leaking over the entire axial length of the blade

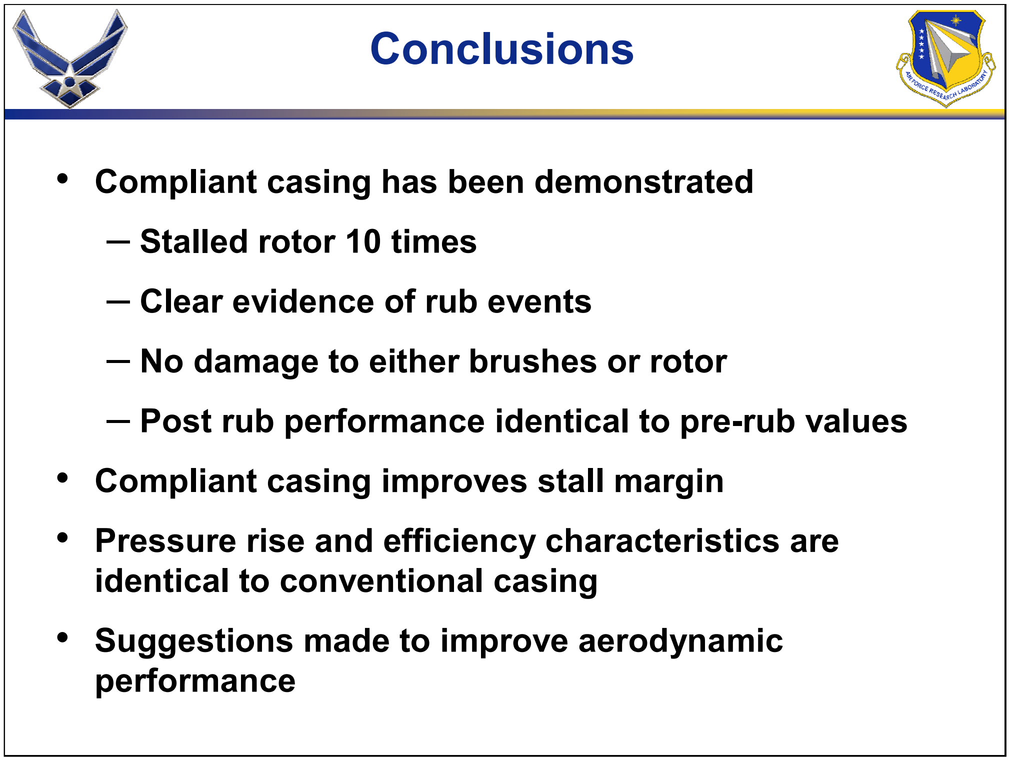
Small-gap regions of compliant casing (right) disrupts tip-leakage vortex

> This segmenting of the tip-leakage vortex into a series of mini-vortices reduces the overall blockage of the low-momentum clearance fluid

This confirms what is widely-known about tip-leakage flows, namely that the magnitude of the leakage vortex scales with the size of the tip gap.

The contribution made in this paper is that we have developed a rub-tolerant casing that allows us to close down the tip gap to values that the aerodynamicists like without suffering a permanent degradation of performance when rub events occur.

This also suggests that anything we can do to minimize the gap between the rotor tip and the brush backing plates (e.g., add an abradable coating to the brush backing plates or reducing the axial gap between adjacent rows of bristles) may actually result in an improvement in pressure rise and efficiency relative to the smooth casing



Conclusions

- **Compliant casing has been demonstrated**
  - **Stalled rotor 10 times**
  - **Clear evidence of rub events**
  - **No damage to either brushes or rotor**
  - **Post rub performance identical to pre-rub values**
- **Compliant casing improves stall margin**
- **Pressure rise and efficiency characteristics are identical to conventional casing**
- **Suggestions made to improve aerodynamic performance**

The things we’ve learned from this investigation are:

Compliant nature of the casing has been demonstrated

- Stalled rotor 10 times
- Clear evidence of rub events
- No damage to either brushes or rotor
- Post rub performance identical to pre-rub values

Compliant casing increased mass flow range between choke and stall by 14% at design speed

Pressure rise and efficiency characteristics are identical to conventional casing, so we haven’t had to trade aerodynamic performance for damage tolerance

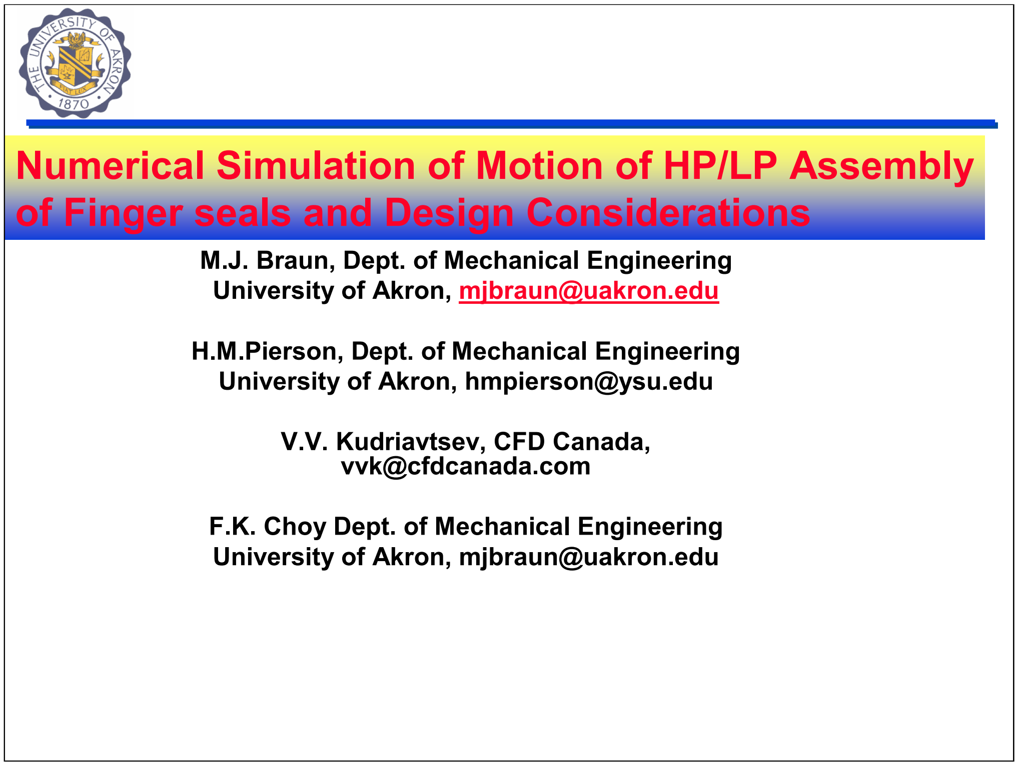
Suggestions have been made to improve this technology in ways that may lead to improvements in aero performance while maintaining rub tolerance.

NUMERICAL SIMULATION OF MOTION OF HP/LP ASSEMBLY OF FINGER SEALS AND DESIGN CONSIDERATIONS

M. Jack Braun and Hazel M. Pierson
University of Akron
Akron, Ohio

V.V. Kudriavtsev
CFD Canada
Toronto, Canada

Fred K. Choy
University of Akron
Akron, Ohio



Numerical Simulation of Motion of HP/LP Assembly of Finger seals and Design Considerations

M.J. Braun, Dept. of Mechanical Engineering
University of Akron, mjbraun@uakron.edu

H.M.Pierson, Dept. of Mechanical Engineering
University of Akron, hmpierson@ysu.edu

V.V. Kudriavtsev, CFD Canada,
vvk@cfdcanada.com

F.K. Choy Dept. of Mechanical Engineering
University of Akron, mjbraun@uakron.edu

ABSTRACT

- The work concerns the development of the Finger Seal concept and design criteria that ensure finger aerodynamic lifting, while maintaining seal integrity. The FS 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, 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.

GOALS (cont'd)

- **In Year II**, in collaboration with the Seal Team of the Mechanical Components Branch, we shall extend the University of Akron based experimental/analytical 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

⇨**Mechanical model of the single finger and assembly of fingers.** This model entail the use in dual mode both of ALGOR and FEMSTRESS to simulate the motion and deformation of single fingers as well as an assembly of HP/LP fingers as they are 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.

⇨)**Hydrodynamic fluid model.** This model uses CFD-ACE+ 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.

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.

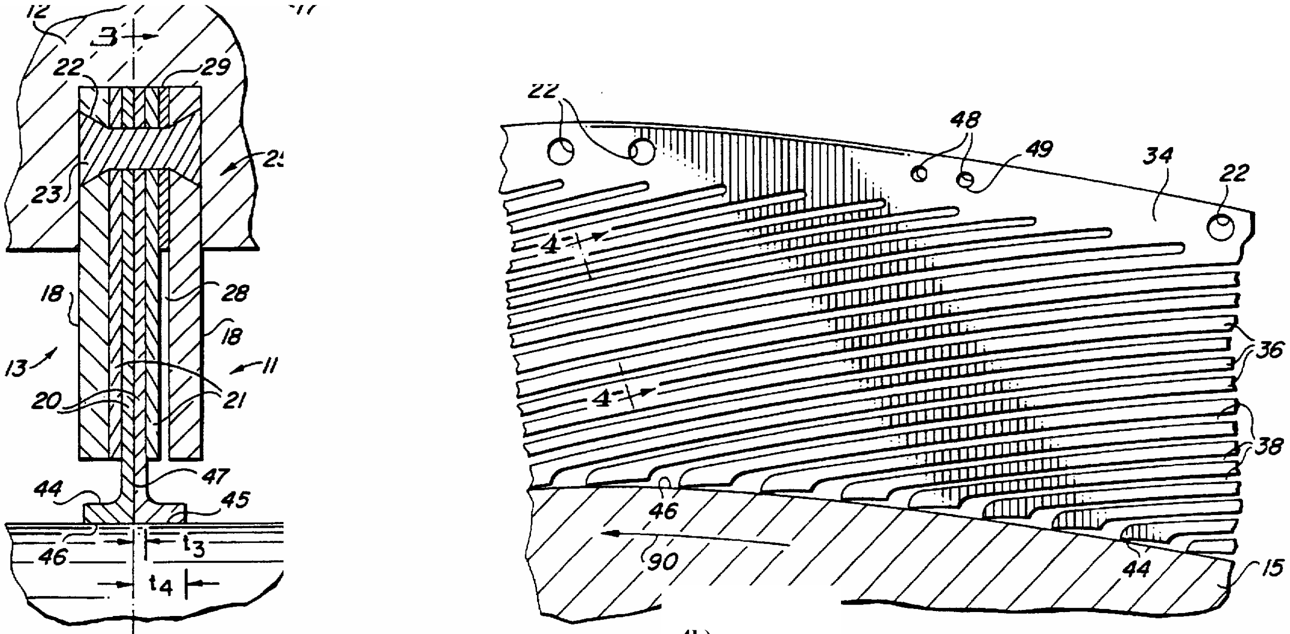
⇨)**Simplified spreadsheet design.** With a), b) and c) implemented we project the possibility that a detailed parametric run will allow creation of a database that can be used for the creation of a simplified calculation methodology that will use a spreadsheet format, without any further need of 3-D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

EXPERIMENTAL PROGRAM

⇨The Tribology Laboratory at the University of Akron possesses a high-speed rig that can be run up to 15,000 rpm. The rig contains all necessary controls and data acquisition system for measuring pressures, temperatures, rotor orbits. The spindle is mounted in cantilever and allows installation of a slip ring at its axial end.

- ➔full pressure and temperature maps
- ➔identification of lift-off and torque characteristics
- ➔high speed visualization of the finger motion and subsequent leakage patterns
- ➔identification of the physics of finger lift-off
- ➔flow visualization of flow patterns before and after finger seal pad lift-off
- ➔effects on sealing efficiency and seal hydrodynamics when
- ➔spiral grooves are etched in the shaft
- ➔grooves are etched on the seal footpads.
- ➔effect of eccentric rotor on seal performance

GEOMETRY OF THE FINGER



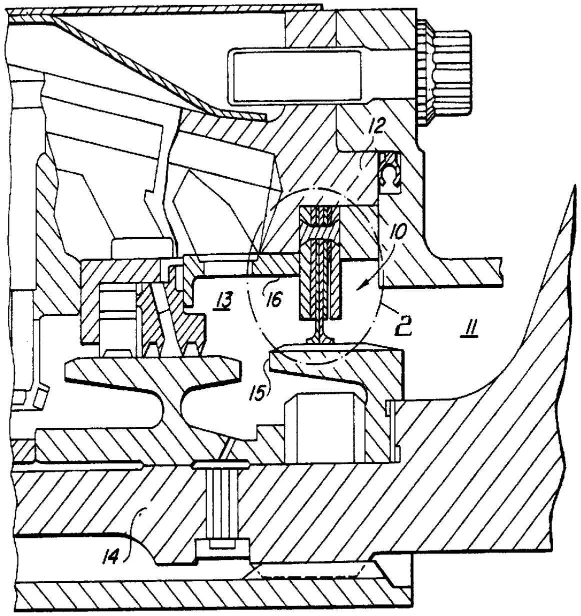
4a)

4b)

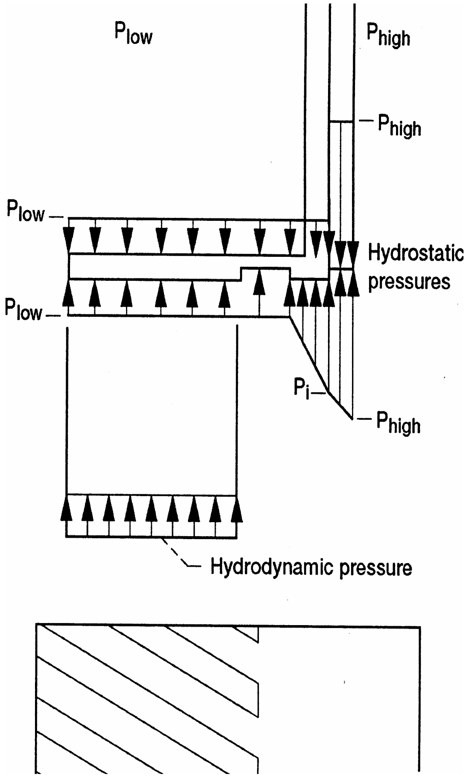
Seal Two row Configuration with Wide Finger Pads. Cross Section and Side View of the Seal
(U.S. Patent No. 5,755,445)

Typical application and Free Body Diagram

U.S. Patent May 26, 1998 Sheet 1 of 3 **5,755,445**

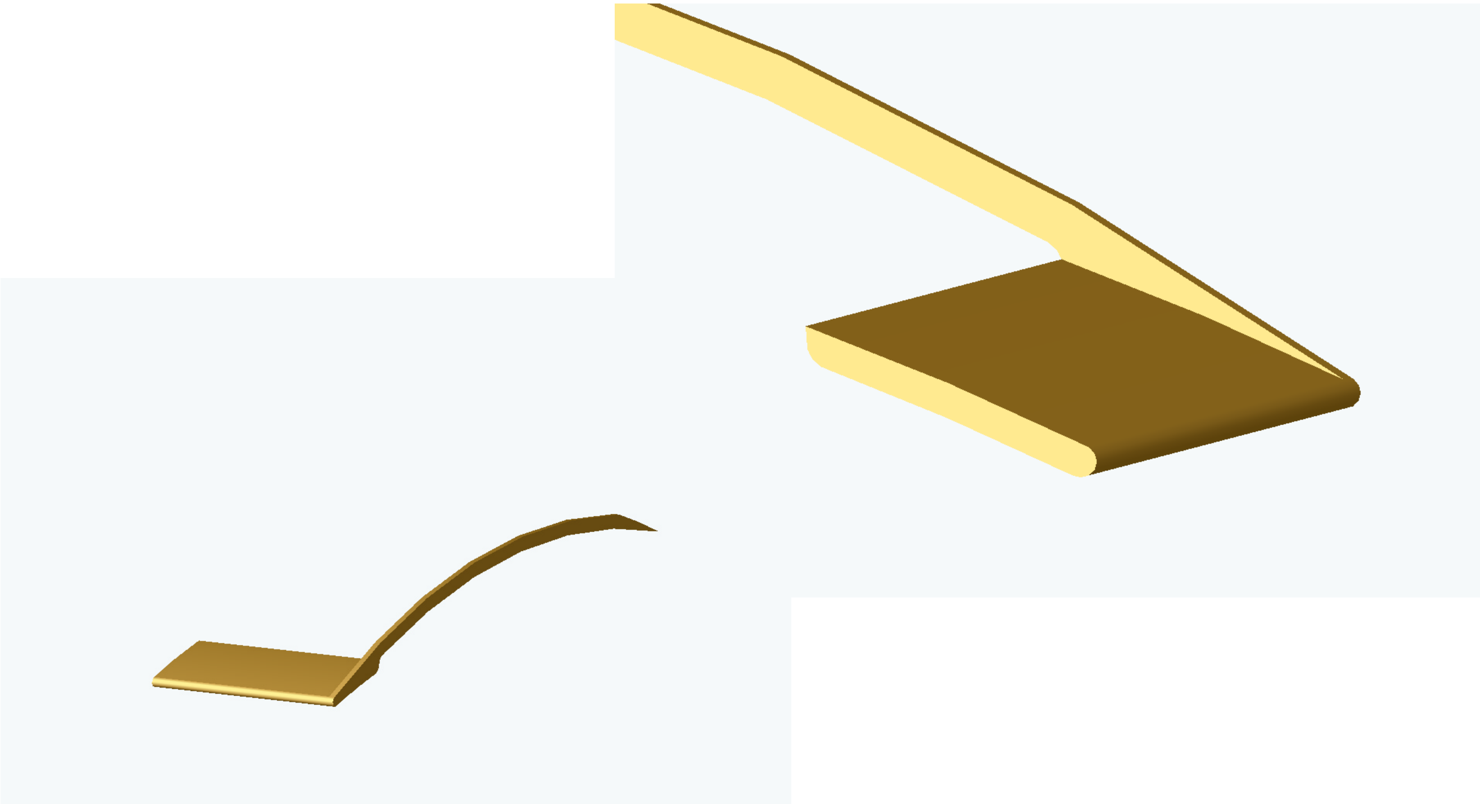


Typical Application of the Finger Seal presented on previous slide (U.S. Patent No. 5,755,445)

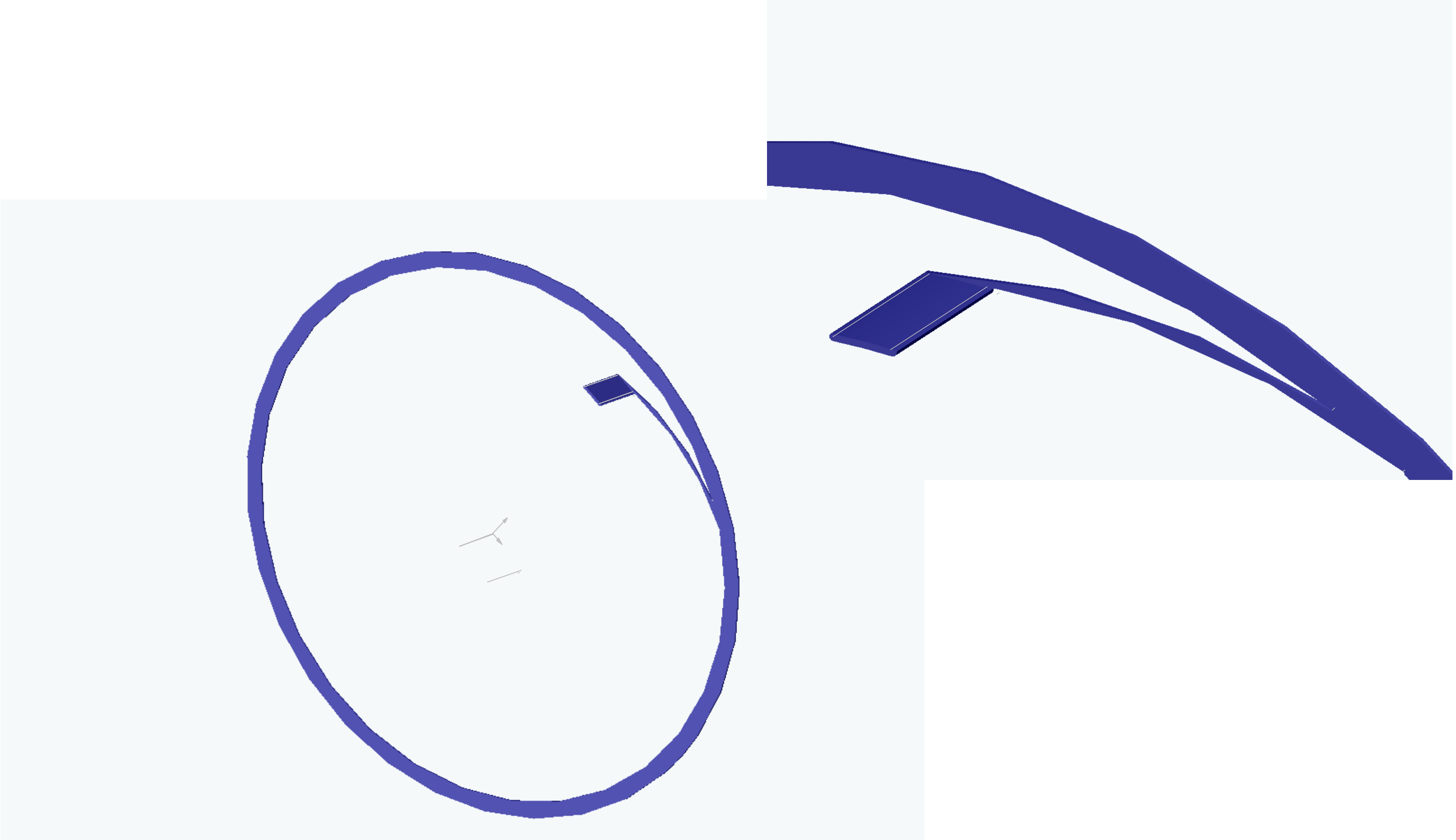


Single Finger as a Free Body Diagram and Geometrical Changes Proposed For Better Wear Behavior

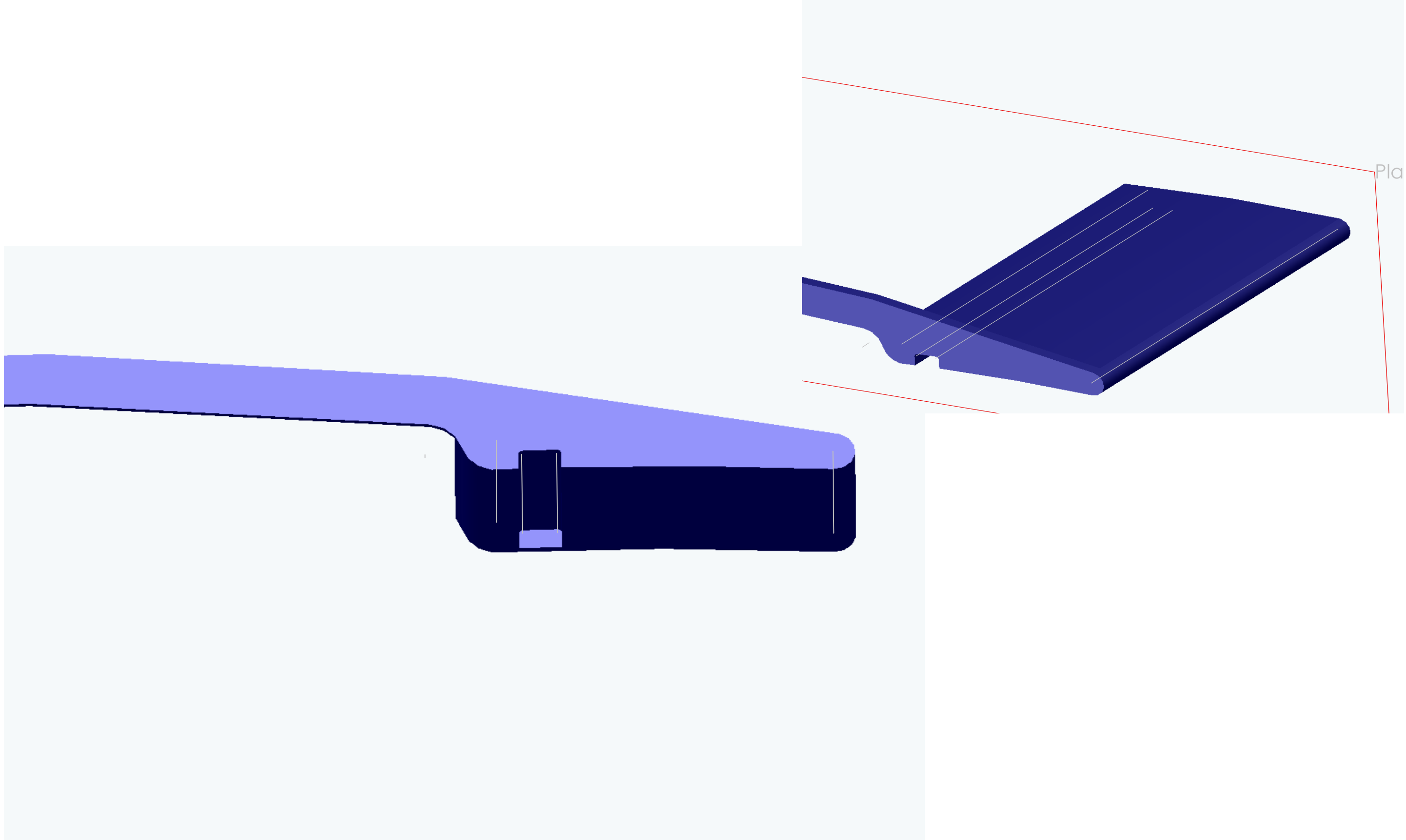
Various finger configurations that are being considered



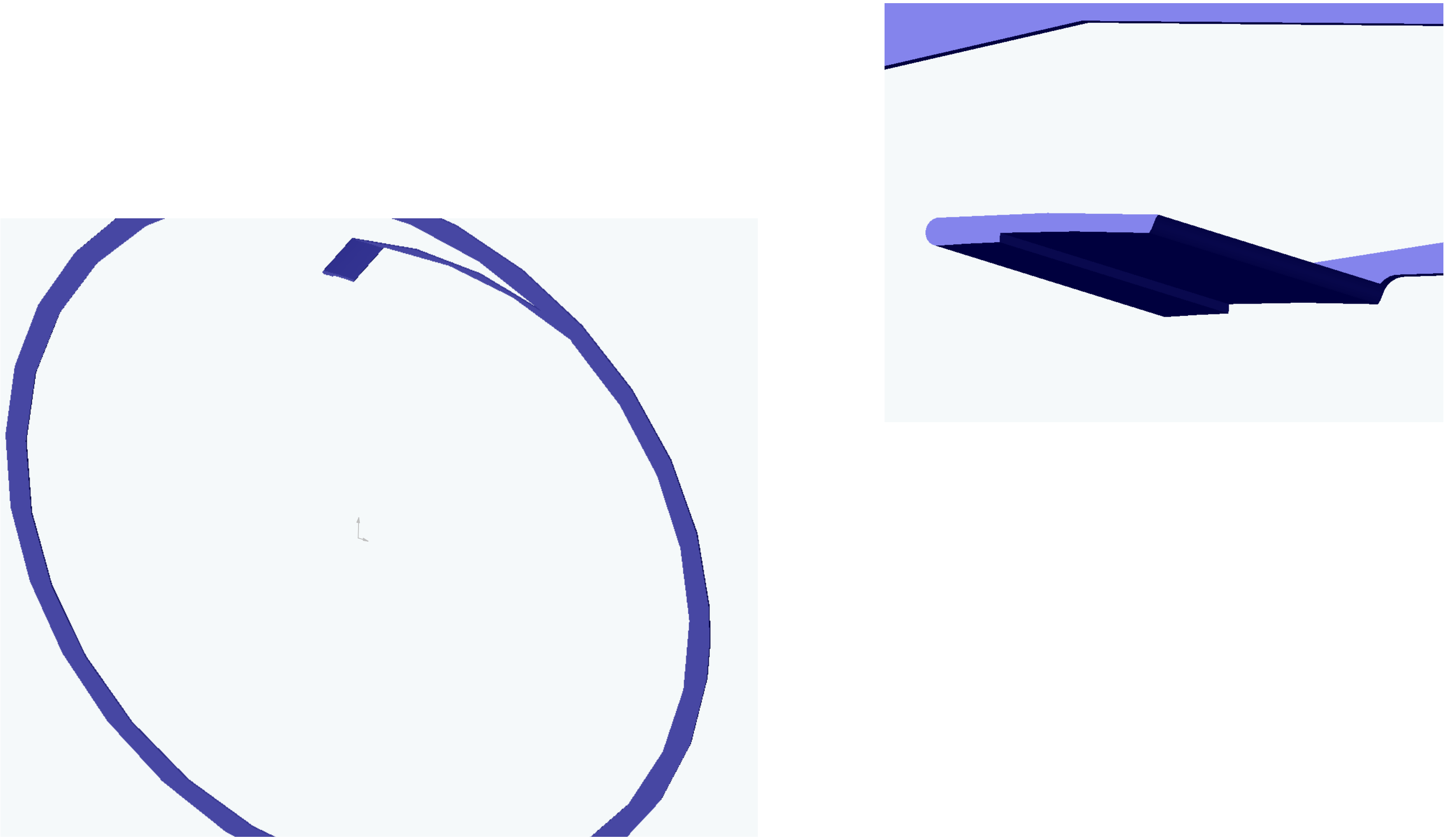
One finger in the rim geometry with basic pad



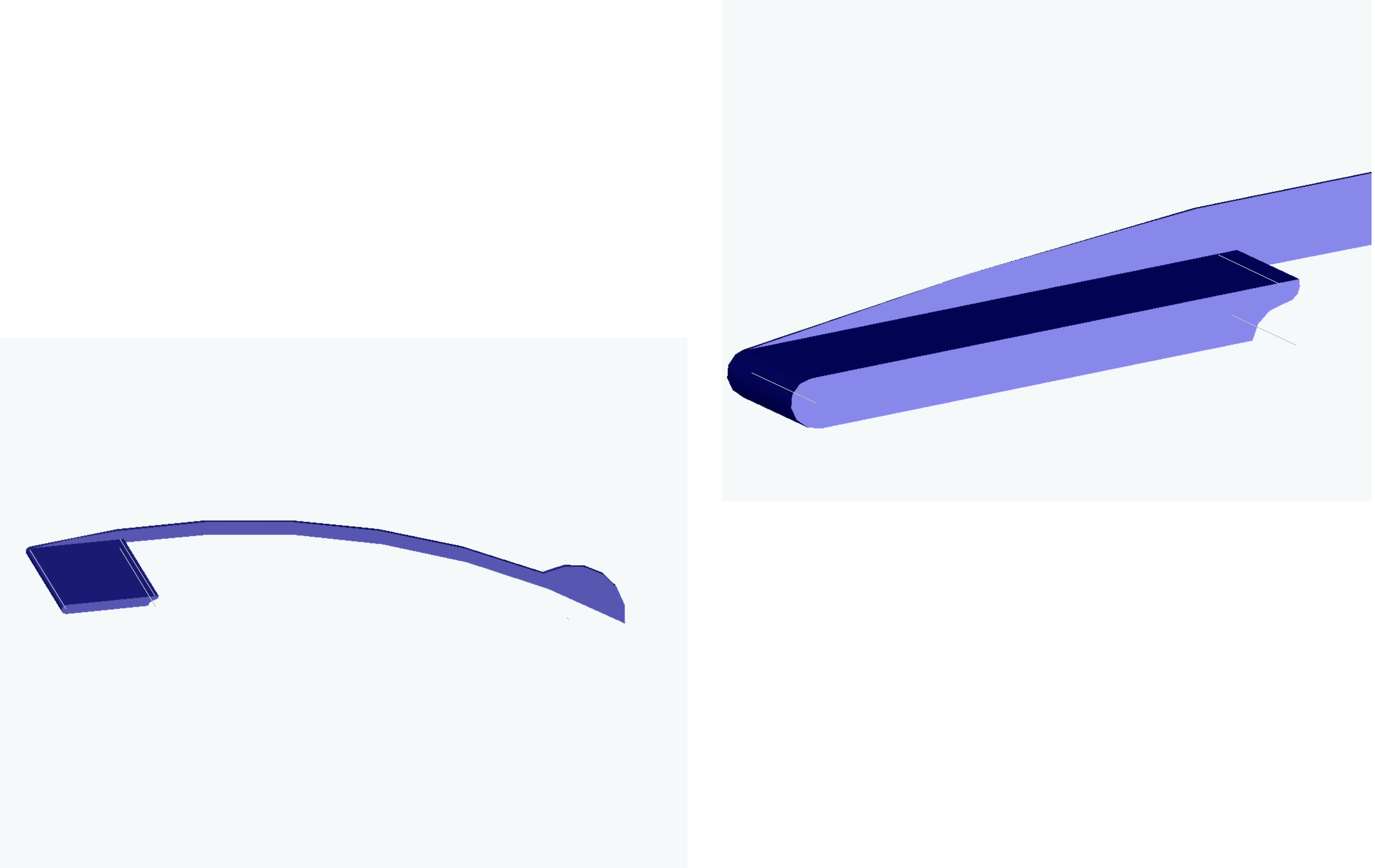
Various finger configurations that are being considered



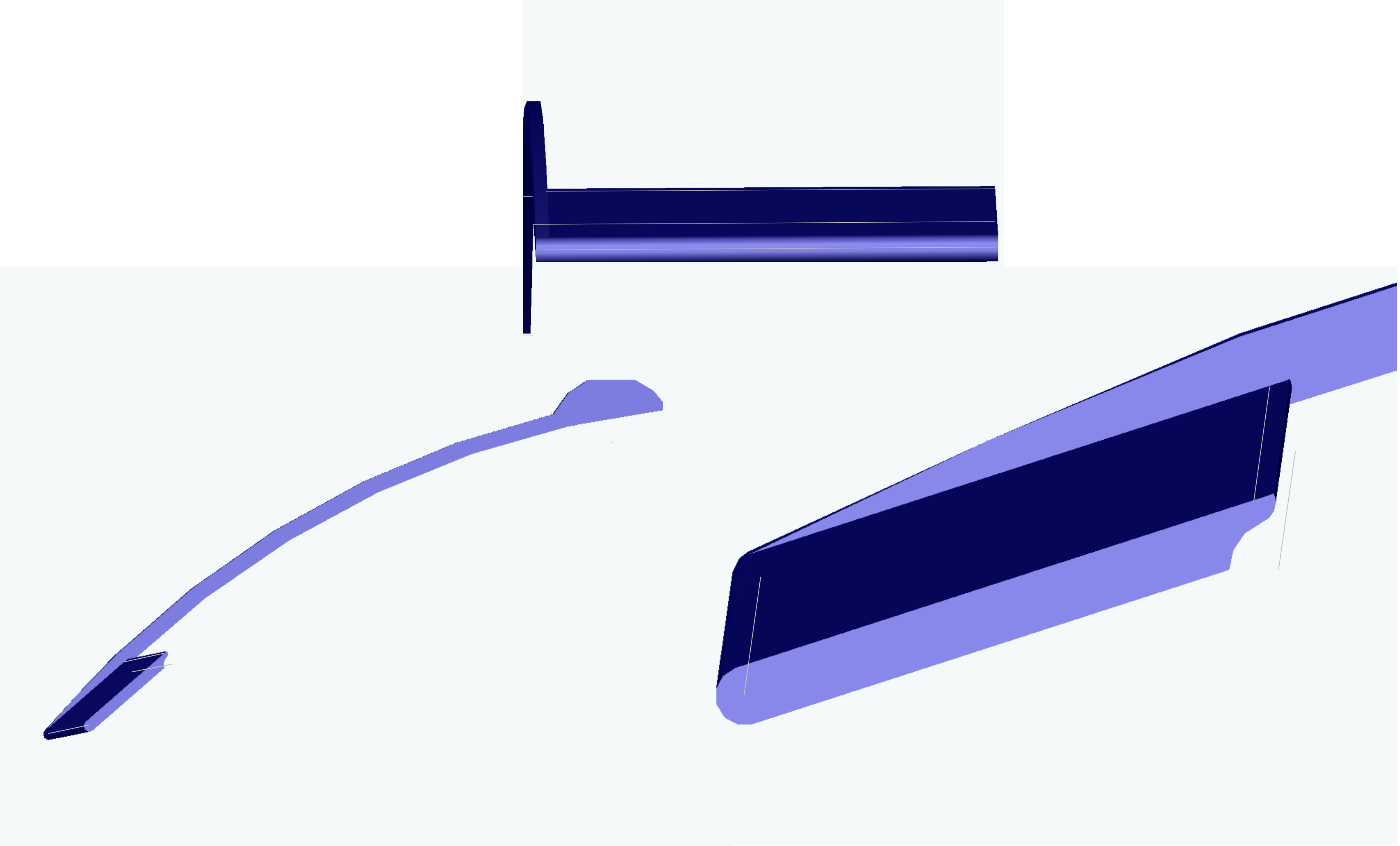
One finger in the rim geometry with Rayleigh pad



One finger with wedge pad

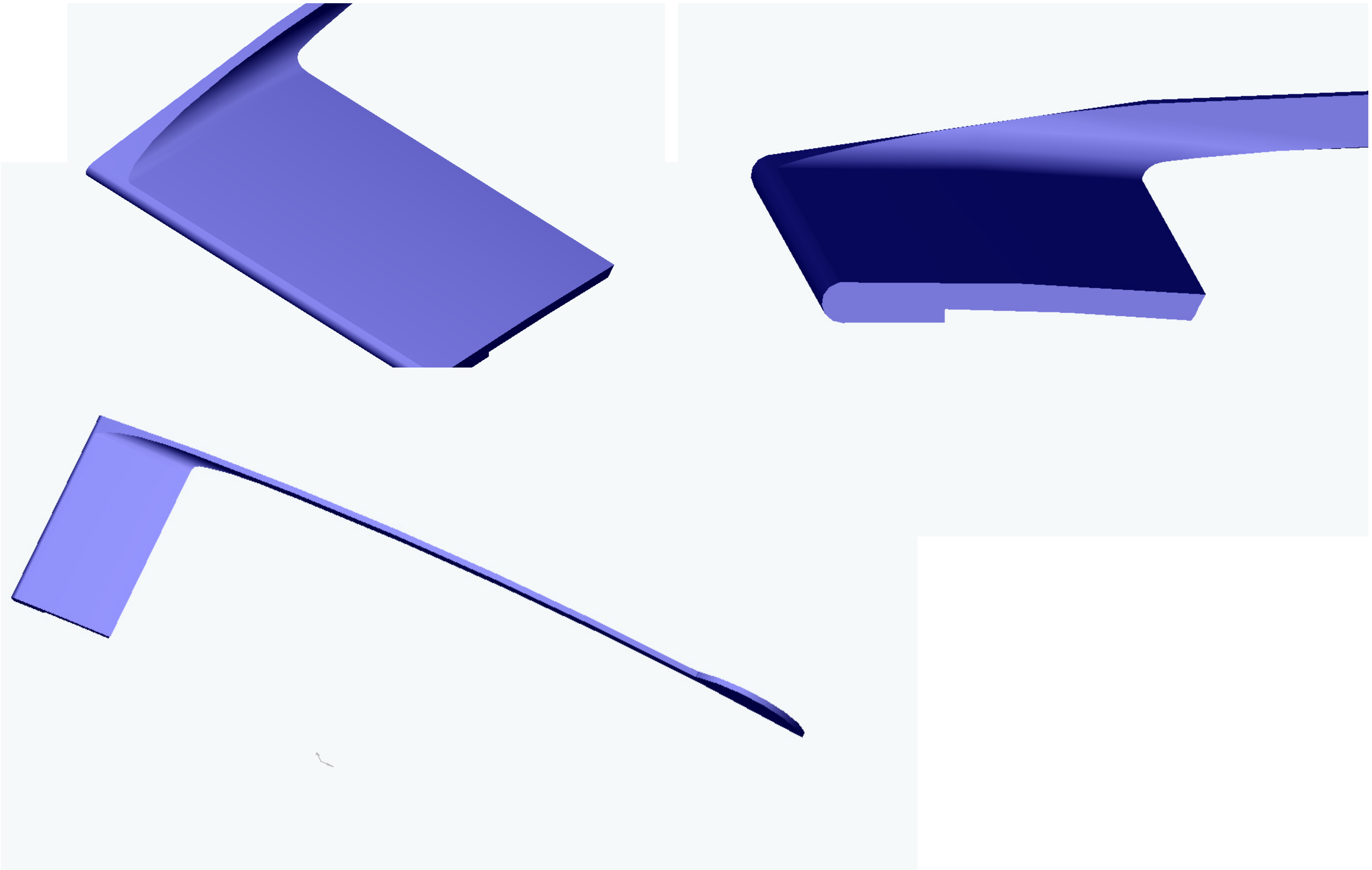


One finger with double wedge pad axial 0.5

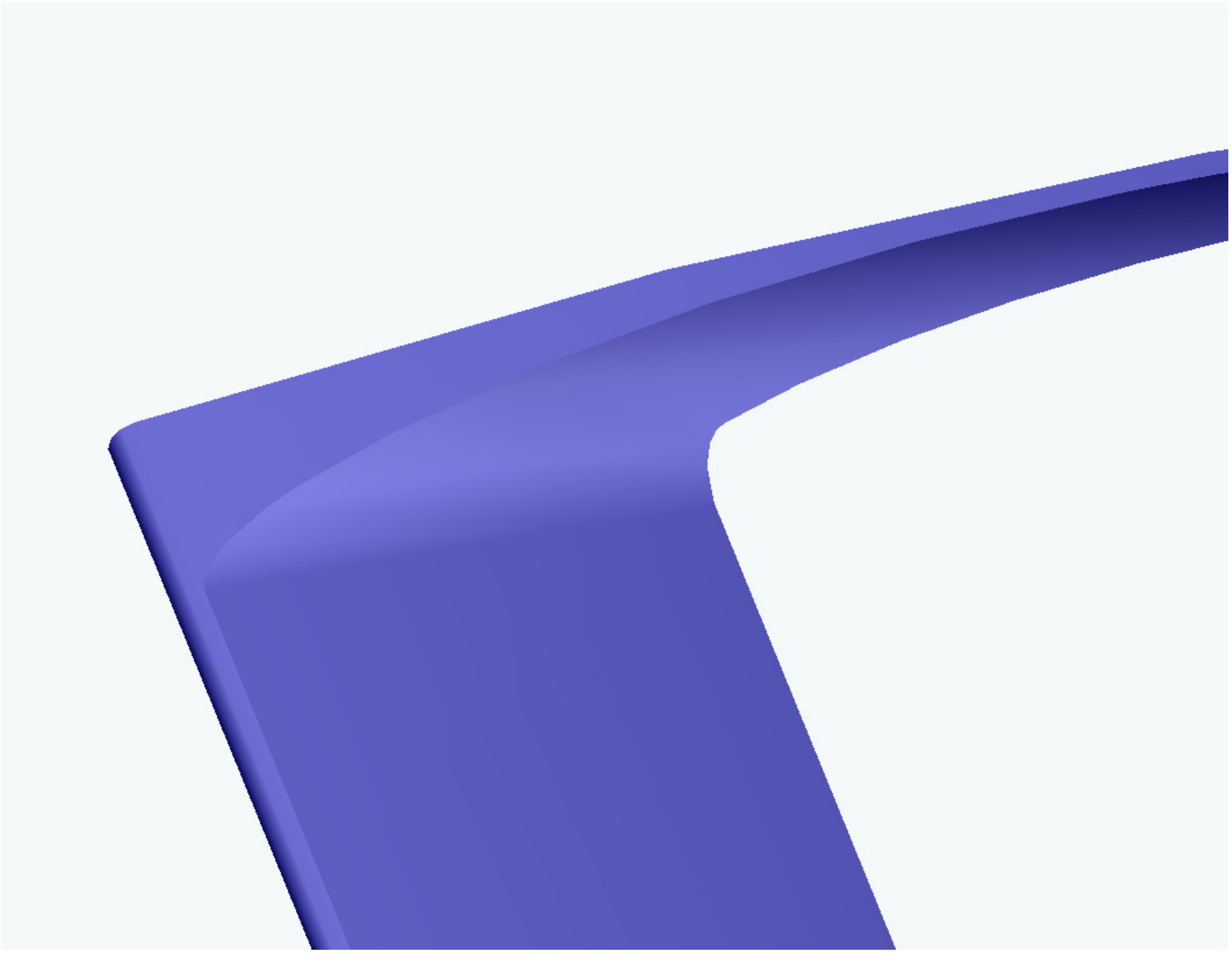


One finger in the rim geometry no pad

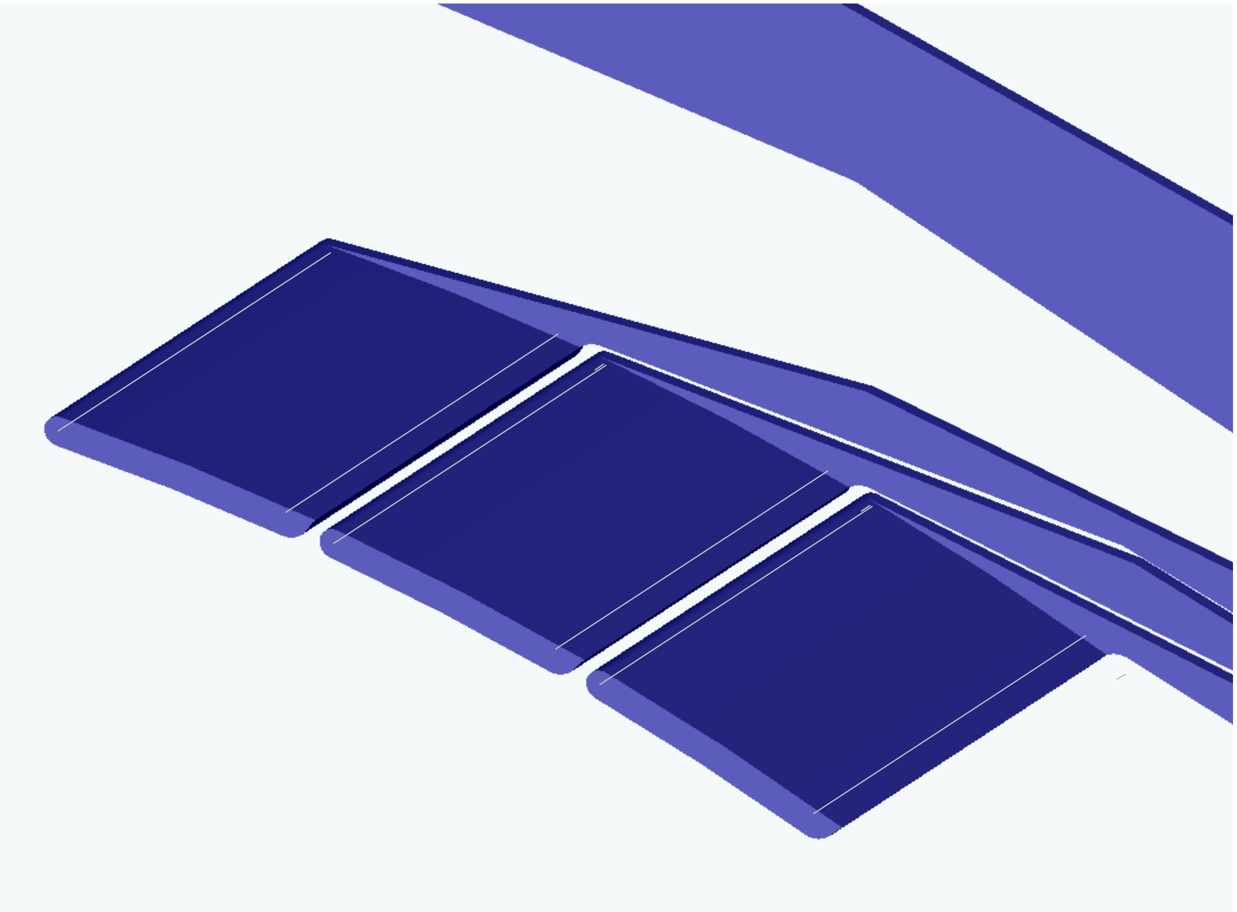
One finger with Rayleigh pad enforced pad R040



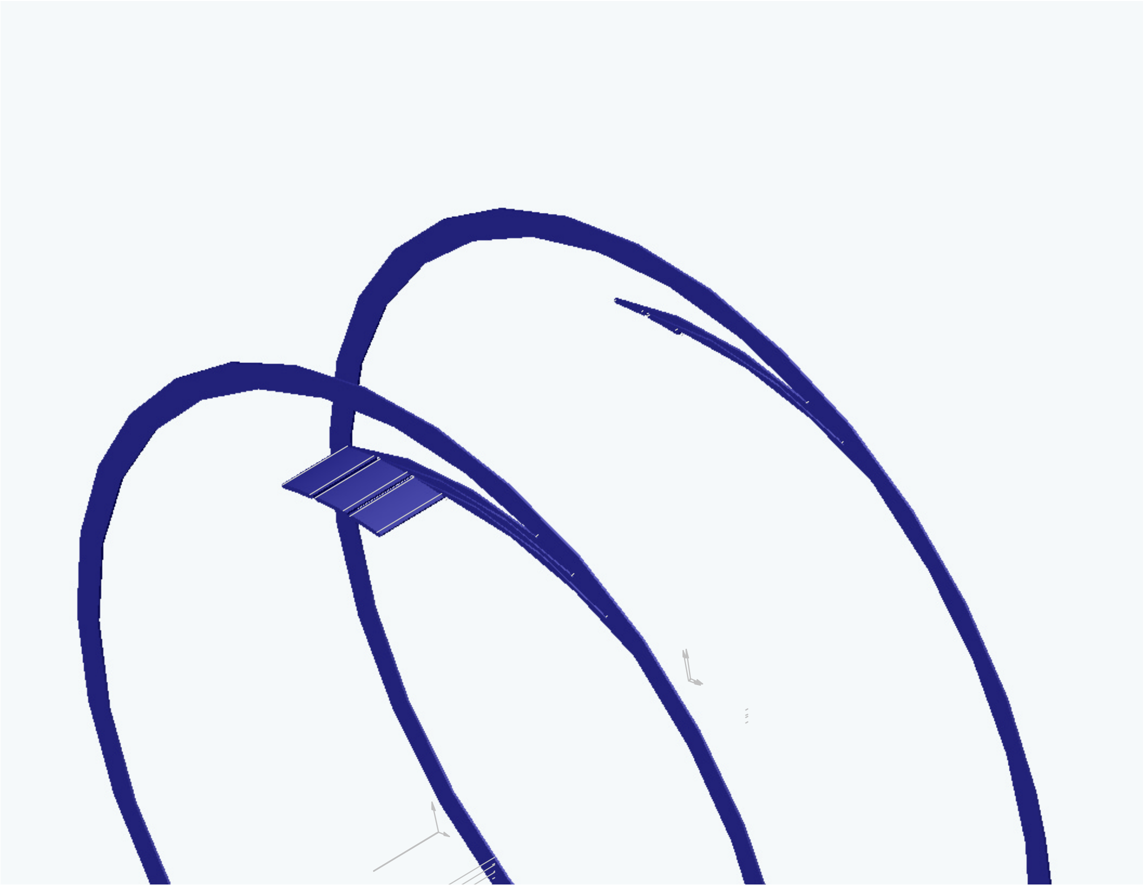
One finger with Rayleigh pad enforced
R 0.100



Three fingers in the rim geometry with basic pad

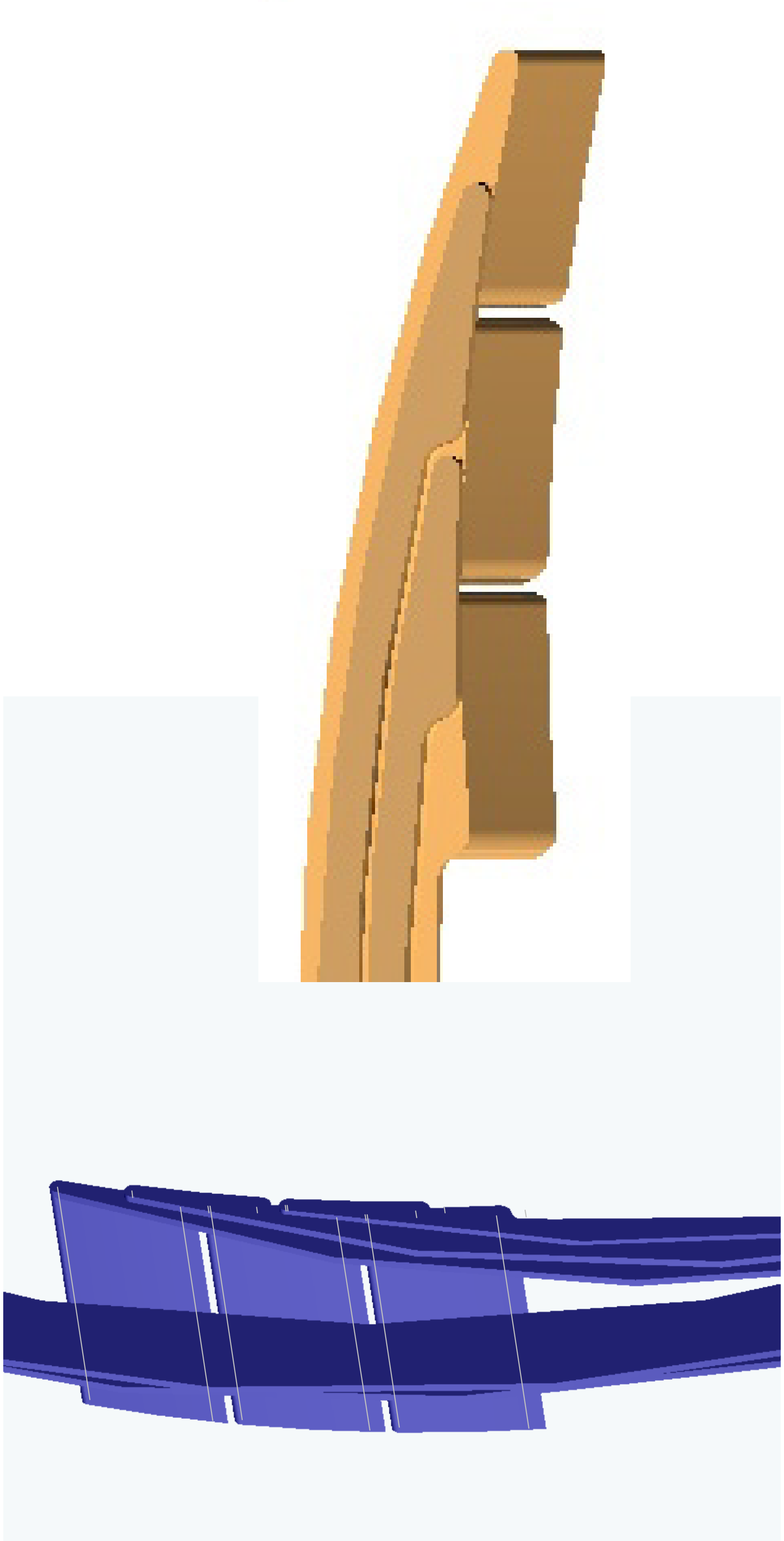


Two rows of basic fingers and pad

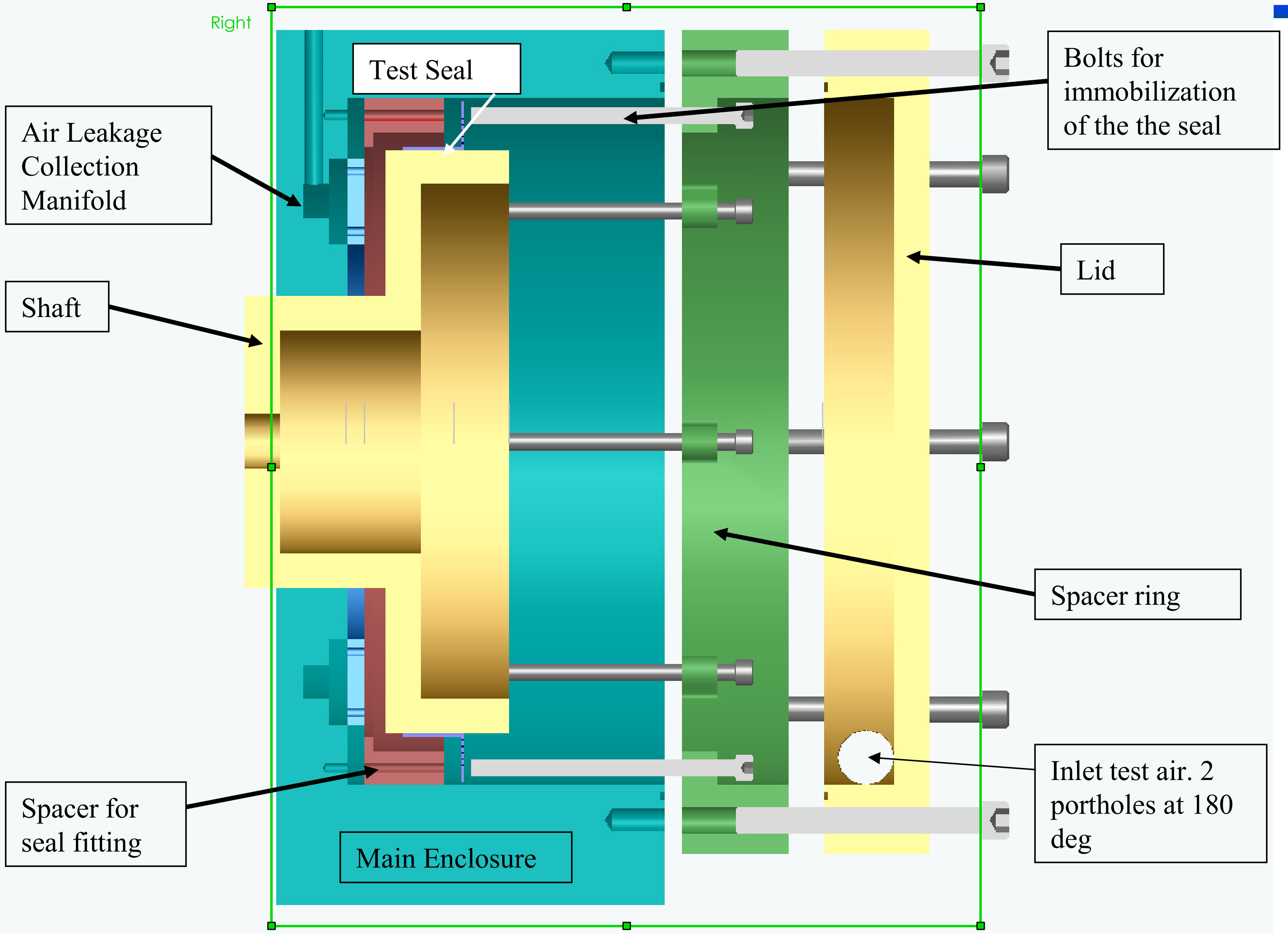


56 fingers in the rim geometry with Rayleigh pad

Assembly of HP and LP fingers



Test Section Cross Longitudinal Section



Detail of the Seal Location

SOME SOLID MODELING USING ALGOR

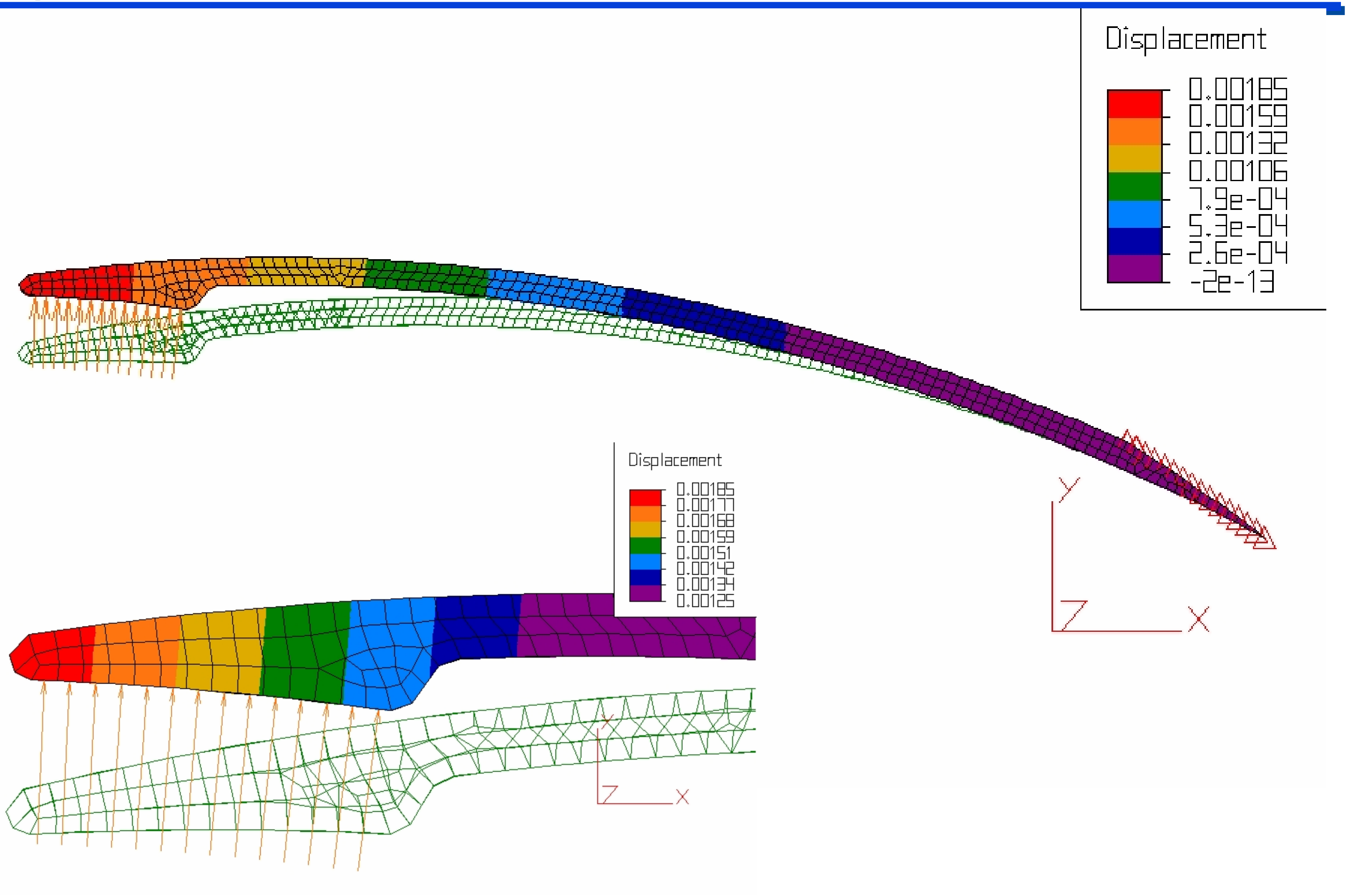
Algor modeling of the finger

These runs were also used to verify the FEMSTRESS results in general

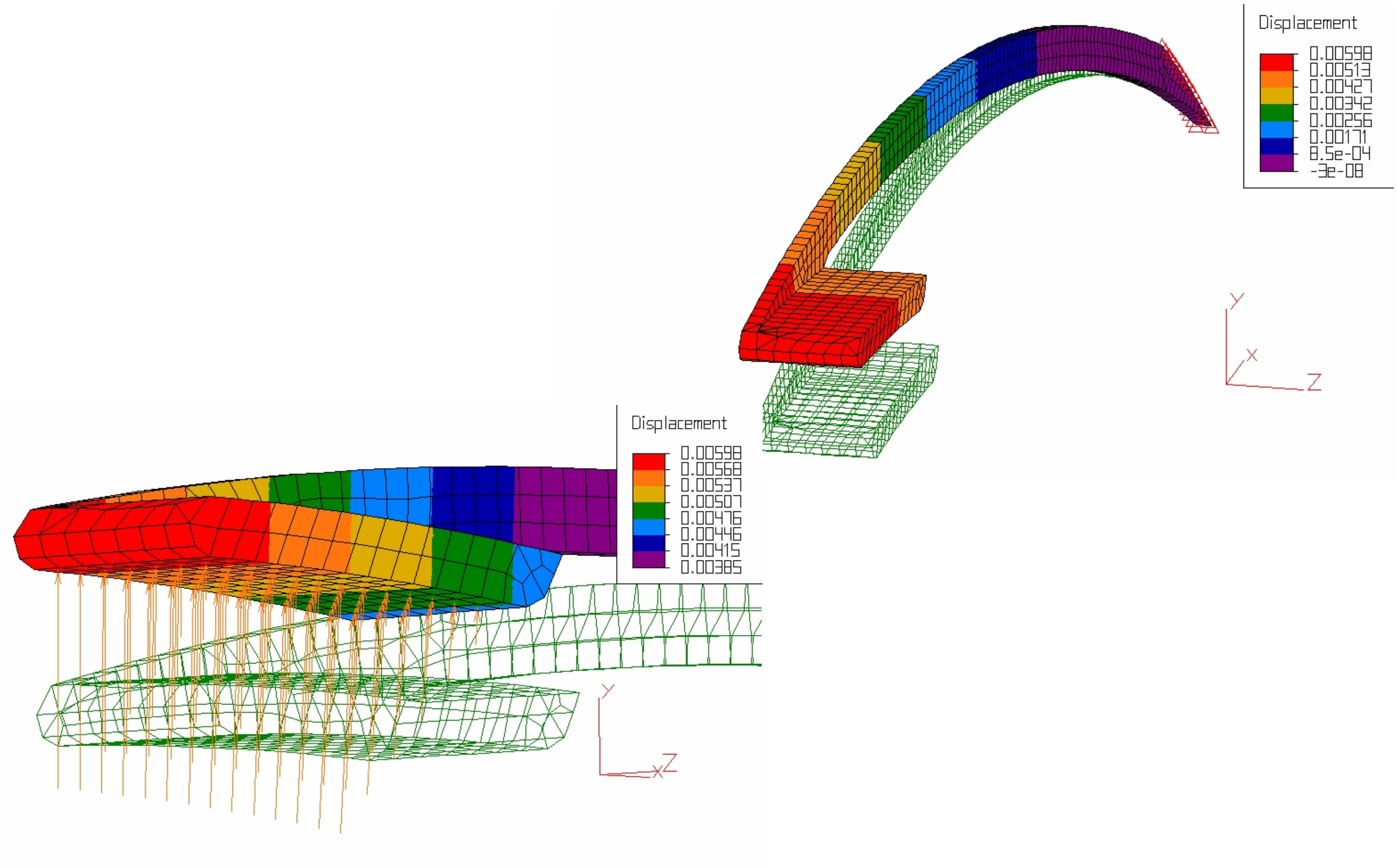
no pad –Existing geometry, ID=5.090 in

the short pad→0.1 in long pad

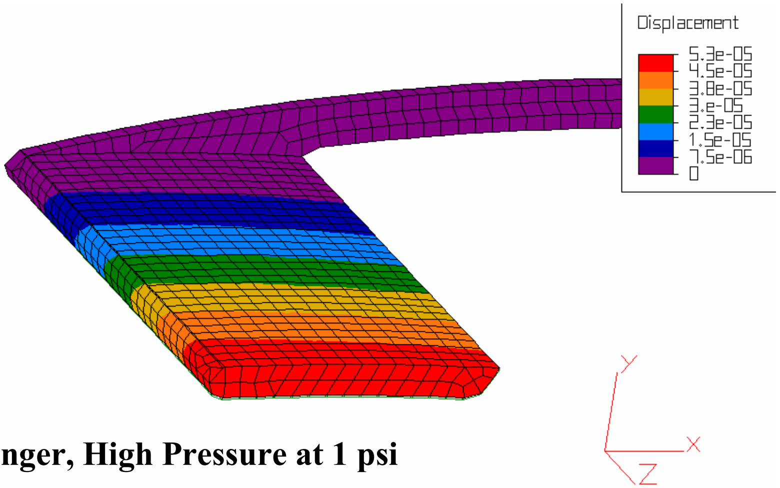
PAD=none
Pressure =1psi



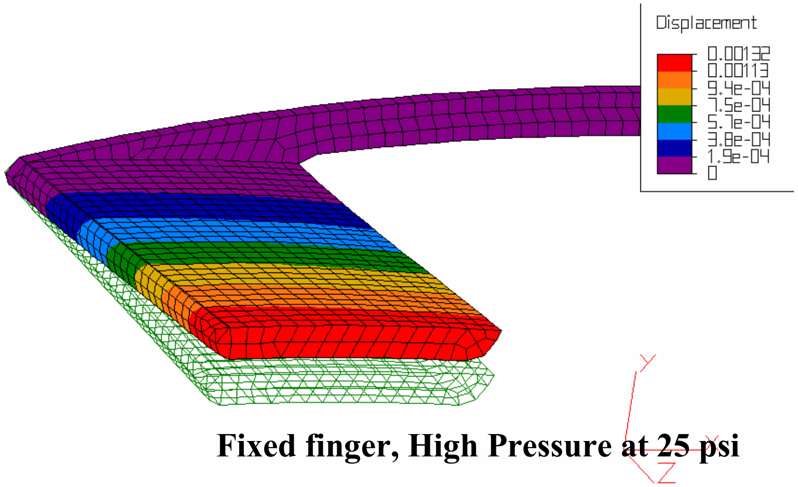
PAD=0.1in long
Pressure =1psi max



Pad deformation; fixed stick; no fillet

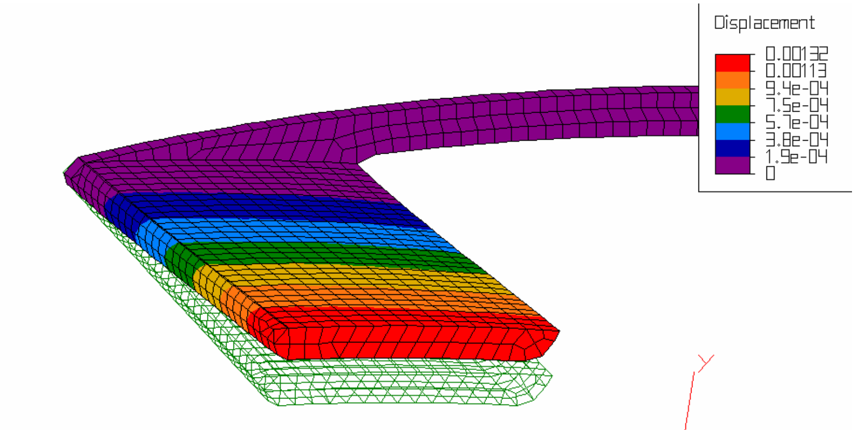


Fixed finger, High Pressure at 1 psi

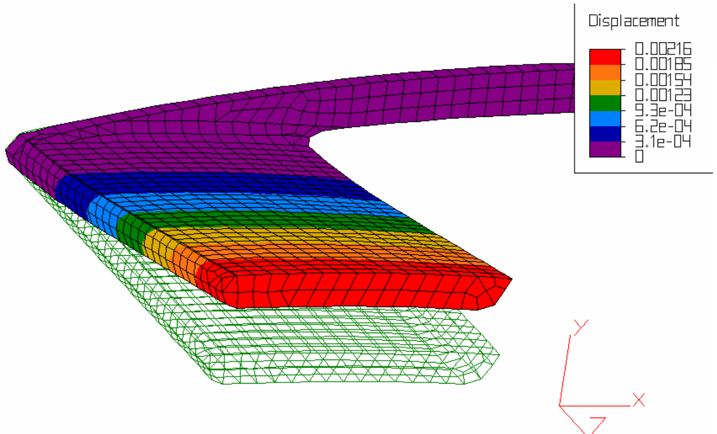


Fixed finger, High Pressure at 25 psi

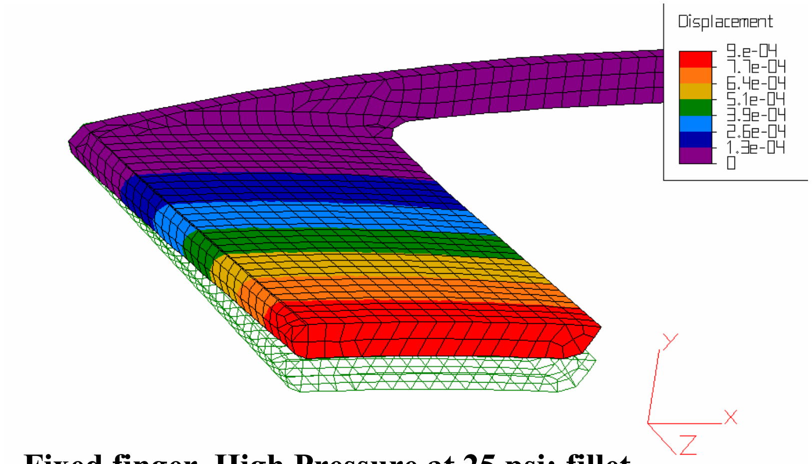
Pad displacement comparison when fillet is added



Fixed finger, High Pressure at 25 psi; no fillet

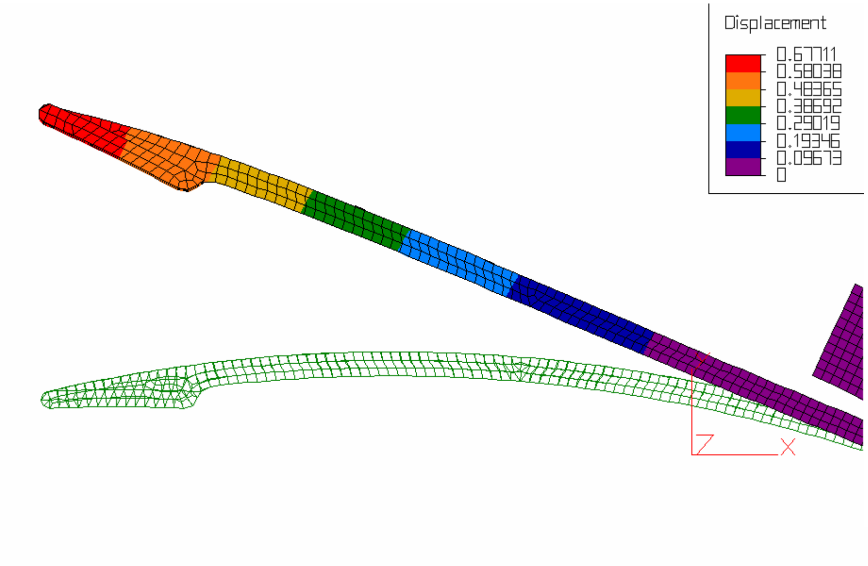


Fixed finger, High Pressure at 60 psi; fillet

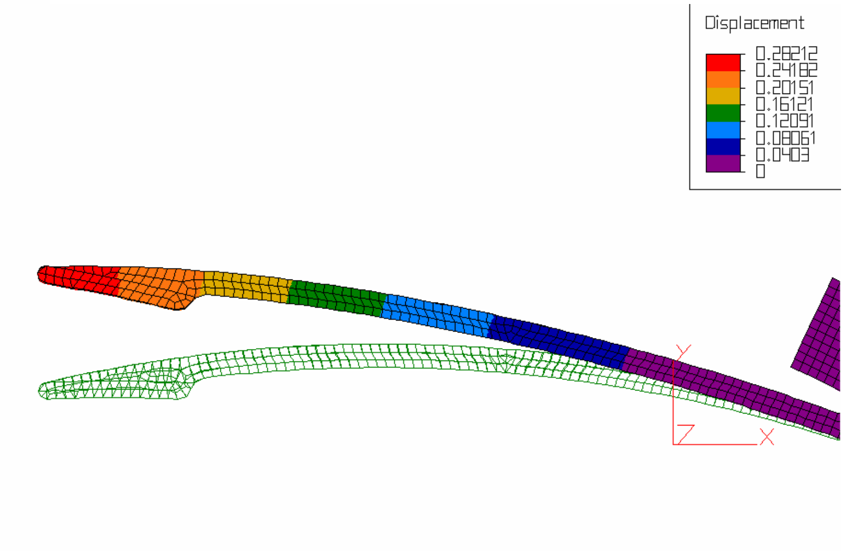


Fixed finger, High Pressure at 25 psi; fillet

Finger motion when Coulomb type friction is applied at 25 and 60 psi pressure differential



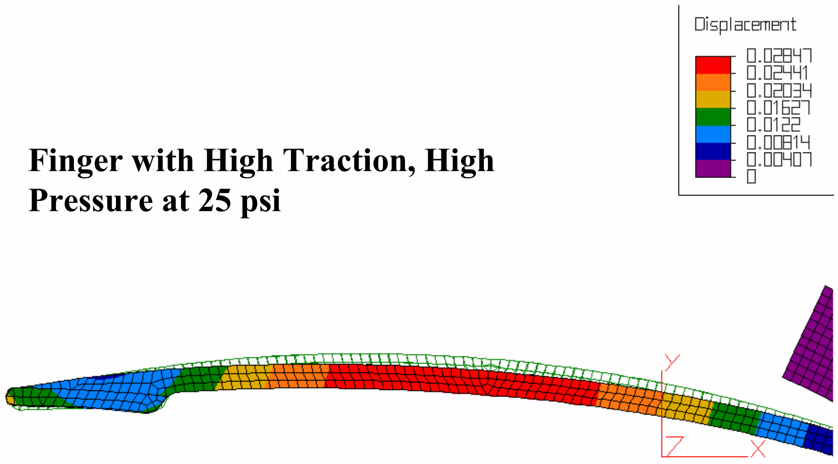
Finger with Traction, High Pressure at 60 psi



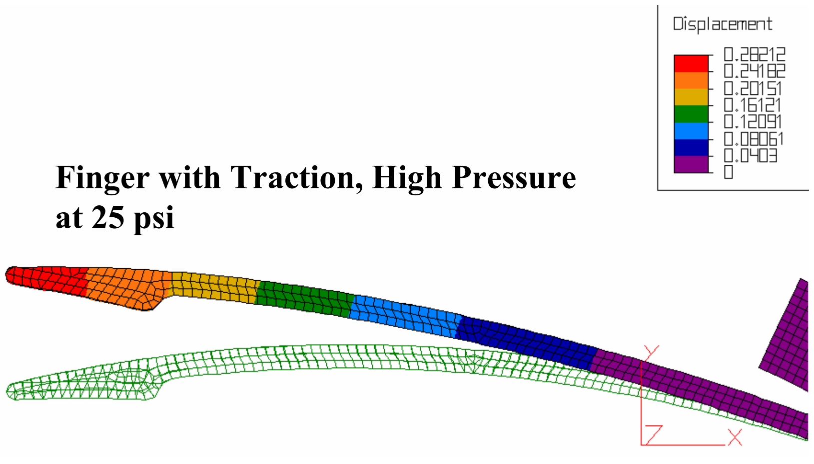
Finger with Traction, High Pressure at 25 psi

Comparison of stick motion with one and two layered fingers.

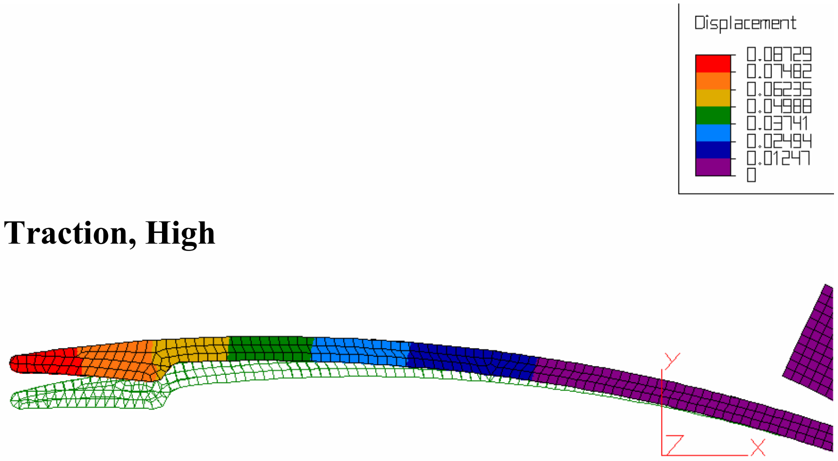
Finger with High Traction, High Pressure at 25 psi



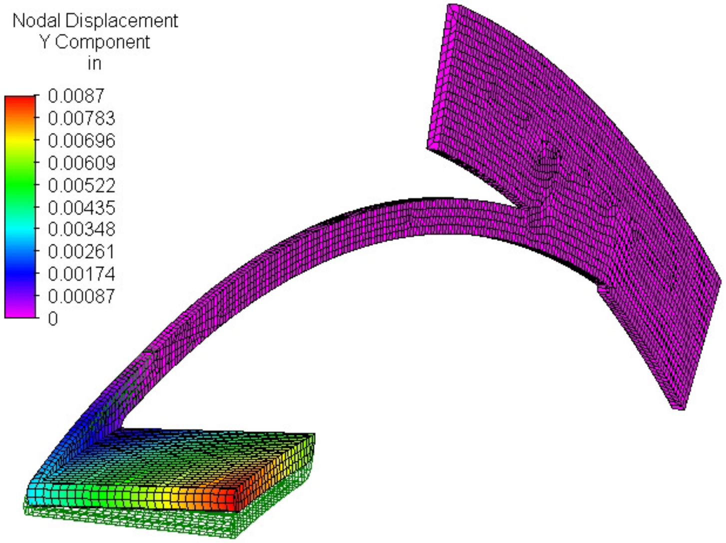
Finger with Traction, High Pressure at 25 psi



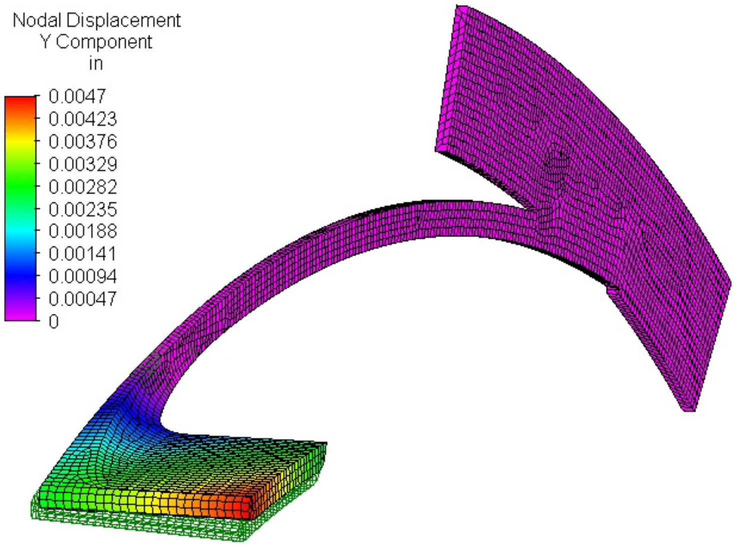
Two layered Finger with Traction, High Pressure at 25 psi



Fully constrained stick; motion of the pad; 25 psi

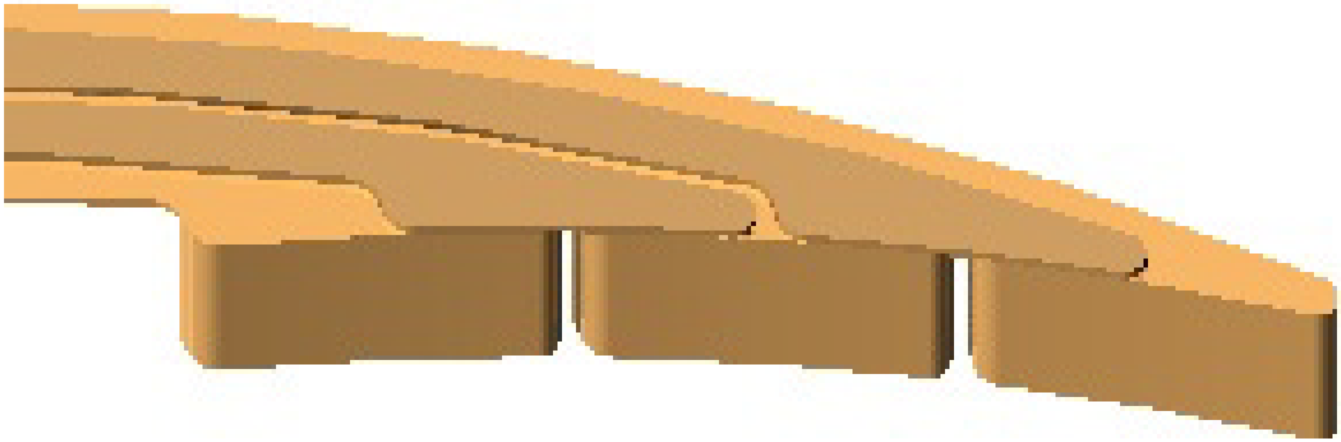


1 low pressure finger fully constrained without fillet

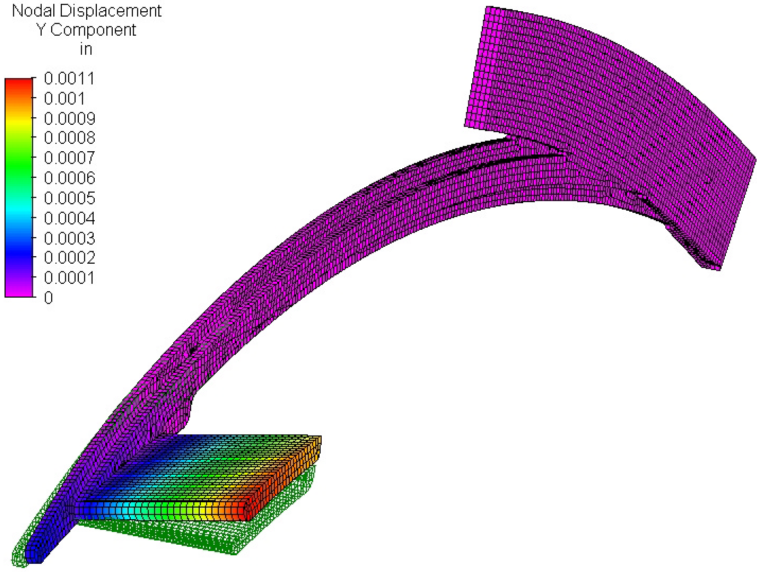


1 low pressure finger fully constrained with fillet

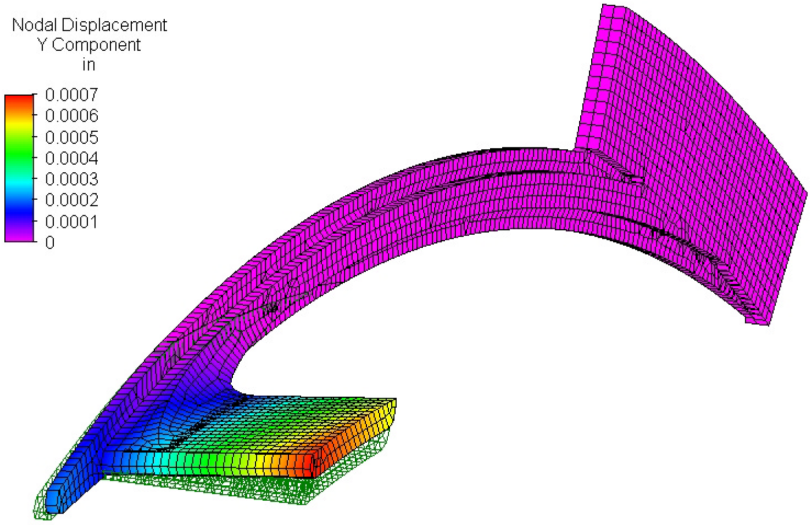
Finger Assembly: 2 HP + 3 LP



Finger Assembly: 2 HP +1 LP; 25 psi; constraint is applied 0.100in from rotor surface

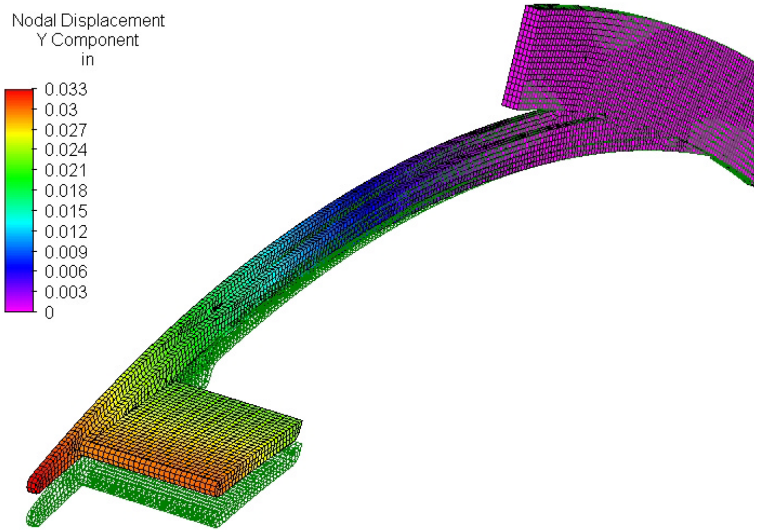


2 high pressure, 1 low pressure fingers fully constrained without fillet

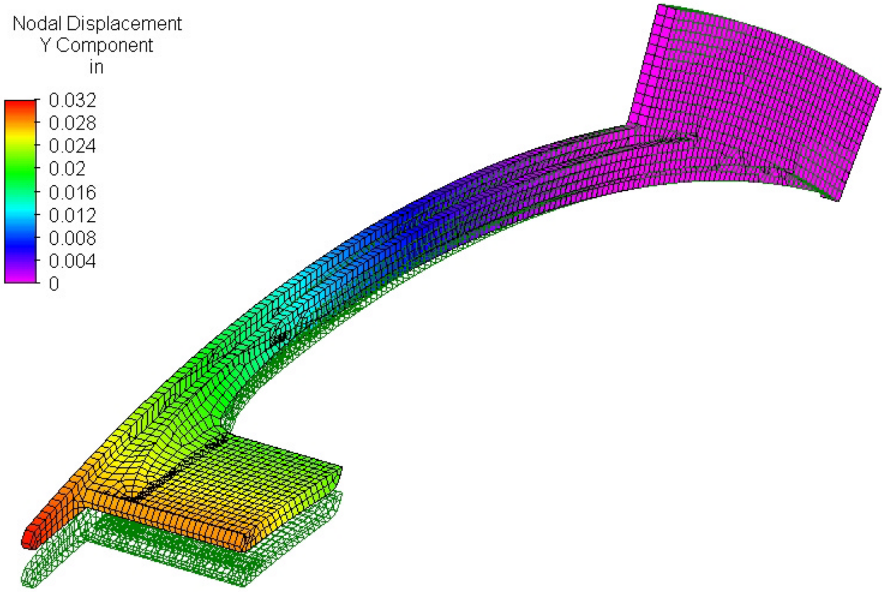


2 high pressure, 1 low pressure fingers fully constrained with fillet

Finger Assembly: 2 HP +1 LP; 25 psi; constraint is applied 0.100in from rotor surface. Traction is 0.3 P



2 high pressure, 1 low pressure finger with traction, without fillet



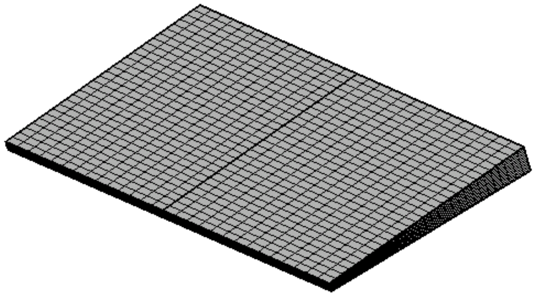
2 high pressure, 1 low pressure finger with traction with fillet

Contents

- Radial Wedge Geometry - without pad/stick deformation
- Radial Wedge Geometry - with deformation
- Radial Wedge Geometry – Two Fingers +Washer (with restriction & with contact friction)

Pressure Distribution and Forces the Pad

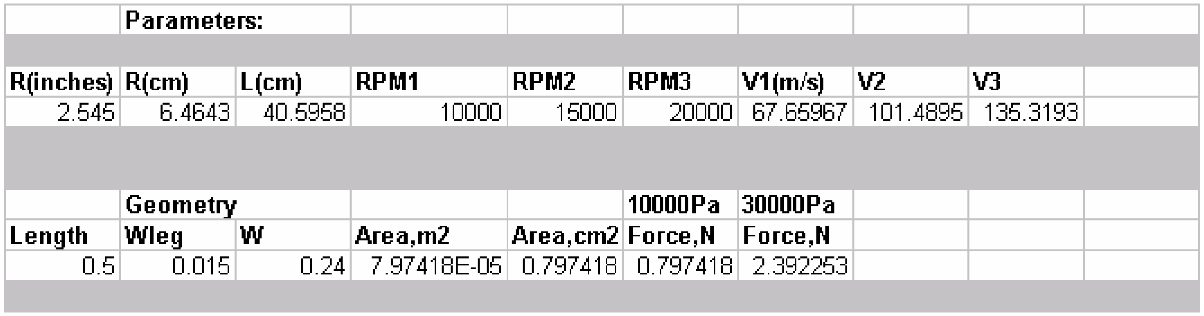
at 10..20,000 rpm



Operational Parameters

We consider linear runner velocities of 30,60,100 (15,000 rpm) and 135 m/s (20,000 rpm).

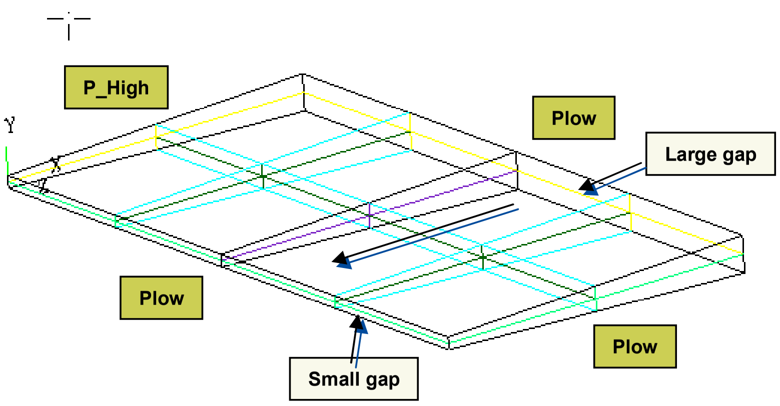
Basic pad surface area is 0.8 cm2 and at average pressure of 10,000 N/m2 (Pa) this constitutes 0.8 Newton (or equivalent of 80 grams of weight). From our previous FEA and FLUID calculations one may expect that average forces on the pad got to be in this ballpark to lift it.

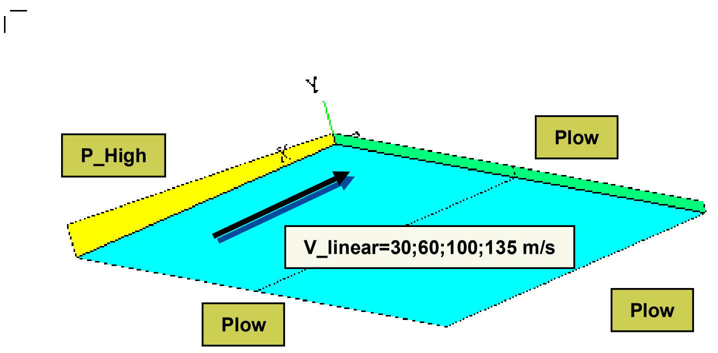


	Parameters:								
R(inches)	R(cm)	L(cm)	RPM1	RPM2	RPM3	V1(m/s)	V2	V3	
2.545	6.4643	40.5958	10000	15000	20000	67.65967	101.4895	135.3193	
	Geometry				10000Pa	30000Pa			
Length	Wleg	W	Area,m2	Area,cm2	Force,N	Force,N			
0.5	0.015	0.24	7.97418E-05	0.797418	0.797418	2.392253			

Radial Wedge –Cartesian Geometry

Small gap=0.25 mil; large gap =0.75 mil;



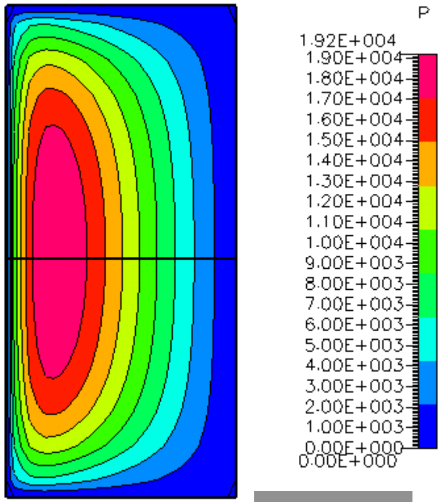


SUMMARY OF FORCES: F=F1+F2

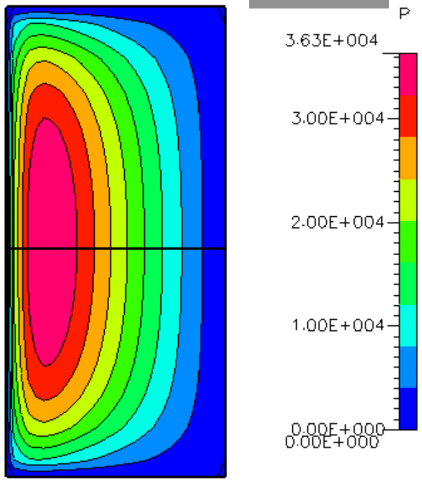
V=135 m/s	Force1_Y=1.14 N	Force2_Y=1.23 N
V=100 m/s	Force1_Y=0.935 N	Force2_Y=1.006 N
V= 60 m/s	Force1_Y=0.624 N	Force2_Y=0.672 N
V= 30 m/s	Force1_Y=0.335 N	Force2_Y=0.361 N

Radial Wedge – Pressures due to Rotation

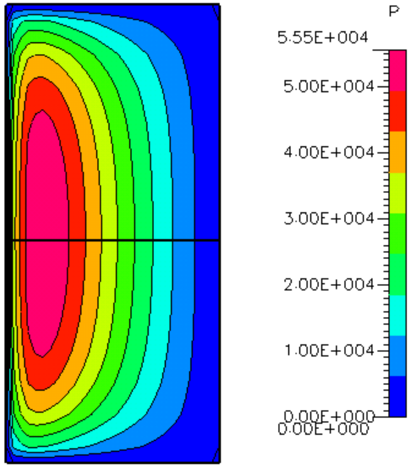
30 m/s



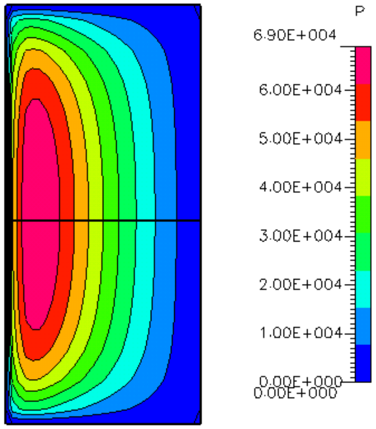
60 m/s



100 m/s



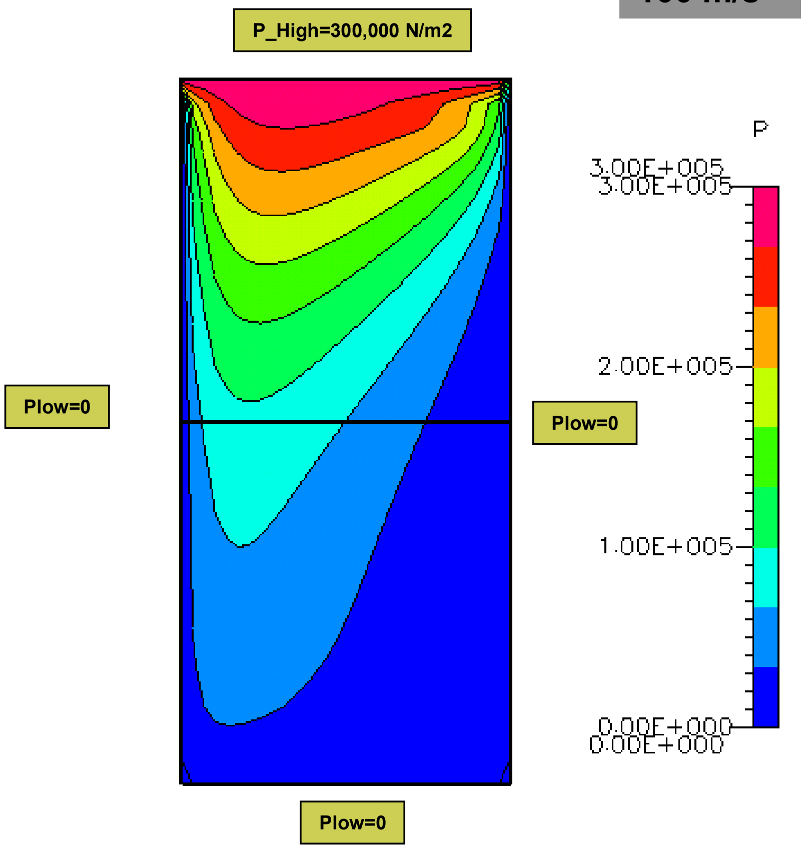
135 m/s



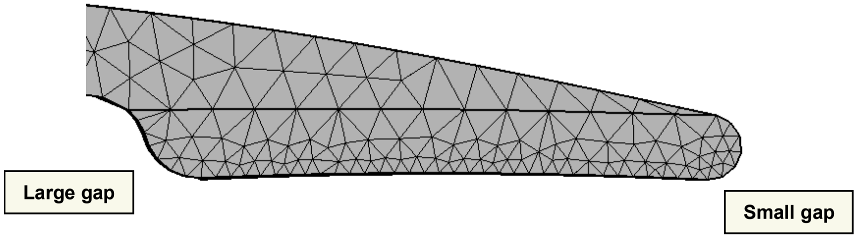
Pressures are in Pa [N/m2], 101000 Pa=14.7 psi

Radial Wedge – pressures due to rotation+ P_high

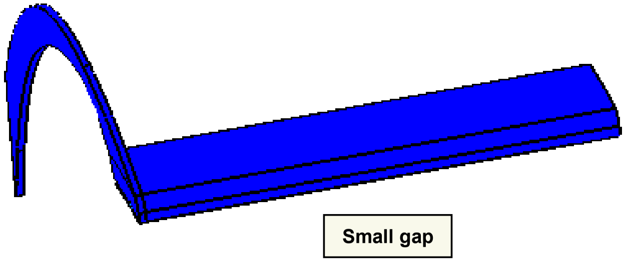
100 m/s



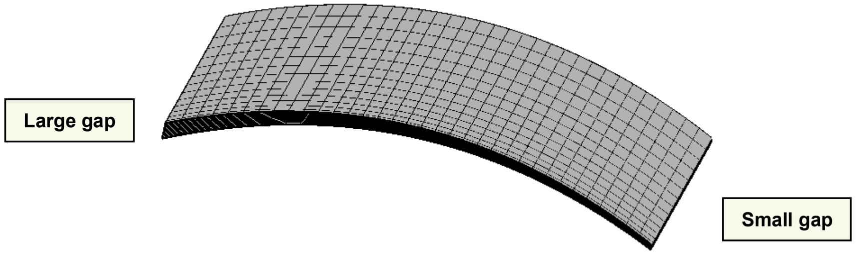
Radial Wedge – Cylindrical Geometry



Radial Wedge Under Pad

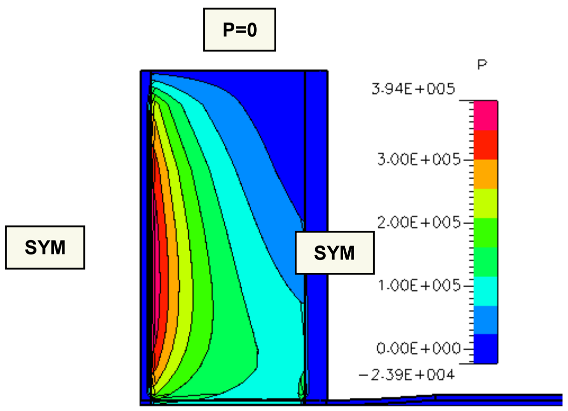


Geometry: pad is not moving

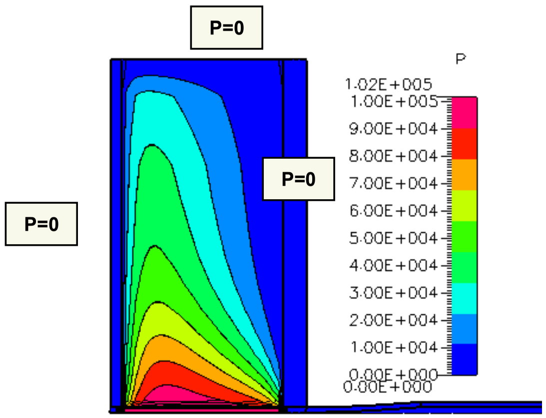


3d film zone-scaled

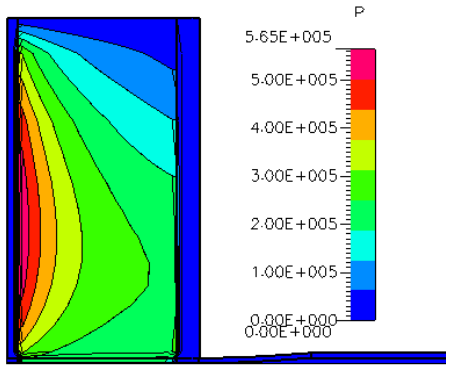
Radial Wedge – Results



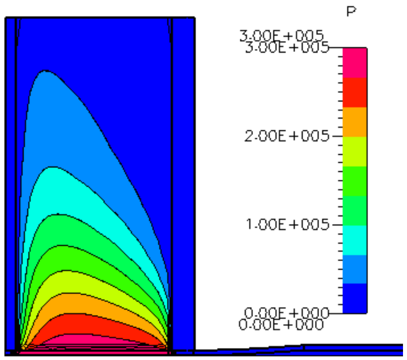
P_high=100,000 N/m2



P_high=100,000 N/m2



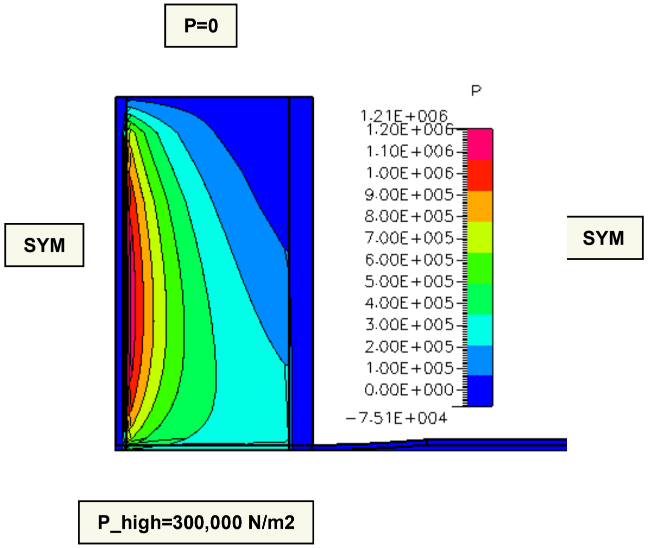
P_high=200,000 N/m2

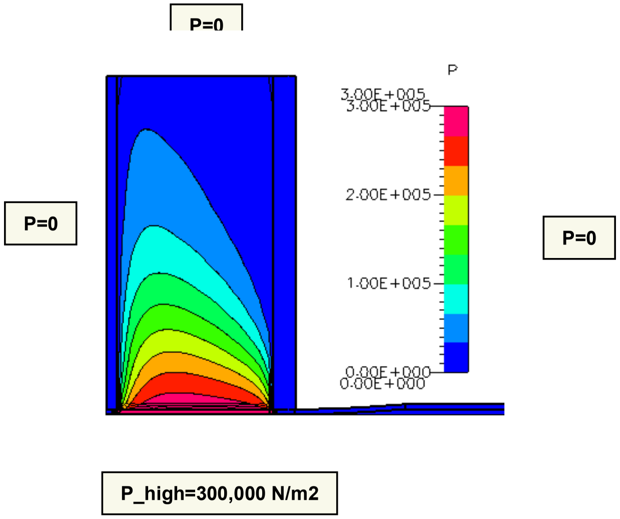


P_high=200,000 N/m2

20,000 RPM

Radial Wedge – Results



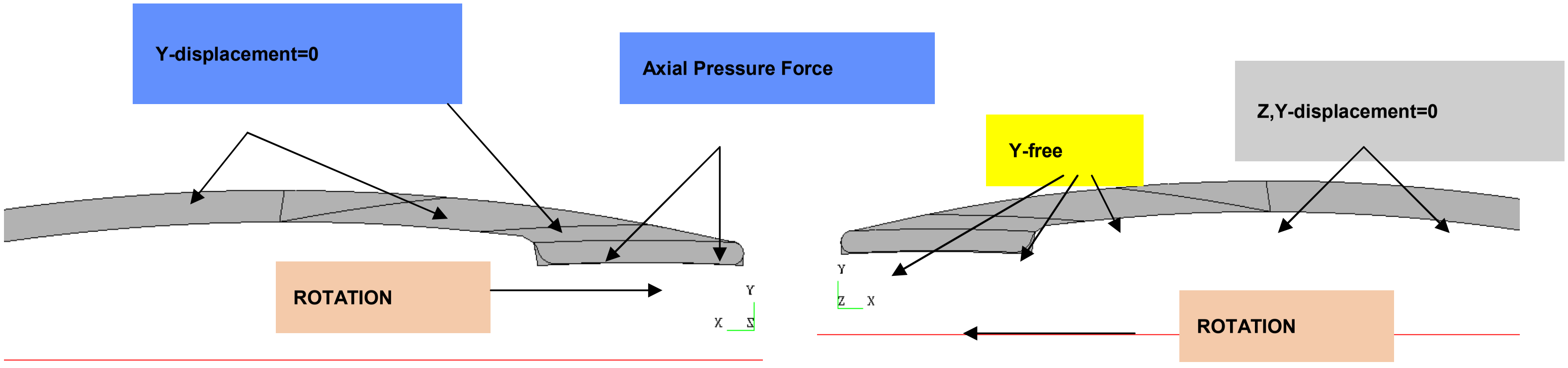


20,000 RPM

Moving Finger Simulation

Omega=2000 rad/sec (19108 RPM),
Phigh=8000 Pa (1 psi)
axial wedge (basic)
Pad L=0.25 inch, stick=15 mil
Film: 0.25 to 0.75 mils thick wedge

Boundary Conditions



Y-displacement=0

Axial Pressure Force

ROTATION

Y-free

Z,Y-displacement=0

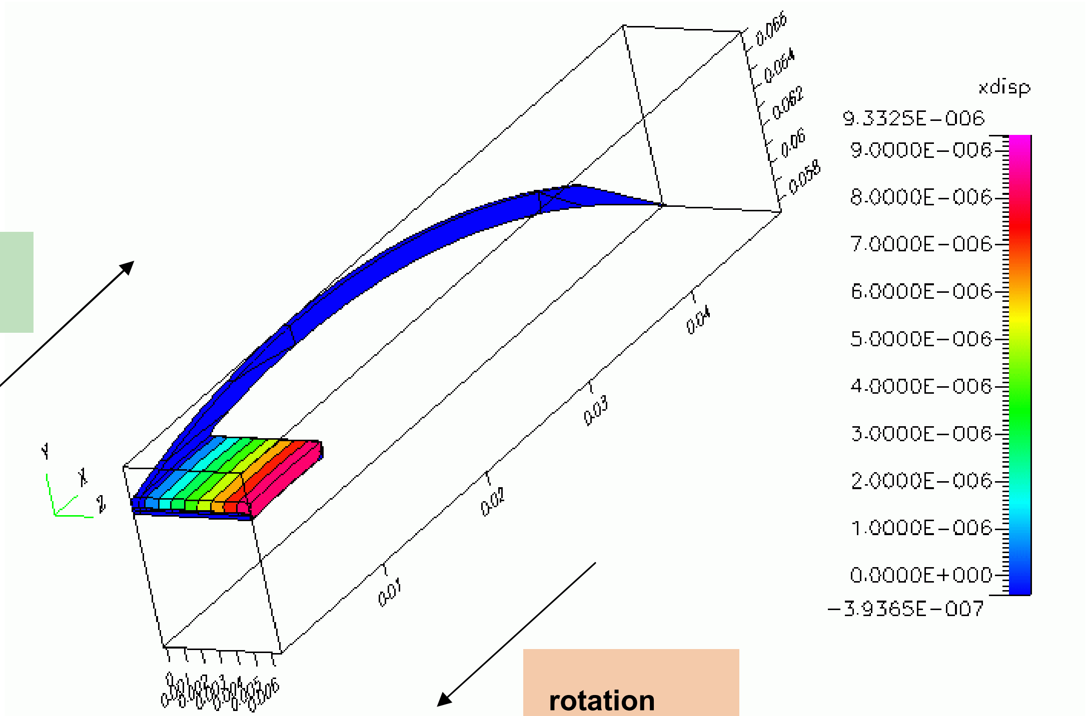
ROTATION

Front view: high P side

Rear view: low P side

Thus most of front surface is restricted for vertical displacement, except for 30 mils (radially,pad thickness) where axial pressure force of <u>1 psi</u> is applied. On the rear end side we restrict both Y and Z(axial) displacement simulating backside support with strong friction. Support is not extended all the way and zone of 100 mils (radially) does not have any restrictions, free to deflect under axial forces from Phigh side.

X-Displacement (circumferential)

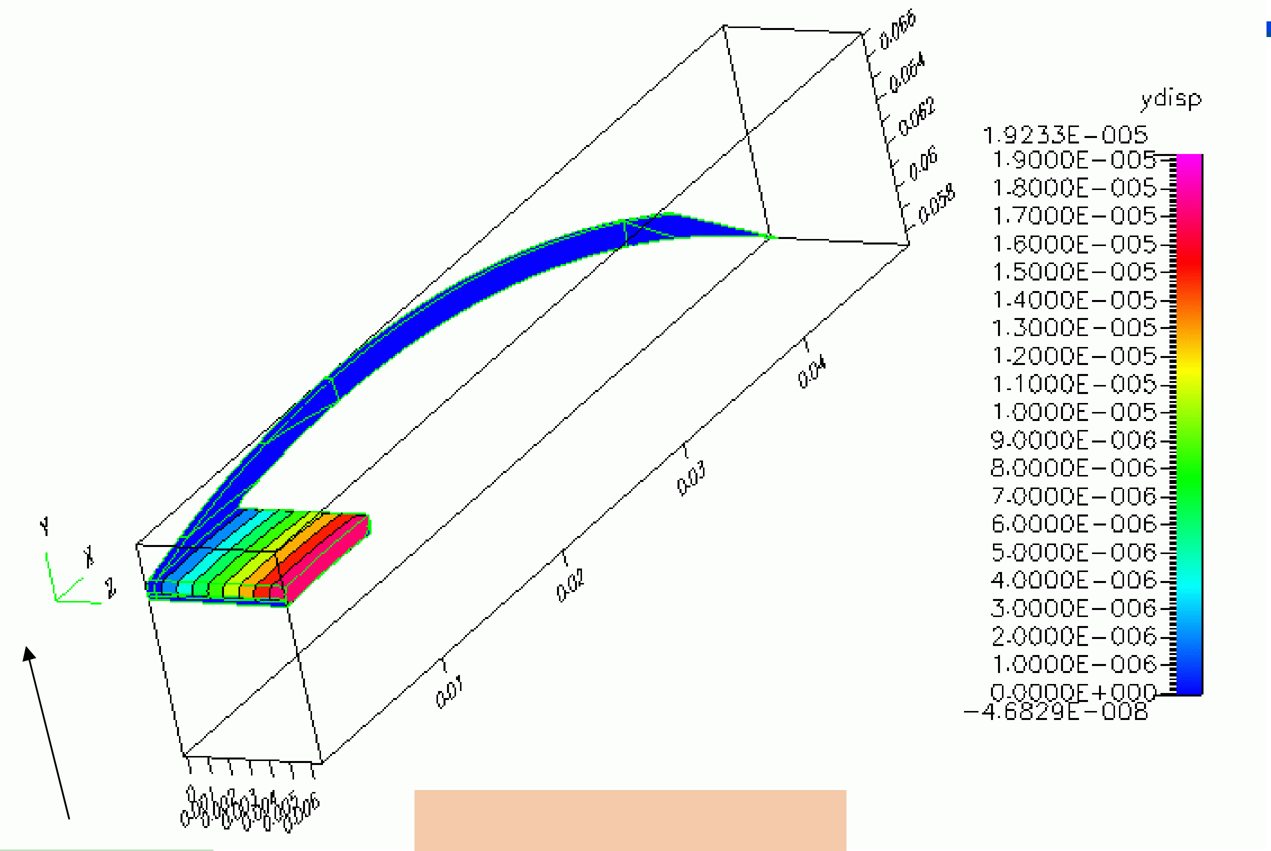


X –direction circumferential

rotation

all displacements are in METERS
1mil=2.54E-5 m, so max displacement =0.33 mil

Y-Displacement (radial lift-off)

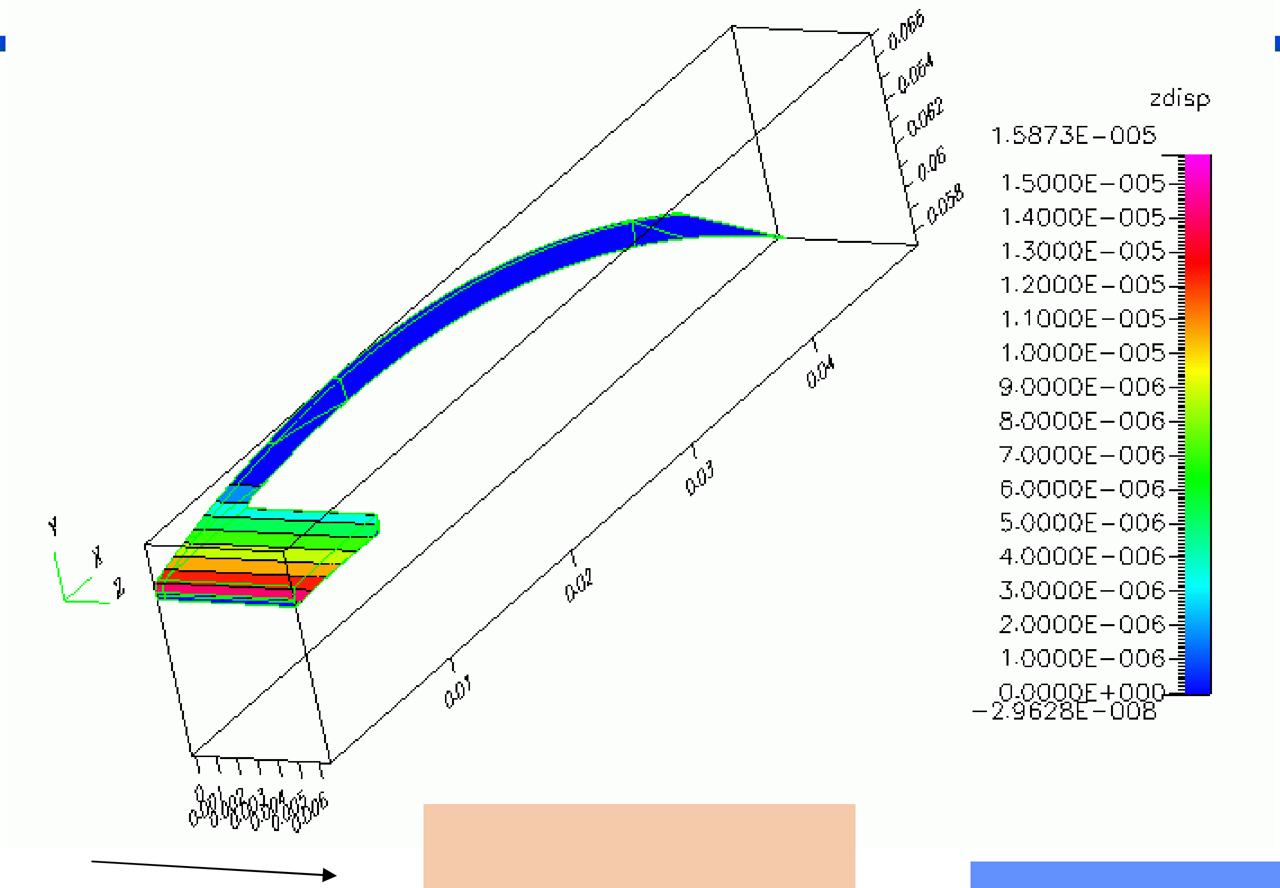


Y -direction

MOST radial DISPLACEMENT
AT THE REAR TIP OF THE PAD (as
expected) since stick is strongly restricted

all displacements are in METERS
1mil=2.54E-5 m, so max displacement =0.75
mil

Z-Axial Displacement



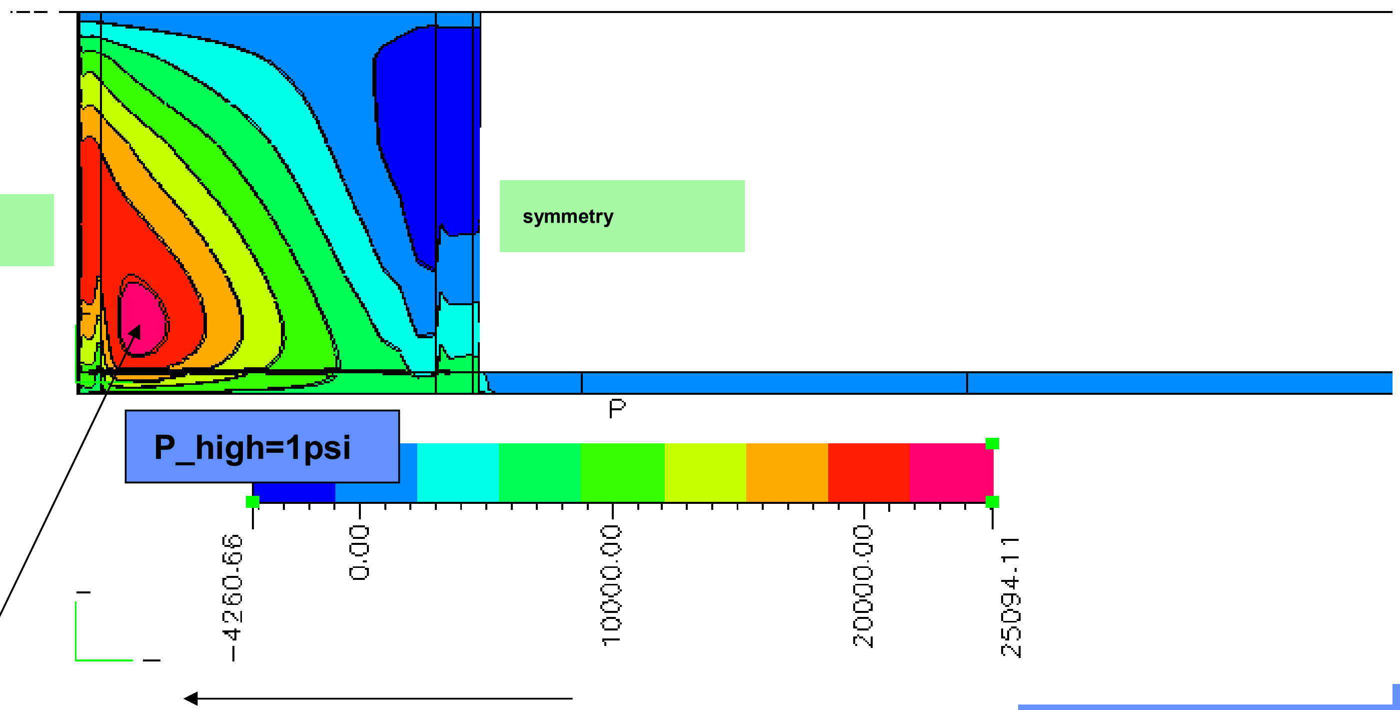
Z -direction

MOST DISPLACEMENT
AT THE front TIP
(largest momentum)

all displacements are in METERS
1mil=2.54E-5 m, so max displacement =0.6 mil

RADIAL PRESSURE FORCE (film)

Plow=0



PEAK PRESSURE

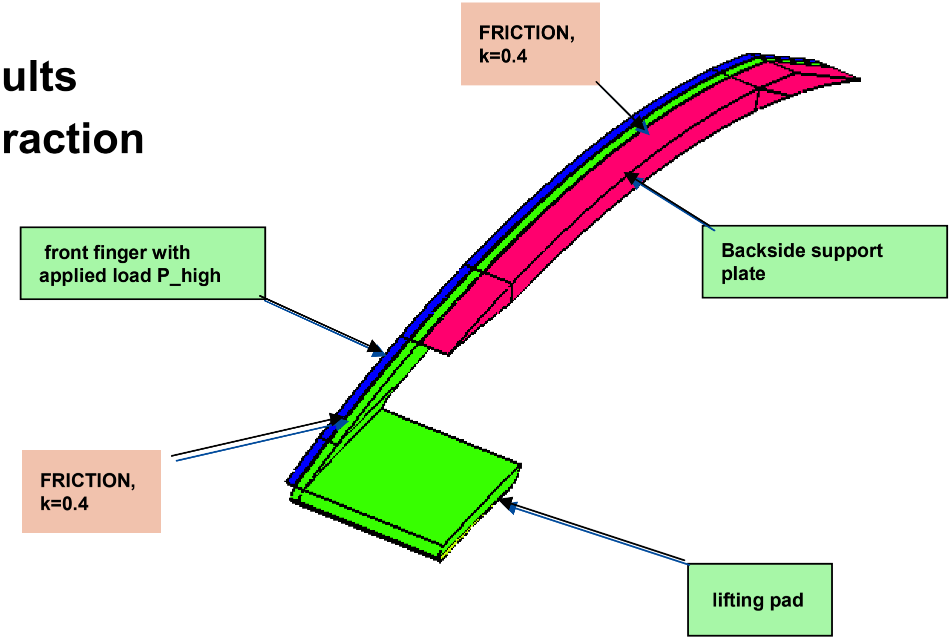
rotation, 2000 rad/sec

NOTE THAT DUE TO INTERACTION OF STRONG ROTATION AND UPSTREAM AXIAL PRESSURE P_max in the film > P_high

all pressures are in PA(N/m2)
Peak pressure is approximately 3 psi

Two Finger Geometry with Friction

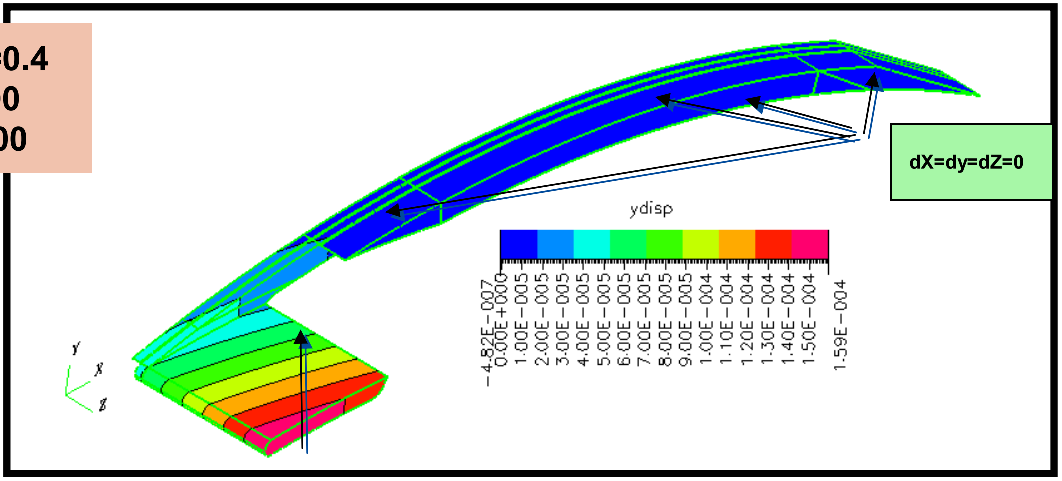
- Solid Modeling Results
- Fluid-Structure Interaction (FSI) Results

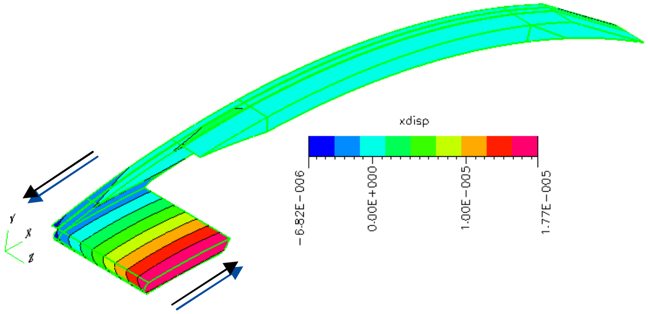


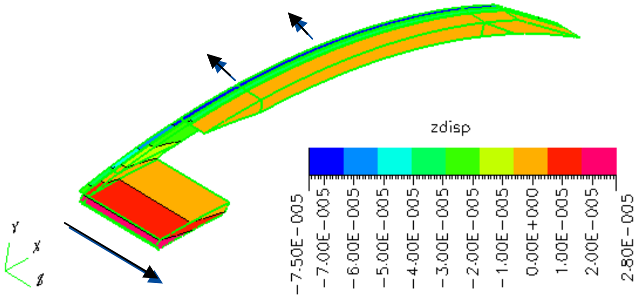
For solid models (stress only) we specified several load values, i.e. P_high=15,000 to 300,000 Pa and P_pad= 15,000 to 300,000 Pa.
For FSI analysis we calculated pressure distributions under the pad and accounted for finger/pad deformation under these forces.

Rear Washer restricted

FRICTION, k=0.4
Phigh=300,000
P_pad=300,000



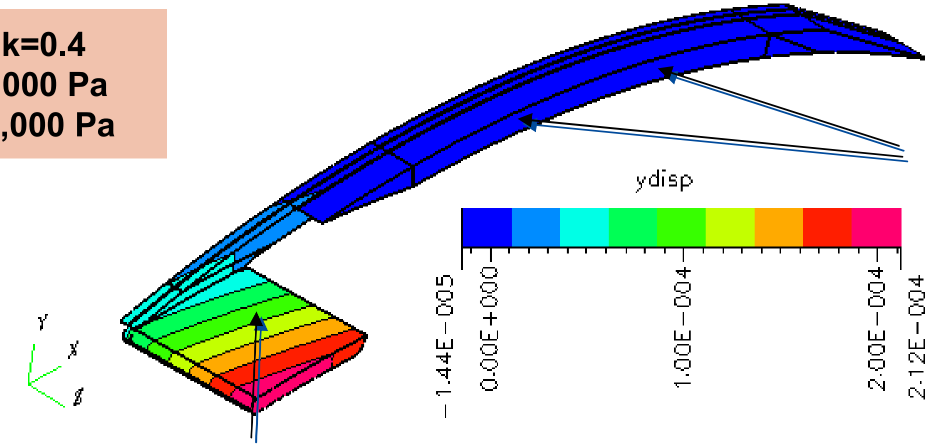


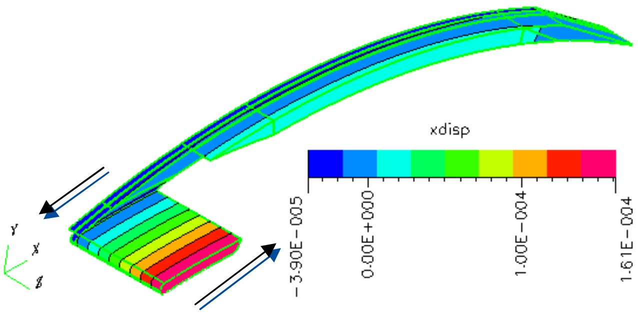


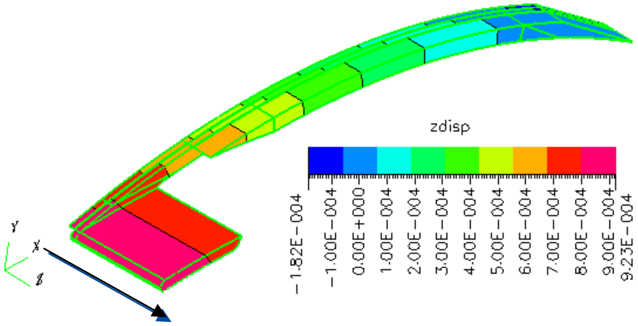
Rear Washer Partially restricted

FRICTION, k=0.4
Phigh=300,000 Pa
P_pad=300,000 Pa

dY=0, only Y restriction, on rear surface only

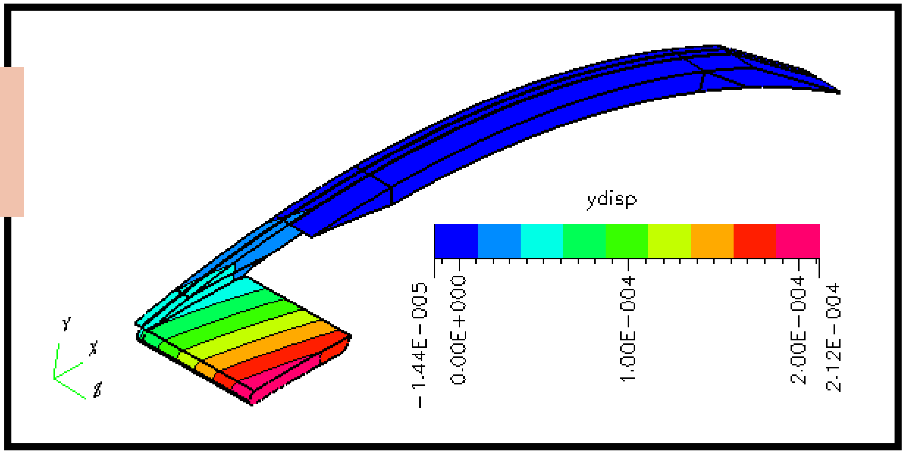




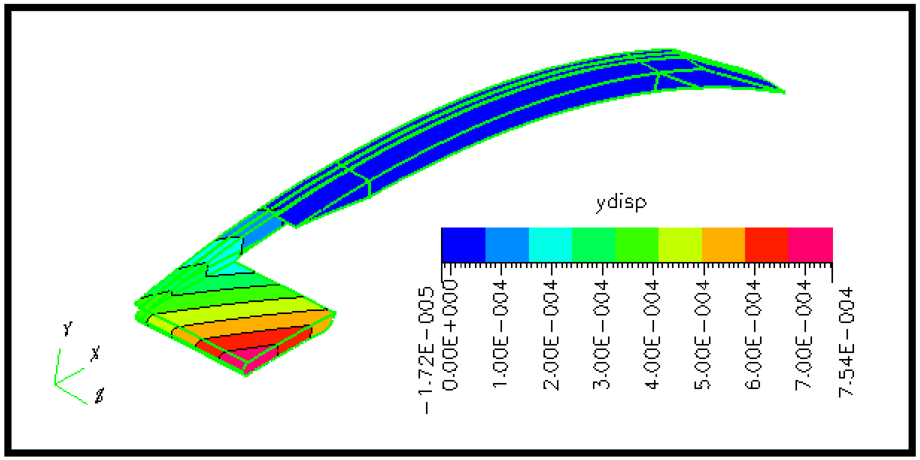


First vs Second FEA

FRICTION, k=0.4
P-high=300,000 Pa
P_pad=300,000 Pa



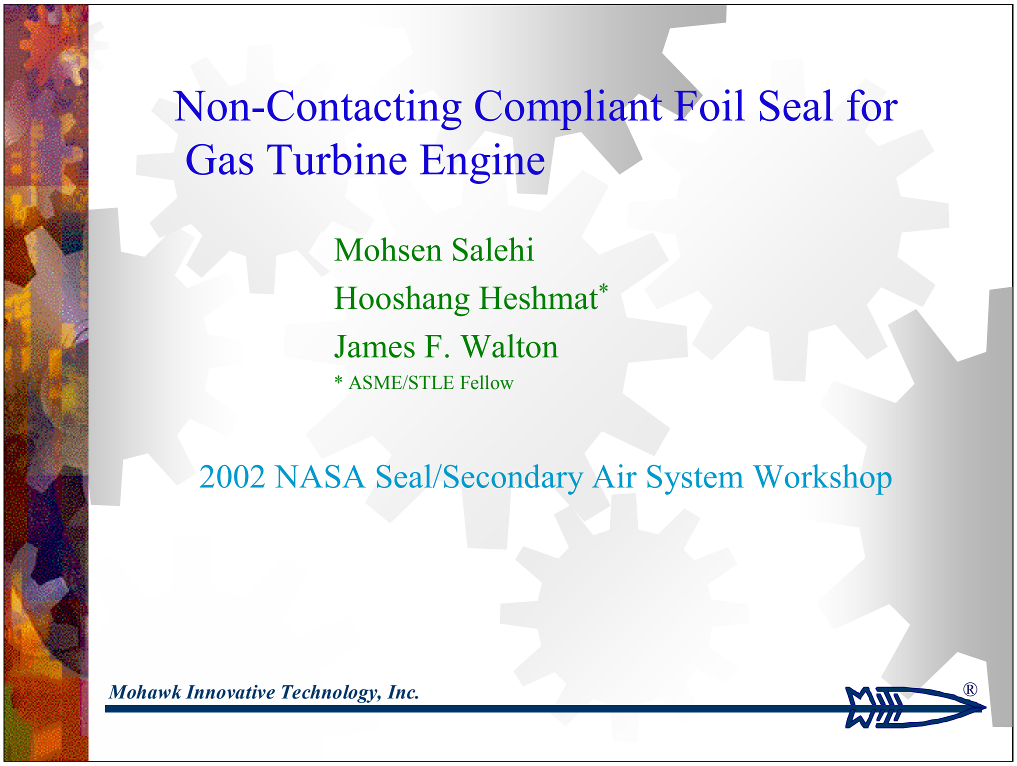
Radial Displacement -max 8.3 mil



Radial Displacement -max 29 mil

NON-CONTACTING COMPLIANT FOIL SEAL FOR GAS TURBINE ENGINE

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



Non-Contacting Compliant Foil Seal for Gas Turbine Engine

Mohsen Salehi
Hooshang Heshmat*
James F. Walton
* ASME/STLE Fellow

2002 NASA Seal/Secondary Air System Workshop

Mohawk Innovative Technology, Inc.

Acknowledgment

- The authors would like to thank :
  - Dr. Margaret Proctor and Dr. Bruce M. Steinetz of NASA for their guidance and sustained interest in our work.
  - Mr. Michael Tomaszewski of MiTi for his contributions to seal fabrication processes

Mohawk Innovative Technology, Inc.

Overview

- Objectives
- Experimental Work
- Accomplishments/Status
- Conclusions/Remarks
- Future Directions

Mohawk Innovative Technology, Inc.

Objectives

(1/2)

- Main Objective : Establish performance and scalability of the CFS by designing, building, testing and then delivering an 8.5 inch diameter seal for NASA testing.

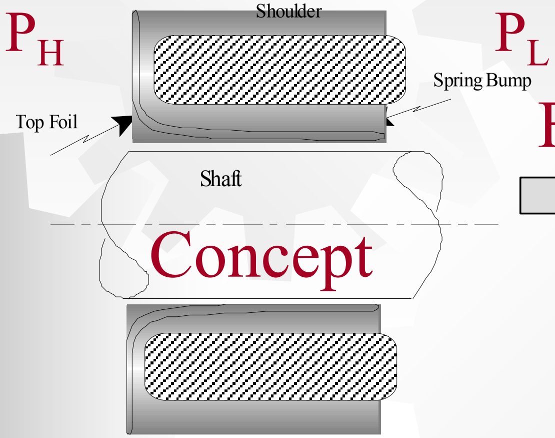
- Enhance current analysis to include:
  - Turbulence
  - Top foil compliance
- Investigate manufacturing/fabrication processes
  - Examine segmented, split or other seal designs
  - Consider forming foils with different thickness
- Modify an existing test rig to test the 6” Dia. seal at speeds to 20,000 rpm, and ΔP [0-100], temperatures to 800 °F

Mohawk Innovative Technology, Inc.

Objectives (Cont’d) (2/2)

- Validate design analysis through experimental studies of 2.84” & 6” diameter seals
  - Differential Pressure
  - Speed
  - Eccentricity
  - Clearance
- Apply lessons learned to the design of the 8.5” diameter seal

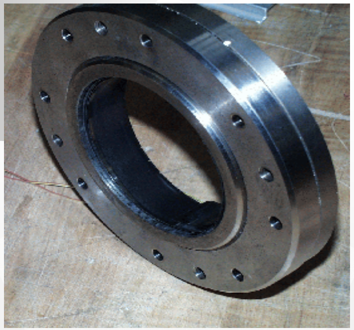
Compliant Gas Foil Seal -Concept to Application



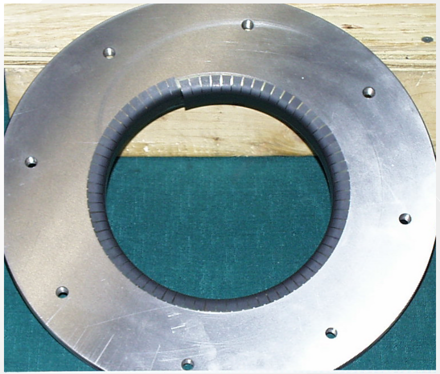
Concept

Fabrication

1.4 inch
(36 mm)



2.84 inch
(72 mm)

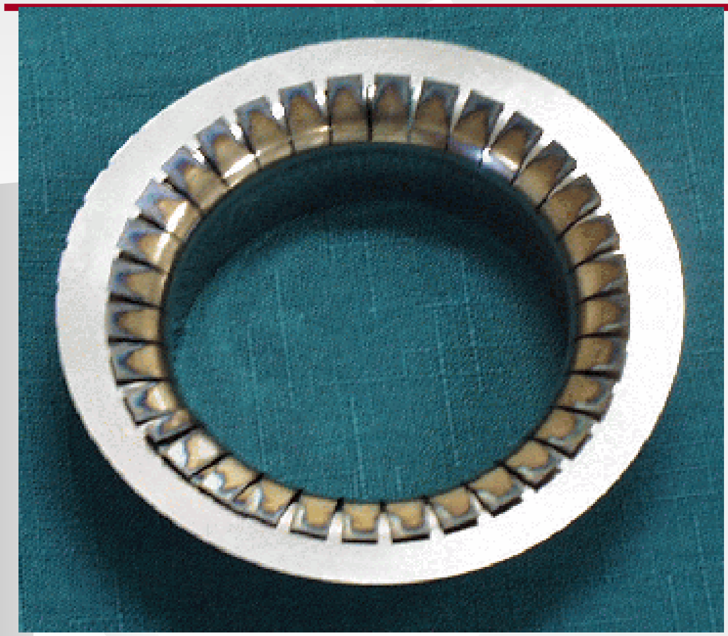


5.950 inch
(150 mm)

8.5 inch
(216 mm)

Mohawk Innovative Technology, Inc.

Compliant Foil Seal

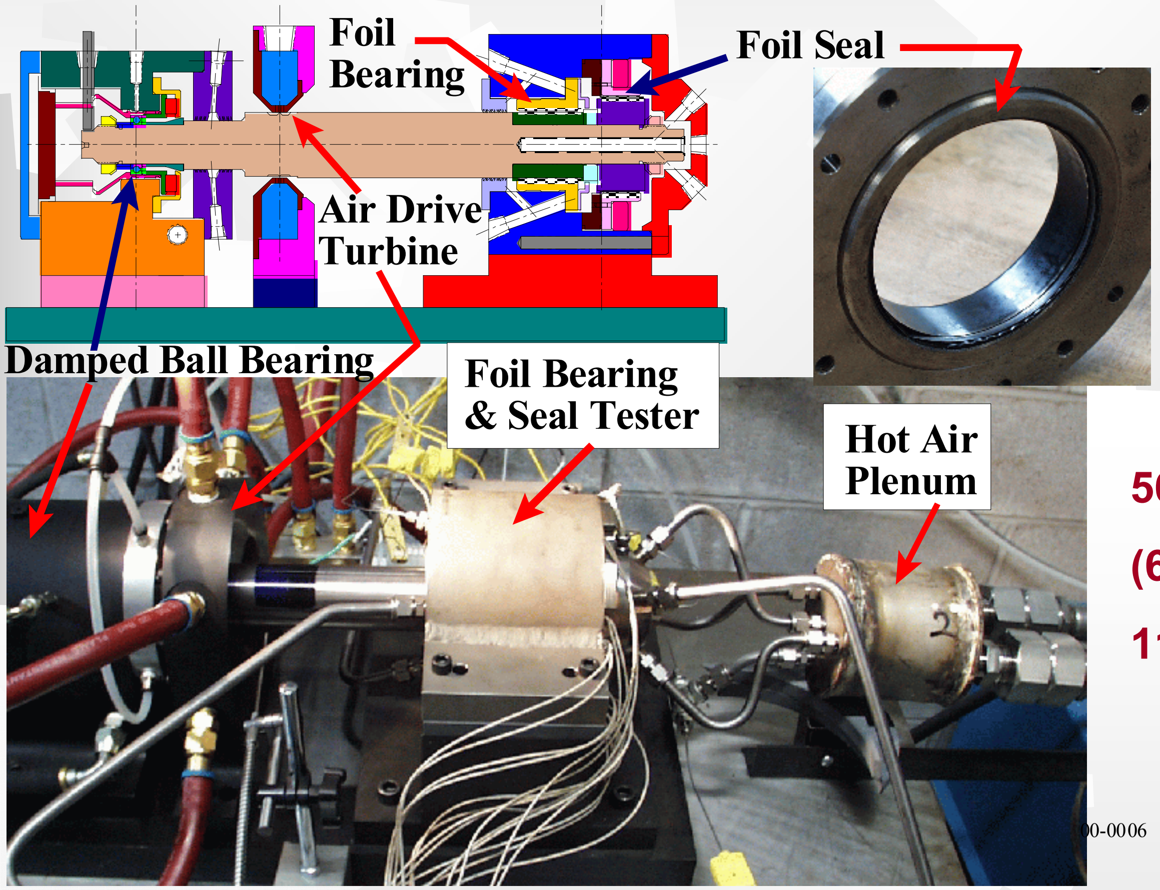


- Nickel Base Alloy for Foils
- MiTi Proprietary Coating for Smooth Lift Off
- Nickel Base Material for Journal
- Electrolized or High Temperature NASA PS304 Coated Journal

Diameter (in)	Length (in)	Radial Clearance (in)	Compliancy (in/lb)
1.40	0.65	0.0015 – 0.006	Various
2.84			
5.95			
8.50			

Mohawk Innovative Technology, Inc.

Gas Turbine Simulator & Seal Tester



72 mm Diameter

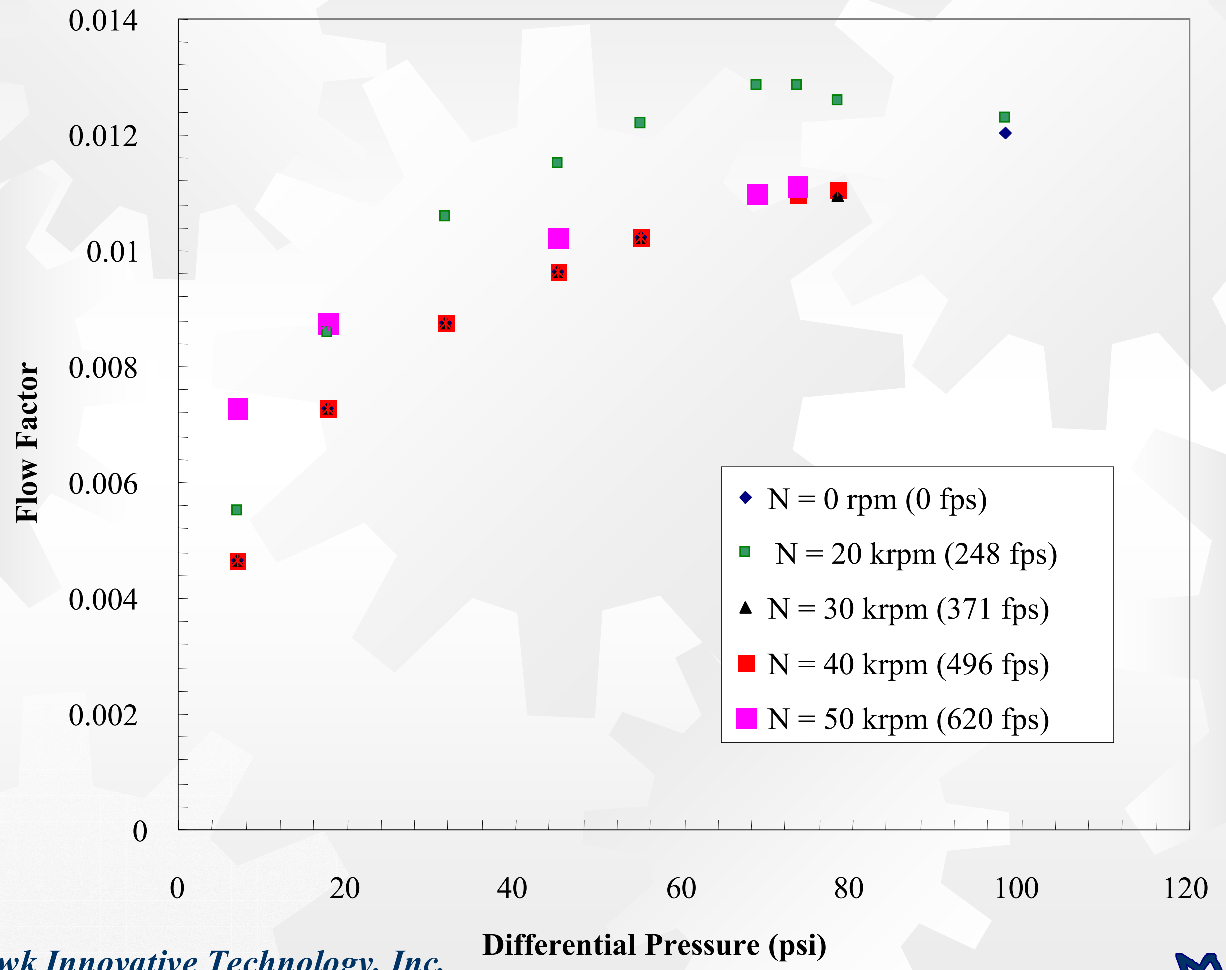
56,000 rpm

(694 ft/sec)

1100° F

Mohawk Innovative Technology, Inc.

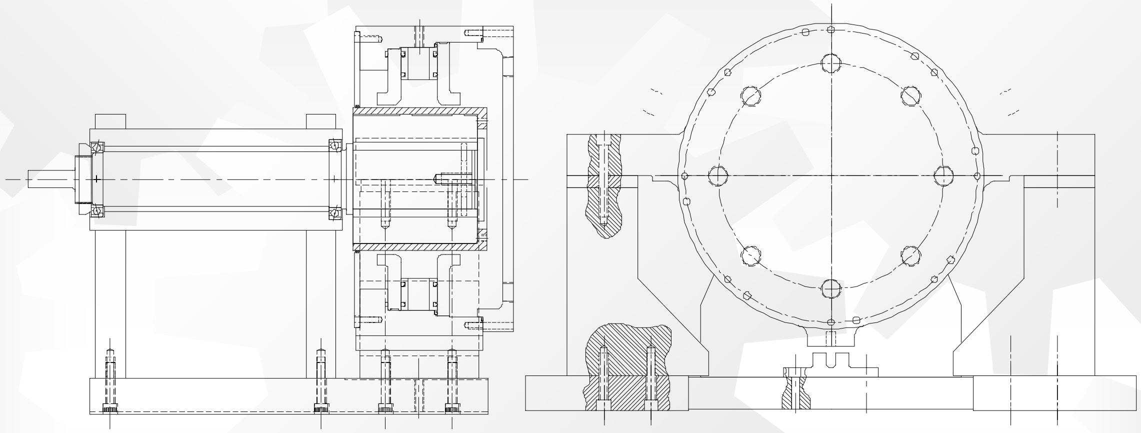
Flow Rate for 72 mm (2.84 inch) Seal



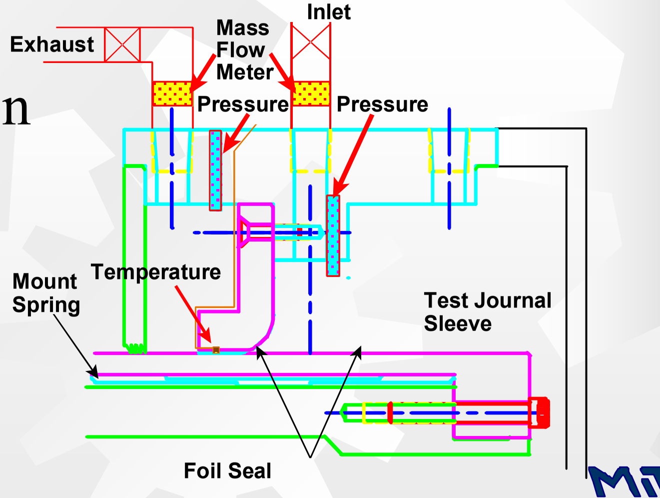
Mohawk Innovative Technology, Inc.

Subcomponent Test Rig for 6 in Seal

Used for both static test and dynamic tests



Seal housing top cross section

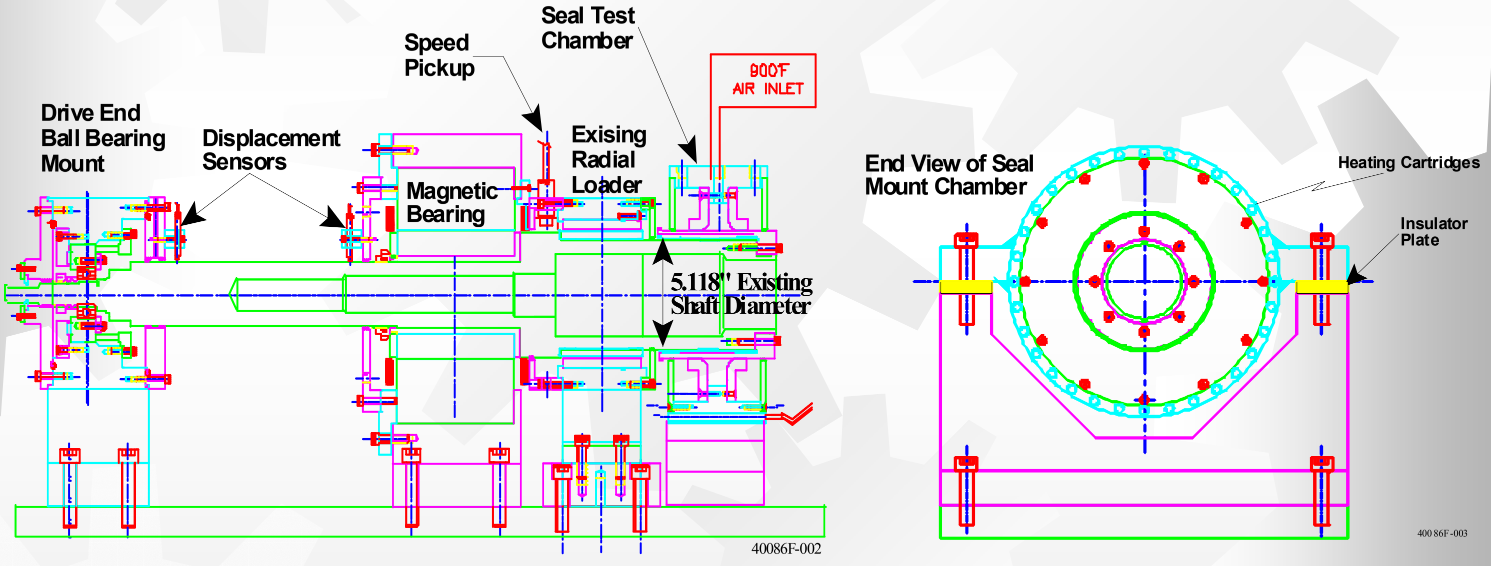


Mohawk Innovative Technology, Inc.

00086F-004

Layout of High-Speed Seal Tester

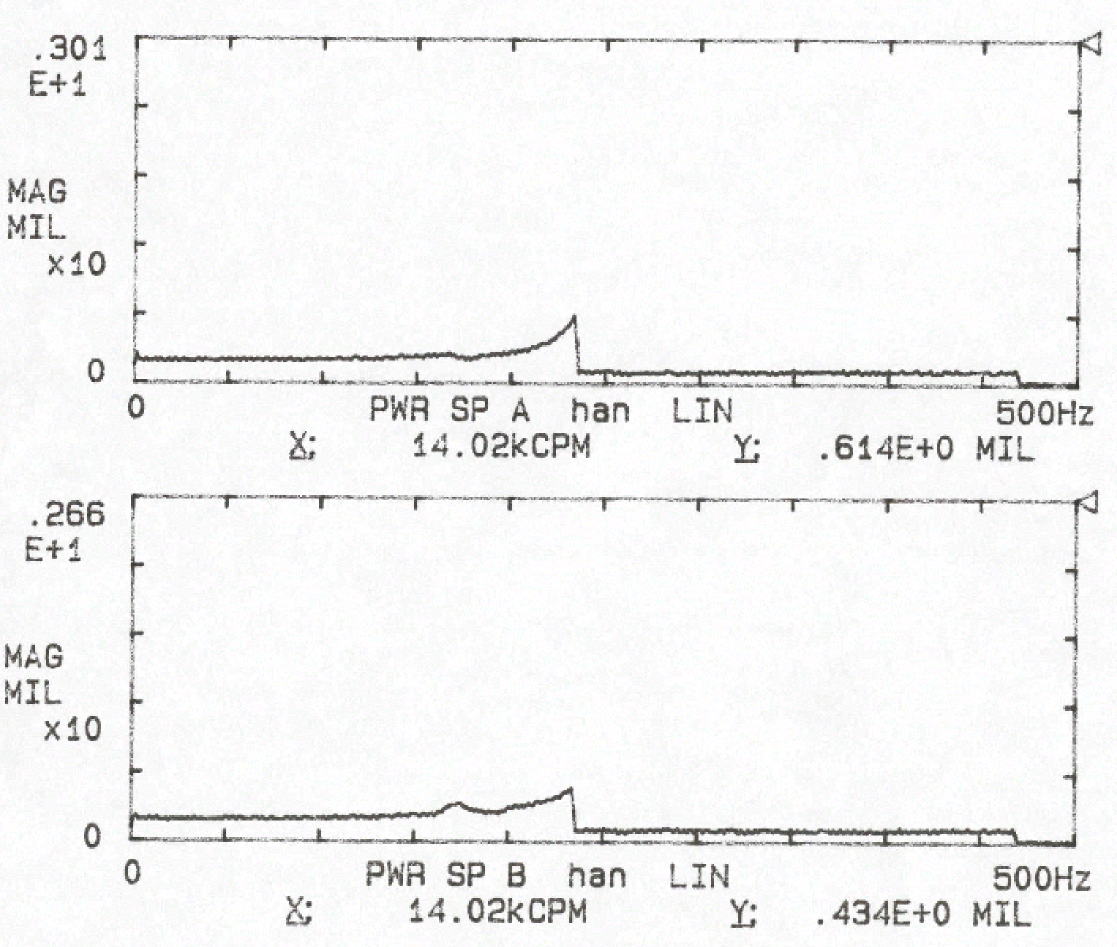
- Designed for 20,000 rpm, 900F, 6" Diameter



Mohawk Innovative Technology, Inc.

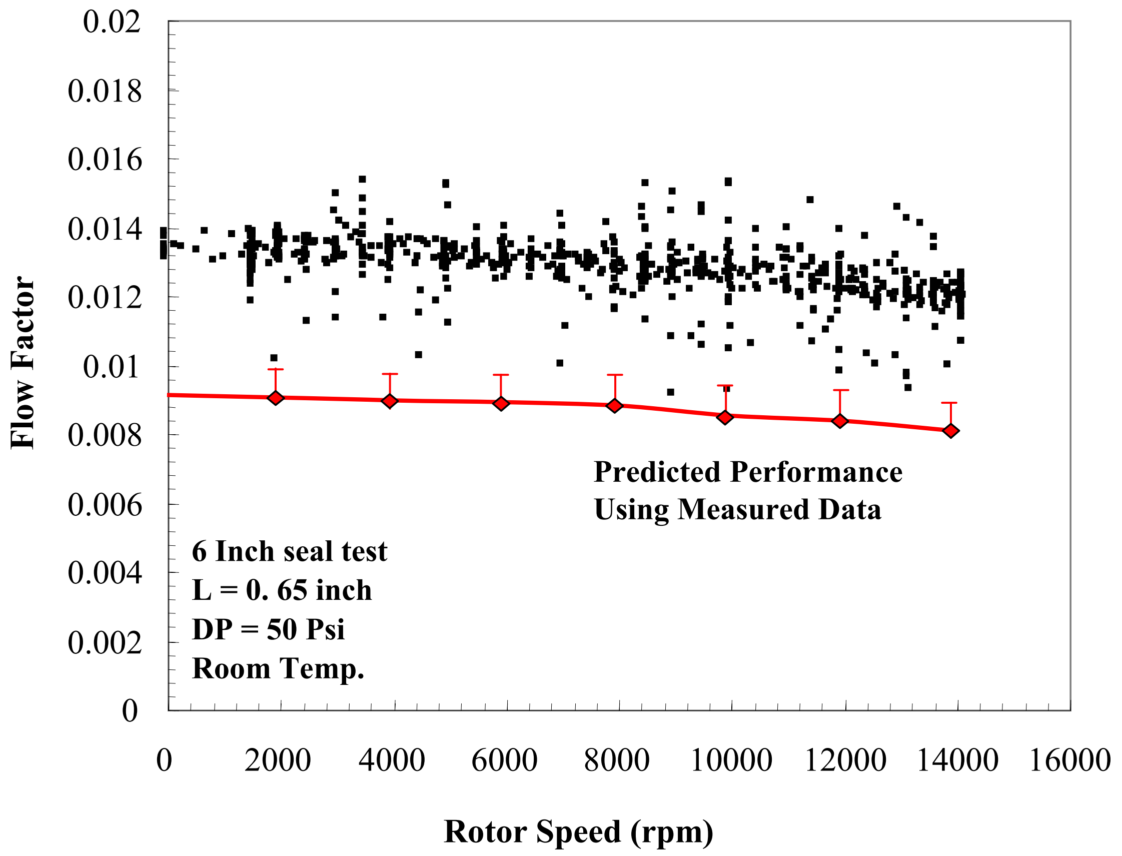
Dynamic Test

6 inch seal test at ΔP = 50 psi, Max speed = 14,000 rpm



Mohawk I

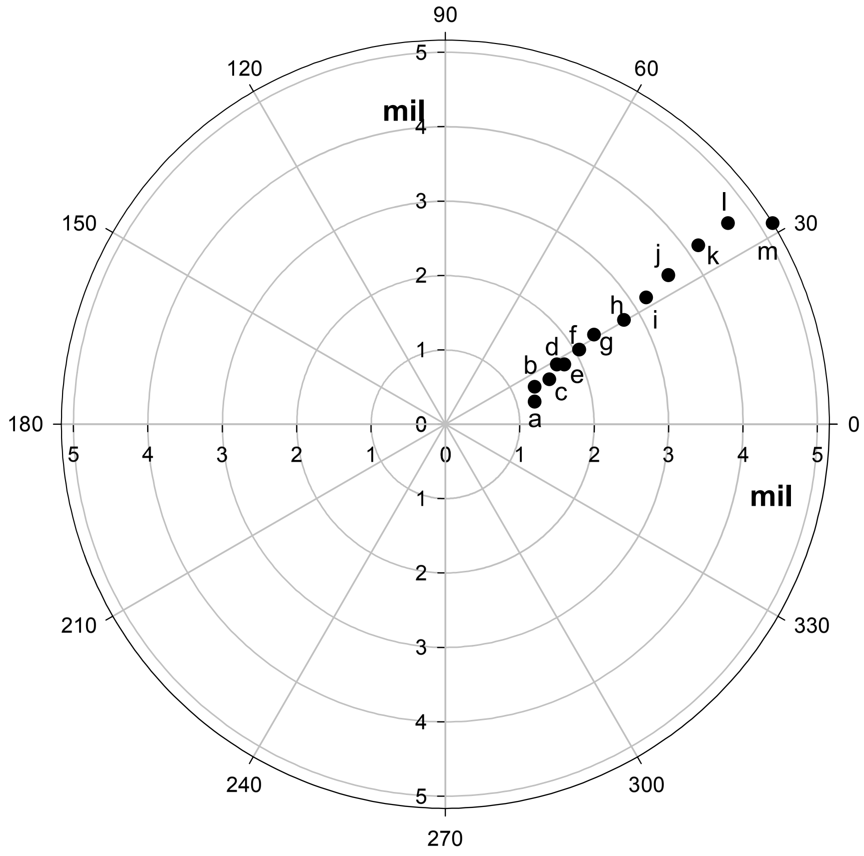
Leakage Flow Experimental Result



Mohawk Innovative Technology, Inc.

Seal Non-Contact Operation

6 inch seal Rotor Motion at ΔP = 50 psi, and Various Speeds

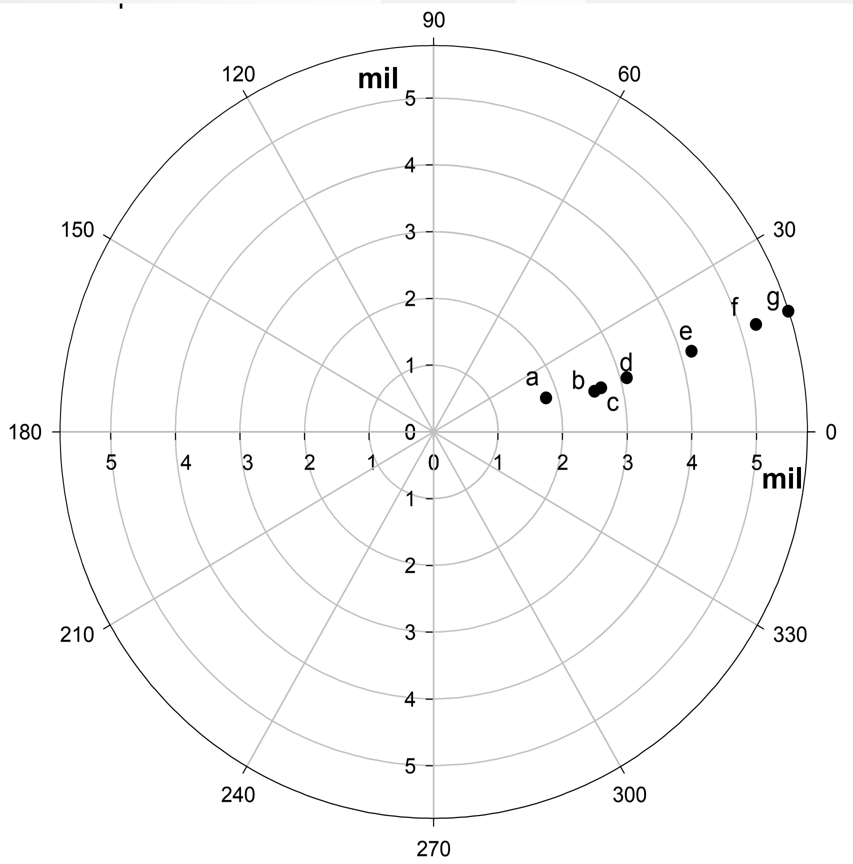


Speed (rpm)	Temperature (°F)
a = 2000	74
b = 3000	75
c = 4,000	77
d = 5,000	76
e = 6,000	77
f = 7,000	
g = 8,000	75
h = 9,000	
i = 10,000	76
j = 11,000	
k = 12,000	75
l = 13,000	
m = 14,000	76

Mohawk Innovative Technology, Inc.

Seal Non-Contact Operation

6 inch seal Rotor Motion at ΔP = 80 psi, and Various Speeds



Speed (rpm)	Temperature (°F)
a = 1500	72
b = 3000	73
c = 4,000	76
d = 5,000	75
e = 6,000	75
f = 7,000	
g = 8,000	74

Mohawk Innovative Technology, Inc.

Accomplishments

D = 5.95 inch (150 mm), L = 0.65 inch (16.5 mm), L/D = 0.1

- Rotor speed up to 14,000 RPM (364 fps)
- Non-contact Operation at Minimum Speed of 1000 RPM
- Eccentric Rotor Operation up to 0.006 inch at Speeds to 14,000 rpm
- Differential Pressure of up to 90 psi tested for 6” Seal
- Flow Factor of 0.01-0.014 at the highest DP and excursion of 0.006 inch

Mohawk Innovative Technology, Inc.

Conclusions/Remarks

- A non-contact compliant foil seal has been successfully demonstrated at sizes to 6” diameter
- Differential pressure to 90 Psi tested statically, and 80 psi dynamically.
- Dynamic tests revealed consistent leakage over speed range tested
- Seal non-contact capability including for rotor eccentric operation was verified

Mohawk Innovative Technology, Inc.

Future Directions (1/2)

- Additional research to improve the performance of the seal.
  - The appropriate range of structural compliance for the elements supporting the seal surface, (i.e., to optimize both hydrodynamic performance and rotor excursion potential)
  - Geometry optimization (e.g. clearance and length)
  - Formation of the flange/face section; and other design and fabrication issues. Some of the parameters are as following

Design Parameters to be Optimized

- **Bump Foil thickness (times No. of layers)**
- **Bump height, length, and pitch**
- **Thickness of Top, Stiffener, Shim Foils**
- **Seal Length, diameter, clearance, preload**
- **Bump foil coating**
- **……..**

Mohawk Innovative Technology, Inc.

Future Directions

(2/2)

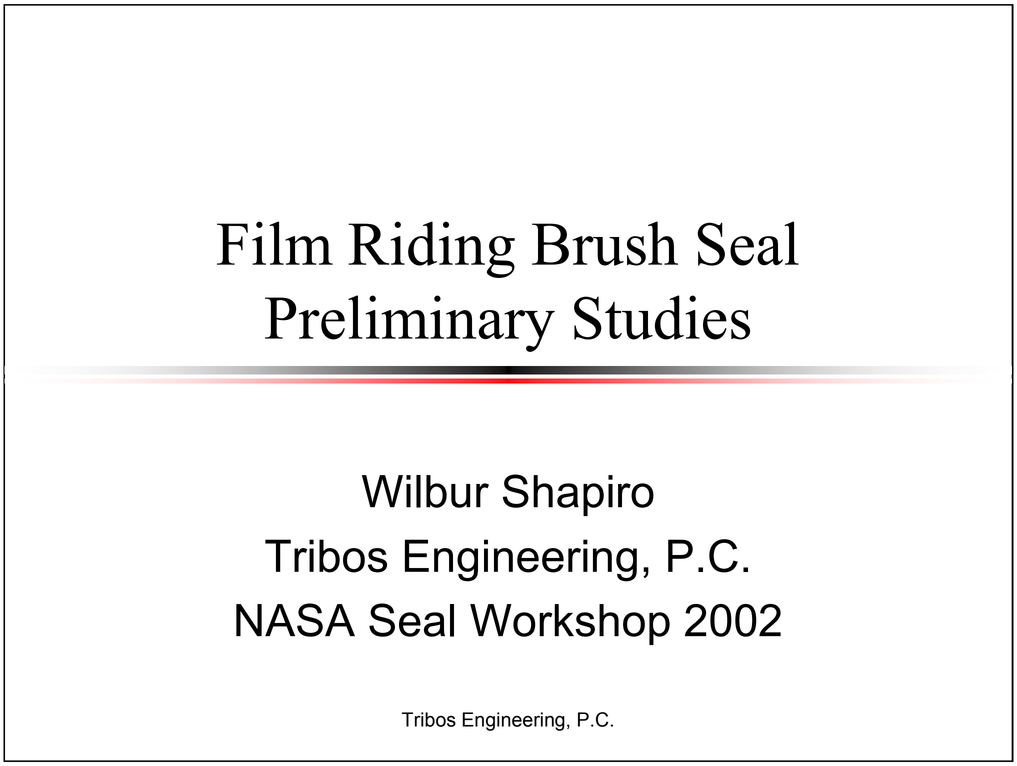
- Static and dynamic performance evaluation of the large seal (8.5 inch ID) at NASA and prior to testing in engine
- Flow visualization study in order to identify the flow passages in a seal
- Highly Instrumented Testing
  - Film Pressures
  - Film Temperatures
  - Film Height (Rotor-Foil Gap)

Mohawk Innovative Technology, Inc.

FILM RIDING BRUSH SEAL PRELIMINARY STUDIES

Wilbur Shapiro
Tribos Engineering, P.C.
Niskayuna, New York

Brush seals can improve engine efficiency by inhibiting secondary flow leakage, bur rotor excursions produce wear that degrades performance. A brush seal combined with a film riding seal precludes brush wear, accommodates rotor excursions without rubbing contact and restricts leakage to lower values than contemporary brush seals. The function of the brush is to act as a secondary seal to limit the hydraulic closing load, and to provide radial resilience.



Film Riding Brush Seal
Preliminary Studies

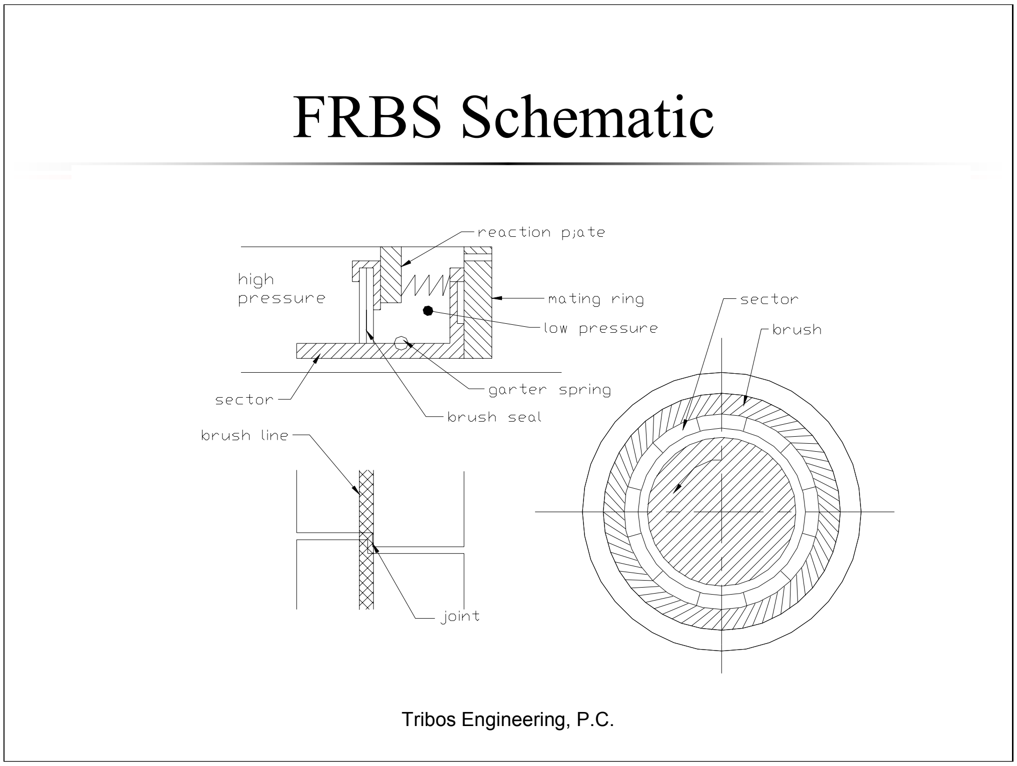
Wilbur Shapiro
Tribos Engineering, P.C.
NASA Seal Workshop 2002

Tribos Engineering, P.C.

Objectives

- Reduce brush wear
  - Eliminate interface rotation
- Reduce overall leakage
- Provide radial compliance

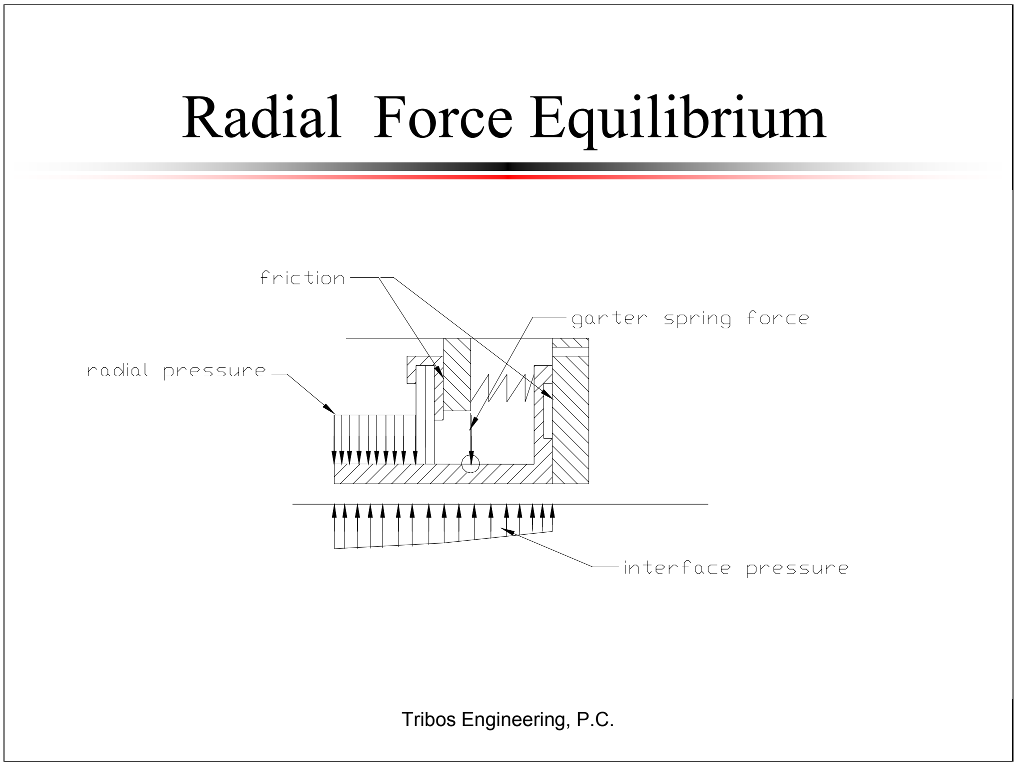
Tribos Engineering, P.C.



FRBS Schematic

Tribos Engineering, P.C.

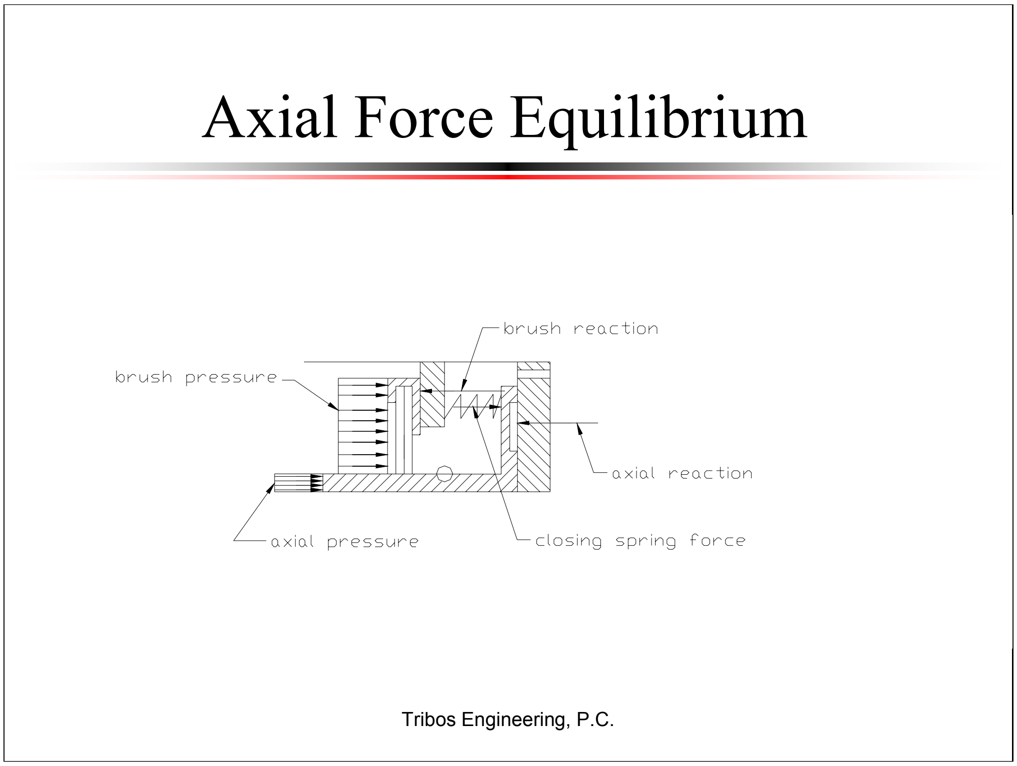
- •L-shaped cylindrical sectors that mate against a housing
- •Sealing occurs through radial clearance between sectors and shaft.
- •Brush acts as secondary seal



Radial Force Equilibrium

Tribos Engineering, P.C.

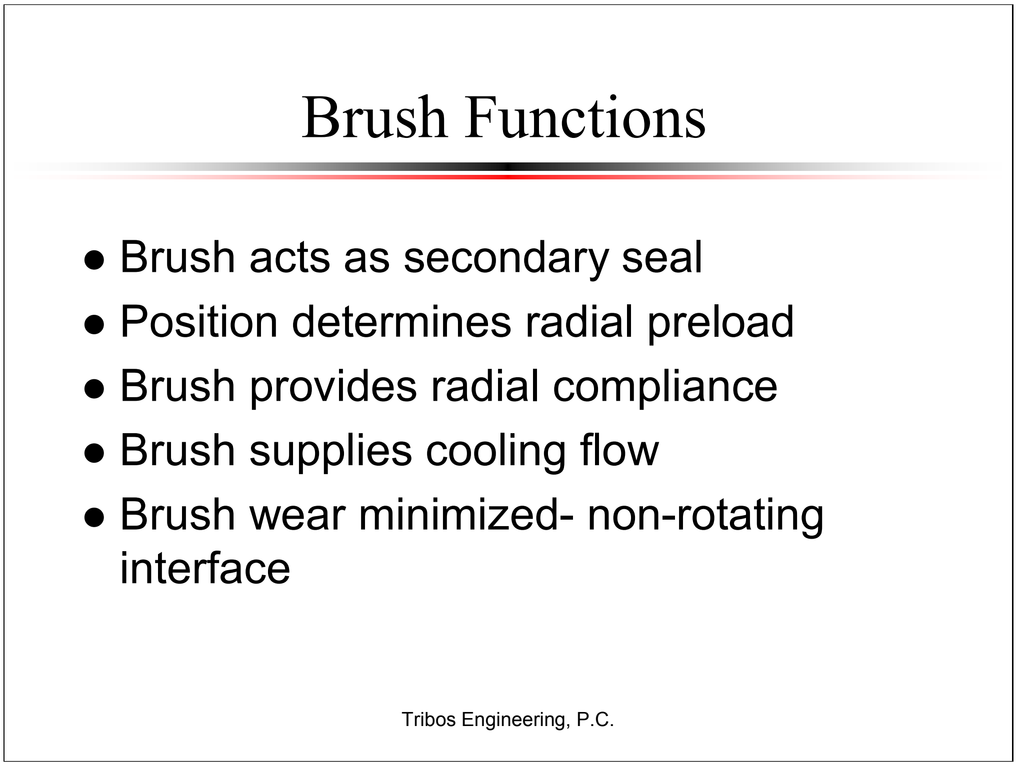
- •Position of brush determines radial preload
- •Friction can occur at brush interface, but radial compliance provided by bristles



Axial Force Equilibrium

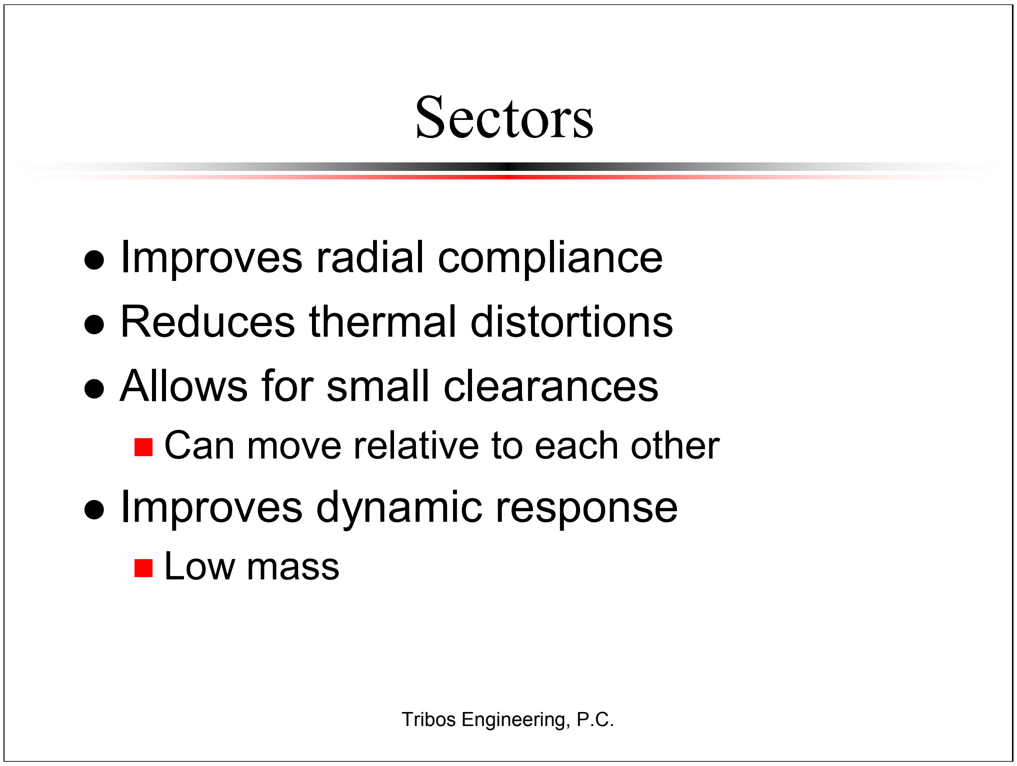
Tribos Engineering, P.C.

- Reaction plate absorbs thrust from brush
- Axial spring load used for force and moment balance



Brush Functions

- Brush acts as secondary seal
- Position determines radial preload
- Brush provides radial compliance
- Brush supplies cooling flow
- Brush wear minimized- non-rotating interface

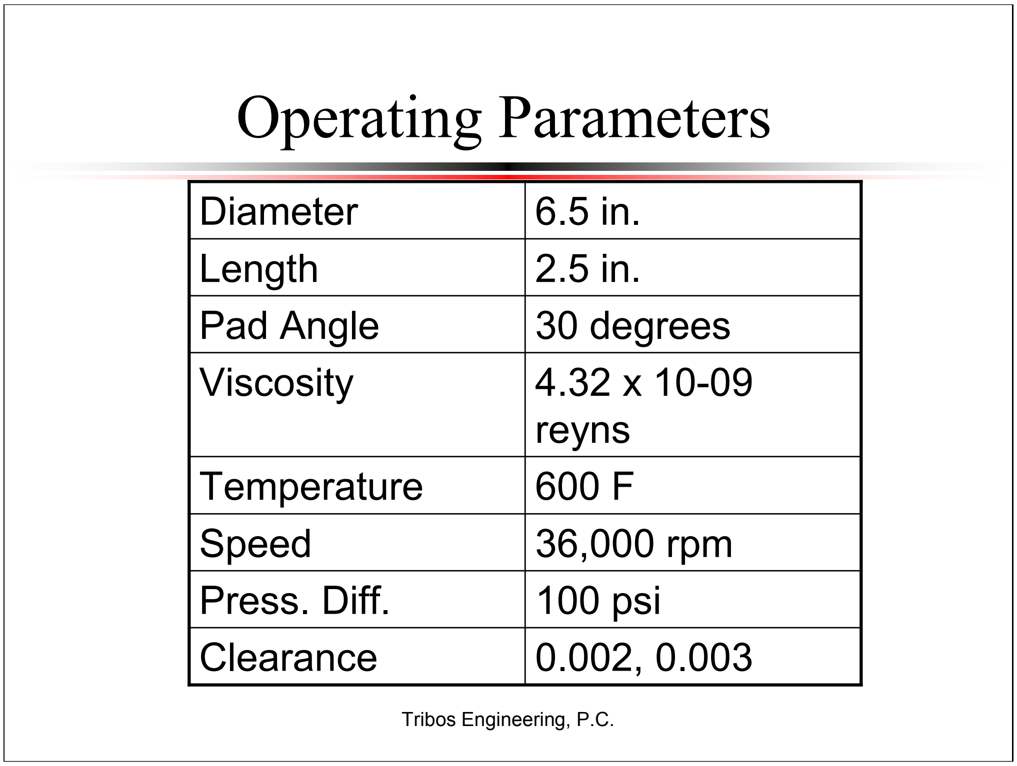


Sectors

- Improves radial compliance
- Reduces thermal distortions
- Allows for small clearances
  - Can move relative to each other
- Improves dynamic response
  - Low mass

Tribos Engineering, P.C.

- Sectors should be as thin as possible to minimize axial loads
- Sectors can follow rotor excursions



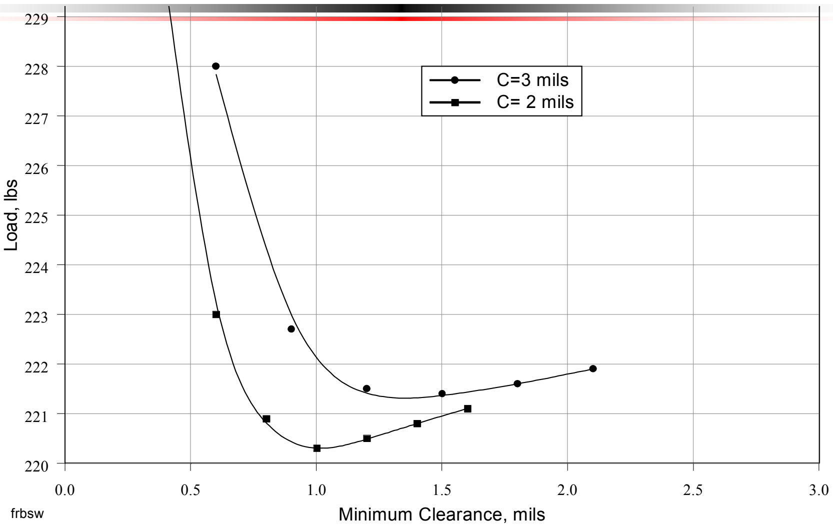
Operating Parameters

Diameter	6.5 in.
Length	2.5 in.
Pad Angle	30 degrees
Viscosity	4.32 x 10-09 reyns
Temperature	600 F
Speed	36,000 rpm
Press. Diff.	100 psi
Clearance	0.002, 0.003

Tribos Engineering, P.C.

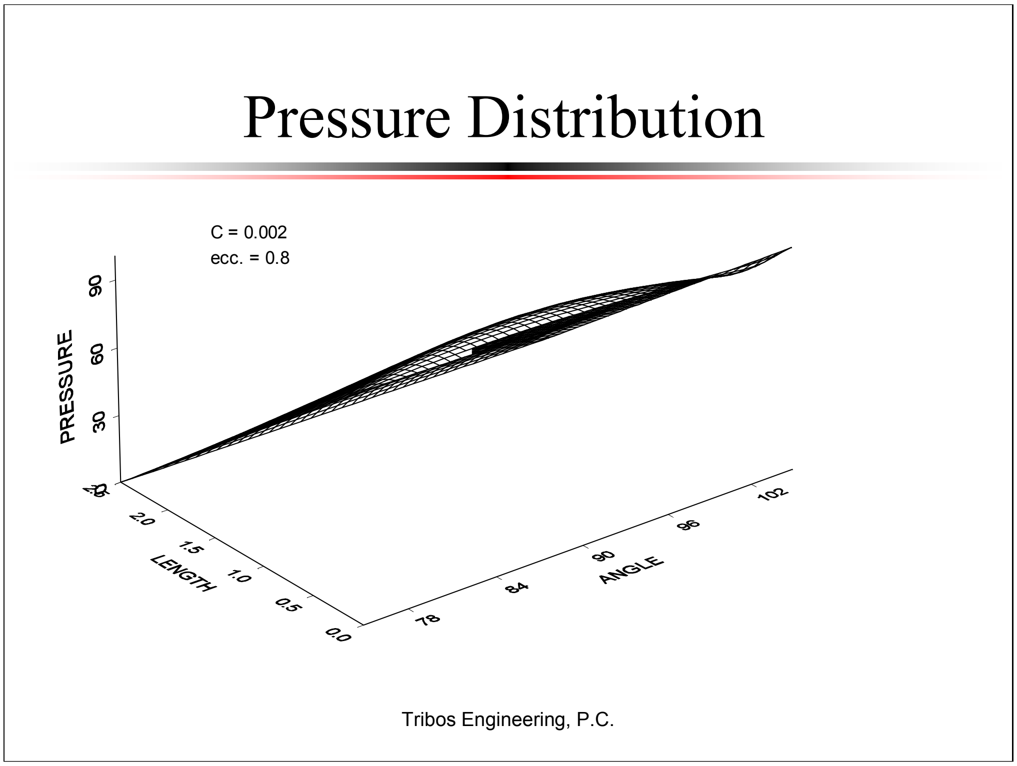
- Examined a potential application

Load Capacity



Tribos Engineering, P.C.

- •Best to operate in steep portion of curve for maximum stiffness
- •For c= 2 mils and a minimum clearance of o.5 mils, load capacity is 226 lbs.
- •To obtain a balanced closing load, the brush would be located approximately 1.8 inches from the high pressure end



Pressure Distribution

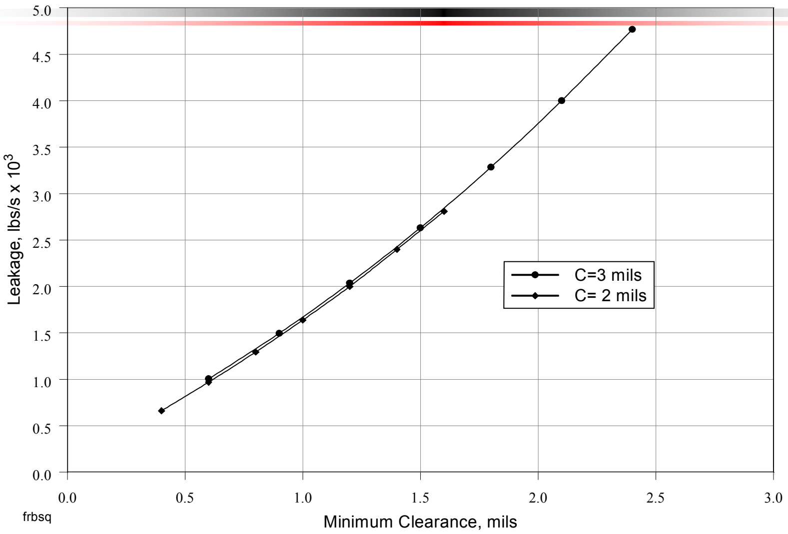
C = 0.002

ecc. = 0.8

Tribos Engineering, P.C.

- The linear drop occurs with and without rotation
- The linear drop has zero stiffness
- The hump above is produced by hydrodynamic action and provides positive stiffness.
- Hydrodynamics may be improved by geometry, such as steps

Leakage



Tribos Engineering, P.C.

- •Not much difference between 2 and 3 mils
- •At 0.5 mils minimum clearance, leakage is 0.7 x 10e-03 lbs/s

Flow Parameter

$$\phi = \frac{\dot{m}\sqrt{T}}{PD}$$

$\phi = flow\ parameter$

$\dot{m} = mass\ \ flow, lbs / s$

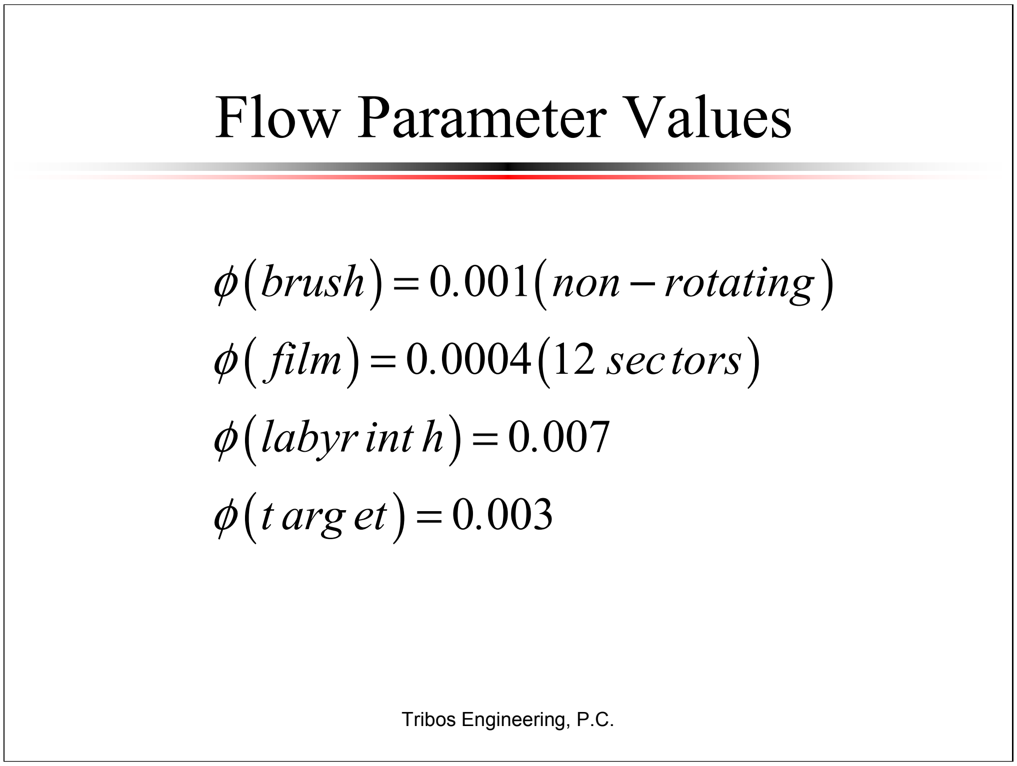
$T = absolute\ temperature, {}^{o}R$

$P = pressure\ differential, psi$

$D = diameter, in.$

Tribos Engineering, P.C.

- Flow parameter is a measure of leakage characteristics



Flow Parameter Values

$$\phi(brush)=0.001(non-rotating)$$

$$\phi(\,film)=0.0004(12\ sec\,tors)$$

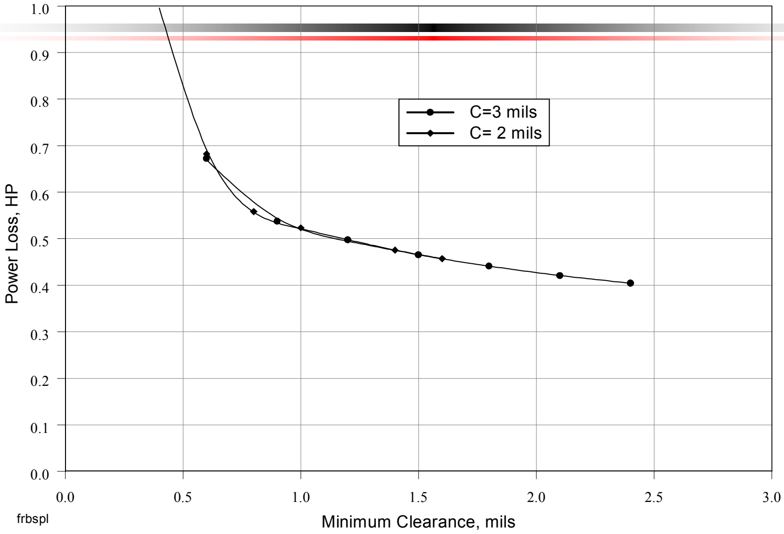
$$\phi(labyr\,int\,h)=0.007$$

$$\phi(t\,arg\,et)=0.003$$

Tribos Engineering, P.C.

- Film flow parameter is very low
- Most leakage will occur across the brush
- Labyrinth flow parameter is much higher
- Additional flow will occur between sectors, but the target value should be readily attained

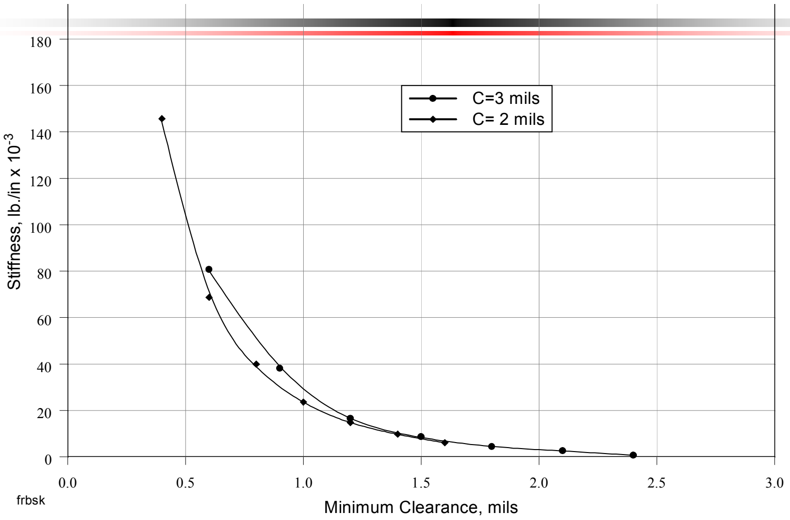
Power Loss



Tribos Engineering, P.C.

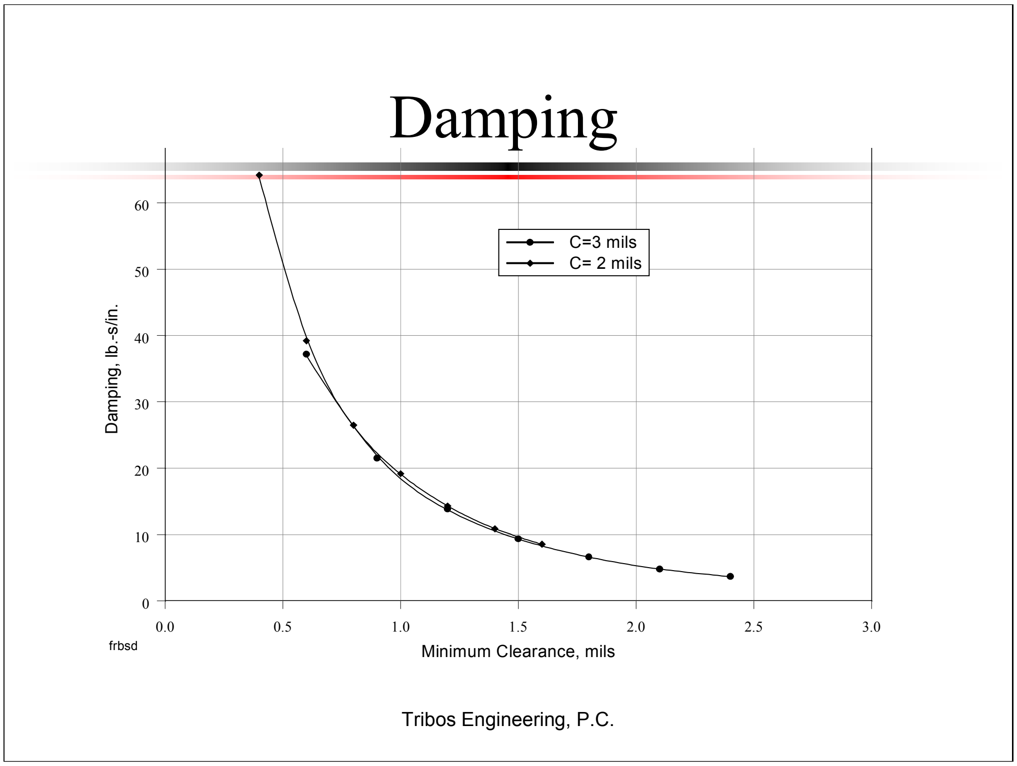
- Curve applies to a single sector
- Total Power loss is relatively high
- Heat generation is mitigated by brush cooling flow
- Sectors reduce distortions

Stiffness



Tribos Engineering, P.C.

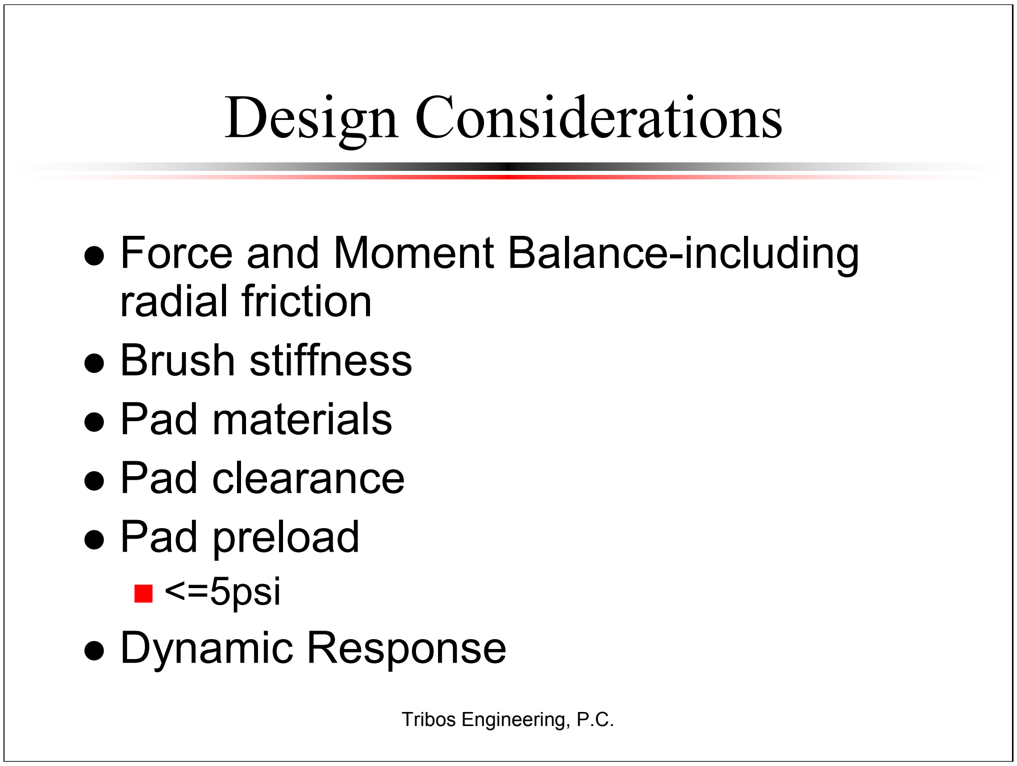
- At a minimum clearance of 0.5 mils , the stiffness is 100,000 lbs/in.
- The stiffness must be sufficient to overcome brush resistance, preload and friction.



Damping

Tribos Engineering, P.C.

- Damping at 0.5 mils clearance is 50 lb-s/in.
- Damping is relatively high so that squeeze-film can assist in preventing contact.



Design Considerations

- Force and Moment Balance-including radial friction
- Brush stiffness
- Pad materials
- Pad clearance
- Pad preload
  - <=5psi
- Dynamic Response

Tribos Engineering, P.C.

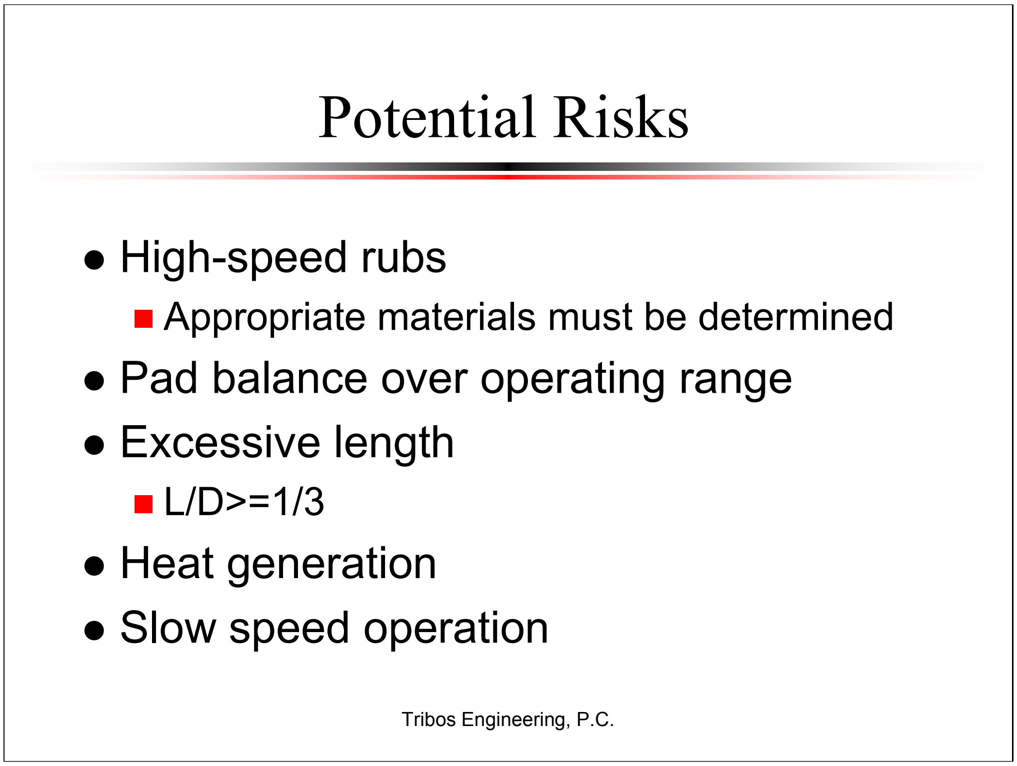
•Sectors require a force and moment balance under all conditions of operation

•Brush stiffness must be less than film stiffness

•Pad materials must withstand high speed rubs

•Pad clearance and preload both effect performance and should be optimized

•Design should accommodate large radial runouts, shock and vibration

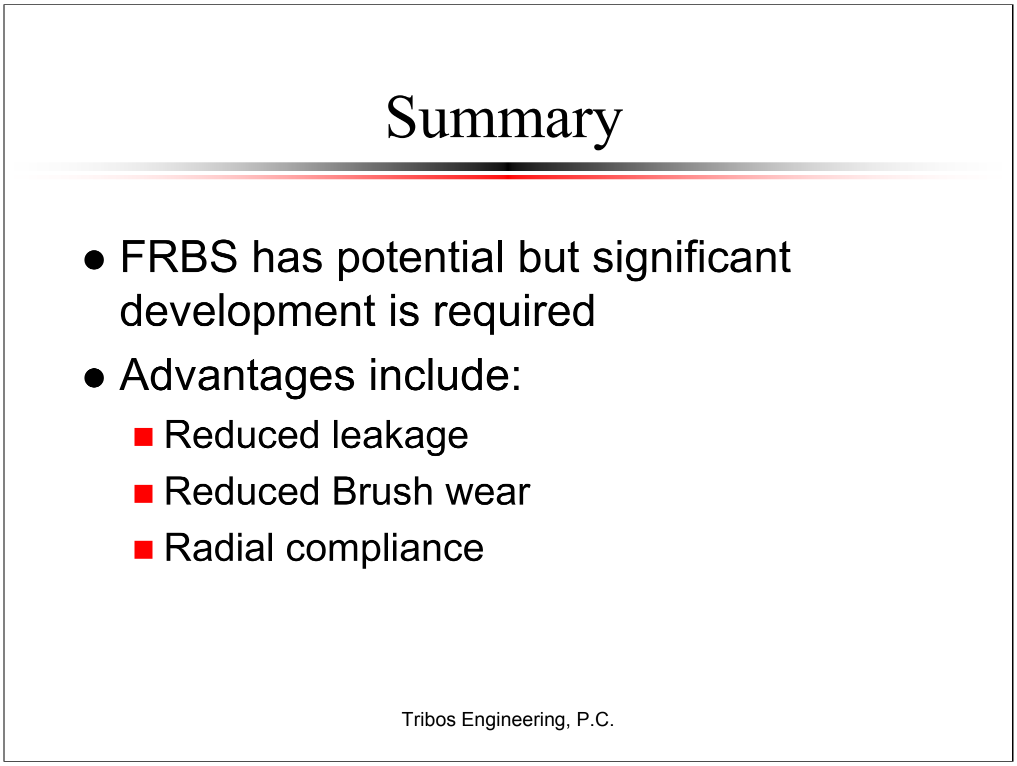


Potential Risks

- High-speed rubs
  - Appropriate materials must be determined
- Pad balance over operating range
- Excessive length
  - L/D>=1/3
- Heat generation
- Slow speed operation

Tribos Engineering, P.C.

- Slow speed reduces hydrodynamic capability



Summary

- FRBS has potential but significant development is required
- Advantages include:
    - Reduced leakage
    - Reduced Brush wear
    - Radial compliance

Tribos Engineering, P.C.

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

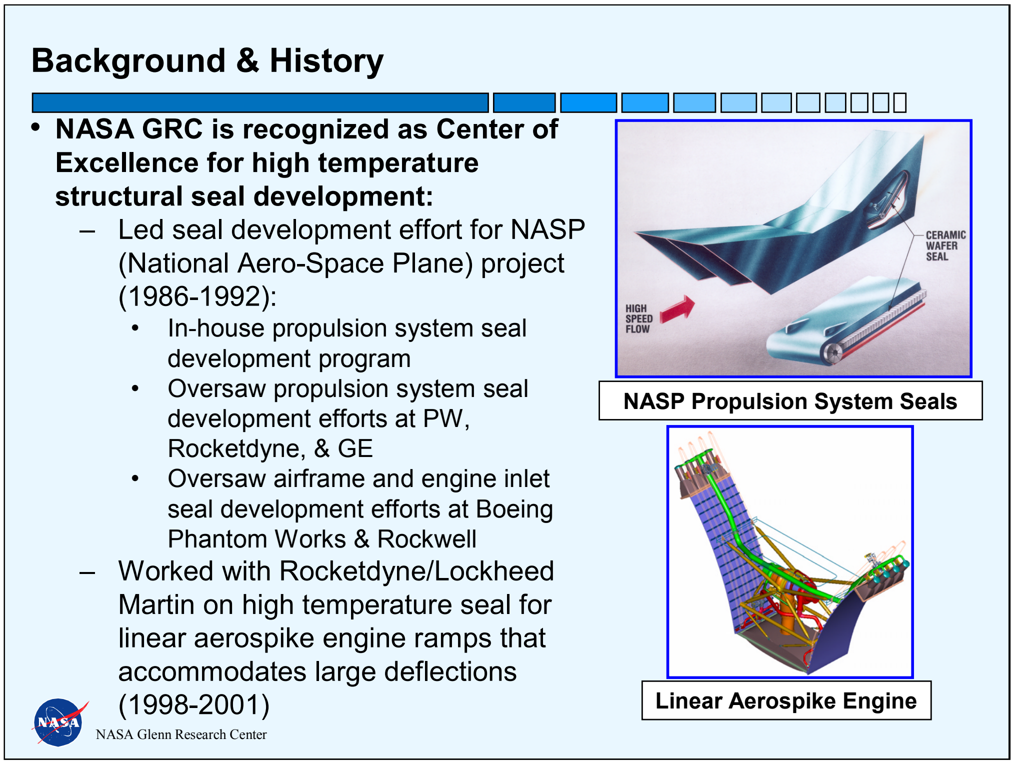
3rd Generation RLV Structural Seal Development Programs at NASA GRC

Mr. Patrick H. Dunlap, Jr.
Dr. Bruce M. Steinetz
NASA Glenn Research Center
Cleveland, OH 44135

Mr. Jeffrey J. DeMange
OAI
Cleveland, OH 44135

2002 NASA Seal/Secondary Air System Workshop
October 23-24, 2002

NASA Glenn Research Center



Background & History

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

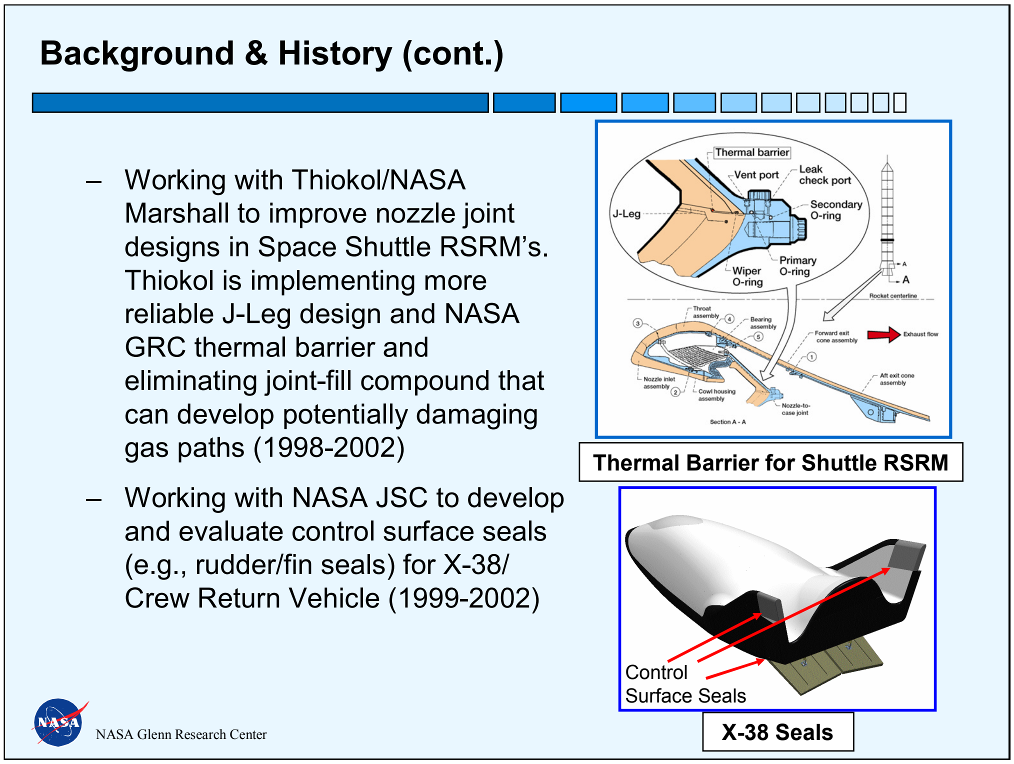
NASP Propulsion System Seals

Linear Aerospike Engine

NASA Glenn Research Center

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

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



Background & History (cont.)

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

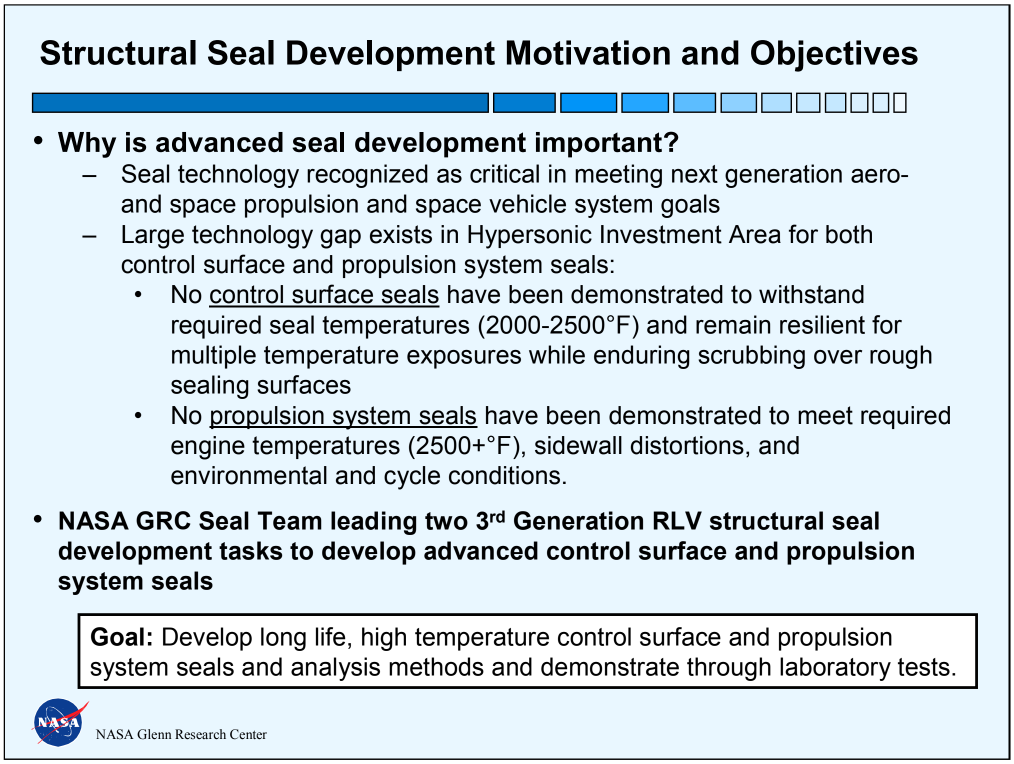
Thermal Barrier for Shuttle RSRM

X-38 Seals

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. Thiokol is currently certifying the thermal barrier for flight so that re-designed joints incorporating the thermal barriers can enter service on a Space Shuttle mission in early 2005. We also recently received a patent for this seal design.

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



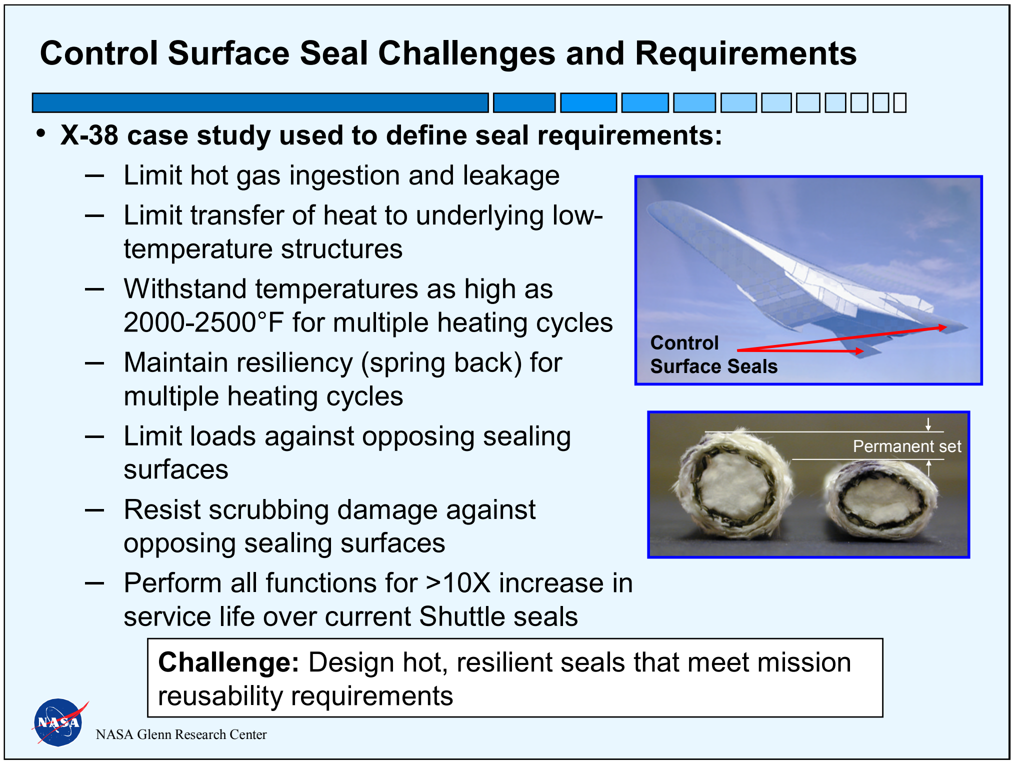
Structural Seal Development Motivation and Objectives

- **Why is advanced seal development important?**
  - Seal technology recognized as critical in meeting next generation aero- and space propulsion and space vehicle system goals
  - Large technology gap exists in Hypersonic Investment Area for both control surface and propulsion system seals:
    - No control surface seals have been demonstrated to withstand required seal temperatures (2000-2500°F) and remain resilient for multiple temperature exposures while enduring scrubbing over rough sealing surfaces
    - No propulsion system seals have been demonstrated to meet required engine temperatures (2500+°F), sidewall distortions, and environmental and cycle conditions.
- **NASA GRC Seal Team leading two 3rd Generation RLV structural seal development tasks to develop advanced control surface and propulsion system seals**

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

NASA Glenn Research Center

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.



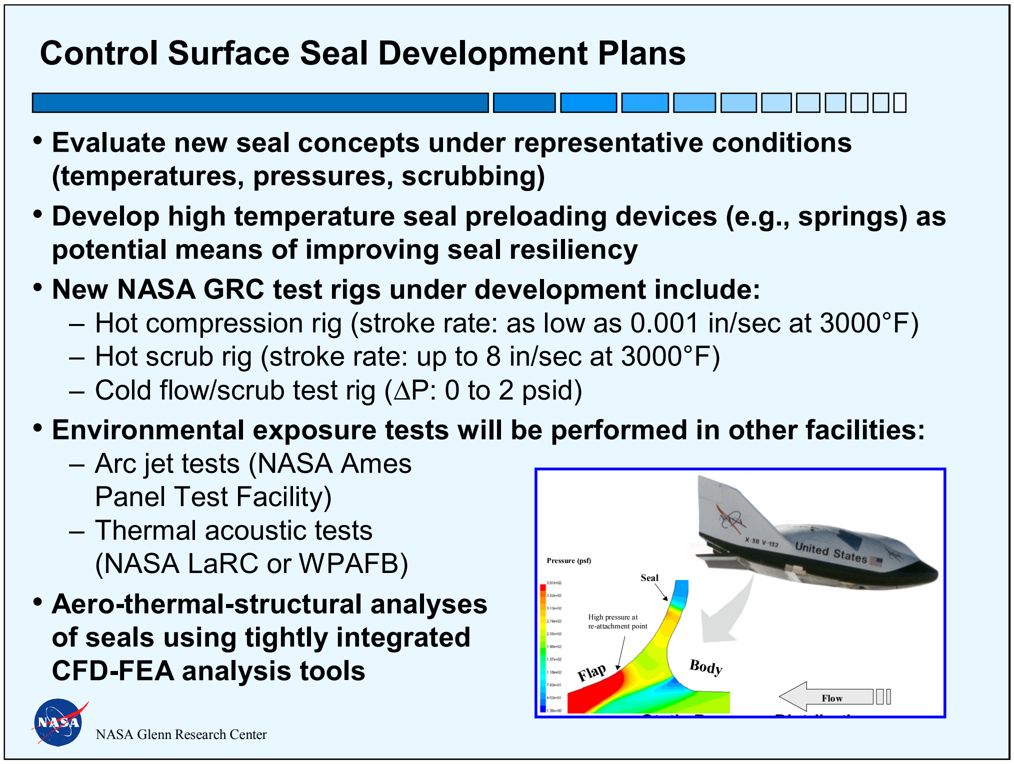
Control Surface Seal Challenges and Requirements

- **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

NASA Glenn Research Center

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



Control Surface Seal Development Plans

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

NASA Glenn Research Center

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

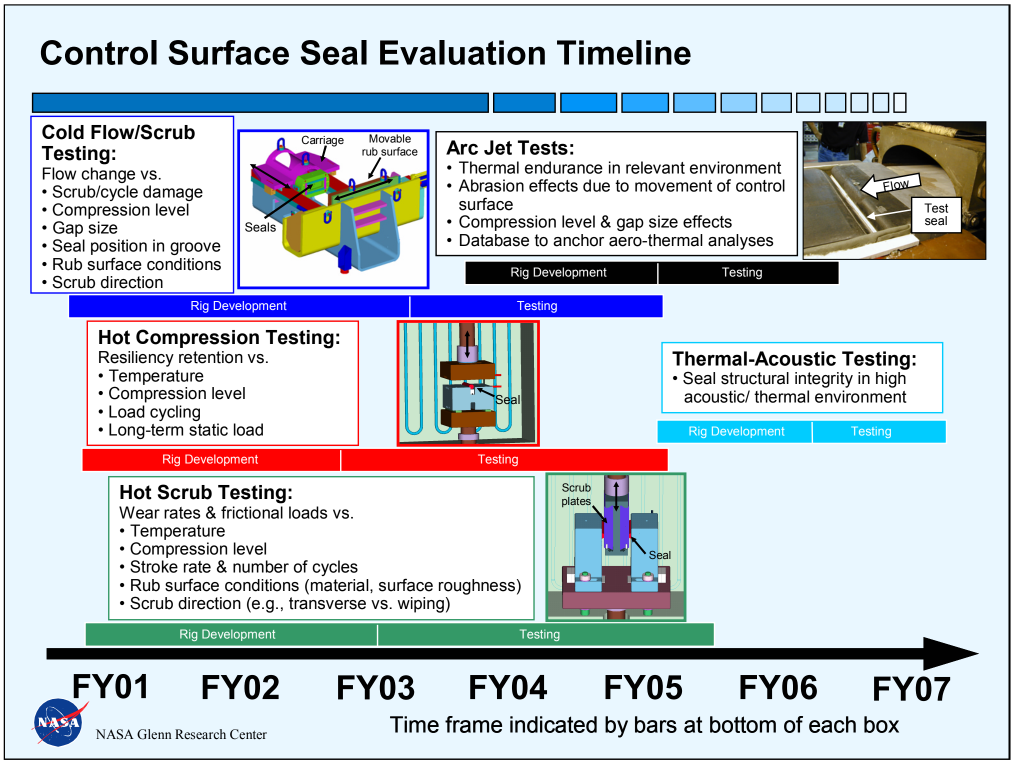
For the compression tests, the seals will be compressed between two plates and will be subjected to multiple compressive load cycles to generate load versus displacement curves for each cycle. We will be able to measure the resiliency, or spring back, of the seals at different temperatures for many load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

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

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

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

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



Control Surface Seal Evaluation Timeline

Cold Flow/Scrub Testing:
Flow change vs.
- Scrub/cycle damage
- Compression level
- Gap size
- Seal position in groove
- Rub surface conditions
- Scrub direction

Arc Jet Tests:
- Thermal endurance in relevant environment
- Abrasion effects due to movement of control surface
- Compression level & gap size effects
- Database to anchor aero-thermal analyses

Hot Compression Testing:
Resiliency retention vs.
- Temperature
- Compression level
- Load cycling
- Long-term static load

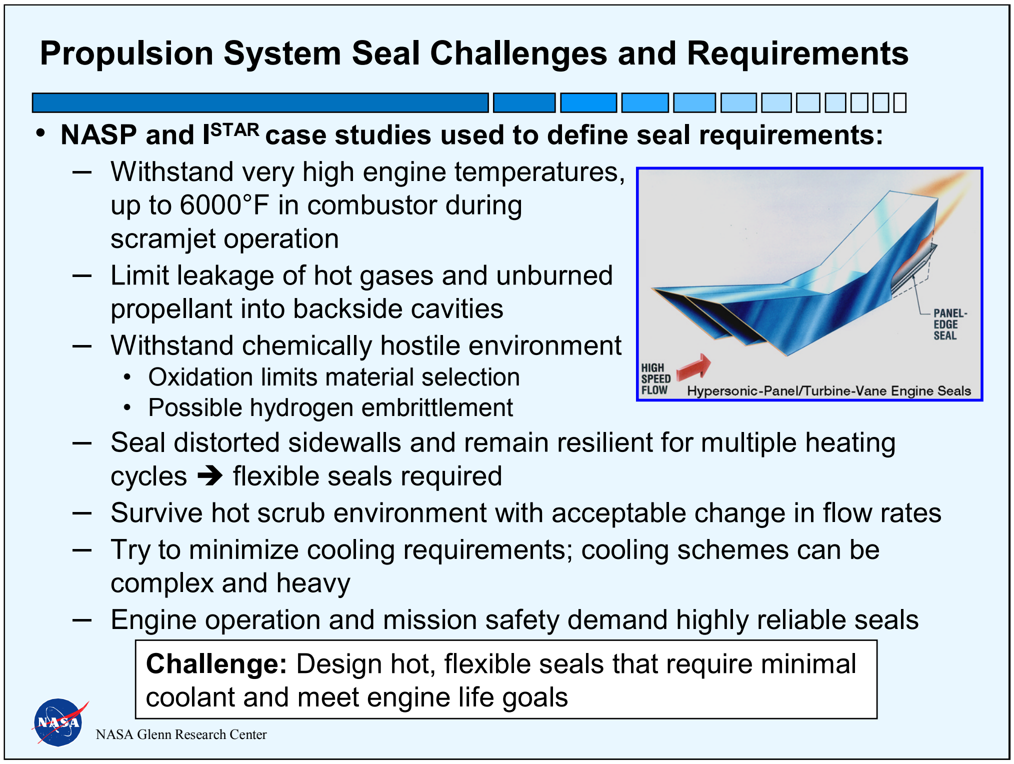
Thermal-Acoustic Testing:
- Seal structural integrity in high acoustic/ thermal environment

Hot Scrub Testing:
Wear rates & frictional loads vs.
- Temperature
- Compression level
- Stroke rate & number of cycles
- Rub surface conditions (material, surface roughness)
- Scrub direction (e.g., transverse vs. wiping)

Time frame indicated by bars at bottom of each box

NASA Glenn Research Center

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



Propulsion System Seal Challenges and Requirements

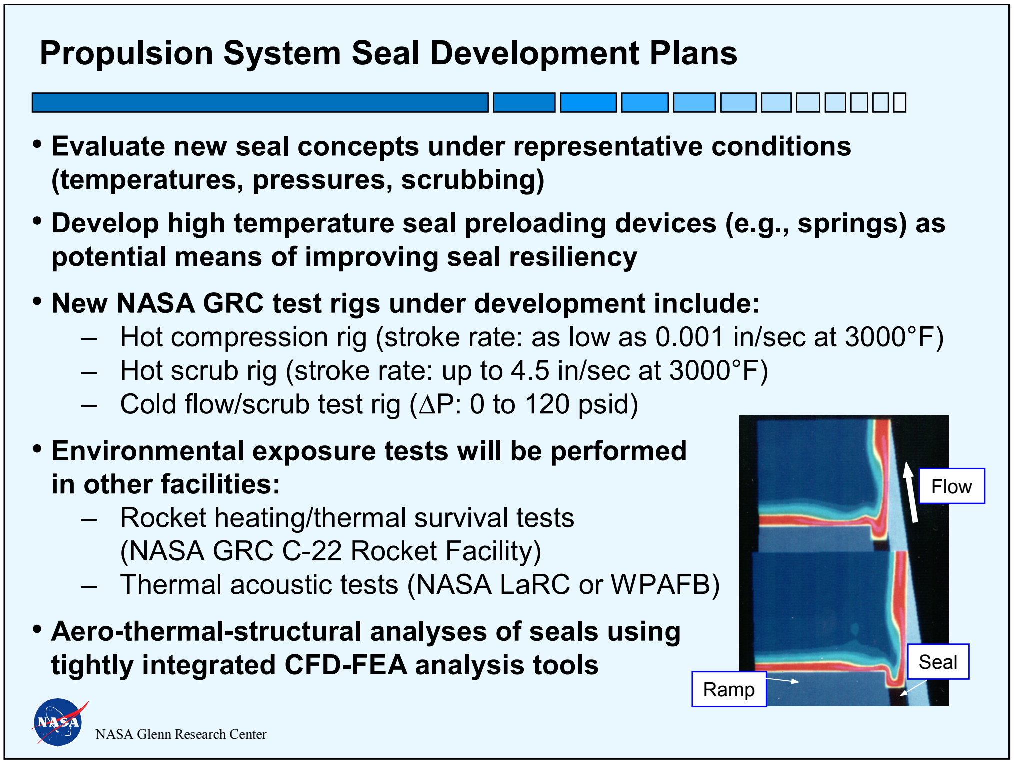
- **NASP and I^{STAR} case studies used to define seal requirements:**
  - Withstand very high engine temperatures, up to 6000°F in combustor during scramjet operation
  - Limit leakage of hot gases and unburned propellant into backside cavities
  - Withstand chemically hostile environment
    - Oxidation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

Hypersonic-Panel/Turbine-Vane Engine Seals

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

NASA Glenn Research Center

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

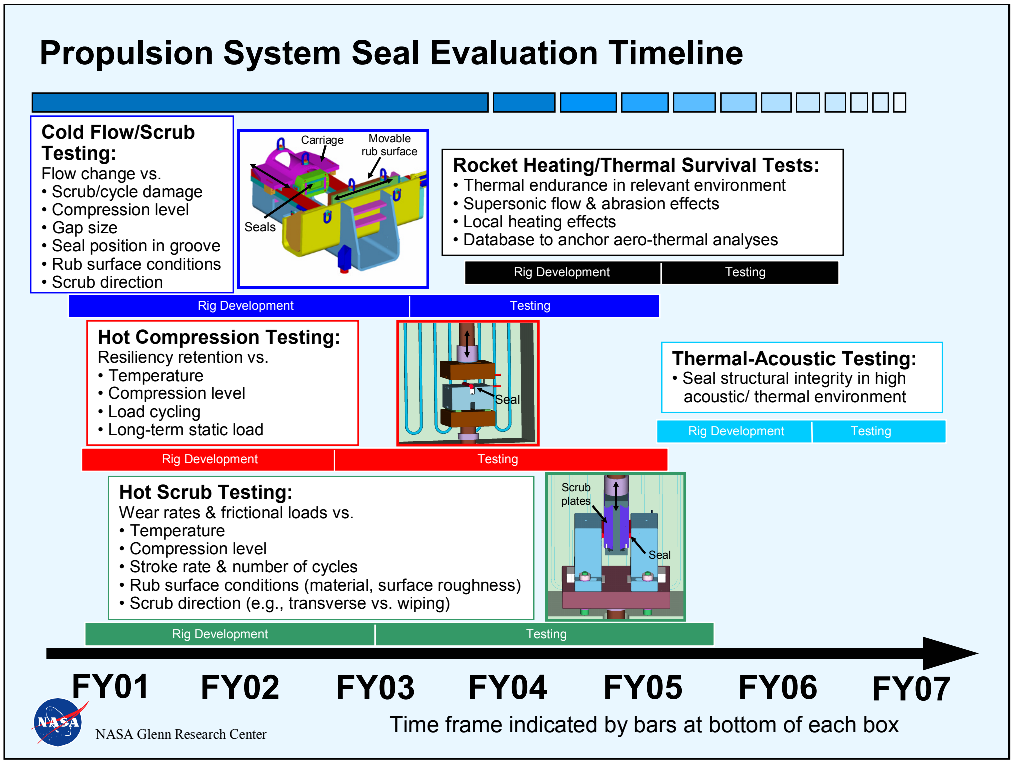


Propulsion System Seal Development Plans

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

NASA Glenn Research Center

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.



Propulsion System Seal Evaluation Timeline

Cold Flow/Scrub Testing:
Flow change vs.
- Scrub/cycle damage
- Compression level
- Gap size
- Seal position in groove
- Rub surface conditions
- Scrub direction

Rig Development | Testing

Rocket Heating/Thermal Survival Tests:
- Thermal endurance in relevant environment
- Supersonic flow & abrasion effects
- Local heating effects
- Database to anchor aero-thermal analyses

Rig Development | Testing

Hot Compression Testing:
Resiliency retention vs.
- Temperature
- Compression level
- Load cycling
- Long-term static load

Rig Development | Testing

Thermal-Acoustic Testing:
- Seal structural integrity in high acoustic/ thermal environment

Rig Development | Testing

Hot Scrub Testing:
Wear rates & frictional loads vs.
- Temperature
- Compression level
- Stroke rate & number of cycles
- Rub surface conditions (material, surface roughness)
- Scrub direction (e.g., transverse vs. wiping)

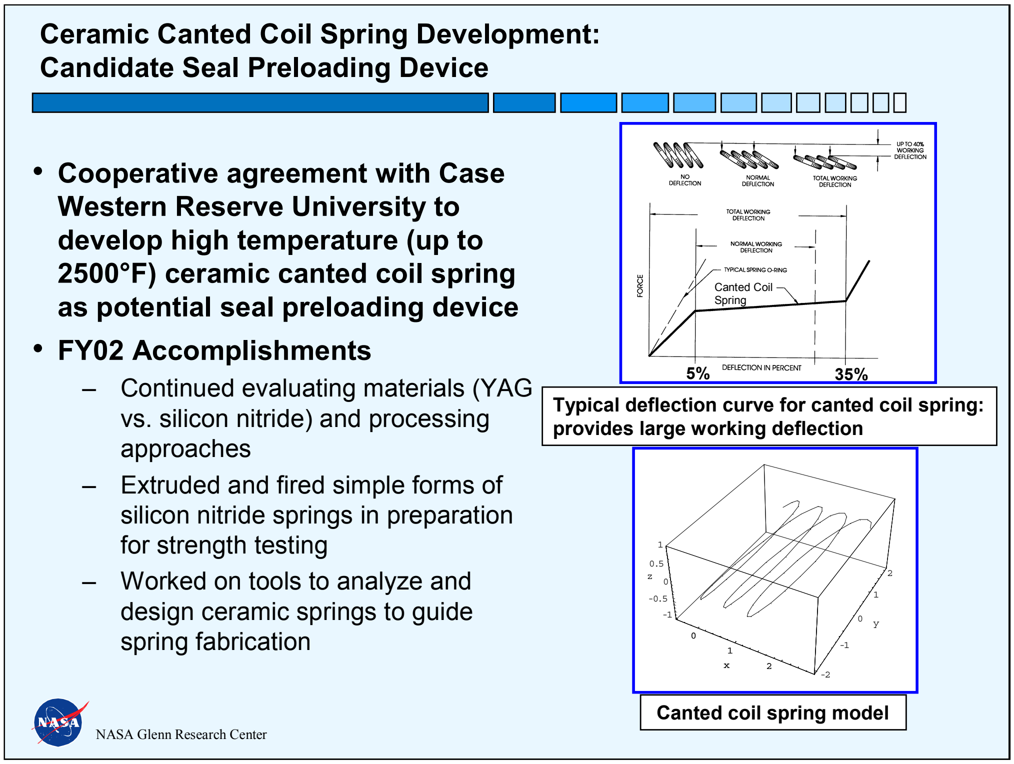
Rig Development | Testing

FY01 FY02 FY03 FY04 FY05 FY06 FY07

Time frame indicated by bars at bottom of each box

NASA Glenn Research Center

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



Ceramic Canted Coil Spring Development: Candidate Seal Preloading Device

- **Cooperative agreement with Case Western Reserve University to develop high temperature (up to 2500°F) ceramic canted coil spring as potential seal preloading device**
- **FY02 Accomplishments**
  - Continued evaluating materials (YAG vs. silicon nitride) and processing approaches
  - Extruded and fired simple forms of silicon nitride springs in preparation for strength testing
  - Worked on tools to analyze and design ceramic springs to guide spring fabrication

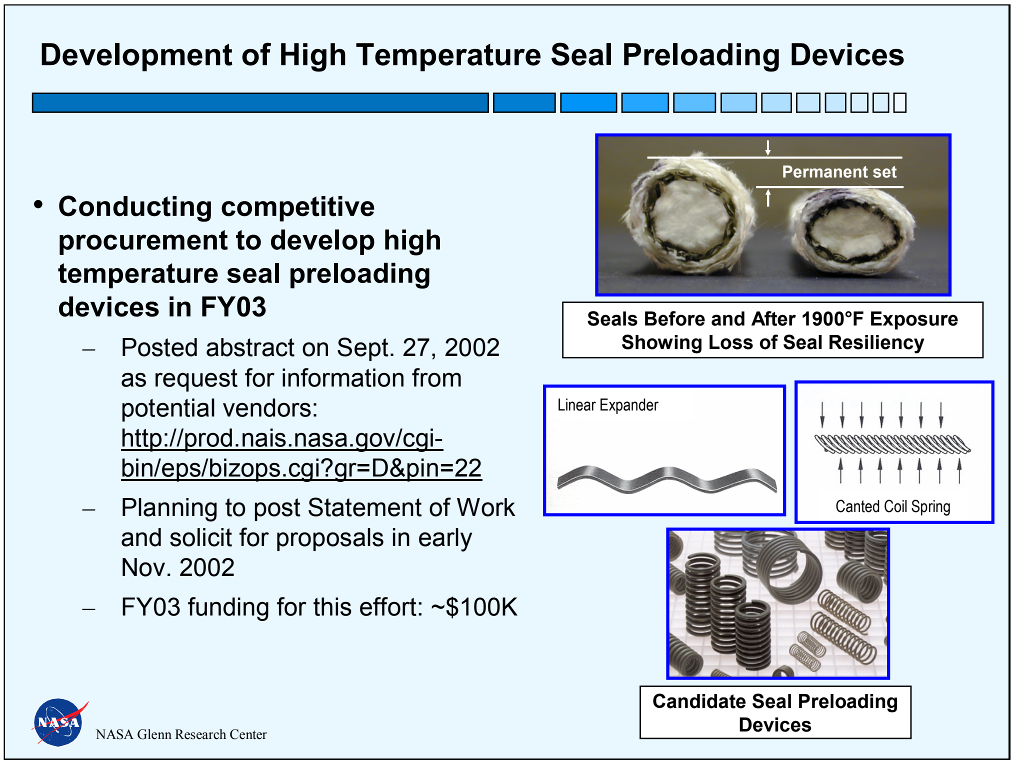
Typical deflection curve for canted coil spring: provides large working deflection

Canted coil spring model

NASA Glenn Research Center

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

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



Development of High Temperature Seal Preloading Devices

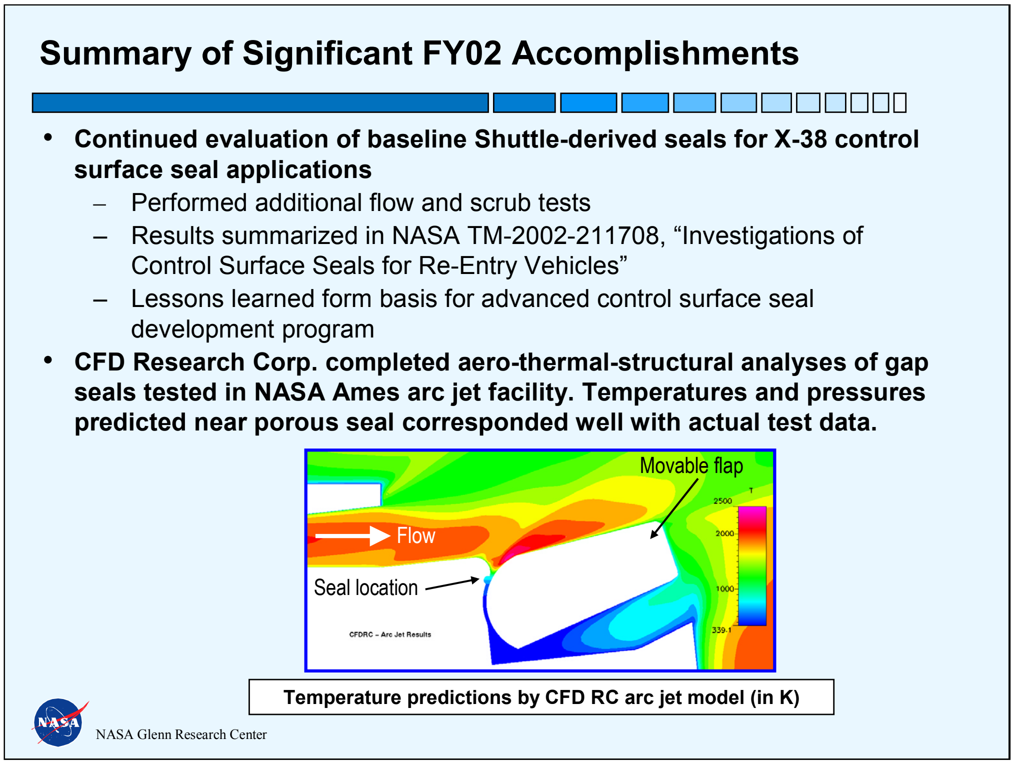
- **Conducting competitive procurement to develop high temperature seal preloading devices in FY03**
  - Posted abstract on Sept. 27, 2002 as request for information from potential vendors: http://prod.nais.nasa.gov/cgi-bin/eps/bizops.cgi?gr=D&pin=22
  - Planning to post Statement of Work and solicit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

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

Candidate Seal Preloading Devices

NASA Glenn Research Center

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



Summary of Significant FY02 Accomplishments

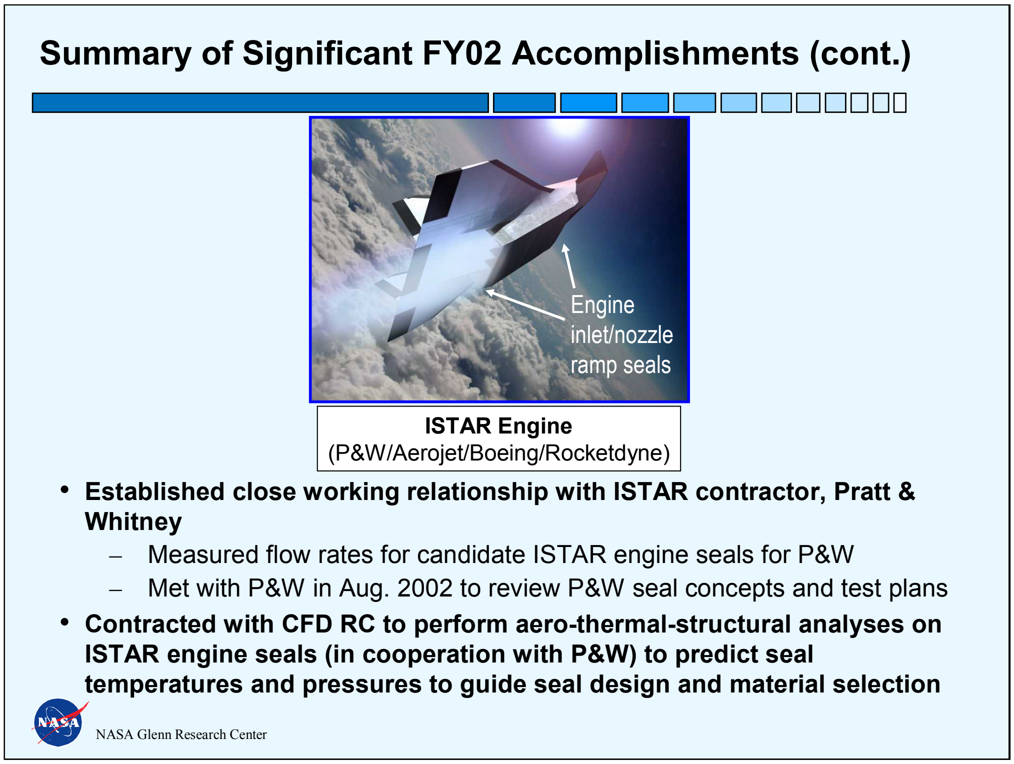
- **Continued evaluation of baseline Shuttle-derived seals for X-38 control surface seal applications**
  - Performed additional flow and scrub tests
  - Results summarized in NASA TM-2002-211708, “Investigations of Control Surface Seals for Re-Entry Vehicles”
  - Lessons learned form basis for advanced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

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

NASA Glenn Research Center

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

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



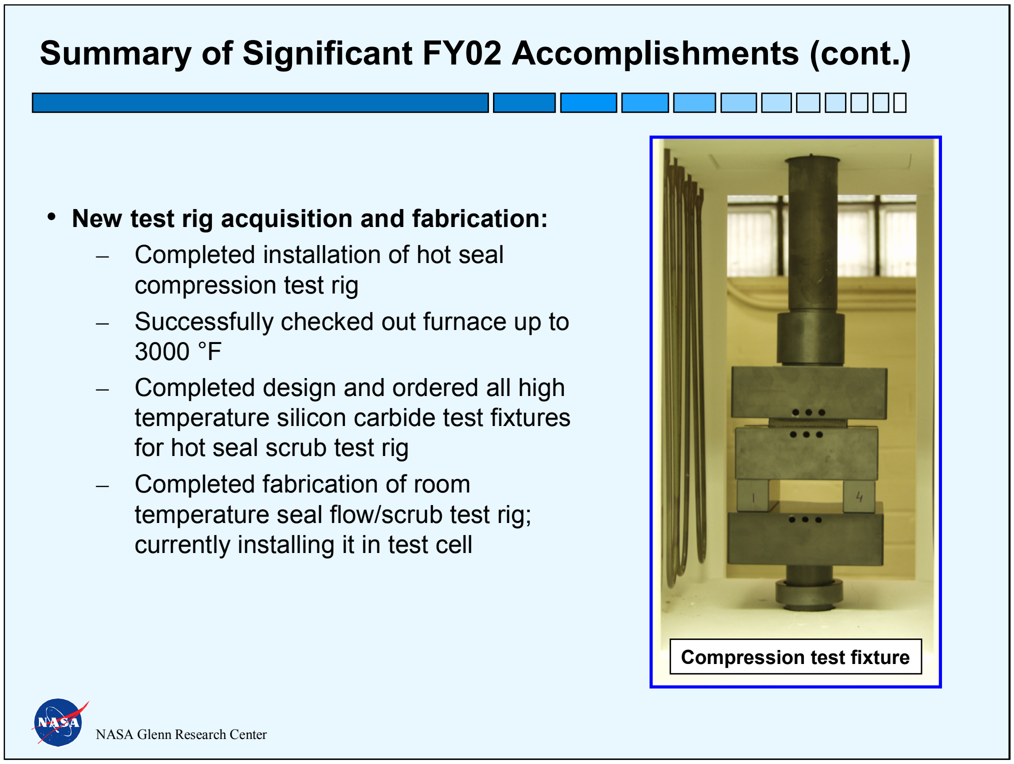
Summary of Significant FY02 Accomplishments (cont.)

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

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

NASA Glenn Research Center

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



Summary of Significant FY02 Accomplishments (cont.)

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

Compression test fixture

NASA Glenn Research Center

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

UPDATE ON THE DEVELOPMENT AND CAPABILITIES OF UNIQUE STRUCTURAL SEAL TEST RIGS

Jeffrey J. DeMange
Ohio Aerospace Institute
Brook Park, Ohio

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

Daniel P. Breen and Malcolm G. Robbie
Analex Corporation
Cleveland, Ohio

Update on the Development and Capabilities of Unique Structural Seal Test Rigs

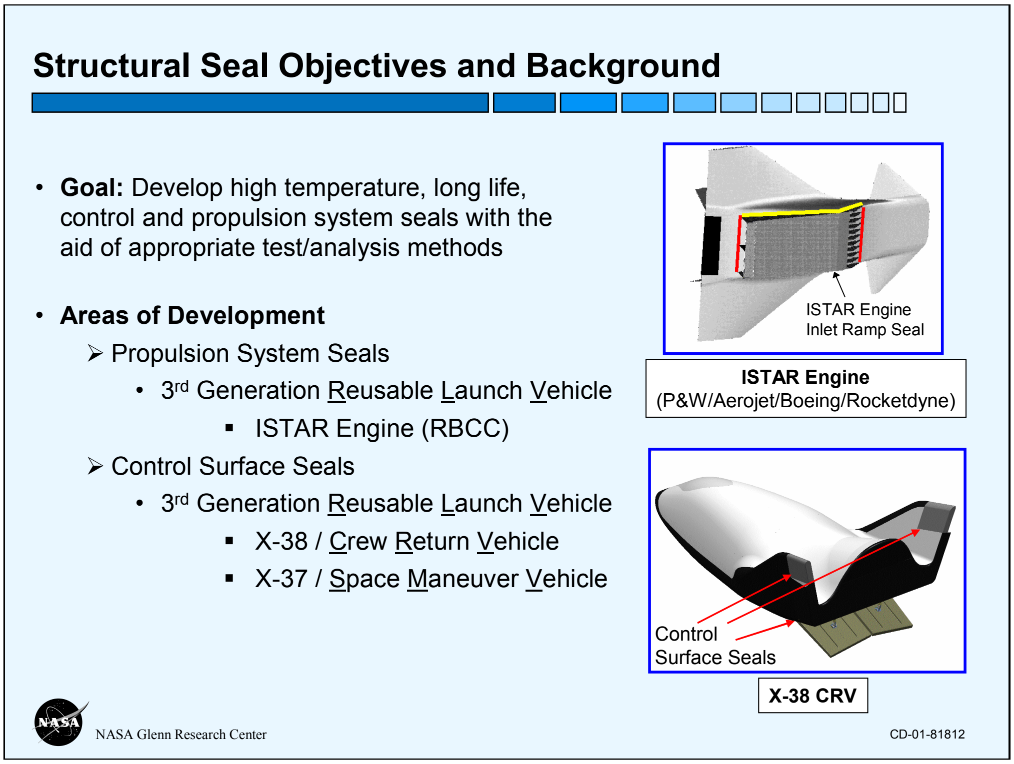
Mr. Jeffrey J. DeMange
OAI
Cleveland, OH

Mr. Patrick H. Dunlap, Jr. and Dr. Bruce M. Steinetz
NASA Glenn Research Center
Cleveland, OH

Mr. Daniel P. Breen & Mr. Malcolm G. Robbie
Analex Corporation
Cleveland, OH

2002 NASA Seals/Secondary Air Flow System Workshop
October 23th – 24th, 2002

CD-01-81812



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 Inlet Ramp Seal

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

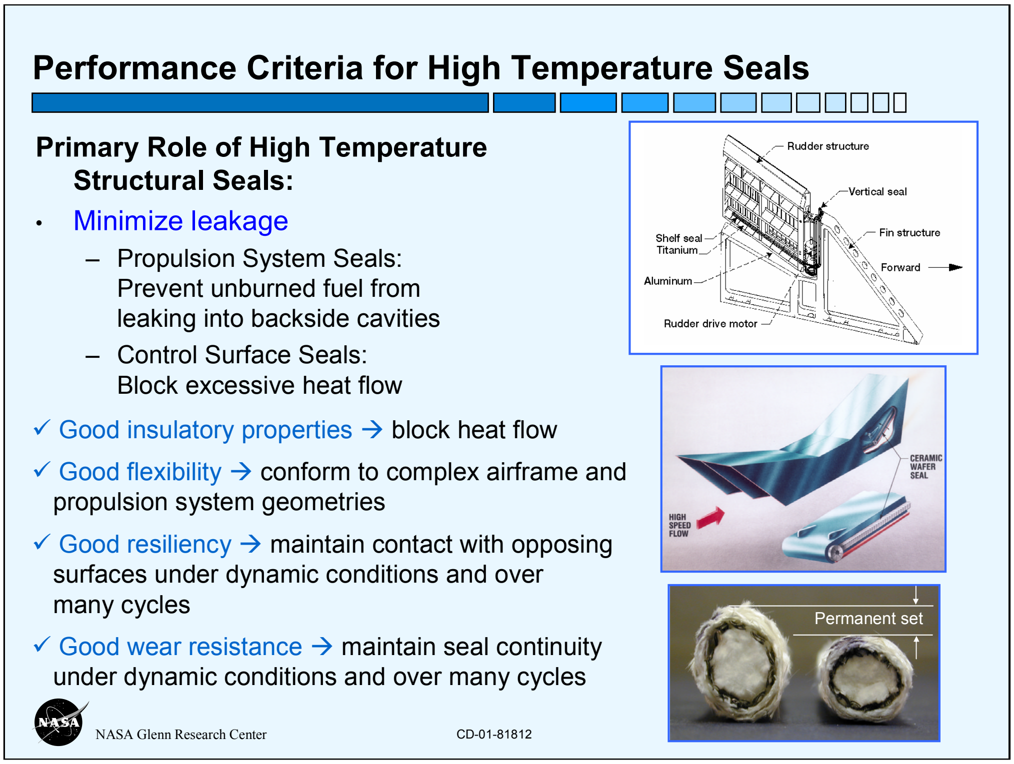
Control Surface Seals

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 by 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

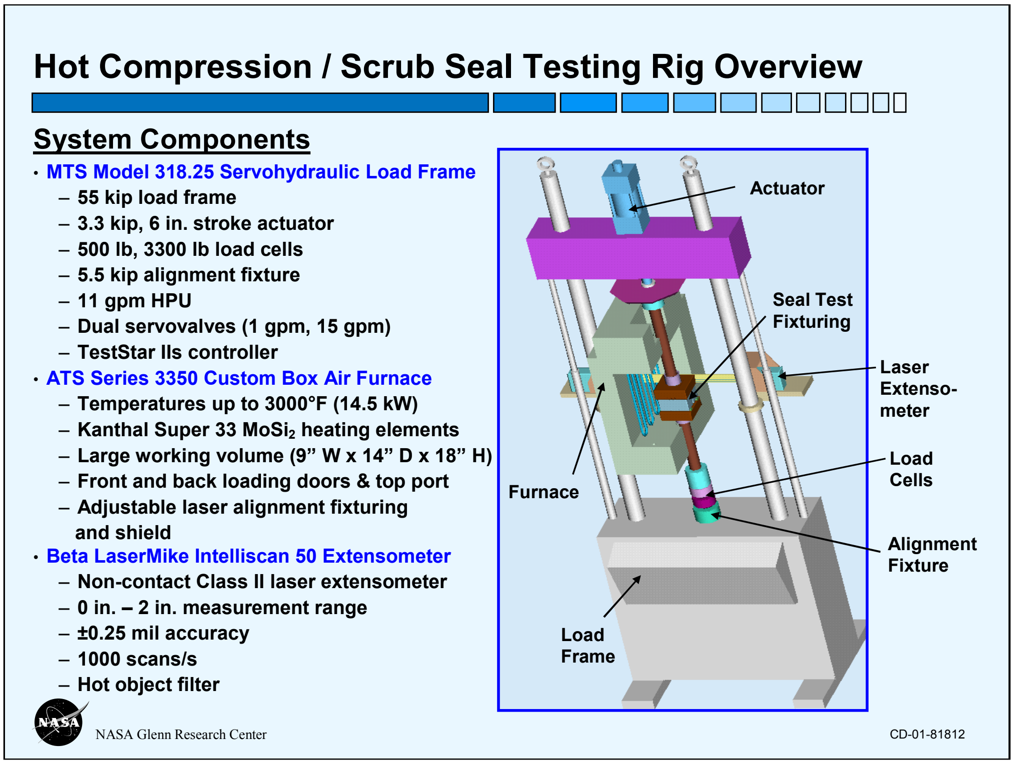
✓ Good flexibility → conform to complex airframe and propulsion system geometries

✓ 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

NASA Glenn Research Center CD-01-81812

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

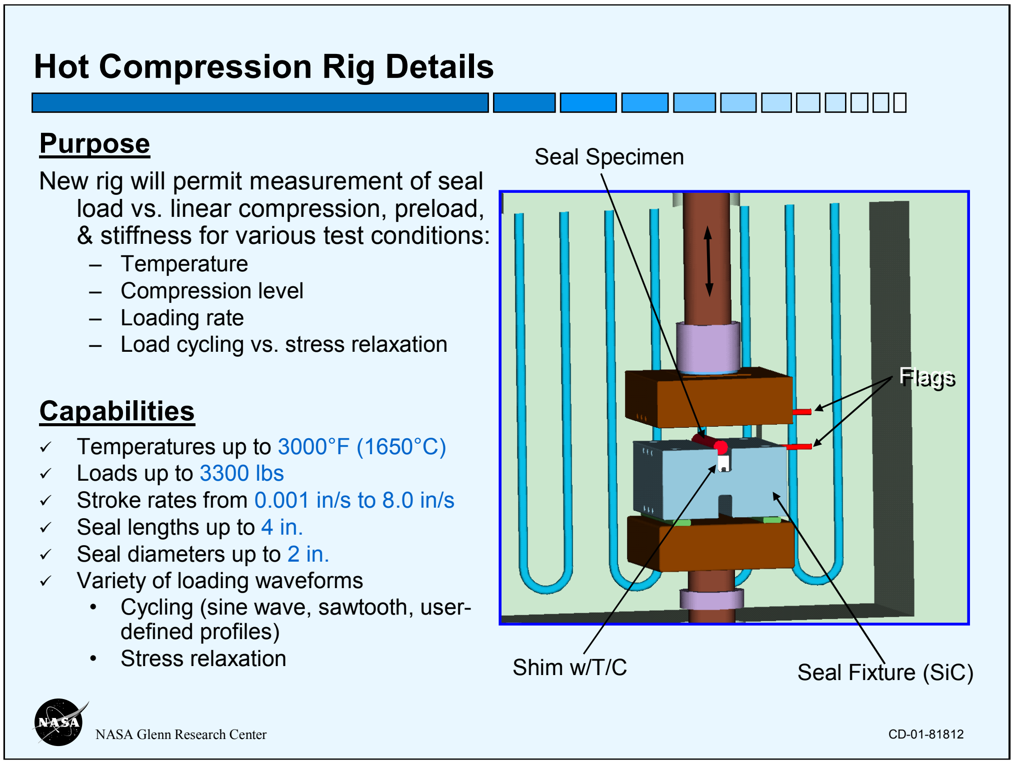
System Components

- **MTS Model 318.25 Servohydraulic Load Frame**
  - 55 kip load frame
  - 3.3 kip, 6 in. stroke actuator
  - 500 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

NASA Glenn Research Center

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 permit independent (i.e. non-simultaneous) testing of both seal resiliency characteristics (compression test) and seal wear performance (scrub test) 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

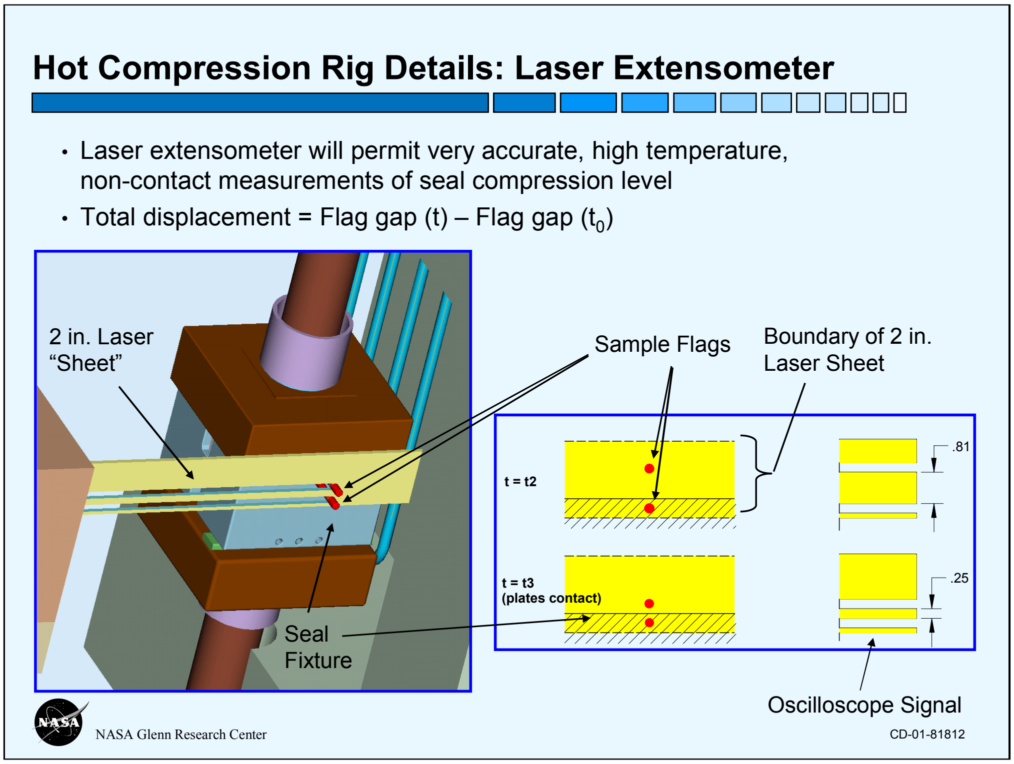
Capabilities

- ✓ 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. These evaluations will be carried out by employing a number of user-defined parameters 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 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.



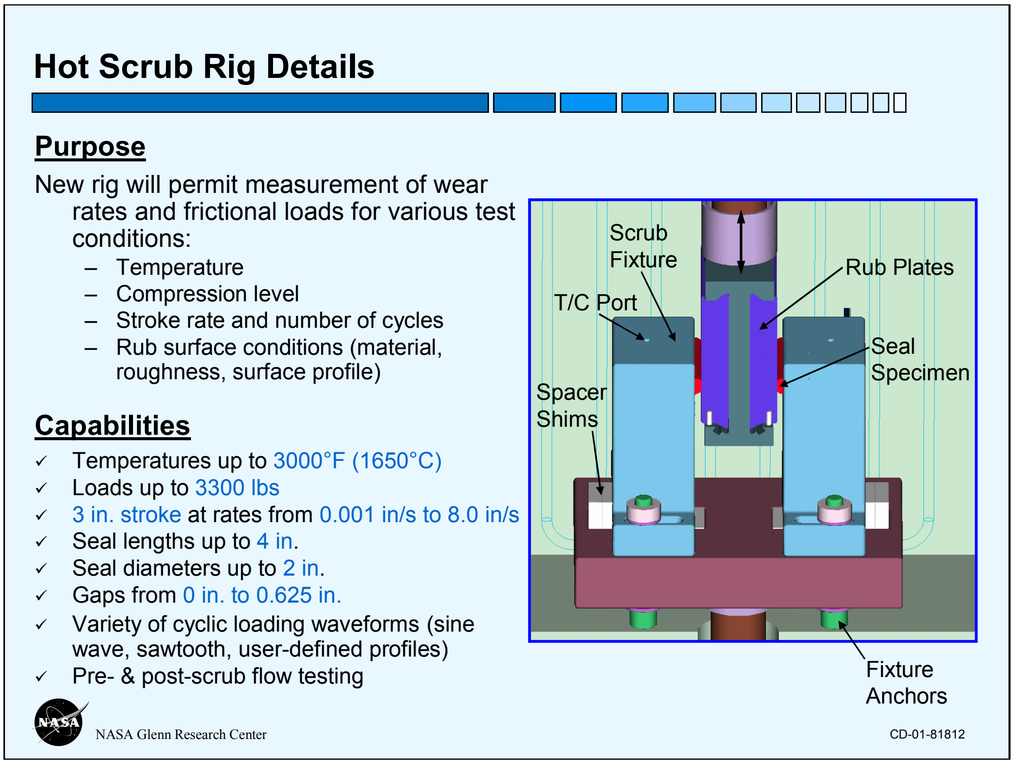
Hot Compression Rig Details: Laser Extensometer

- Laser extensometer will permit very accurate, high temperature, non-contact measurements of seal compression level
- Total displacement = Flag gap (t) – Flag gap (t_0)

NASA Glenn Research Center

CD-01-81812

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)

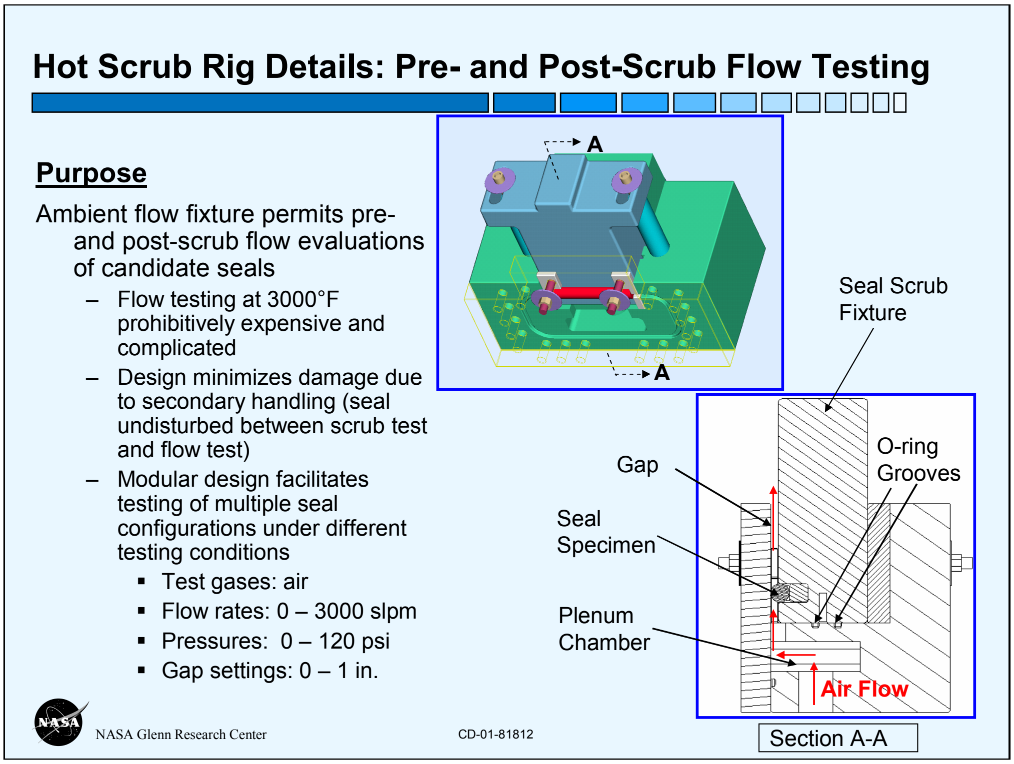
Capabilities

- ✓ 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 0.625 in.
- ✓ Variety of cyclic loading waveforms (sine wave, sawtooth, user-defined profiles)
- ✓ Pre- & post-scrub flow testing

NASA Glenn Research Center

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 through combination of 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

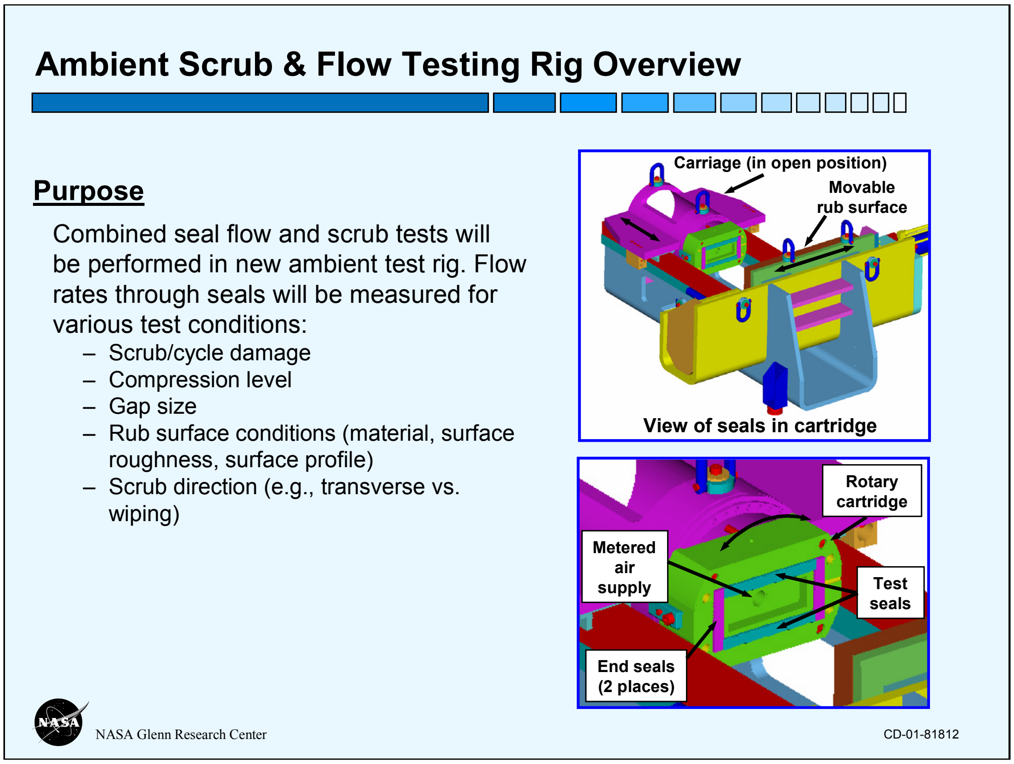
Purpose

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.

NASA Glenn Research Center CD-01-81812

Room temperature leakage tests will also be performed on seal candidates using the same seal holder described for the high temperature scrubbing test. This design will allow a specimen which has just completed a scrubbing evaluation to be “dropped into” this flow fixture, thereby minimizing damage of the seal due to secondary handling. Seal leakage as a function of wear damage can then be easily evaluated.



Ambient Scrub & Flow Testing Rig Overview

Purpose

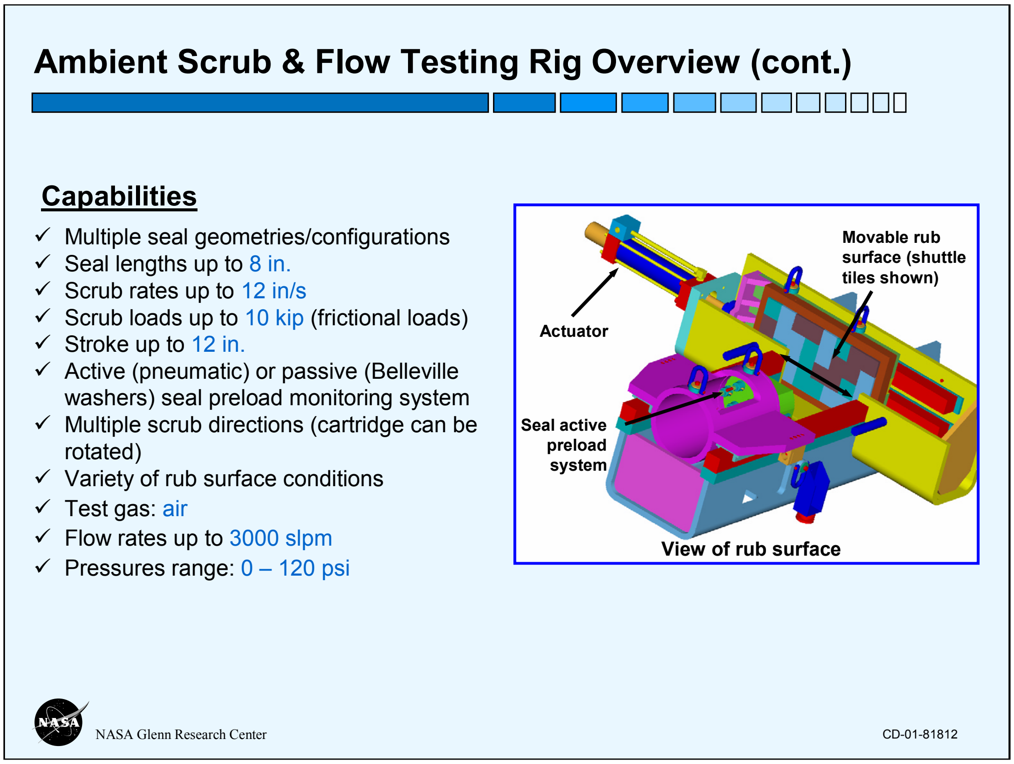
Combined seal flow and scrub tests will be performed in new ambient test rig. Flow rates through seals will be measured for various test conditions:

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

NASA Glenn Research Center

CD-01-81812

A second rig being design at the NASA Glenn Research Center will permit simultaneous evaluation of room temperature leakage as a function of seal 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 via 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.)

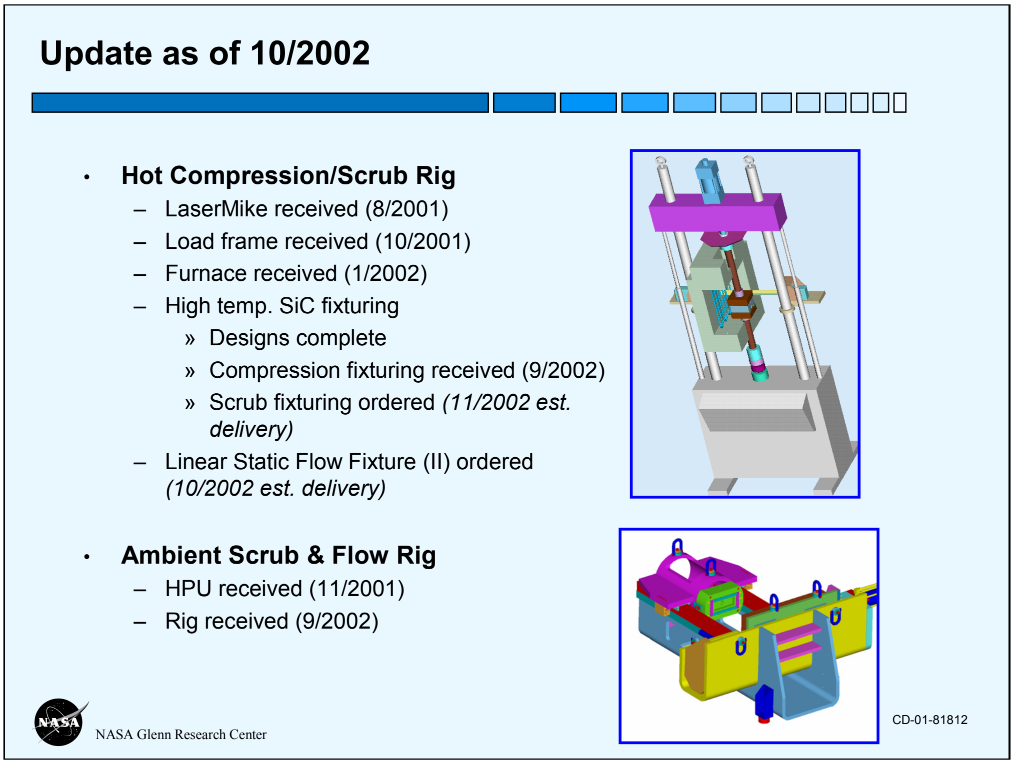
Capabilities

- ✓ 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

View of rub surface

NASA Glenn Research Center CD-01-81812

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.



Update as of 10/2002

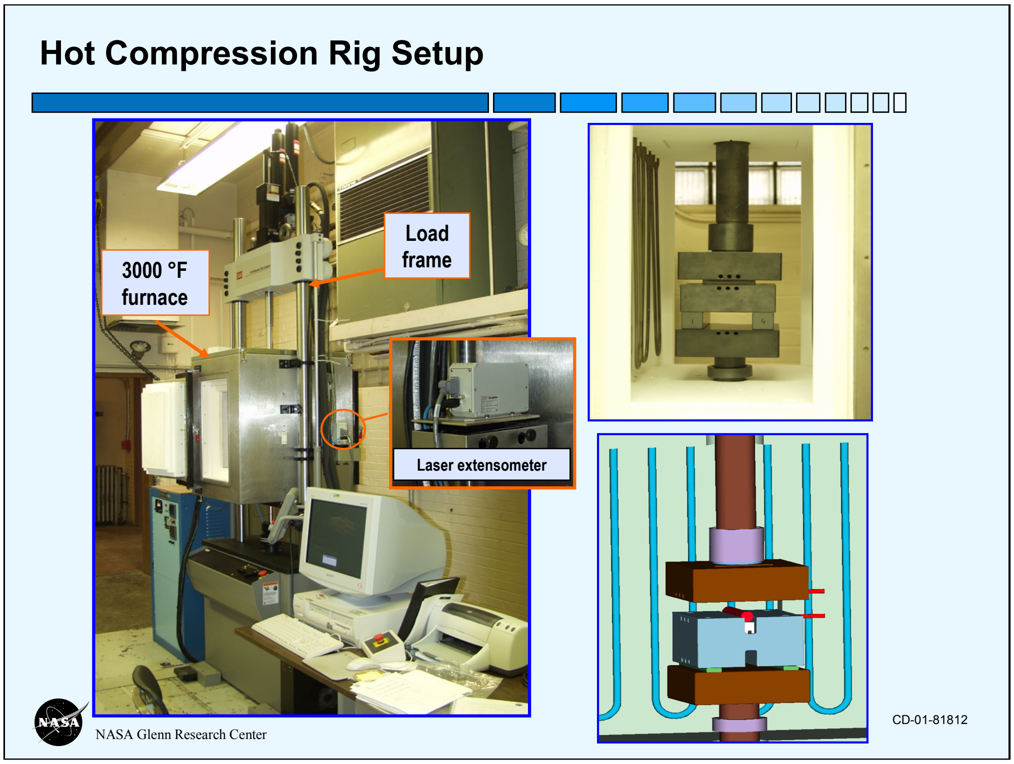
- **Hot Compression/Scrub Rig**
  - LaserMike received (8/2001)
  - Load frame received (10/2001)
  - Furnace received (1/2002)
  - High temp. SiC fixturing
    - Designs complete
    - Compression fixturing received (9/2002)
    - Scrub fixturing ordered *(11/2002 est. delivery)*
  - Linear Static Flow Fixture (II) ordered *(10/2002 est. delivery)*

- **Ambient Scrub & Flow Rig**
  - HPU received (11/2001)
  - Rig received (9/2002)

NASA Glenn Research Center

CD-01-81812

Most of the major components for these state-of-the-art test rigs were acquired by the fall of 2002. Both rigs are currently in the final stages of buildup and integration and will be tested and debugged over the next few months. Seal testing is scheduled to commence in FY03.

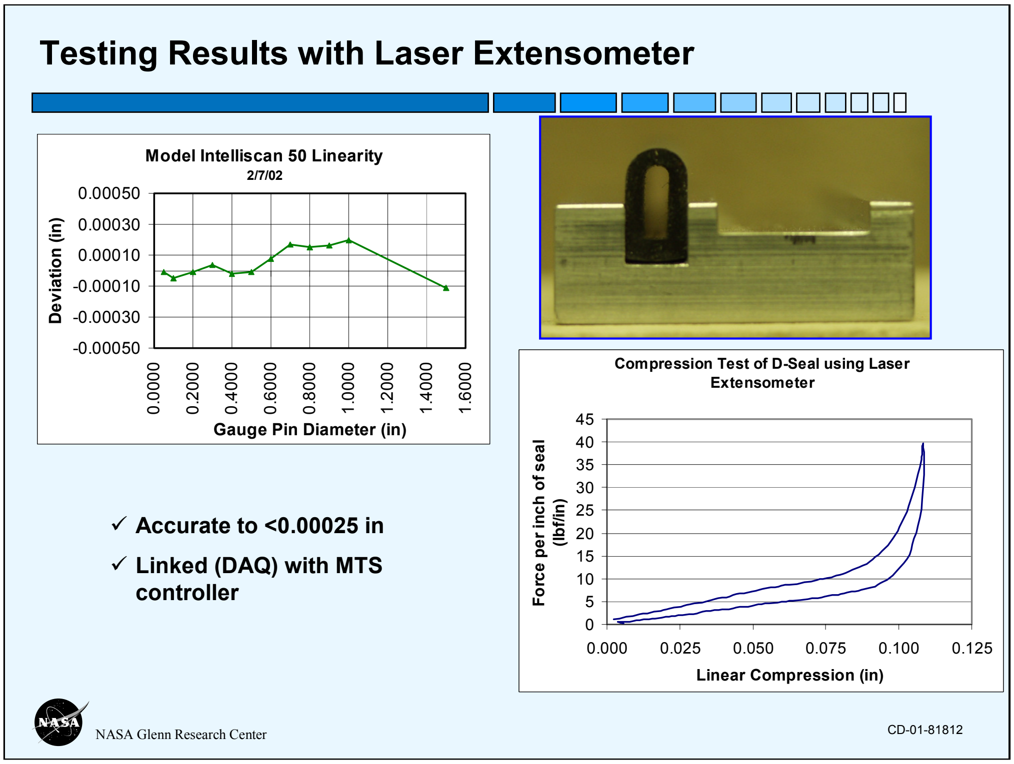


Hot Compression Rig Setup

NASA Glenn Research Center

CD-01-81812

The Hot Compression / Scrub rig is shown on the left with most of the major components installed. The exception is that the high temperature test fixturing was not installed at the time of this picture. The SiC compression fixturing was received and installed in late September of 2002 and is shown in the upper right corner along with the original conceptual schematic in the lower right corner. The SiC scrub fixturing is expected to be delivered in November of 2002.



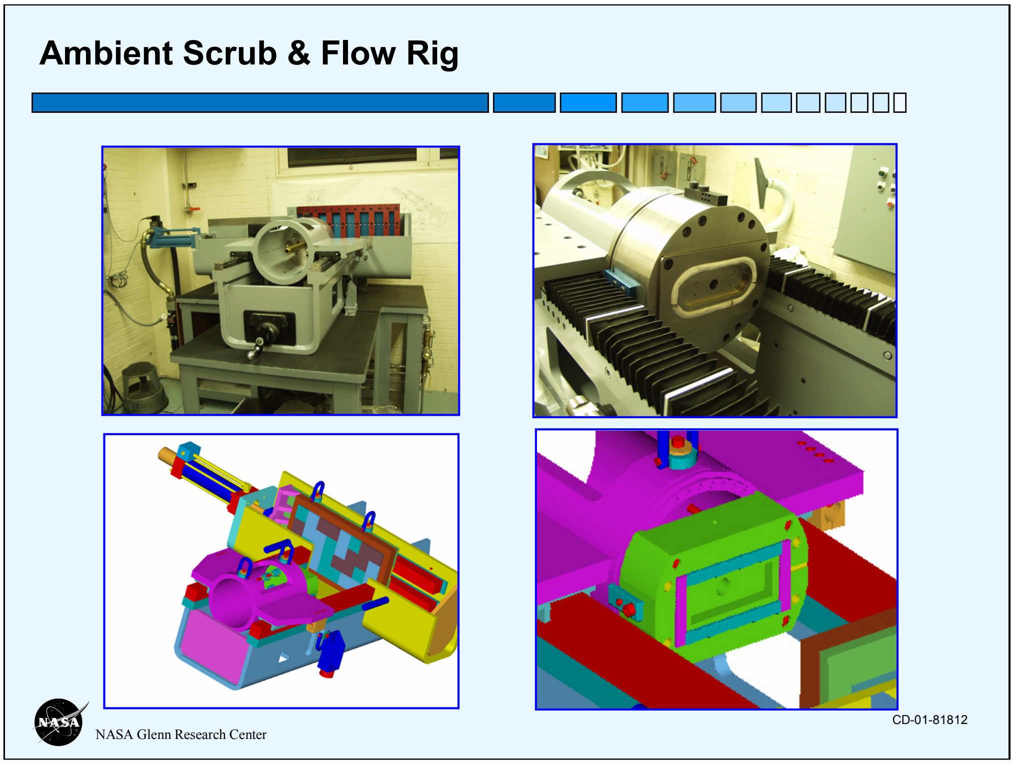
Testing Results with Laser Extensometer

- ✓ Accurate to <0.00025 in
- ✓ Linked (DAQ) with MTS controller

NASA Glenn Research Center

CD-01-81812

The Laser Extensometer is a key component for the accurate testing of the next generation of high temperature seals. Results of the check out of the laser received by NASA GRC demonstrated excellent accuracy (down to 0.25 mil). A typical test plot conducted on a D-seal in the compression rig at room temperature is shown in the bottom right corner.

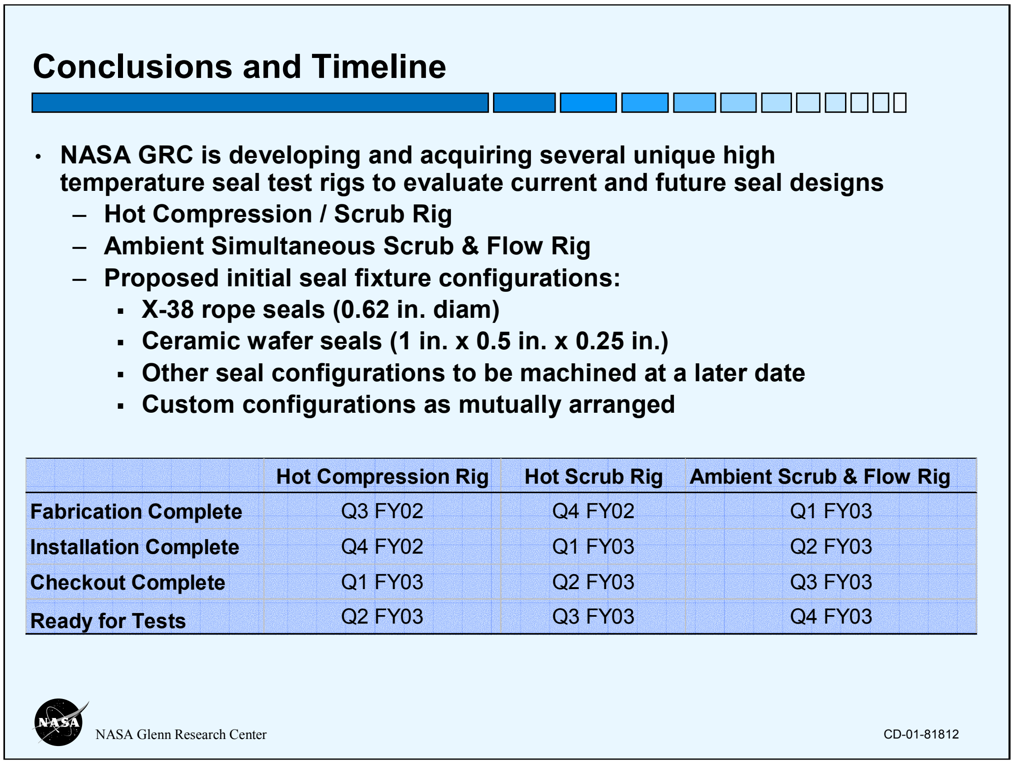


Ambient Scrub & Flow Rig

NASA Glenn Research Center

CD-01-81812

The Ambient Scrub and Flow Rig was received and installed with it's initial build in mid-October 2002. The test rig with the single rope seal holder is shown in the top photographs. For comparison, the conceptual schematics (with the wafer seal holder) are also shown.



Conclusions and Timeline

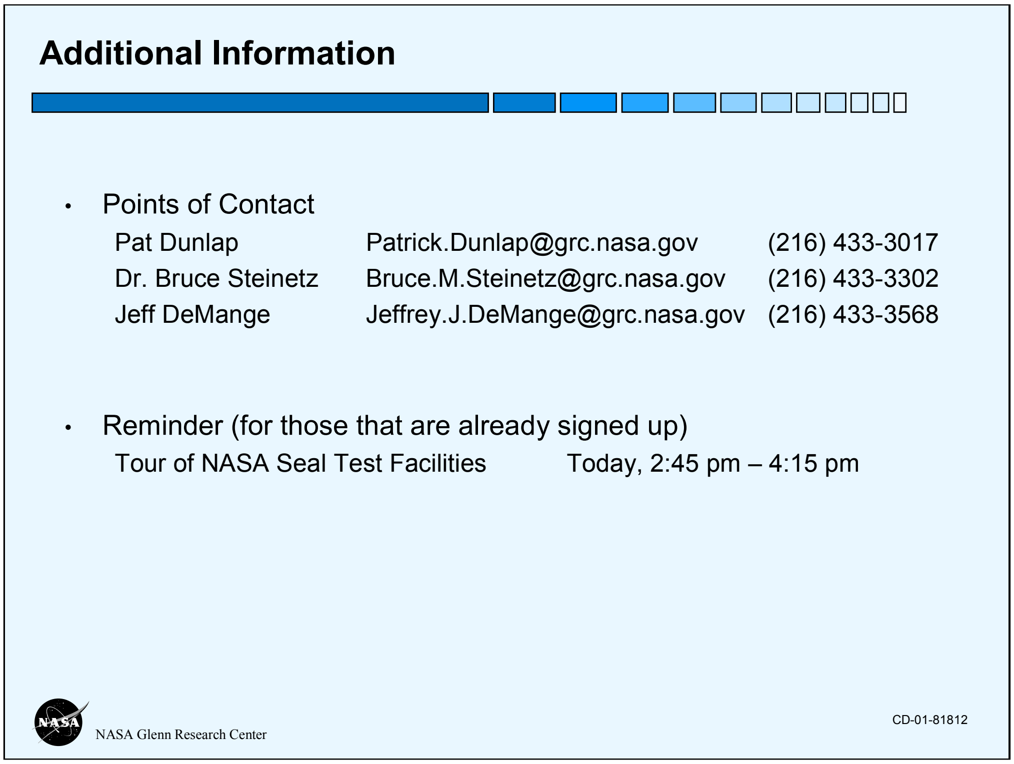
- NASA GRC is developing and acquiring several unique high temperature seal test rigs to evaluate current and future seal designs
  - Hot Compression / Scrub Rig
  - Ambient Simultaneous Scrub & Flow Rig
  - Proposed initial seal fixture configurations:
    - X-38 rope seals (0.62 in. diam)
    - Ceramic 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 Rig	Hot Scrub Rig	Ambient Scrub & Flow Rig
Fabrication Complete	Q3 FY02	Q4 FY02	Q1 FY03
Installation Complete	Q4 FY02	Q1 FY03	Q2 FY03
Checkout Complete	Q1 FY03	Q2 FY03	Q3 FY03
Ready for Tests	Q2 FY03	Q3 FY03	Q4 FY03

NASA Glenn Research Center

CD-01-81812

NASA Glenn's structural seal research capabilities 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.



Additional Information

- Points of Contact

Pat Dunlap	Patrick.Dunlap@grc.nasa.gov	(216) 433-3017
Dr. Bruce Steinetz	Bruce.M.Steinetz@grc.nasa.gov	(216) 433-3302
Jeff DeMange	Jeffrey.J.DeMange@grc.nasa.gov	(216) 433-3568

- Reminder (for those that are already signed up)

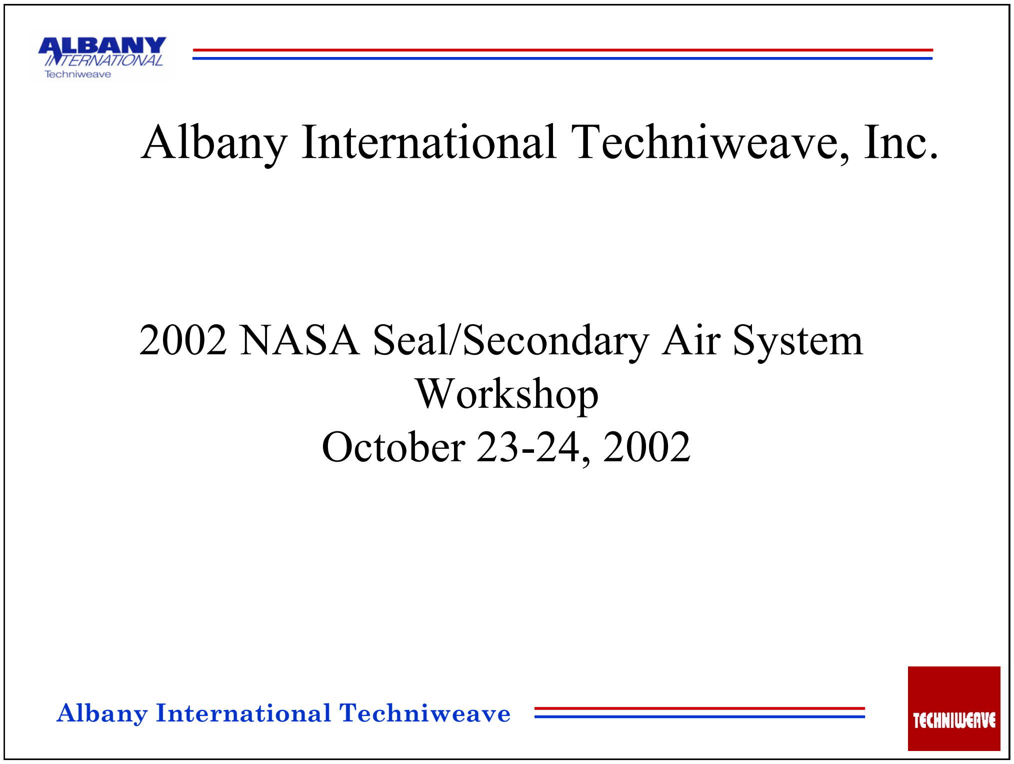
Tour of NASA Seal Test Facilities — Today, 2:45 pm – 4:15 pm

NASA Glenn Research Center

CD-01-81812

OVERVIEW OF SEAL DEVELOPMENT AT ALBANY-TECHNIWEAVE

Bruce Bond
Albany Techniweave, Inc.
Rochester, New Hampshire



Albany International Techniweave, Inc.

2002 NASA Seal/Secondary Air System Workshop
October 23-24, 2002

Albany International Techniweave

Rope Seal Testing Protocol

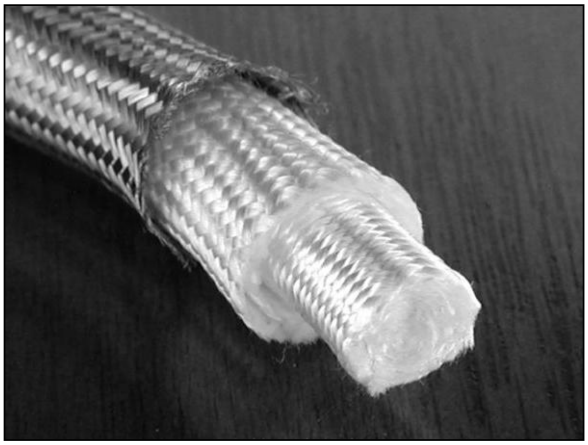
- Room Temperature
  - Compression
  - Resiliency
  - Leakage

Albany International Techniweave

Albany International Techniweave, Inc. (AIT) has been fabricating a wide variety of rope seals since 1990 for NASA and other aerospace companies. Each customer typically tested the seals as they deemed necessary for their individual application. AIT is now developing standardized testing protocols for its family of high temperature seals in order to provide basic engineering data to its customers. Although testing at high temperature would be ideal, the difficulty and cost makes it prohibitive. AIT is developing room temperature data to establish a baseline. It is anticipated that selected tests at high temperature will provide the basis for establishing correlations between the room temperature data and performance at elevated temperatures. Thus we are working on establishing baseline compression, resiliency, and leakage data.

ALBANY INTERNATIONAL
Techniweave

Hybrid Rope Seal

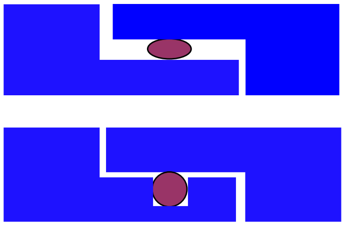


Albany International Techniweave

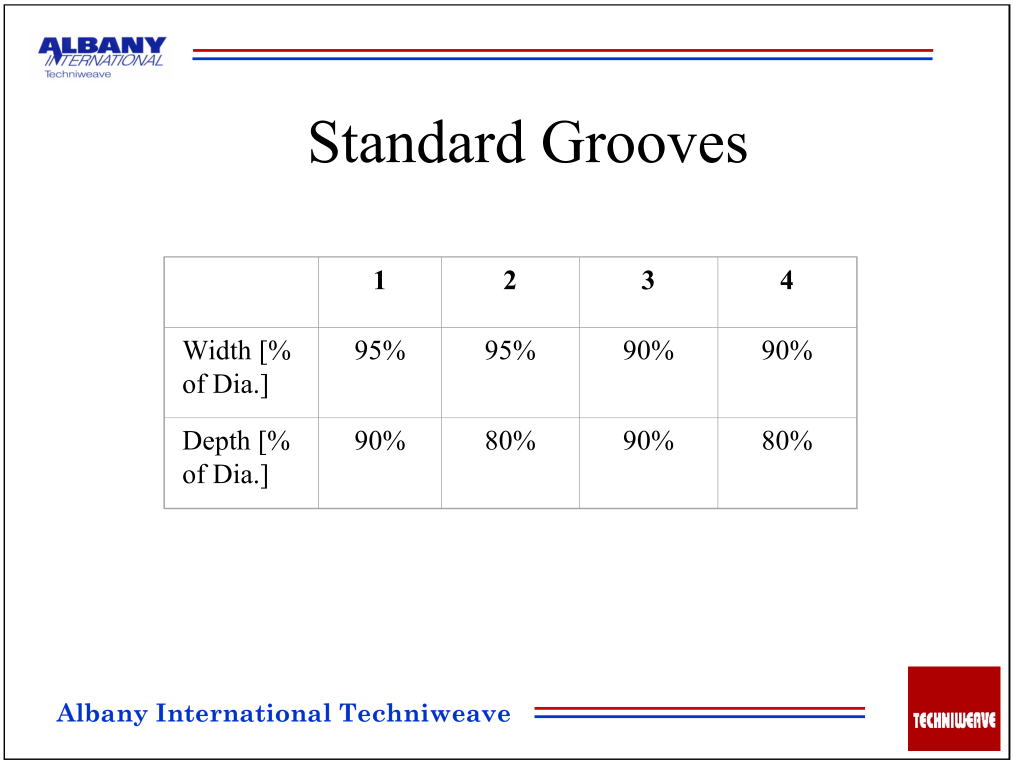
TECHNIWEAVE

The “Hybrid” seal is one of most popular seal designs. In this case it incorporates a tightly braided, multi-layered, ceramic core with a heat resistant wire overbraid. The overbraid toughens the seal and minimizes damage both during assembly and in use.

Typical Configurations



Seals can be used as a barrier between two plates or in a more conventional "O" ring groove as shown above.



ALBANY INTERNATIONAL Techniweave

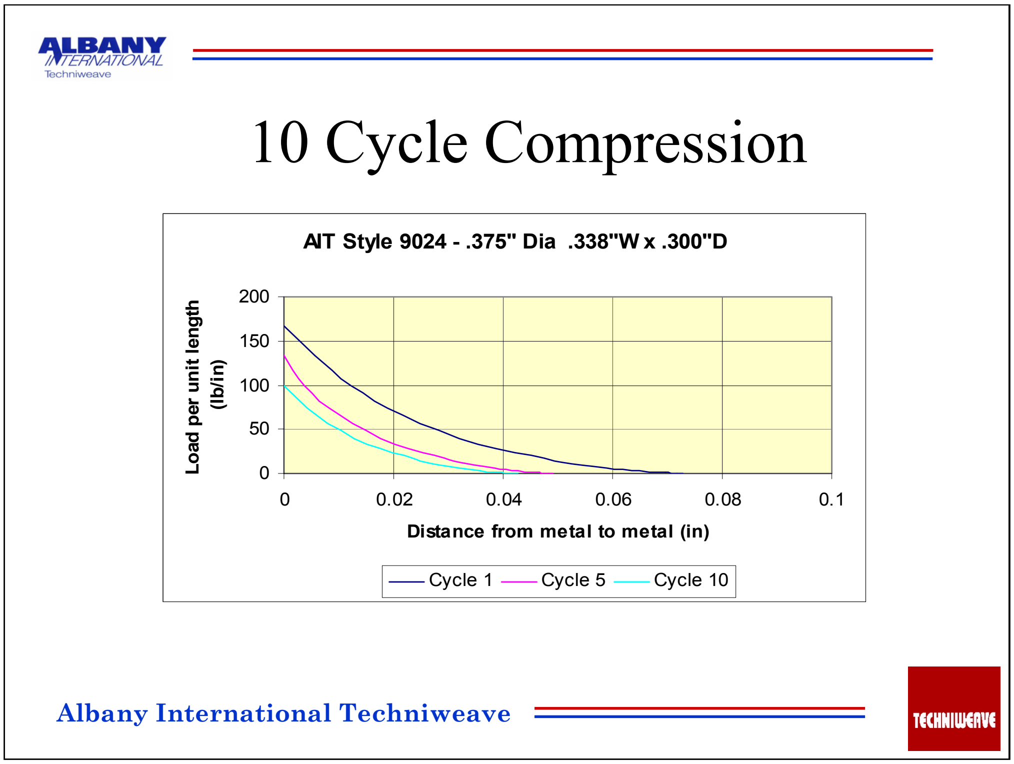
Standard Grooves

	1	2	3	4
Width [% of Dia.]	95%	95%	90%	90%
Depth [% of Dia.]	90%	80%	90%	80%

Albany International Techniweave

TECHNIWEAVE

Compression tests have been conducted using rectangular grooves. While the dimensions of the groove offer unlimited possibilities, we have elected to test four groove variations for each of our standard seals. We have concentrated on grooves with widths slightly less than the nominal diameter of the seal to ensure the seal would be held in place during assembly. The width and depth dimensions of the grooves for the four test conditions are described as a percentage of the nominal seal diameter. Compression of seals in groves shallower than 80% of the seal diameter exhibited significant distortion and is not considered to be of interest at this time



ALBANY INTERNATIONAL Techniweave

10 Cycle Compression

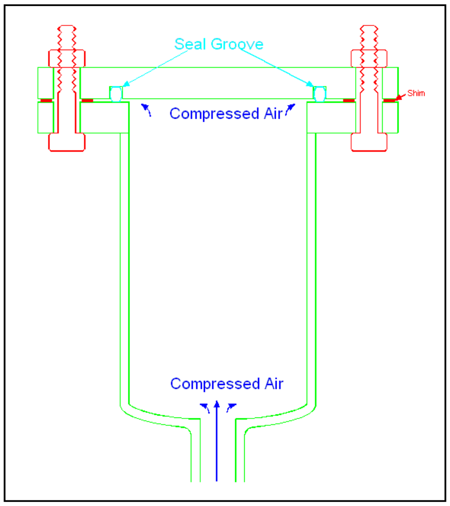
Albany International Techniweave

TECHNIWEAVE

. An Instron™ testing machine was used to compress the seal until the top platen made full contact with the grooved plate. The process was repeated 10 times to provide an understanding of the relaxation that might occur. The data has been graphically presented with only the first, fifth, and tenth cycle included.

ALBANY INTERNATIONAL
Techniweave

Leakage Testing



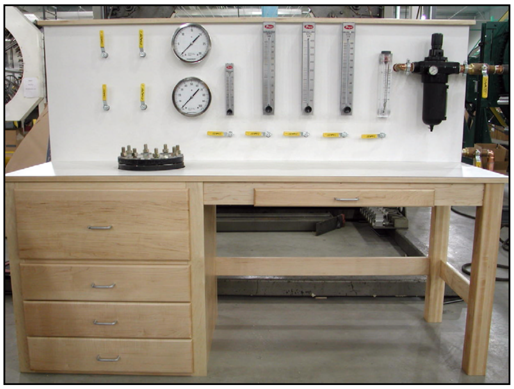
Albany International Techniweave

TECHNIWEAVE

The flange was shimmed away from the flat base plate using shim washers to provide uniform spacing,

ALBANY INTERNATIONAL
Techniweave

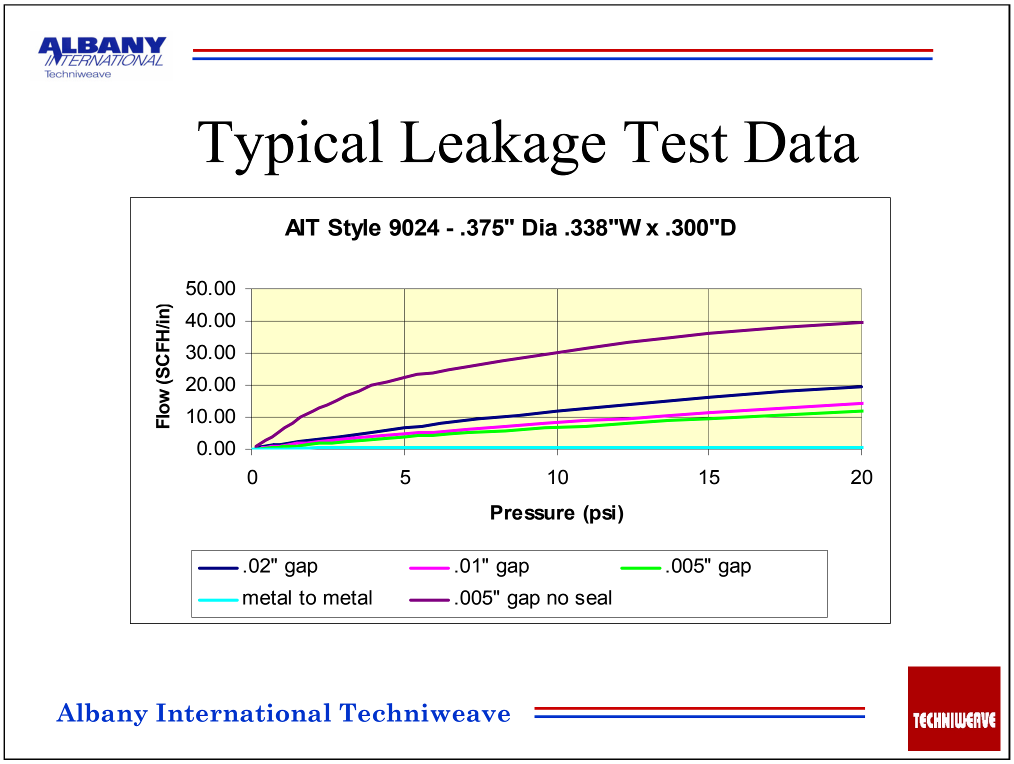
Leakage Test Fixture



Albany International Techniweave

TECHNIWEAVE

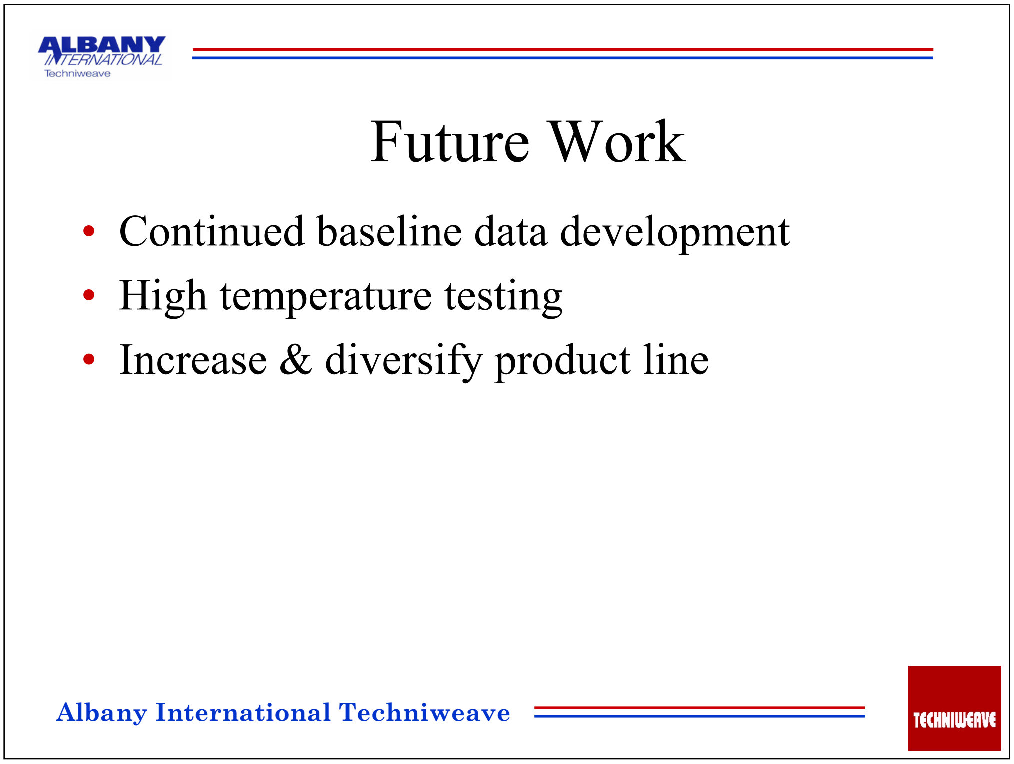
The seals were tested for leakage using the test apparatus pictured below that provides for flows from .20 SCFH to 100 SCFM and pressures from 2 inches of water (.07 x PSIG) to 100 PSIG. All seals were tested with the fiber sizing removed. The grooves were machined into a blank flange with the centerline corresponding to a circumferential length of 18 inches. The grooves have the same configuration as those used in the compression testing. The gas is standard shop compressed air from a rotary screw compressor equipped with a cooler for moisture removal. The butted seal ends were coated with caulking and allowed to dry overnight to eliminate this leakage path. The seals were compressed to a complete metal to metal condition (fully compressed into the groove) ten times using an arbor press to seat the seal and “precondition” it prior to testing.



Typical Leakage Test Data

Albany International Techniweave

The full metal to metal condition represents a condition with no shims, the flanges tightly bolted, and the seal fully compressed. Machining variations provide a minimal leakage path which is impeded by the seal. The flow data has been presented as flow vs. pressure with a separate line for each shim height.



Future Work

- Continued baseline data development
- High temperature testing
- Increase & diversify product line

Albany International Techniweave

HIGH TEMPERATURE METALLIC SEAL DEVELOPMENT

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

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

Based on the ASTM stress relaxation studies, UHT seals have been fabricated using a candidate superalloy, an oxide dispersion strengthened (ODS) alloy and a proprietary composite structure. Seal characterization tests are being conducted in the temperature range 1500 °F to 1800 °F by monitoring the change in the seal free height as a function of the exposure time. Results of an advanced superalloy seal, obtained so far, will be presented and compared with those of standard Waspaloy seals.

An innovative knowledge–based seal design and application engineering software has also been developed by Advanced Products. This Integrated Product Engineering (IPE) approach will be explained and demonstrated.

Advanced

High Temperature Metallic Seal Development

Dr. Amit Datta, President,
Advanced Components & Materials, Inc.

Mr. D.Greg More, Director of Engineering,
The Advanced Products Company

Advanced

Objective

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

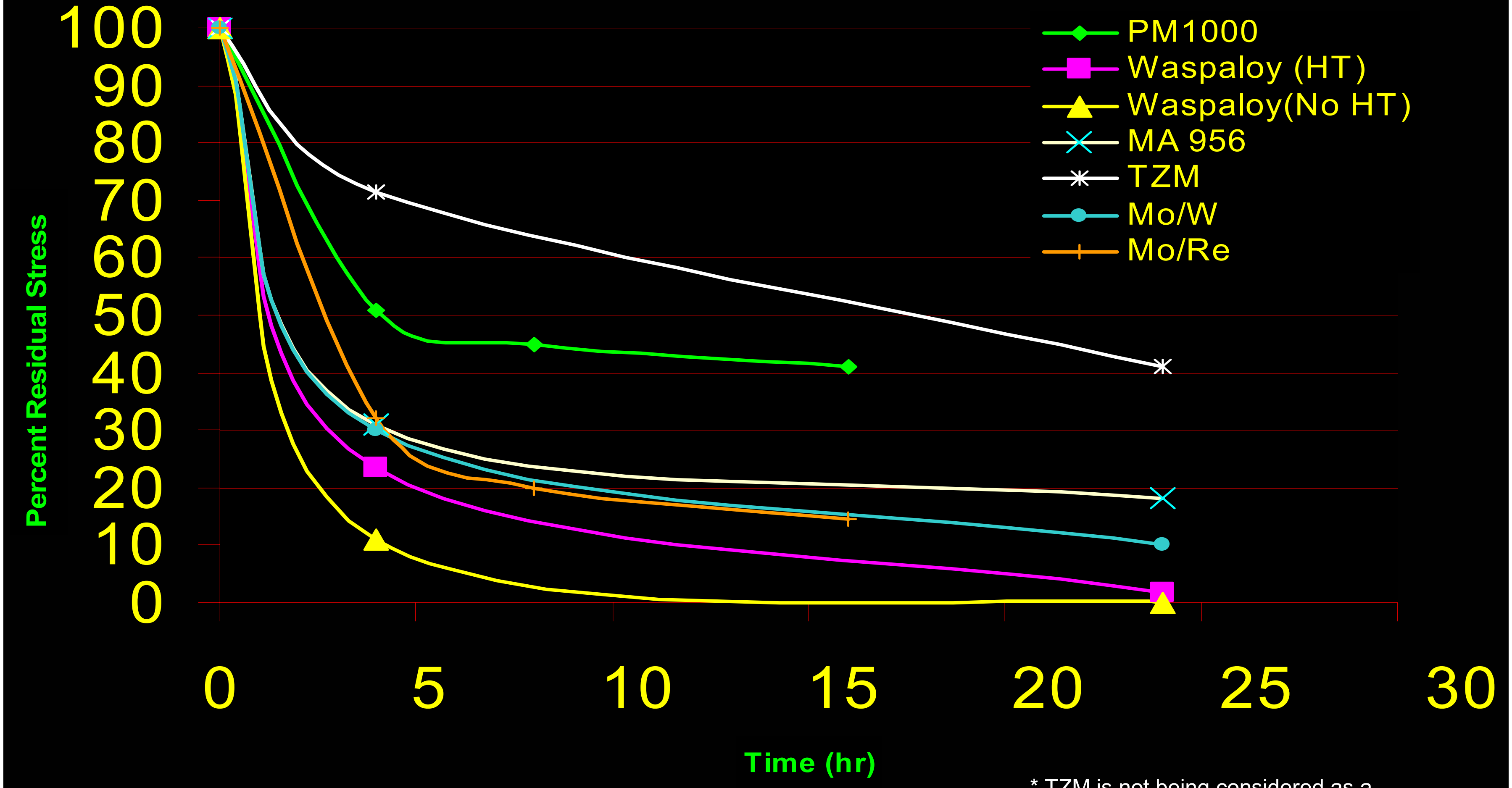
Advanced

Development Approach

- Screen Metallic Alloys using ASTM E-328 Stress Relaxation tests in the 1600 - 1800 °F Range
- Fabricate seals from alloys that performed the best in the generic screening test
- Performance test seals at elevated temperatures in simulated application cavities at temperatures ranging from 1400 - 1800 °F
- Candidate alloys include - Superalloys, ODS alloys, Refractory alloys, composite alloy structures

Screening Stress Relaxation Studies at 1800 °F

Advanced



* TZM is not being considered as a candidate seal material due to it's poor oxidation resistance.

Advanced

Screening Stress Relaxation Studies at 1600 °F

Stress Relaxation Studies

- ASTM Style Testing
  - Primary focus has now shifted to alloys capable of operating at 1600 - 1800 °F
  - We now have a good understanding of short term material behavior in the 1400 - 1600 °F temperature range

UHT Seal Test Stand

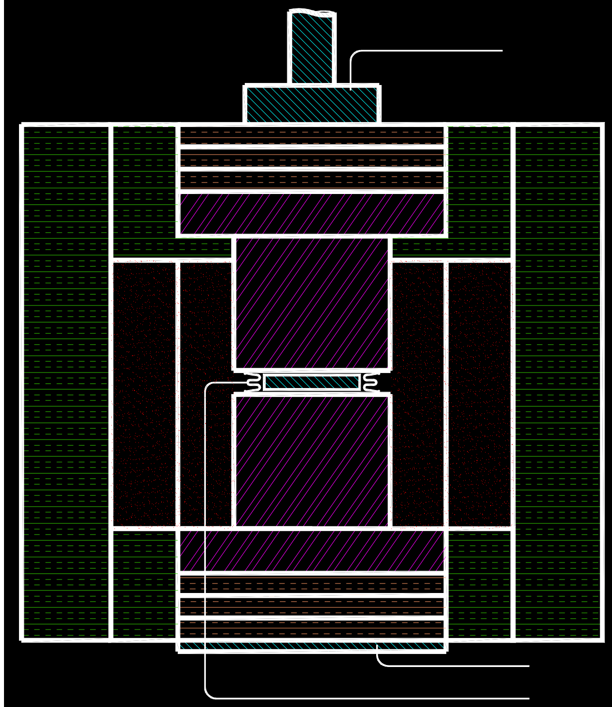
Advanced

Performance Requirements

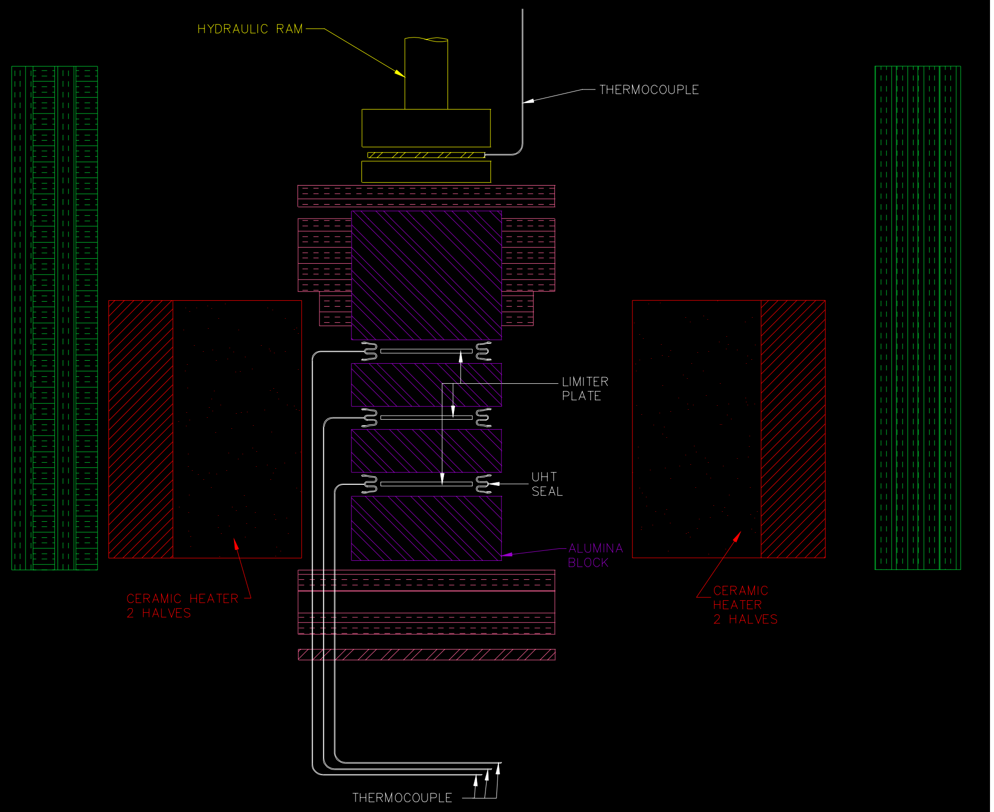
- Room Temperature through 1800 °F continuous test temperature
  - Test Stand has demonstrated operation at 2200 °F
- PLC controls with built in safety mechanisms
- Multiple thermocouple locations for accurate seal temperature monitoring
- Capable of extended test duration's to examine long term seal performance

UHT Seal Test Rig

Advanced



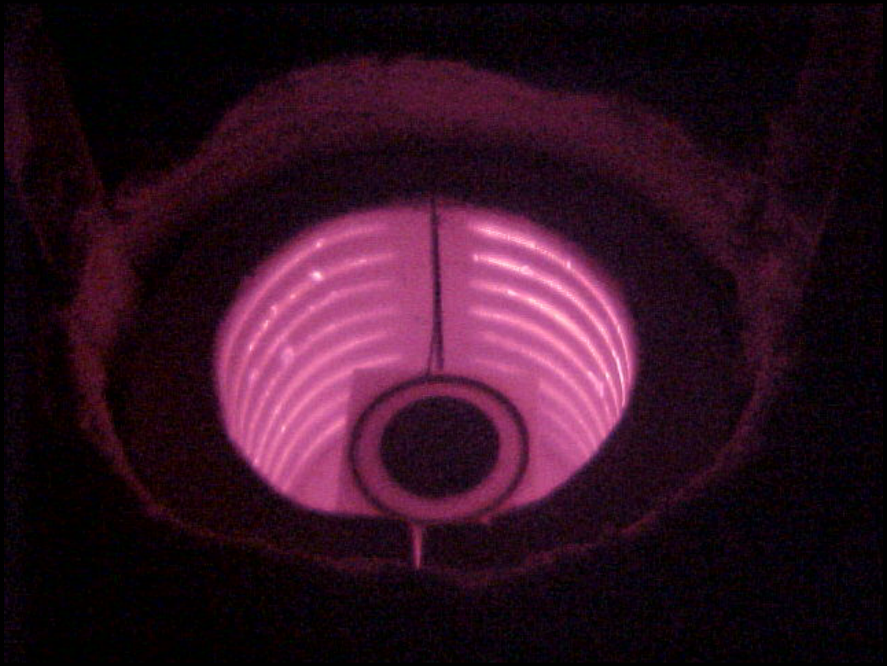
Compact View

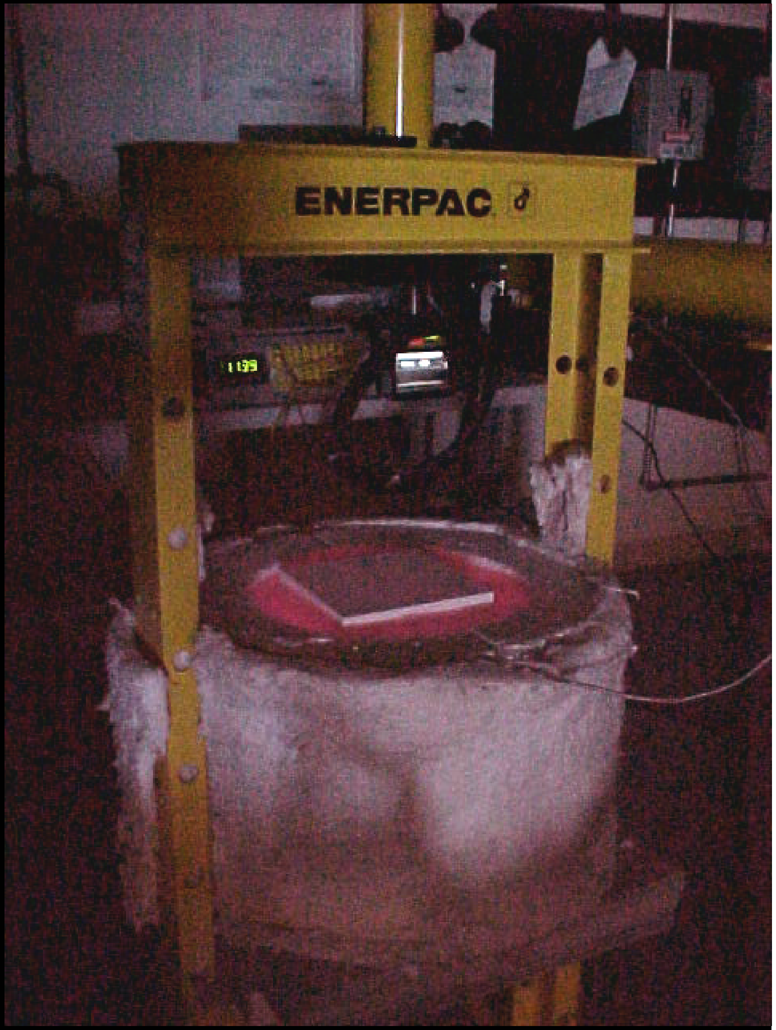


Exploded View

UHT Seal Test Stand

Advanced

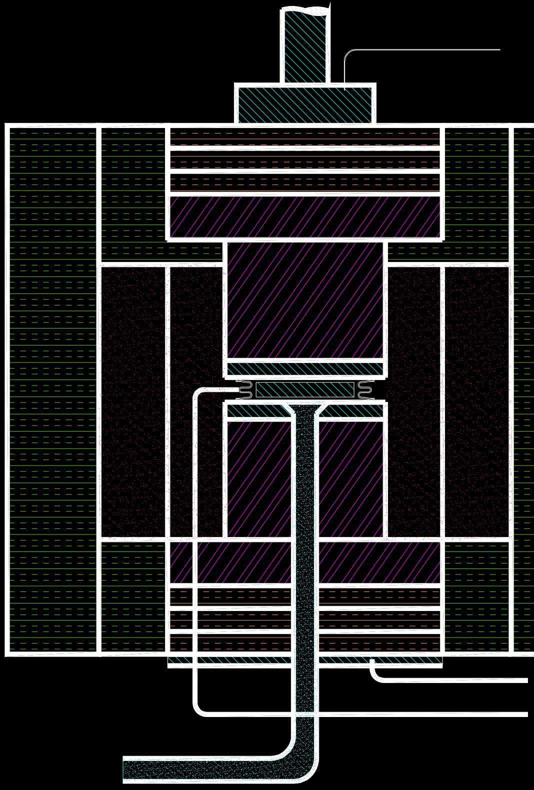


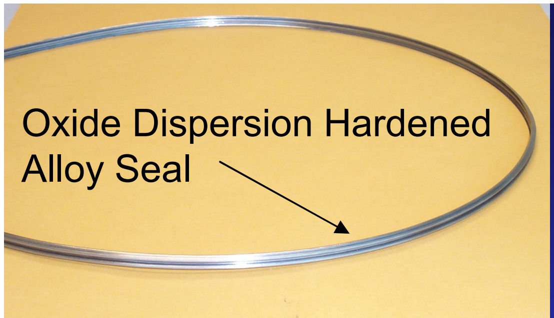


Advanced

UHT Seal Test Rig
Future Modifications

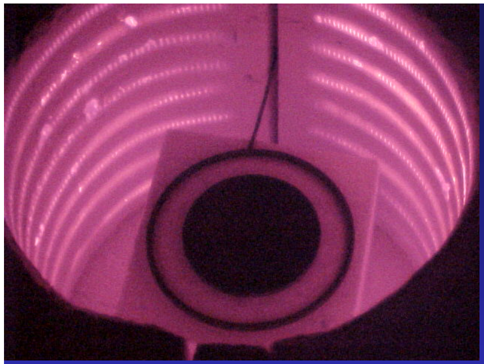
- Seal leak testing at temperature
  - Rig will be modified to determine leakage
  - Metallic plates will be used a seal seat
  - Mass flow meters will be used to measure leakage
- Flange movement to simulate engine cyclic motions or vibrations
  - For a potential program with an engine OEM





UHT Seal Design

- Seal cross section designed to minimize stress levels
- Seals from the following materials have been manufactured and tested in UHT test stand
  - Waspaloy - Baseline
  - Precipitation hardenable alloy with a higher precipitation temperature than Waspaloy
  - Solid solution hardened alloy
  - Oxide Dispersion Hardened Alloy(1800 ^{o}F)
  - Composite superalloy
- Thermomechanically processed material to enhance mechanical properties



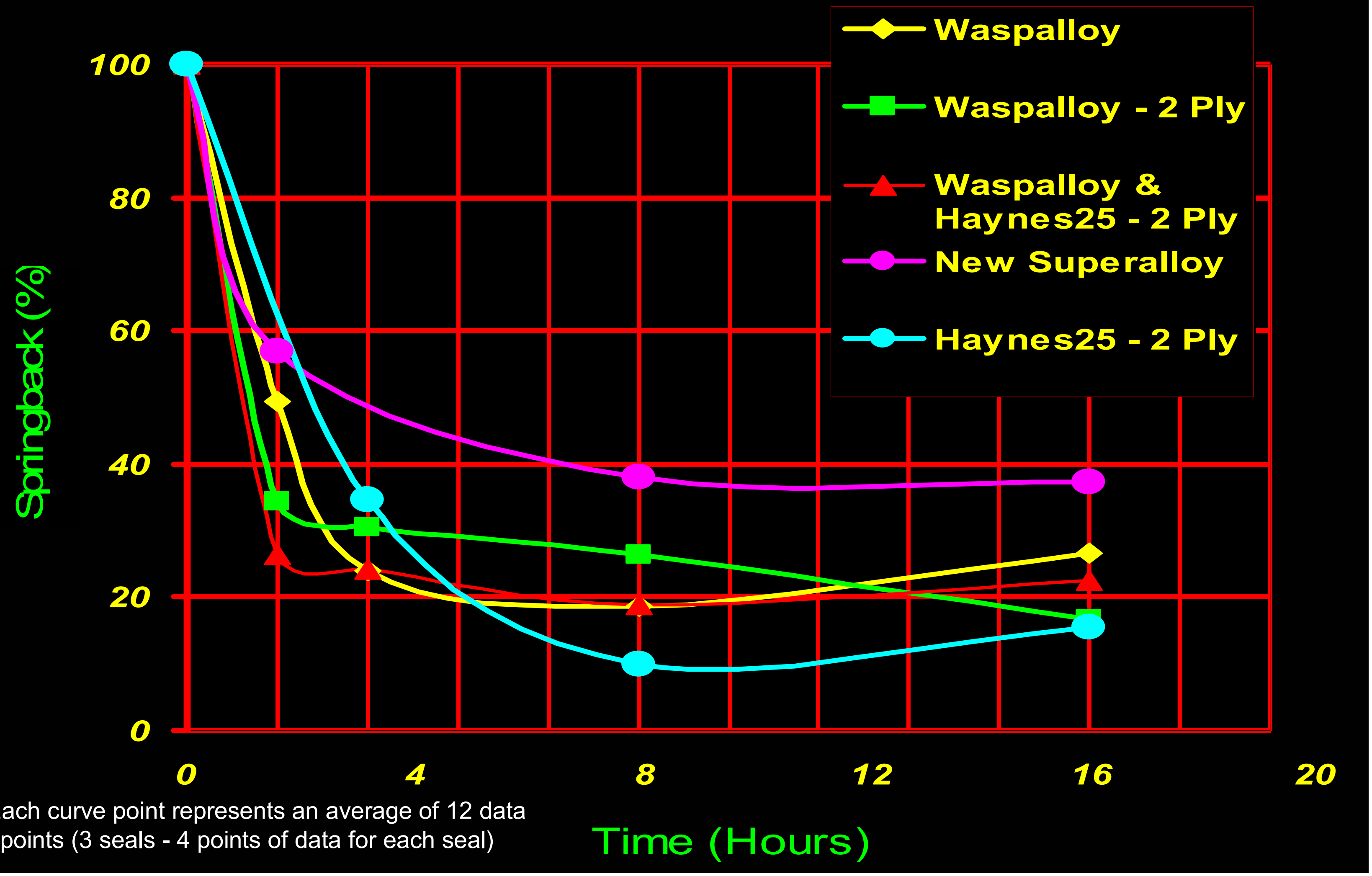
Advanced

UHT Seal Testing

- Seal testing procedure
  - – A standard seal cross section has been selected for testing to maintain constant strain levels
  - – Measure seal free height prior to test
    - All seals are manufactured to the same nominal free height dimensions
  - – Compress seal 15% in UHT test stand
  - – Hold at temperature for a controlled time
  - – Cool and measure seal height
  - – Calculate percent loss in seal free height
  - – Calculate usable springback after long term high temperature exposure

Seal Springback vs. Time
at 1600 °F

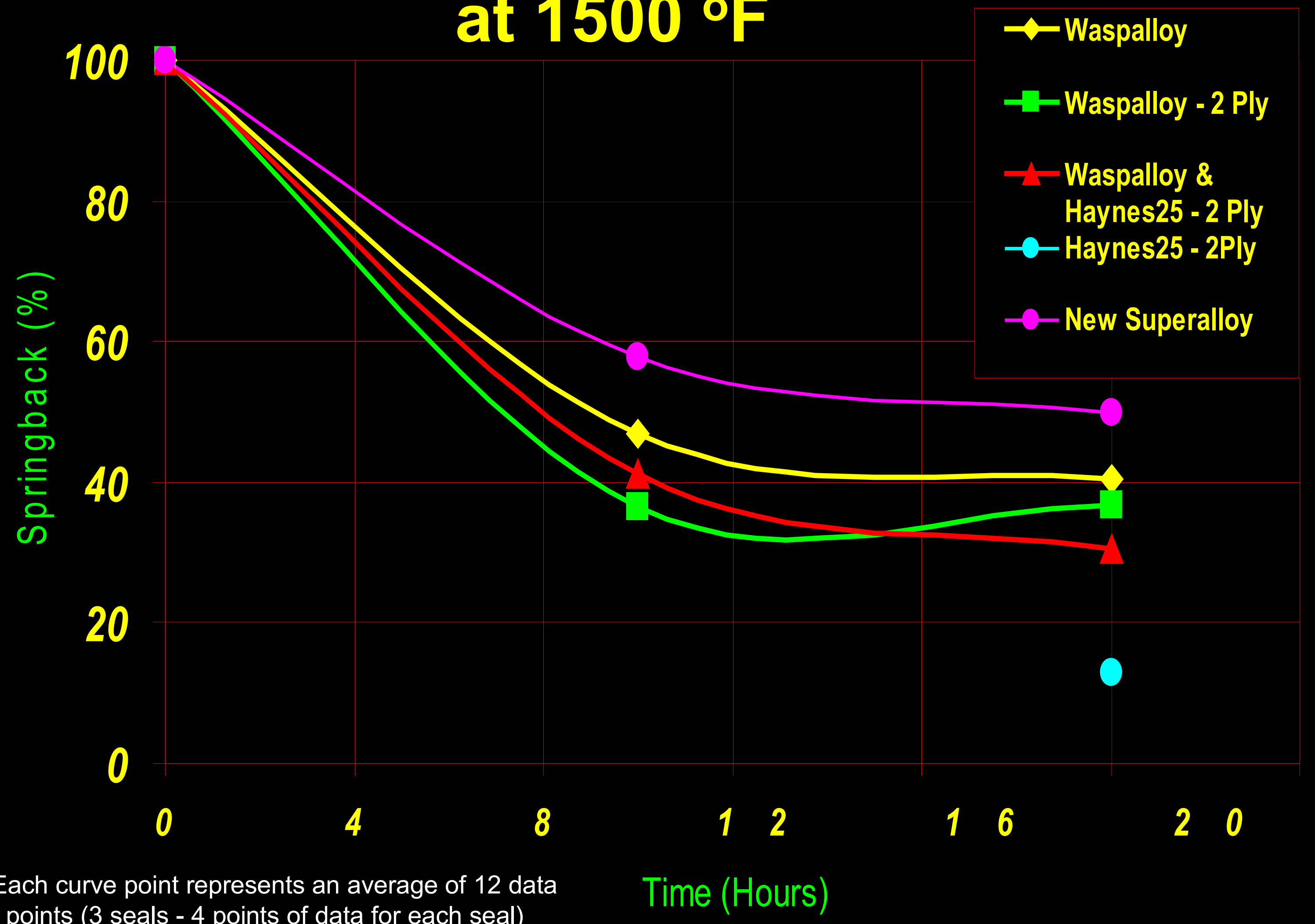
Advanced



* Each curve point represents an average of 12 data points (3 seals - 4 points of data for each seal)

Advanced

Seal Springback vs. Time at 1500 °F



* Each curve point represents an average of 12 data points (3 seals - 4 points of data for each seal)

Advanced

Summary

- UHT test rig is being used extensively to demonstrate the performance of seals at Ultra High Temperature conditions
- UHT Seal testing has been successful in demonstrating the performance of seals produced from new alloys in UHT conditions
- Several materials have demonstrated superior characteristics when compared with traditional high temperature seal materials
- Focus is now shifting from 1400 - 1600 °F temperature range to 1600 - 1800 °F
- Efforts have been initiated for sealing materials at 1800 - 2200 °F

Hexoloy® SiC COMPONENTS

Dean P. Owens
Saint-Gobain Advanced Ceramics
Niagara Falls, New York

Silicon Carbide is a unique ceramic material which has come to dominate the world wide mechanical seal market. A brief description of material properties, additional applications and alternate materials will be discussed.

Hexoloy®
SiC Components

Advanced Ceramics
Niagara Falls, New York

SAINT-GOBAIN
ADVANCED CERAMICS

Hexoloy® is a registered trademark of Saint-Gobain Advanced Ceramics, Niagara Falls, New York.

Hexoloy® Silicon Carbide

SAINT-GOBAIN
ADVANCED CERAMICS

Hexoloy® is a sintered silicon carbide ceramic product of Saint-Gobain Advanced Ceramics and its Structural Ceramics Division.

www.carbo.com

Mechanical Seals

SAINT-GOBAIN
ADVANCED CERAMICS

The first and still the largest application for Hexoloy® silicon carbide is in mechanical seals where erosion and corrosion resistance are required for severe service environments.

www.carbo.com

Bearings

SAINT-GOBAIN
ADVANCED CERAMICS

The bearing industry
— with tight tolerances achieved by diamond grinding
— utilizes Hexoloy® products

www.carbo.com

Automotive Water Pump Seals

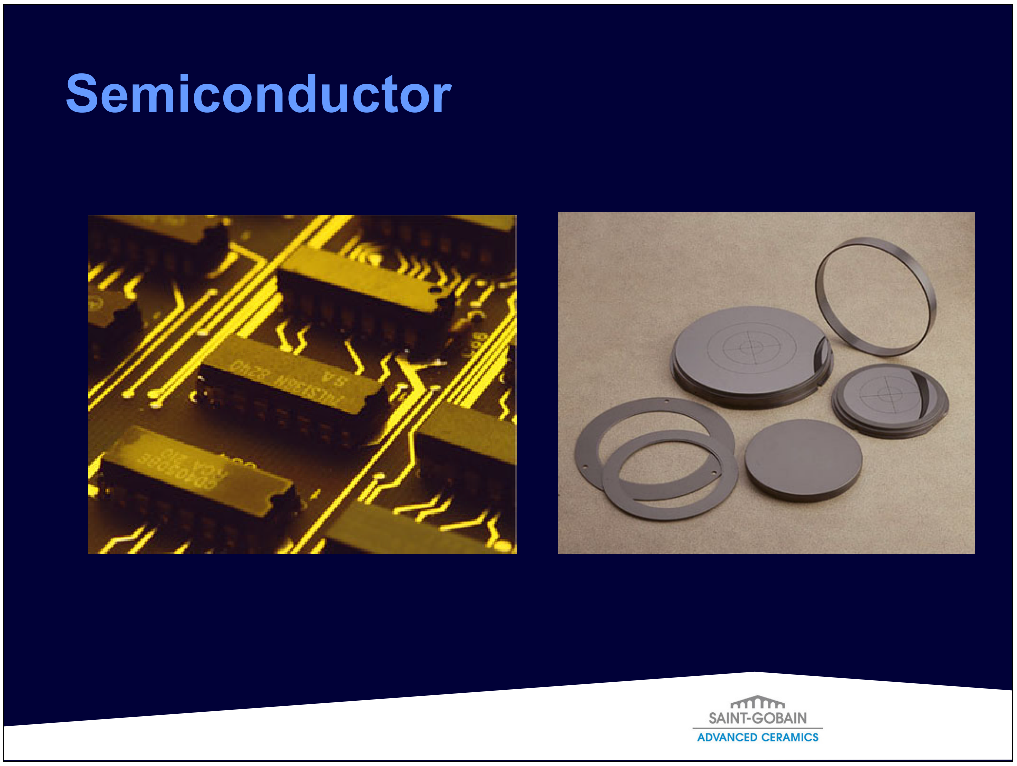
SAINT-GOBAIN
ADVANCED CERAMICS

Nearly every new vehicle in Europe and North America uses a Hexoloy® seal face in its water pump.

Mining

SAINT-GOBAIN
ADVANCED CERAMICS

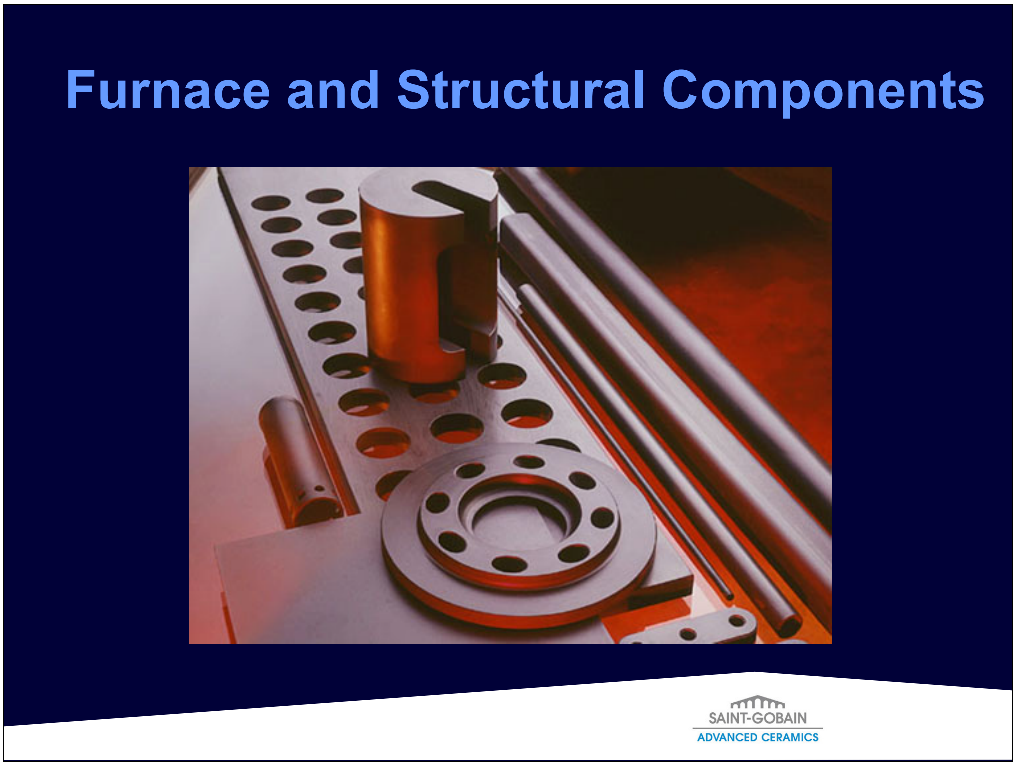
The most severe mining applications use Hexoloy® SiC in liners and valves.



Semiconductor

SAINT-GOBAIN
ADVANCED CERAMICS

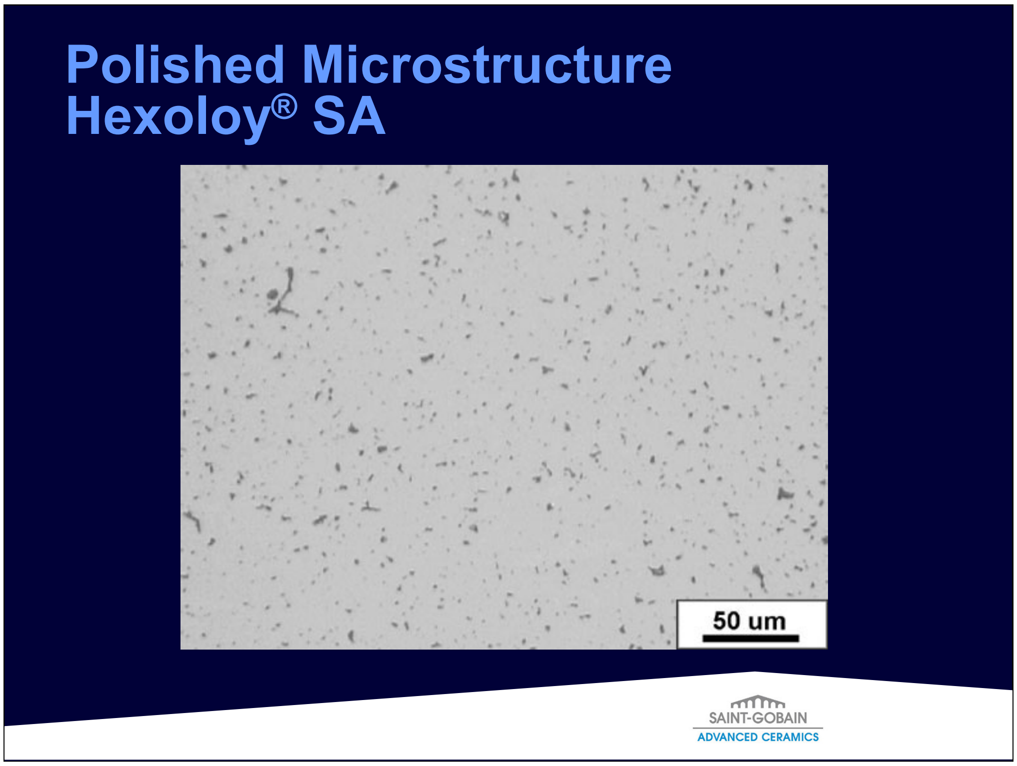
Hexoloy® SiC offers the chemical resistance and mechanical stiffness features desirable for wafer processing.



Furnace and Structural Components

SAINT-GOBAIN
ADVANCED CERAMICS

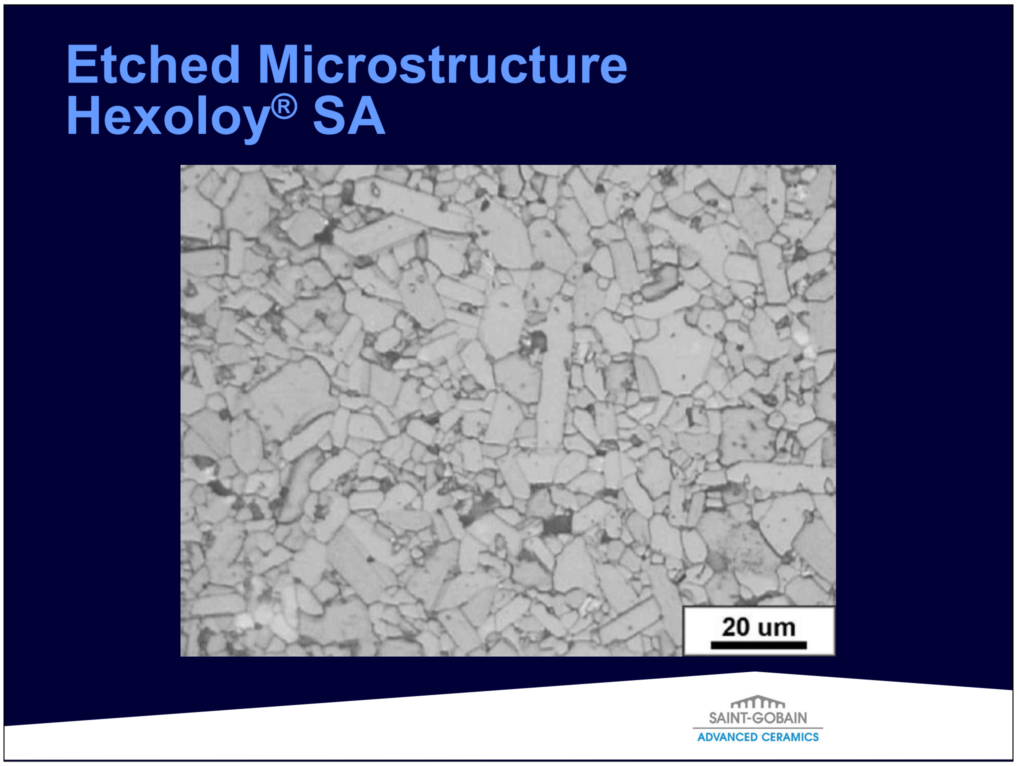
High temperature strength and oxidation resistance make Hexoloy® SiC and ideal candidate for furnace applications.



Polished Microstructure Hexoloy® SA

SAINT-GOBAIN
ADVANCED CERAMICS

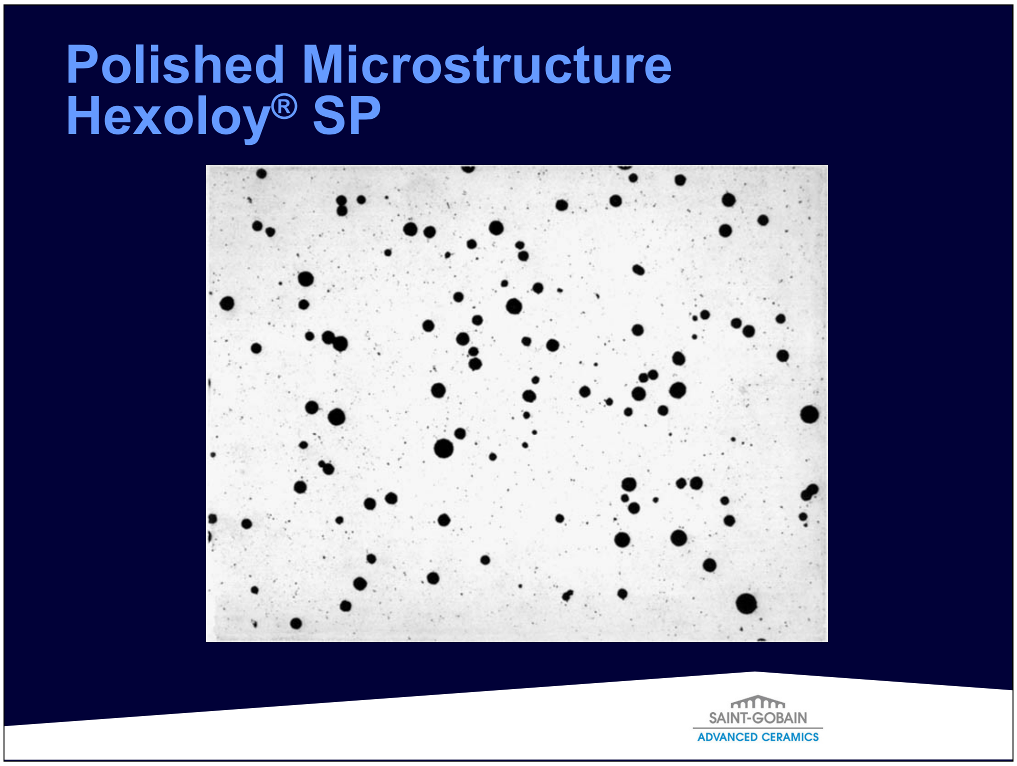
Photomicrograph of polished surface showing approximately 2-3% closed porosity



Etched Microstructure Hexoloy® SA

SAINT-GOBAIN
ADVANCED CERAMICS

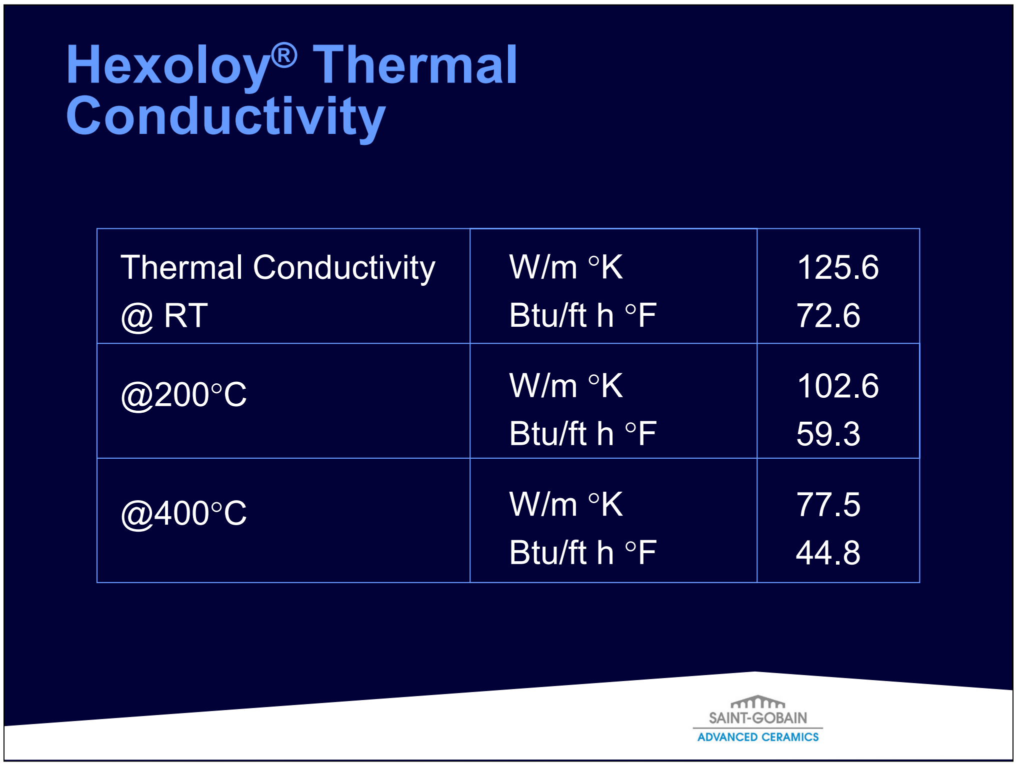
Photomicrograph of etched surface showing
self-sintered grain structure with
average grain size 4-10 microns and
no secondary phase,
which might be susceptible to erosion and corrosion.
Historical seal face tungsten carbide
has Co bond and alumina glass phase holding grains together



Polished Microstructure Hexoloy® SP

SAINT-GOBAIN
ADVANCED CERAMICS

Photomicrograph of polished surface showing induced spherical porosity at average size >40 microns.



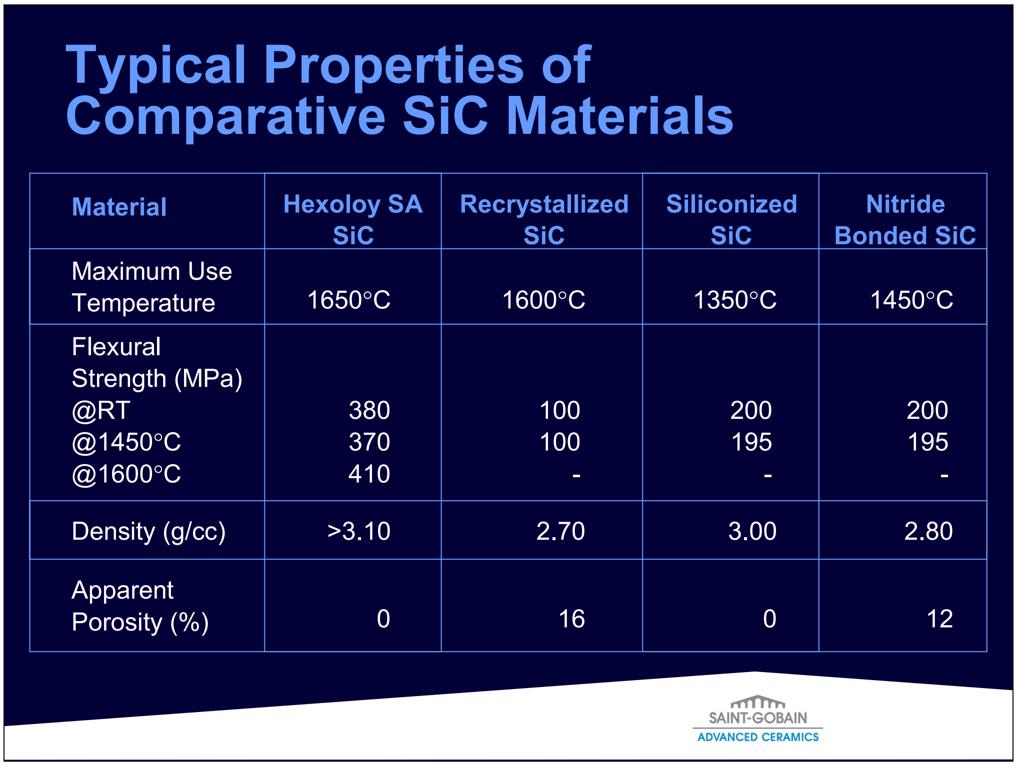
Hexoloy® Thermal Conductivity

Thermal Conductivity @ RT	W/m °K Btu/ft h °F	125.6 72.6
@200°C	W/m °K Btu/ft h °F	102.6 59.3
@400°C	W/m °K Btu/ft h °F	77.5 44.8

SAINT-GOBAIN
ADVANCED CERAMICS

Lower density and higher thermal conductivity give Hexoloy® SiC advantages over other seal face candidates such as tungsten carbide and alumina.

Thermal Conductivity @ RT	W/m °K Btu/ft h °F	125.6 72.6
@200°C	W/m °K Btu/ft h °F	102.6 59.3
@400°C	W/m °K Btu/ft h °F	77.5 44.8



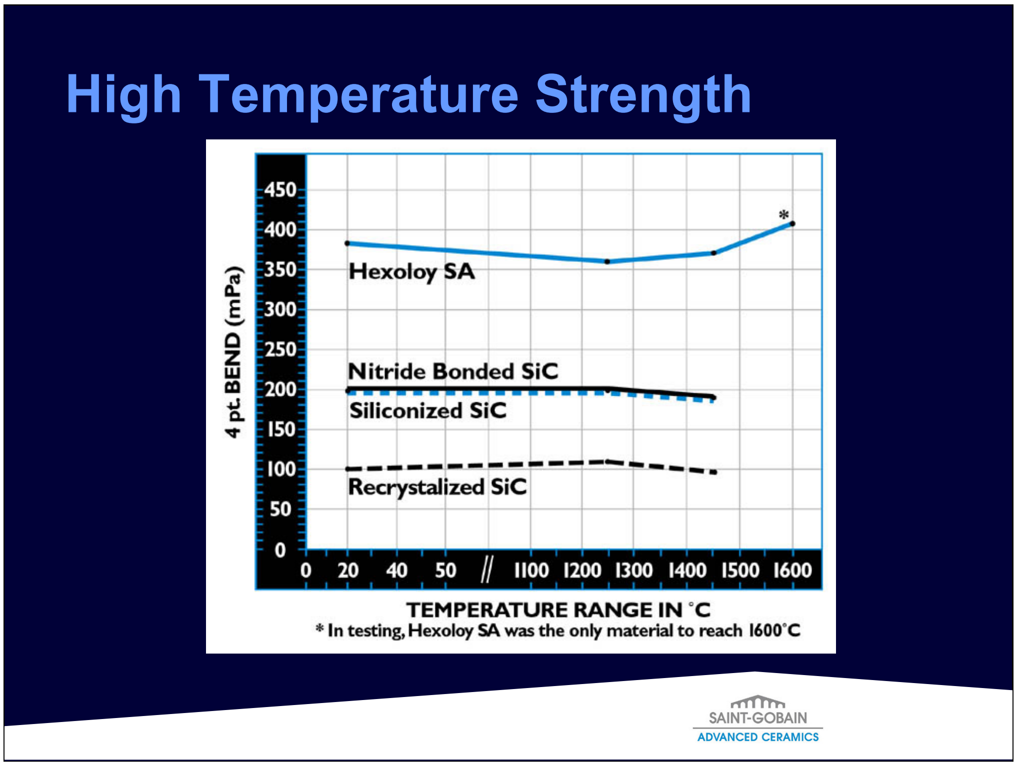
Typical Properties of Comparative SiC Materials

Material	Hexoloy SA SiC	Recrystallized SiC	Siliconized SiC	Nitride Bonded SiC
Maximum Use Temperature	1650°C	1600°C	1350°C	1450°C
Flexural Strength (MPa) @RT @1450°C @1600°C	 380 370 410	 100 100 -	 200 195 -	 200 195 -
Density (g/cc)	>3.10	2.70	3.00	2.80
Apparent Porosity (%)	0	16	0	12

SAINT-GOBAIN
ADVANCED CERAMICS

- **Siliconized SiC was a popular seal material choice but continuous Si metal phase resulted in erosion/corrosion issues**
- **Nitride bonded SiC offers outstanding wear resistance**
- **Recrystallized SiC's purity is important in the semiconductor industry**

Material	Hexoloy SA SiC	Recrystallized SiC	Siliconized SiC	Nitride Bonded SiC
Maximum Use Temperature	1650°C	1600°C	1350°C	1450°C
Flexural Strength (MPa) @RT @1450°C @1600°C	 380 370 410	 100 100 -	 200 195 -	 200 195 -
Density (g/cc)	>3.10	2.70	3.00	2.80
Apparent Porosity (%)	0	16	0	12

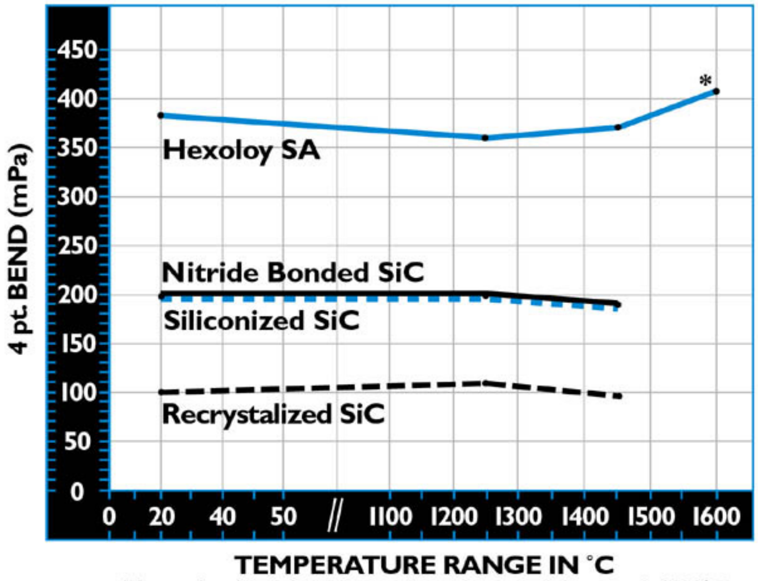


High Temperature Strength

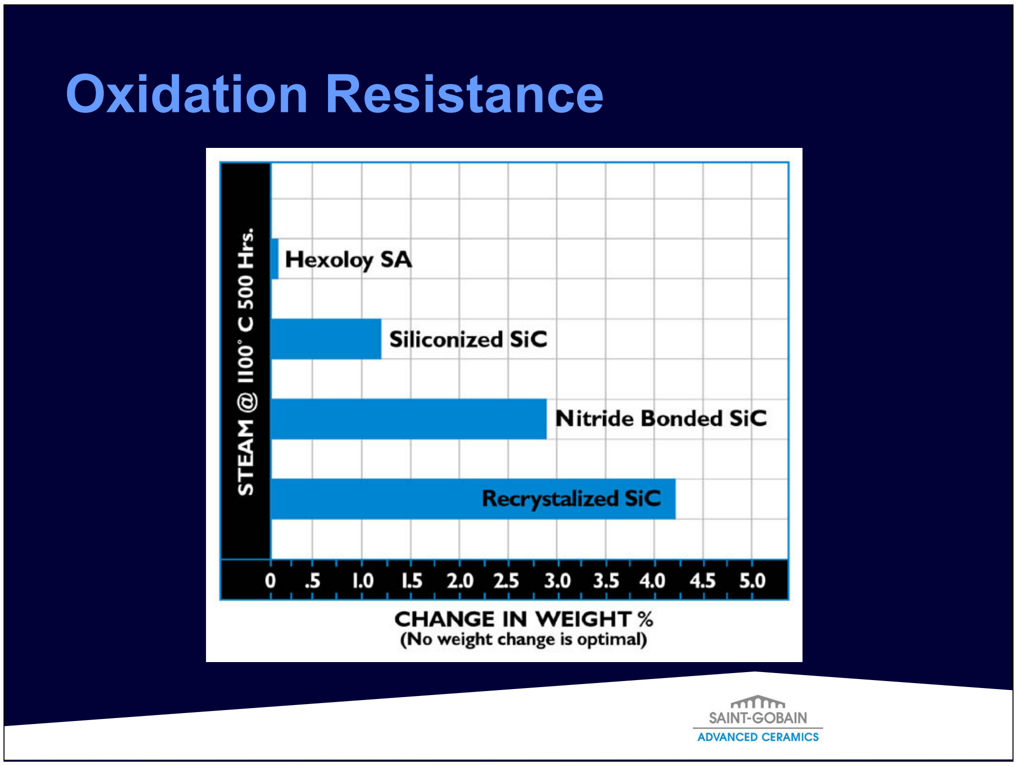
* In testing, Hexoloy SA was the only material to reach 1600°C

SAINT-GOBAIN
ADVANCED CERAMICS

Hexoloy® SA SiC exhibits dramatic strength advantage over alternate SiC materials with no drop off at elevated temps.



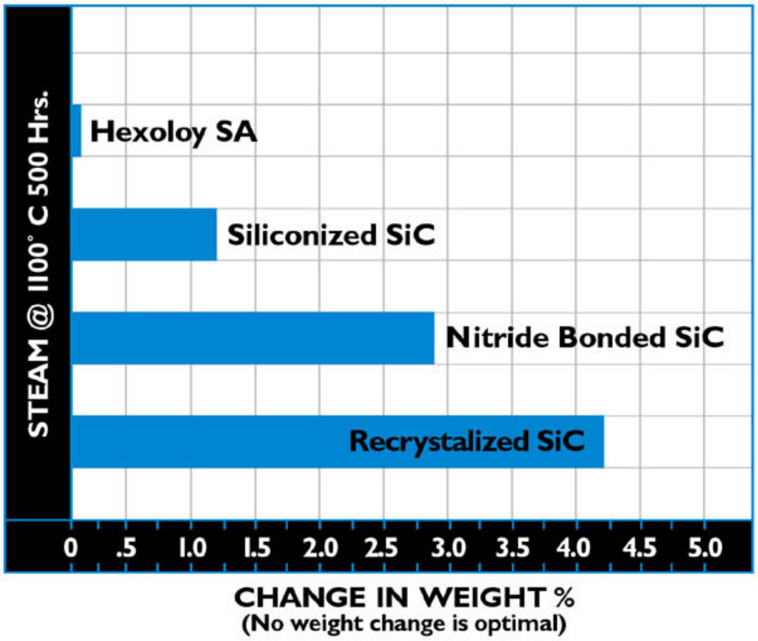
* In testing, Hexoloy SA was the only material to reach 1600°C

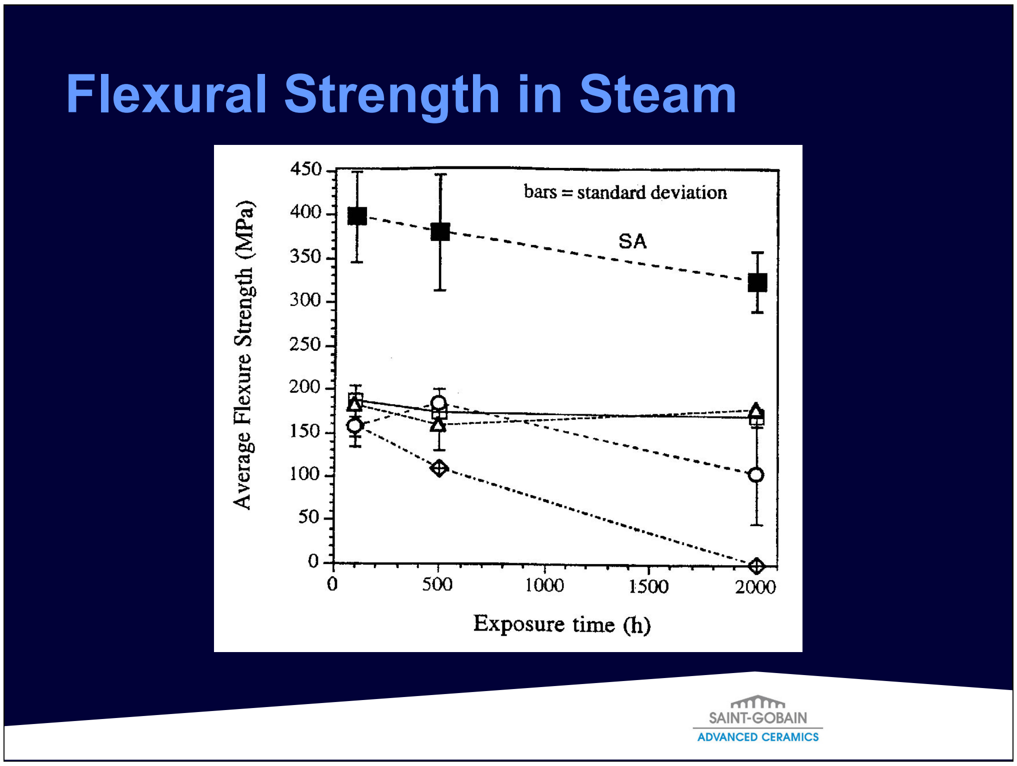


Oxidation Resistance

SAINT-GOBAIN
ADVANCED CERAMICS

Hexoloy® SA shows negligible weight and dimensional change in oxidizing atmospheres.

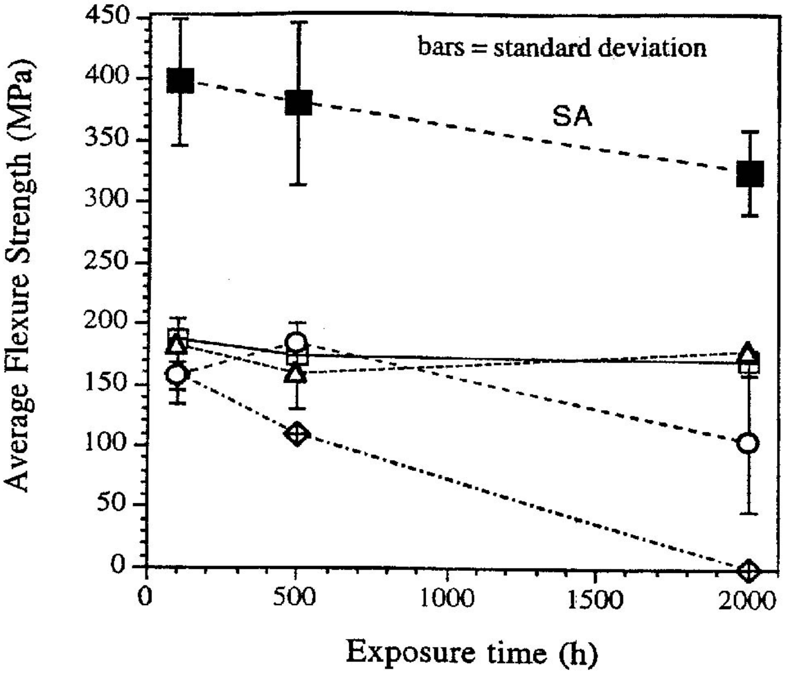




Flexural Strength in Steam

SAINT-GOBAIN
ADVANCED CERAMICS

Testing at Oak Ridge National lab at 1260°C and 50% water shows significant strength advantage maintained over other ceramic materials.



Hexoloy® SiC

Cost-effective solutions
for a wide range
of applications
in a variety of shapes

SAINT-GOBAIN
ADVANCED CERAMICS

Hexoloy® SiC

Cost-effective solutions
for a wide range of applications
in a variety of shapes

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
September 2003

3. REPORT TYPE AND DATES COVERED
Conference Publication

4. TITLE AND SUBTITLE
2002 NASA Seal/Secondary Air System Workshop

5. FUNDING NUMBERS
WBS–22–708–87–06
WBS–22–713–82–31

6. AUTHOR(S)
Bruce M. Steinetz and Robert C. Hendricks, editors

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–13997–1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CP—2003-212458-VOL1

11. SUPPLEMENTARY NOTES

Proceedings of a conference held at Ohio Aerospace Institute sponsored by NASA Glenn Research Center, Cleveland, Ohio, October 23–24, 2002. Responsible person, Bruce M. Steinetz, organization code 5950, 216–433–3302. The Propulsion and Power Program and Space Technology Project Office at NASA Glenn Research Center cosponsored this work.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Categories: 37, 7, 20, and 27 Distribution: Nonstandard
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

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

The 2002 NASA Seal/Secondary Air System Workshop covered the following topics: (i) Overview of NASA's perspective of aeronautics and space technology for the 21st century; (ii) Overview of the NASA-sponsored Ultra-Efficient Engine Technology (UEET), Turbine-Based Combined-Cycle (TBCC), and Revolutionary Turbine Accelator (RTA) programs; (iii) Overview of NASA Glenn's seal program aimed at developing advanced seals for NASA's turbomachinery, space propulsion, and reentry vehicle needs; (iv) Reviews of sealing concepts, test results, experimental facilities, and numerical predictions; and (v) Reviews of material development programs relevant to advanced seals development. The NASA UEET and TBCC/RTA program overviews illustrated for the reader the importance of advanced technologies, including seals, in meeting future turbine engine system efficiency and emission goals. For example, 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
Seals; High temperature; Materials; Numerical code flow; Experimental; Design

15. NUMBER OF PAGES
351

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT