NASA/CP—2006-214383/VOL1

2005 NASA Seal/Secondary Air System Workshop

October 2006

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2005 NASA Seal/Secondary Air System Workshop

Proceedings of a conference held at Ohio Aerospace Institute
sponsored by NASA Glenn Research Center
Cleveland, Ohio
November 8–9, 2005

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

October 2006

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Executive Summary
Volume 1

The 2005 NASA Seal/Secondary Air System workshop covered the following topics: (i) Overview of NASA's new Exploration Initiative program aimed at exploring the Moon, Mars, and beyond; (ii) Overview of the NASA-sponsored Propulsion 21 project; (iii) Overview of NASA Glenn Research Center's seal project aimed at developing advanced seals for NASA's turbomachinery, space, and reentry vehicle needs; (iv) Reviews of NASA prime contractor, vendor, and university advanced sealing concepts including tip clearance control, test results, experimental facilities, and numerical predictions; and (v) Reviews of material development programs relevant to advanced seals development.

NASA's Propulsion 21 project is developing advanced turbine engine technologies aimed at reducing fuel burn, emissions, and noise through a consortium of Ohio organizations. Development of advanced clearance control techniques is a subelement of the Propulsion 21 project. Turbine engine studies have shown that reducing high-pressure turbine (HPT) blade tip clearances will reduce fuel burn, lower emissions, retain exhaust gas temperature margin, and increase range. GE presented an approach for a fast-acting thermal active clearance control (ACC) system. NASA Glenn researchers presented efforts underway to develop new ACC kinematic systems, actuators, control methods, and sensors. Test results were shown for a new NASA Glenn active clearance control test rig used to evaluate a fast-acting ACC concept incorporating seals and control methods. Radatech presented an overview of their microwave blade tip sensor development efforts. Microwave tip sensors show promise of operation in the extreme gas temperatures (>2000 °F) present in the HPT location.

The workshop also covered several programs NASA is funding to develop technologies for the Exploration Initiative and advanced reusable space vehicle technologies. NASA plans on developing an advanced docking and berthing system that would permit any vehicle to dock to any on-orbit station or vehicle. Seal technical challenges (including space environments, temperature variation, and seal-on-seal operation) as well as plans to develop the necessary "androgynous" seal technologies were reviewed. Future reentry and other hypersonic vehicles pose a variety of challenges including high-temperature, resiliency at operating temperature to accommodate gap changes during operation, and durability to meet mission requirements. Researchers also reviewed tests completed for the shuttle main landing-gear door seals.

Contents

NASA'S EXPLORATION ARCHITECTURE

Timothy Tyburski
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio


A Bold Vision for Space Exploration
NASA
Complete the International Space Station
Safely fly the Space Shuttle until 2010
Develop and fly the Crew Exploration Vehicle no later than 2012
Return to the moon no later than 2020
Extend human presence across the solar system and beyond
Implement a sustained and affordable human and robotic program
Develop supporting innovative technologies, knowledge, and infrastructures
Promote international and commercial participation in exploration
"It is time for America to take the next steps.
Today I announce a new plan to explore space and extend a human presence across our solar system. We will begin the effort quickly, using existing programs and personnel. We'll make steady progress – one mission, one voyage, one landing at a time"
President George W. Bush – January 14, 2004

The Moon - the 1st Step to Mars and Beyond….

- **Gaining significant experience in operating away from Earth's environment**
  - Space will no longer be a destination visited briefly and tentatively
  - "Living off the land"
  - Field exploration techniques
  - Human support systems
  - Dust mitigation and planetary protection

- **Developing technologies needed for opening the space frontier**
  - Crew and cargo launch vehicles (125 metric ton class)
  - Earth entry system – Crew Exploration Vehicle
  - Mars ascent and descent propulsion systems (liquid oxygen / liquid methane)

- **Conduct fundamental science**
  - Astrobiology, historical geology, exobiology, astronomy, physics

Next Step in Fulfilling Our Destiny As Explorers

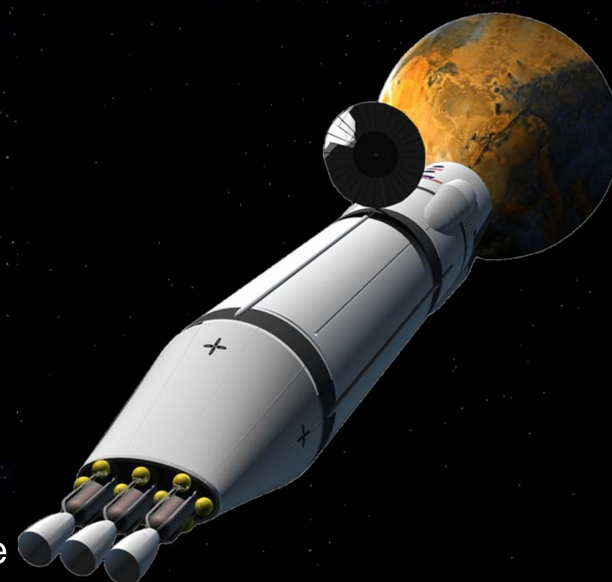
How We Will Get to Mars

- **4 – 5 assembly flights to low Earth orbit with a 100 metric ton class launch system**

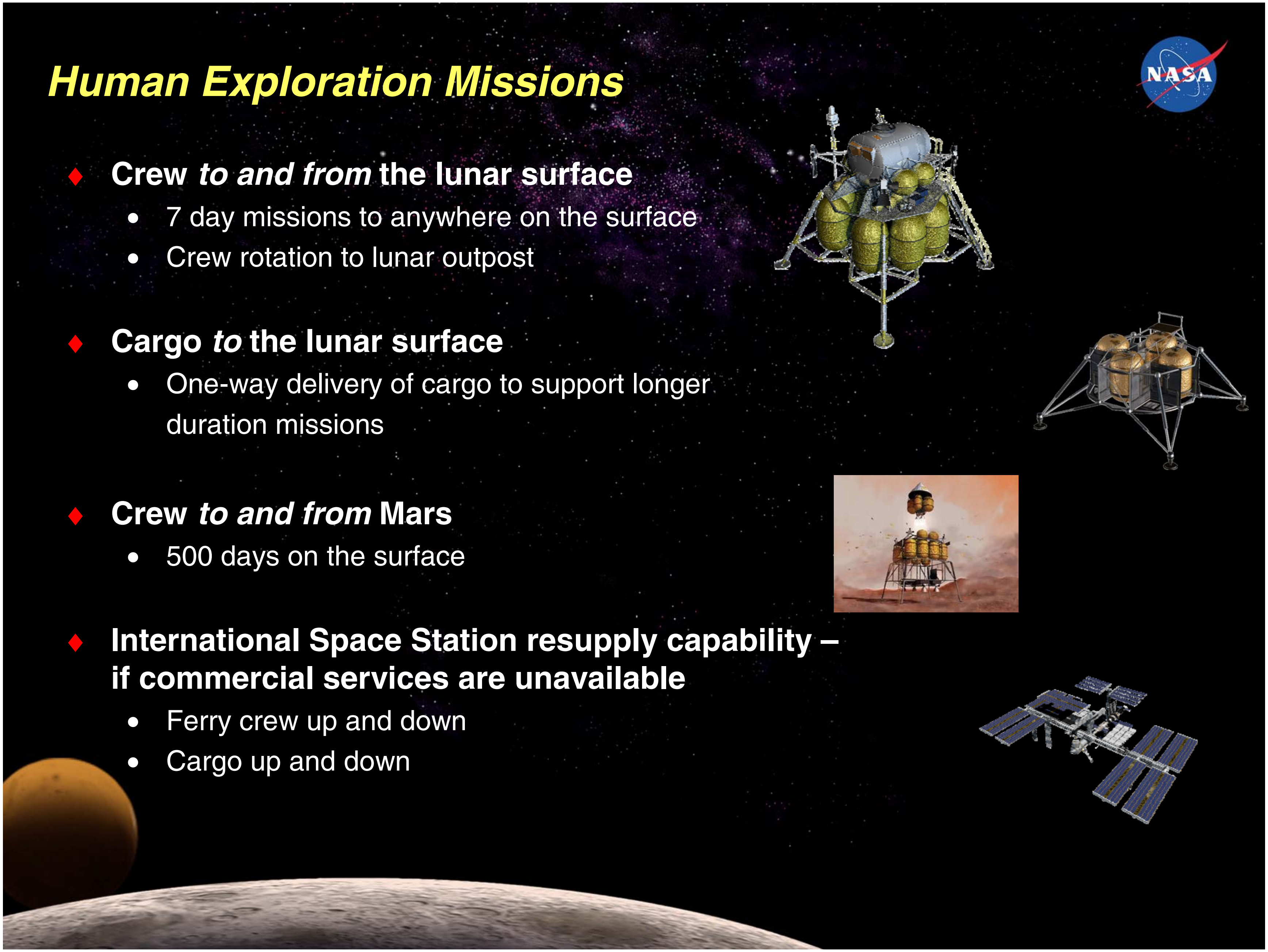
- **Pre-deployed Mars surface outpost before the crew launches**
  - Habitat and support systems
  - Power
  - Communications
  - Mars ascent / descent vehicle

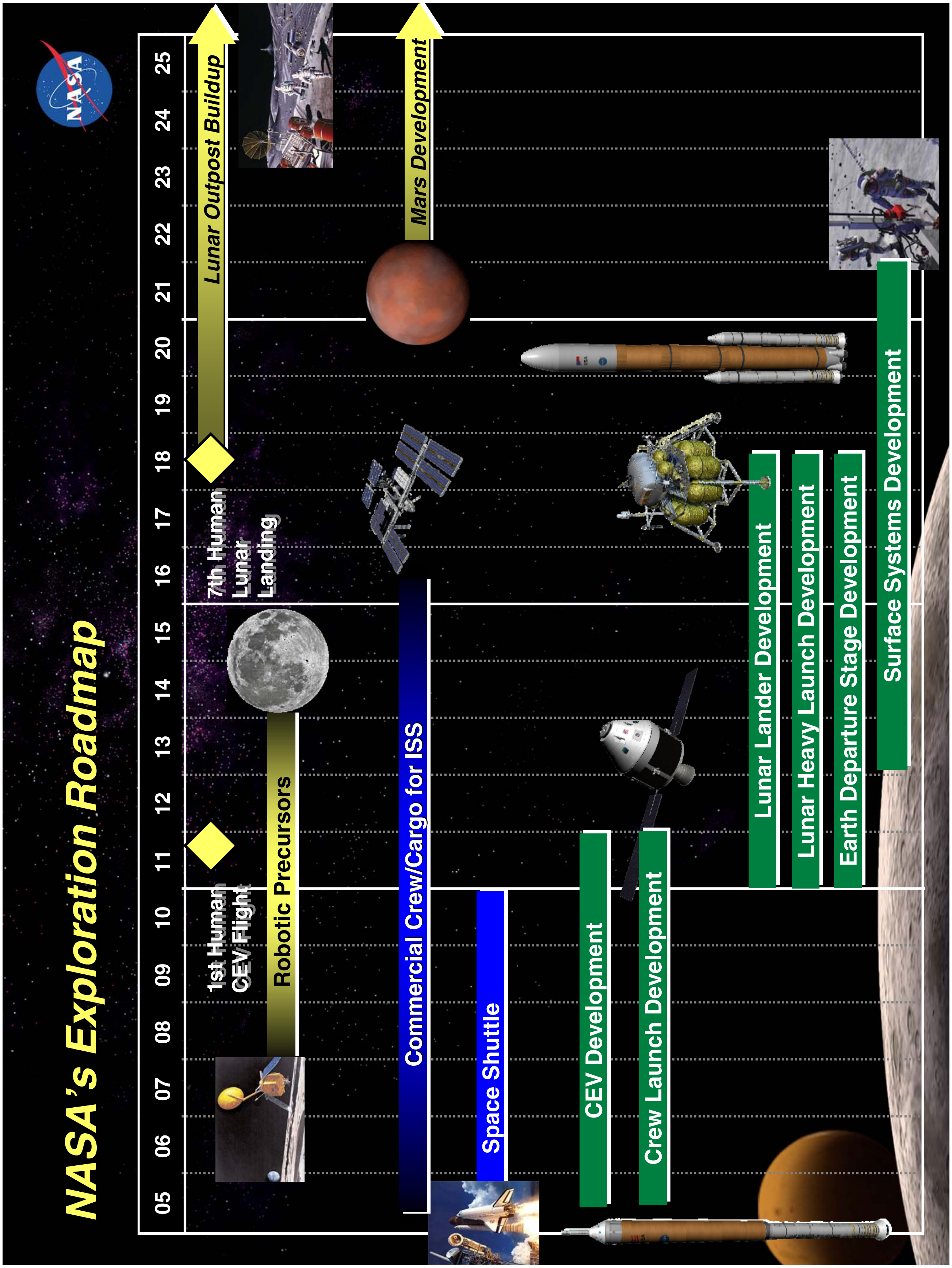
- **180 day transit time to/from Mars**
  - 6 crewmembers
  - Dedicated in-space crew transit vehicle
  - Dedicated Earth entry system (CEV)

- **500 days on the surface**
  - Capability to explore large regions of the surface
  - Multi-disciplinary science investigations
  - In-Situ resource utilization
    - Consumables: Oxygen and water
    - Propellants: Liquid oxygen and methane




A Safe, Accelerated, Affordable and Sustainable Approach
Meet all U.S. human spaceflight goals
U.S. system capable of servicing the International Space Station
Significant advancement over Apollo
Double the number of crew to lunar surface
Four times number of lunar surface crew-hours
Global lunar surface access with anytime return to the Earth
Enables a permanent human presence while preparing for Mars and beyond
Can make use of lunar resources
Significantly safer and more reliable
Minimum of two lunar missions per year
Provides a 125 metric ton launch vehicle for lunar and later Mars missions and beyond
Higher ascent crew safety than the Space Shuttle
1 in 2,000 (1 in 1,700 to 4,200) for the Crew Launch Vehicle
1 in 220 (1 in 160 to 310) for the Space Shuttle
Orderly transition of the Space Shuttle workforce
Requirements-driven technology program

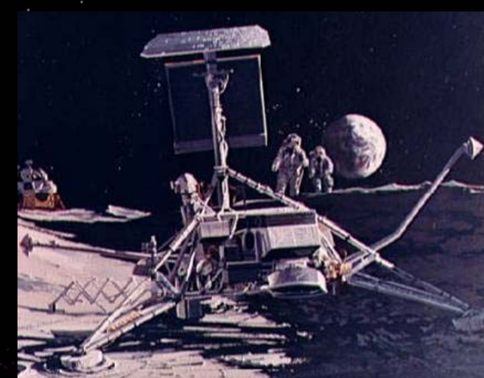

Human Exploration Missions
Crew to and from the lunar surface
7 day missions to anywhere on the surface
Crew rotation to lunar outpost
Cargo to the lunar surface
One-way delivery of cargo to support longer duration missions
Crew to and from Mars
500 days on the surface
International Space Station resupply capability – if commercial services are unavailable
Ferry crew up and down
Cargo up and down

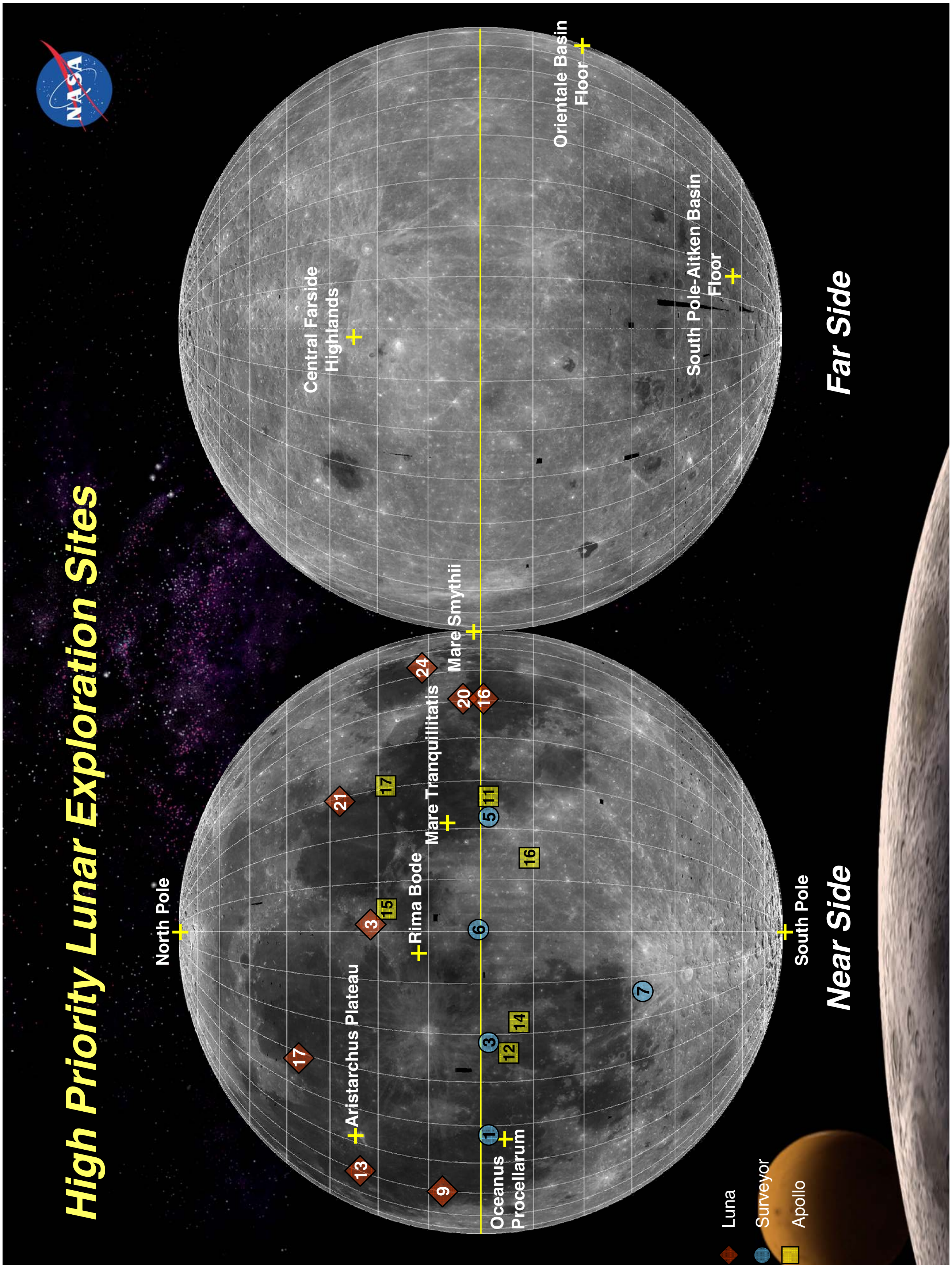


NASA's Exploration Roadmap
05
06
07
08
09
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
1st Human CEV Flight
7th Human Lunar Landing
Robotic Precursors
Lunar Outpost Buildup
Mars Development
Commercial Crew/Cargo for ISS
Space Shuttle
CEV Development
Crew Launch Development
Lunar Lander Development
Lunar Heavy Launch Development
Earth Departure Stage Development
Surface Systems Development

Paving the Way – Robotic Precursor Missions

- **Provide early information for human missions to the Moon**
  - Key knowledge needed for human safety and mission success
  - Infrastructure elements for eventual human benefit
  - Scientific results to guide human exploration
- **May be evolvable to later human systems**
- **Most unknowns are associated with the North and South Poles – a likely destination for a lunar outpost**
- **Key requirements involve establishment of**
  - Support infrastructure – navigation/communication, beacons
  - Knowledge of polar environment – temperatures, lighting, etc.
  - Polar deposits – composition and physical nature
  - Terrain and surface properties




High Priority Lunar Exploration Sites
North Pole
Aristarchus Plateau
Rima Bode
Mare Tranquillitatis
Mare Smythii
Oceanus Procellarum
South Pole
Near Side
Central Farside Highlands
South Pole-Aitken Basin Floor
Orientale Basin Floor
Far Side
Luna
Surveyor
Apollo
17
21
3
13
9
24
20
16
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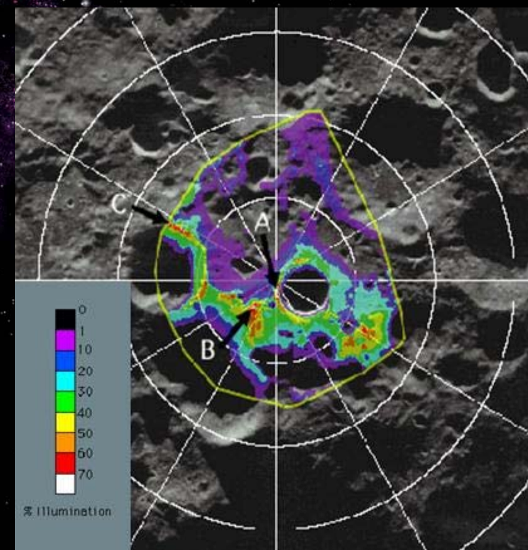
17
11

Possible South Pole Outpost

- The lunar South Pole is a likely candidate for outpost site
- Elevated quantities of hydrogen, possibly water ice (e.g., Shackelton Crater)
- Several areas with greater than 80% sunlight and less extreme temperatures
- Incremental deployment of systems – one mission at a time
  - Power system
  - Communications/navigation
  - Habitat
  - Rovers
  - Etc.

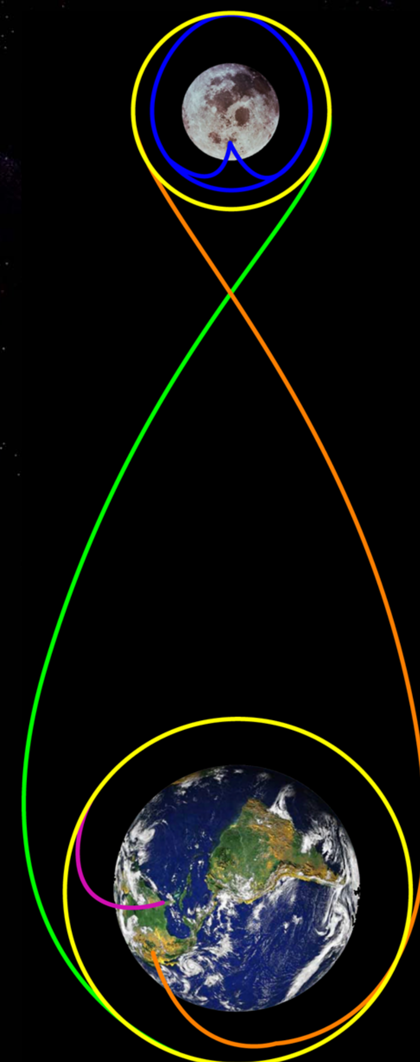



Lunar Surface Activities
Initial demonstration of human exploration beyond earth orbit
Learning how to operate away from the Earth
Conduct scientific investigations
Use the moon as a natural laboratory
Planetary formation/differentiation, impact cratering, volcanism
Understand the integrated effects of gravity, radiation, and the planetary environment on the human body
Conduct in-situ resource utilization (ISRU) demonstrations
Learning to "live off the land"
Excavation, transportation and processing of lunar resources
Begin to establish an outpost - one mission at a time
Enable longer term stays
Testing of operational techniques and demonstration of technologies needed for Mars and beyond…..

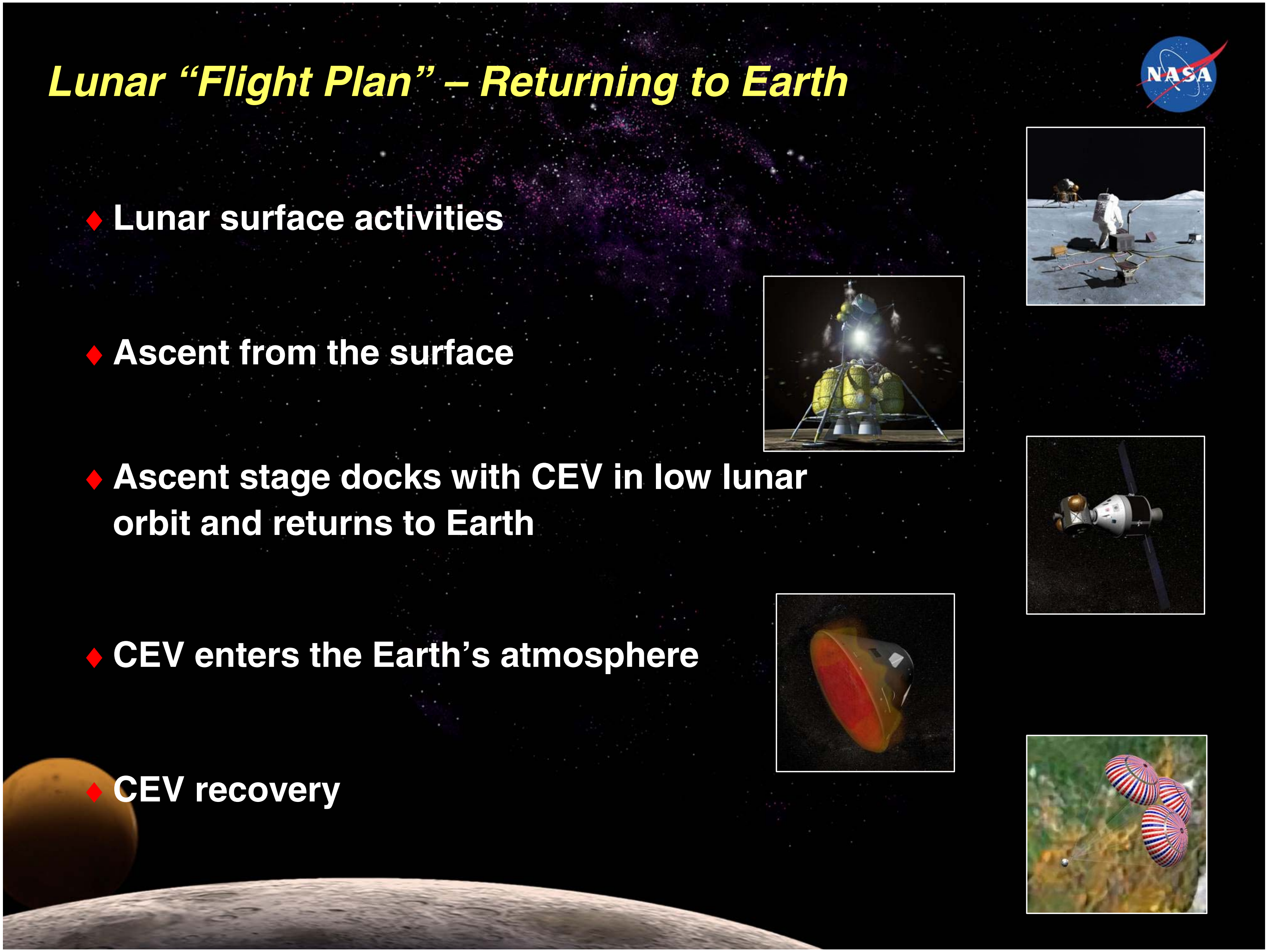
How We Plan to Return to the Moon

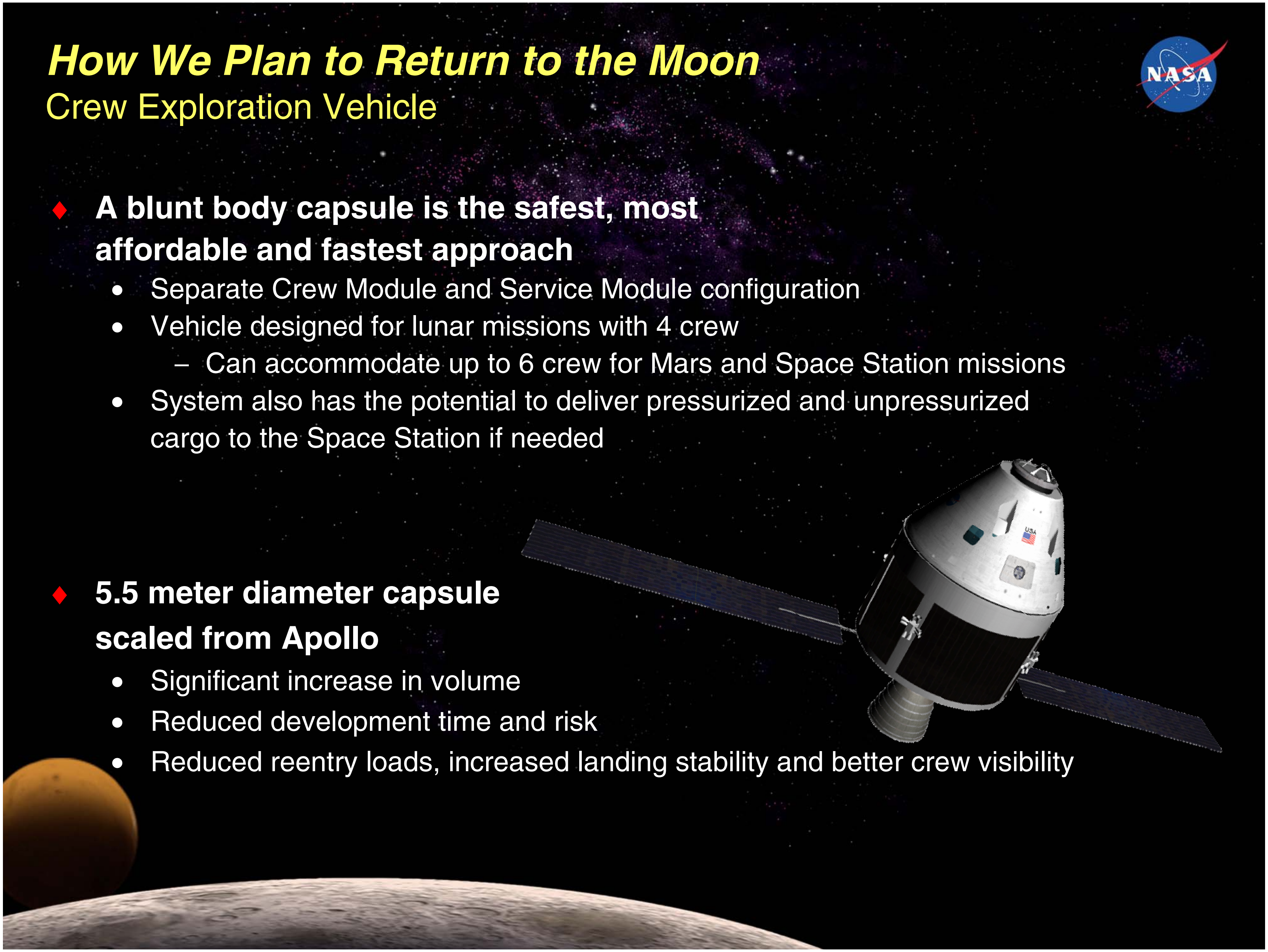
Mission Mode – “EOR-LOR”

- **After launch, the elements that take the crew to lunar orbit perform an “Earth Orbit Rendezvous (EOR)”**
- **At the completion of lunar surface activities the elements perform a “Lunar Orbit Rendezvous (LOR)” and return to Earth**
  - “Direct Return” eliminated because it increases crew system complexity, has small margins, has the greatest number of operations issues and highest sensitivity to mass growth
- **High efficiency cryogenic lander propulsion is an enabler**
- **The Crew Exploration Vehicle only *has to be* qualified for one launch system**
- **Mode has the highest calculated mission reliability and safety**



Lunar "Flight Plan" – Getting to the Moon
Heavy lift launch of the Earth departure stage and lander
Launch of the Crew Exploration Vehicle (CEV)
CEV docks with earth departure stage / lander in low Earth orbit
Transfer to the moon
CEV and lander arrive in low lunar orbit
Lunar landing


Lunar "Flight Plan" – Returning to Earth
Lunar surface activities
Ascent from the surface
Ascent stage docks with CEV in low lunar orbit and returns to Earth
CEV enters the Earth's atmosphere
CEV recovery


How We Plan to Return to the Moon
Crew Exploration Vehicle
A blunt body capsule is the safest, most affordable and fastest approach
Separate Crew Module and Service Module configuration
Vehicle designed for lunar missions with 4 crew
– Can accommodate up to 6 crew for Mars and Space Station missions
System also has the potential to deliver pressurized and unpressurized cargo to the Space Station if needed
5.5 meter diameter capsule scaled from Apollo
Significant increase in volume
Reduced development time and risk
Reduced reentry loads, increased landing stability and better crew visibility

Servicing the International Space Station

- NASA will invite industry to offer commercial crew and cargo delivery service to and from the Station
- The CEV will be designed for lunar missions

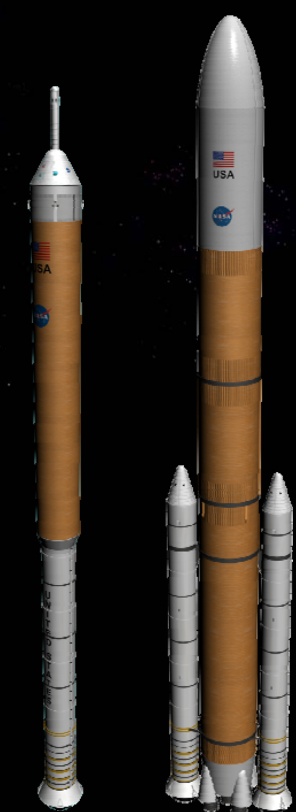
  but, if needed, can service the International Space Station. Annually, the CEV has the potential for:
  - 2 crew flights
  - 3 pressurized cargo flights
  - 1 unpressurized cargo flight

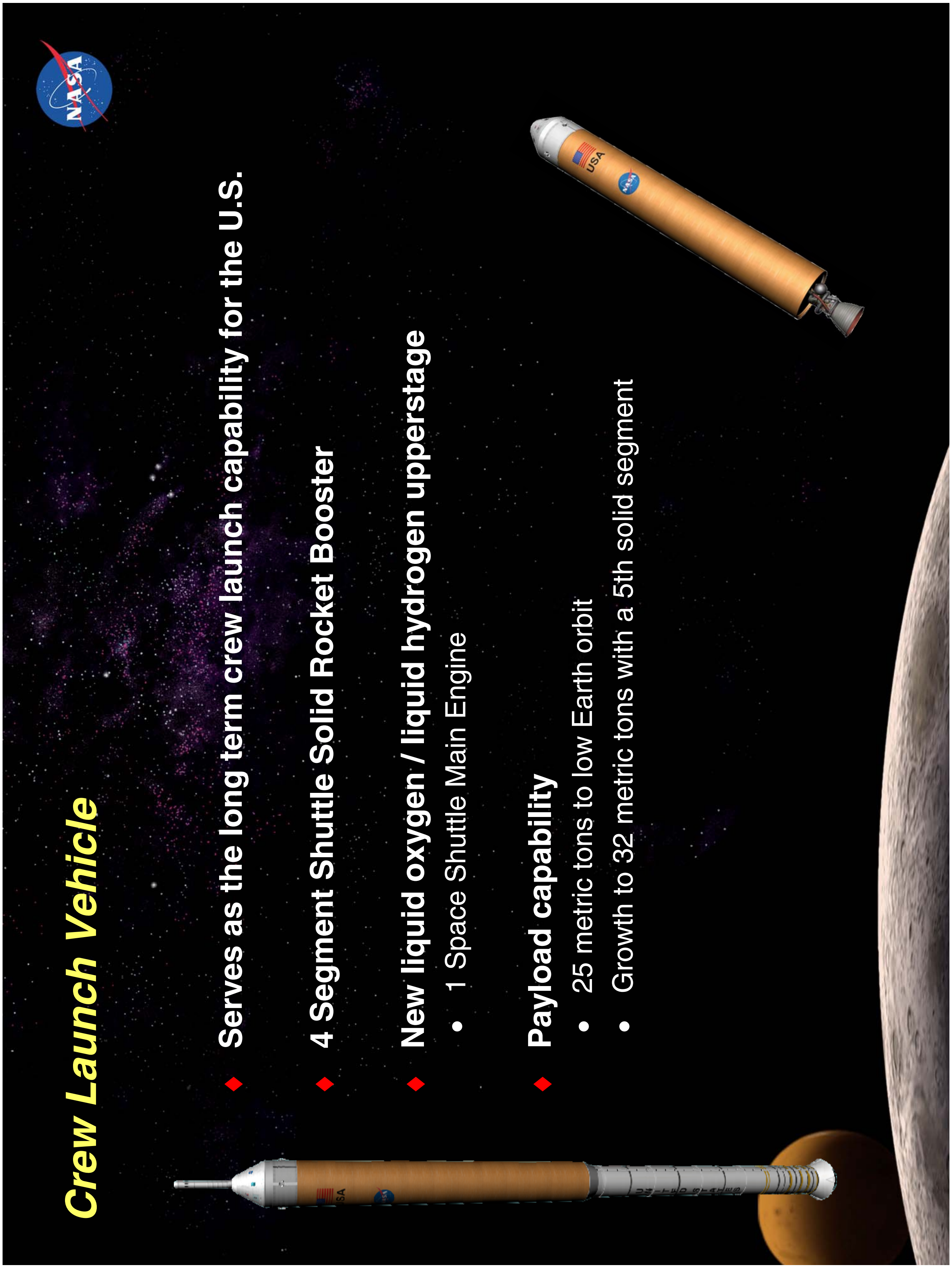
- The CEV will be able to transport crew to and from the station and stay for 6 months

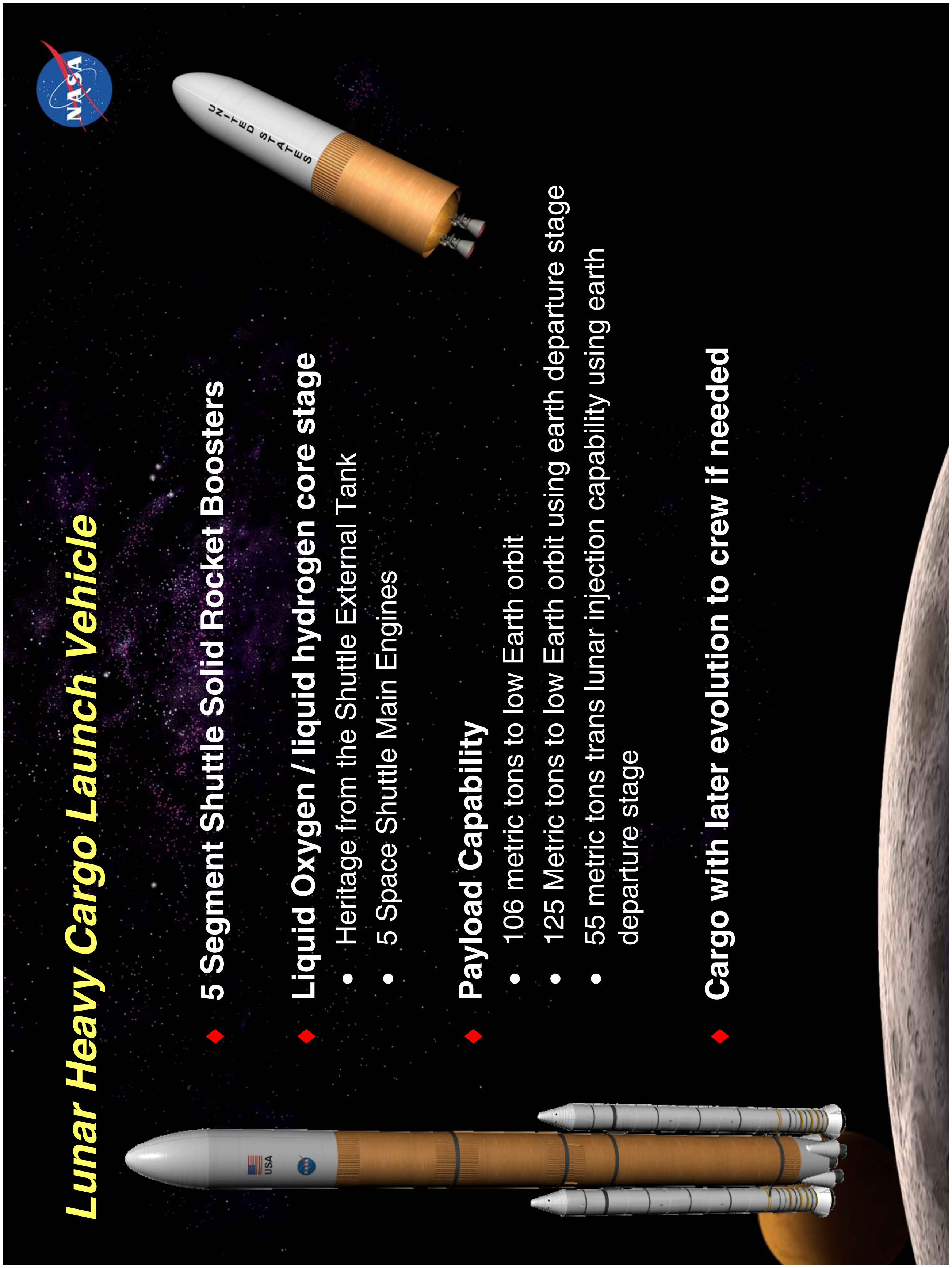
How We Plan to Return to the Moon

Launch Systems

- **Continue to rely on the EELV fleet for scientific and International Space Station cargo missions in the 5-20 metric ton range to the maximum extent possible.**
  - New, commercially-developed launch capabilities will be allowed to compete.
- **The *safest, most reliable, and most affordable* way to meet exploration launch requirements is a system derived from the current Shuttle solid rocket booster and liquid propulsion system.**
  - Capitalizes on human rated systems and 85% of existing facilities
  - The most straightforward growth path to later exploration super heavy launch needs.
  - Ensures national capability to produce solid propellant fuel at current levels.
- **125 metric ton lift capacity required to minimize on-orbit assembly and complexity – increasing mission success**
  - A clean-sheet-of-paper design incurs high expense and risk.
  - EELV-based designs require development of *two* core stages plus boosters - increasing cost and decreasing safety/reliability.
  - Current Shuttle lifts 100 metric tons to orbit on every launch.
    - – 20 metric tons is payload/cargo; remainder is Shuttle Orbiter.
    - – Evolution to exploration heavy lift is straightforward.
      - 125 metric ton capability
      - Lower production costs
      - Easier to human-rate if needed




Crew Launch Vehicle
Serves as the long term crew launch capability for the U.S.
4 Segment Shuttle Solid Rocket Booster
New liquid oxygen / liquid hydrogen upperstage
1 Space Shuttle Main Engine
Payload capability
25 metric tons to low Earth orbit
Growth to 32 metric tons with a 5th solid segment
USA
NASA

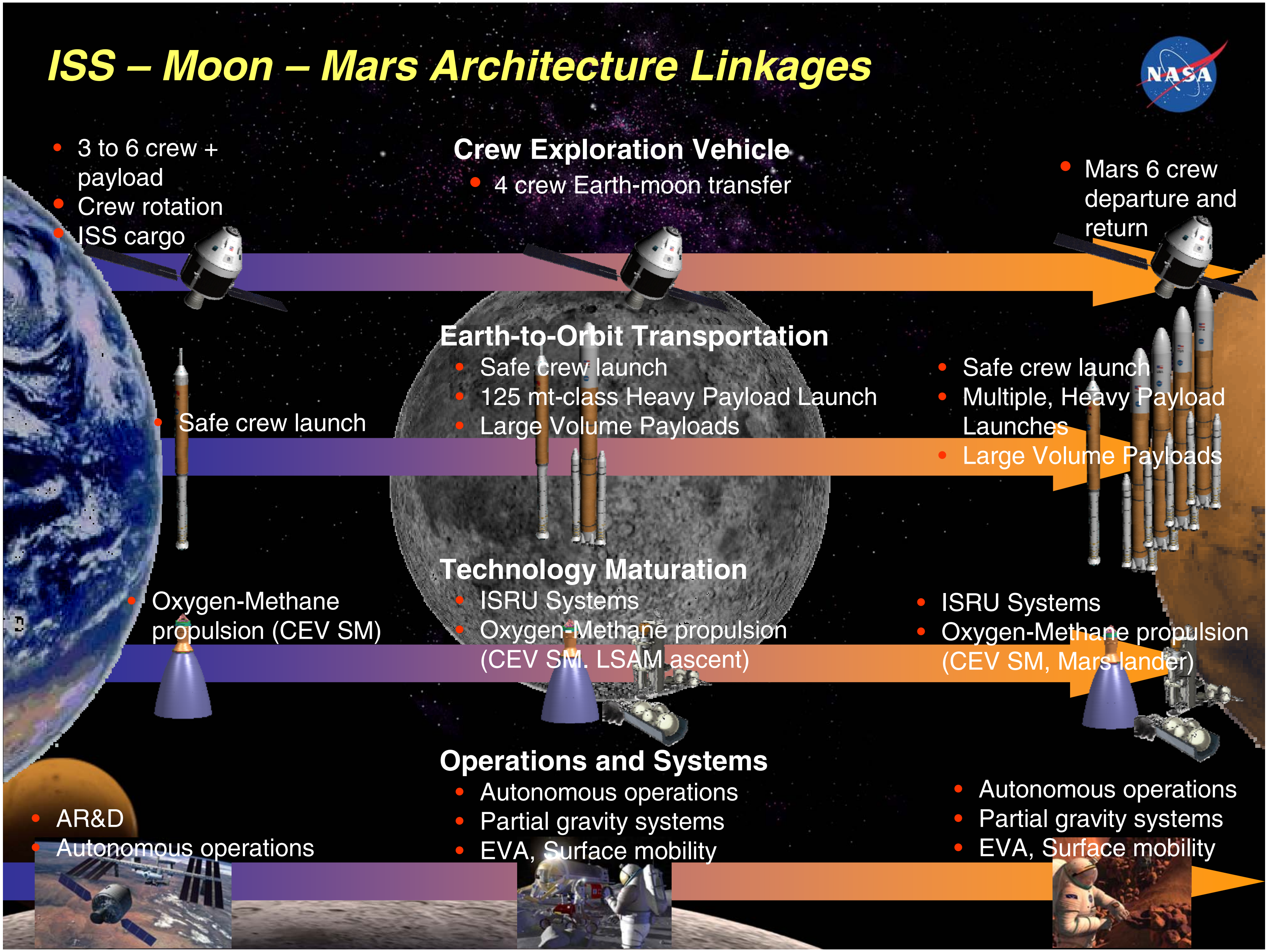


Lunar Heavy Cargo Launch Vehicle
5 Segment Shuttle Solid Rocket Boosters
Liquid Oxygen / liquid hydrogen core stage
Heritage from the Shuttle External Tank
5 Space Shuttle Main Engines
Payload Capability
106 metric tons to low Earth orbit
125 Metric tons to low Earth orbit using earth departure stage
55 metric tons trans lunar injection capability using earth departure stage
Cargo with later evolution to crew if needed
UNITED STATES
USA

Earth Departure Stage

- **Liquid oxygen / liquid hydrogen stage**
  - Heritage from the Shuttle External Tank
  - J-2S engines (or equivalent)
- **Stage ignites suborbitally and delivers the lander to low Earth orbit**
  - Can also be used as an upper stage for low-earth orbit missions
- **The CEV later docks with this system and the earth departure stage performs a trans-lunar injection burn**
- **The earth departure stage is then discarded**


How We Plan to Return to the Moon
Lunar Lander and Ascent Stage
4 crew to and from the surface
Seven days on the surface
Lunar outpost crew rotation
Global access capability
Anytime return to Earth
Capability to land 21 metric tons of dedicated cargo
Airlock for surface activities
Descent stage:
Liquid oxygen / liquid hydrogen propulsion
Ascent stage:
Liquid oxygen / liquid methane propulsion
NASA


ISS – Moon – Mars Architecture Linkages
NASA
3 to 6 crew + payload
Crew rotation
ISS cargo
Crew Exploration Vehicle
4 crew Earth-moon transfer
Mars 6 crew departure and return
Safe crew launch
Earth-to-Orbit Transportation
Safe crew launch
125 mt-class Heavy Payload Launch
Large Volume Payloads
Safe crew launch
Multiple, Heavy Payload Launches
Large Volume Payloads
Oxygen-Methane propulsion (CEV SM)
Technology Maturation
ISRU Systems
Oxygen-Methane propulsion (CEV SM. LSAM ascent)
ISRU Systems
Oxygen-Methane propulsion (CEV SM, Mars lander)
AR&D
Autonomous operations
Operations and Systems
Autonomous operations
Partial gravity systems
EVA, Surface mobility
Autonomous operations
Partial gravity systems
EVA, Surface mobility

Potential Commercial Opportunities

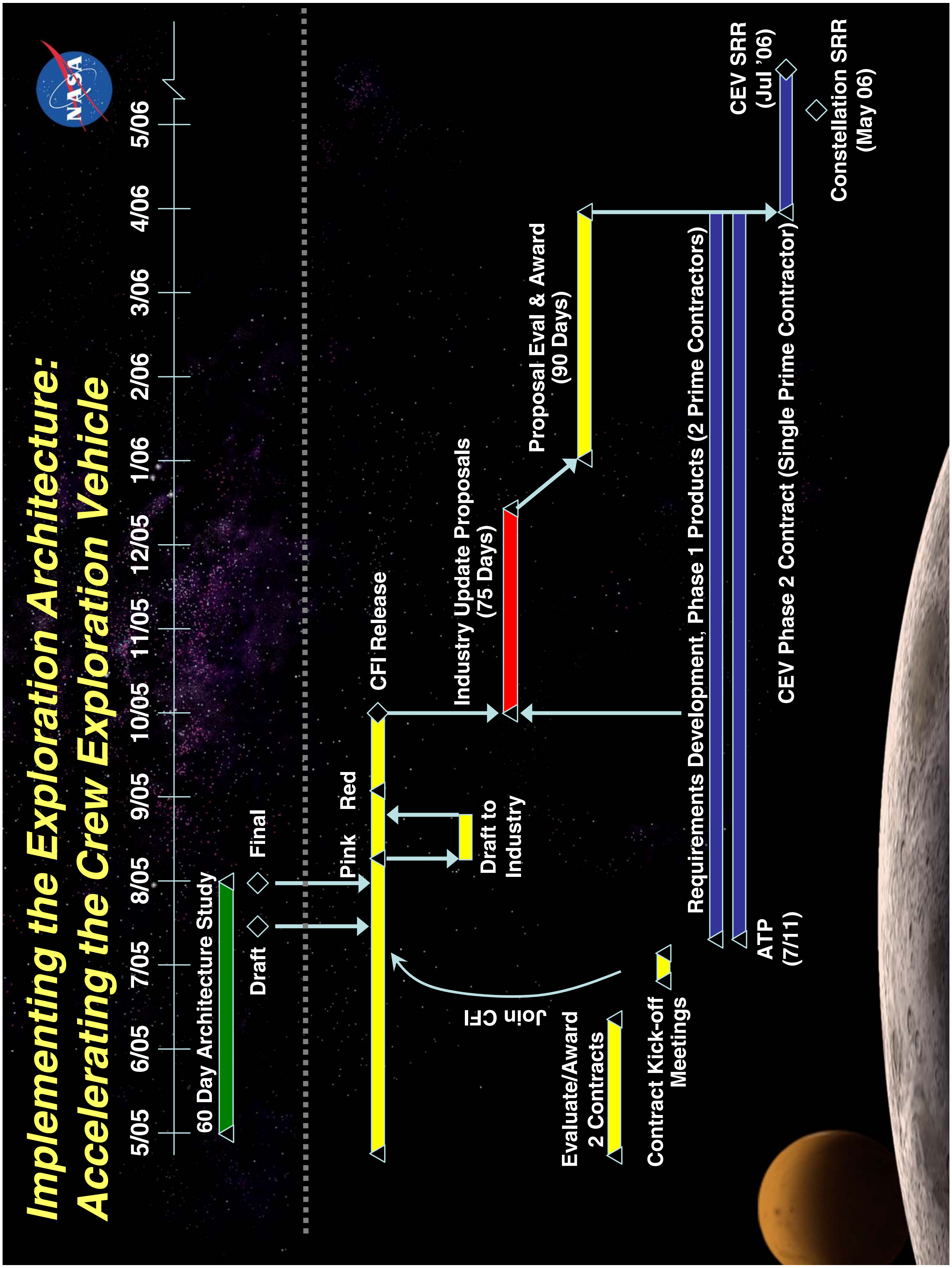
- **Commercial services for space station crew/cargo delivery and return**
- **Purchase launch / communications services as available**
- **Innovative programs to encourage entrepreneurs**
  - Centennial challenges prizes
  - Low-cost sub-orbital and orbital launch demo
  - Independent space station cargo re-entry demo
  - Independent crew transport demo
  - Space station cargo pathfinder demo
- **Propellant delivery to low Earth orbit for lunar missions**
  - Propellant depot in low Earth orbit
  - Propel earth departure stages/lunar lander after on-orbit transfer
  - Continual commercial replenishment as available
  - Government guaranteed purchase on delivery a certain price


Potential International Opportunities
Continue International Space Station cooperation re-focused on human exploration
Purchase of additional international partner transportation assets for the space station
Coordination of lunar robotic pre-cursor missions
Cooperate on variety of lunar surface systems
Habitats
Rovers
Power and logistics
Science and in-situ resource utilization equipment
Provide alternate transportation resources
Transportation of international astronauts on the CEV
Cooperation on Mars pre-cursor/science missions
Preparation for joint human Mars missions


A Safe, Accelerated, Affordable and Sustainable Approach
Meet all U.S. human spaceflight goals
U.S. system capable of servicing the International Space Station
Significant advancement over Apollo
Double the number of crew to lunar surface
Four times number of lunar surface crew-hours
Global lunar surface access with anytime return to the Earth
Enables a permanent human presence while preparing for Mars and beyond
Can make use of lunar resources
Significantly safer and more reliable
Minimum of two lunar missions per year
Provides a 125 metric ton launch vehicle for lunar and later Mars missions and beyond
Higher ascent crew safety than the Space Shuttle
1 in 2,000 (1 in 1,700 to 4,200) for the Crew Launch Vehicle
1 in 220 (1 in 160 to 310) for the Space Shuttle
Orderly transition of the Space Shuttle workforce
Requirements-driven technology program

Implementing the Exploration Architecture: Transition from ESAS to ESMD

- **Architecture**
  - The Exploration Architecture has been defined
  - An Exploration Architecture Requirements Document will be finalized in September
- **Requirements**
  - Element specifications for the Crew Exploration Vehicle (CEV), Crew and Cargo Launch Vehicles, and ISS Cargo Delivery Vehicles are in draft; will be validated and baselined by October
  - New CEV requirements will be included in the Call For Improvement that be the basis for updated Industry proposals
  - Research and Technology programs will be tightly focused on supporting CEV development and the initial return to the moon
- **Organization**
  - A streamlined HQ directorate is being formed
  - Program and Project Offices are being established at the NASA centers
  - Key individuals from ESAS are joining ESMD


Implementing the Exploration Architecture:
Accelerating the Crew Exploration Vehicle
5/05
6/05
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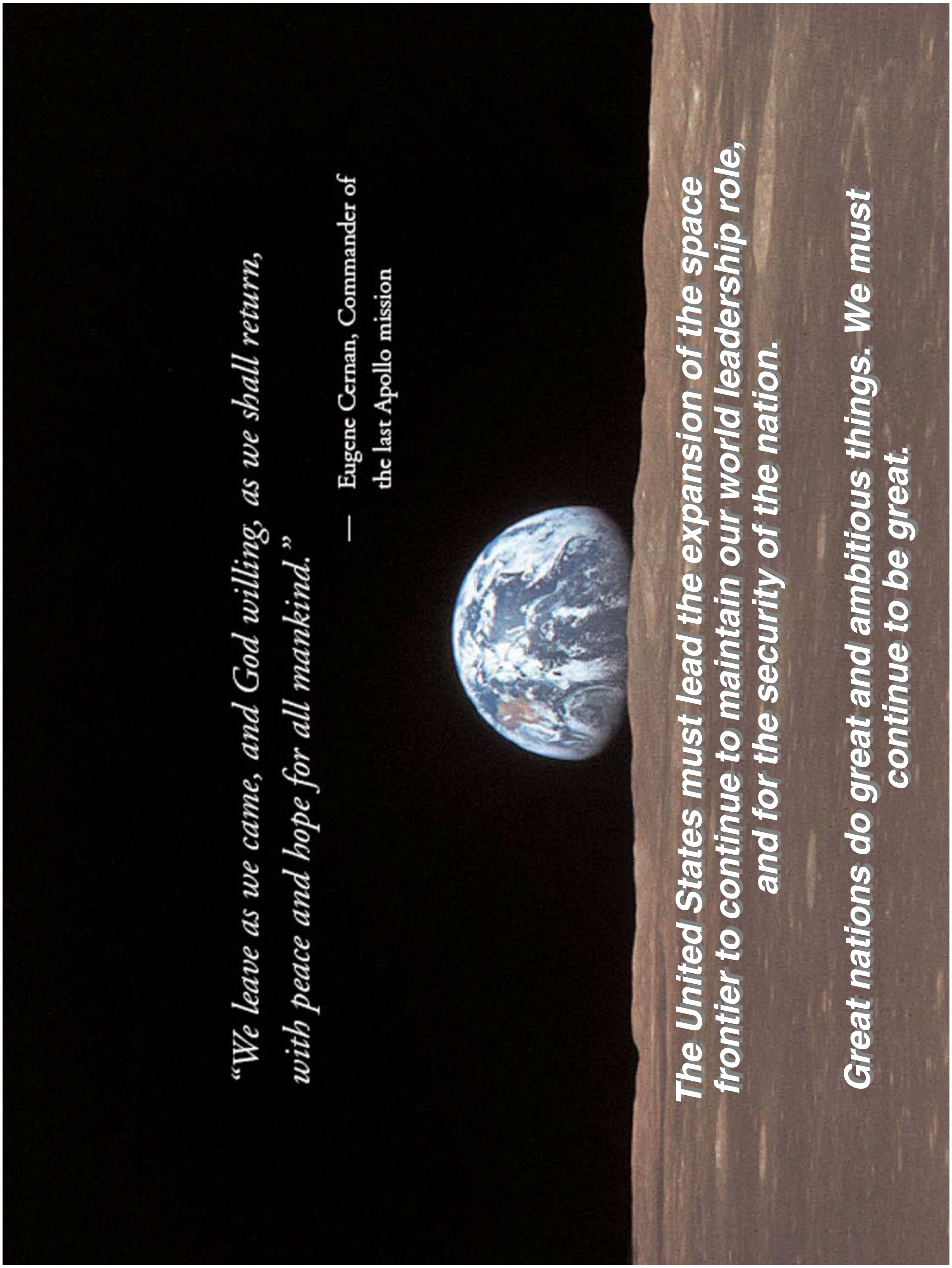
10/05
11/05
12/05
1/06
2/06
3/06
4/06
5/06
60 Day Architecture Study
Draft
Final
Pink
Red
CFI Release
Draft to Industry
Industry Update Proposals (75 Days)
Proposal Eval & Award (90 Days)
Join CFI
Evaluate/Award 2 Contracts
Contract Kick-off Meetings
Requirements Development, Phase 1 Products (2 Prime Contractors)
ATP (7/11)
CEV Phase 2 Contract (Single Prime Contractor)
CEV SRR (Jul '06)
Constellation SRR (May 06)

Our Destiny is to Explore!

- The goals of our future space flight program must be worthy of the expense, difficulty and risks which are inherent to it.
- We need to build beyond our current capability to ferry astronauts and cargo to low Earth orbit.
- Our steps should be evolutionary, incremental and cumulative.
- To reach for Mars and beyond we must first reach for the Moon.

A committed and long term lunar effort is needed, and we need to begin that investment now!


"We leave as we came, and God willing, as we shall return,
with peace and hope for all mankind."
— Eugene Cernan, Commander of
the last Apollo mission
The United States must lead the expansion of the space
frontier to continue to maintain our world leadership role,
and for the security of the nation.
Great nations do great and ambitious things. We must
continue to be great.

OVERVIEW OF NASA'S PROPULSION 21 EFFORT

Mary Jo Long-Davis
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Propulsion 21

Overview of NASA's Propulsion 21 Effort

Mary Jo Long-Davis

NASA
(216) 433-8708
Mary.J.Long-Davis@nasa.gov

Propulsion 21: Partners & Purpose

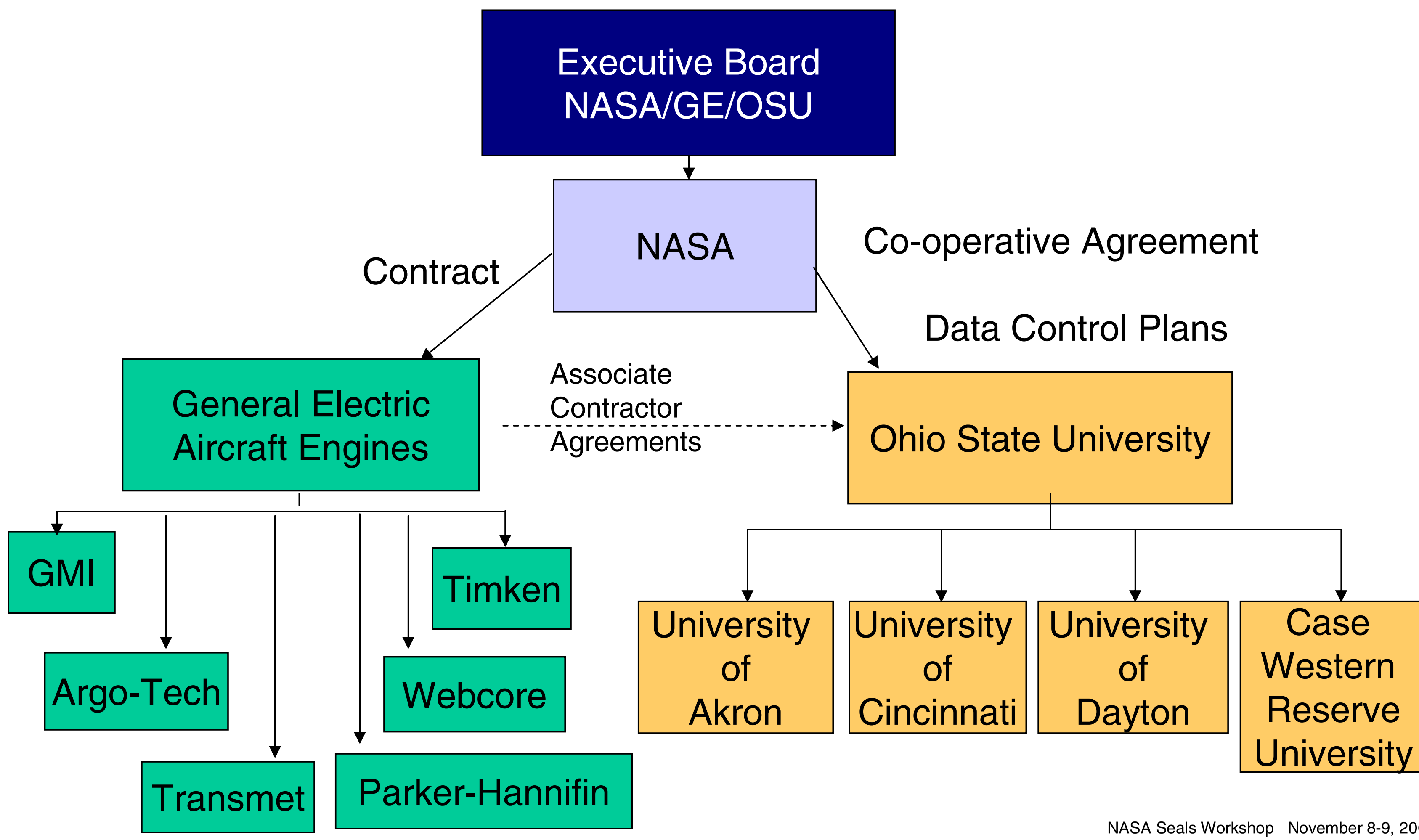
GE Aircraft Engines · NASA · The Ohio State University · The University of Akron · Parker · University of Cincinnati · TIMKEN · CWRU · Argo-Tech · University of Dayton · Glennan Microsystems Incorporated · Webcore · Air Force Research Laboratory · Transmet Corporation

State-wide coalition focused on research and development aimed at three aircraft engine-related goals:

- more **energy efficient**
- **quieter**
- more **reliable**

NASA Seals Workshop November 8-9, 2005

Management Structure



NASA Seals Workshop November 8-9, 2005

Propulsion 21 Technologies

Turbine Engine Prognostics
- Disk Life Meter
- Sub-System Health Management

Active Controls for Emissions and Noise reduction
- Intelligent Combustor
- Active Noise Reduction

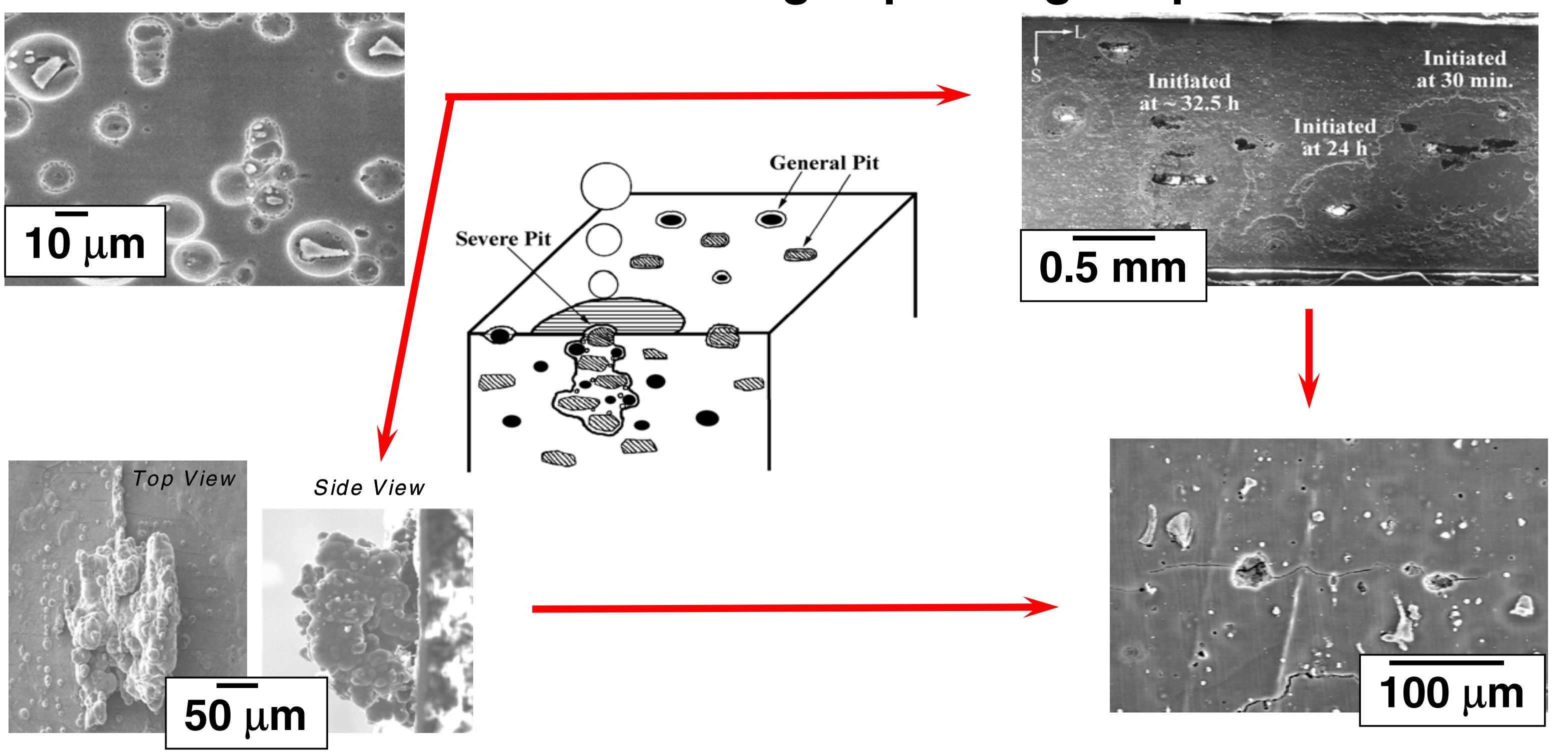
Active Structural Control
- Turbine Cooling Control
- Smart Containment System
- High Pressure Turbine Clearance Control

Modeling, Analysis and System Studies
- System Studies

Disk Life Meter

Objective:

Develop materials models and sensors to measure remaining life in turbine disk materials at sustained high operating temperatures.



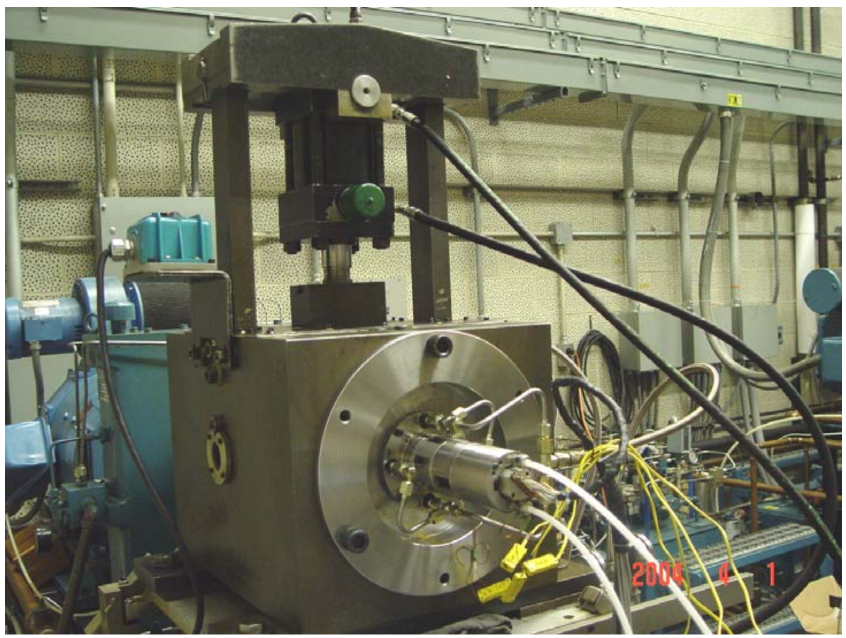
Pit Formation and Growth Now Need to Be Understood

NASA Seals Workshop November 8-9, 2005

Sub System Health Management

Objective:

Develop bearing diagnostics and health monitoring system for inter-shaft bearings to provide early detection of impending bearing failure. Demonstrate a conceptual monitoring system for a differential roller bearing.

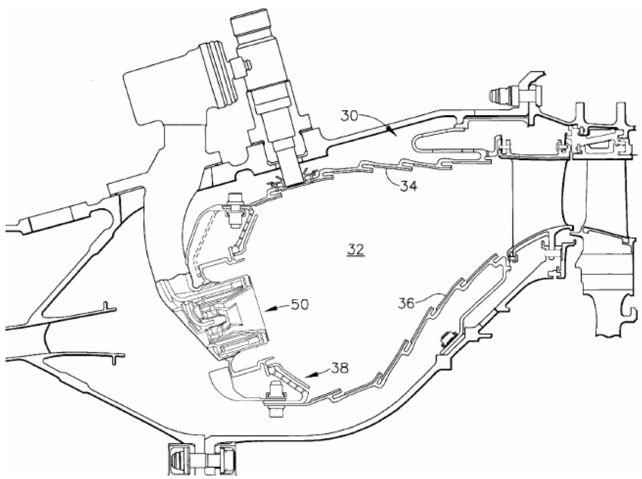


Assembled Bearing Test Rig

Intelligent Combustor

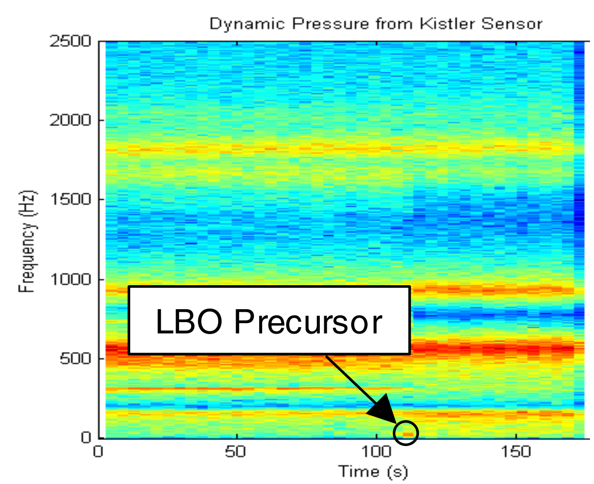
Objective:

Develop a combustor incorporating advanced diagnostics and active combustor control to reduce NOx emissions by 85% relative to 1996 ICAO standards, while retaining the performance of existing combustors.



New swirler concepts

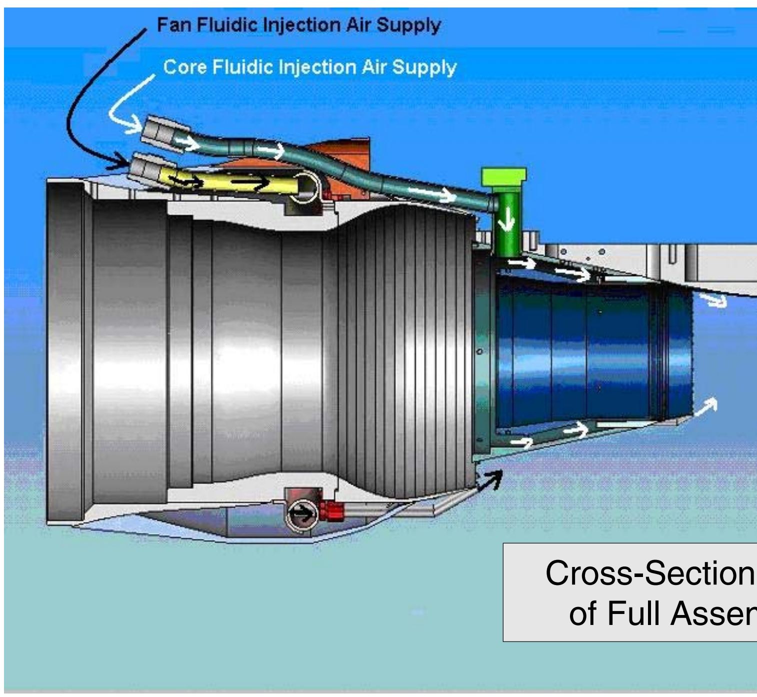
Lean blow-out precursor identification



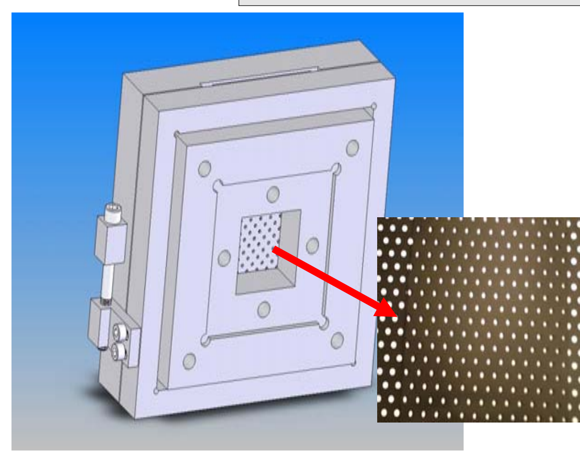
Active Noise Control

Objective:

Use fluidic injection, shape memory alloys, and/or plasma actuators to enhance exhaust nozzle jet mixing to actively reduce jet engine noise. Incorporate active/smart concepts into acoustic liner design to increase liner acoustic performance.



Cross-Section View of Full Assembly

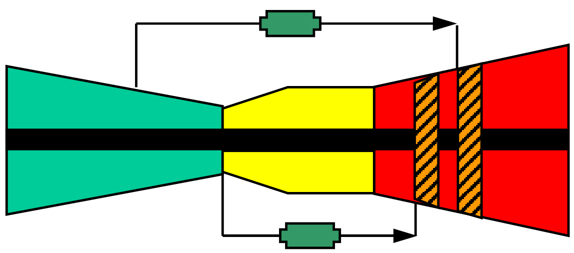


SMA Sliding Face-Sheet Fixture

Turbine Cooling Control

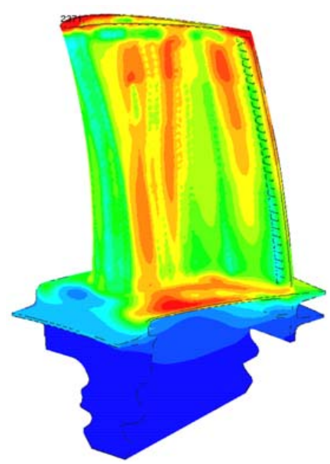
Objective:

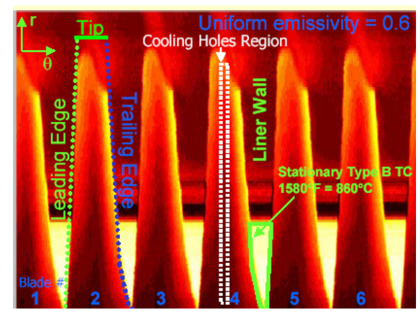
Develop and demonstrate innovative turbine system and component cooling technologies with active flow and temperature control, including prognostic / diagnostic sensors, for improved engine fuel burn and emissions.



Thermal Management & 3D System Simulation

Advanced Cooling Concepts
Cooled Cooling Air, Active Flow Control, Next-Gen Airfoil Cooling



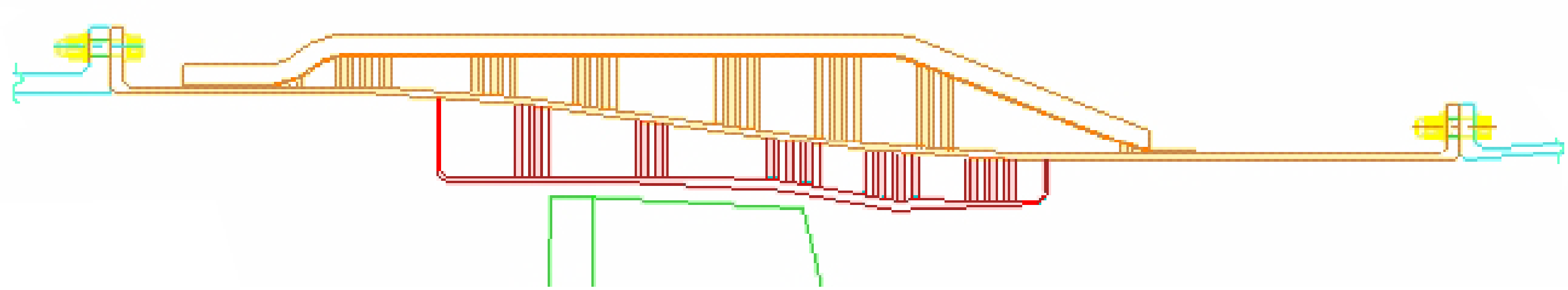


Sensors for Active Control & Prognostics

Smart Containment System

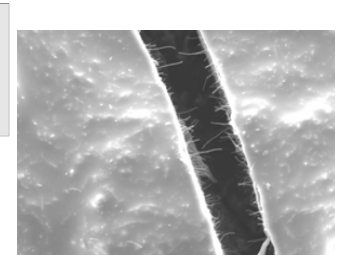
Objective:

Develop an innovative “smart” softwall containment system that capitalizes on the anisotropic nature of composites.



Conceptual design of smart containment system

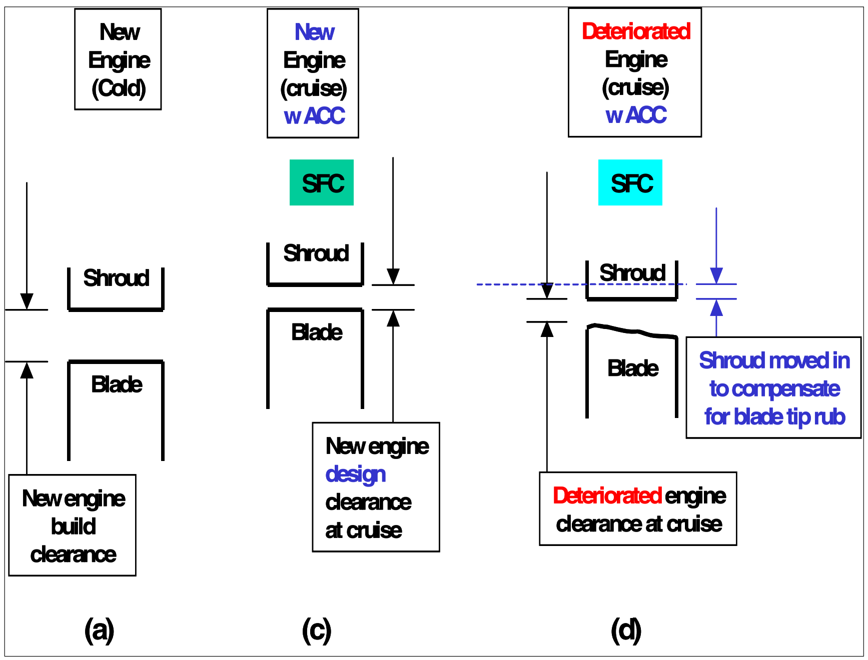
Nanofiber circuit diagnostic grid



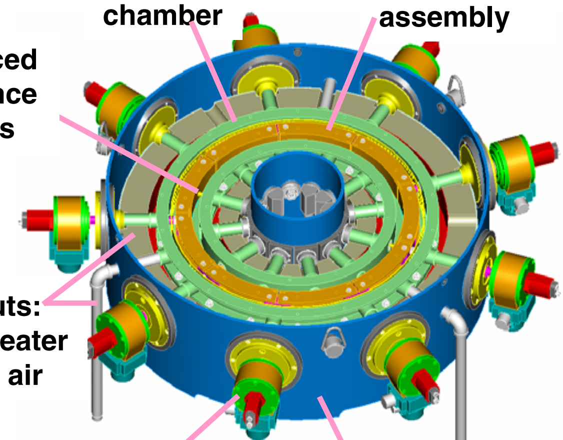
High Pressure Turbine (HPT) Clearance Control

Objective:

Develop an HPT clearance control system that can adapt to changing environment/requirements.



Active clearance control rig tests advanced concepts



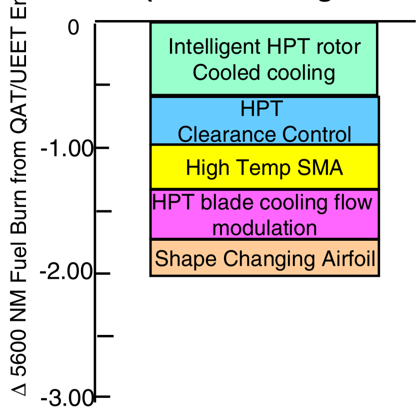
System Studies

Objective:

Perform technology assessment and identify needed modeling improvements to handle adaptive technologies.

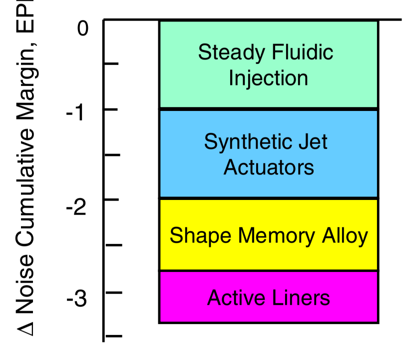
CO_2 Reduction (Fuel Burn)

(Baseline Engine is 2015 QAT/UEET)



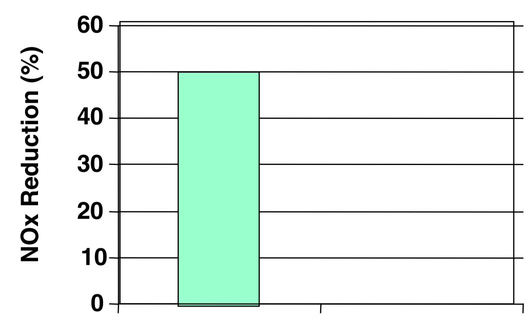
Noise Reduction

(Baseline Engine is 2015 QAT/UEET)



NOx Reduction

(Baseline Engine is 2015 QAT/UEET)



Summary

- Propulsion 21 technologies contribute to reducing CO_2 and NO_x emissions and noise
- Integrated Government/Industry/University research efforts have produced promising initial technical results
- Graduate students from 5 partnering universities will benefit from this collaborative research--> educating the future engineering workforce
- Phase 2 Efforts scheduled to be completed 3QFY06

OVERVIEW OF NASA GLENN SEAL PROJECT

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

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

Josh Finkbeiner
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Jeff DeMange
University of Toledo
Toledo, Ohio

Christopher C. Daniels
University of Akron
Akron, Ohio

Shawn Taylor
University of Toledo
Toledo, Ohio

Jay Oswald
J&J Technical Solutions, Inc.
Cleveland, Ohio

NASA Glenn hosted the Seals/Secondary Air System Workshop on November 8-9, 2005. At this workshop NASA and our industry and university partners shared their respective seal technology developments. We use these workshops as a technical forum to exchange recent advancements and "lessons-learned" in advancing seal technology and solving problems of common interest. As in the past we are publishing the presentations from this workshop in two volumes. Volume I will be publicly available and individual papers will be made available on-line through the web page address listed at the end of this presentation. Volume II will be restricted under International Traffic and Arms Regulations (I.T.A.R.). And Export Administration Regulations (E.A.R.)

Workshop Agenda
Tuesday, Nov. 8, Morning

Registration	**8:00 a.m.–8:30 a.m.**
Introductions	**8:30-8:50**
Introduction	Dr. Bruce Steinetz, R. Hendricks/NASA GRC
Welcome	Dr. Rich Christiansen, Deputy Director/NASA GRC
	Dr. Ted Keith, R&T Director, NASA GRC
Program Overviews and Requirements	**8:50-10:20**
Overview of NASA's Exploration Initiative	Dr. Timothy Tyburski for Mr. Harry Cikanek/NASA GRC
Overview of NASA's Propulsion 21Project	Ms. Mary Jo Long Davis/ NASA GRC
Overview of NASA Glenn Seal Project	Dr. Bruce Steinetz et al/NASA GRC
Overview Comments	Mr. Robert C. Hendricks/NASA GRC
Break	**10:20 -10:35**
Turbine Seal Development Session I	**10:35-12:15**
Commercial Airplane Aero Seal Needs	Mr. Chris Jasklowski/Boeing
Applying Brush Seals To Steam Turbines	Mr. Norm Turnquist, R. Chupp/GE Global Research Center
Advanced Seal Rig Experiments & Analysis	Mr. Roger Paolillo/Pratt and Whitney
Comparison of Labyrinth, Annular, Brush, and Finger Seal Power Loss and Leakage Characteristics	Mr. Irebert Delgado/U.S. Army Res. Lab, M. Proctor/NASA GRC
High Misalignment Carbon Seals: Progress Report	Mr. Dennis Shaughnessy, L. Dobek/Pratt & Whitney
Lunch: OAI Sun Room	**12:20-1:20**

NASA Glenn Research Center
Seal Team

The first day of presentations included overviews of current NASA programs. Dr. Tyburski reviewed the goals and objectives of NASA's new Exploration Initiative targeting both robotic and manned missions to the Moon, Mars and beyond. Ms. Mary Jo Long-Davis of the Ultra-Efficient-Engine Technology (UEET) project office, reviewed project plans and objectives of the Propulsion 21 project. Propulsion 21 is developing advanced turbine engine technologies aimed at reducing fuel burn, emissions, and noise using a consortium of Ohio organizations.

Dr. Steinetz presented an overview of NASA seal developments for both NASA's aeronautic and space projects. Mr. Hendricks presented a call-to-action for the community to address the sobering fact that the world is consuming greater oil resources than it is discovering. Though improved sealing technology can play a role in reducing fuel burn by improving engine efficiency, there is a need to start addressing alternate energy sources to help ward-off a future energy crisis.

Mr. Jasklowski of Boeing presented current pylon/nacelle to engine seal challenges and needs. Dr. Chupp presented an overview of recent successes that GE Energy Systems has had in applying advanced seals including brush and abradable seals to steam turbines. Mr. Paollilo presented an overview of several novel labyrinth seal geometries being evaluated both analytically and experimentally. Mr. Delgado compared labyrinth, annular, brush, and finger seal power loss and leakage characteristics. Mr. Shaughnessy of P&W presented an overview of the work P&W and Stein Seal are doing to develop high misalignment carbon seals for a geared fan application.

Turbine engine studies have shown that reducing high pressure turbine (HPT) blade tip clearances will reduce fuel burn, lower emissions, retain exhaust gas temperature margin and increase range. Mr. Sak presented an overview of GE's approach for a fast acting thermal active clearance control system. Mr. Taylor presented an overview of the new Active Clearance Control Test rig aimed at demonstrating advanced ACC kinematic systems, actuators, control methods, and sensors. Mr. Taylor presented recent leakage and clearance control data collected using the test rig. Mr. Geisheimer of Radatech presented an overview of their microwave blade tip sensor development efforts. Microwave tip sensors show promise of operation in the extreme gas temperatures present in the HPT location. Mr. DeCastro presented a design of a shape memory alloy (SMA) actuator for active clearance control in the high-pressure turbine. Shape memory alloy actuators are being considered to reduce system weight of future ACC systems.

Mr. Holloway presented the design of a rotating carbon fiber brush seal being developed for future bearing compartments for either co- or counter-rotating intershaft locations. Mr Grondahl presented an overview of a new pressure actuated leaf seal. This concept employs pressure actuation to cause metal laminates to flex radially toward the shaft at operating pressures but spring away for start-up and shut-down to minimize the chances of seal-to-rotor rub. Mr. Trabert of Perkin Elmer presented leakage data of brush seals both before and after 3000 hrs of engine operation. The brush seals showed very similar leakage performance after these extended periods of use. Dr. Braun presented investigations into a non-contacting finger seal under development by NASA GRC and University of Akron. Mr. Lee presented unique equipment that is used for precision alignment of rotors and seals. Precision alignment allows tighter sealing, reduced oil leakage, and helps reduce balance weight addition through preferred part orientation during assembly.

Workshop Agenda
Wednesday, Nov. 9 Morning

Registration at OAI	**8:00-8:30**
Space Systems Development	**8:30-10:10**
Future Space Vehicle Docking/Berthing Mechanism and Seal Needs: An Update	Mr. James Lewis (or designee)/NASA Johnson Space Center
Falcon/Common Aero Vehicle Program Objectives And Seal Challenges	Mr. Brian Zuchoswski, D. Johnson/ Lockheed-Martin
Overview of NASA's In-Situ Resource Utilization Project And Seal Challenges	Mr. Kurt Sacksteder, Diane Linne/ NASA GRC
Break	**10:10-10:25**
Structural Seal Development Session I	**10:25-12:00**
An Update on High Temperature Structural Seal Development at NASA GRC	Mr. Patrick Dunlap, B. Steinetz/NASA GRC, J. Demange/U. of Toledo
High Temperature Testing of the X-37 Flaperon Seals	Mr. Jeff Demange/U. of Toledo, P. Dunlap/NASA GRC
High Temperature Gaskets and Sealants for Re-entry and Hypersonic Environments	Dr. Jay Singh, Tara Shpargel, QSS Group/NASA GRC
High Temperature Metallic Seal Development: An Update	Dr. Amit Datta, Advanced Components and Materials Mr. Greg More Parker Co.
Lunch OAI Sun Room	**12:00-1:00**

NASA Glenn Research Center
Seal Team

NASA is developing a standardized system for docking and berthing for future exploration system vehicles such as the Crew Exploration Vehicle. Mr. Lewis leads the Advanced Docking and Berthing project at NASA JSC but due to another time commitment asked Dr. Steinetz to present the goals and objectives of this project. DARPA and the Air Force (with support from NASA) are developing a hypersonic payload delivery system that can reach Mach 10 conditions. Mr. Zuchowski presented an overview of project goals and identified extensive vehicle seal challenges. Mr. Sacksteder presented an overview of NASA's plans to develop In-Situ Resource Utilization techniques to enable future astronauts to harvest resources from either the Moon (e.g. ice) and Mars (e.g. CO2) to allow astronauts to live off the land to extend mission duration.

Mr. Dunlap presented an overview of the structural seal development activities underway for hypersonic systems (e.g. both propulsion systems and vehicles), re-entry vehicles (e.g. X-vehicles and CEV), and future docking and berthing systems. Mr. DeMange presented control surface (e.g. hinge-line) seal development efforts underway at GRC for future re-entry vehicles – such as the X-37. Dr. Singh reviewed materials development for Shuttle repair strategies. These include both high temperature materials for leading edge crack repair and high temperature gaskets. Mr. More of Parker presented recent progress in developing higher temperature metal seals (e.g. E- or other) that incorporate single-crystal blade alloy finger preloaders capable of 1600+°F operation.

Workshop Agenda
Wednesday, Nov. 9, Afternoon

Structural Seal Development Session II	**1:00-2:30**
Investigations of Shuttle Main Landing Gear Door Environmental Seals	Mr. Josh Finkbeiner, et al/NASA GRC
Elastomeric Seal Development for the Advanced Docking / Berthing System	Dr. Chris Daniels/U. of Akron, P. Dunlap, B. Steinetz/NASA GRC
Space Environments Effects on Materials and GRC's Test Capabilities	Dr. Sharon Miller, Dr. Bruce Banks/NASA GRC
Metallic Seal Development for Adv. Docking/Berthing System	Mr. Jay Oswald/J&J Tech. Sol., C. Daniels/U. of Akron P. Dunlap, B. Steinetz/NASA GRC
General Interest	**2:30-3:00**
Mapping Technological Opportunities - Evolving a Labyrinth Seal -	Mr. Dana Clarke/Applied Innovation Alliance, LLC
Tour of NASA Seal Test Facilities	**3:15-4:15**
Adjourn	

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Seal Team

In preparation for Shuttle Return to Flight, NASA JSC requested that NASA GRC assist in performing tests with the Shuttle Main Landing Gear Door seals. Mr. Finkbeiner presented compression and flow results for Shuttle main landing gear door seals. Tests performed and observations made aided in reducing seal compressions loads assisting JSC and KSC in closing the Shuttle main landing gear doors for flight.

Dr. Daniels and Mr. Oswald presented test results for elastomeric and metal seals being considered for future advanced docking and berthing systems that JSC is developing for future space vehicle docking and berthing needs. Dr. Banks presented an overview of space environments potentially damaging effects on materials and summarized GRC's atomic and ultra violet (UV) test capabilities being used to evaluate material candidates for the Docking and Berthing project.

Mr. Clark presented techniques his company uses- inspired by the theory of inventive problem solving (TRIZ) - to map technological opportunities by identifying how a technology (e.g. seals) evolve over time.

NASA Glenn Seal Team

Seal Team Leader: Bruce Steinetz
Mechanical Components Branch/RXM

Turbine Seal Development
Develop non-contacting, low-leakage turbine seals
Margaret Proctor: Principal Investigator/POC
Irebert Delgado, Dave Fleming, Joe Flowers

Structural Seal Development
Develop resilient, long-life, structural seals for extreme environments
Pat Dunlap: Principal Investigator
Jeff DeMange, Josh Finkbeiner, Jay Oswald, Malcolm Robbie, Art Erker, Joe Assion

Turbine Clearance Management
Develop novel approaches for blade-tip clearance control.
Shawn Taylor: Principal Investigator
Jim Smialek (RX), Malcolm Robbie, Art Erker

Exploration System Seals
Advanced Docking/Berthing, CEV, Aerocapture, Fuel Cell Seals,
Pat Dunlap; Chris Daniels: Co-Principal Investigators
Jay Oswald, Josh Finkbeiner, Art Erker, Joe Assion

NASA Glenn Research Center
Seal Team

The Seal Team is divided into four primary areas. The principal investigators and supporting researchers for each of the areas are shown in the slide. These areas include turbine seal development, structural seal development, clearance management, and seals for NASA's Exploration Systems Initiative. The first area focuses on high temperature, high speed shaft seals for turbine engine secondary air system flow management. The structural seal area focuses on high temperature, resilient structural seals required to accommodate large structural distortions for both space- and aero-applications.

Our goal in the clearance management project is to develop advanced approaches and technologies for minimizing blade-tip clearances and leakage. We are planning on applying either rub-avoidance or regeneration clearance control concepts (including smart structures and materials) to promote higher turbine engine efficiency and longer service lives.

We are also contributing seal expertise in a range of emerging areas for NASA's Exploration Initiative. These include seal developments and studies for the advanced docking and berthing, crew exploration vehicle (CEV), aerocapture, and fuel cell projects.

Turbine Engines:
Seal Challenges and Projects Supported

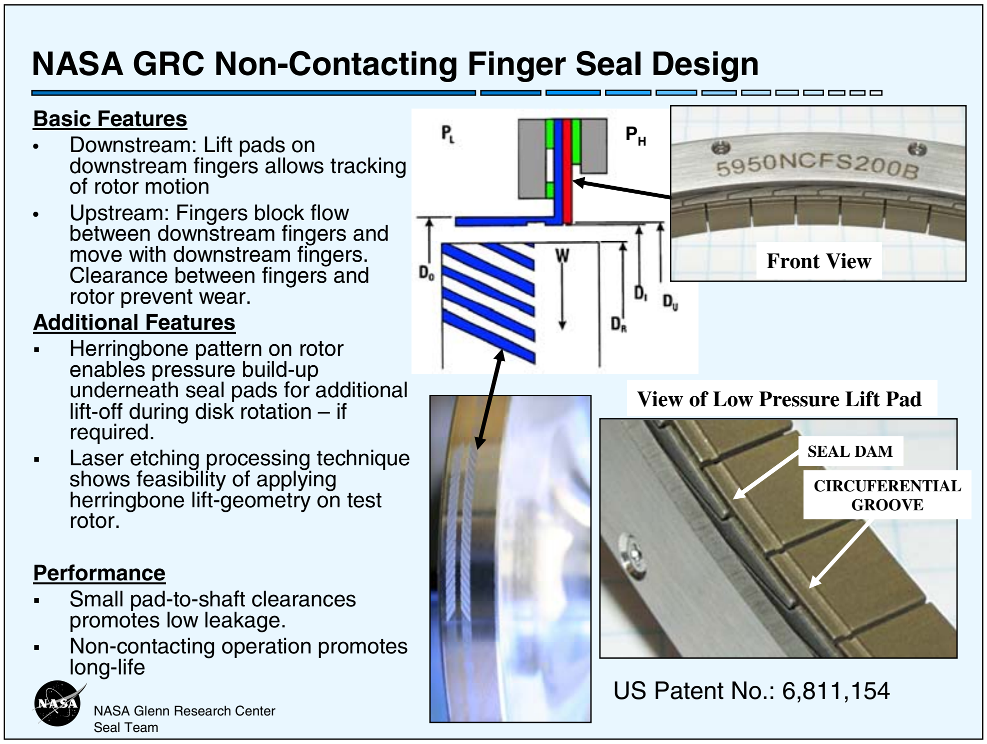
Turbine Shaft Seals: Challenges and Goals

- Challenges:
  - Minimize leakage to enable: reduced fuel consumption and emissions
  - High temperatures: up to 1500°F
  - High speeds up to 1500 fps
  - Moderate pressure 250 psi
  - Operate with little or no wear for long life 3-10,000 hrs
  - Minimize heat generation

- GRC non-contacting seal project goal:
  - Develop non-contacting seal designs and design methods to enable low-leakage and virtually zero wear:
    - » Demonstrate hydrodynamic and/or hydrostatic lift geometries.
    - » Demonstrate under engine simulated operating conditions
    - » Transfer technology to private sector

NASA Glenn Research Center
Seal Team

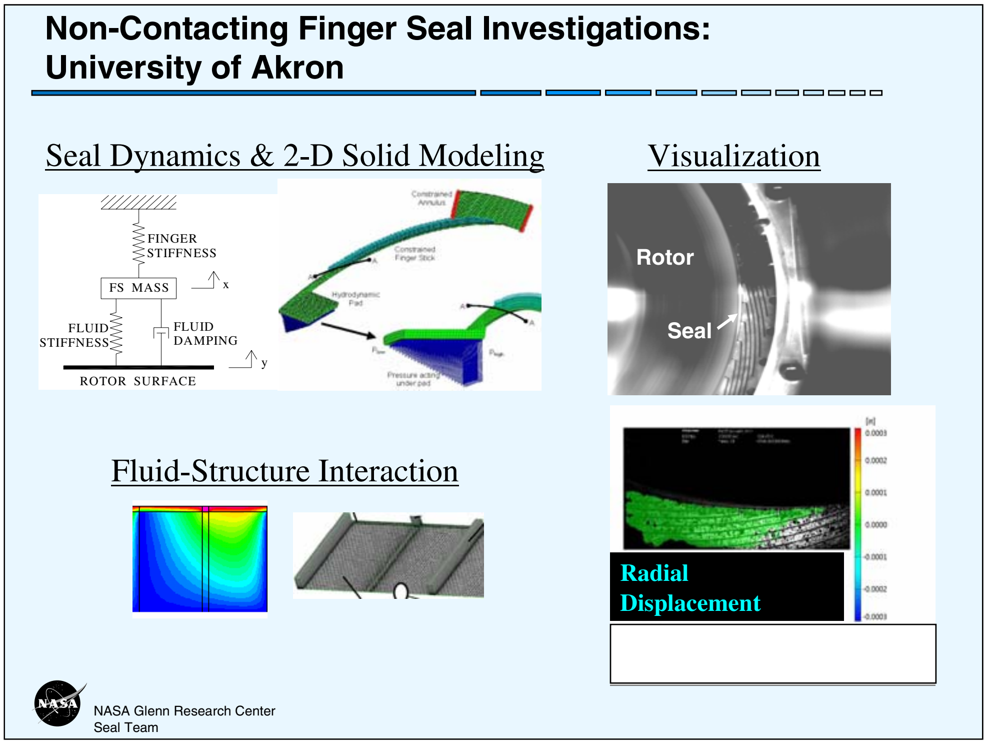
Designers of future turbine engine seals face ever increasing challenges (Steinetz and Hendricks, 1998) including high temperature, high speed operation, the need to operate for long lives with little or no wear while minimizing heat generation. One of NASA GRC's turbine engine seal goals is to develop non-contacting seal designs that incorporate hydrostatic and/or hydrodynamic lift geometries. Seals under development will be fabricated and tested in NASA GRC's high temperature, high speed seal rig to assess their performance under engine simulated conditions.



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

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

A non-contacting finger seal based on the GRC patent (US Patent No.: 6,811,154) has been fabricated (see upper right figure) and will be tested in GRC's turbine seal test rig. The seal will be tested against a rotor that has a herringbone lift geometry that is fashioned onto the rotor surface using a laser etching process. (see laser etch sample in lower middle photo).



Dr. J. Braun and his team at the University of Akron are performing analyses and tests of this GRC concept through a cooperative agreement (Braun et al, 2003). University researchers developed an equivalent spring-mass-damper system to assess lift characteristics under dynamic excitation. Fluid stiffness and damping properties were obtained utilizing CFD-ACE+ (3-D Navier-Stokes code) and a perturbation approach. These stiffness and damping properties were input into the dynamic model expediting the solution for design purposes. Dr. Braun an expert in advanced visualization techniques has investigated the finger seal lift-off using unique lighting and measurement techniques during seal operation at ambient temperature using the Univ of Akron's test rig. These measurements are providing useful insights into seal operation for design evolution.

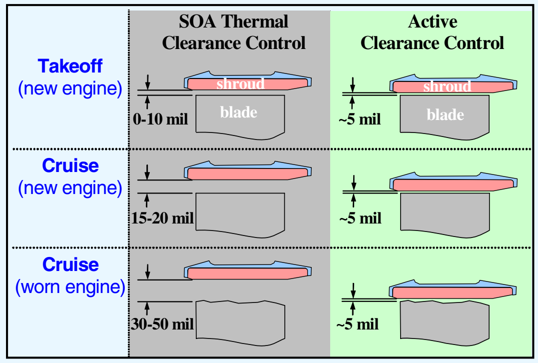
More details can be found in Braun et al, 2006 in this Seal Workshop Proceedings. After feasibility tests are complete at the University, seals will be tested under high speed and high temperature conditions at NASA GRC.

Turbine Clearance Management

Motivation for Tip Clearance Control + Challenges

The Problem:
Clearances between the shroud and blade tips vary over the operation and life of an engine. Wear and thermal erosion increases blade tip clearance.

Benefits of Clearance Control:
- Increased engine efficiency & reduced SFC (0.8-1% SFC)
- Reduced NOx & CO emissions
- Delayed rise in exhaust gas temperature (EGT)



ACC System Challenges:

Temperature: Gas path - **>2500°F**
Cooling air - **>1200°F**
Case - **600°F** (w/ soak back)

Load/Response: Actuators must react **~2000 lbf**
move **~0.05"** in **10 sec**

Accuracy: Current Systems - **0.015-0.020-in**
Goal – **<0.005-in**

Size/Weight: Small, lightweight ACC systems required
Goal current thermal systems **(<100 lbs)**.

NASA Glenn Research Center
Seal Team

Benefits of Active Clearance Control

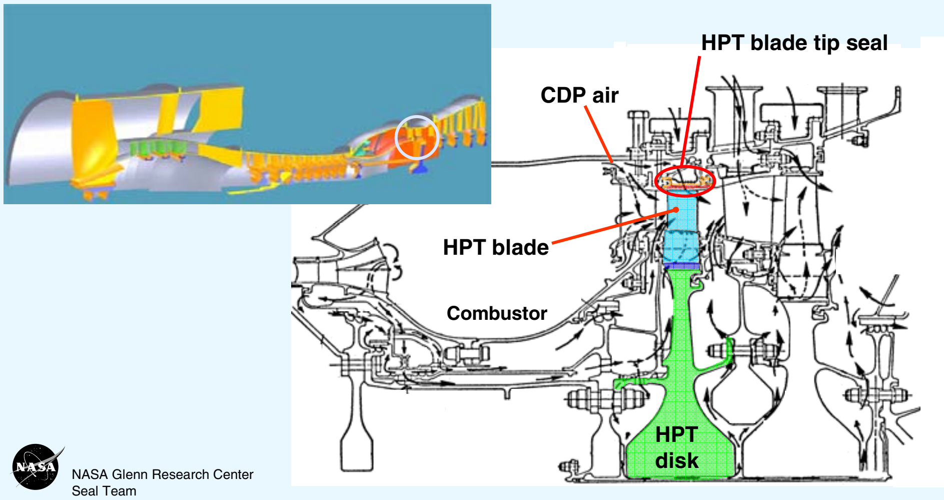
Blade tip clearance directly influences gas turbine performance, efficiency, and life (Lattime and Steinetz, 2002). Reducing air leakage over the blade tips increases turbine efficiency and permits the engine to meet performance and thrust goals with less fuel burn and lower rotor inlet temperatures. Running the turbine at lower temperatures increases the cycle life of hot section components, which in turn, increases engine service life by increasing the time between overhauls.

Lattime and Steinetz [2003], GE [2004], and Wiseman and Guo [2001] provide overviews of the many benefits of advanced active clearance control systems. Some of the more noteworthy benefits of implementing fast mechanical ACC systems in the HPT of a modern high bypass engine are provided herein for completeness. In terms of fuel savings, a tip clearance reduction of 0.010-in. results in ~0.8 to 1 percent decrease in specific fuel consumption. By reducing fuel burn significant reductions in NOx, CO, and CO2 emissions are also possible. Reducing tip clearances by 0.010-in. decreases exhaust gas temperature (EGT) ~10 °C. Deterioration of EGT margin is the primary reason for aircraft engine removal from service. Running the engine at lower operating temperatures can result in increased life of hot section components and extend engine time-on-wing (up to 1000 cycles). Additional benefits include increased payload and mission range capabilities.

There are a number of technical challenges that need to be addressed to fielding an effective active clearance control system, as shown in the chart. Two primary challenges include the high temperature environment and the need for accurate control.

Turbine Clearance Management Goal

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



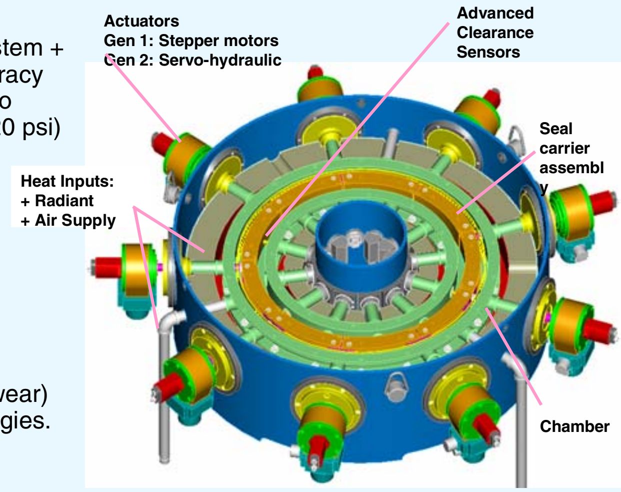
NASA Glenn Research Center
Seal Team

System studies have shown the benefits of reducing blade tip clearances in modern turbine engines. Minimizing blade tip clearances throughout the engine will contribute materially to meeting NASA's Ultra-Efficient Engine Technology (UEET) turbine engine project goals. Large SFC and emissions improvements are achievable by improving blade tip clearances in the high pressure turbine.

Active Clearance Control Concept & Evaluation Test Rig

Purpose:

- Evaluate ACC kinematic system + actuator response and accuracy under appropriate thermal (to 1200°F) and pressure (to 120 psi) conditions.
- Evaluate clearance sensor response and accuracy
  - Capacitance
  - Microwave
- Measure ACC system seal performance (leakage and wear) and identify mitigation strategies.



NASA Glenn Research Center
Seal Team

NASA GRC is developing a unique Active Clearance Control (ACC) concept and evaluation test rig. The primary purpose of the test rig is to evaluate ACC kinematic systems, actuator concept response and accuracy under appropriate thermal (to 1200+F) and pressure (up to 120 psig) conditions. Other factors that will be investigated include:

•Actuator stroke, rate, accuracy, and repeatability

•System concentricity and synchronicity

•Component wear

•Secondary seal leakage

•Clearance sensor response and accuracy

The results of this testing will be used to further develop/refine the current system design as well as other advanced actuator concepts. More details regarding this test rig can be found in Taylor, et al 2006 (in this Seal Workshop Proceedings), Steinetz et al, 2005, and Lattime et al, 2003.

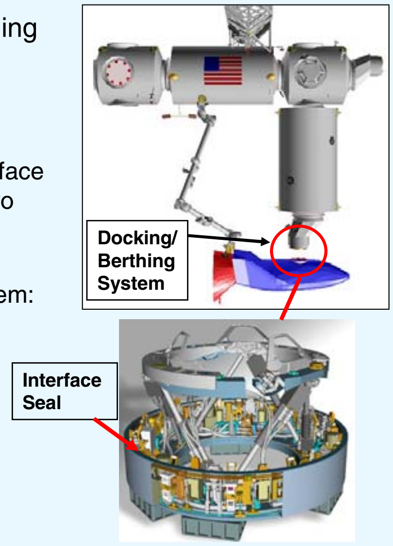
Exploration Systems:
Seals Challenges and Projects Supported

Advanced Docking/Berthing System

What is the Advanced Docking and Berthing System (ADBS)?

System under development by JSC to:

- Provide gender-neutral (androgynous) interface permitting docking/berthing between any two space vehicles
- Reduce impact loads between two mating space craft. (e.g. Low Impact Docking System: LIDS)
- Become new Agency standard for docking/berthing systems.



ADBS

NASA Glenn Research Center
Seal Team

In preparation for the Exploration Initiative, NASA has identified the need for a standard docking and berthing system to allow easy docking between space faring vehicles and platforms orbiting either Earth (e.g. the Space Station) the Moon or Mars. NASA Johnson is developing an advanced docking and berthing system (ADBS) that has several important features:

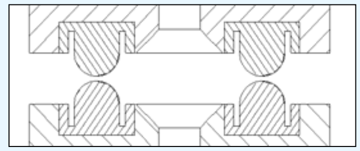
\+ The system will be androgynous or gender-neutral permitting docking and berthing between any two space vehicles, giving NASA and the astronauts maximum mission planning flexibility.

\+ Using a soft capture system, minimal loads will be imparted between systems minimizing potential for damage.

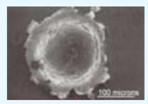
For additional information regarding the ADBS project and system, see James Lewis' presentation in this Workshop Proceedings.

Advanced Docking and Berthing System: Seal Challenges

- Seal on seal interface for androgynous system
- Extremely high reliability: Man rating
- Relative large diameter ≥ 54"
- Extremely low leakage rates: 0.044 lb/day (3.8×10^{-4} SCFM)
- Temperature: -50°C to +50°C and thermal gradients
- Long term (years) exposure to space environments: Atomic Oxygen (AO); Ultraviolet (UV) radiation, Seal surface damage
  - » Cracking
  - » Embrittlement
  - » Material loss
  - » Loss in strength
  - » Reduced deformability
  - » Micro-meteoroid damage

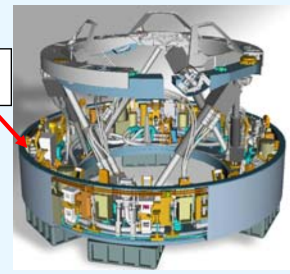


Seal-on-seal interface



Ref: Aluminum Impact Crater

Interface Seal



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Seal Team

A unique seal challenge posed by the androgynous ADBS system is the need for a seal-on-seal interface as shown in the upper inset figure. This seal prevents leakage of cabin pressure while the two vehicles are mated together.

Challenges posed by this new system include:

Extremely high reliability for man rating

Relative large diameter ≥ 54"

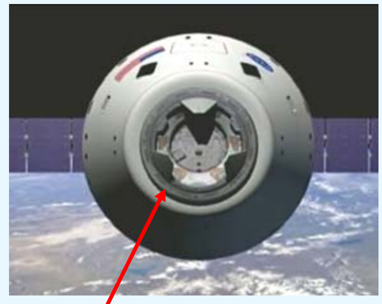
Extremely low leakage rates: 0.044 lb/day (3.8×10^{-4} SCFM)

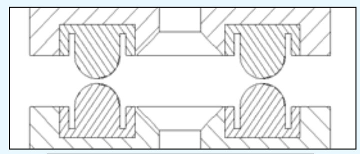
Temperature: -50 °C to +50 °C and thermal gradients

Long term (years) exposure to space environments: Atomic Oxygen (AO); Ultraviolet (UV) radiation, Seal surface damage due to micrometeors.

NASA GRC's Support of ADBS Project

- Goal: Provide JSC with a seal-on-seal system that meets all performance requirements.
- Approach
  - Identify candidate elastomeric and metallic seals via NASA and vendor concepts.
  - Perform coupon-level and small-scale environmental exposure and flow tests of candidate seals.
  - Down-select between competing concepts and materials based on requirements.
  - Perform full-scale flow tests (incl. variable gap, offset, hot and cold, seal-on-seal)
    - Assess loads: compression, separation
  - Support JSC through flight qualification for CEV and other applications





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NASA Johnson requested the GRC Seal Team to assist in assessing and developing candidate seal technology for the ADBS system, shown in an artist's rendering of the Crew Exploration Vehicle.

The following elements are planned during the development project:

+ Perform coupon-level and small-scale environmental exposure and flow tests of candidate sub-scale seals

+ Down-select between competing concepts and materials based on requirements

+ Perform full-scale flow tests. Using a new test rig under design, candidate full-scale seals will be subjected to both nominal and off-nominal conditions (e.g. variable gap and offset conditions). The seal's ability to seal under both warm and cold conditions will also be assessed while tested in a seal-on-seal condition.

+ Assess loads: compression, separation

+ Support JSC through flight qualification for CEV and other applications

Astronaut Space Suit & Air lock: Seal Challenges

- Extremely high reliability: Man rated
- Multiple suit locations to enhance astronaut mobility and effectiveness
- Extremely low leakage rates.
  – Apollo astronaut experience: after first EVA neck and wrist joint leaks amounted to 0.15 psi/min decay – too high for future missions.
- Long term (years) exposure to space environments: Dust, Ultraviolet (UV) radiation,
  » Seal leakage
  » Seal/joint damage
  » Dust ingestion:
    - Breathing hazard
    - Shortens mission

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Seal Team

During the Apollo program, astronauts found that the suits exhibited several limitations. Dust was able to compromise the seals in the joints causing pressure loss of up to 0.15 psi/minute. This is too high for future Exploration Initiative missions in which astronauts will be expected to perform longer, more frequent missions outside of the landing vehicle.

NASA is now defining programs to develop advanced technologies for future space suits, air locks and quick-disconnect umbilicals. Development of robust seals that overcome the dust issues is essential to meeting future mission requirements.

In-Situ Resource Utilization (ISRU) + Seal Challenges

- Benefits of ISRU: *In-situ production of mission critical consumables (propellants, life support consumables, and fuel cell reactants) significantly reduces delivered mass to surface.*
- Extraction and refinement of nearly any valuable resource from lunar regolith requires thermal and chemical or electrochemical processes in reusable enclosed reactors.

Seal Challenges:

- Long term (years) exposure to space environments: Ultraviolet (UV) radiation, Micrometeroid damage
- Dust: abrasive and electrostatically charged
- Temperatures: Cryogenic (propellants) thru high temperatures for regolith processing
- Low leakage rates to maximize product yield
- Extremely high reliability

Applications

- Resource processing
- Mission consumable production (Life Support & Propellant)
- Surface cryogenic fluid & propellant storage & distribution
- Chemical reagent storage & distribution
- Gas storage & distribution
- Water & earth storable fluid storage & distribution

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Seal Team

NASA is evaluating In-Situ Resource Utilization (ISRU) technologies that would help allow astronauts to “live-off-the-land.” for either Lunar or Martian missions. These technologies would help increase mission success for a manned mission to Mars that would entail a 6 month transit time and a 500 day stay.

Some of the technologies under consideration, include production of mission critical consumables including:

+ propellants (e.g. harvesting the Martian atmosphere carbon-monoxide to make methane fuel)

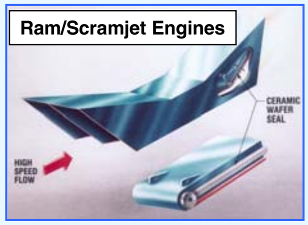
+ life support consumables, (e.g. harvesting Lunar ice believed to be at the poles)
+ fuel cell reactants

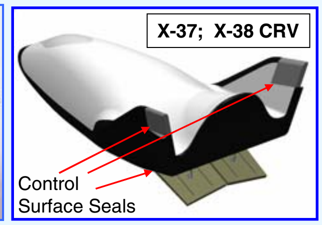
Achieving these ambitious goals however requires solving several important seal challenges, as shown in the chart. For additional information about NASA’s ISRU project, please see Sackstedder 2006, in this Workshop Proceedings.

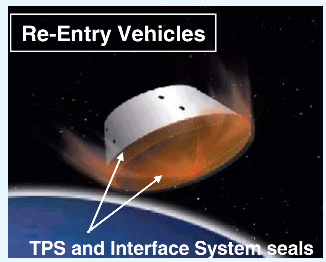
Re-Entry and Hypersonic Vehicle: Seal Challenges and Projects Supported

NASA GRC Structural Seal Development Goals:

- Develop hot (2000-2500+°F), flexible, dynamic structural seals for ram/scramjet propulsion systems (TBCC, RBCC)
- Develop reusable re-entry vehicle control surface seals to prevent ingestion of hot (6000 °F) boundary layer flow
- Develop TPS and interface system (e.g. landing system) seals for future the Exploration Initiative.







High temperature seals critical for mission success

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Seal Team

NASA is currently funding research on advanced technologies that could greatly increase the reusability, safety, and performance of future hypersonic vehicles. Research work is being performed 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 2006, et al, and DeMange 2006, et al in this Seal Workshop Proceedings and Dunlap 2003, et al and DeMange 2003, et al for further details.

Seal Challenges and Design Requirements

- **Control surface seals:**
  - Limit hot gas flow and heat transfer to underlying low-temperature structures
  - Withstand temperatures of 1800-2200+F:
  - Stay resilient for multiple load/heating cycles
  - Limit loads against sealing surfaces
  - Resist scrubbing damage

Baseline control surface seal design

- **Propulsion system seals:**
  - Withstand temperatures of 2000-2500+ °F and high heat fluxes with minimal cooling Limit leakage of hot gases and unburned propellant into backside cavities
  - Survive in chemically hostile environment (e.g., oxidation, hydrogen embrittlement)
  - Seal distorted sidewalls and remain resilient for multiple heating cycles
  - Survive hot scrubbing with acceptable change in flow rates

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Seal Team

NASA GRC is developing high temperature seals and preloading techniques to help meet the challenges posed by future re-entry and hypersonic vehicle control-surfaces. These seals must limit hot gas ingestion and leakage through sealed gaps to prevent damage of low-temperature structures (including actuators) downstream of the seal. Gas temperatures that reach the seal can be as >2200 °F. The seals must be able to withstand these extreme temperatures and remain resilient, or “springy”, for multiple heating cycles. The upper image on this chart shows what happens to a baseline Shuttle thermal barrier/seal incorporating an knitted Inconcel X750 spring tube after exposure to 1900 °F temperatures in a compressed state. The seals took on a permanent set. 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.

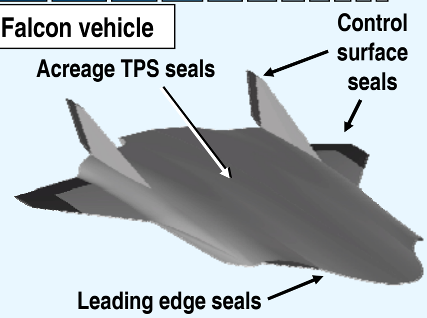
Oswald et al 2005, performed finite element analyses on various spring tube designs defining desirable knit parameters to minimize stress while still supporting the necessary loads. Taylor et al 2005, identified the benefits of Rene’41 material over conventional Inconel X-750. Substituting specially heat treated Rene’41 wires raised the operating temperature 250 °F to approximately 1750 °F. The Seal Team is also working on preloading techniques with higher temperature capability and on seal designs that will be more resistant to wear than the conventional seals shown.

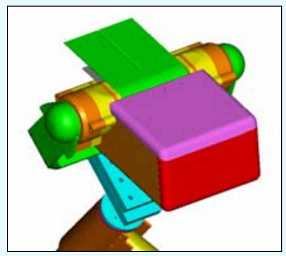
Ram/scramjet propulsion system seals must withstand similar punishing temperatures while using minimum cooling. The seals must limit leakage of hot gases and unburned propellant into backside cavities. They must exhibit good resiliency and flexibility to maintain sealing contact with adjacent walls. And must exhibit acceptable change in flow rate with cycling. The seals must meet all of these requirements while resisting the extreme heat fluxes shown in this NASA GRC hydrogen rocket test chamber.

FALCON Hypersonic Vehicle Seal Development

- Objective: Develop high temperature seals for control surfaces and access doors on future hypersonic vehicles
- Requirements
  - Temperature: Extreme
  - Life: Reusable
  - Mission duration: Less than 2 hrs
- Approach
  - Identify and develop high temperature seals and preload devices
  - Perform critical function performance tests at GRC
  - Perform arc jet tests on leading concepts at JSC
- Partner organizations: DARPA, Lockheed Martin

Falcon vehicle





Model of GRC seal arc jet test fixture

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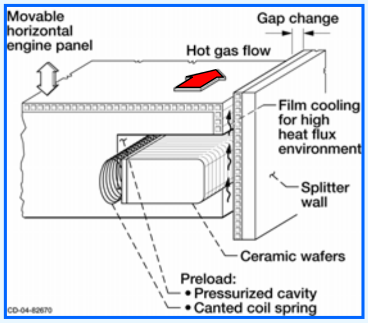
NASA Glenn is working to develop high temperature seal technology and test techniques for future hypersonic vehicles under DARPA (Defense Advanced Research Project Agency) sponsorship. Vehicle thermal protection system (TPS) seals are required for control surfaces, leading edges and acreage TPS locations. Seals are required to operate under extreme temperatures of hypersonic flight (2000+°F), survive flight times of approximately 2 hrs, and be reusable.

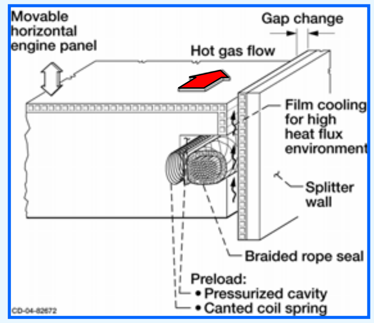
Glenn is developing advanced concepts made of high temperature refractory and ceramic materials, assessing their performance using both GRC's state-of-the-art high temperature seal test rigs and a new arc jet test fixture. Using this new fixture (being fabricated), control surface seals can be tested under hypersonic heating conditions (Finkbeiner et al 2004). The seals are scrubbed against a ceramic-matrix composite (carbon/silicon carbide) control surface, as the flap is articulated during arc jet exposure simulating flight.

Example Structural Seals Being Investigated



Ceramic Wafer Seal

- High temperature operation: 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: 2400+°F
- Flexible: seals & conforms to complex geometries
- Hybrid design (ceramic core/superalloy wire sheath) resists abrasion
- Tandem seals permit central cavity purge (cooling)

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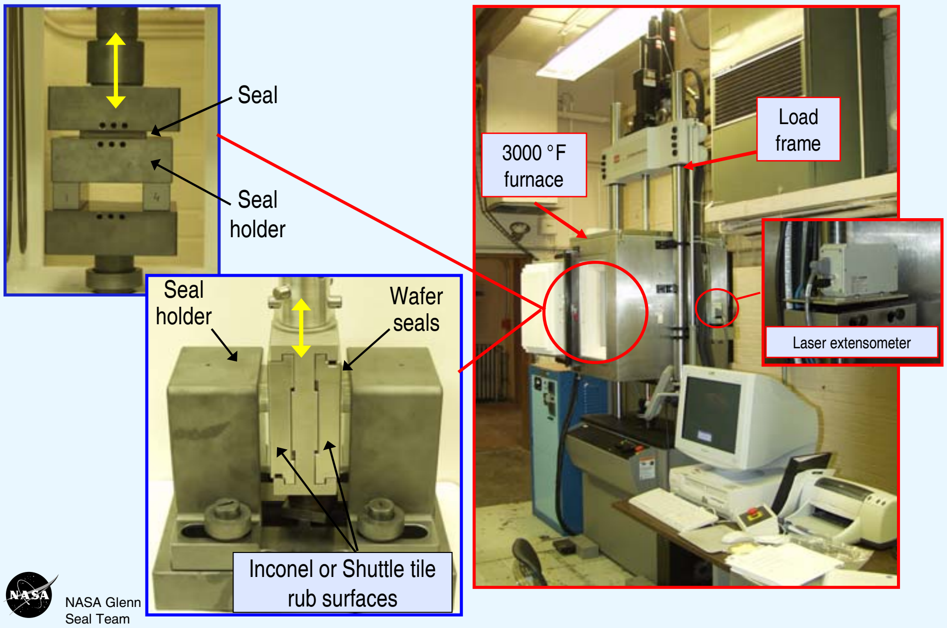
Seal Team

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. The ceramic wafer seal's high temperature (2200 °F) performance was demonstrated in GRC's scrub and flow fixtures (Dunlap et al, 2004). Dunlap et al (2005) investigated wafer size, shape, and dimensional tolerance on seal leakage performance using a design-of-experiments approach. Demange et al (2003) evaluated a variety of braided rope seal configurations with engineered cores to provide greater flexibility than early NASP seal designs.

Hot Compression/Scrub Seal Test Rig: Overview

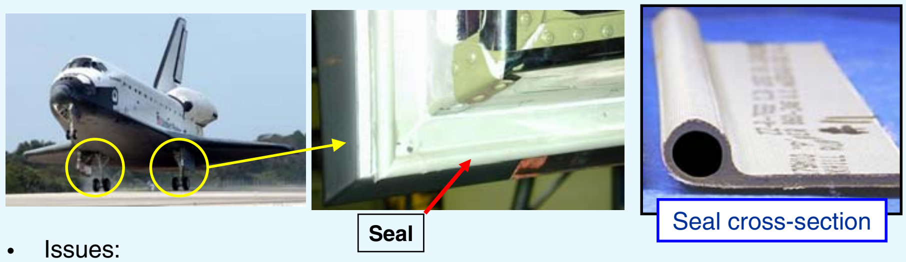


NASA GRC has installed state-of-the-art test capabilities for evaluating seal performance at temperatures up to 3000 °F (1650 °C). This one-of-a-kind equipment is being used to evaluate existing and new seal designs by simulating the temperatures, loads, and scrubbing conditions that the seals will have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

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

Space Shuttle Main Landing Gear Door Seal Assessments

Shuttle Main Landing Gear Door Seal Tests: STS114



- Issues:
  - Environmental seals prevented main landing gear (MLG) doors on Discovery from closing completely: must be fully closed for flight without steps in outer mold line (OML)
  - Seal performance (leakage, loads) vs. amount of compression not well-characterized
- Objective:
  - Determine optimal compression on seals to minimize leakage without putting excessive loads on doors
- NASA Johnson Space Center requested testing of MLG environmental seals at GRC
  - Room temperature compression tests
  - Flow tests

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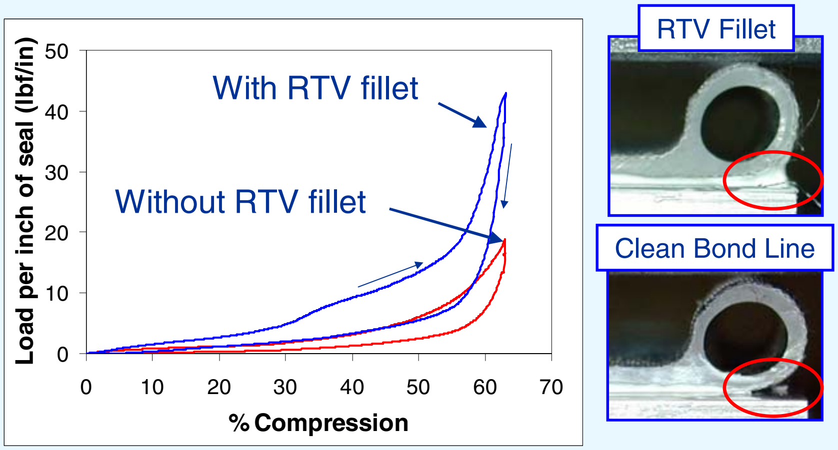
Seal Team

In preparing Shuttle Discovery for the Return-to-Flight mission, engineers at NASA Kennedy Space Center (KSC) and NASA Johnson Space Center (JSC) uncovered a problem in which the environmental seals around the perimeter of the main landing gear doors were preventing the doors from closing completely. This condition is unacceptable for flight because the outer mold line must be smooth during a mission. Raised areas and steps in that surface (such as can be caused by a door that is not fully closed) disrupt the flow of hot reentry gases over the surface and can lead to excessive heating in localized areas.

When this problem was identified, engineers at NASA JSC asked the Seals Team at GRC to help them solve this problem by performing room temperature compression and flow tests on the seals to characterize their performance and determine an optimal compression on the seals to minimize leakage without putting excessive loads on the doors.

Shuttle MLG Door Seal Tests – Key Findings



- Loads for seal with excess RTV were more than 2X those for seal with clean bond line.
- GRC also determined preload conditions for acceptable leakage flow.

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Through discussions with JSC and KSC, it was learned that the RTV used to bond the seals to the MLG doors can often squeeze out under the seal bulb during installation. In these cases the RTV can form a “fillet” below the bulb as opposed to a clean bond line. KSC and JSC thought that this fillet could be playing a role in why the MLG doors would not close.

GRC performed a series of compression tests on both bulb configurations and discovered that peak loads for seals with an RTV fillet below their bulbs were more than twice as high as those for seals with a clean bond line. Finkbeiner et al, 2005 documents the results of these studies.

Shuttle MLG Door Seal Tests – GRC Recommendations

- Implications for Return-to-Flight
  - GRC recommended removal of excess RTV from Discovery seals
  - Seal installation procedure amended to include removal of excess RTV
- Closure of 2 MLG doors successful!!
  - Starboard door – Removal of excess RTV
  - Port-side door
    - » Removal of excess RTV
    - » Custom shims
    - » Door closure mechanism adjusted

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Seal Team

Based on these test results, GRC recommended removing the excess RTV from behind the seal bulbs on Discovery and suggested amending the installation procedure for these seals to include removing the excess RTV for future missions.

KSC followed GRC’s recommendations and was successful in closing the MLG doors for flight. The starboard MLG door was able to close completely by removing the excess RTV from behind the seal bulbs. The solution for the port-side door was somewhat more complicated, though, and also involved installing custom shims and adjusting the door closure mechanism.

Summary

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

- **NASA Glenn's Role**

  Partnered with key government and contractor organizations to
  - **Develop advanced seal technology**
  - **Provide technical consultation**

  for the Nation's key aero- and space advanced technology development programs.

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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.

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

NASA Seals Web Sites

- **Turbine Seal Development**
  - **http:/www.grc.nasa.gov/WWW/TurbineSeal/TurbineSeal.html**
    - » NASA Technical Papers
    - » Workshop Proceedings
- **Structural Seal Development**
  - **http://www/grc.nasa.gov/WWW/structuralseal/**
    - » NASA Technical Papers
    - » Discussion
    - » Seal Patents
  - **http://www/lerc.nasa.gov/WWW/TU/InventYr/1996Inv_Yr.htm**

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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.

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Seal Team

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NASA Glenn Research Center
Seal Team

GLOBAL ENERGY AND AVIATION CONCERNS

Robert C. Hendricks
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Dave Daggett and Peter Anast
The Boeing Commercial Airplane Group
Seattle, Washington

Nathan Lowery
Princeton University
Princeton, New Jersey

National Aeronautics and Space Administration

Global Energy and Aviation Concerns

R. C. Hendricks
NASA GRC
Dave Daggett and Peter Anast
The Boeing Commercial Airplane Group
Nathan Lowery
Princeton University

Seals and Secondary Air Flows Workshop
Ohio Aerospace Institute
8-9 November 2005

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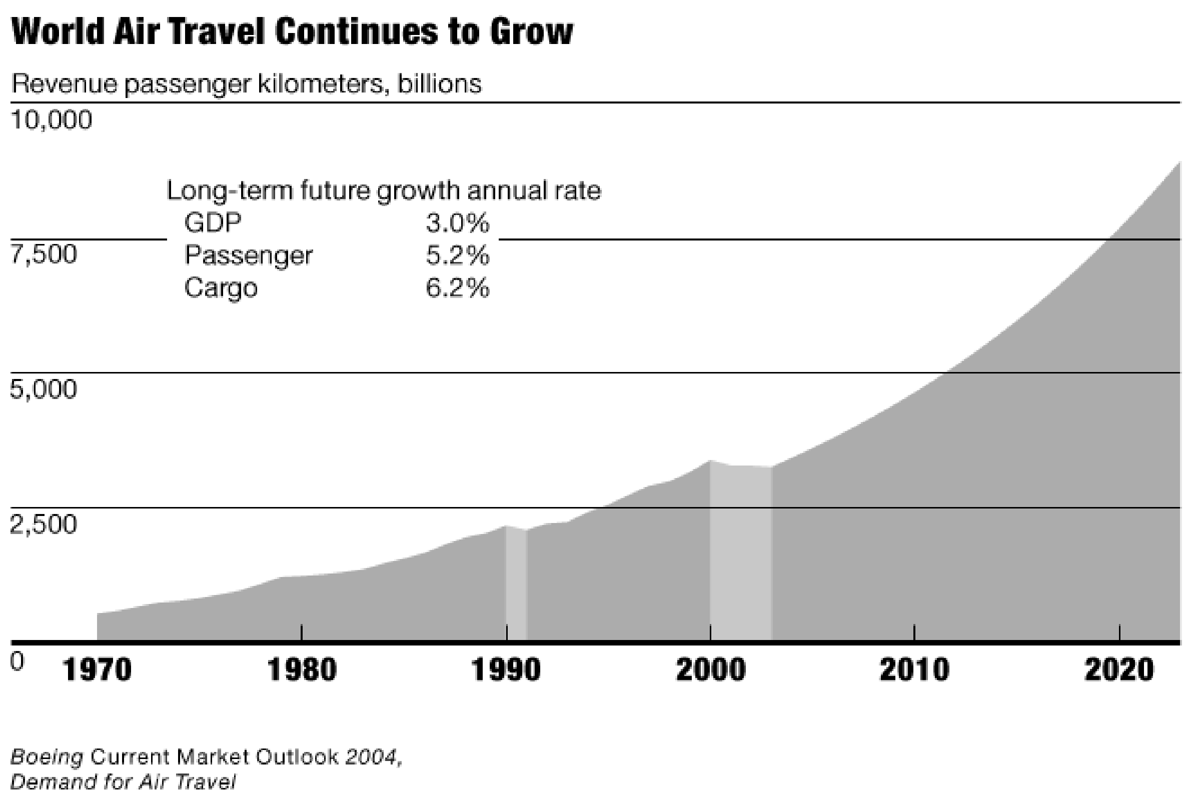
Windows of Opportunity

- From time to time we feel it necessary to draw your attention to changes that we feel will affect the seals and secondary flow community. In the past we have cited changes and needs in technical direction in several areas such as :
- Dr. Keith cited our Navy-NASA seals conferences and out of them grew a community of understanding under the leadership of Larry Ludwig. And from this community came the ***Self-acting Face Seal*** as well as a greater understanding of face seals use in engines.
- Attention was then turned to Rocket Engines for the Space Program and required the development of ***Cryogenic Sealing*** and applications.
- With the advent of the very high power-density Space Shuttle Main Engine came the need for understanding of the ***Rotordynamics of Turbomachines***
- The complex interaction between sealing and secondary flows required more accurate and validated methods for design and the codes ***SCISEAL, INDSEAL*** and ***SCISEAL-TURBO*** were developed to meet these needs.
- We cited that future demands of ***Anthropogenic Global Emissions and Control*** would become major issues and major opportunities for the sealing and secondary flow community.
- With the development of new seals and emissions demands, we then cited the needs for ***Reliability and Life and Field Data Feedback*** for design support and integration into our codes.
- Today we want to draw your attention to ***Global Energy and Aviation Concerns***.

✓ For references, see Seals and Secondary Air Flow, and Rotordynamic Instability Problems in High Performance Turbomachinery Workshops as cited in **NASA/TM—2004-211991/PART1, PART2, PART3**

National Aeronautics and Space Administration

Air traffic is expected to grow at least 5% per year [Daggett (2005)]



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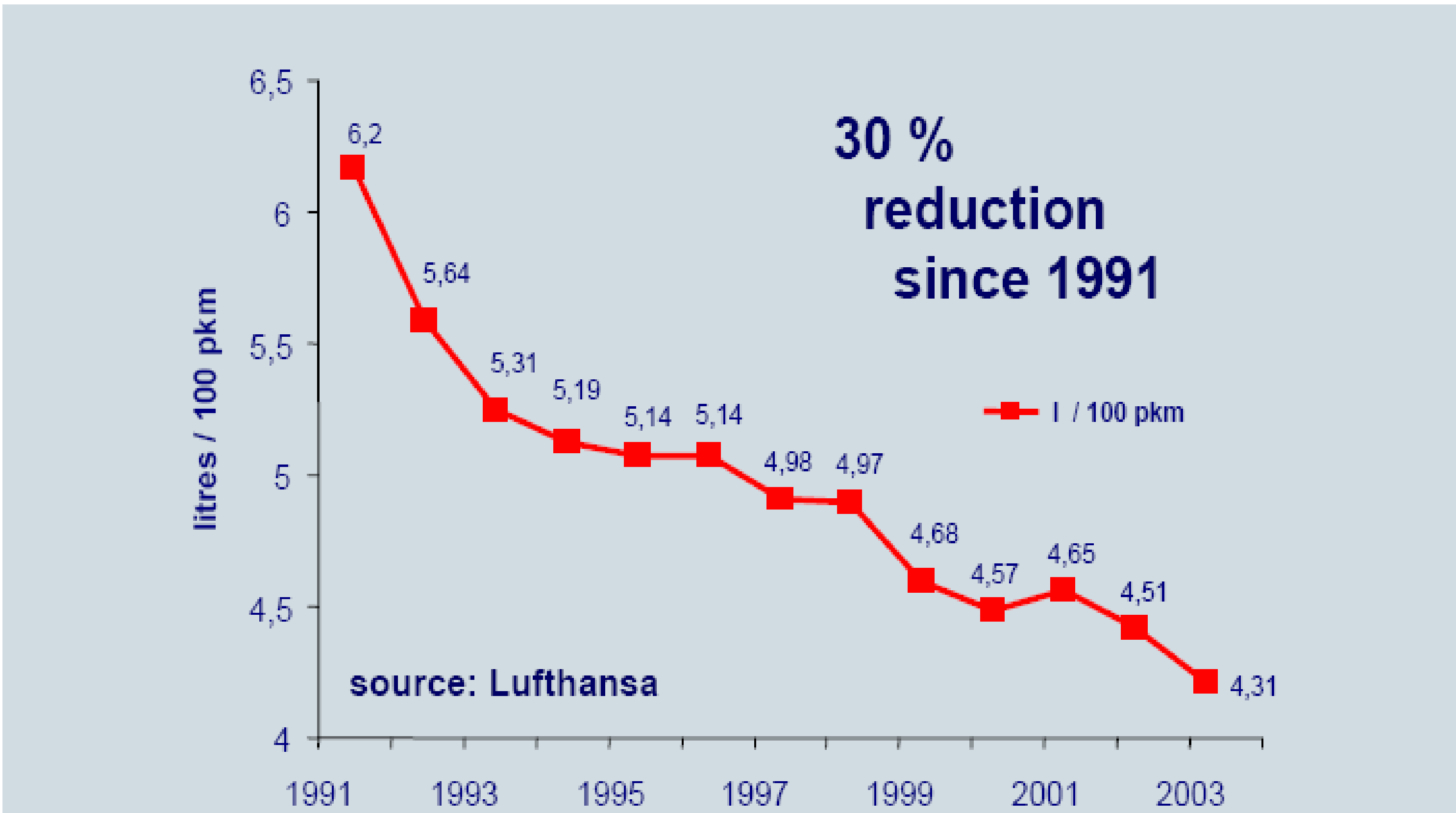
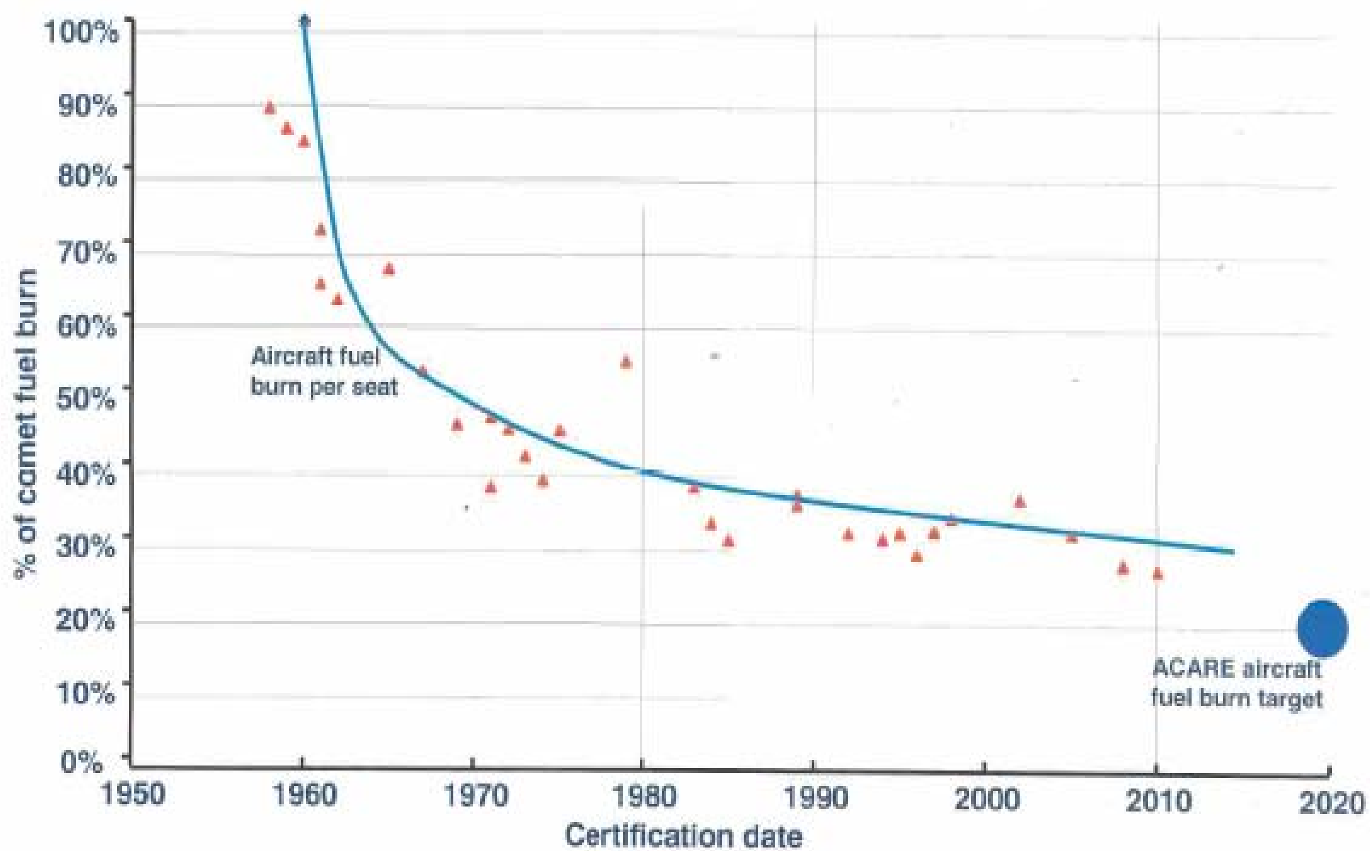
Fleet fuel consumption (liter/passenger-km) shows 30% reduction since 1991, Broichhausen (2005)



www.nasa.gov

Fuel Efficiency Improvement of Long Range Transport Aircraft: Reduce (2003)-fuel burn 50% , Smith (2005).

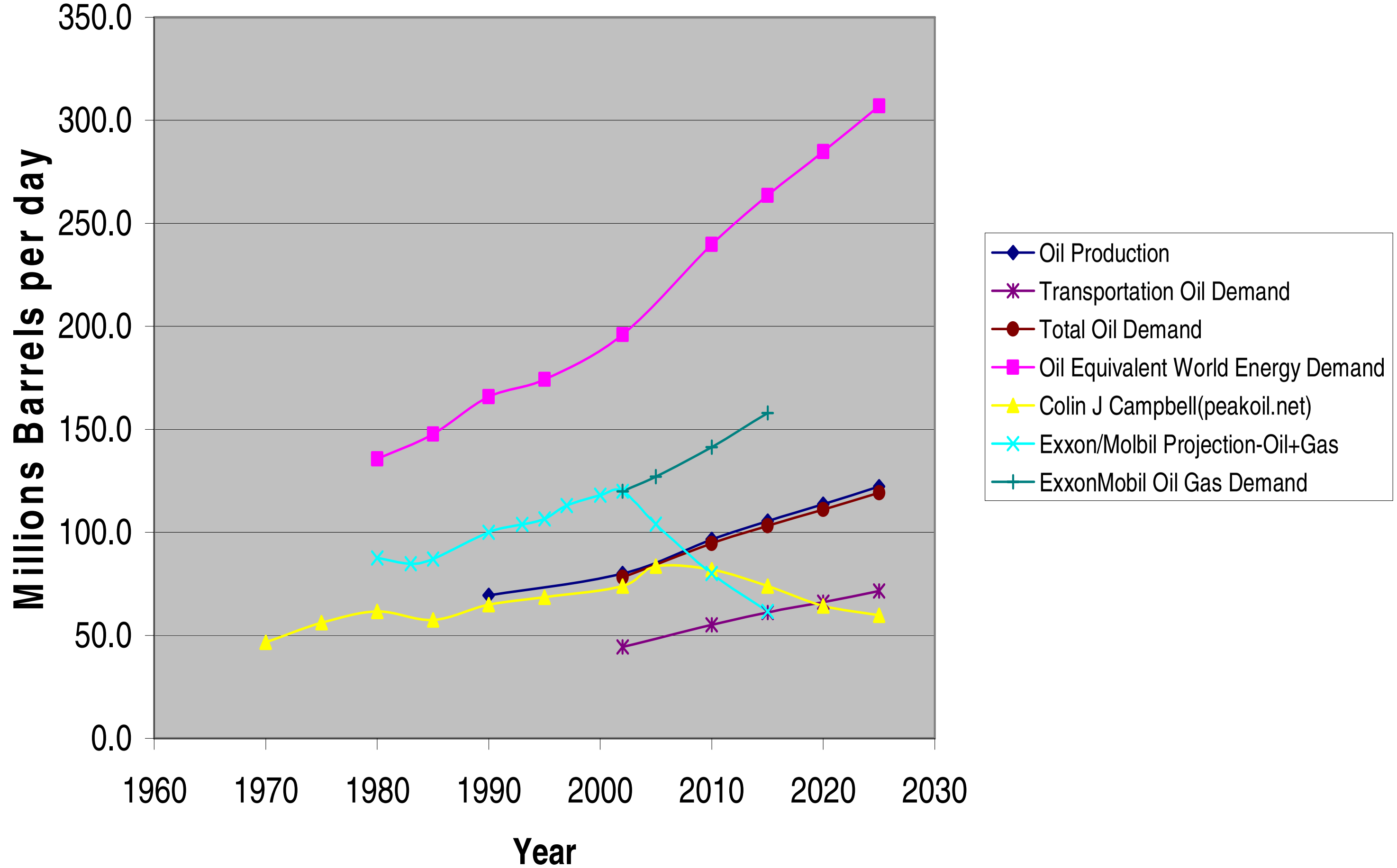


Investment and Cost of Growth

- We select air travel as it is of interest to the NASA Aviation Program, yet our concern permeates the transportation and industrial power generation community as well and hence the full spectrum of sealing and secondary flows.
- Air travel is projected to return to its pre-911 growth of 5% per year.
- In some areas (Asia Pacific Rim) this growth is already at 14%
- We are doing well reducing total fuel burn in terms of liters of fuel / passenger-km and aircraft efficiency has been reduced but is nearing a plateau (EU 2020 goal: reduce fuel burn long-range aircraft 50%)
- But here are some of the problems we face.
- Our total energy demand is projected to rise nearly linearly over the decades while our energy supply for transportation (oil) declines.
- Our nation's economic and military security depend on oil.
- The current production of oil appears limited to 84Mbbl/day and would require significant capital investment of $16 Trillion to meet these demands for oil.
- The problem is that oil availability is limited and it is not a question as to if we will run out of "cheap oil" but when.
- Most of the proven oil reserves reside in the middle east with 2/3 in Saudi Arabia.
- Rapidly rising foreign interests in oil and natural gas have expanded foreign presence and heighten potential for conflict.

National Aeronautics and Space Administration

World Energy, Oil/Gas and Transportation vs Production Reality [Source: EIA and Others]



www.nasa.gov

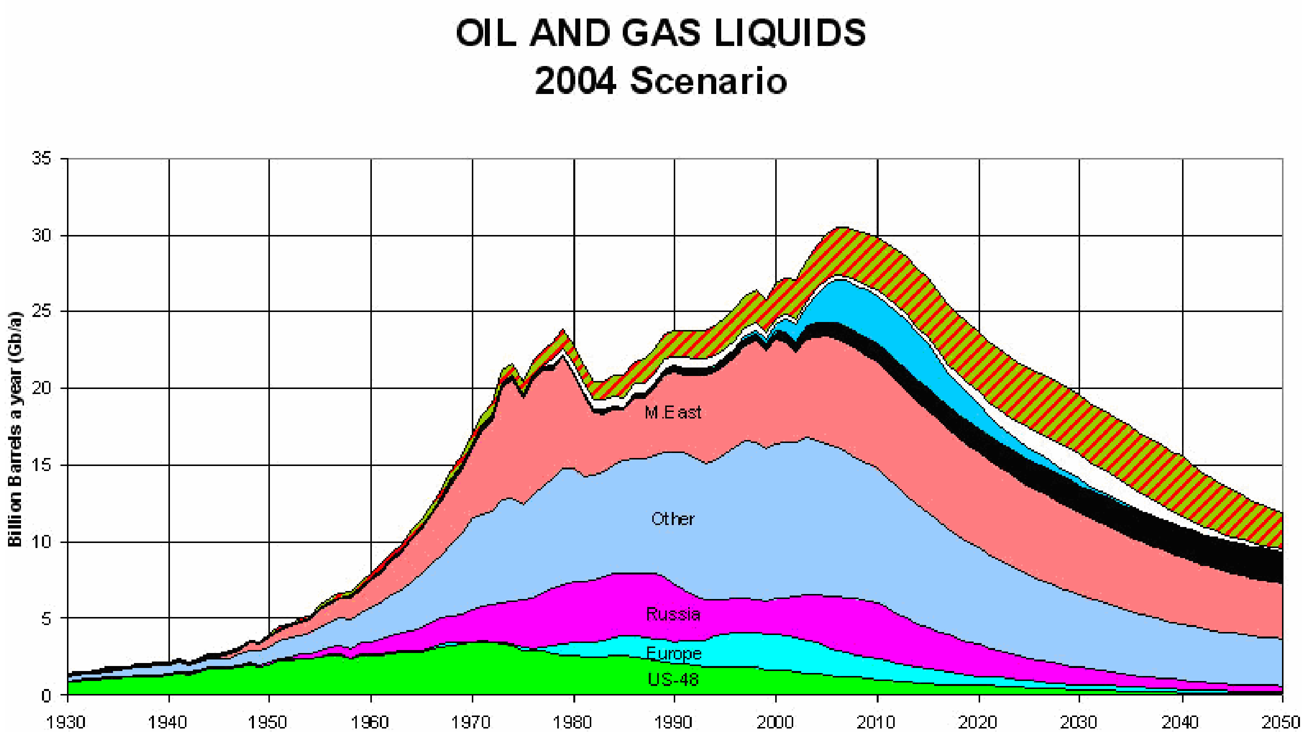
Oil consumption

http://www.peakoil.net/uhdsg/Default.htm

Uppsala Hydrocarbon Depletion Study Group

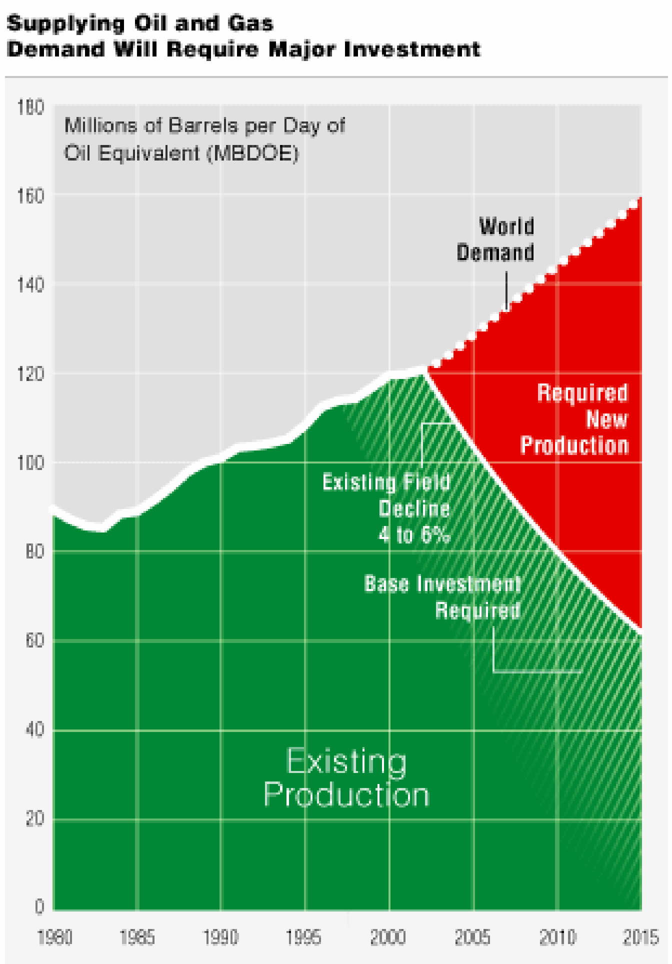
OIL AND GAS LIQUIDS 2004 Scenario

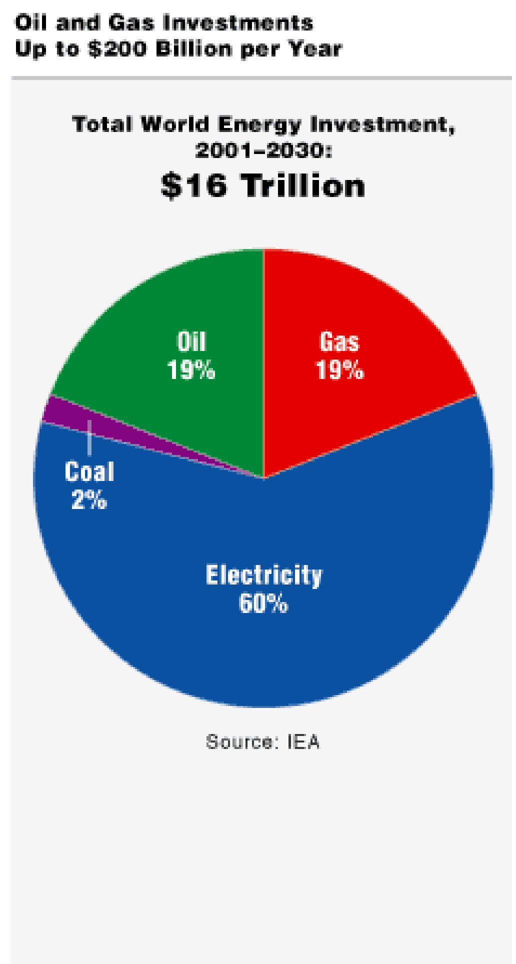
Updated by Colin J. Campbell, 2004-05-15



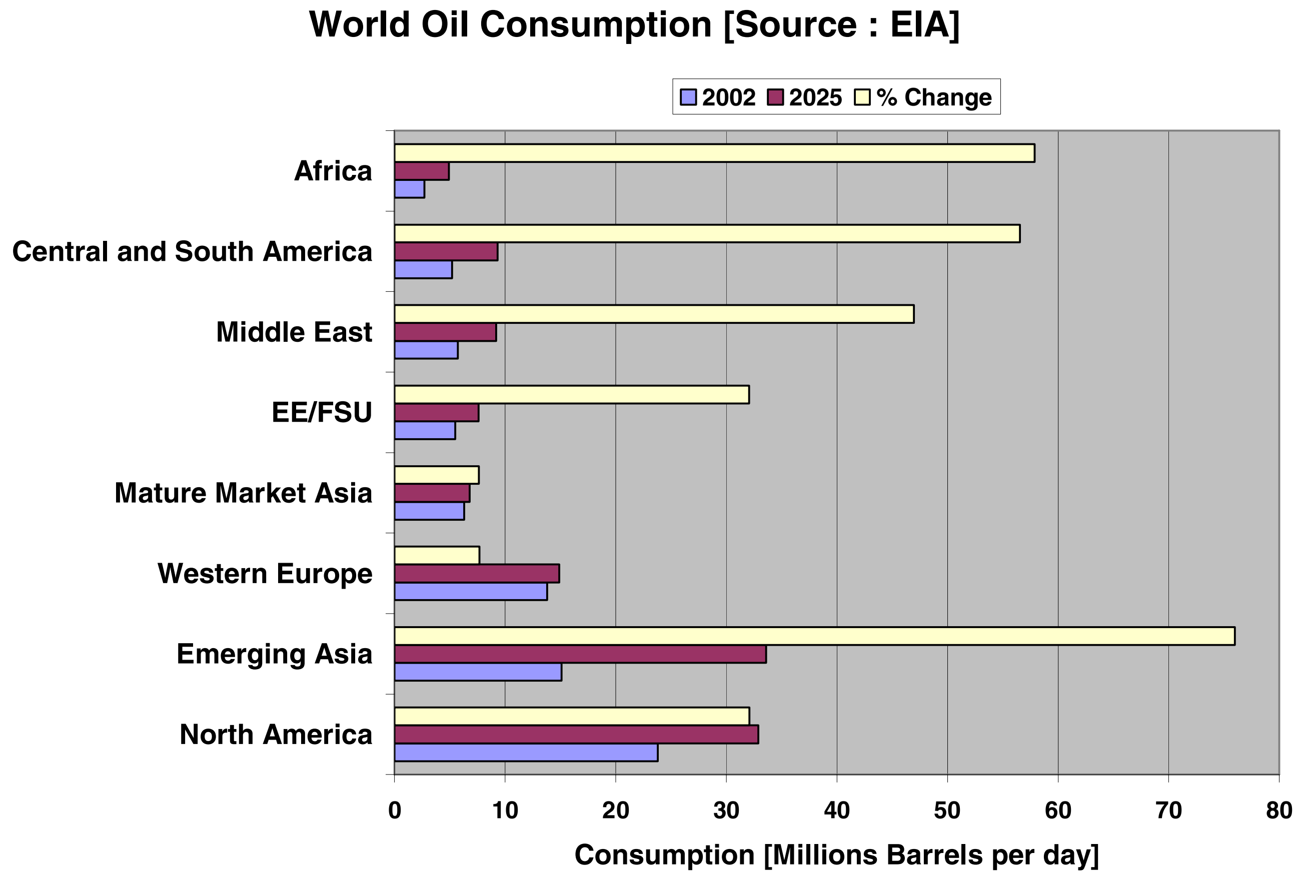
Oil and gas production, demand and investment

http://www.exxonmobil.com/corporate/Newsroom/Publications/eTrendsSite/chapter1.asp





World Oil Consumption by Regions for year 2002 and projection for year 2025 with percent increase in consumption.



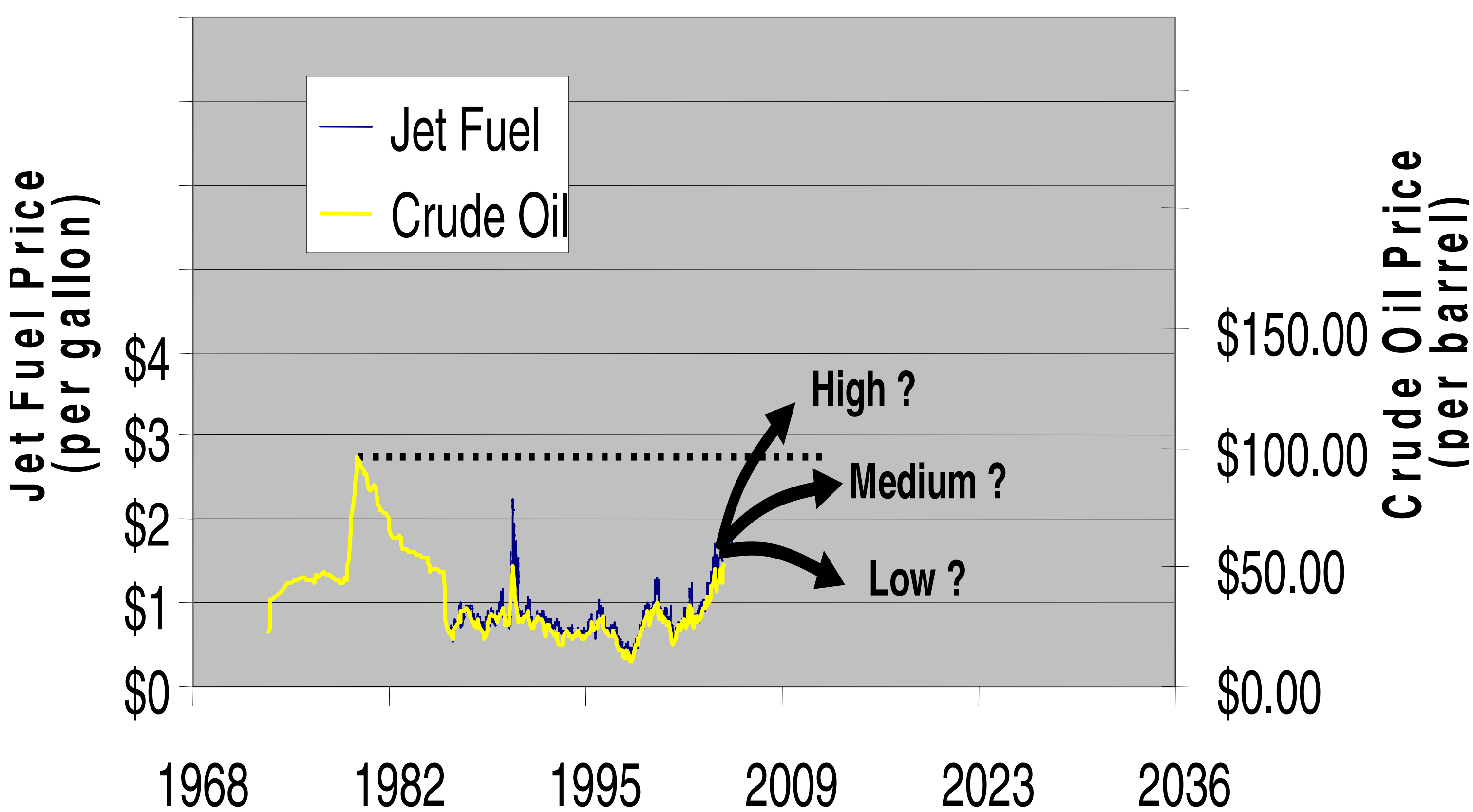
Fuel Price Scenarios

- The cost of fuel and availability becomes the major concern. For aviation this fuel is Jet A.
- The price of Jet A closely follows the price of crude oil and we are looking to the price in year 2020.
- The low-price ($1.33/gal) represents a linear extrapolation of fuel and crude oil prices for over a decade; current price highs will settle back down
- The medium-price ($2.67/gal) is a linear extrapolation over the past 5 years and nearly double the low-price.
- The high-price is a linear extrapolation over the past 3 years, ($ 5.12/gal) extending the trend in supply and demand and nearly four times the low-price. Not unreasonable as European petrol is $5/gal and some places diesel is $7/gal.
- This means that fuel costs will rise from about ¼ to ½ the cost of operating the aircraft.

National Aeronautics and Space Administration

Comparison of historical price of crude oil to Jet-A fuel with possible future projections to the year 2020.

low $1.33/gal : **medium** $2.67/gal : **high** $5.51/gal



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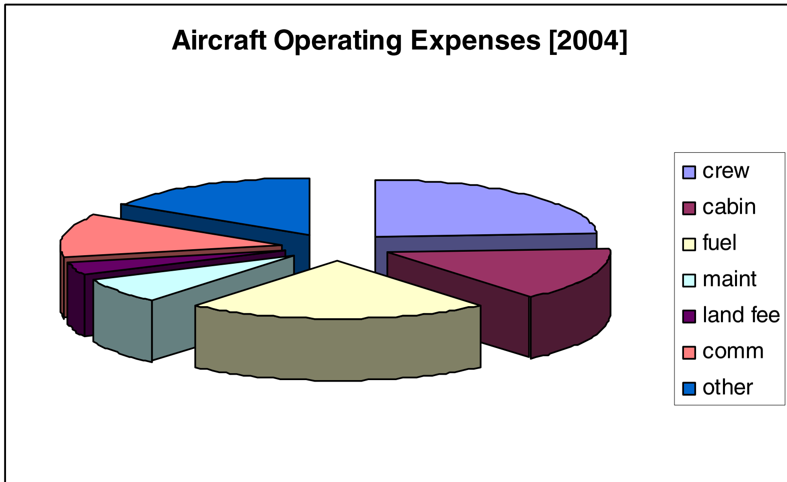
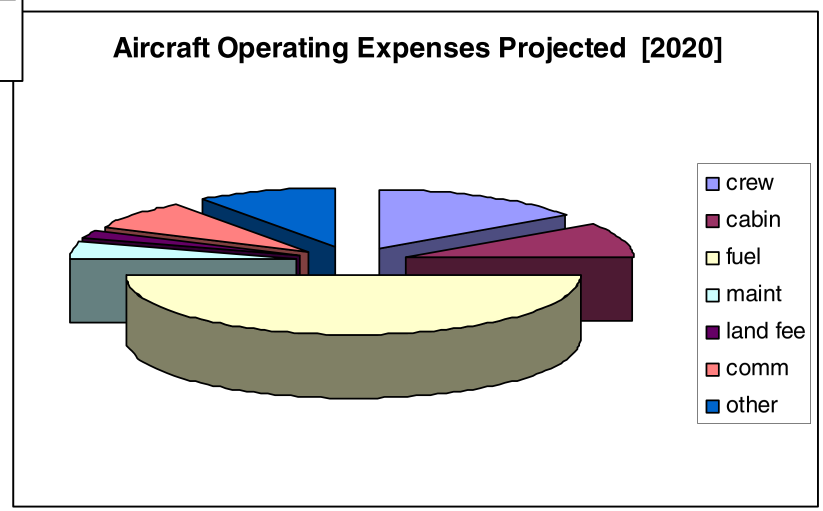
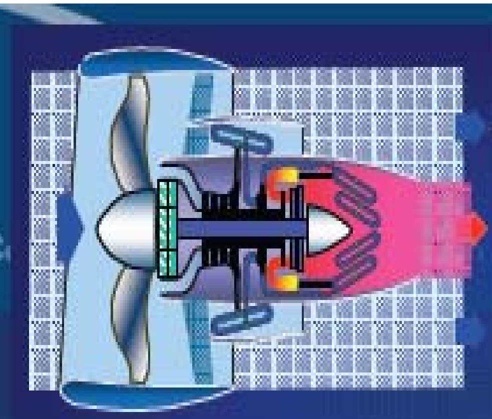
Aircraft Operating Expenses





National Aeronautics and Space Administration

Visions of future aircraft and engine configurations
[Szodruch (2005) and Broichhausen (2005)].



Hydrogen | Intercooler/Recuperator | Solar/Fuel Cells

Lower

&

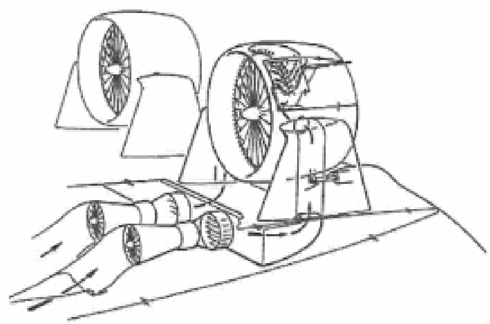
Slower

www.nasa.gov

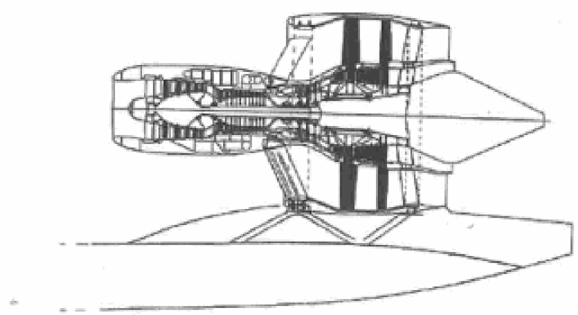
Potential Industrial Response

- So how will the aviation and transportation community in general respond.
- Systems integration designs from the well-head to disposal (cradle to grave). Engines and aircraft will be blended, green, efficient and integrated.
- Looking ahead to hydrogen which we feel will be the fuel of the future, yet appears more distant than first perceived. Gas to Liquid Fuel (GTL) as from natural gas (NG), coal or bio-mass appears to be an intermediate solution. Bio mass will help and is projected to produce 5 B-gal/year, but we use some 180Bgal of fuel per year(13.6Bgal 2004-domestic aviation only). Yet as with all new fuels, these fuels along with their additive packages, reactions both in energy release and materials life must be assessed. These can be very challenging problems yet very good opportunities for the seals and secondary flow community.
- Intercooling and recuperating in engines to increase overall energy utilization; Synergistic heat engine, fuel-cell electric and geared fan system
- Use renewable energy sources as solar, wind and more efficient energy conversion methods such as fuel cells
- Flights may become lower and slower with larger engine fans or turboprops
- Embedded engines may drive external fans or aft-mounted fans may be used particularly for blended wing body (BWB) aircraft

2005 vision of future aircraft configurations The Environmental Challenge, Bringing Technology to Market [Smith (2005)]



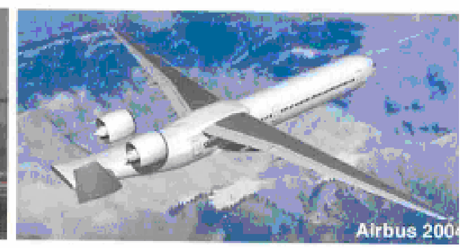
Embedded engine core with remote fan system



Aft fan concept

Silent Aircraft Initiative (Design SAX03)

Blended Wing Body concept



Pro-active green aircraft concept

Fuel Consumption and Global Warming Issues

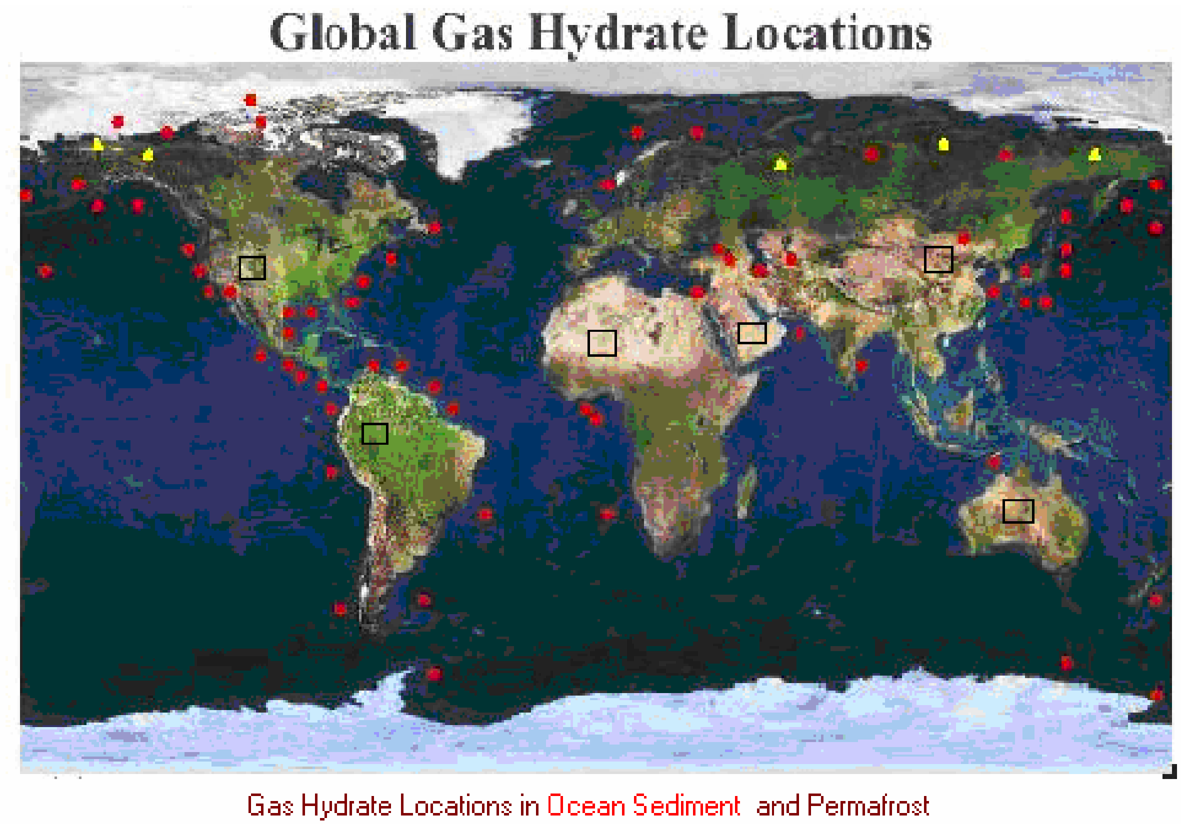
- **A few sobering comments about Global Warming and green house gases (GHG : CO2, CH4, N2O, SO4, H2*) are warranted. GHG-atmospheric lifetime: CO2 (5-200yr); CH4 (12-160 yr); N2O (>100yr)**
- **Vast deposits of gas hydrates (methane) encompass the Americas and Japan but harvesting is quite complex and expensive**
- **Even if we could tap into gas hydrates (methane) and make GTL liquid fuels, we cannot continue pumping GHG - CO2 into the atmosphere unabated. [Industrial revolution starts around 1760 - England (red arrow)**

  Oil Rush - Titusville PA, Drake Oil Well 1859 (blue or yellow arrow)]
- **Small changes in ocean temperatures spawn large changes in planetary response. Hansen Global Warming & anthropogenic global warming**
- **Ocean sequestered Methane Gas Hydrates are approaching thermal stability limits.**
- **Uncontrolled release of methane from ocean gas hydrates exacerbates global warming.**
- **Methane traps over 20 times more heat per molecule than carbon dioxide.**
- **For those who know hydrogen, it is environmentally benign, easy to work with and forgiving as long as you respect and obey its power and authority; but when violated, it can unleash fury like hell never knew.**
- **(Added) Hansen Global Warming Model & anthropogenic global warming**
- Currently, and for the near term, most of the hydrogen produced will be by steam reformation of natural gas (methane) (or coal). *Upper atmosphere H2 can grab O and prevents O2 from becoming O3; H2-air engines produce NOx

Red dots : Global distribution of gas hydrates
Open boxes : Smally's likely areas for massive solar power generation [20 TWe]

http://www.netl.doe.gov/scngo/NaturalGas/hydrates/databank/HydLocations.htm

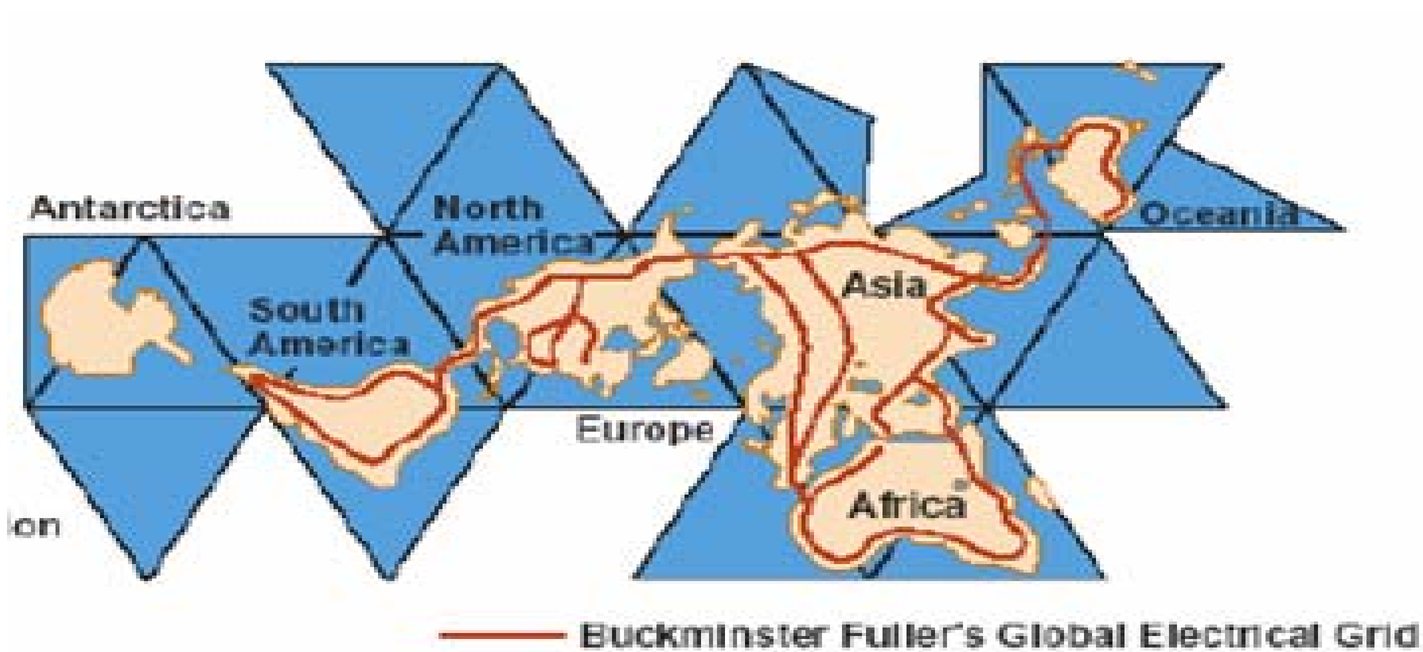
Smalley http://www.sciscoop.com/story/2004/11/3/20322/6497



The Fuller game of planet Earth global electrical grid

http://www.bfi.org/ and Hoffert, http://gcep.stanford.edu/events/workshops_solar_10_04.html

It is interesting that Fuller's energy lines tend to follow some lines of early human migration



Anthropogenic Greenhouse Gases (GHG's) Concentrations, Rates and Atmospheric Lifetimes [http://www.grida.no/climate/ipcc_tar/wg1/016.htm]

Table 1: *Examples of greenhouse gases that are affected by human activities. [Based upon Chapter 3 and Table 4.1]*

	CO_2 (Carbon Dioxide)	CH_4 (Methane)	N_2O (Nitrous Oxide)	CFC-11 (Chlorofluoro-carbon-11)	HFC-23 (Hydrofluoro-carbon-23)	CF_4 (Perfluoro-methane)
Pre-industrial concentration	about 280 ppm	about 700 ppb	about 270 ppb	zero	zero	40 ppt
Concentration in 1998	365 ppm	1745 ppb	314 ppb	268 ppt	14 ppt	80 ppt
Rate of concentration change [b]	1.5 ppm/yr [a]	7.0 ppb/yr [a]	0.8 ppb/yr	-1.4 ppt/yr	0.55 ppt/yr	1 ppt/yr
Atmospheric lifetime	5 to 200 yr [c]	12 yr [d]	114 yr [d]	45 yr	260 yr	>50,000 yr

[a] Rate has fluctuated between 0.9 ppm/yr and 2.8 ppm/yr for CO_2 and between 0 and 13 ppb/yr for CH_4 over the period 1990 to 1999.

[b] Rate is calculated over the period 1990 to 1999.

[c] No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes.

[d] This lifetime has been defined as an "adjustment time" that takes into account the indirect effect of the gas on its own residence time.

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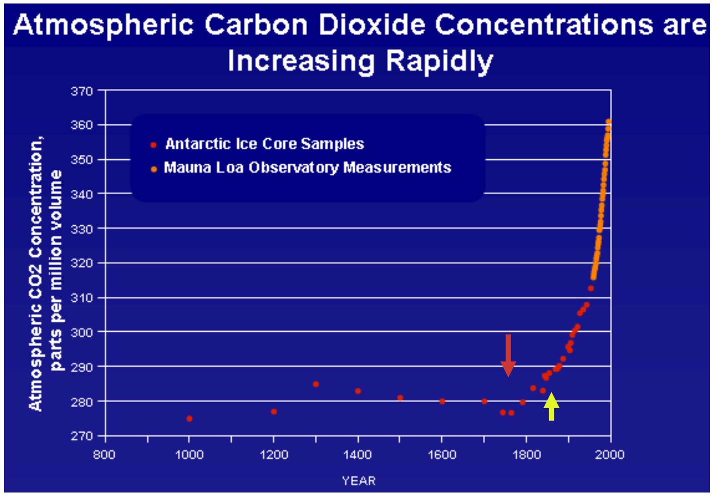
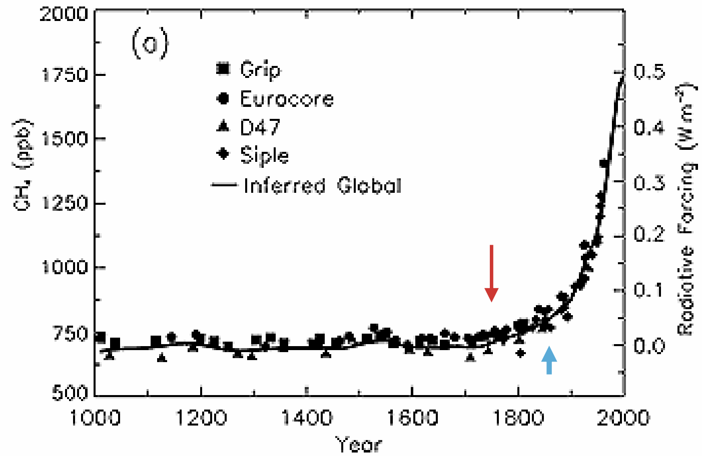


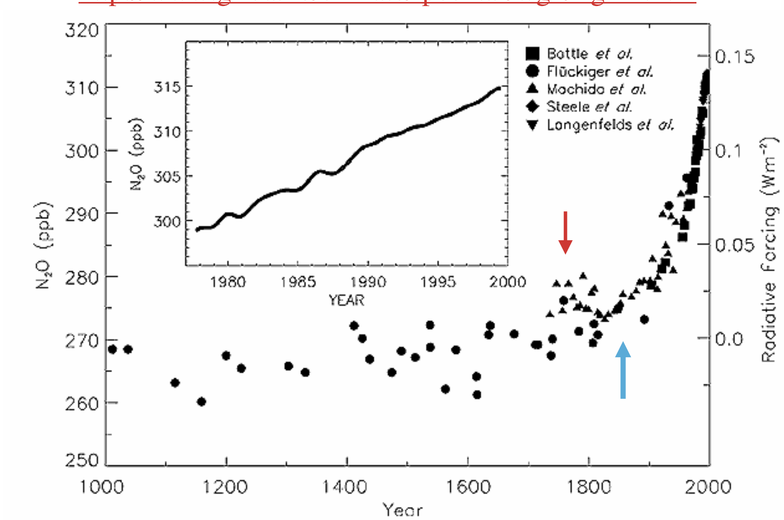
Methane Concentrations (ppBillion)

http://www.grida.no/climate/ipcc_tar/wg1/fig4-1.htm



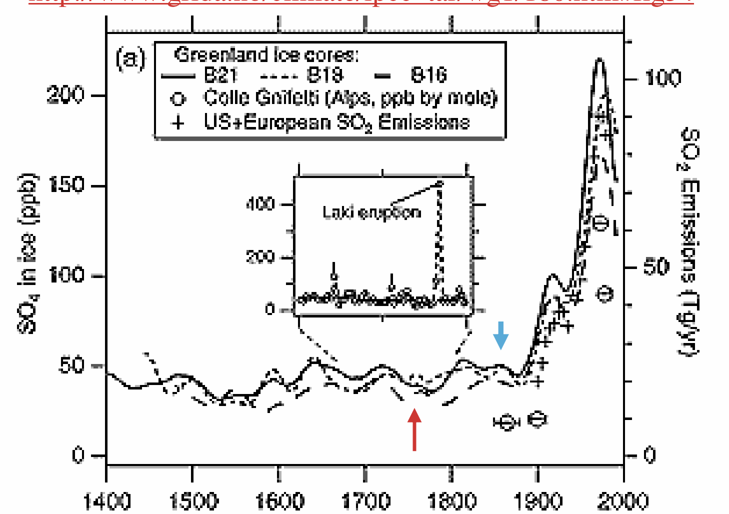
Nitrous Oxide Concentrations (ppBillion)

http://www.grida.no/climate/ipcc_tar/wg1/fig4-2.htm



Sulphate Concentrations Peak ? (ppBillion)

http://www.grida.no/climate/ipcc_tar/wg1/180.htm#fig54



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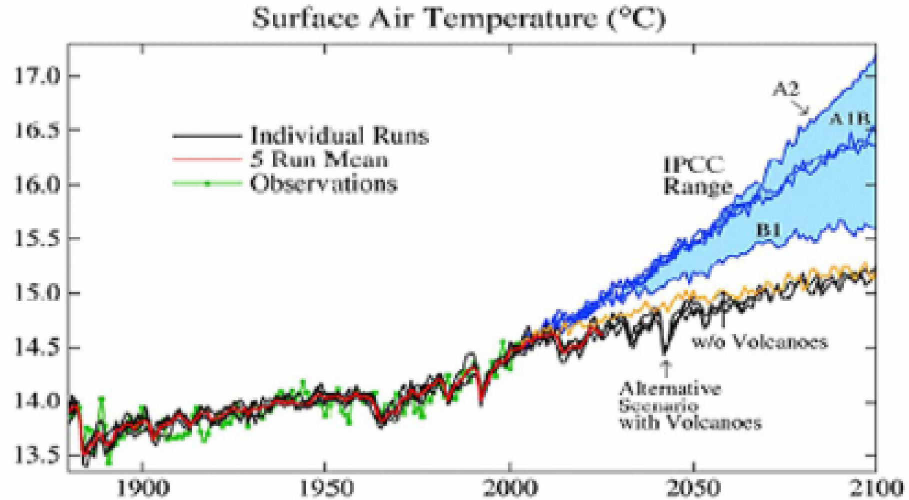
21st Century Global Warming



Climate Simulations for IPCC 2007 Report

- **Climate Model Sensitivity ~ 2.7°C for 2xCO_2**
  (consistent with paleoclimate data & other models)
- **Simulations Consistent with 1880-2003 Observations**
  (key test = ocean heat storage)
- **Simulated Global Warming < 1°C in Alternative Scenario**

Conclusion: Warming < 1°C if additional forcing ~ 1.5 W/m^2 25

Source: Hansen et al., *to be submitted to J. Geophys. Res.*

Hansen, J.E., (2005) Is There Still Time to Avoid "Dangerous Anthropogenic Interference" with Global Climate? A Tribute to Charles David Keeling, Presentation at the American Geophysical Union, San Francisco, Dec. 6, 2005. http://www.columbia.edu/~jeh1/ [**Added after Presentation**]

Solar Wind Energies and New Energy Sources Need Development and Expansion

- Renewable energy sources are usually diffuse and require large facilities
- Biofuels work better, are more economical to produce for ground transportation, but sharply increase competition for food croplands.
- Noble laureate Richard Smalley (deceased-2005) conceptual 20 TWe power generation covers hundreds x hundreds of miles. Combined with Fuller's superconducting power grid system would enable renewable planetary energy.
- A solar-wind project in Australia will have a 7km diameter collector interfacing with a 1 km tower to extract 200 MW from wind turbines mounted at the base.
- GE Energy's 3.5MW Wind Turbine is large and placing this in perspective, it is as if one were rotating a Boeing 747-200; the blade diameter is that large.
- Wind turbines are rapidly gaining popularity in Europe and photovoltaic (PV) is expected to also expand rapidly.
- It becomes clear that we need (and still have time) to develop new sources of energy. Hf 178 bombarded by X-rays produces Gamma-rays for heating. The reaction stops when the X-rays stop; the half life is about 30 years and seems manageable vs 30 000 years. Water splitting needs to be perused as do ultra fast ultra intense laser applications in terms of fusion and new materials developments including new ways to strip and re-bind hydrogen into fuels. New methods and tools for development are being found in quantum mechanical applications to macro-systems and need to be developed into a set of new tool boxes for development of these new energy sources.

Solar - Wind turbines are BIG : A Perspective View

EnviroMission http://www.wentworth.nsw.gov.au/solartower/

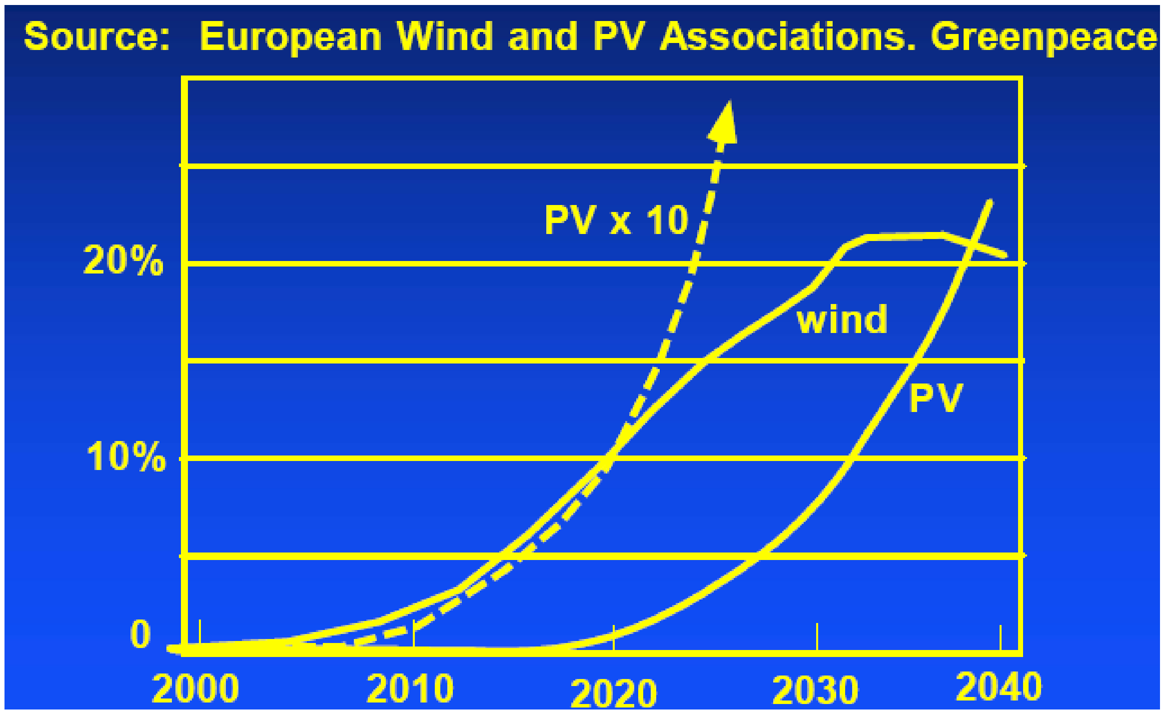
Thresher (2004): http://gcep.stanford.edu/events/workshops_wind_04_04.html

200MW Solar-Wind
7km collector ; 1 km tower

3.5MW GE Wind Turbine

Potential Expansion of Solar and Wind Energy Sources

Green, M. (2004): http://gcep.stanford.edu/events/workshops_solar_10_04.html



SUMMARY

- Oil Limited

  Demand > Supply ; Reduce Dependency
- GTL fuels (NG ; coal ; bio) ; H2 future
- Promote, Develop Energy Efficient Integrated Engines and Vehicle Systems
- Develop solar-wind energy sources

  [reduce emissions, go CO2 neutral ; plant trees]
- R&D New Energy Sources

  {e.g., Hf178, Gas Hydrates, Ultra Fast Ultra Intense Laser Applications, water splitting ,Quantum-Macro …}
- ✓ Challenges and Opportunities Abound

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BRUSH SEALS FOR IMPROVED STEAM TURBINE PERFORMANCE

Norman Turnquist and Ray Chupp
GE Global Research
Niskayuna, New York

Fred Baily, Mark Burnett, and Flor Rivas
GE Energy
Schenectady, New York

Aaron Bowsher and Peter Crudgington
Cross Manufacturing
Devizes, United Kingdom

Brush Seals for Improved Steam Turbine Performance

NASA Seals Workshop
November 08-09, 2005

Norman Turnquist, Ray Chupp – GE Global Research, Niskayuna, NY
Fred Baily, Mark Burnett, Flor Rivas – GE Energy, Schenectady, NY
Aaron Bowsher, Peter Crudgington – Cross Manufacturing, Devizes, UK

GE Energy has retrofitted brush seals into more than 19 operating steam turbines. Brush seals offer superior leakage control compared to labyrinth seals, owing to their compliant nature and ability to maintain very tight clearances to the rotating shaft. Seal designs have been established for steam turbines ranging in size from 12 MW to over 1200 MW, including fossil, nuclear, combined-cycle and industrial applications.

Steam turbines present unique design challenges that must be addressed to ensure that the potential performance benefits of brush seals are realized. Brush seals can have important effects on the overall turbine system that must be taken into account to assure reliable operation. Subscale rig tests are instrumental to understanding seal behavior under simulated steam-turbine operating conditions, prior to installing brush seals in the field. This presentation discusses the technical challenges of designing brush seals for steam turbines; subscale testing; performance benefits of brush seals; overall system effects; and field applications.

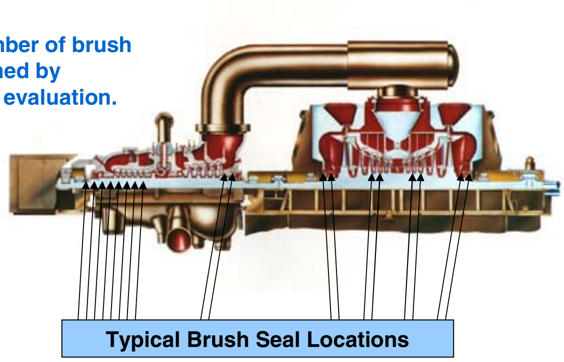
Brush Seals for Improved Steam Turbine Performance

- Steam Turbine Applications
- Performance Benefits
- Seal Design Parameters
- System Considerations
- Laboratory Testing
- Field Experience
- Summary

Outline of presentation

Brush Seal Locations – Shaft Seals

Allowable number of brush seals determined by Rotordynamic evaluation.



Brush Seals at LP rotor ends reduce Steam Seal System needs; seals at HP/IP rotor ends reduce supply leakage.

Brush Seals at selected HP and LP interstage locations further improve heat rate.

Brush seals applied to maximize performance benefit.

-Typically interstage locations of High Pressure Section

-Low Pressure section interstage as well

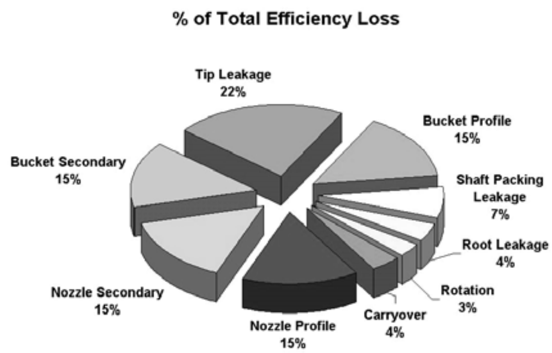
-Also end packings to prevent end leakage (some steam leakage from HP end seals is used to seal LP ends, so LP ends must be sealed as well

-Total permissible number of seals per rotor is evaluated from standpoint of rotordynamics

Performance Benefits

Typical Sources of Steam Turbine Stage Efficiency Loss

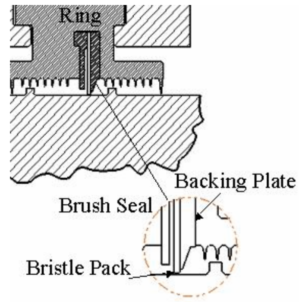
Sealing accounts for nearly 1/3 of total turbine stage efficiency loss.



Sealing accounts for roughly 1/3 of total stage efficiency loss in a steam turbine.

Pressure Drop Capability

- **Decreased Backing Plate Clearance**
  - Improves ΔP Capability
  - But Increases Risk of Rotor Rubs
- **Increased Backing Plate Clearance**
  - Bristles Deform at Inner Diameter
  - Leads to Increased Steam Leakage



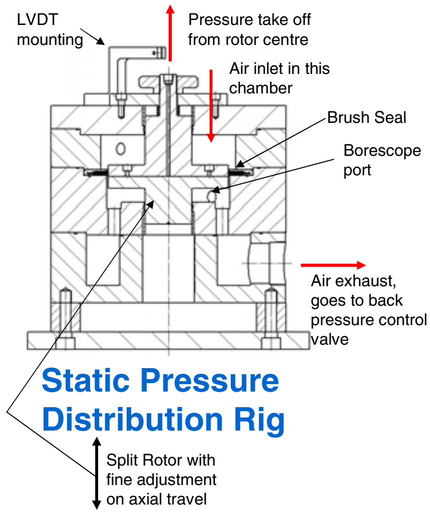
Pressure drop capability of Brush Seals exceeds 2.7 MPa (400 psid); 4.1 MPa (>600 psid for seals in series).

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

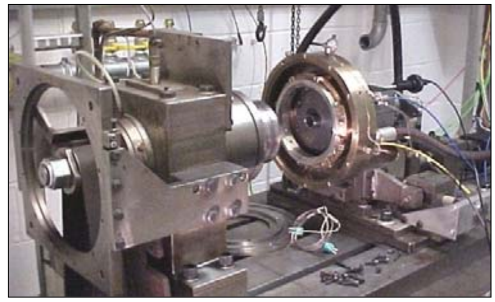
End packing seals typically up to 600 psid.

Can be up to 2000 psid at inlet end of ST; GE is developing compliant seals to handle this.

Seals Test Rigs at Cross Manufacturing



Static Pressure Distribution Rig



Ambient Dynamic Rig

Ambient dynamic rig capability:

Maximum Pressure = 1.8 MPa (260 psia)

Maximum speed = 20,000 rev/min

Maximum surface speed = 136 m/s (444 ft/s)

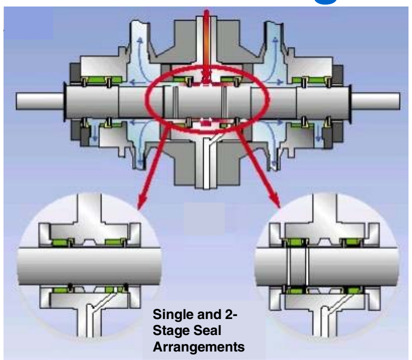
Axial displacement capability

Radial displacement capability

Subscale testing has been conducted jointly between GE and Cross Mfg. in the UK.

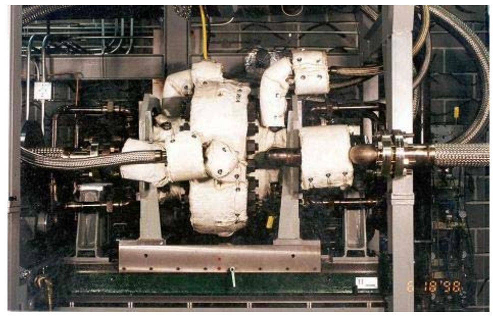
Cross' two subscale rigs are used to perform screening tests on new seal designs, evaluating leakage behavior, wear, and robustness.

Seals Test Rig at GE Global Research



Rig Capabilities:

- **Steam at up to 8.3 MPa (1200 psi); 400 °C (750°F)**
- **Air at up to 3.1 MPa (450 psi), 540°C (1000°F)**
- **Rotor surface speeds up to 245 m/s (800 ft/s)**
- **CrMoV rotor on tilting-pad bearings**
- **Stepped rotor allows wear/hysteresis testing**



Test for:
- **Leakage**
- **Durability / pressure capability**
- **Seal / rotor wear**
- **Seal hysteresis**
- **Rotor dynamics**

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

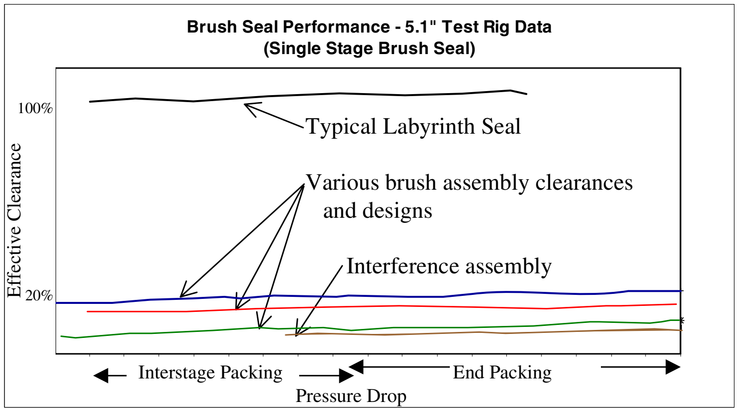
Capable of 800 ft/s surface speed (36000 RPM).

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

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

Seal Leakage Performance

Brush Seal Effective Clearance generally less than 1/3 that of Labyrinth Seals

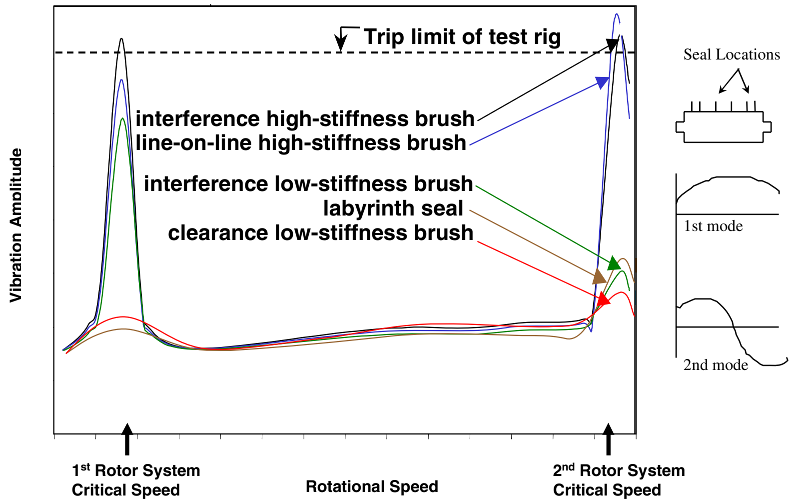


Various brush seal arrangements tested over pressure ranges typical of steam turbine interstage seals.

Even with assembly clearance, brush seal leakage is typically <1/3 that of a conventional labyrinth seal.

Rotor Dynamic Response

Seal design, clearance, and location influence Rotor Dynamics.



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

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

Impact on rotordynamic response is reduced with increasing assembly clearance.

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

Rotordynamics & Turbine Operation

- Contacting Seals at Midspan
  - Influence Behavior Below 1st Bending Critical Speed
  - Start-Up Affected
- Contacting Seals at Rotor Ends
  - Influence Behavior Below 2nd Critical Speed
  - Stability at Running Speed Affected
- Design Methodology Developed
  - Relates Several Rotordynamic System Parameters
  - Determines Acceptable Number of Seals to Apply

Turbine Can Be Started and Operated Normally with NO SPECIAL CONSIDERATIONS

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

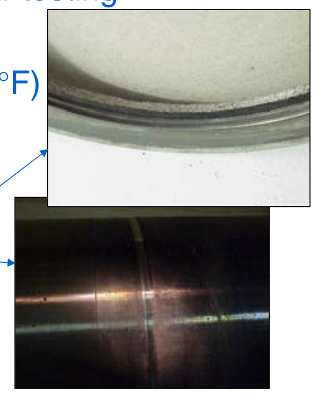
GE has developed a tool to assess rotordynamic impact; validated through lab testing and field experience.

Brush seals are applied in GE steam turbines with no added constraints on turbine operability.

Bristle / Rotor Wear

- Brush Seals Contact the Rotor during machine transients
- Optimum bristle material is temperature-dependent, and is determined via sliding and rotational wear testing
  - Haynes® 25 for T > 260°C (500°F)
  - Hastelloy® C-276 for T < 260°C (500°F)

  ® - Haynes International
- No rotor coating required



Typical Brush Seal and Rotor Surface after Wear Testing on GRC Rig

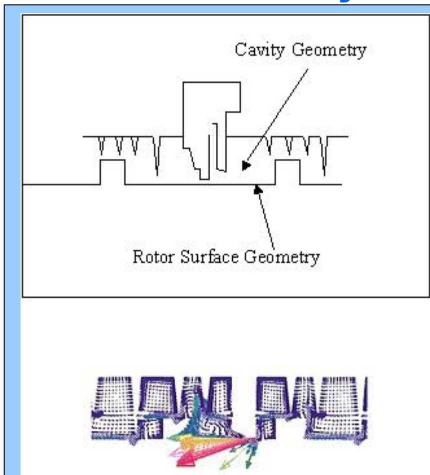
Haynes 25 is standard bristle material for ST applications >500°F

Hastelloy C276 is standard bristle material for ST applications <500°F

Temperatures typically range from 500-1050 F in high pressure turbine section, <500°F in low pressure section.

Used on uncoated CrMoV rotor.

Bristle Stability

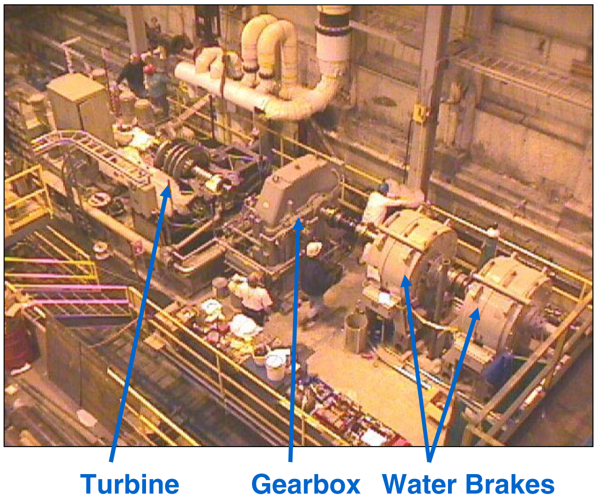


Computational Fluid Dynamics (CFD) Model of Brush Seal with Velocity Vectors

- **Bristle Stability affected by:**
  - **Inlet swirl**
  - **Steam density**
  - **Seal pressure drop**
  - **Cavity / rotor geometry**
  - **Seal (bristle) stiffness**
- **Bristle instability can lead to high cycle fatigue of bristles and/or abnormal bristle pack wear**
- **Bristle stiffness must be carefully selected to balance stability concerns with frictional heating, wear issues**

Bristle aerodynamic stability is an important design consideration.

Steam Turbine Test Vehicle



- 3.5 MW Boiler Feed-Pump Turbine
- Steam path modified to mimic thermodynamic design of a utility steam turbine
- Interstage and Bucket Tip Brush Seals tested
- 1% Efficiency improvement measured for brush seals

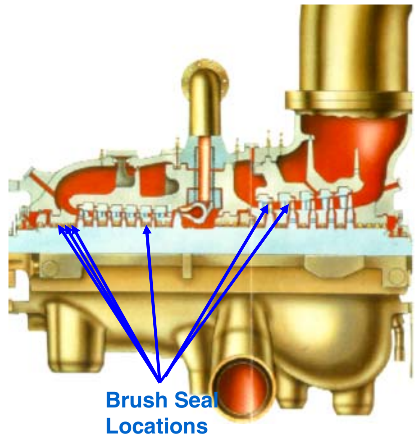
Fully Instrumented Test Vehicle Allows for Pressures, Temperatures to be Measured at Discrete Radial Positions at each stage.

Velocity profiles at specified locations measured.

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

Field Experience

- 85 MW HP Section
- 250 MW Opposed Flow High Pressure/Intermediate Pressure Section
- 700 MW HP Sections
- 900 MW HP Sections
- 1000 MW Nuclear Turbine
- Brush Seals applied at HP End Packings, Interstage, and Bucket Tips



250 MW HP/IP Section

Approx. 20 machines in the field with approximately 200 brush seals.

Fleet leader has eight years of service.

Inspection Results - HP Shaft Seals

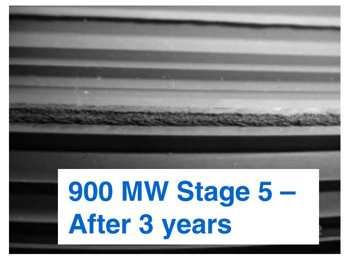
Seals inspected after 17 months of service.
Seals found in excellent condition and returned to service.

End packing seals (3 brushes shown).

Polishing of rotor surface.

Minimal brush wear observed.

Inspection Results - HP Shaft Seals

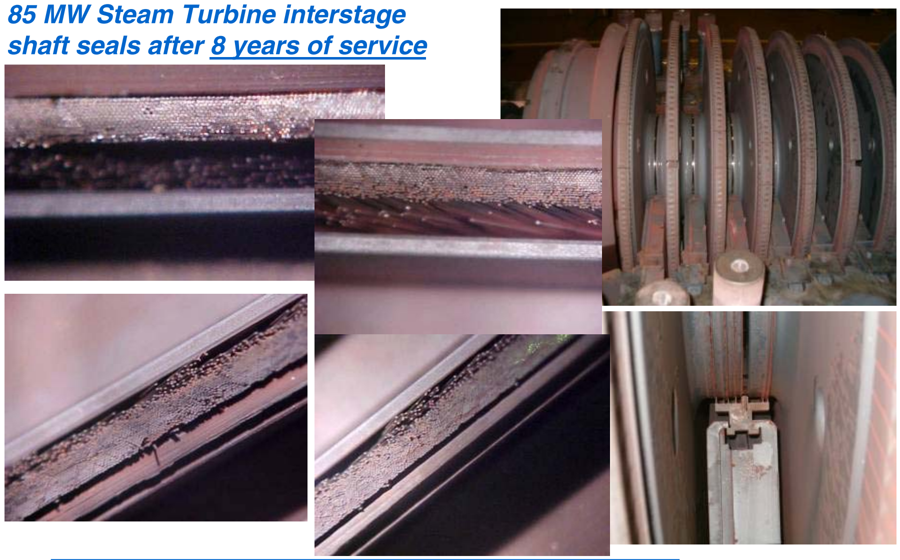


Shaft seal durability established.

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

Inspection Results - HP Shaft Seals

85 MW Steam Turbine interstage shaft seals after 8 years of service



Long term shaft seal durability established.

Most recent inspection results.

85 MW power generation turbine; 8 interstage seals in high pressure steam interstage locations.

8 years of service; approximately 30 startups.

Polished rotor at all seal locations.

Polished bristle tips around seal circumference at all seal locations.

Seals performing as intended after 8 years of service.

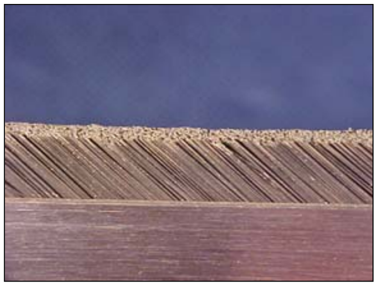
Bucket Tip Seals / Integral Cover Buckets

- 250 MW unit - Seal installed adjacent to integral cover buckets of second IP stage
- Overall seal integrity is good after 17 months; seal returned to service
- Some stray bristles at seal segment ends; segment end design improved
- New bucket cover designs eliminate radial inflow/outflow, allowing wider use of brush seals

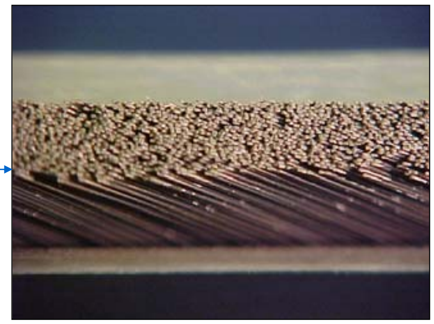
Tip seal in this unit looked very good. This end segment is slightly gnarled at the end, but along the circumference, the bristles survived. Note that over bucket tips, gaps between cover sections or radial steps at the junction of adjacent cover sections are important design considerations.

Further work underway to improve robustness of bucket tip brush seals.

Brush Seal Quality



- Consistent bristle angle control of a production class GE Steam Brush Seal.
- Bristle angle control is essential to achieving the expected seal performance (Leakage, Wear, etc.).



- Consistent bristle density (packing) of a production class GE Steam Brush Seal.
- Pack consistency is essential for the seal to operate at the design pressure drop.
- Bristle tips are free, not fused or hooked together.
- Having the bristle tips free ensures consistent seal stiffness and seal behaviour.

Brush seal quality is crucial to achieving intended seal stiffness and leakage performance, and for ensuring that the seals do not adversely affect turbine operation (rotor heating, rotordynamics, rotor thrust, leakage, etc.).

Patents

- Flower, R.F.J., “Brush Seals”, US Patent No. 5090710
- Flower, R.F.J., “Sealing Device”, US Patent No. 5474305
- Turnquist, N.A., et. al. "Combined Labyrinth and Brush Seals for Rotary Machines," US Patent No. 6045134
- Turnquist, N.A., et. al., “Steam Turbine Having Brush Seal Assembly,” US Patent No. 6053699
- Turnquist, N.A., et. al., "Combined Labyrinth and Brush Seals for Rotary Machines," US Patent No. 6105967
- Bagepalli, B.S., et. al., "Brush Seals and Combined Labyrinth and Brush Seals for Rotary Machines," US Patent No. 6131910
- Turnquist, N.A., et. al., “Method for Overhauling a Steam Turbine to Increase Its Power,” US Patent No. 6260269
- Turnquist, N.A., et. al., “Arrangement and Method for Radially Positioning a Turbine Brush Seal,” US Patent No. 6308958
- Crudgington, P.F., “Cavity Brush Seal”, US Patent No. 6772482
- Crudgington, P.F., and Bowsher, A., “Brush Seal Element”, US Patent No. 6799766

Cross (the seal vendor), and GE (the turbine OEM) have several patents on brush seals and their application to steam turbines.

Summary

Brush Seals are an effective means of improving steam turbine efficiency.

- Brush seals provide significant performance benefit in Overall Heat Rate due to reduced leakage rates for utility steam turbines (actual benefit is application-specific).
- Brush seal design characteristics are well understood.
- Consideration of the turbine as a system is important for the full performance benefit of brush seals to be realized.
- Analytical predictions and extensive lab testing have been verified with field experience.
- Brush seal quality is essential to maximizing performance benefit.
- Joint development between seal vendor and turbine manufacturer has led to several patents.

Conclusions

ADVANCED SEAL RIG EXPERIMENTS AND ANALYSIS

Roger Paolillo
Pratt & Whitney
East Hartford, Connecticut

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis

NASA Glenn Research Center / OAI
Cleveland, Ohio
November 8, 2005
Turbine Seal Development Session

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis
Topics for Discussion

- Advanced Sealing
  - Compliant
  - Non-Contact
  - Labyrinth seals
- Labyrinth Seals in Gas Turbines
  - Typical lab seal design parameters
  - Typical flow parameter correlation based on available empirical rig data
- CFD: Labyrinth Seal Physics Based Models
  - Validated with available empirical rig data
  - Evaluate additional geometric effects through sensitivity analyses
  - Evaluate additional aerodynamic effects through sensitivity analyses
- ASR rig
  - Tri-party agreement offers a win-win-win situation
  - Rig capabilities simulate engine operating conditions of surface speed, temperature, and pressure level
  - Accurate measurements of clearance and measured seal flow
- Test Articles
  - How related to analysis work
  - How modified for rig
- Test Results
  - Concave seal
  - Hammerhead seal
- Conclusions/Future Work

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Advanced Seal Rig Experiments & Analysis
Rotating Seal options: Why Still Work On Labyrinth Seals

- **Compliant Seals eg. Brush Seals, Finger Seals**
  - **3-5X flow reduction**
  - **developing higher surface speed, temperature, and pressure levels**
  - **interference/debris/durability issues**
- **Non Contact Seals eg. Aspirating, Film Riding**
  - **5-10X flow reduction but still improving surface speed, temperature, and delta pressure levels**
  - **limited applications**
  - **interference issues**
- **Labyrinth Seals still the workhorse seal in gas turbine engines**
  - **long history of use in compressors, turbines, around bearing compartments**
  - **cheaper to make than many other seals**
  - **small improvement x many seals (up to 50*) = big gain in performance/operability**
  - **well and still investigated by academia & industry**
  - **with a proper abradable seal land can handle interference**

*NASA/TM 2004-211991/Part 1 "Turbomachine Sealing and Secondary Flows"
R, C. Hendricks, B. M. Steinetz and M. J. Braun

Why still work to reduce leakage of of labyrinth seals.

Still the workhorse seal in gas turbines

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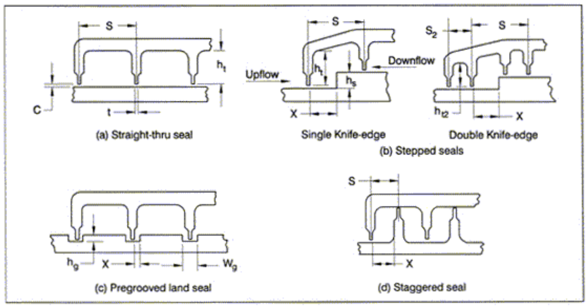
Advanced Seal Rig Experiments & Analysis
Empirical Labyrinth Seal Analysis Model based on '70's Rig Tests & Literature Data



Lab Seal Flow; $W = \phi\alpha\gamma K_1(Pu / Tu^{1/2})\ A$

Where:

ϕ	= flow parameter, f(#KE)
Tu	= upstream temperature
Pu	= upstream pressure
A	= area based on seal clearance
α	= discharge coefficient, f(C,t, KE tip radius)
γ	= carry over factor, f(C,S, hs, pressure ratio)
K_1	= land porosity eg. honeycomb land, f(C)

Labyrinth seal design system based on seal's leakage from the early '70's from gas turbine engine testing and rig testing

All empirically developed design systems

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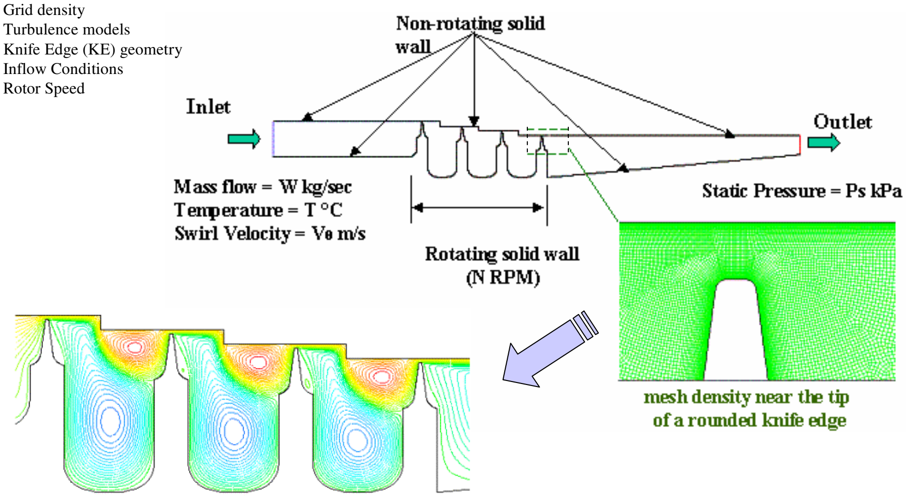
Advanced Seal Rig Experiments & Analysis

CFD Sensitivity Studies Developed A Physics Based Lab Seal Model That Could Predict Rig Data & Literature Results Reasonably Well

Sensitivity Studies Included:
- Grid density
- Turbulence models
- Knife Edge (KE) geometry
- Inflow Conditions
- Rotor Speed



Labyrinth Seal Stream Contours

Advent of CFD maturity has provided a physics based modeling approach to assessing seal leakage

The CFD models must be first validated with the available test data before these seal models can be used to explore leakage reduction designs.

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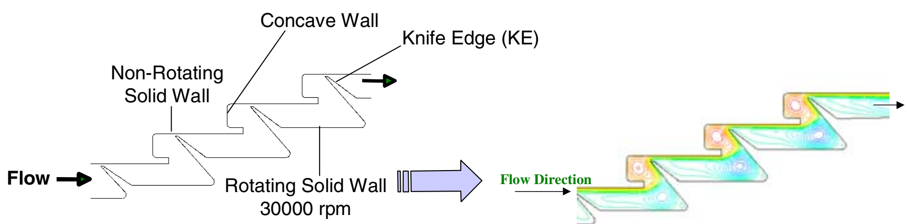
Advanced Seal Rig Experiments & Analysis
CFD Lab Seal Model Used to Assess Sealing Effectiveness of Canted KE Configurations

Stocker advanced labyrinth design which showed 20-25% seal flow reduction were modeled as starting point.
Optimization studies were performed on the following parameters:

- step height
- step shape
- KE angle
- KE axial position
- Rotor Speed

In limited optimization studies no labyrinth seal design was found better than the initial Stocker configuration



Max radius = 76.3E-03 m
Pressure ratio = 2
All walls are adiabatic

Labyrinth Seal Stream Contours

Best leakage reduction concepts found in the literature are evaluated with validated CFD models
2D axisymmetric CFD models sensitivity studies did not improve upon existing design concepts

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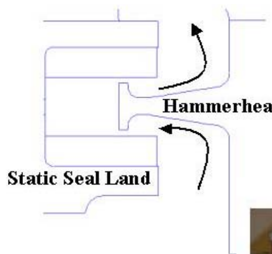
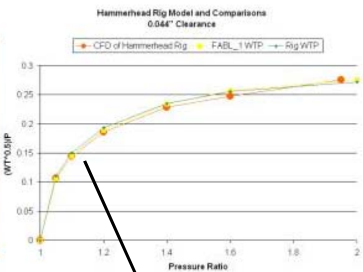
Advanced Seal Rig Experiments & Analysis

Empirical & CFD Labyrinth Seal Models Matched Static Cold Flow Testing of Baseline Hammerhead Seal Design



Hammerhead seal is basically a compact labyrinth seal design



CFD model & Lab Seal flow parameter model match static cold flow results

The hammerhead seal design is an attempt to minimize the geometric design space needed for multiple knife edged labyrinth seals

The hammerhead seal design also attempts to maintain a tight clearance for one set of knife edges at all times of gas turbine engine operation

Initially the seal is modeled as a conventional labyrinth seal of the same number of knife edges.

Static cold flow tests confirm this modeling approach.

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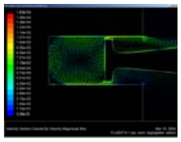
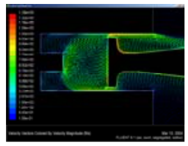
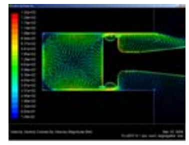
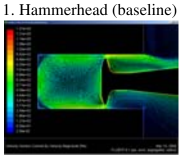
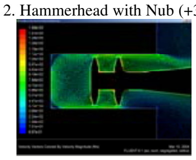
CFD Hammerhead Model Used to Assess Sealing Effectiveness of Various Configurations

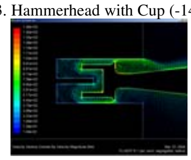

1. Hammerhead (baseline)

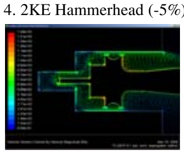

2. Hammerhead with Nub (+3%)

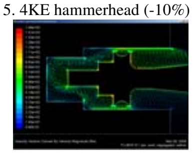

3. Hammerhead with Cup (-14%)

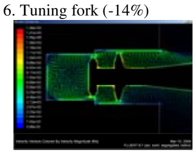

4. 2KE Hammerhead (-5%)


5. 4KE hammerhead (-10%)


6. Tuning fork (-14%)


7. Inverse tuning fork (-33%)


8. Mod Inverse tuning fork (-20%)


9. 4KE Stepped hammerhead (-24%)

Trial 1 matches static cold flow tests
Trial 2 is the 2KE hammerhead seal tested in ASR
Trial 9 is the 4KE hammerhead seal tested in ASR
Trial 7 has highest effectiveness; shows benefit of tight clearances forcing air through tortuous paths

CFD modeling is used as an analytical test tool to explore best leakage design concepts

As expected, if it behaves like a labyrinth seal then the same leakage reduction features work best (more knife edges, stepped seal lands)

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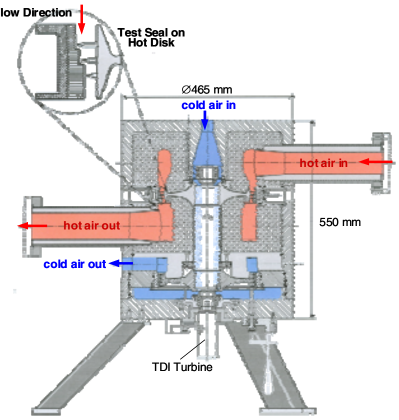
Advanced Seal Rig Experiments & Analysis

Advanced Seal Rig (ASR) Designed & Built to Test Seals at Engine Operating Conditions



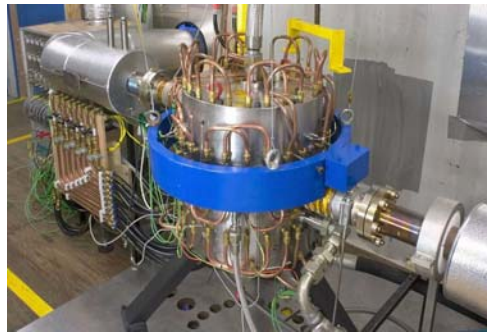


Table 1. Functional requirements		
Parameter	Specification values	
	ISO-units	USA-units
Gas temperature upstream	20 - 815 °C	70 - 1500 °F
Gas pressure upstream	12.0 – 24.1 bars	175 – 350 psi
Gas pressure difference	1.0 – 7.0 bars	15 – 100 psi
Diameter disk	254 mm	10 inch
Rotational speed	Static – 365 m/s	Static – 1200 ft/s
Seal gap width	0.1 – 0.4 mm	3.1 – 15 mils
Mass flow	0.04 -.8 kg/s	0.09 – 1.6 lb/s

Rig developed at the National Aerospace Laboratory (NLR) in The Netherlands to test advanced seal concepts at near gas turbine engine operating conditions.

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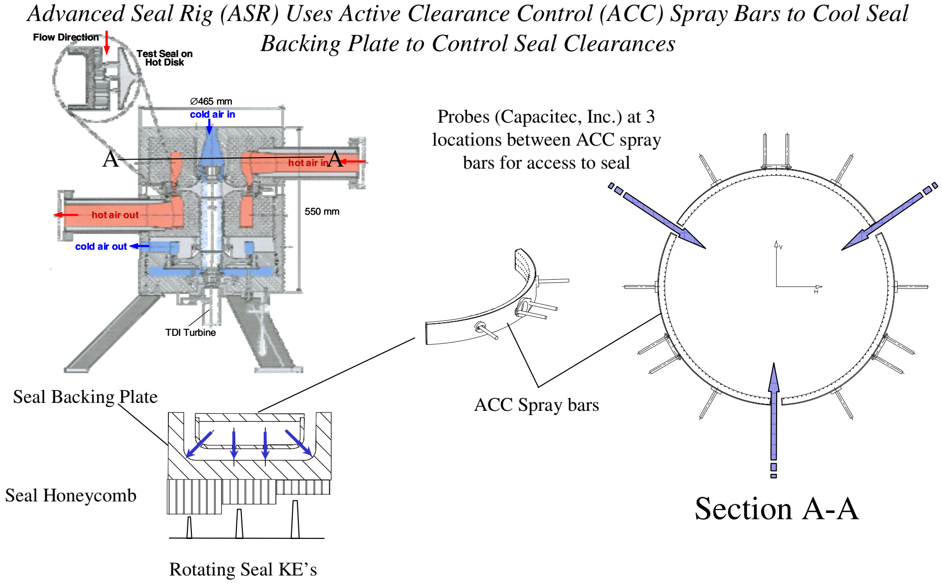
Advanced Seal Rig Experiments & Analysis

Advanced Seal Rig (ASR) Uses Active Clearance Control (ACC) Spray Bars to Cool Seal Backing Plate to Control Seal Clearances



A clearance control design feature utilizes external spray bars to impinge cold shop air on the outer diameter of the test seal static backing plate to radially move the test seal land inward to the desired seal clearance.

Three equally circumferentially spaced probes (Capacitec, Inc.) are installed measure seal clearance and determine the level of active clearance control air needed.

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Advanced Seal Rig Experiments & Analysis
Advanced Seal Rig (ASR) Typical Test Plan to Simulate Engine Operating Conditions

Test Point	Temperature	Upstream Pressure	Pressure Ratio	Speed (rpm)	Clearance
1	Low Temoperature 400C (750F)	Low Pressure 12 Bar (175 psia)	Pr 1.1	rpm 3500	Clr .38mm (.015")
2					Clr .25mm (.010")
3					Clr .127mm (.005")
4				rpm 15000	Clr .38mm (.015")
5					Clr .25mm (.010")
6					Clr .127mm (.005")
7			Pr 1.25	rpm 3500	Clr .38mm (.015")
8					Clr .25mm (.010")
9					Clr .127mm (.005")
10				rpm 15000	Clr .38mm (.015")
11					Clr .25mm (.010")
12					Clr .127mm (.005")
13			Pr 1.40	rpm 3500	Clr .38mm (.015")
14					Clr .25mm (.010")
15					Clr .127mm (.005")
16				rpm 15000	Clr .38mm (.015")
17					Clr .25mm (.010")
18					Clr .127mm (.005")
19			Pr 1.80	rpm 3500	Clr .38mm (.015")
20					Clr .25mm (.010")
21					Clr .127mm (.005")
22				rpm 15000	Clr .38mm (.015")
23					Clr .25mm (.010")
24					Clr .127mm (.005")

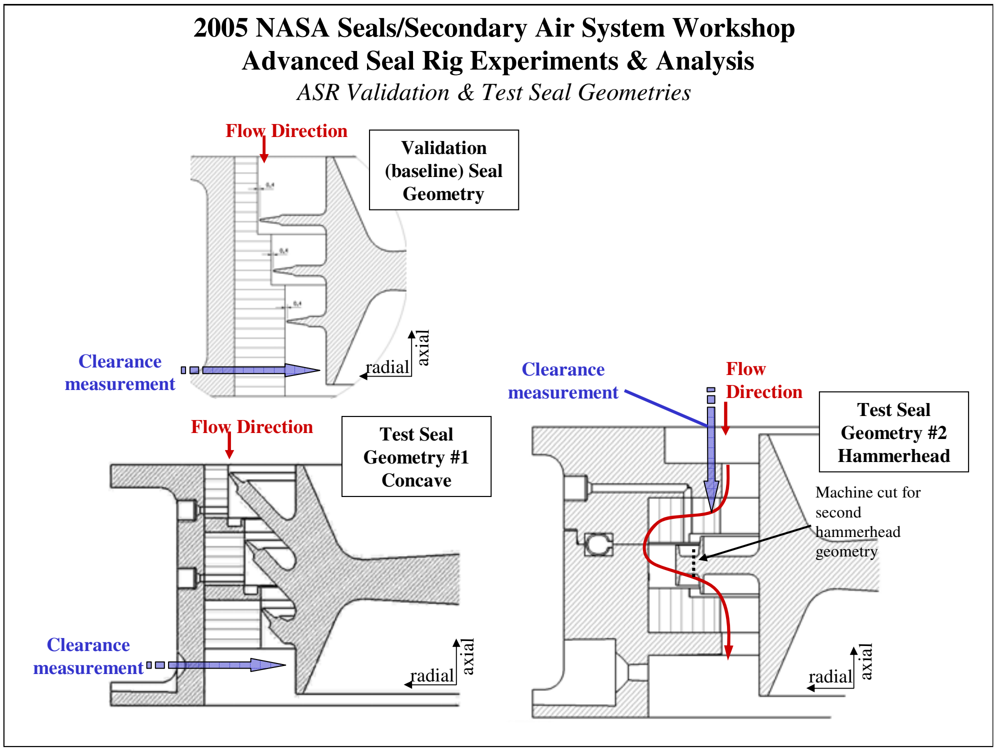
Set upstream temperature and pressure

Adjust downstream pressure to achieve pressure ratio

Set speed

Use ACC to obtain desired clearance

The seal rig can independently vary temperature, pressure, pressure ratio, speed, and seal clearance.



The baseline seal geometry was used to validate the rig. The baseline seal is a standard 3 knife edge stepped seal configuration that is typically found in many gas turbine engines.

Rig data matched within 10% the lab seal design predictions (AIAA-2005-3092).

The advanced lab seal design test results would then be assessed against both the existing lab seal design system predictions and against the baseline seal data.

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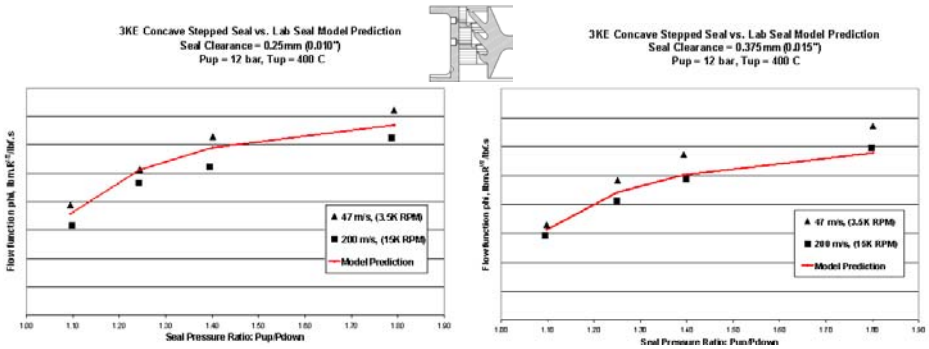
Advanced Seal Rig Experiments & Analysis
Concave Seal Compared Well to Empirical Lab Seal Model



• One empirical labyrinth seal model prediction (no rotational variation)
• Concave seal flow reduction with increasing rotational speed
• Comparisons with the lab seal model predictions show reduction is apparent (8%) only at the tighter clearance test point

Concave seal test data compared well with the lab seal design system predictions.

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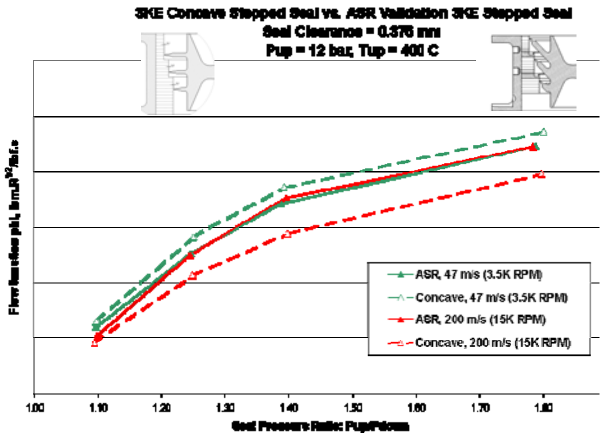
Advanced Seal Rig Experiments & Analysis

Concave Seal Compared to ASR Validation (Baseline) Lab Seal



- **ASR Validation seal confirms no rotational variation**
- **Concave seal flow is reduced by 10% between 3500 & 15000 rpm test points**
- **Concave test at low speed has negligible rotation benefit; should equal ASR seal flow**
- **Higher concave seal flow at 3500 rpm probably due to 3X increase in KE to Step distance**

Concave seal test data compared to baseline seal clearly shows a rotational effect that reduces seal leakage.

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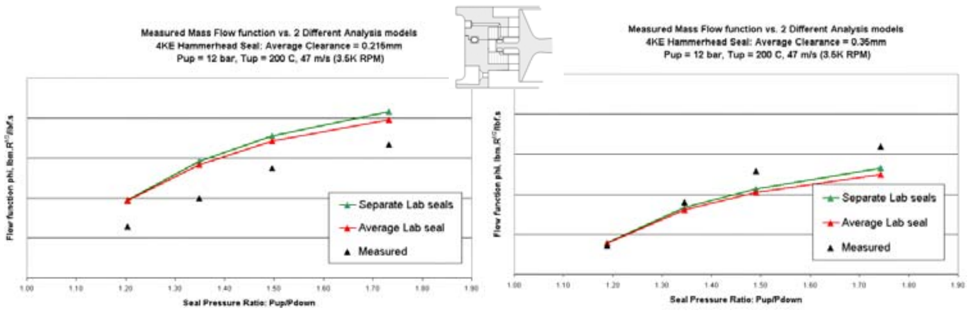
Advanced Seal Rig Experiments & Analysis
4KE Hammerhead Seal Compared to Empirical Lab Seal Models Shows Additional Restriction at Tighter Clearances



- **Empirical labyrinth seal model predictions show minimal change due to different clearances between upstream and downstream hammerhead knife edges**
- **Tighter hammerhead seal clearances introduce additional restriction of air through the seal than is accounted for in the model prediction**

4KE Hammerhead seal compared to empirical design system labyrinth seal model (4 knife edge stepped seal) shows additional restriction effect at the tighter clearances test condition. "Stretching out" hammerhead seal into an elongated staggered labyrinth seal type configuration possibly providing additional flow path restrictions.

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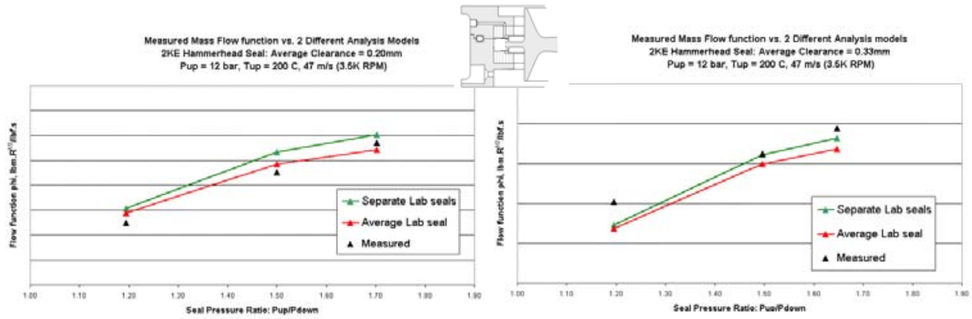
Advanced Seal Rig Experiments & Analysis

2KE Hammerhead Seal Compared to Empirical Lab Seal Models



- **Empirical labyrinth seal model predictions show change due to different clearances between upstream and downstream hammerhead knife edges**
- **Larger hammerhead seal clearances do not introduce much additional restriction of air through the seal than is accounted for in the model prediction**

2KE Hammerhead Seal Compared to Empirical Lab Seal Models
Staggered restriction benefit with tight clearances is lost with the reduction in number of knife edges

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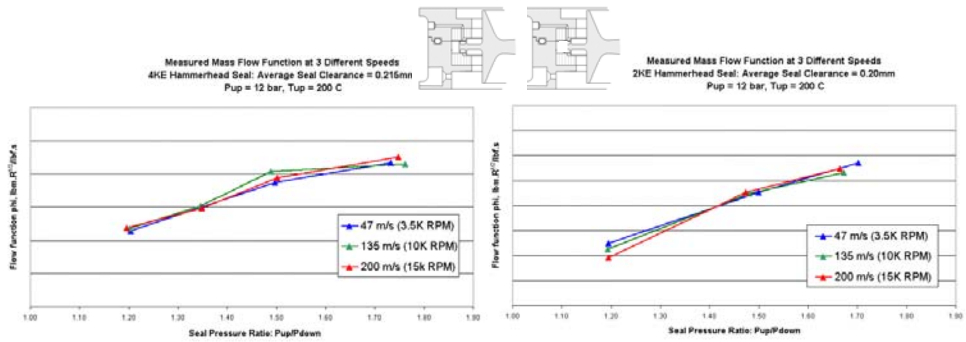
Advanced Seal Rig Experiments & Analysis
4KE & 2KE Hammerhead Seals Show No Rotational Effect



- **Hammerhead Seal Test Results Show No Influence of Rotational Speed**

4KE & 2KE Hammerhead Seals Show No Rotational Effect

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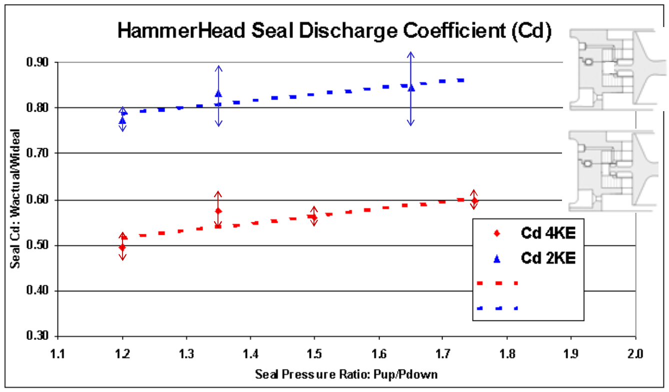
Advanced Seal Rig Experiments & Analysis
4KE & 2KE Hammerhead Seal Discharge Coefficient Comparison Matches Trend Predicted by CFD Models



- **Comparison of Discharge Coefficients Show that the 4KE Hammerhead Seal to be at least 25% more effective than the 2KE Seal**
- **These Results are in Line with the Hammerhead Seal Design CFD Sensitivity Studies (Trail 4 vs. Trial 9)**

4KE & 2KE Hammerhead Seal Discharge Coefficient Comparison Matches Trend Predicted by CFD Models

Arrows show data scatter but trend is still apparent.

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Advanced Seal Rig Experiments & Analysis
Conclusions/Future Work

- CFD Modeling, Validated With Existing Rig Data, Used to Define New Seal Designs with Seal Reducing Features
- An Advanced Seal Rig is Available to Test Seals at Engine Operating Conditions
  - Phase 2 plan underway to extend rig capabilities to 365 m/s & 815°C by end of 2005
- Test Data Suggests that Concave Seal Flow is Reduced with Increasing Rotational Speed
  - Additional testing at higher speeds planned
  - A second canted seal design with seal angles reversed (with flow direction) planned
  - 3D CFD analysis planned to investigate concave seal features providing rotation benefit; modeling of honeycomb cell structure will be included
- Empirical Labyrinth Seal Model Requires Updates for both Rotational and Axial Spacing Between Knife Edges and Steps
  - Testing planned utilizing baseline validation seal for different axial spacings
- Test Data Shows that Hammerhead Seal Flow Does Not Change with Rotational Speed
- Hammerhead Seals are Basically a Compact Seal that Behaves Like a Labyrinth Seal; Seal Flow is Reduced with More Knife Edges and Steps Between Knife Edges
- Maintaining Tight Clearances Between the Hammerhead Seal and its Static Land Will Reduce Seal Flow by Forcing Air to Travel Through a More Tortuous Path

HIGH MISALIGNMENT CARBON SEALS FOR THE FAN DRIVE GEAR SYSTEM TECHNOLOGIES

Dennis Shaughnessy and Lou Dobek
United Technologies—Pratt & Whitney
East Hartford, Connecticut

Aircraft engines of the future will require capability bearing compartment seals than found in current engines. Geared systems driving the fan will be subjected to inertia and gyroscopic forces resulting in extremely high angular and radial misalignments. Because of the high misalignment levels, compartment seals capable of accommodating angularities and eccentricities are required. Pratt & Whitney and Stein Seal Company selected the segmented circumferential carbon seal as the best candidate to operate at highly misaligned conditions. Initial seal tests established the misalignment limits of the current technology circumferential seal. From these results a more compliant seal configuration was conceived, designed, fabricated, and tested. Further improvements to the design are underway and plans are to conduct a durability test of the next phase configuration. A technical approach is presented, including design modification to a "baseline" seal, carbon grade selection, test rig configuration, test plan and results of analysis of seal testing.

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High Misalignment Carbon Seals

Program Objective

The use of the reduction gear system as the platform for EVNERT demonstration engines will provide revolutionary improvements in engine performance, weight, size, and noise. Due to high periodic radial and angular misalignments introduced into the gear system, high misalignment seals are required to provide adequate compartment sealing beyond present capability. These seals must also have adequate life.

Current Phase Objective

- Fabricate modified seal housing and retaining hardware, new test seals
- Conduct iterative misalignment tests to verify design improvements
- Conduct durability testing.

November 8-9, 2005

Overall program objective identifies the need for seals capable of periodic high radial and angular misalignment.

The current phase objective are to fabricate a modified seal housing and retaining hardware, conduct iterative misalignment tests, and durability tests.

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High Misalignment Carbon Seals

Background

Tomorrow's Engines with Geared Fans will be subjected to extreme conditions such as:

- High angular and radial seal misalignments
  Gyroscopic loads - angular misalignment
  Sun input gear orbiting - radial/eccentric misalignment
- Higher LPC shaft speed; ~10,000 RPM
- Large Diameter Fan Hub

Seals capable of accommodating high misalignment, high rubbing speeds, low pressure differentials and large diameters must be developed.

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

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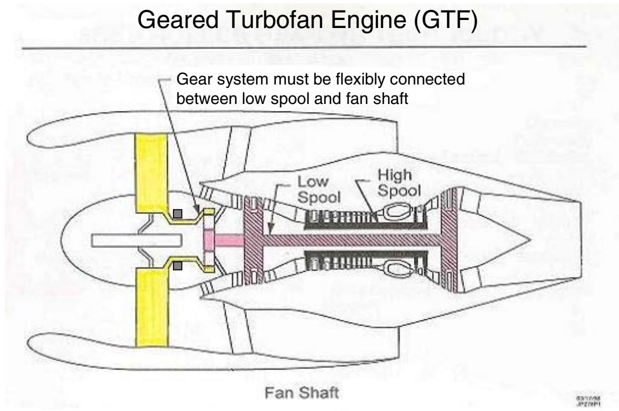
High Misalignment Carbon Seals



Geared Turbo Fan Provides

- **3%-4% TSFC improvement over conventional turbofan engines.**
- **30db noise reduction.**

November 8-9, 2005

Misalignment seals are located along the flexible shaft between the low spool and fan shaft.

High Misalignment Carbon Seals

	CURRENT FOCUS FWD. AIR/OIL SEAL	REAR AIR/OIL SEAL	FDGS/LPC COMPARTMENT SEAL
Required Life (hours)	30,000	30,000	30,000
Delta P (psi)	<50	<50	40-50
Surface Speed (ft/s)	33	90	345
Buffer Air Temperature (deg. F)	350	350	415
Angular Misalignment (deg)	0.5	0.2	0.1
Eccentricity (inches)	0.005	0.02	0.005
Sealing Diameter (inches)	2.95	2.95	11.2
Type	Segmented/ bellows/ other	Segmented/ other	Segmented/ ring/ other

Seal Operating Conditions

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

Critical requirements are highlighted.

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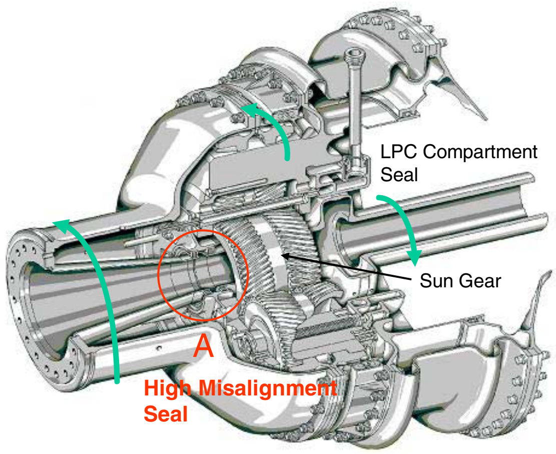
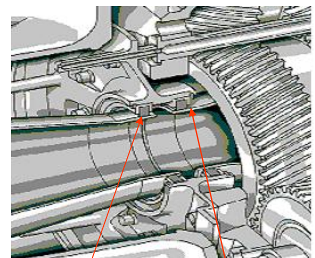
High Misalignment Carbon Seals

Fan Drive Gear System must withstand periodic misalignments as high as 0.105” due to “g” and gyro loads.



LPT Input Shaft Rotation
CCW from rear



Detail A

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Fan drive gear systems must withstand periodic misalignments as high as 0.105” due to “g” and gyro loads.

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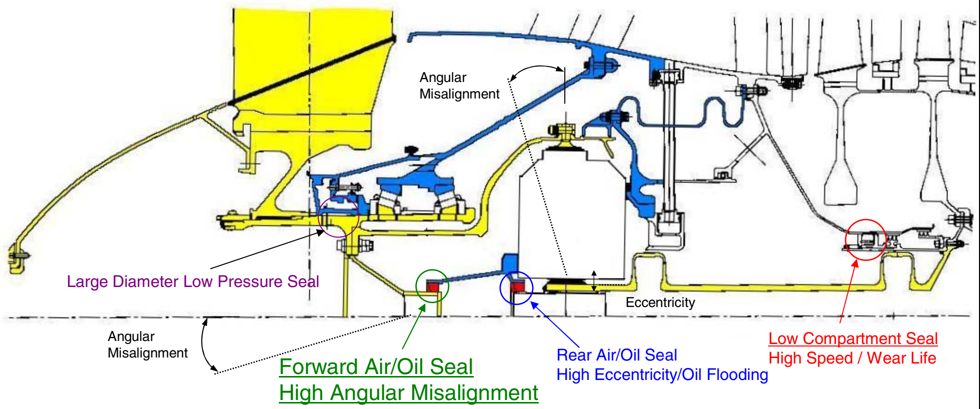
High Misalignment Carbon Seals



Advanced Engine Seal Locations

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Seal locations within the forward compartments of the fan drive geared engine. Forward air/oil seal represents the location of the highest source of angular and radial misalignment.

High Misalignment Carbon Seals

Approach - Misalignment Seal Test Rig Program

Stein Seal selected as the seal supplier/tester.

Step 1 – Previous Update
- "Baseline" seal design
- Carbon grade "X" - high strength, low modulus.
- Misalignment increased in steps up to 0.020 in. radial & 0.5° angular

Step 2 – Previous Update
- Misalignment increased in steps up to 0.040 in. radial & 0.5° angular

Step 3 – Previous Update
- Alternate seal with Carbon grade "X" tested
- Misalignment increased in steps up to 0.105 in. radial & 0.5° angular
- Alternate seal with Carbon grade "Y" tested
- Misalignment increased in steps up to 0.105 in. radial & 0.5° angular

Step 4 – Current Phase
- **Modify seal housing and retaining hardware**
- **Fabricate test seals**
- **Conduct three – 20 hour misalignment tests**
- **Conduct two – 100 hour durability tests**

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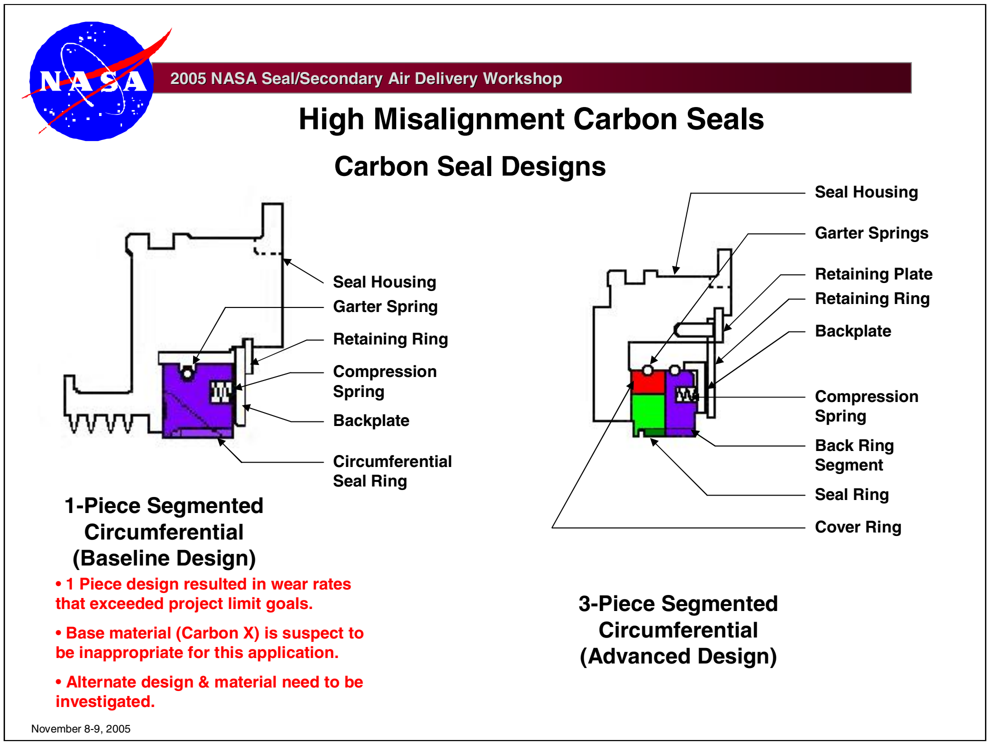
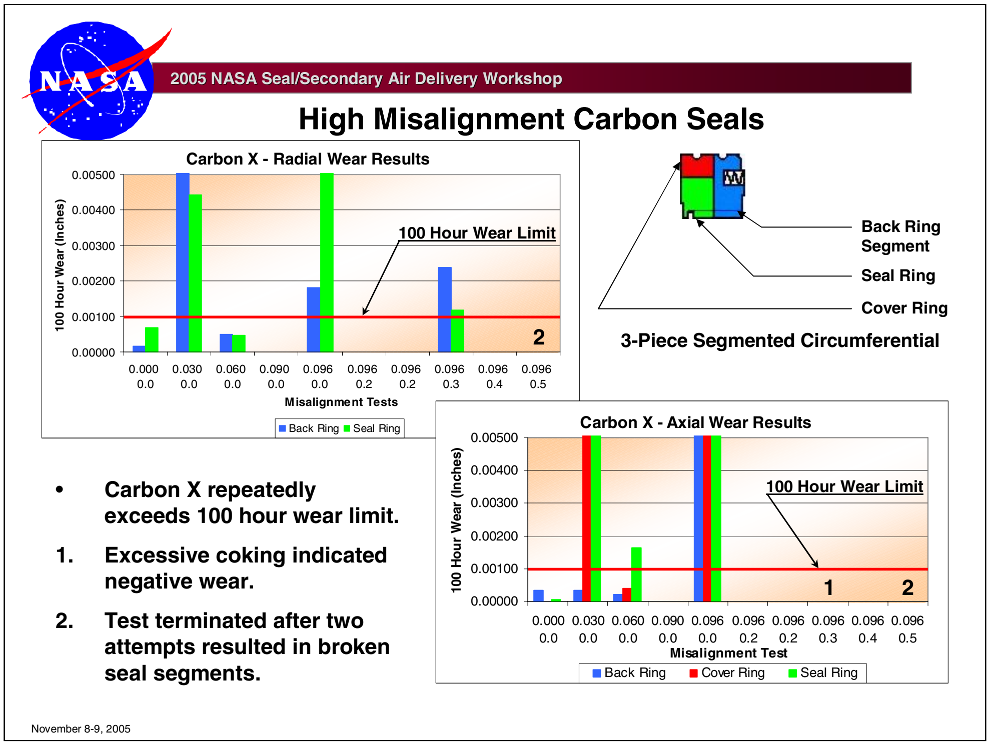
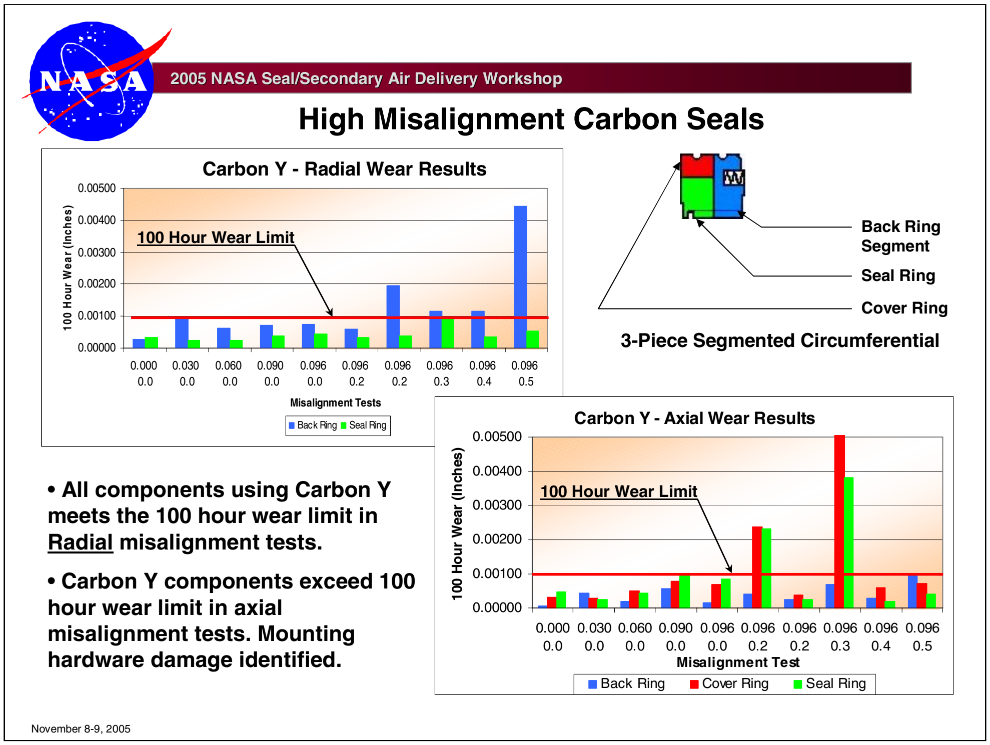
Technical approach of misalignment seal development program. The current phase represents the fourth main step since starting from "baseline" seal testing.



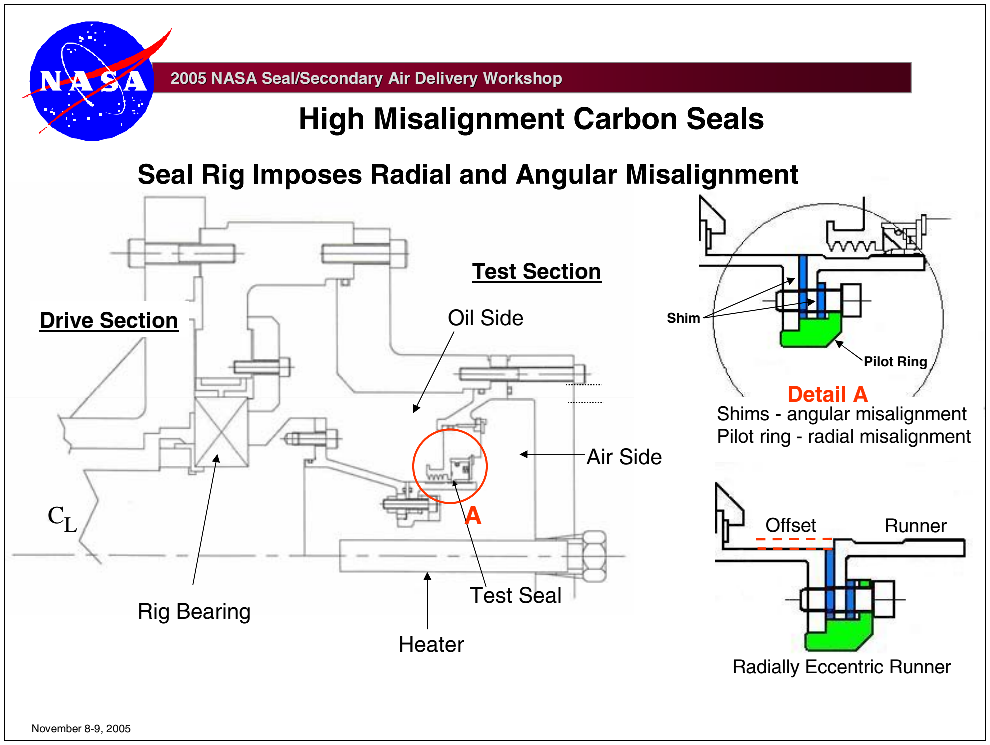
Baseline seal was compose of a one-piece 4 segmented seal. Alternate design is composed of a three-piece design, each piece consisting of four segments.



Carbon X repeatedly exceeds the 100 hour wear limit goal and testing was terminated after multiple failures.



Carbon Y meets the 100 hour wear limit under purely radial misalignment conditions. Seal retaining hardware suffered fatigue and failure during combination radial & angular misalignment tests. These failures are to be investigated at the potential reasons for the 100 hour wear limit to be exceeded.



Seal test rig schematics used to impose radial and angular misalignment. Shims are used to impose angular misalignment and pilot rings are used to impose radial misalignment.

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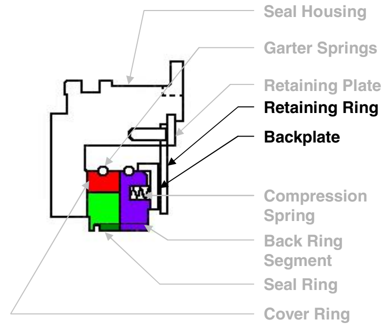
High Misalignment Carbon Seals

Retaining Ring

Backplate



Backplate tang steadily wearing into slot of Retaining Ring. Current Seal Housing prohibited design change to increase Retaining Ring to the full thickness of the tang.

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Photos of seal retaining hardware show the wear the occurred during misalignment testing.

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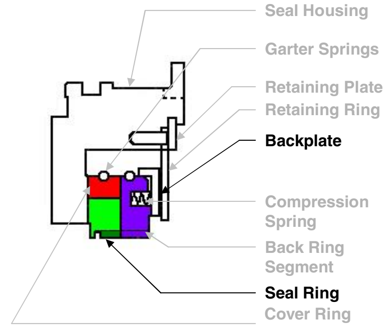
High Misalignment Carbon Seals

Seal Ring wear during test phase of advanced design misalignment tests

Backplate failure during test phase of advanced design misalignment tests



Backplate Key steadily wore into slot of Back Ring and Seal Ring. Modification increased the number of Keys from one to two.

Backplate stress crack identified after test with the largest combination of Radial and Angular misalignment. Modification increased the corner radii at the keys.

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Photos of seal and associated retaining hardware show the wear and stress fracture that occurred during misalignment testing.

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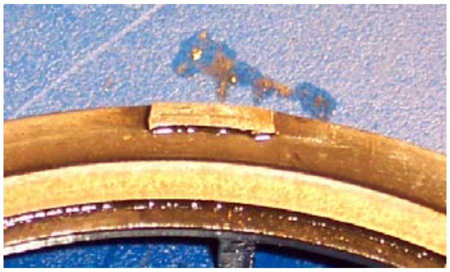
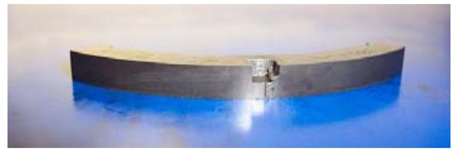
High Misalignment Carbon Seals



Backplate Tab Failure



Seal Ring Notch Wear

Back Ring Tab Failure

Seal Assembly

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Photos of the seal assembly and signs of wear that occurred during misalignment testing.

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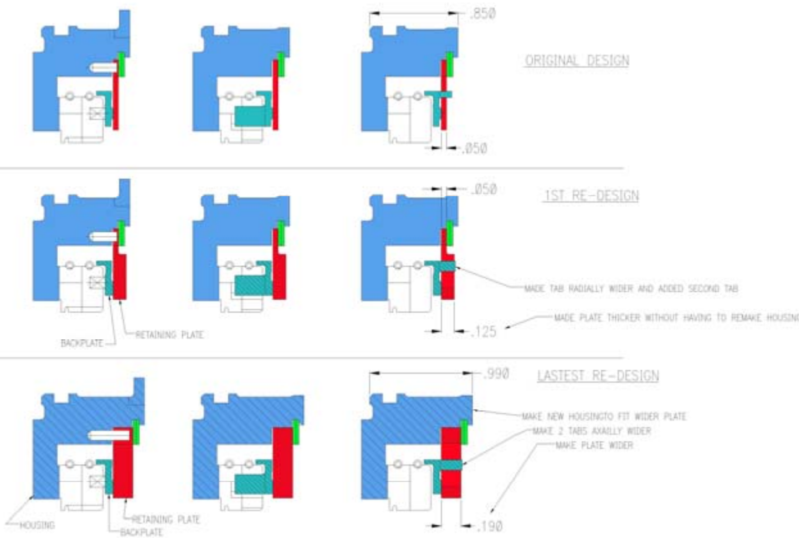
High Misalignment Carbon Seals



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Sections through the test seal illustrate the original design, modifications made during the phase 3 test program and the latest re-design for the current tests phase.

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High Misalignment Carbon Seals

Conclusions

- The baseline design does not meet wear requirements based on Phase II test results and should not be further developed.
- The optimized three-piece carbon design is a significant improvement over the baseline seal.
- The Carbon Y material appears to offer more consistent results and improved wear performance than the baseline Carbon X material.
- Seal retaining hardware on the 3-piece design worn in several instances and may explain carbon wear rates that were greater than goal.

Recommendations - Awaiting test program results

November 8-9, 2005

Conclusions identify that baseline seal design should not be further developed. Also the 3-piece design is a significant improvement over the baseline design. Carbon Y material appears to offer improved wear results from that of Carbon X. Further work is needed to improved the seal retaining hardware.

Recommendations are pending the results of the current test phase results.

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High Misalignment Carbon Seals

Plans for Next Year & Beyond

2006 Oil windback design
EVNERT demo engine hardware

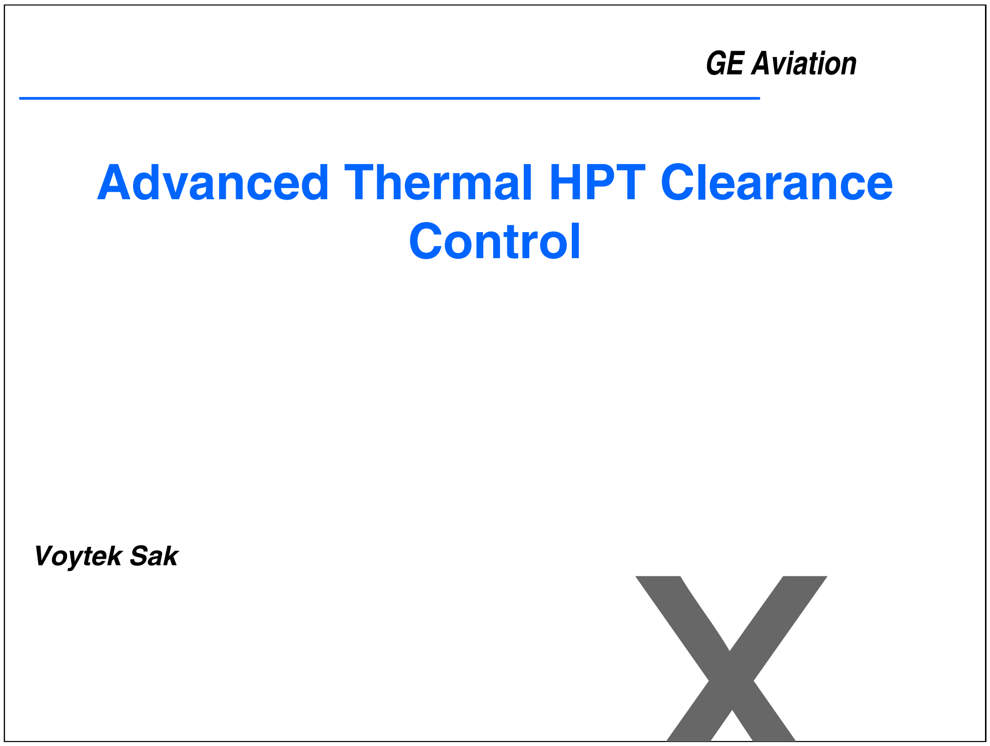
2007 Oil windback tests
EVNERT demo engine tests

November 8-9, 2005

Plans for continuation include windback design and testing.

ADVANCED THERMAL HPT CLEARANCE CONTROL

Wojciech (Voytek) Sak
General Electric Aircraft Engines
Cincinnati, Ohio



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Background and Introduction

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Background and Introduction

NASA PROPULSION 21 DESIGN CRITERIA

•OBJECTIVE:

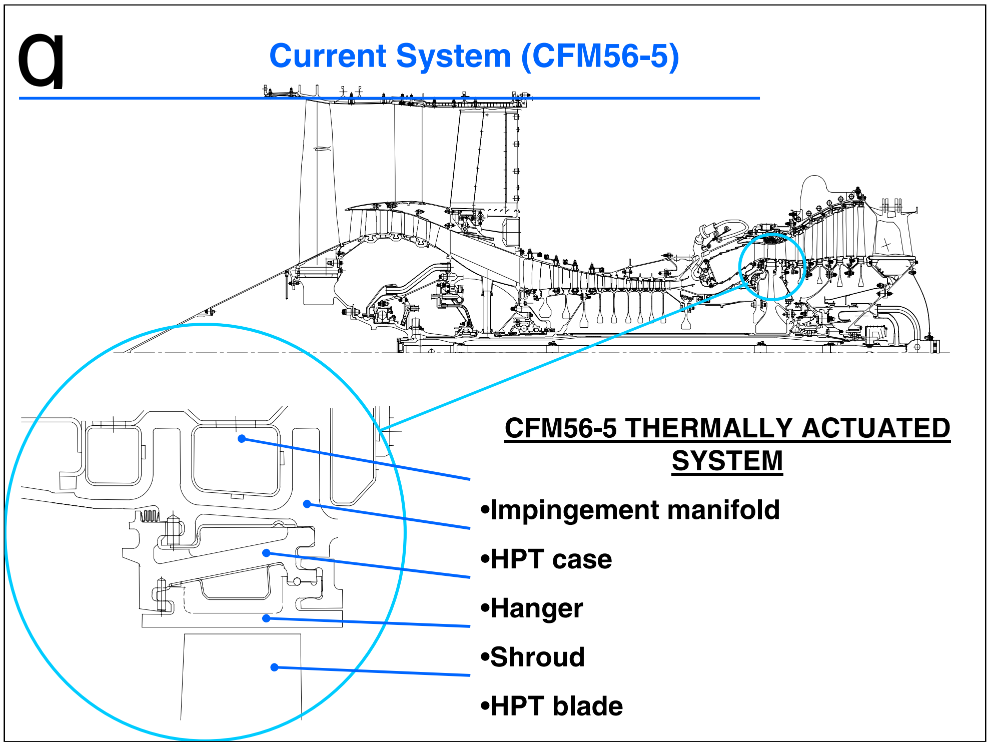
Develop a fast acting HPT Active Clearance Control System to improve engine efficiency and reduce emissions

•CHALLENGE:

Reduction of HPT blade clearance throughout engine operation

System complexity, reliability and cost must remain comparable or surpass today's engines

Reduced clearance may increase possibility of rubs



One of the currently used systems is presented on this slide. This is a CFM56-5 system targeted for improvement. The components of this system are the shroud, which is the closest part to the blade. Next is the hanger interconnecting the shroud and the HPT case. And finally, parts of the Active Clearance System are the HPT case and the impingement manifold. The impingement manifold distributes mid-compressor or compressor discharge air to the case which either expands or contracts depending on the temperature of the fluid. Mid-compressor discharge cools, while compressor discharge heats the case.

α

Design Requirements

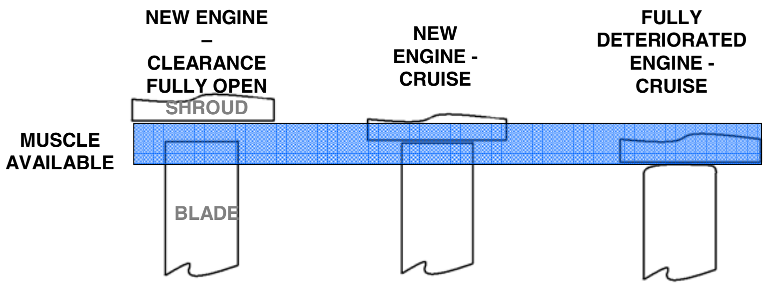
SYSTEM RANGE

- **HPT CASE "MUSCLE"**

  $\delta_T = L\alpha\ \ T$ – deflection depends on temperature

- **DETERIORATED ENGINE SYSTEM PERFORMANCE**

  Maintain new engine HPT clearance throughout engine life



The "Holy Grail" of clearances is a reliable system allowing for generous and nearly instantaneous control of HPT shroud diameter. Such a system would respond to blade tip position throughout an entire engine mission, as well as its entire life. The "muscle" of an HPT clearance control system is the difference between the smallest and largest shroud radius it can produce. A new engine may not need as much closure capability as a deteriorated one, but a good clearance control system should be able to compensate for the wear.

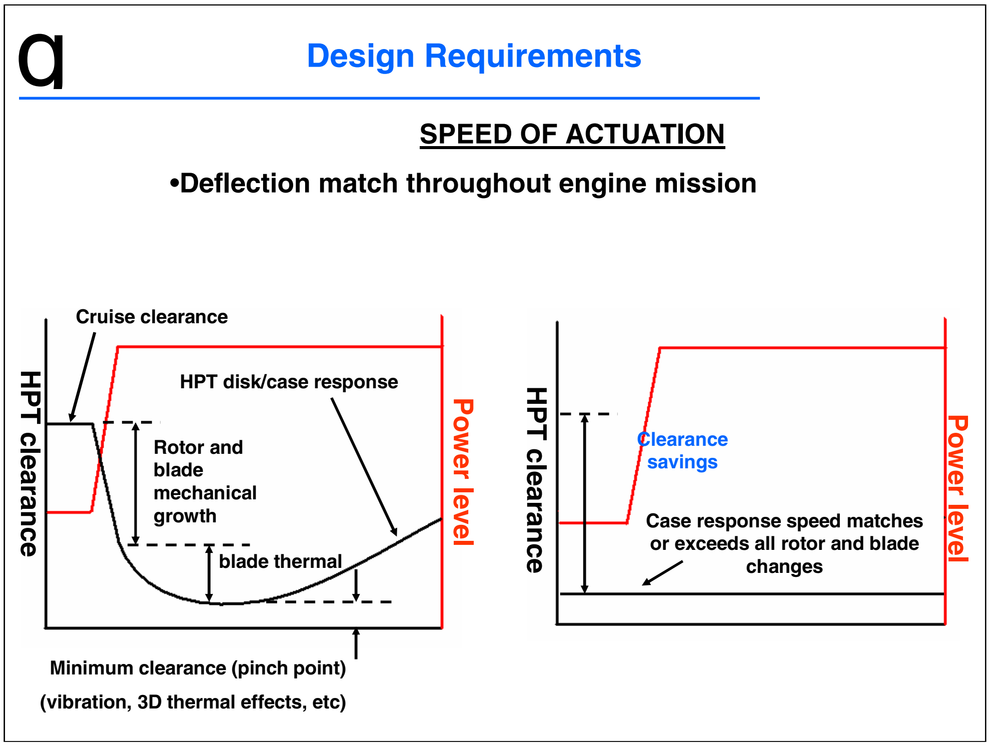
A thermally controlled system is contained within boundaries of the temperatures available for thermal control. In the case of the CFM56 this means the temperatures of the air at which compressor bleed is extracted.

δ_T – deflection of member

L - length of member

α – coefficient of thermal expansion

  T – temperature difference



For a system to be considered truly fast-acting the response of the shroud (or the case which carries it) needs to match or exceed that of the HPT blade tip. If this is achieved no extra clearance needs to be provided for the protection against rubs which would occur during engine acceleration.

This slide shows what happens to HPT clearance during a change in engine power level. An immediate effect is mechanical growth caused by increased rotational velocity. The second relatively fast effect is the thermal expansion of the blade due to increased flame temperature. Finally, change in pressures also causes instantaneous deflections on all parts – this is however, the smallest element of the change in clearance. All three of these cause closure of the HPT clearance. The much slower thermal growth of the rotor can easily be surpassed by the growth of the case, which is why clearances increase after the pinch point.

Benefits of Improvement in ACC System

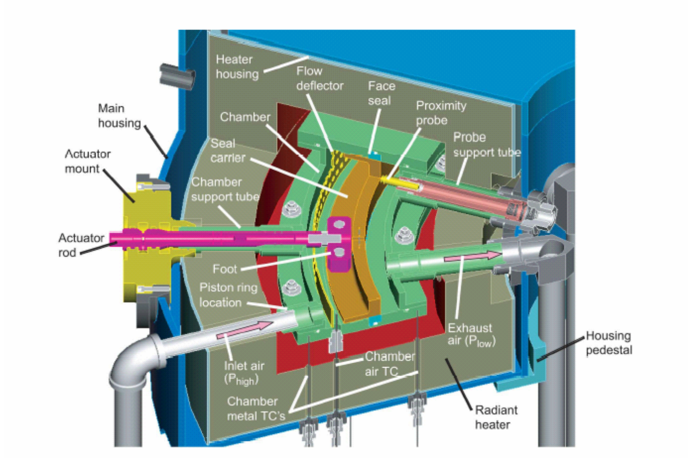
- **Increase in HPT efficiency**
  - **0.01” HPT clearance = 1% HPT efficiency**
  - **1% HPT efficiency = 0.9% fuel burn**
  - **Emissions reduction for 1% of HPT efficiency:**
    - **10% NOx**
    - **16% CO**
- **Higher efficiency also means:**
  - **Cooler temperatures – longer life**

What is the benefit of reducing HPT clearance? Long-range engines can increase their HPT efficiency by as much as 1%. This translates into fuel savings as well as reduction in emissions and longer time on wing. Smaller engines on aircraft running shorter routes will see less increase in efficiency due to smaller core diameters (closer clearances) and shorter cruise periods.

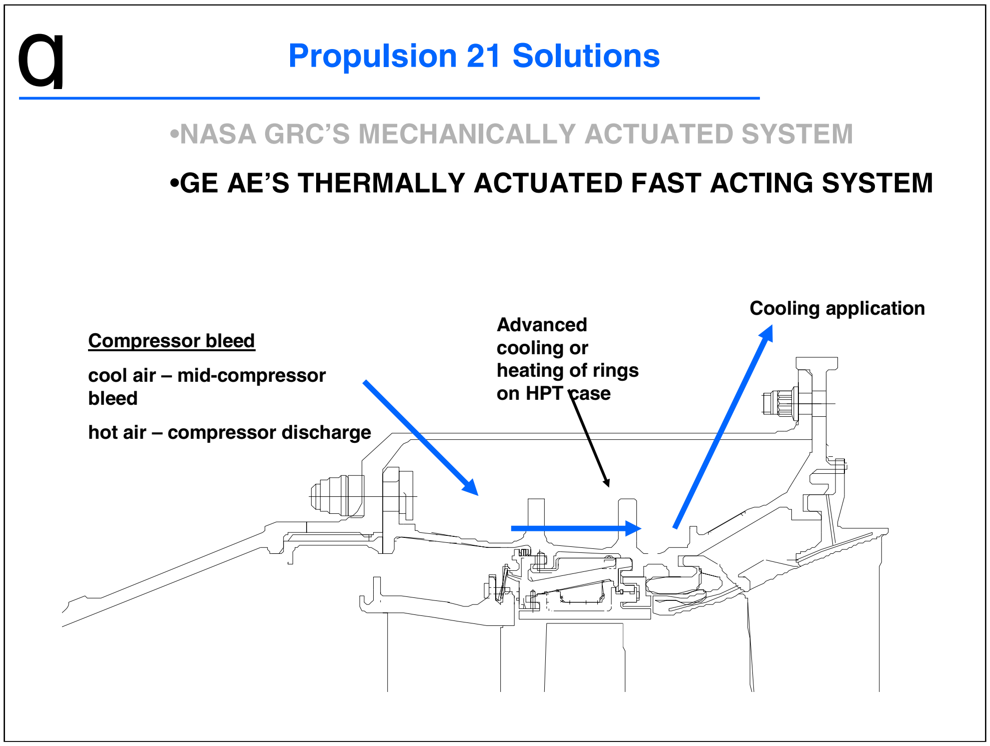
Propulsion 21 Solutions

•NASA GRC'S MECHANICALLY ACTUATED SYSTEM

•GE AE'S THERMALLY ACTUATED FAST ACTING SYSTEM



Under Prop 21 funding NASA GRC has been working on a rig which uses mechanical actuation of individual shroud segments. This system has the possibility of setting shroud radius locally based on the input from a clearance probe. Dr Bruce Steinetz will discuss the progress on this effort.

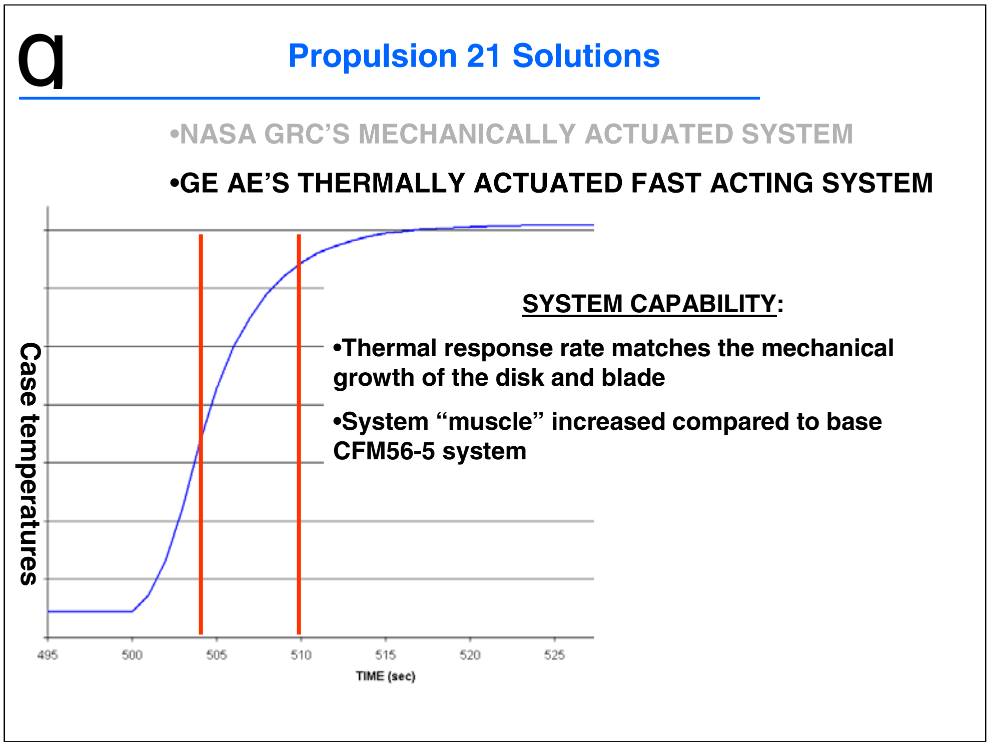


GE Aircraft Engines is working, under Prop 21, on a thermally actuated system which promises to provide fast response. This system uses hot and cool air as heat sinks for a convection cooled or heated case. In order quickly change the temperature of the case, and thereby its diameter, a significant temperature difference as well as mass of air are needed. This flow is "borrowed" form rotor cooling for Active Clearance Control purposes.

Propulsion 21 Solutions

- NASA GRC'S MECHANICALLY ACTUATED SYSTEM
- **GE AE'S THERMALLY ACTUATED FAST ACTING SYSTEM**
  - **Advanced thermal design increases heat convection beyond current system's capability**
  - **Air used in ACC reused in rotor cooling**
  - **HPT case time constants allow for elimination of rub protection (analysis)**

Increased flow through the HPT case, as well as improved heat transfer method allows for faster case response. The flow through the ACC system would be labeled as "non-chargeable", meaning it would return to core flowpath.



This is a result of analysis of a flight maneuver where speed was increased from cruise to climb. This type of change typically is executed to bring aircraft to a higher altitude. The reason for this change may be to make the flight more efficient as the aircraft burns off fuel, or to increase passenger comfort during excessive air turbulence.

It is assumed that this acceleration is linear over 4 sec. This is the time allowed for the system to react and respond to the clearance change associated with the acceleration. The system allows for rub protection to be excluded from cruise clearance setting. Also, the amount of "muscle" provides for clearance changes associated with normal deterioration of an engine.

Summary of Fast Thermally Controlled ACC

- **ADVANTAGE:**
  - **HPT ACC system fast enough to reduce cruise clearance**
- **CHALLENGES:**
  - **Minimize cost, weight and complexity of proposed system**
- **WORK AHEAD:**
  - **Rig test system**
  - **Develop best FADEC schedule for system**
  - **Clearance Probe development – May provide best benefit with this Prop21 program**
  - **Control logic**
  - **Engine test**

TEST RIG FOR ACTIVE TURBINE BLADE TIP CLEARANCE CONTROL CONCEPTS: AN UPDATE

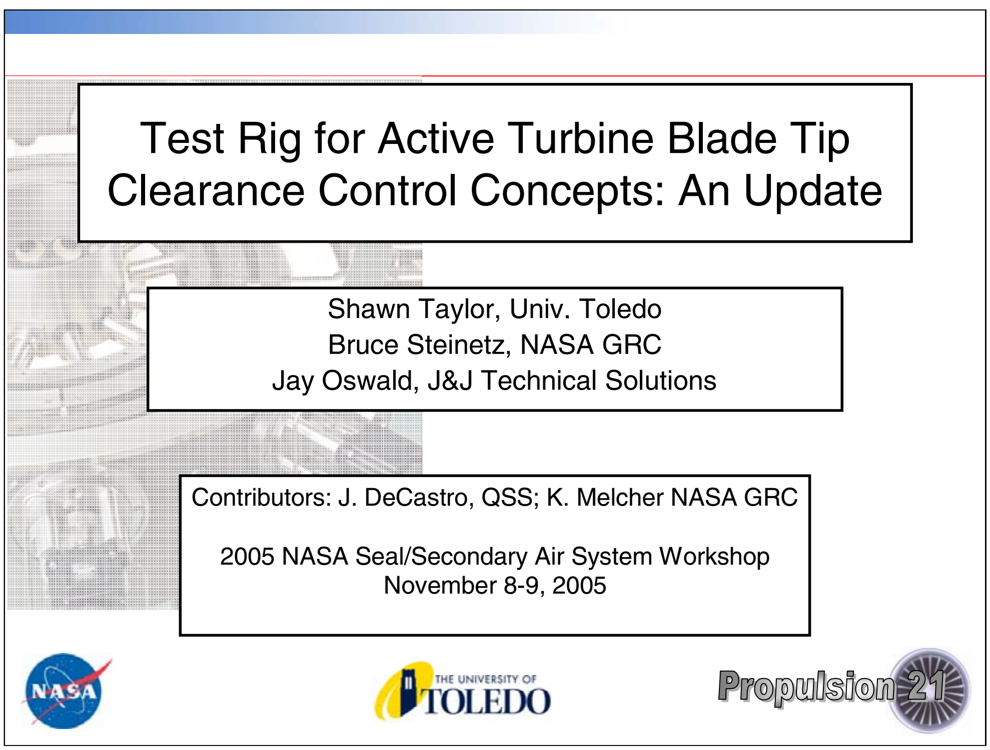
Shawn Taylor
University of Toledo
Toledo, Ohio

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

Jay Oswald
J&J Technical Solutions, Inc.
Cleveland, Ohio

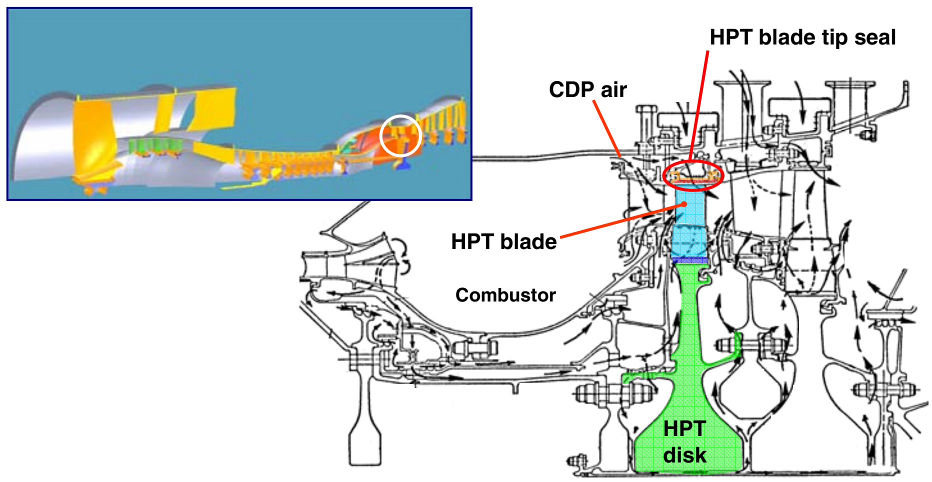
Jonathan DeCastro
QSS Group, Inc.
Cleveland, Ohio

Kevin Melcher
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

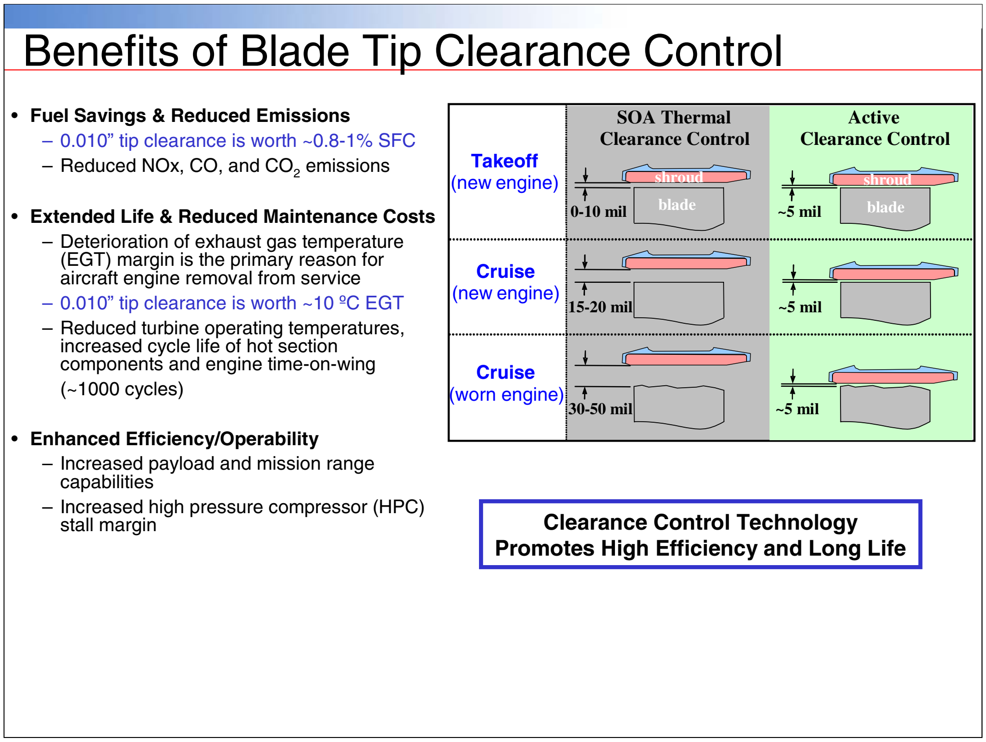


Active Clearance Control (ACC) Objective

Develop and demonstrate a fast-acting active clearance control system to improve turbine engine performance, reduce emissions, and increase service life



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



You may ask why would we want to pursue this?

Well I am glad you asked: benefits of clearance control in the turbine section include lower specific fuel consumption (SFC), lower emissions (NOx, CO, CO2), retained exhaust gas temperature (EGT) margins, higher efficiencies, longer range (because of lower fuel-burn).

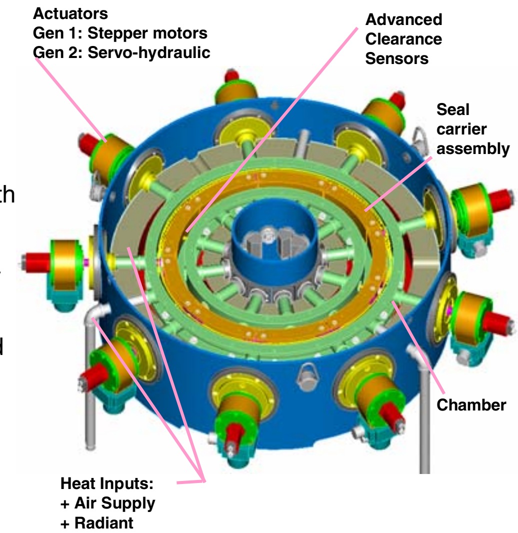
Blade tip clearance opening is a primary reason for turbine engines reaching their FAA certified exhaust gas temperature (EGT) limit and subsequent required refurbishment. As depicted in the chart on the right, when the EGT reaches the FAA certified limit, the engine must be removed and refurbished.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

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.

ACC Test Rig Goals

- Evaluate individual component seal leakages under engine simulated pressure (up to 120 psig) and temperature conditions.
  - Current: Ambient temperature
  - Future: 1200°F
- Evaluate overall system leakage both statically and during motion.
- Evaluate candidate actuators' ability to position the seal carriers at the required rate, accuracy, and repeatability under engine simulated conditions.
- Evaluate candidate clearance sensors as part of the ACC closed-loop feedback control system.

Active Clearance Control Test Rig



With these challenges in mind, we set-out to develop a fast-acting mechanically actuated active clearance control system and test rig for its evaluation.

In this test rig a series of 9 independently controlled linear actuators position 9 seal carriers. These seal carriers move inward and outward radially simulating a camera iris. More details of the test rig will be given on the next chart.

The goals of research effort are summarized here.

Using the new ACC test rig, we have been able to assess:

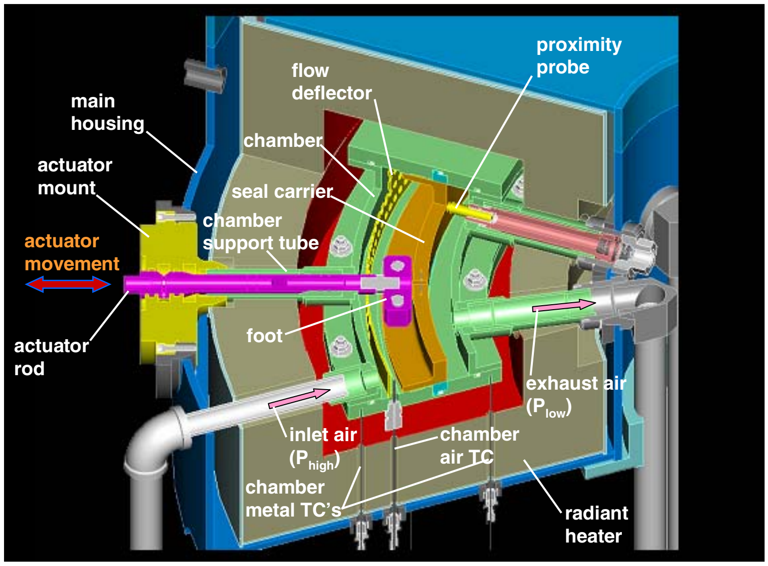
+ Individual component seal leakage rates and to compare them to an industry reference level at engine simulated pressures but at ambient temperature. High temperature tests are planned in the future.

+ Evaluate system leakage both statically and dynamically

+ Evaluate candidate actuator's ability to position the seal carriers in a repeatable fashion

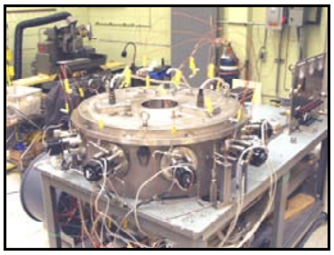
+ Evaluate clearance sensors as part of the closed loop feedback control.

ACC Test Rig Components



Recent Accomplishments

- Test rig installed and instrumented
  - Completed ambient temperature leakage and seal carrier actuation evaluations.
  - Investigated face seal to seal carrier interface for possible leakage reduction.
- Completed preliminary checkout of air and radiant heaters
- Obtained safety permit for hot testing



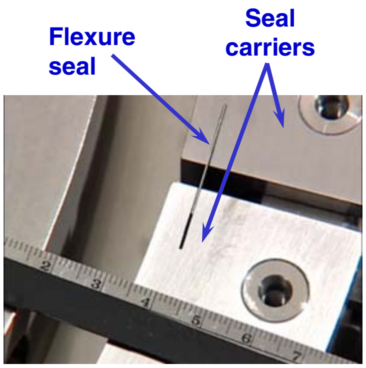
Fully Instrumented Rig Assembly

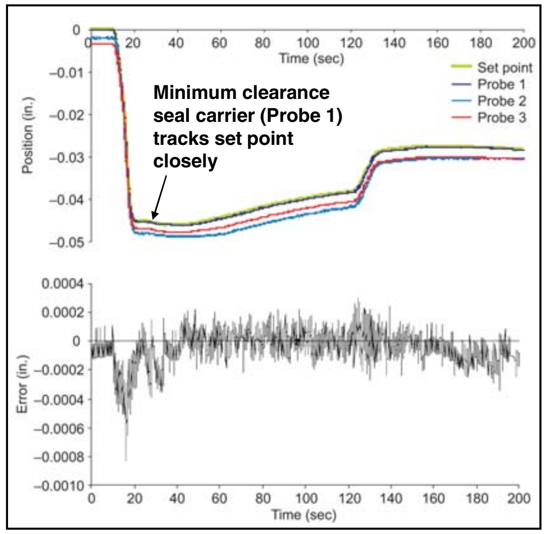
Completed Heater Controls

Simulated Engine Take-off Clearance Profile

Simulated engine take-off transient:

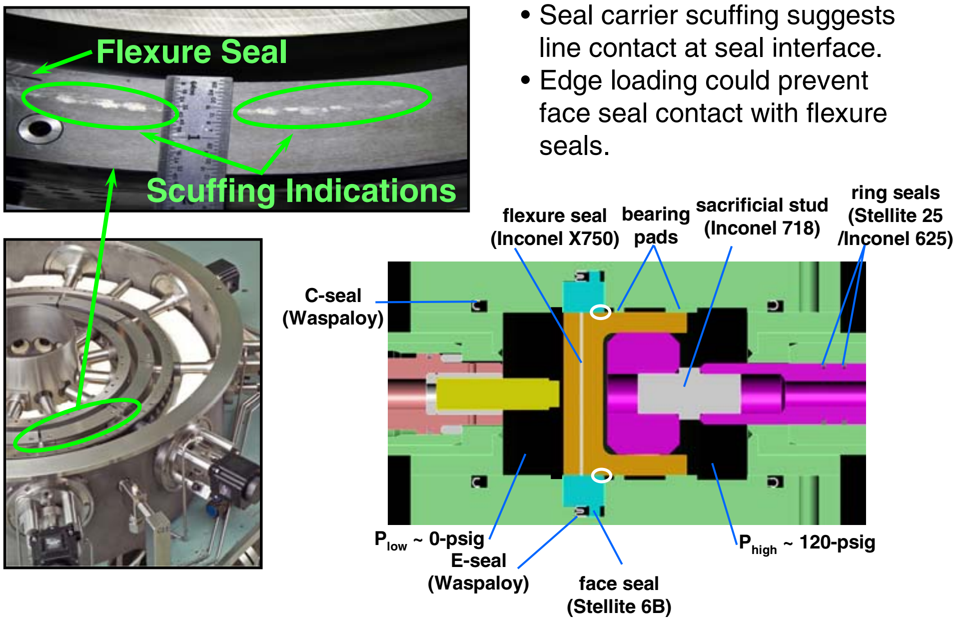
- Closed-loop position control using capacitance probes at 20 psig.
- Seal carrier tracked the set-point to within 0.001”.



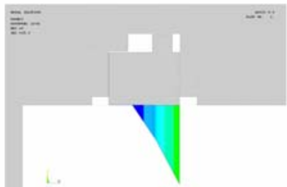


Seal Carrier Scuffing Indications

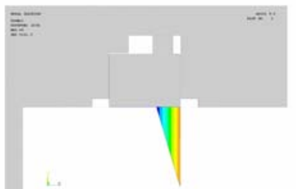
- Seal carrier scuffing suggests line contact at seal interface.
- Edge loading could prevent face seal contact with flexure seals.



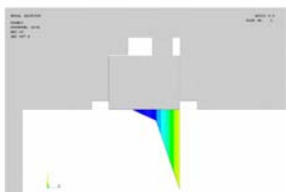
Face Seal Finite Element Analysis



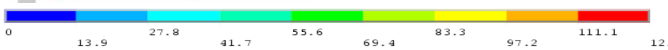
Static Carriers



Inward Carrier Motion



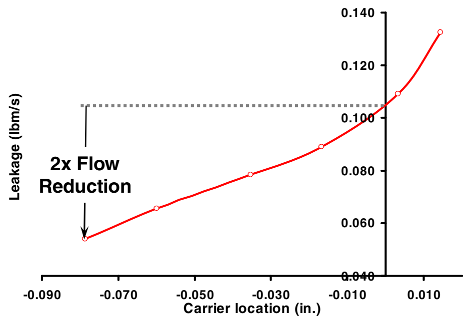
Outward Carrier Motion



FEA at 120 psig

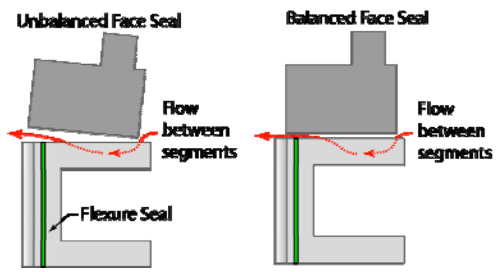
- Unbalanced face seal pressure profile causes outer edge loading when seal carriers are both static and in motion.
- Edge loading caused scuffing indications on seal carriers.

Repositioning Carrier Reduces Leakage

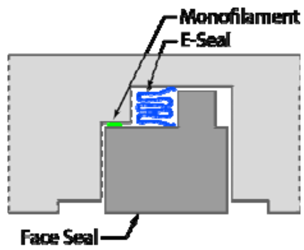


Seal	Leakage, % of total
Outer C-Seals	1
Air Inlet Rings	2
Actuator Rod Ring Seals	6
Face Seals	7
Flexure Seals	85
Total	100

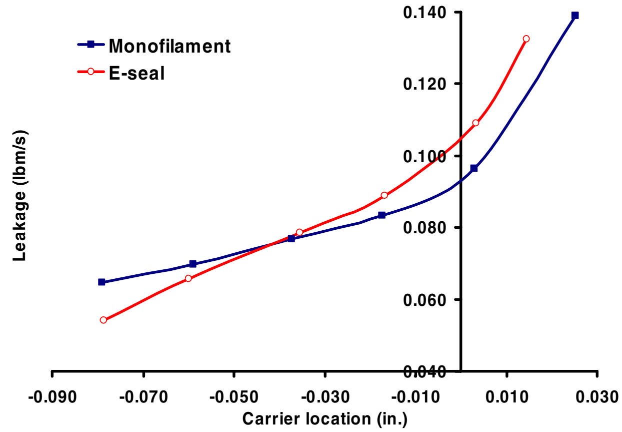
- Face seal unbalance:
  - Causes leakage dependence on seal carrier position.
  - Increases leakage over flexure seals due to edge loading.
  - Goal: achieve leakage independent of carrier position.



Monofilament Trial Seal



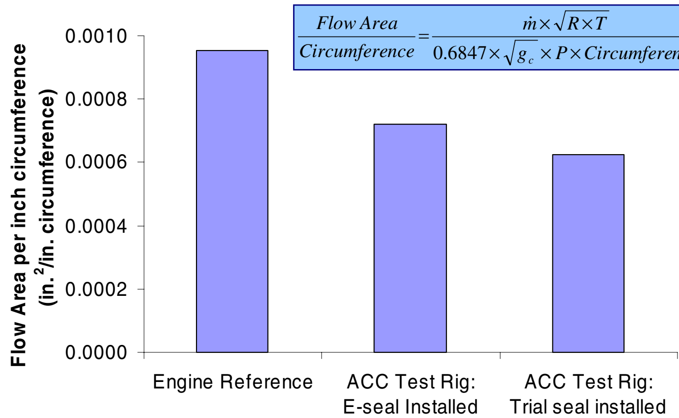
Monofilament Substituted for E-seal, Radially Inward



- Monofilament substitution for E-seal shifts applied preload line of action radially inward, improving pressure profile balance.
- Balancing pressure profile reduces leakage dependence on carrier location, indicated by the decreased line slope in the monofilament data.

ACC Unit Leakage vs. Industry Ref. Level

$$\frac{Flow\ Area}{Circumference} = \frac{\dot{m} \times \sqrt{R \times T}}{0.6847 \times \sqrt{g_c} \times P \times Circumference}$$

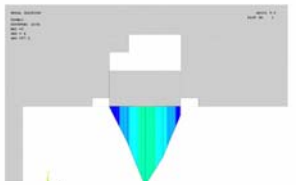


- Industry Reference Level: Determined for forward/aft side seals for an idealized elastic ring structure. Each seal having leakage rate of 0.1% core flow.
- ACC Test Rig: Effective unit leakage flow area back calculated from measured flow.

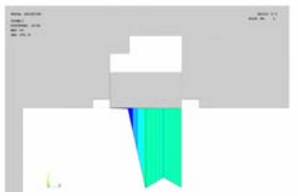
If one were to idealize the ACC system as an elastic structure (e.g. a rubber ring or band) that could move radially inward/outward, seals would only be required between the sides of the moving structure and the surrounding static structure. Engine designers have acknowledged that seals in these areas leaking less than 0.1% of core flow would be an acceptable loss considering the potential for the significant gains possible through tighter HPT blade tip clearances. Converting this level into an effective flow area per unit circumference we found a level of about 0.00096 in^2/in unit flow area.

Back-calculating the equivalent unit flow area per unit circumference using the measured ACC system leakage rates and the equation for isentropic flow under choked flow conditions, we obtained a value of 0.0008 in^2/in. We see that the unit flow areas compare favorably. We recognize that further assessments are required at high temperature before we can claim victory. However these results are encouraging.

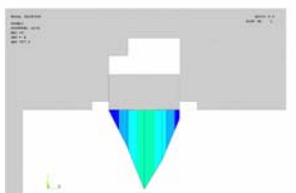
Face Seal Improvement with FEA



Static Carriers



Inward Carrier Motion

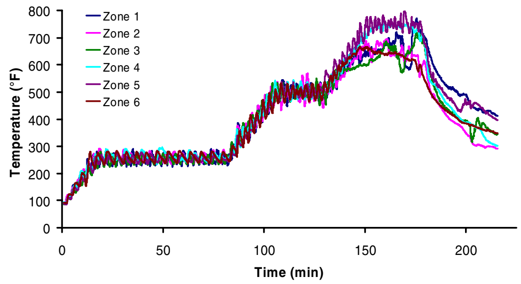


Outward Carrier Motion

FEA at 120 psig

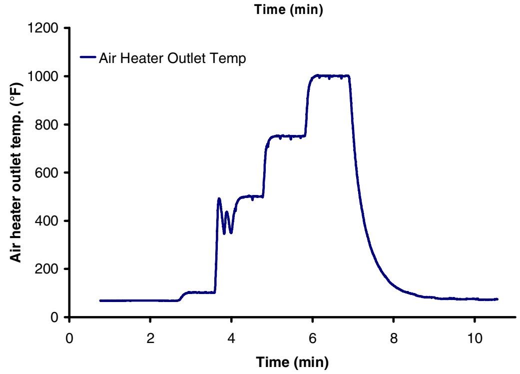
- Face seal pressure unbalance can be improved by decreasing the seal height.
- Balancing the face seal pressure profile mitigates seal edge loading.

Radiant and Air Heater Check-out



Radiant Heaters

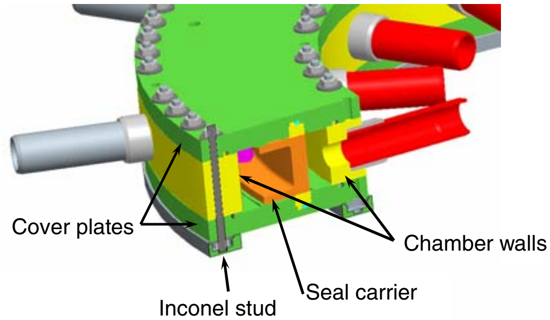
• Demonstrated simultaneous operation of all 6 zone heaters.



Air Heater

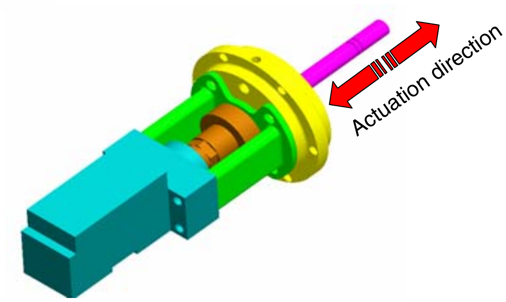
• Demonstrated ability to reach 1000°F with new air heater.

New Hardware Updates



Weldless Test Chamber
- Inconel 718 construction
- Cover plate to be attached with Inconel 718 studs
- Extends test temperature capabilities to 1200°F

Servo-hydraulic Actuator System
- Scheduled delivery Nov., ’05
- Higher load capacity extends operation range to the full 120 psi design pressure



Summary

- Rig is installed and operational.
  - Ambient temperature tests proved actuator displacement range.
  - Tests showed that the closed-loop position control followed the set-point to less than 0.001” for a simulated engine take-off clearance change.
  - Leakage tests show flow rates comparable to industry engine reference levels.
- Acquired safety permit for hot testing.

Future Work

- Perform leakage and actuation tests at elevated temperatures.
- Install turn-key hydraulic actuator system to extend testing to full 120 psig test chamber pressure.
- Complete design and fabrication of new test chamber to extend high temperature testing to 1200°F.
- Investigate face seal modifications to enhance seal performance and mitigate leakage dependence on carrier position.

Acknowledgements

- Arthur Erker, Analex
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- Toby Mintz, Analex
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- Mike McGhee, NASA GRC
- Tom Lawrence, NASA GRC

Contact Information

Shawn C. Taylor

Senior Research Associate, U. Toledo

NASA Glenn Research Center, Cleveland, OH

216.433.3166

shawn.c.taylor@grc.nasa.gov

MICROWAVE BLADE TIP CLEARANCE SYSTEM: AN UPDATE

Jon Geisheimer
Radatec, Inc.
Atlanta, Georgia

Microwave Blade Tip Clearance System: An Update

2005 NASA Seal/Secondary Air System Workshop

Jon Geisheimer
75 Fifth St. NW, Suite 211
Atlanta, GA 30308
404-526-6037
jong@radatec.com

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Overview

- Sensor Basics
- System Overview
- Laboratory Measurements
- Example Tip Clearance Data
- Example HCF Data
- Future Directions

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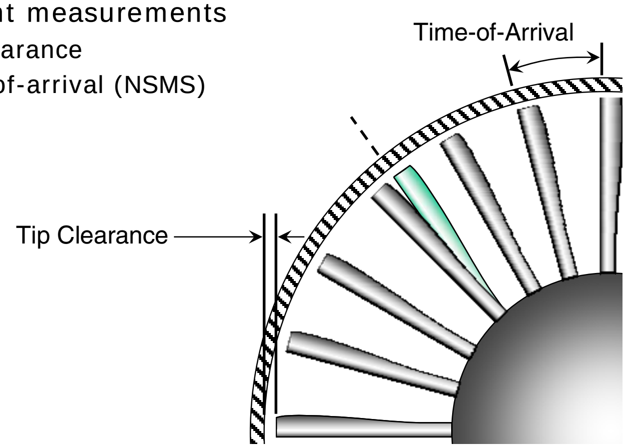
Blade Tip Sensing

- Important measurements
  - Tip clearance
  - Time-of-arrival (NSMS)



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Why Measure Blade Tips?

- In the HPT for every 1 mil improvement in clearance[1]
  - SFC decreases 0.1%
  - EGT margin increases 1°C
- Newer engines use compressor bleed air and a model to close clearances open loop
- Measuring clearances and closing the control loop can add additional efficiencies
- Tip clearance control has been identified as a key technology for future engines
- Additional benefits in prognostics, NSMS, and condition-based maintenance

[1]Wiseman, et al., "An investigation of life extending control techniques for gas turbine engines," Proceedings of the American Controls Conference, Arlington, VA, June 25-27, 2001

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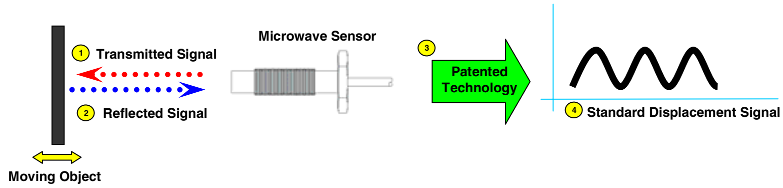
Sensor Overview



- Non-contact displacement sensor
- Phase-based microwave technique
- Measures displacement smaller than the transmitted wavelength

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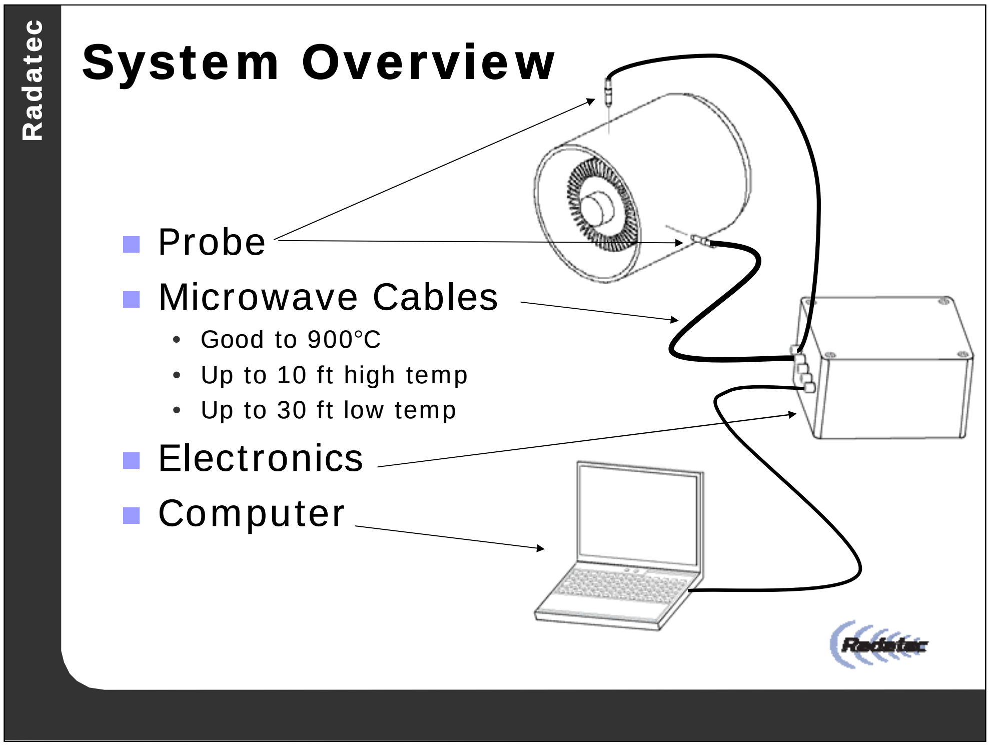
Why Use Microwaves for Tip Clearance?

- Ability to withstand high temperature (>1000°C)
- “See through” combustion contaminants
- Large bandwidths (limited only by sampling)
- High signal to noise ratios (active system)
- Not RPM dependant

The microwave displacement sensor operates similar to many other non-contact displacement sensors, but tends to be more robust to environmental effects. Microwaves can penetrate through many non-metallic materials such as oil, that would give problems to other sensors. In addition, the techniques are phase-based, so the displacement measurement is somewhat independent of the metal or surface finish being examined. Because an active microwave beam is used, the sensor can take measurements at any target speed from DC on up. Other sensors based on resonant cavity techniques only give valid readings over a certain range of motion. The motion of the target encodes the information of the transmitted electromagnetic wave and the only practical limitation to bandwidth is how fast you can sample the data.



This example shows the current state of the hardware, where two probes are used to fully characterize radial motion. Right now, a computer is being used to collect the raw data and then the radar to displacement conversion as well as the data analysis is being performed off-line. One of the major efforts currently ongoing is to develop the real-time signal processing for the sensor to generate real-time displacement outputs.

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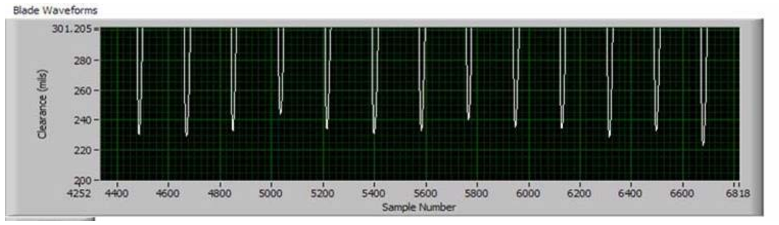
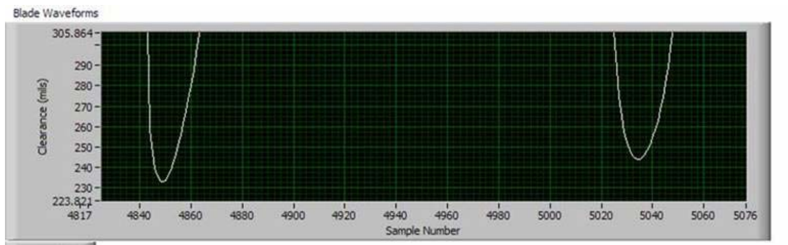
Example Waveforms





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Probes

- High temperature nickel-alloy metals
- Ceramic dielectrics

¼” 5.8 GHz, In Development

½” 5.8 GHz, Tested to gas paths > 2000°F

Old Probe, 5/8” 24 GHz

Size Doesn’t indicate Measurement Range

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Probe Reliability

- Designed for 2500°F gas path
- Use compressor bleed air for active cooling
- General testing approach
  - Air furnace isothermal exposure
  - Temperature transient cycling
- Probe construction- Meggitt Safety Systems

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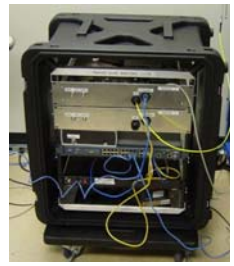
Current Prototype

- 2U, 19” rack per sensor
- Rack mount computer
- Ethernet communications



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Compact PCI Product Platform

- Now in prototype build
- CompactPCI 6U Chassis Based System
- 1 Sensor per 6U Slot

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Real Time Processing

- Field Programmable Gate Array (FPGA) runs algorithms in real time
  - Runs continuously at sample rates up to 20 MHz
  - Converts microwave signals to displacement
  - Extracts features from blade
- Able to continuously extract tip clearance and time of arrival (ToA) digitally in real time for every blade
- Clearance and ToA streamed to PC via 10/100 Mb Ethernet (UDP/IP)

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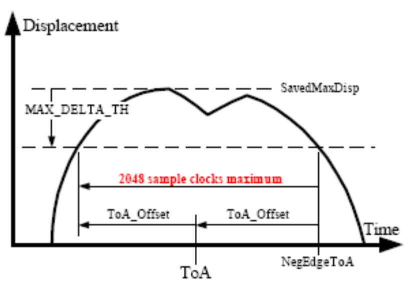
Feature Extraction

- Blade waveform is measured in distance, not voltage
- First, pick out peak of blade
- Then, go down the blade a set distance on both the pressure and suction side of the waveform (distance to go down is a parameter that can be changed)
- Notate time of arrival and time of departure



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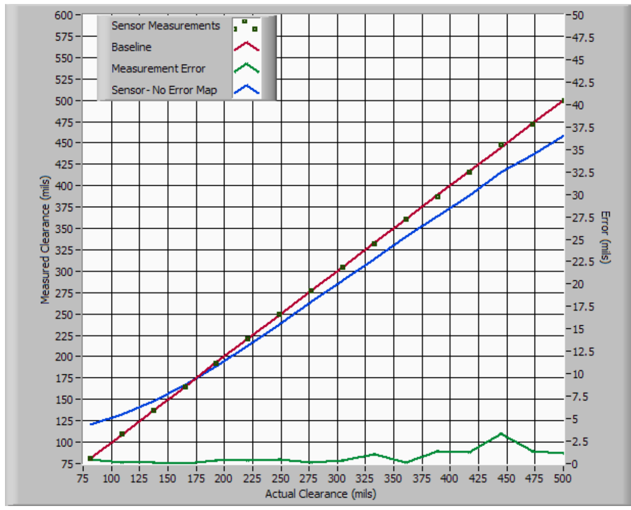
Laboratory Tests- Turbine Blade Linearity



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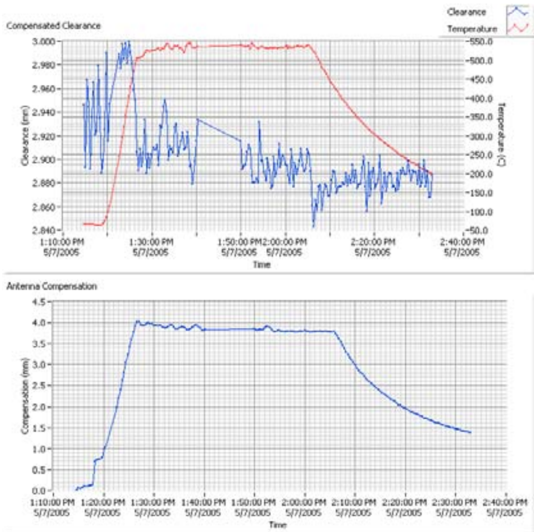
Laboratory Tests- Cable Compensation



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Sensor Specifications

- **Sensor Bandwidth-** 10 MHz (20 MHz sampling)
  - Same waveforms from zero RPM to full speed
- **Resolution-** 0.5 mils
- **Linearity-** ~1% of full scale range, target dependent
- **Sample Rate-** 20 MHz
- **Onboard Memory-** 32 MB
- **Probe Temperature-** >1800°F
- **Microwave Cabling-** 0.142” cable up to 30’
- **Digital Data Outputs-** Time of arrival, tip clearance
- **Analog Outputs (10 MHz bandwidth)-**
  - Blade waveforms
  - Voltage proportional to TOA
  - Voltage proportional to clearance
- **Sensor to PC Communications-** 10/100 Ethernet, UDP/IP

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Power Systems Testing

- Large frame power systems engine
- Second stage turbine
- Gas paths of 2000°F
- Active cooling design

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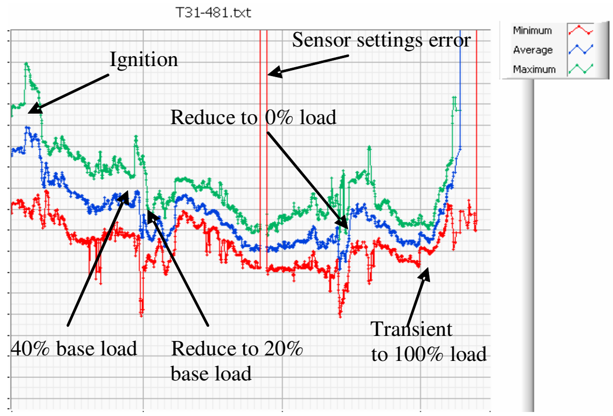
Example Clearance Plot



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High Cycle Fatigue (HCF)

- Spin pit test
- Fan blade monitoring
- Seeded defect in blade
- Oil jet excitation to induce stress

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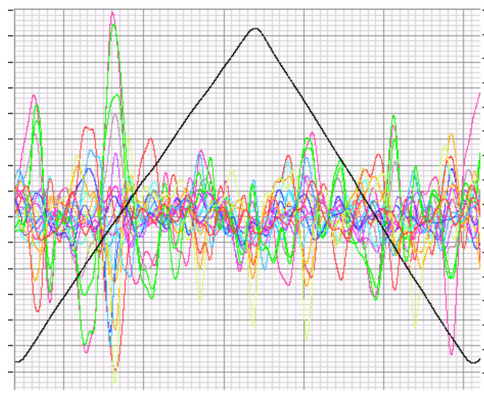
Example Resonance



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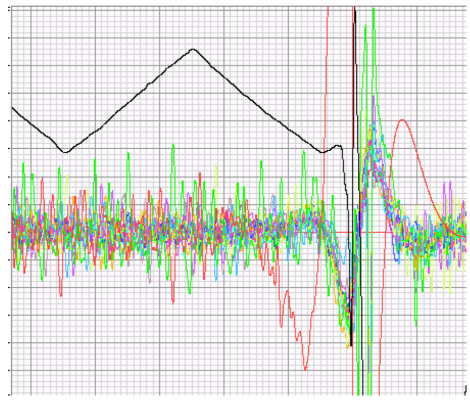
Blade Lengthening Event



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Future Directions

- Working with NASA Glenn to test system in high pressure burner rig, Q1 2006
  - 2500°F 1st stage turbine temperatures
- Compact PCI-based Tip Clearance Product
  - Power systems
  - Aero tests
  - Laboratory instrumentation
- More large frame power systems testing in turbine and compressor
- More spin pit testing

PROGRESS ON SHAPE MEMORY ALLOY ACTUATOR
DEVELOPMENT FOR ACTIVE CLEARANCE CONTROL

Jonathan DeCastro
QSS Group, Inc.
Cleveland, Ohio

Kevin Melcher and Ronald Noebe
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

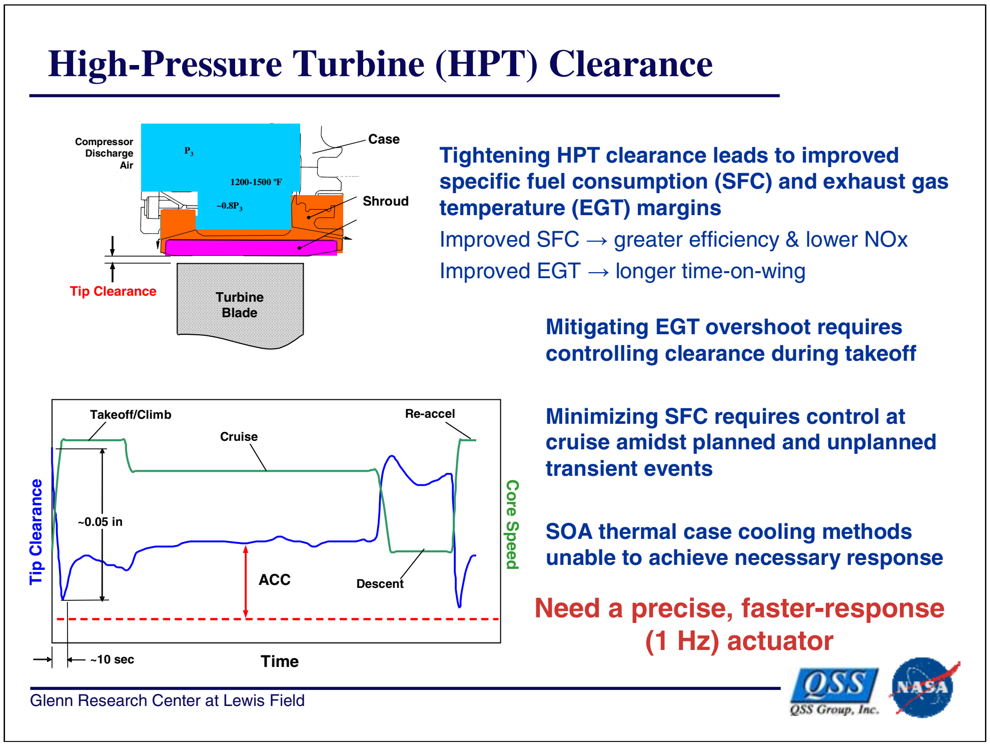
Results of a numerical analysis evaluating the feasibility of high-temperature shape memory alloys (HTSMA) for active clearance control actuation in the high-pressure turbine section of a modern turbofan engine has been conducted. The prototype actuator concept considered here consists of parallel HTSMA wires attached to the shroud that is located on the exterior of the turbine case. A transient model of an HTSMA actuator was used to evaluate active clearance control at various operating points in a test bed aircraft engine simulation. For the engine under consideration, each actuator must be designed to counteract loads from 380 to 2000 lbf and displace at least 0.033 in. Design results show that an actuator comprised of 10 wires 2 in. in length is adequate for control at critical engine operating points and still exhibit acceptable failsafe operability and cycle life. A proportional-integral-derivative (PID) controller with integrator windup protection was implemented to control clearance amidst engine transients during a normal mission. Simulation results show that the control system exhibits minimal variability in clearance control performance across the operating envelope. The final actuator design is sufficiently small to fit within the limited space outside the high-pressure turbine case and is shown to consume only small amounts of bleed air to adequately regulate temperature.

Presentation Outline

- Objective and scope for active clearance control
- Survey of candidate actuators
- Design of a high-temperature shape memory alloy actuator
- Analytical evaluation of active clearance control system
- Concluding remarks and future work

Glenn Research Center at Lewis Field

QSS Group, Inc.



The gap between the turbine blades and shroud can cause severe leakage of hot combustor gas past the HPT blades. Leakage of this energetic flow can lead to penalties in specific fuel consumption (SFC) and exhaust gas temperature (EGT). If the clearance can somehow be reduced, significant increases in engine efficiencies and substantially improved engine longevity can be realized. Specifically, 10 mils reduction in clearance roughly translates into 1% SFC reduction and 10 deg. C EGT reduction.

As shown by the above plot, clearance varies widely throughout a normal mission. Because of this, engine manufacturers incorporate a cold-build clearance to avoid any detrimental rubs between the turbine shroud and the blades. During takeoff, for example, the blades expand rapidly due to centripetal loads caused by rotor acceleration, creating a pinch point at maximum power. As the slower thermal effects begin to dominate, the clearance again opens up at climb and cruise.

In modern engines, the larger gap at steady-state is only partially alleviated by thermal active clearance control systems, which rely upon preferentially blowing cool fan air on the HPT flange depending upon the operating conditions. These systems suffer from very slow response times, and therefore cannot operate with tight clearances because the possibility exists that re-accel or re-burst events can still cause rubs.

Therefore, it is extremely important to develop an actuation system with a response time at least as fast as the clearance transients it is likely to encounter. In order to control clearance to much lower levels, about 0.005 inches (indicated by the red dashed line), the actuator must be capable of ultra-precise positioning.

Clearance Control Actuator Candidates

Active Clearance Control System

Goal: Control clearance to within 5.0 mils without blade-to-shroud incursions

- Use segmented shroud ring: one actuator per "floating" shroud segment
- Measure clearance gap for feedback (25-MHz microwave probes)

Actuators

Near term solution: *conventional servo-hydraulics*

- Currently in the works

Longer term solution: *smart materials*

- Using "smart material" actuators facilitates thrust toward an all-electric engine

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The concept that the active clearance control group is investigating uses a set of actuators that are mounted circumferentially around the turbine, with each one attached to a "floating" shroud segment. Each actuator maintains closed-loop control of clearance based on instantaneous clearance measurements at the shroud by high-bandwidth clearance probes. These independently-actuated shroud segments collectively form the annular shroud ring assembly. Such a concept places high demands on an actuator, as it must not only position precisely to within one thousandth of an inch of the desired set-point, but must do so amidst widely varying pressure loads acting on the ring.

There are two solutions to the active clearance control problem. The first is centered around utilizing established *conventional* actuator technology, which primarily encompasses servo-hydraulic actuators. These actuators are presently used in engine applications such as variable stator vanes and variable area nozzles. They therefore offer the lowest risk for an active clearance control solution. We are investigating this solution presently, as assembly of the servo-hydraulics is underway for evaluation in the NASA tip clearance test rig.

A second solution exists in the realm of *smart material* actuator technology…

Survey of Actuator Candidates

Actuator	Energy density	Approx. system weight	Rate capability	Max. temperature	Power consump.
Shape Memory Alloy	500 J/kg	0.9 lb	~ 0.1 in/sec	930 °F	Low
Piezoceramics (PZT)	10 J/kg	43 lb	200 in/sec	400 °F	Moderate
Servohydraulics	40 J/kg	58 lb	0.5 in/sec	600 °F	High

High-temperature shape memory alloys **(HTSMA)** have high energy densities & demonstrate excellent robustness at elevated temperatures seen in HPT

- Recently developed at GRC
- Composition: $Ni_{30}Pt_{20}Ti_{50}$

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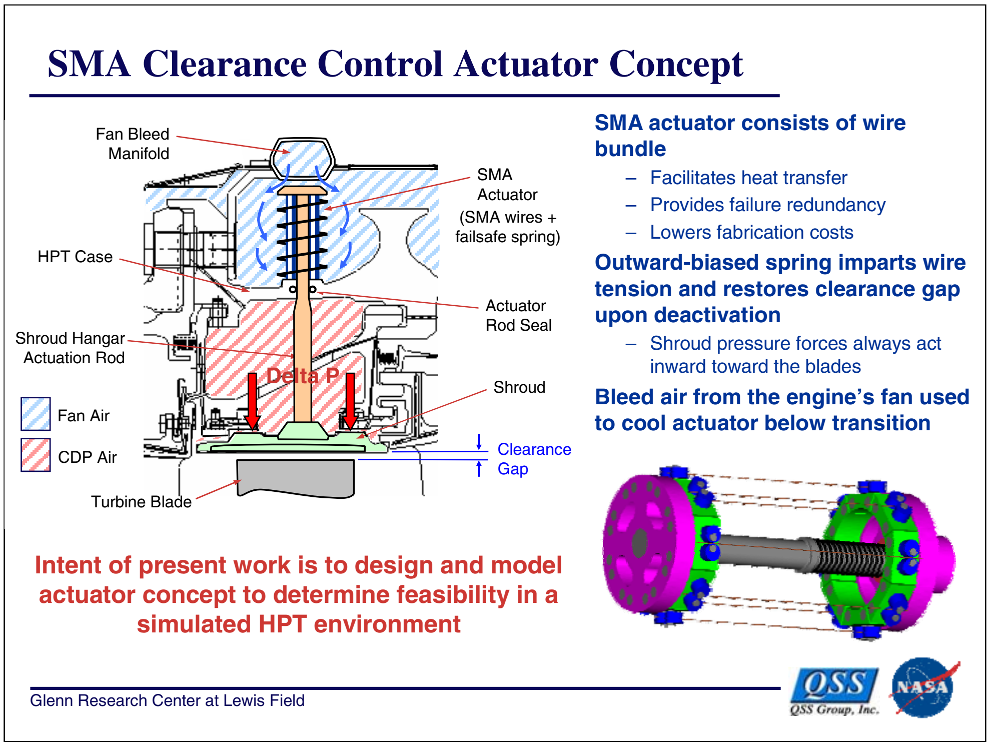
Based on our preliminary survey of clearance control actuators, shape memory alloy actuators are a strong candidate for clearance control because they offer close to an order of magnitude higher energy density than conventional and piezoelectric actuators. This higher energy density translates into a commensurate decrease in actuator weight or decrease in power consumption, which is extremely advantageous for implementation.

These actuators are generally regarded as higher-risk technologies, but if the technology development is pursued immediately, we can realize the benefits of these actuators as the technology matures. Researchers at Glenn are developing highly robust smart materials just for this purpose. The recently-developed high-temperature shape memory alloy (HTSMA) is capable of operating indefinitely close to the highest temperatures seen in the HPT exterior (900 - 1000 deg. C).



By virtue of the fact that these alloys can be manufactured into a number of different configurations, we have the freedom to optimize the actuator design for clearance control. The actuator concept shown above consists of several SMA wires attached to the exterior of the HPT case, where more "benign" temperatures are expected (<900 deg. C), and attached at the other end to a push rod that moves the shroud toward and away from the blades. When the SMA wires are heated up, the material constricts, causing the shroud to move inward toward the blades. When cooled, the wires expand, causing motion away from the blades. The delta P across the shroud always acts toward the blades, so a biasing spring must be incorporated in the design in order to keep the SMA wires in tension and furthermore guaranteeing a failsafe upon wire failure.

An important feature of this concept, which is a testament to the alloy itself, is that it may be possible to completely operate this material via modulated fan bleed air, thereby eliminating the need to draw power from the engine's power bus. Note that this is exactly how SOA thermal clearance control systems operate, a therefore requiring little to no modification to the bus. The major barrier for implementing many smart material actuator concepts is in the fact that they require large power draws to operate, however it will be shown that HTSMAs do not suffer from this limitation.

The goal of our present work was to perform a system-level feasibility study of such actuators for active clearance control. Shape memory alloys have a large amount of hysteresis as well as moderate response times, due to a dependence on thermal activation. This can potentially thwart rub-free clearance control.

HTSMA Actuator Feasibility Study

Assessment will determine:

- Whether precise clearance control can be established with hysteresis and response time limitations
- How much fan air bleed is necessary to retain performance specs
- What control law is necessary for precise actuator positioning

A detailed model of HTSMA actuator used to:

- Optimally design clearance control actuator
- Perform closed-loop evaluation in "test bed" engine simulation

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The feasibility study itself was concerned with the question of whether or not the actuator can operate in a simulated HPT environment, knowing the material properties and having a representative model of the material. What would be gained by such a study is an understanding of: 1) how well the actuator can position a shroud segment amidst hysteresis and heat transfer time lags; 2) how much power draw, in this case bleed air, is necessary for clearance control; and 3) what control laws are required to compensate for nonlinearities and maintain a constant clearance gap through control of the shroud position.

Optimal Actuator Design

Design Requirements – Candidate Engine

Stroke capability	> 0.05 in
Rate capability	> 0.01 in/sec
Force capability	> 2200 lbf
Number of actuators	20
Actuator headroom	2 in
Temperature inside case	> 1300 °F
Temperature outside case	900 °F

- Number of actuators: Actuator must be lightweight
- Actuator headroom: Actuator must fit within available limited headroom
- Temperature outside case: Installation on exterior of high-temp/ high-pressure case

Design optimization
9 steady-state operating points, excluding ground idle

Optimization Results

Length	2.0 in
Peak Strain	2.5 %
HTSMA Area	0.0664 in^2
Cold Clearance	0.090 in
Preload Force	8040 lbf
Spring Constant	16080 lbf/in

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The desired requirements are as follows. The actuator stroke should be large enough to cover the entire operating envelope, and therefore be on the order of 0.05 inches. The maximum rate-of-change should be about 0.01 inches, which is based upon the rates seen during takeoff. The maximum force that the actuator must be designed to withstand is 2200 lbf, which occurs at the max power condition. This force plays a large role in how the failsafe spring is designed. Of course, we must also obey spatial and environmental constraints. Given that the actuator must be placed outside of the case due to temperature considerations, we are limited to a radial headroom of 2 inches.

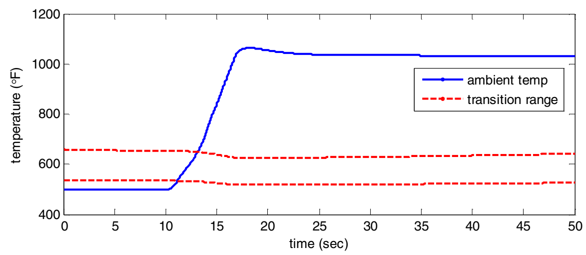
To achieve a feasible design, the optimization consisted of nine operating points, representative of the majority of the flight envelope. Ground idle was not included in the optimization because this would require a longer (by about 20%) actuator to accommodate this operating point. Active clearance control benefits are much less significant at that point, so this is a reasonable course of action. The optimal design results are as shown in the table. Of further note is that the peak strain is limited to less than 2.5% to avoid life cycle deterioration of the material.

Active Clearance Control Evaluation

PID controller with anti-windup protection developed for simulation

Resistive heating was used for actuation

- Slow heating times → slight degradation in performance
- Slow cooling times → *blade rubs*



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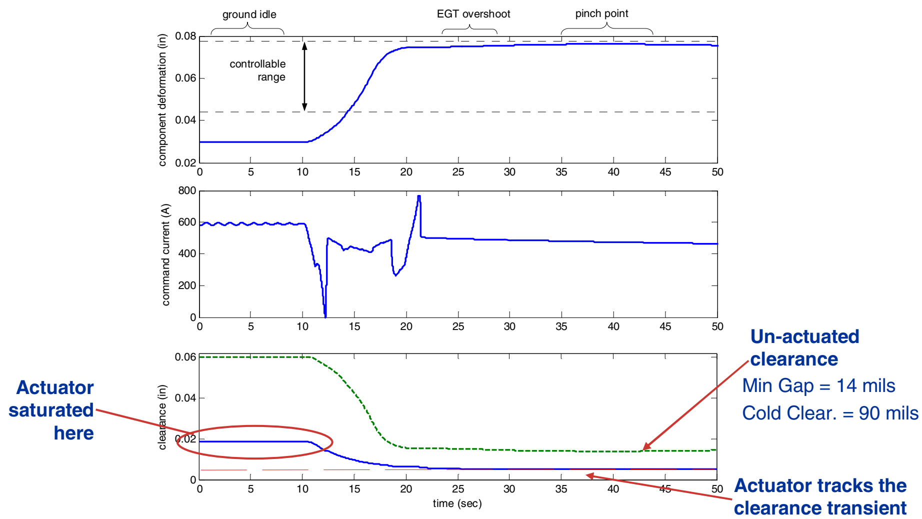
Now that a static design is complete, transient evaluation of the actuator can be conducted. For the subsequent experiments, a simple proportional-integral-derivative (PID) controller was designed with anti-windup protection to avoid problems when saturation limits are encountered. Being that the controller is linear, it cannot directly compensate for the highly nonlinear hysteresis effects. As stated earlier, one of the goals of the evaluation is to assess the efficacy of this approach.

Because transition temperatures of the present HTSMA are higher than the ambient temperature at low-power operating conditions, resistive heating was employed as the actuation mechanism. Because of the actuator configuration, the actuator's cooling time is much more important than heating time, because slow cooling times can result in blade rubs, while slow heating times do not. It is therefore of utmost importance to avoid prohibitively slow cooling times. We can still obtain an assessment of this cooling time, as this heat transfer mechanism is the same whether active cooling or resistive heating is employed.

ACC Amidst a Takeoff Transient

Baseline: Bleed air = 100% SOA; 10 wires - 0.092-in dia. (to satisfy 0.0664-in² design area)



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For the baseline design case, fan bleed air was set to a value identical to SOA thermal clearance control, and the wire count was set to 10, with a wire diameter of 0.092 inches. The higher the wire count, the lower the diameter, allowing faster heat transfer. If response time becomes problematic, it may be possible to explore higher wire counts.

The plot shows the actuator's response during a takeoff transient. The top plot shows the sum total of HPT component deformation (shroud, blades, case), the middle plot shows the command current, and the bottom plot shows the HPT clearance. Because of the exclusion of ground idle, the actuator is saturated at its full excursion toward the blades until takeoff occurs. At this point, the clearance quickly converges to the 5-mil set point within a few seconds, as shown by the blue line.

During failsafe operation, the clearance follows a profile similar to the green line, with the larger conservative clearances restored over the course of the transient. Of note is that the failsafe spring correctly prevents the un-actuated shroud from causing blade rubs.

Air Consumption Assessment

Effect of fan air bleed quantities on control performance

10 wires – 0.092-inch diameter

PID gains re-tuned for each test run

Bleed air (% of SOA)	Min. clearance (in)	Set point convergence (sec)	Current at A_f (A)
100%	5.0	21.8	562
20%	5.0	22.0	407
5%	1.1	35.2	322
1%	-18.4	85	268

Wire count of 10 allows about 80% reduction in bleed air vs. SOA

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By virtue of the fact that the HTSMA's transition temperatures reside just below the ambient temperatures at high power, only small portions of fan bleed air are necessary to maintain wire temperature below transition, in order to preserve full actuator authority. It is because of this that only small bleed air quantities are needed, as shown in the above table. For the 10-wire baseline case, only 20% of the present bleed air is needed in order to provide full authority without blade rubs. If the number of wires is increased to 30, which allows the diameter to be reduced to 0.053 inches, the required air is only 5%. Both scenarios are substantial improvements over state-of-the-art.

For reference, employment of resistive heating requires approximately 0.4 kW for the 100% bleed air case (0.66V at 562A). It important to note here that the designer can trade current draw for voltage by modification of the electrical configuration, for example, by placing wires in parallel instead of in series.

Step Response Evaluation

Response to step changes in clearance at key engine operating points – Baseline Case

CES operating point	Martensite fraction (%)	Settling time (sec)	
		+0.005 in	–0.005 in
Pinch Point	95.4	3.14	3.19
Climb	37.3	3.03	3.26
Cruise	20.5	3.01	3.27
Descent	0.9	3.03	3.38
		Away from blades	*Toward blades*

PID controller demonstrates uniform response across the operating envelope despite nonlinearities

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Evaluating the step responses at various operating conditions revealed that the system's response was uniform across the operating envelope. The results provide a strong indication that the linear PID controller is able to successfully control of the HTSMA with the nonlinear actuator, particularly amidst the prominent hysteresis.

Research Contributions

Developed shape memory alloy-based active clearance control actuator

- Based on GRC-developed robust hi-temp shape memory alloy (HTSMA)
- Very high energy density (actuation energy-to-weight ratio)
- Capable of fast clearance changes during fast transients, i.e. takeoff
- Failsafe design avoiding blade rubs due to HTSMA failure

Demonstrated Active Clearance Control Analytically

- Demonstrated control of clearance over critical portions of flight envelope
- Developed modified PID control law that meets clearance control objectives in the presence of actuator nonlinearities (delays, hysteresis, and saturation)

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In summary, a shape memory alloy actuator has been designed analytically for active clearance control. The actuator used here consists of HTSMA material recently developed at GRC exhibiting high robustness at the elevated temperatures of the HPT. Active clearance control simulations confirm that the wire-based actuator exhibits very high energy density, requiring much less air than SOA thermal control systems, and provides the heat transfer rate necessary for fast actuation during transients such as takeoff. Additionally, the design is failsafe to blade rub events. Use of a linear PID controller showed that tight control of clearance can be maintained throughout the operating envelope, to within 1 mil of the set point, given that the actuator is prone to slow response and highly nonlinear behavior in open loop.

Future Work

Develop application-specific HTSMA

- Design for active cooling via engine bleed air to control position (eliminating draw from power bus)

Perform studies on a simplified single/multi-wire actuator

Detailed actuator design, fabrication, & bench test

Closed-loop demonstration of tip clearance control system in NASA Static Tip Clearance Test Rig

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For future work, it would be desirable to iterate upon HTSMA composition to obtain transition temperatures just below the ambient temperature of the HPT. The tailored HTSMA would allow for full authority control over the engine's operating envelope using modulated fan air bleed.

Further studies on a single-wire and multi-wire actuator to confirm results from this study are also warranted. Such foundational work would permit a detailed actuator design to be pursued, with eventual testing in the NASA tip clearance test rig.

Thanks for listening.

Questions?

Reference:

J. DeCastro, K. Melcher, & R. Noebe: "System-Level Design of a Shape Memory Alloy Actuator for Active Clearance Control in the High-Pressure Turbine**,"** *Proceedings of the 41st AIAA Joint Propulsion Conference*, AIAA paper AIAA-2005-3988.

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ROTATING INTERSHAFT BRUSH SEAL PROJECT

Stephen Krawiecki
Diversitech, Inc.
Cincinnati, Ohio

Jayesh Mehta
TK Engineering
Cincinnati, Ohio

Gary Holloway
Diversitech, Inc.
Cincinnati, Ohio

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U. S. AIR FORCE SMALL BUSINESS INNOVATION RESEARCH PROGRAM (SBIR)

TITLE---ROTATING INTERSHAFT BRUSH SEAL PROJECT

NASA SEAL WORKSHOP

NOVEMBER 8,2005

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The pursuit of high Mach number flight presents several challenges to the airframe and engine design engineers. Most obvious is the resulting high temperatures encountered as the aircraft approaches Mach 3 and above. The encountered high temperatures and shaft speeds of engines require rethinking in the areas of material selections, component design and component operating life.

In the area of sump compartment sealing, one of the most difficult sealing applications is the sealing of an engine's rear sump. Normally this sump will need some method of sealing ***between two rotating shafts*. This sealing operation is done with an intershaft seal.** The aft sump region also presents an additional design requirement for the intershaft seal. ***This region has to absorb the engine's thermal growth, which means that in the seal area, axial movement, on the order of 0.30 in., between the rotating shafts must be tolerated***. A new concept or new technology of sealing an intershaft sump configuration is being developed. ***This concept, called a rotating intershaft brush seal*** has key attributes that will allow this seal to perform better, in the demanding environment of sealing an aft sump with two rotating shafts, when compared to today's sealing technology of labyrinth and carbon seals.

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U. S. AIR FORCE SMALL BUSINESS INNOVATION RESEARCH PROGRAM (SBIR)

PROJECT TITLE---ROTATING INTERSHAFT BRUSH SEALS FOR SEALING BETWEEN TWO ROTATING SHAFTS

PROJECT NUMBER----FA8650-04-M-2463

OBJECTIVE----PROVIDE A SEALING FUNCTION BETWEEN TWO ROTATING SHAFTS AND ABSORB AXIAL TRANSLATION DUE TO THERMAL GROWTH

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<u>U.S. AIR FORCE PROJECT MANAGEMENT TEAM</u>

- **1LT. DAN DOAK, PROGRAM MANAGER**
- **DR. LEWIS ROSADO, TECHNICAL MANAGER**

<u>PROJECT TEAM MEMBERS</u>

- **STEPHEN KRAWIECKI, DESIGN ENGINEER, DIVERSITECH, INC**
- **DR. JAYESH MEHTA, AERODYNAMIST, TK ENGINEERING**
- **GARY HOLLOWAY, VICE PRESIDENT, DIVERSITECH, INC.**

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PROGRAM SUPPORTERS AND PARTICIPANTS

- REXNORD CORP.
- GE AVIATION (GE AIRCRAFT ENGINES)
- NORTH CAROLINA A&T STATE UNIVERSITY
- LONZA CORP.
- AZTEC CORP.
- POLYCRAFT INC.
- NASA GLENN

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CONCEPT AND POTENTIAL BENEFITS

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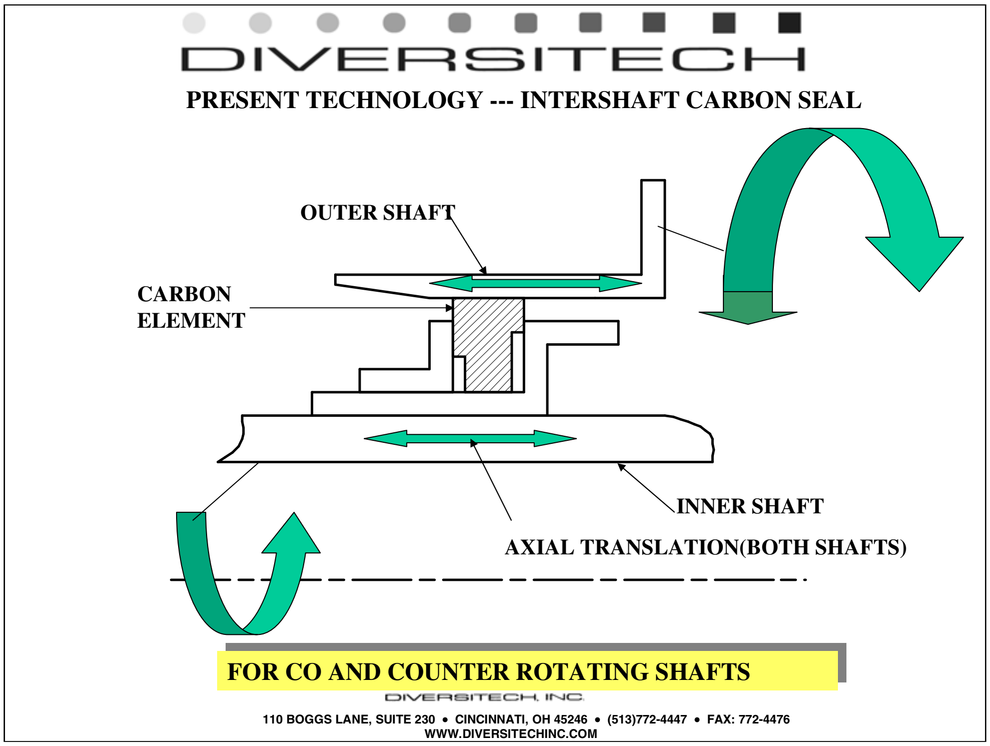
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PRESENT TECHNOLOGY --- INTERSHAFT CARBON SEAL
OUTER SHAFT
CARBON ELEMENT
INNER SHAFT
AXIAL TRANSLATION(BOTH SHAFTS)
FOR CO AND COUNTER ROTATING SHAFTS
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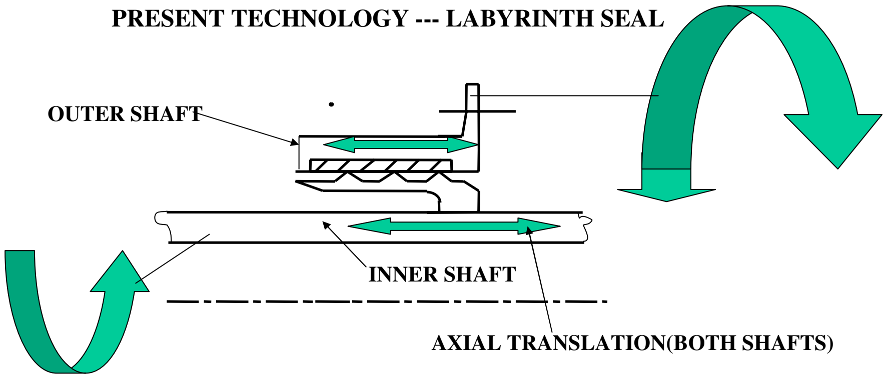
PRESENT TECHNOLOGY --- LABYRINTH SEAL



FOR CO AND COUNTER ROTATING SHAFTS

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CARBON SEALS OFFER THE FOLLOWING ATTRIBUTES

- LOW LEAKAGE FLOW WHICH OFFERS LESS LUBRICANT CONSUMPTION AND EMISSIONS
- GOOD OPERATING LIFE
- REQUIRES HIGHLY POLISHED AND COATED SURFACES
- RUBBING SURFACES WHICH REQUIRE LUBRICANT COOLING DIRECTLY OR INDIRECTLY
- PRONE TO DAMAGE DURING HANDLING AND ENGINE ASSEMBLY DUE TO THE BRITTLE CHARACTERISTIC OF THE CARBON MATERIAL

LABYRINTH SEALS OFFER THE FOLLOWING ATTRIBUTES

- NON-CONTACTING SEALING SURFACES, ELIMINATING THE NEED TO COOL THE SEAL
- HIGH LEAKAGE FLOWS, RESULTING IN HIGH LUBRICANT CONSUMPTION WHEN COMPARED TO CARBON SEALS
- GOOD OPERATING LIFE
- DOES NOT REQUIRE POLISHED SURFACES
- ROBUST DESIGN, NOT PRONE TO DAMAGE DURING HANDLING OR ENGINE ASSEMBLY

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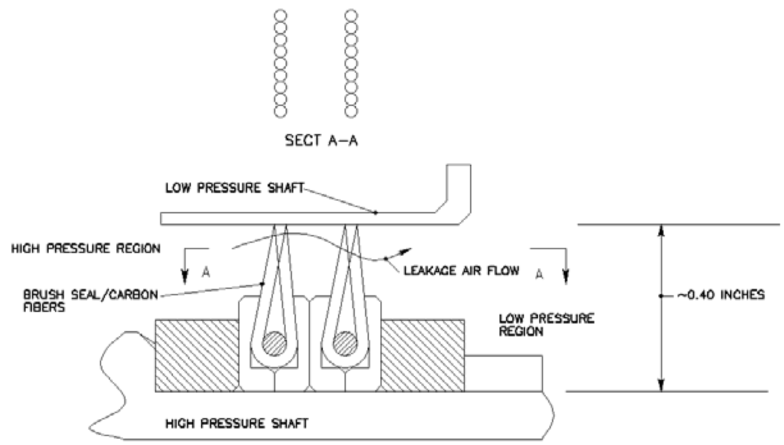
INTERSHAFT BRUSH SEAL CONCEPT

APPROACH-----USE A CARBON FIBER BRUSH SEAL BETWEEN TWO ROTATING SHAFTS



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POTENTIAL BENEFITS

- MORE ROBUST DESIGN FOR ENGINE ASSEMBLY
  - LESS CHANCE OF BREAKAGE, COMPARED TO CARBON SEAL
- POTENTIAL LESS HEAT GENERATION DUE TO REDUCED NUMBER OF RUBBING SURFACES
  - POTENTIAL USE OF HIGH CONDUCTIVITY CARBON FIBERS k~500 BTU/HR-^{o}F-ft (Cu k~230 BTU/HR-^{o}F-ft
  - LESS RUBBING SURFACE COMPARED TO CARBON SEAL
- ABLE TO ABSORB SHAFT AXIAL TRANSLATION BETTER WHEN COMPARED TO PRESENT TECHNOLOGY CARBON SEALS
- POTENTIALLY LESS COSTLY
- LESS LEAKAGE FLOW WHEN COMPARED TO LABYRINTH SEALS

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SEAL TECHNOLOGY COMPARISON

PARAMETER	SEAL CONFIGURATION		
	CARBON SEAL	ROTATING BRUSH SEAL	LABYRINTH SEAL
AIR LEAKAGE	LOW	MEDIUM	HIGH
OPERATING LIFE	SHORT TO MEDIUM	LONG	LONG
NEEDS POLISHED SURFACES	YES	NO	NO
RUBBING SURFACES	YES	YES	NO
ASSEMBLY DAMAGE POTENTIAL	HIGH	LOW	LOW
SEALS BETWEEN ROTATING SHAFTS	YES	YES	YES
AXIAL SHAFT TRANSLATION CAPABILITY	LOW	HIGH	HIGH
HEAT GENERATION	HIGH	MEDIUM	LOW

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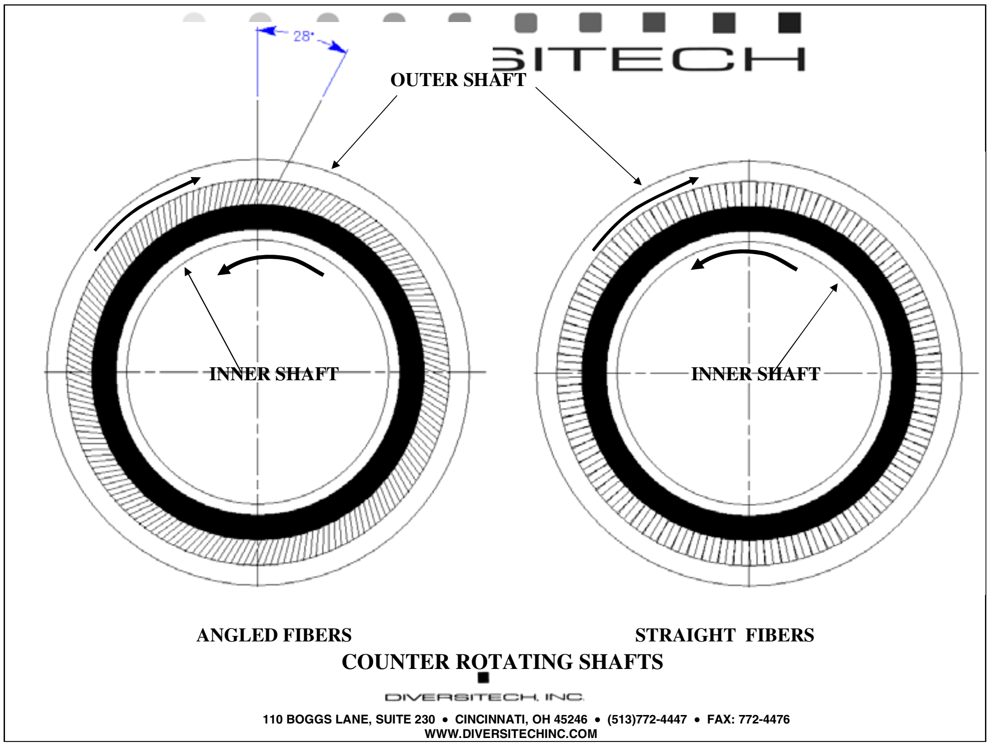
28°
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INNER SHAFT
INNER SHAFT
ANGLED FIBERS
STRAIGHT FIBERS
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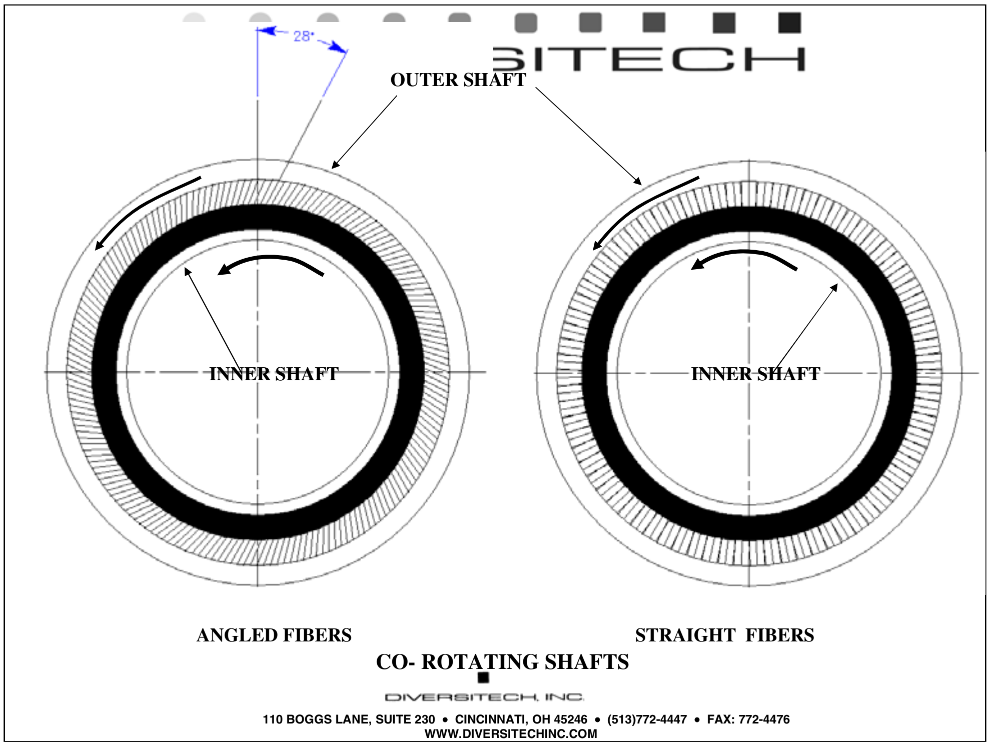
28°
OUTER SHAFT
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DESIGN

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PROGRAM STRUCTURE

- **FIBER RESEARCH AND SELECTION**
- **LEAKAGE AND HEAT GENERATION ANALYSIS**
- **WEAR AND LIFE ANALYSIS**
- **ROTATING BRUSH SEAL CONFIGURATION DEVELOPMENT**
- **POTENTIAL USE ANALYSIS-END USERS AND SEAL MANUFACTURERS**

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Task 1-Carbon Fiber Research
Effort undertaken to identify carbon fibers which could be used for the rotating brush seal application
Key parameters that will be used for fiber ranking
1. Fiber thermal conductivity--interface temperature impact
2. Fiber elastic modulus-fiber stiffness
3. Fiber strain capability- deflection and deformation limitations, assembly robustness
4. Fiber strength-high speed limitations
5. Fiber endurance limit -impact on fatigue life and engine cycles
5. Fiber hardness--impact on wear life
6. Tow size available-impact on fiber density and seal thickness

Task 2-Leakage and Heat Generation Analysis
Effort undertaken to analyze the brush seal performance under various speed and pressure combinations.
Will use CFD codes such as Fluent or NASA developed brush seal codes and ANSYS for seal stresses and deflections
Analysis will be undertaken for
1. Leakage flow
2. Delta p limitations
3. Fiber packing
4. Fiber stress and deflection
5.Limiting rubbing speeds due to heat generation and material temperature limits
6. Energy loss due to fiber rubbing

Task 3-Wear and Life Analysis
Analysis will undertaken to development a wear model
The wear model will account for the following interactions
1. Fiber and outer shaft material harness
2. Rubbing speeds between the fiber and shaft rubbing surface
3. Interface temperature
4. Interface friction

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PROGRAM STRUCTURE

- **FIBER RESEARCH AND SELECTION**
- **LEAKAGE AND HEAT GENERATION ANALYSIS**
- **WEAR AND LIFE ANALYSIS**
- **ROTATING BRUSH SEAL CONFIGURATION DEVELOPMENT**
- **POTENTIAL USE ANALYSIS-END USERS AND SEAL MANUFACTURERS**

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Task 4-Conceptual Configuration Development
Under this task two seal configurations will be developed for manufacture under a Phase II program. The two configurations are:

•Proof of concept configuration-small scaled

-This configuration would be used for verification of key operating parameters such as leakage performance, heat generation. This seal type could be tested at a seal vendor such as Rexnord Corp.

•Full scale configuration

-This configuration would be a full scaled engine size that could be tested on test rigs and engines (F110 size) such as GE Aircraft Engines

Task 5-Potential Use Analysis
Under this task, Diversitech will survey key companies about the potential benefit and interest in this technology

End Users	Seal Manufactures
GE Transportation	Rexnord Seal Company
Pratt & Whitney	Stein Seal Company
Allison Advance Development Company	Kaydon Ring and Seal
Honeywell	Perkin Elmer Corporation
Williams International	
Teledyne	

Commercialization Strategy
Based on successful development of the rotating brush seal concept the potential aircraft engine market is as follows:

•New engine applications both military and commercial
•Existing engines such as the GE-F110, GE-CFM-56

Seal Manufacturers
Potential new product line for the seal manufactures who supply the aircraft industry

•Rexnord Corp
•Stein Seal
•Kaydon Ring and Seal Company
•Perkin Elmer Corp

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SEAL PARAMETERS USED IN THIS STUDY WERE:

- **INNER SHAFT RPM---------5,000 TO 20,000**
- **INLET TEMPERATURE-------400 ^{O}F**
- **INLET PRESSURE-------------60 PSIA**
- **SEAL Δp ---------------------5,10,15,20,25,30,35,40 PSID**
- **EXIT (SUMP)TEMPERATURE 300 ^{O}F**
- **SEAL OUTER DIAMETER--------7.55 INCHES (FIXED)**
- **INNER DIAMETERS---------------6.65, 7.1,7.3 INCHES**

MAX. ENGINE SOAKBACK TEMPERATURE-------550^{O}F

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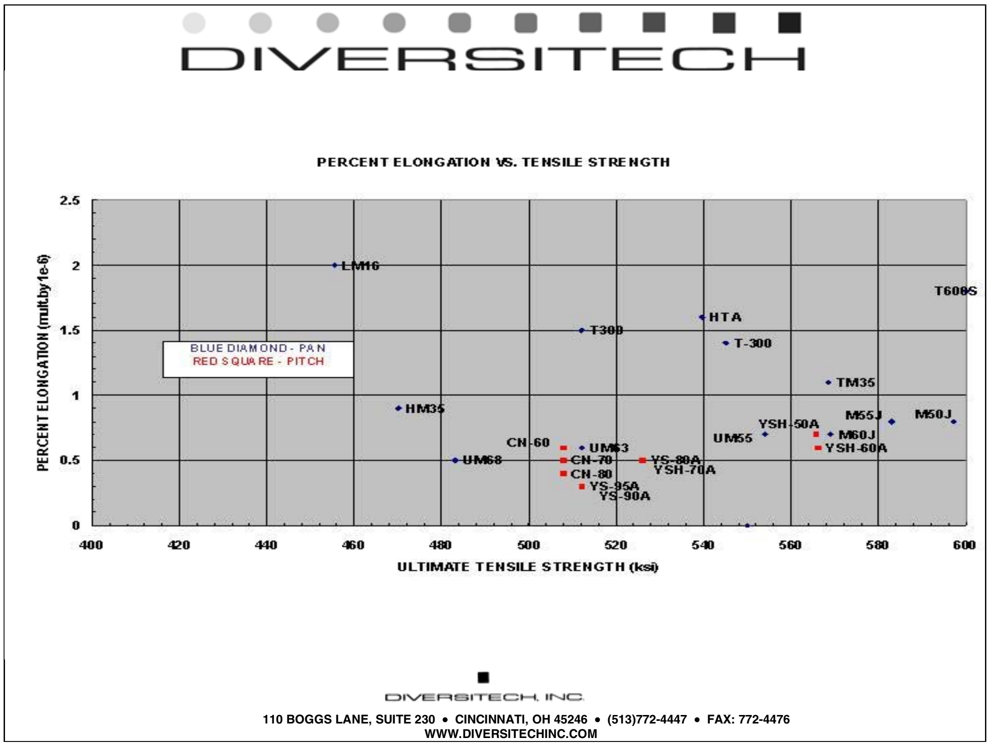
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PERCENT ELONGATION VS. TENSILE STRENGTH
PERCENT ELONGATION (mult.by1e-6)
ULTIMATE TENSILE STRENGTH (ksi)
2.5
2
1.5
1
0.5
0
400
420
440
460
480
500
520
540
560
580
600
BLUE DIAMOND - PAN
RED SQUARE - PITCH
LM16
T300
HTA
T-300
T600S
TM35
HM35
M55J
M50J
YSH-50A
UM55
M60J
YSH-60A
CN-60
UM63
UM68
CN-70
YS-80A
YSH-70A
CN-80
YS-95A
YS-90A
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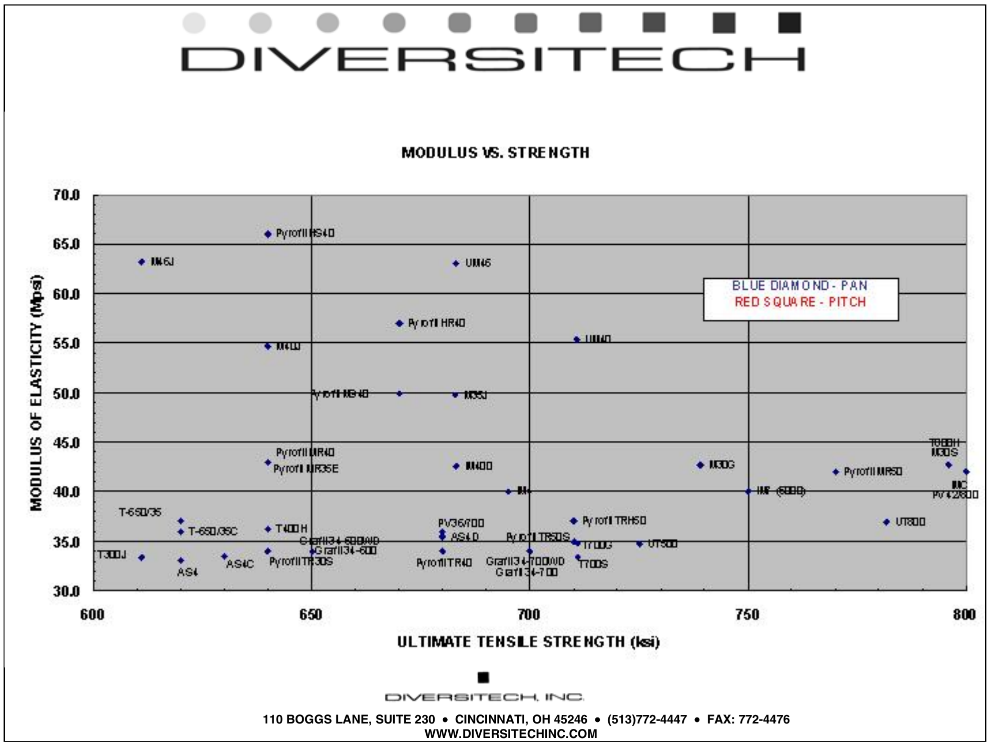

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MODULUS VS. STRENGTH
MODULUS OF ELASTICITY (Mpsi)
ULTIMATE TENSILE STRENGTH (ksi)
BLUE DIAMOND - PAN
RED SQUARE - PITCH
Pyrofil HS40
Pyrofil HR40
Pyrofil MR40
Pyrofil MR35E
Pyrofil TR30S
Pyrofil TR40
Pyrofil TRH50
Pyrofil MR50
T-650/35
T-650/35C
T400H
T300J
AS4
AS4C
AS4D
PV36/700
Grafil 34-600
Grafil 34-700
T700S
UT500
UT800
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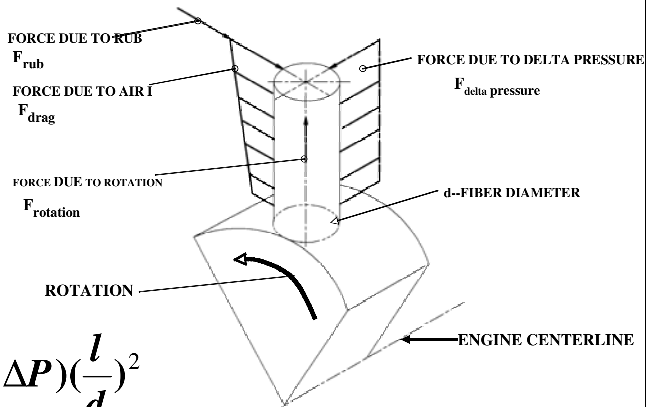
FIBER FORCE MODEL



$$\sigma_{Pressure/Bending} = \left(\frac{16}{\pi}\Delta P\right)\left(\frac{l}{d}\right)^2$$

$$\sigma_{P/A} = \frac{\rho_{fiber/composite}}{2g}(R^2{}_O - R^2{}_i)(\omega)^2$$

$$\sigma_{drag/bending} = 2(C_{drag})\left(\frac{\rho_{air}}{\pi g}\right)\left[(R_o + R_i)(\omega)\right]^2\left(\frac{l}{d}\right)^2$$

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Vortex Shedding Frequency

$$f = 0.22(\frac{V}{D}) = 0.22(\frac{R_0 * \omega}{D_{FIBER}})(cycles / \sec ond)$$

R_o= Tip Radius of Fiber

D= Fiber Diameter

ω = Seal Rotational Speed (radians/second)

$$F_{vib} \approx (C_d \cdot \rho \frac{V^2}{2g} \cdot A) \sin(2\pi f)t = F_{DRAG} \cdot \sin(2\pi f)t$$

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FIBER VOLUME FRACTION	MATRIX MATERIAL	CARBON FIBER MATERIAL
	PT-30	T300
	TENSILE STRENGTH (PSI)	TENSILE STRENGTH (PSI)
100	0	512,000
0	5000	0
	MODULUS (PSI)	MODULUS (PSI)
100	0	33,400,000
0	400,000	0
	STRAIN (%)	STRAIN (%)
100	0	1.5
0	2	0
	DENSITY (LBS/IN^3)	DENSITY (LBS/IN^3)
------	0.0455	0.0635

50% FIBER VOLUME COMPOSITE PROPERTIES
MATRIX/CARBON FIBER
PT-30/T300
TENSILE STRENGTH (PSI)
258,500
MODULUS (PSI)
16,900,000
STRAIN (%)
1.75
DENSITY (LBS/IN^3)
0.0545

PROPERTIES BASED ON RULE OF MIXTURES

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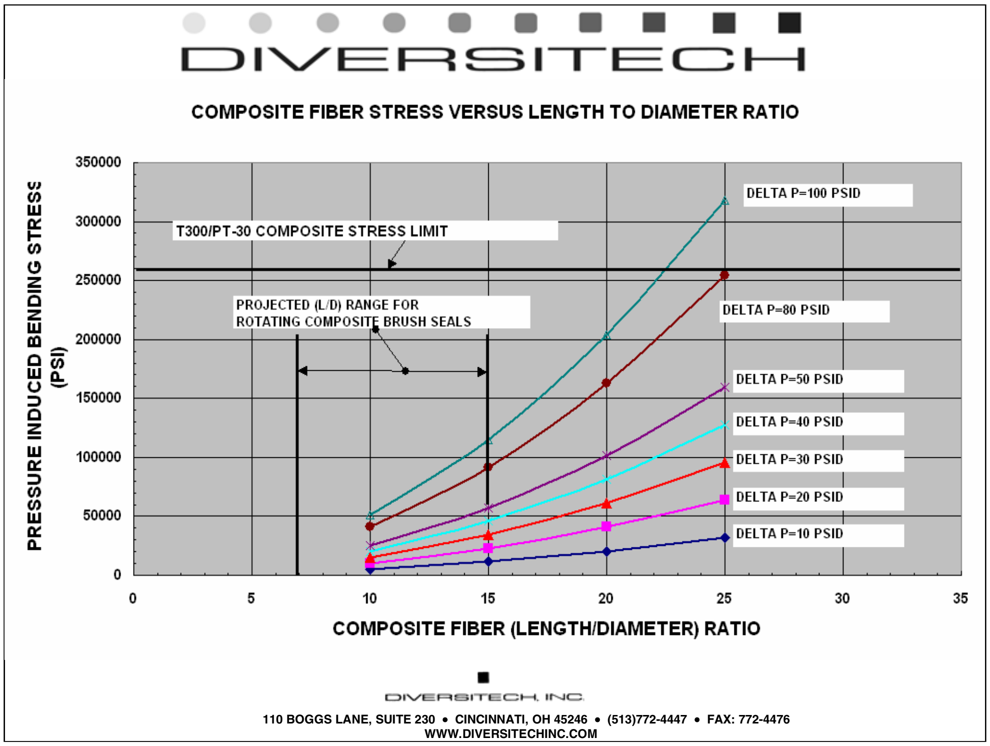
DIVERSITECH
COMPOSITE FIBER STRESS VERSUS LENGTH TO DIAMETER RATIO
PRESSURE INDUCED BENDING STRESS (PSI)
COMPOSITE FIBER (LENGTH/DIAMETER) RATIO
T300/PT-30 COMPOSITE STRESS LIMIT
PROJECTED (L/D) RANGE FOR ROTATING COMPOSITE BRUSH SEALS
DELTA P=100 PSID
DELTA P=80 PSID
DELTA P=50 PSID
DELTA P=40 PSID
DELTA P=30 PSID
DELTA P=20 PSID
DELTA P=10 PSID
350000
300000
250000
200000
150000
100000
50000
0
0
5
10
15
20
25
30
35
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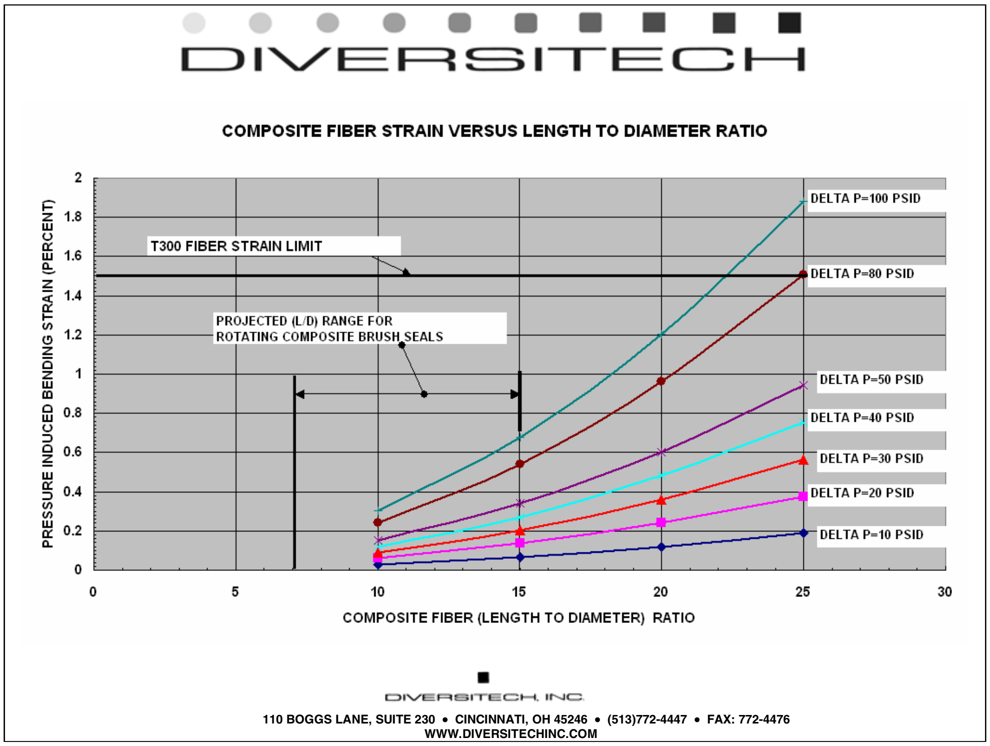

DIVERSITECH
COMPOSITE FIBER STRAIN VERSUS LENGTH TO DIAMETER RATIO
PRESSURE INDUCED BENDING STRAIN (PERCENT)
COMPOSITE FIBER (LENGTH TO DIAMETER) RATIO
T300 FIBER STRAIN LIMIT
PROJECTED (L/D) RANGE FOR
ROTATING COMPOSITE BRUSH SEALS
DELTA P=100 PSID
DELTA P=80 PSID
DELTA P=50 PSID
DELTA P=40 PSID
DELTA P=30 PSID
DELTA P=20 PSID
DELTA P=10 PSID
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
5
10
15
20
25
30
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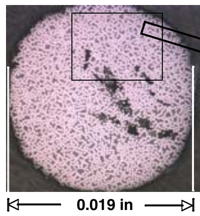
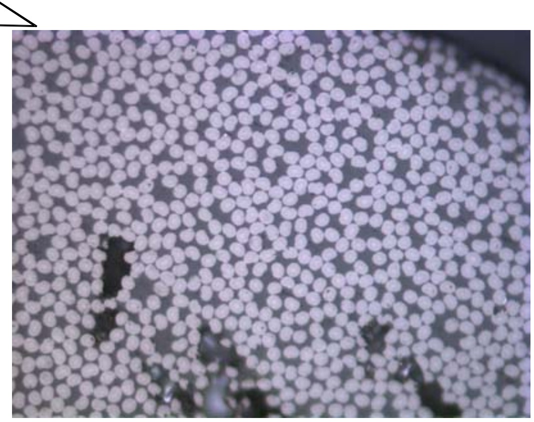
Microscopy of Fiber Distribution and Fiber Volume Fraction of T650/PT-30 Pultruded Rods





Sample #	V_f, %
1	66.0
2	67.3
3	59.5
4	67.1
5	67.0

Average = 65.1%

STD = 3.3%

CV% = 5.1%

Center for Composite Materials Research

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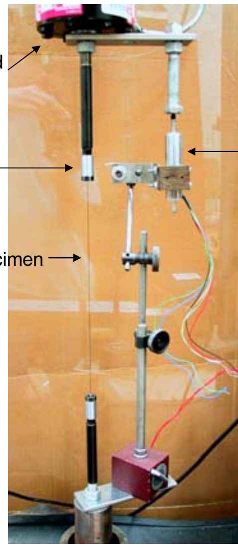
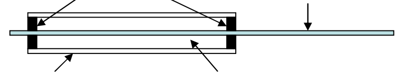
Tension Test and Results of T650/PT30 Pultruded Composites

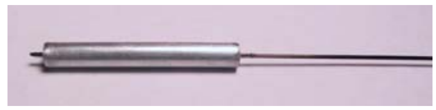
Baseline Case

Test Setup on MTS Frame



Close-up of lower collet





Specimen #	Tensile Strength (ksi)	Modulus (Msi)	Strain (%)
div-ten-BL-1	253.6	19.99	1.26
div-ten BL-2	262.7	20.16	1.30
div-ten-BL-3	257.0	20.14	1.27
div-ten BL-4	267.3	20.10	1.33
div-ten-BL-5	266.6	19.97	1.33
div-ten BL-6	250.3	20.06	1.25
div-ten-BL-7	249.7	19.59	1.27
div-ten BL-8	261.2	20.10	1.29
div-ten-BL-9	242.5	19.76	1.23
div-ten BL-10	235.1	19.93	1.17
Average	**254.6**	**19.98**	**1.27**
STD	10.5	0.18	0.05
CV (%)	**4.1**	**0.91**	**3.8**

Center for Composite Materials Research

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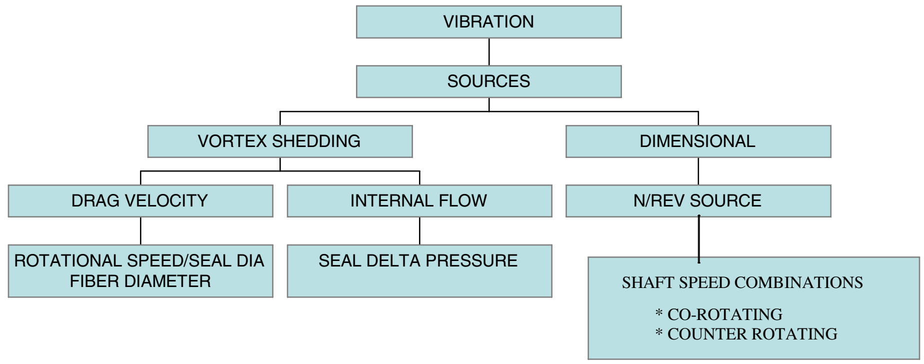

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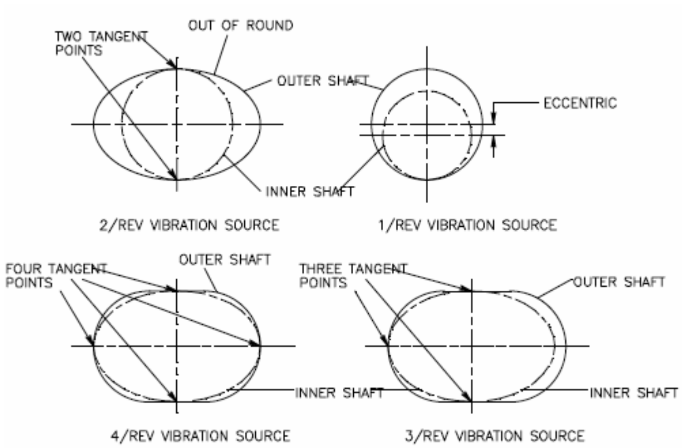
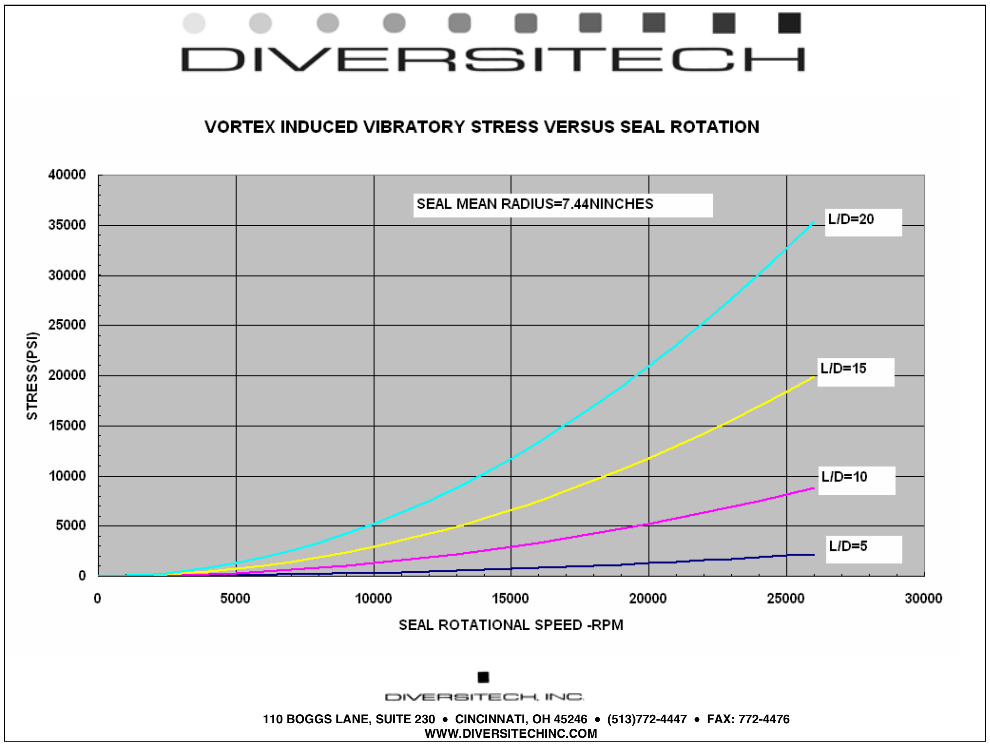
DIMENSIONAL VIBRATION SOURCES



CYCLIC INPUT	FREQUENCY INPUT FOR CO-ROTATING SHAFTS (CPS)	FREQUENCY INPUT FOR COUNTER ROTATING SHAFTS (CPS)
1/REV	$f_1=(\omega_{outer}-\omega_{inner})/60$	$f_1=(\omega_{outer}+\omega_{inner})/60$
2/REV	$f_2=2(\omega_{outer}-\omega_{inner})/60$	$f_2=2(\omega_{outer}+\omega_{inner})/60$
3/REV	$f_3=3(\omega_{outer}-\omega_{inner})/60$	$f_3=3(\omega_{outer}+\omega_{inner})/60$
4/REV	$f_4=4(\omega_{outer}-\omega_{inner})/60$	$f_4=4(\omega_{outer}+\omega_{inner})/60$

2-4476


DIVERSITECH
VORTEX INDUCED VIBRATORY STRESS VERSUS SEAL ROTATION
SEAL MEAN RADIUS=7.44NINCHES
L/D=20
L/D=15
L/D=10
L/D=5
STRESS(PSI)
40000
35000
30000
25000
20000
15000
10000
5000
0
0
5000
10000
15000
20000
25000
30000
SEAL ROTATIONAL SPEED -RPM
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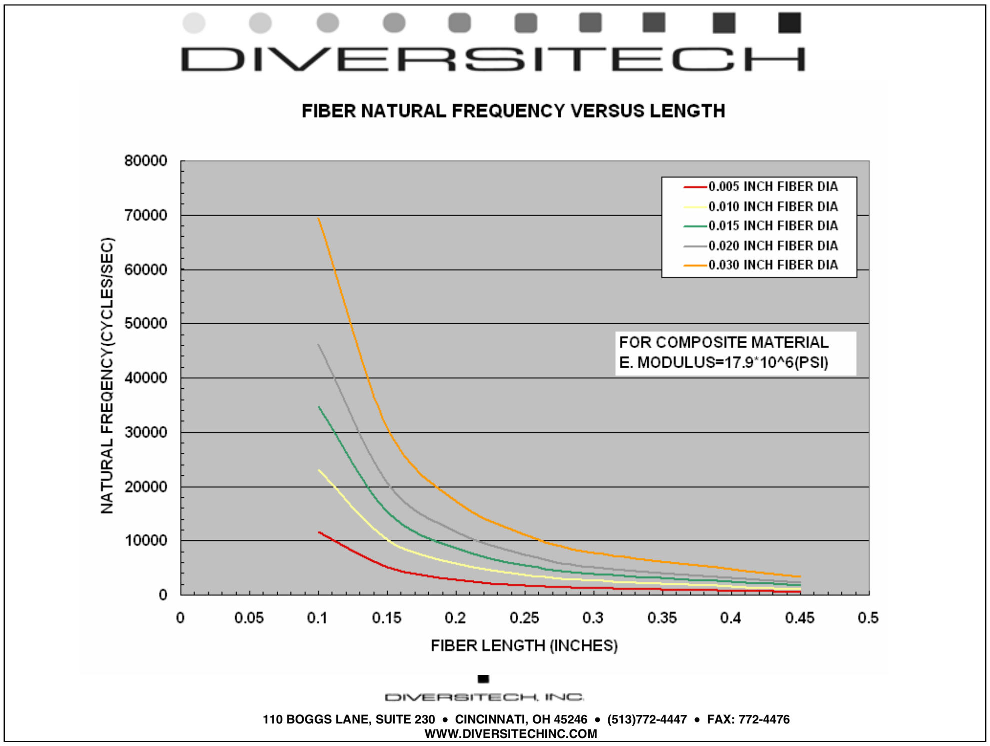
DIVERSITECH
FIBER NATURAL FREQUENCY VERSUS LENGTH
NATURAL FREQENCY(CYCLES/SEC)
80000
70000
60000
50000
40000
30000
20000
10000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
FIBER LENGTH (INCHES)
0.005 INCH FIBER DIA
0.010 INCH FIBER DIA
0.015 INCH FIBER DIA
0.020 INCH FIBER DIA
0.030 INCH FIBER DIA
FOR COMPOSITE MATERIAL
E. MODULUS=17.9*10^6(PSI)
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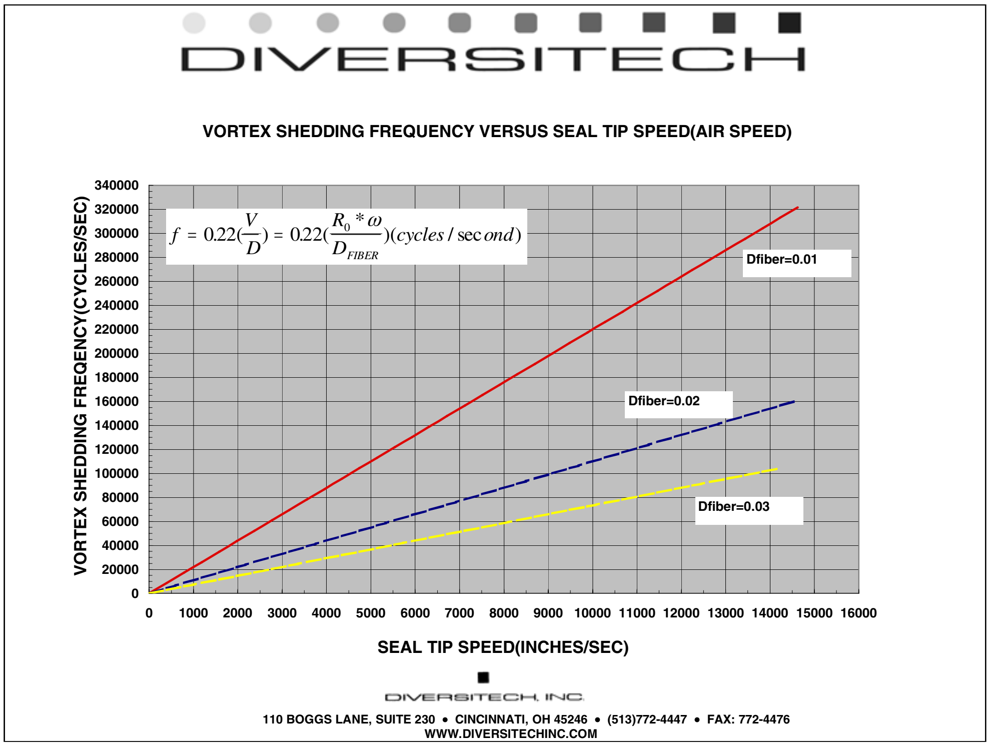
DIVERSITECH
VORTEX SHEDDING FREQUENCY VERSUS SEAL TIP SPEED(AIR SPEED)
VORTEX SHEDDING FREQENCY(CYCLES/SEC)
SEAL TIP SPEED(INCHES/SEC)
$f = 0.22(\frac{V}{D}) = 0.22(\frac{R_0 * \omega}{D_{FIBER}})(cycles/second)$
Dfiber=0.01
Dfiber=0.02
Dfiber=0.03
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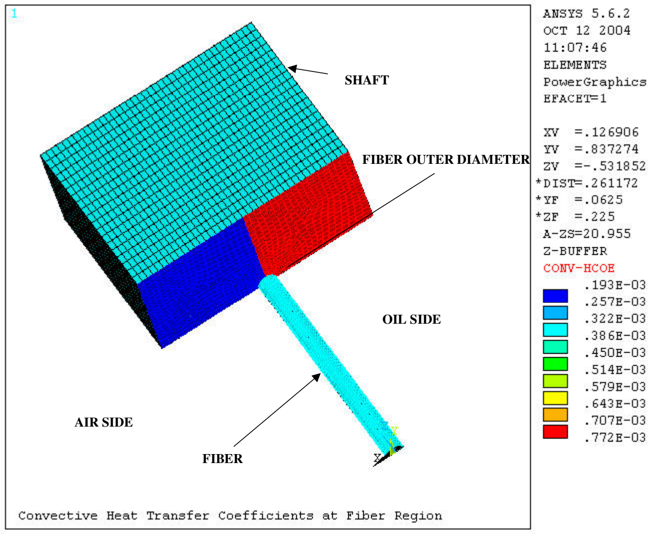

FIGURE 333

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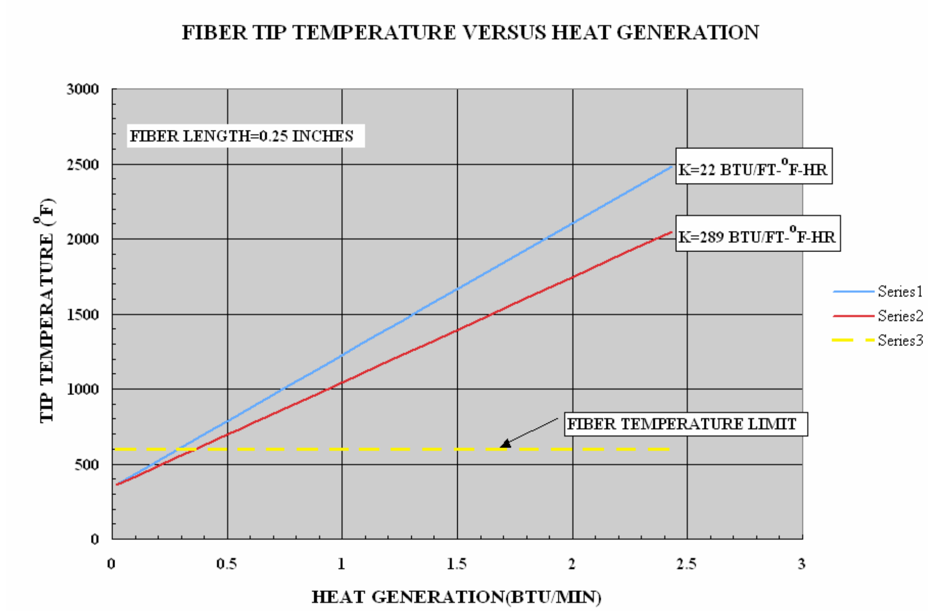

FIGURE 333

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PROBLEM

•HEAT GENERATION WILL CAUSE TEMPERATURE TO EXCEED MATERIAL LIMITS

SOLUTION

•MINIMIZE RUBBING CONTACT BY DESIGNING FOR CLEARANCE OPERATION

BENEFITS

• LOW WEAR AND HIGHER SPEED CAPABILITY

• MINIMIZES VIBRATION INPUTS AND FATIGUE DAMAGE

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AERO DESIGN

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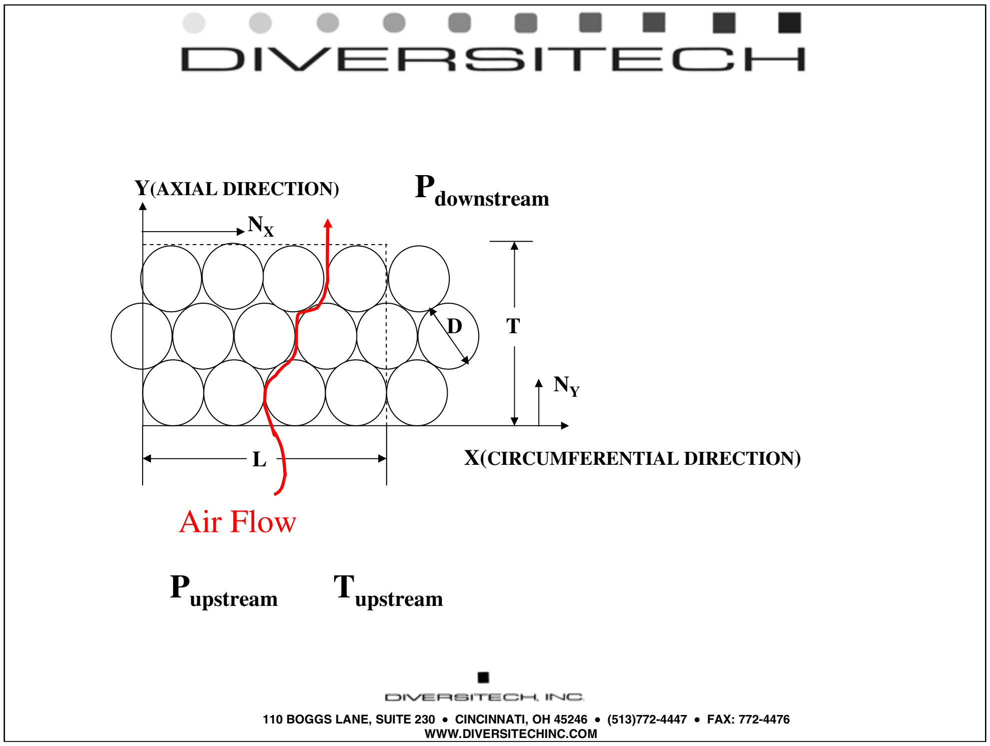
DIVERSITECH
Y(AXIAL DIRECTION)
$P_{downstream}$
N_X
D
T
N_Y
L
X(CIRCUMFERENTIAL DIRECTION)
Air Flow
$P_{upstream}$
$T_{upstream}$
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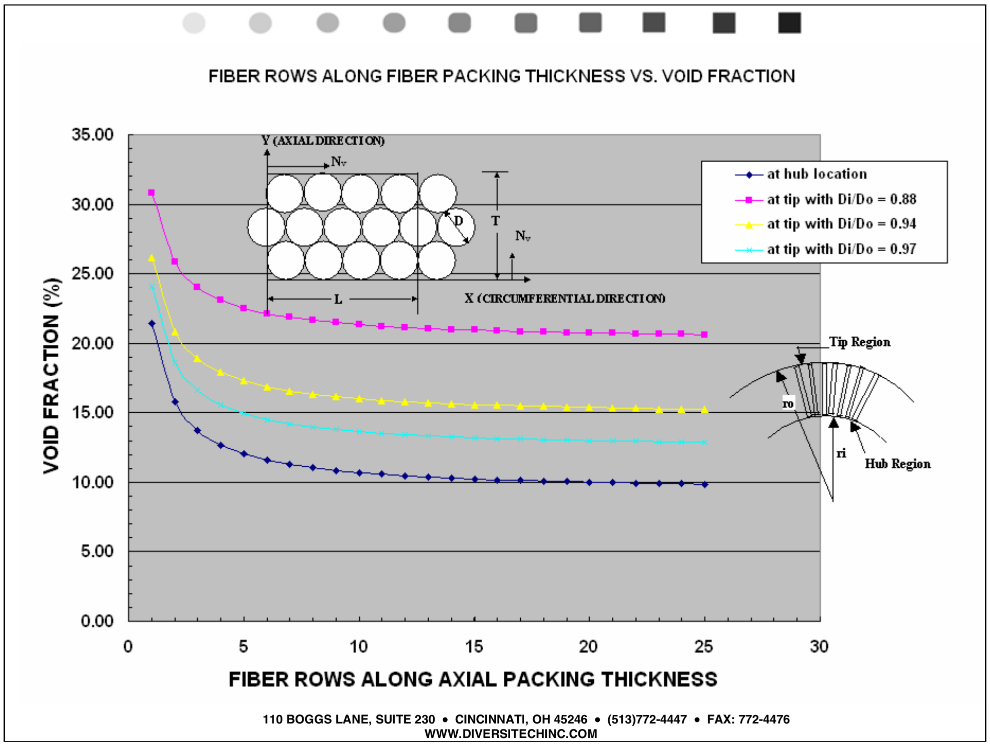

FIBER ROWS ALONG FIBER PACKING THICKNESS VS. VOID FRACTION
VOID FRACTION (%)
FIBER ROWS ALONG AXIAL PACKING THICKNESS
Y (AXIAL DIRECTION)
X (CIRCUMFERENTIAL DIRECTION)
D
T
L
at hub location
at tip with Di/Do = 0.88
at tip with Di/Do = 0.94
at tip with Di/Do = 0.97
Tip Region
Hub Region
ro
ri
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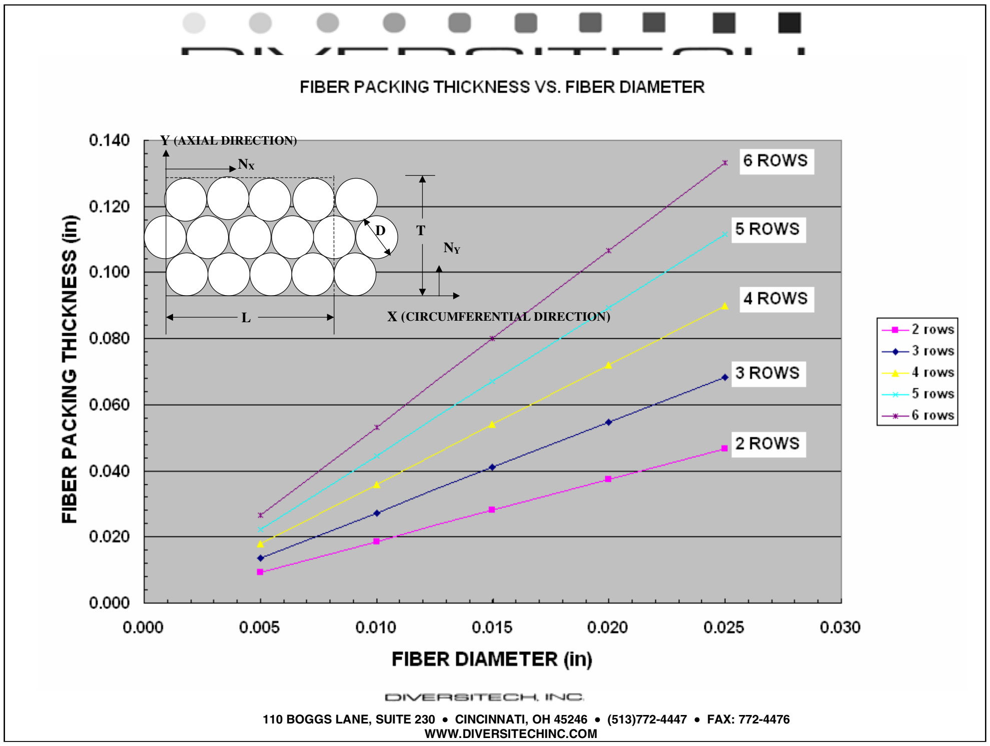
FIBER PACKING THICKNESS VS. FIBER DIAMETER
FIBER PACKING THICKNESS (in)
FIBER DIAMETER (in)
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
0.000
0.005
0.010
0.015
0.020
0.025
0.030
Y (AXIAL DIRECTION)
X (CIRCUMFERENTIAL DIRECTION)
D
T
L
6 ROWS
5 ROWS
4 ROWS
3 ROWS
2 ROWS
2 rows
3 rows
4 rows
5 rows
6 rows
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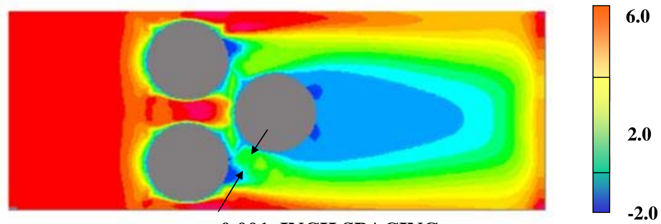
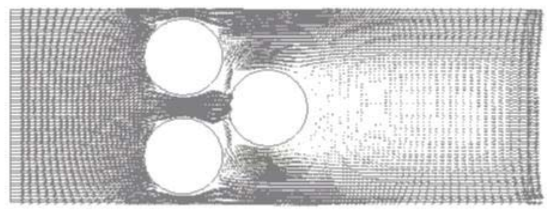
CONCERT Based Velocity Contours And Velocity Vectors
Six Rows – Do = 7.18 Inches, Di = 6.782 Inches, Pu = 60 psia, Pu/Pd = 2.0



0.001 INCH SPACING

Velocity Contours for Three Rows – Velocity In Ft/Sec.



Velocity Vectors for Three Rows

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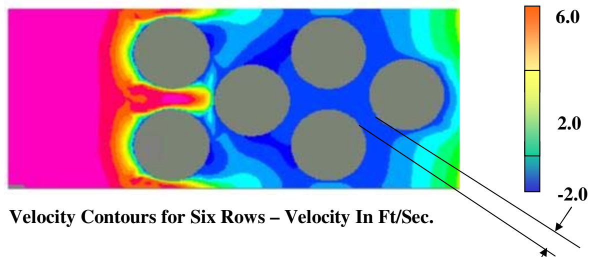
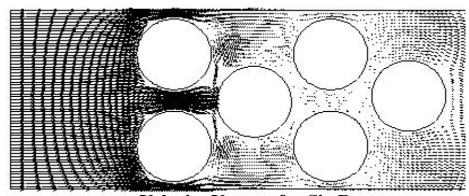
CONCERT Based Velocity Contours And Velocity Vectors
Six Rows – Do = 7.18 Inches, Di = 6.782 Inches
Pu = 60 psia, Pu/Pd = 2.0



Velocity Contours for Six Rows – Velocity In Ft/Sec.



Velocity Vectors for Six Rows

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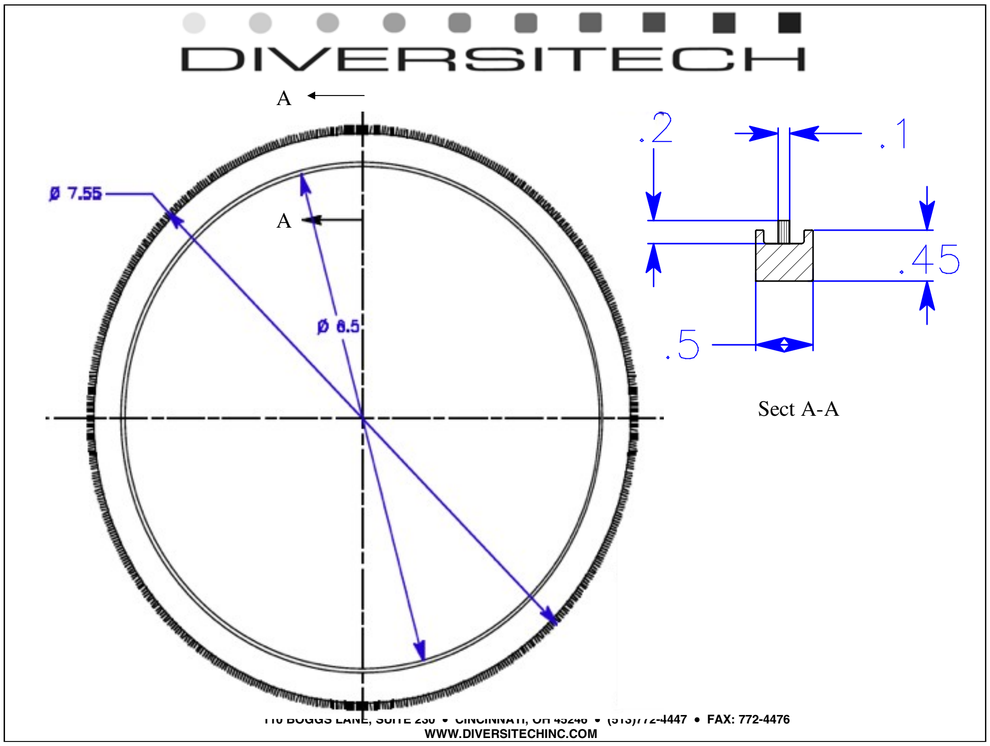
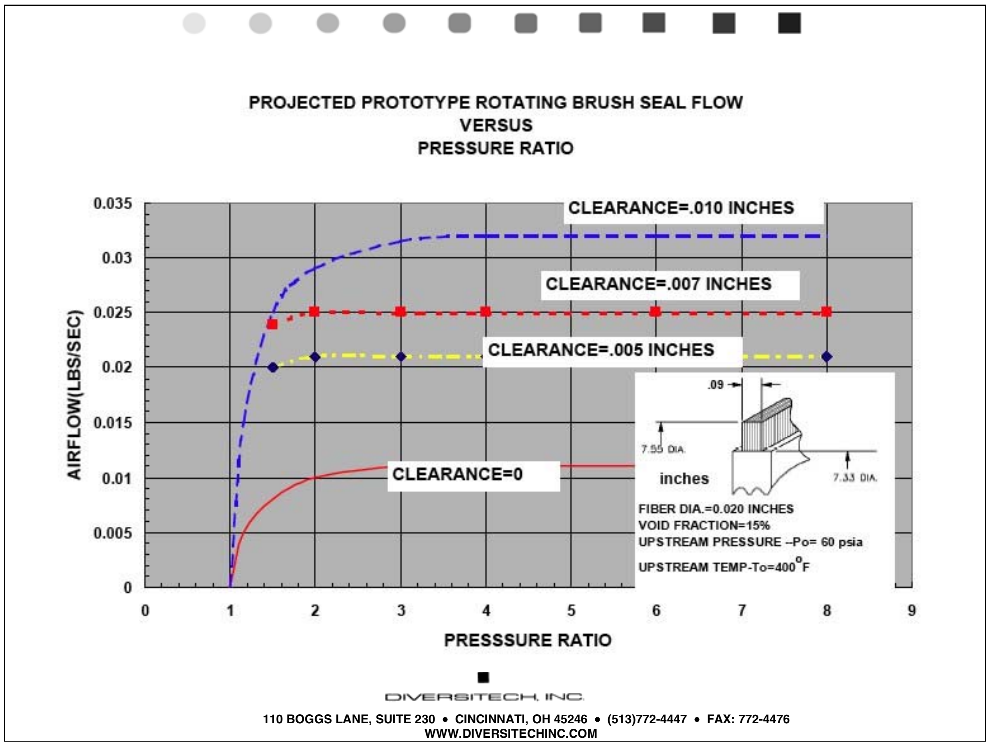


Resulting Seal From Phase 1 Design Effort


PROJECTED PROTOTYPE ROTATING BRUSH SEAL FLOW
VERSUS
PRESSURE RATIO
AIRFLOW(LBS/SEC)
PRESSSURE RATIO
CLEARANCE=.010 INCHES
CLEARANCE=.007 INCHES
CLEARANCE=.005 INCHES
CLEARANCE=0
.09
7.55 DIA.
7.33 DIA.
inches
FIBER DIA.=0.020 INCHES
VOID FRACTION=15%
UPSTREAM PRESSURE –Po= 60 psia
UPSTREAM TEMP-To=400°F
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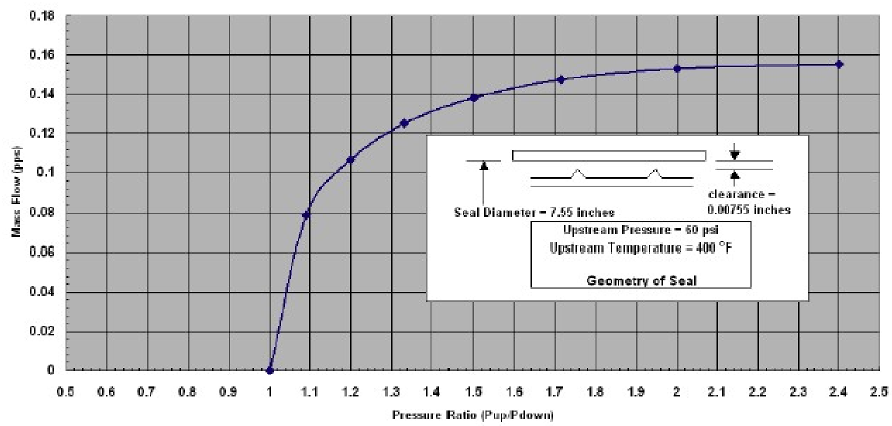
TWO TOOTH LABYRINTH SEAL MASS FLOW
VS.
PRESSURE RATIO



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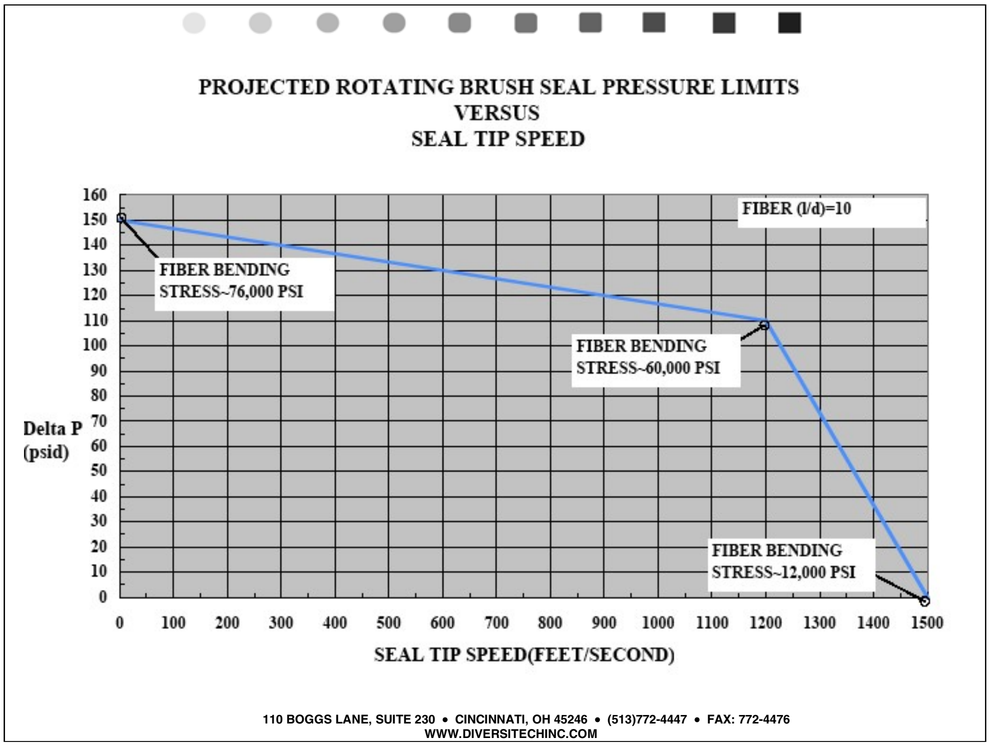
PROJECTED ROTATING BRUSH SEAL PRESSURE LIMITS
VERSUS
SEAL TIP SPEED
FIBER (l/d)=10
FIBER BENDING
STRESS~76,000 PSI
FIBER BENDING
STRESS~60,000 PSI
FIBER BENDING
STRESS~12,000 PSI
Delta P
(psid)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
SEAL TIP SPEED(FEET/SECOND)
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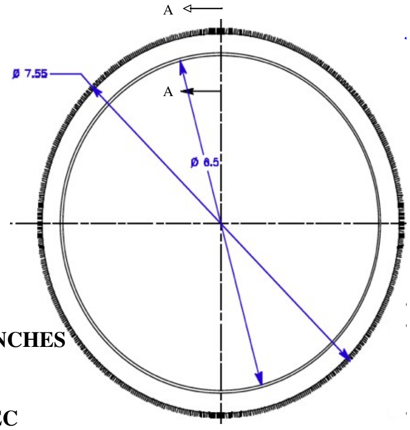

RESULTING SEAL DESIGN

- **NON-CONTACTING**
- **COMPOSITE ROD DIAMETER---0.020 INCHES**
- **TEMPERATURE CAPABILITY -600 ^{o}F**
- **TIP SPEED CAPABILITY-->= 1200 FT/SEC**
- **DELTA P CAPABILITY> 100PSID**
- **AXIAL TRANSLATION CAPABILITY**
- **SEALS BETWEEN CO OR COUNTER ROTATING SHAFTS**
- **COMPACT SPACING**

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SPECIAL THANKS TO THE FOLLOWING PROGRAM SUPPORTERS

- **US AIR FORCE AFRL/PRTM -WRIGHT PATTERSON AFB---CONCEPT SUPPORT AND PROGRAM FUNDING**
- **REXNORD CORP.- CONCEPT SUPPORT AND SEAL TESTING**
- **GE AVIATION (GE AIRCRAFT ENGINES)- CONCEPT SUPPORT AND SEAL TESTING(COUNTER ROTATING) AND BEARING CONTAMINATION TESTING**
- **NORTH CAROLINA A&T STATE UNIVERSITY-MATERIAL EVALUATION AND RESIN CONSULTATION**
- **LONZA CORP.-HIGH TEMPERATURE RESIN**
- **AZTEC CORP.-PULTRUDED COMPOSITE ROD MANUFACTURE**
- **POLYCRAFT INC.-COMPOSITE SEAL MANUFACTURE**
- **NASA GLENN- SEAL SOFTWARE USE**

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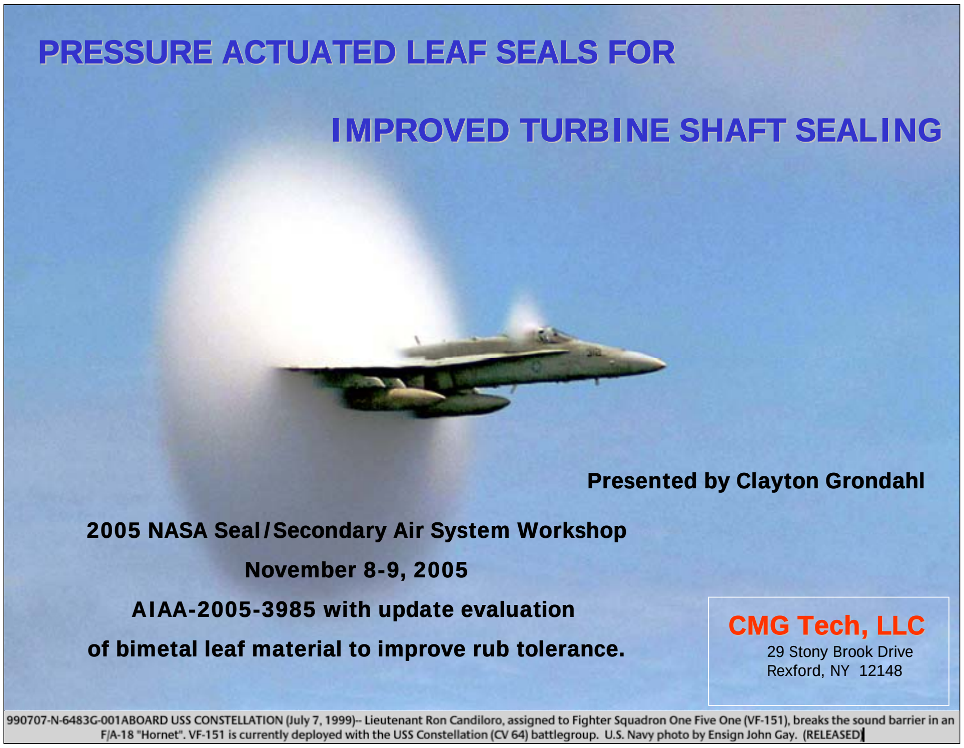
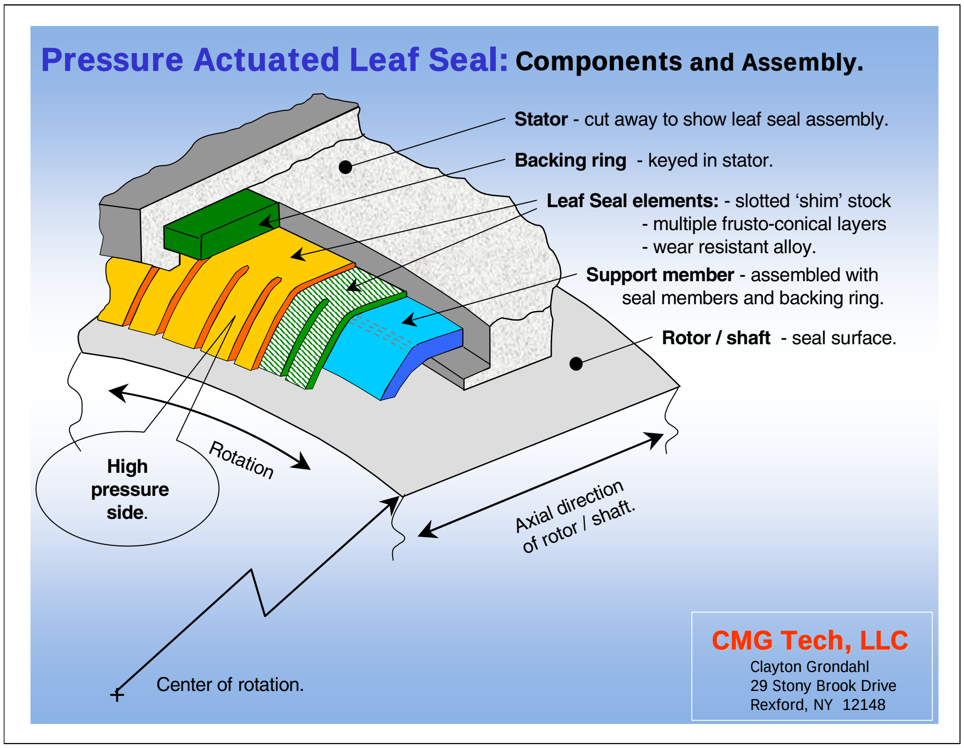
PRESSURE ACTUATED LEAF SEALS FOR IMPROVED TURBINE SHAFT SEALING

Clayton Grondahl
CMG Tech, LLC
Rexford, New York



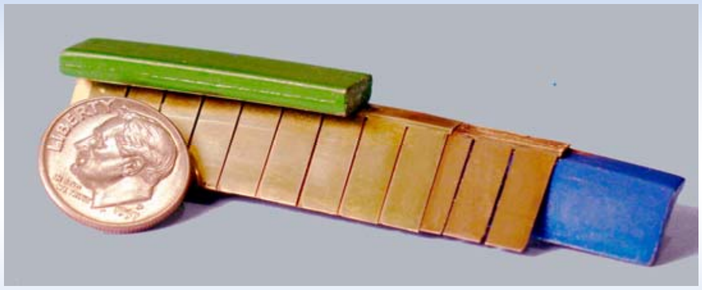
This presentation introduces a shaft seal in which leaf seal elements are constructed from slotted shim material formed and layered into a frusto-conical assembly. Limited elastic deflection of seal leaves with increasing system pressure close large startup clearance to a small, non-contacting, steady state running clearance. At shutdown seal elements resiliently retract as differential seal pressure diminishes. Large seal clearance during startup and shutdown provides a mechanism for rub avoidance. Minimum operating clearance improves performance and non-contacting operation promises long seal life. Design features of this seal, sample calculations at differential pressures up to 2400 psid and benefit comparison with brush and labyrinth seals is documented in paper, AIAA–2005–3985, presented at the Advanced Seal Technology session of the Joint Propulsion Conference in Tucson this past July. In this presentation use of bimetallic leaf material will be discussed. Frictional heating of bimetallic leaf seals during a seal rub can relieve the rub condition to some extent with a change in seal shape. Improved leaf seal rub tolerance is expected with bimetallic material.



Pressure actuated leaf seal features are patented per US 6644667 or Patent Pending per publication US 2004/0150165.

Leaf Seal assembly contains as few as 4 components.

Pressure Actuated Leaf Seal: Full Size Model Photo.



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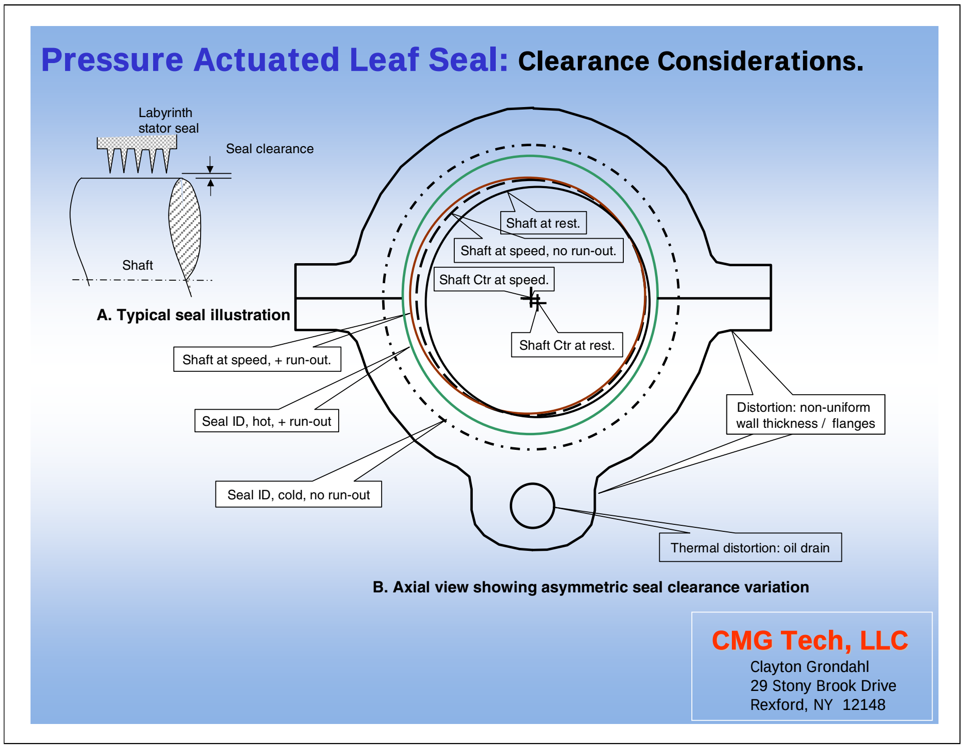
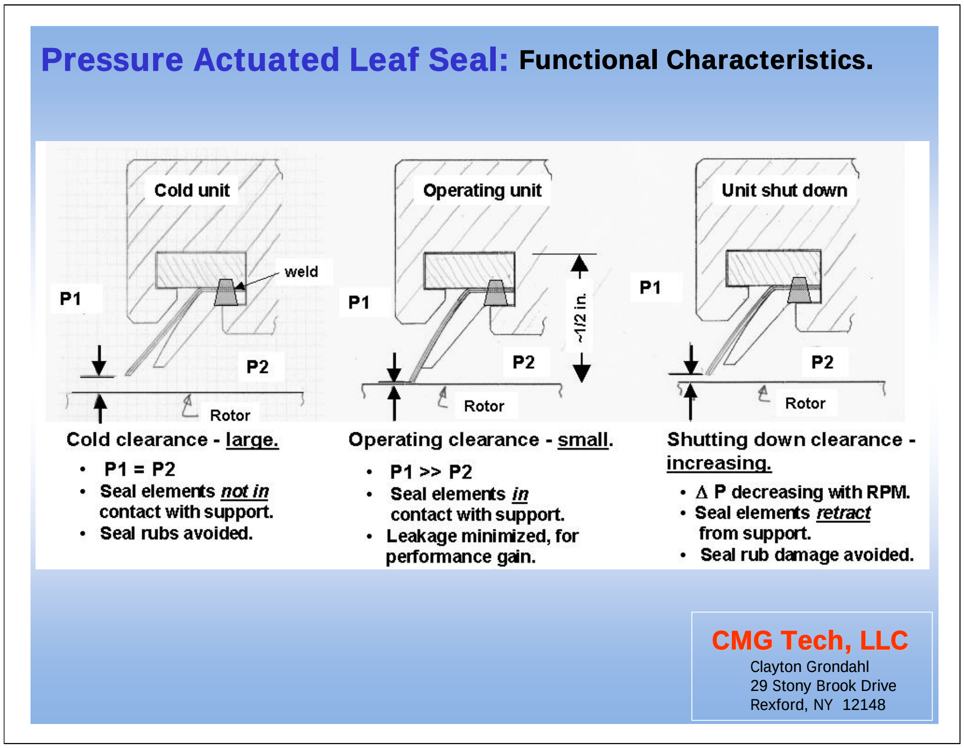
Rexford, NY 12148

Leaf seal radial height and axial length is small, of the order of 0.5 inches as shown.



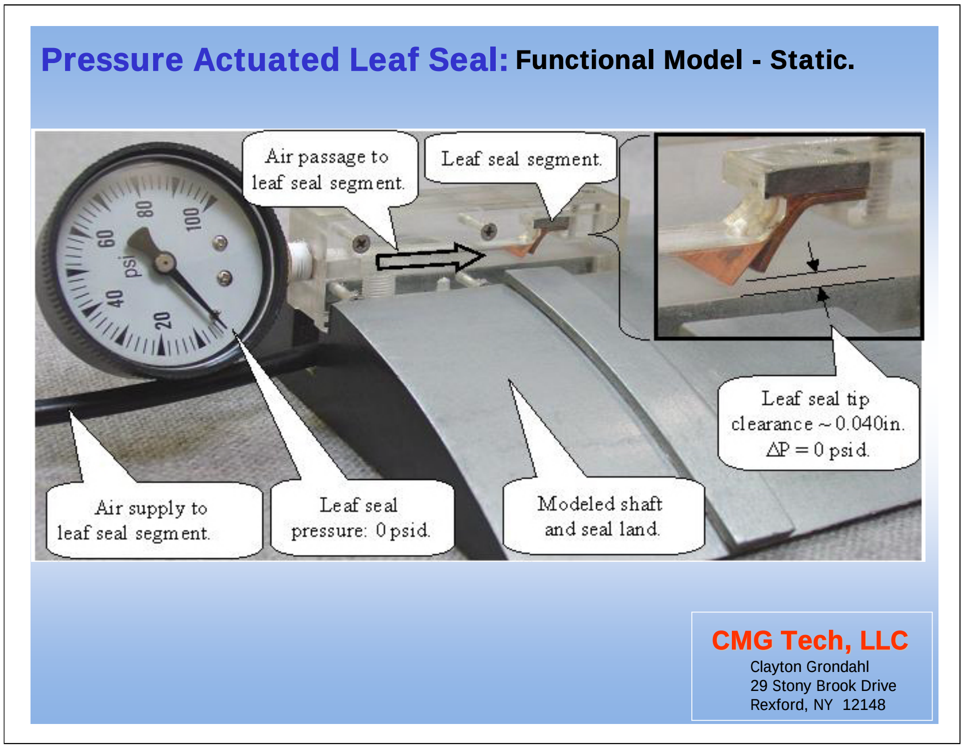
Turbo machinery seal clearances are neither static or uniform. Hence the need for a robust resilient seal.



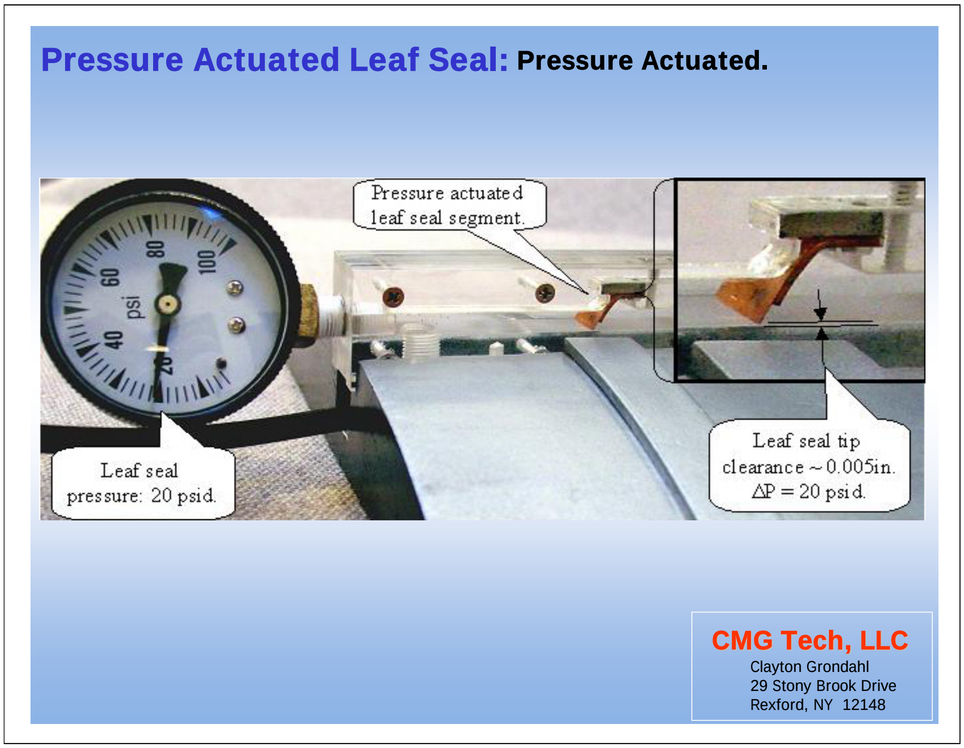
A radius on the high pressure side of the support member facilitates flexure of the frusto-conical leaf seal members toward the shaft as pressure is applied.

Large seal clearance at startup and shutdown minimizes seal rub hazard during these most vulnerable periods.

Small seal clearance at normal operating conditions provides performance benefits.

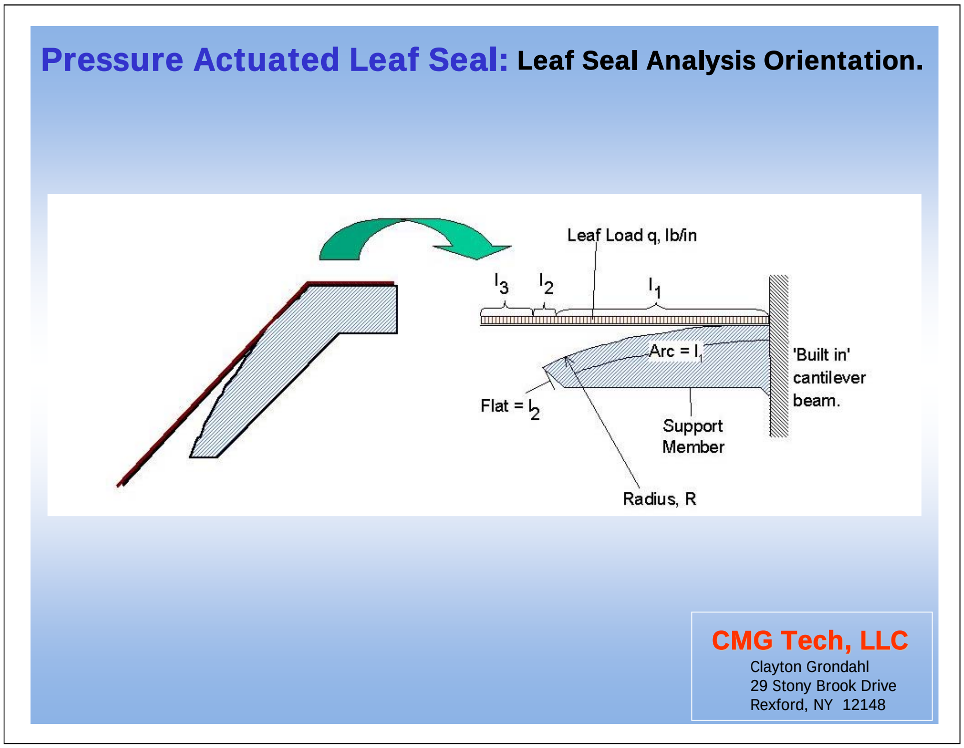


Static model shows large clearance under leaf tip without differential seal pressure.

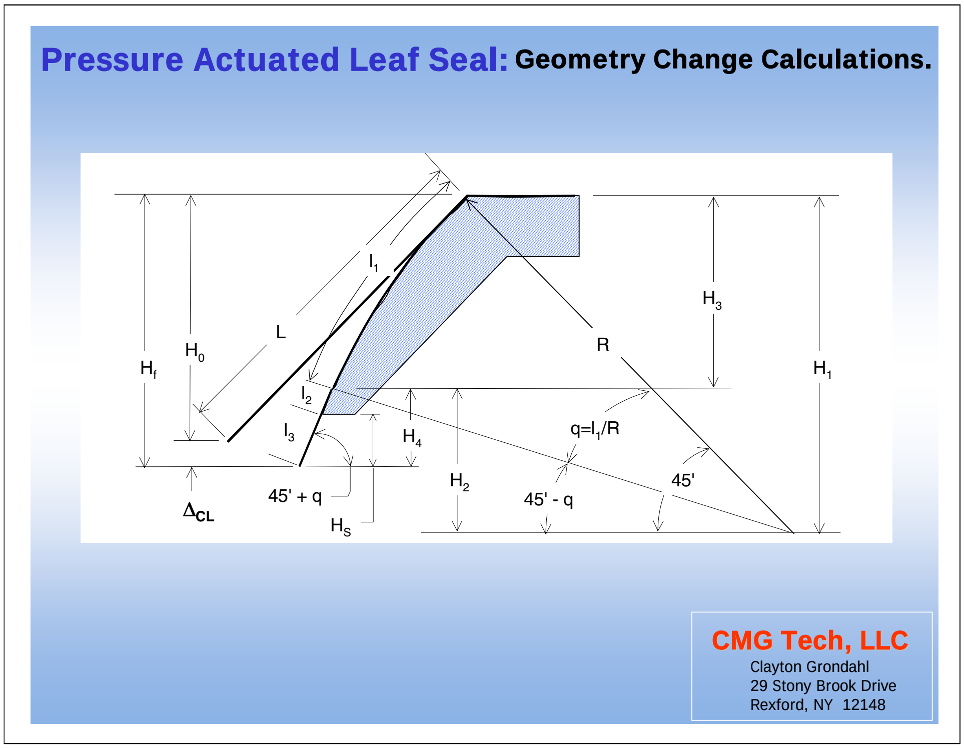


Pressurized model shows small clearance under leaf tip with differential seal pressure applied.

Video shows action of the previous 2 slides.



Preliminary stress analysis and leaf bending has considered leaves as beams in bending.



Change in clearance is calculated from geometry shown.

Pressure Actuated Leaf Seal: Preliminary Design Analysis.

Seal Pressure, psid.		Seal Variables, inches.						Δ Seal Clearance and Geometry, inches.				Bending Stress, psi.	
Seal Operating ΔP	Engagement ΔP	Support Radius	Leaf Thickness	Arc Length	Flat Length	Unsupported Leaf Length	# Leaves	Δ Seal Clearance	Seal Angle	Support Height	Unsupported Leaf Deflection	Unsupported Leaves	Leaves Over Radius R.
40	20	2.00	0.010	0.43	0.08	0.12	2	0.056	57.2	0.101	0.000	8640	77747
150	50	2.20	0.014	0.43	0.08	0.12	2	0.051	56.1	0.100	0.000	16531	98951
600	150	2.50	0.016	0.43	0.08	0.12	4	0.045	54.7	0.098	0.001	25313	99516
2400	200	2.50	0.016	0.43	0.08	0.12	6	0.045	54.7	0.098	0.003	67500	99516

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29 Stony Brook Drive
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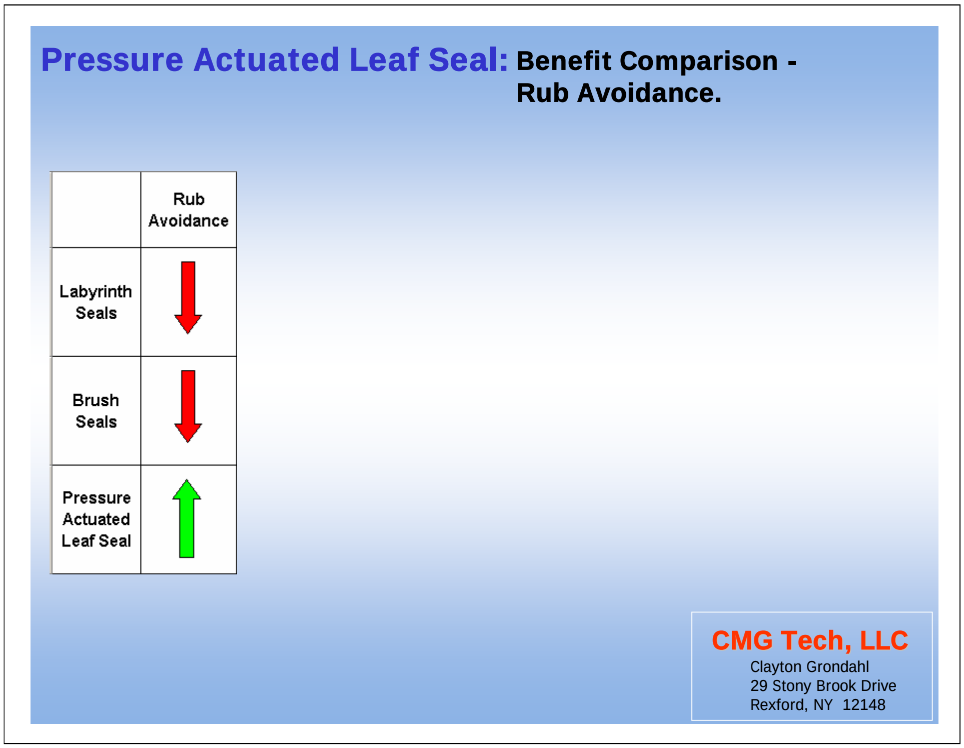
A large range of differential seal pressure capability is tabulated here using various leaf thickness, support radius, and number of leaves. Acceptable leaf stress is shown in applications up to 2400 psi differential seal pressure.

In all cases, substantial seal closure of ~0.05in is shown to be possible.


Pressure Actuated Leaf Seal: Benefit Comparison -
Rub Avoidance.
Rub Avoidance
Labyrinth Seals
Brush Seals
Pressure Actuated Leaf Seal
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Pressure Actuated Leaf Seal: Benefit Comparison - Rub Tolerance.

	Rub Avoidance	Rub Tolerance
Labyrinth Seals	↓	↓
Brush Seals	↓	↑
Pressure Actuated Leaf Seal	↑	TBD

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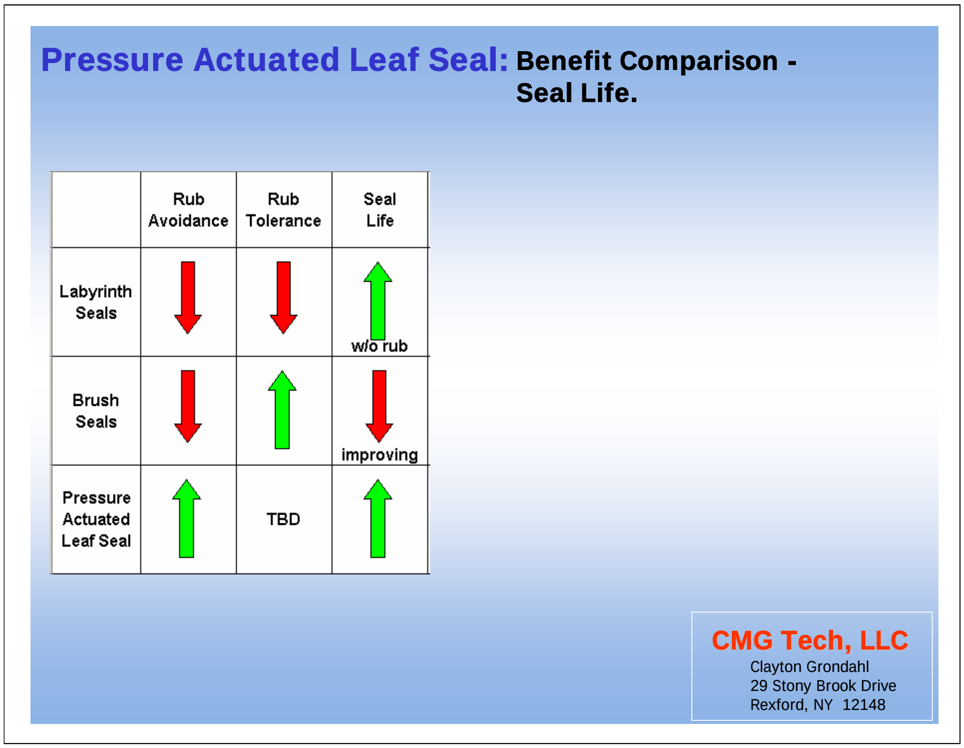
Pressure Actuated Leaf Seal: Benefit Comparison - Seal Life.
Rub Avoidance
Rub Tolerance
Seal Life
Labyrinth Seals
w/o rub
Brush Seals
improving
Pressure Actuated Leaf Seal
TBD
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Pressure Actuated Leaf Seal: Benefit Comparison - Low Leakage.

	Rub Avoidance	Rub Tolerance	Seal Life	Low Leakage
Labyrinth Seals	↓	↓	↑ w/o rub	↓
Brush Seals	↓	↑	↓ improving	↑
Pressure Actuated Leaf Seal	↑	TBD	↑	↑

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Pressure Actuated Leaf Seal: Benefit Comparison - Hi ΔP, > 300psid.

	Rub Avoidance	Rub Tolerance	Seal Life	Low Leakage	Hi DP >300psid
Labyrinth Seals	↓	↓	↑ w/o rub	↓	↑
Brush Seals	↓	↑	↓ improving	↑	↓
Pressure Actuated Leaf Seal	↑	TBD	↑	↑	↑

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29 Stony Brook Drive
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Pressure Actuated Leaf Seal: Benefit Comparison - Reverse Rotation.

	Rub Avoidance	Rub Tolerance	Seal Life	Low Leakage	Hi DP >300psid	Reverse Rotation
Labyrinth Seals	↓	↓	↑ w/o rub	↓	↑	↑
Brush Seals	↓	↑	↓ improving	↑	↓	↓
Pressure Actuated Leaf Seal	↑	TBD	↑	↑	↑	↑

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Pressure Actuated Leaf Seal: Benefit Comparison - Seal Length.

	Rub Avoidance	Rub Tolerance	Seal Life	Low Leakage	Hi DP >300psid	Reverse Rotation	Seal Length
Labyrinth Seals	↓	↓	↑ w/o rub	↓	↑	↑	↓
Brush Seals	↓	↑	↓ improving	↑	↓	↓	↑
Pressure Actuated Leaf Seal	↑	TBD	↑	↑	↑	↑	↑

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29 Stony Brook Drive
Rexford, NY 12148

Pressure Actuated Leaf Seal: Benefit Comparison - Summary.

	Rub Avoidance	Rub Tolerance	Seal Life	Low Leakage	Hi DP >300psid	Reverse Rotation	Seal Length	Cost to Manufacture
Labyrinth Seals	↓	↓	↑ w/o rub	↓	↑	↑	↓	↑
Brush Seals	↓	↑	↓ improving	↑	↓	↓	↑	↓
Pressure Actuated Leaf Seal	↑	TBD	↑	↑	↑	↑	↑	↑

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29 Stony Brook Drive
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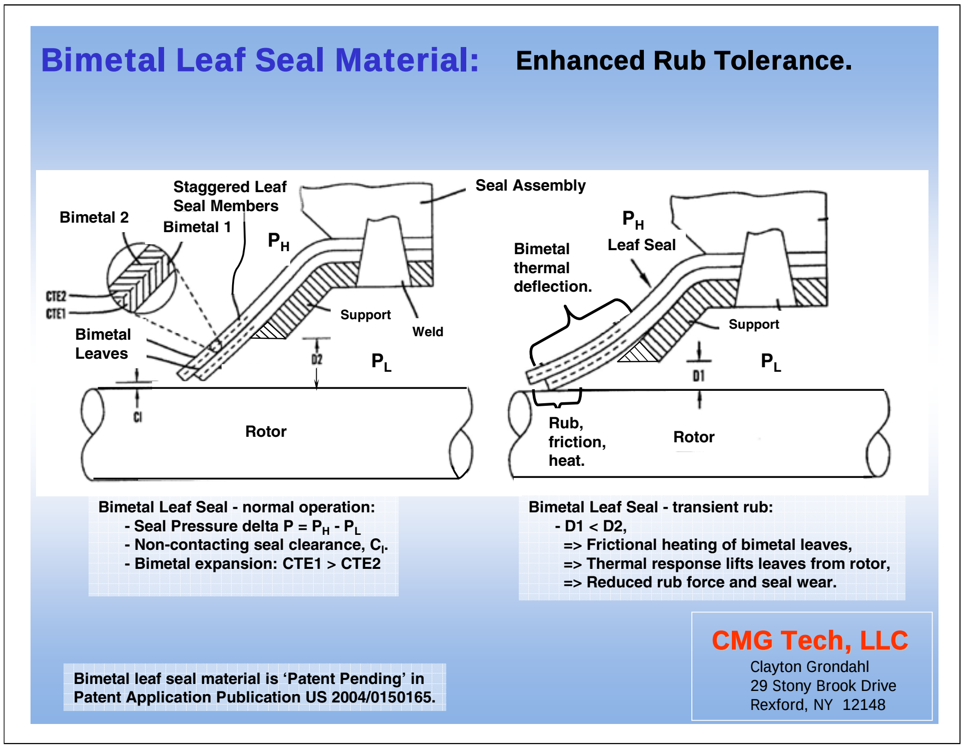
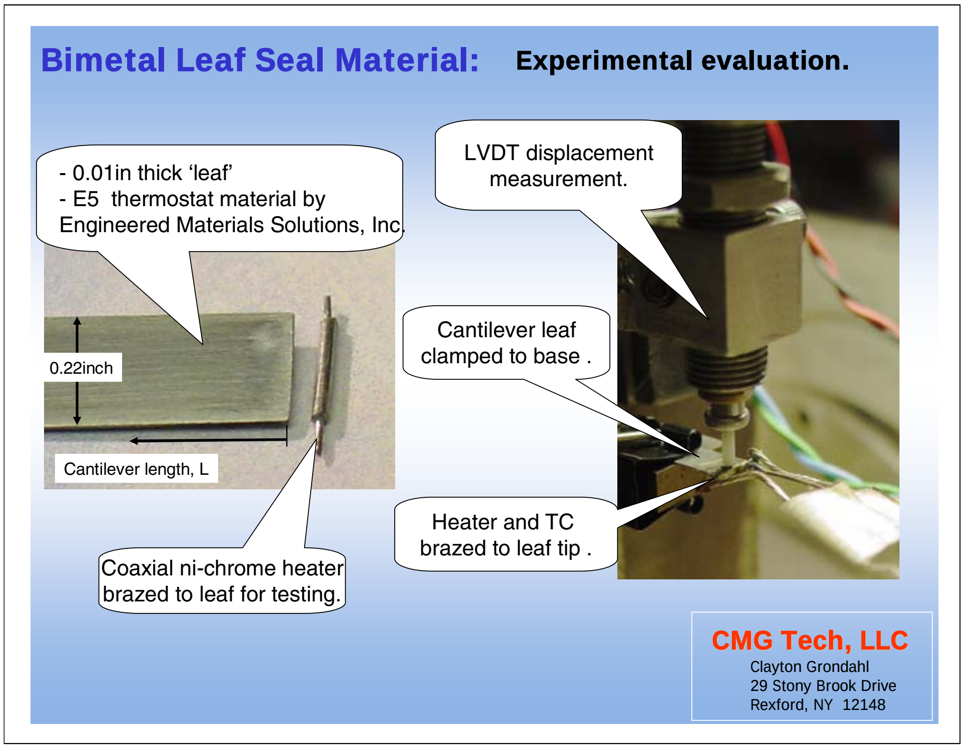
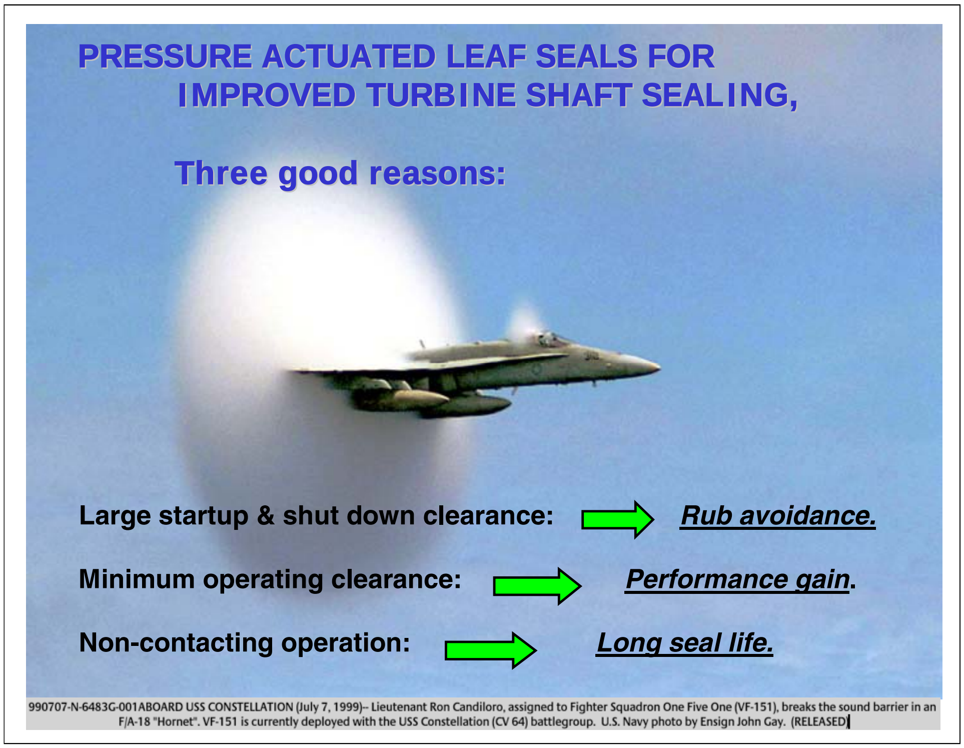
Pressure Actuated Leaf Seal benefits, compared to both labyrinth seals and brush seals, shows a strong basis for development.



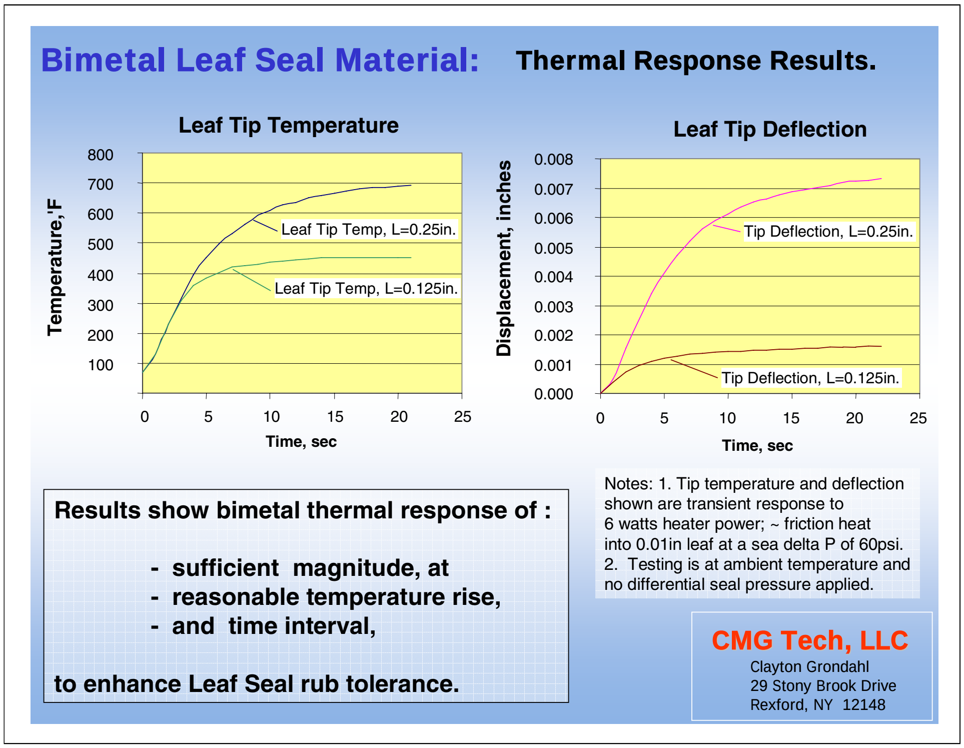
Leaf seal rub tolerance may be enhanced by use of bimetallic leaf material as illustrated.



A selected bimetal leaf material was tested to show concept feasibility.



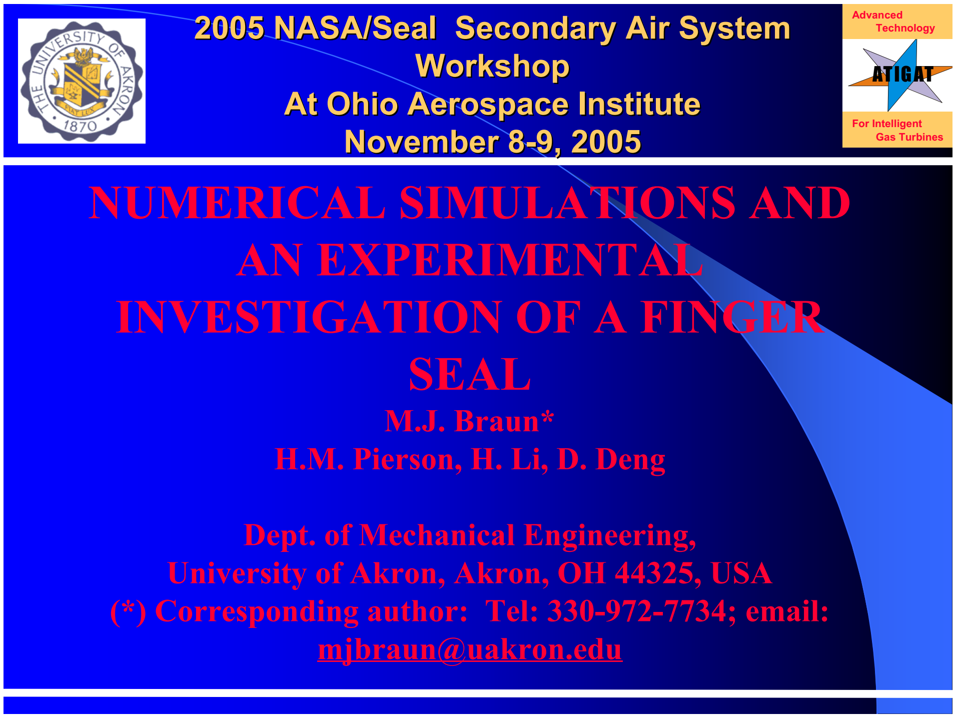
There appears to be an adequate rationale for the development of the Pressure Actuated Leaf Seal for a wide range of applications.



Test results show that a bimetal leaf of proximate seal geometry can respond rapidly to a change in tip temperature and deflect several mils. In a seal application movement away from a moving component could relieve friction heating during a transient rub.

NUMERICAL SIMULATIONS AND AN EXPERIMENTAL INVESTIGATION OF A FINGER SEAL

Minel Braun, Hazel Pierson, H. Li, and Dingeng Dong
University of Akron
Akron, Ohio



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ACKNOWLEDGEMENT

The authors want to express their gratitude to M. Proctor and B. Steinetz of NASA Glenn Research Center, Cleveland, Ohio for the financial support and technical consultations.

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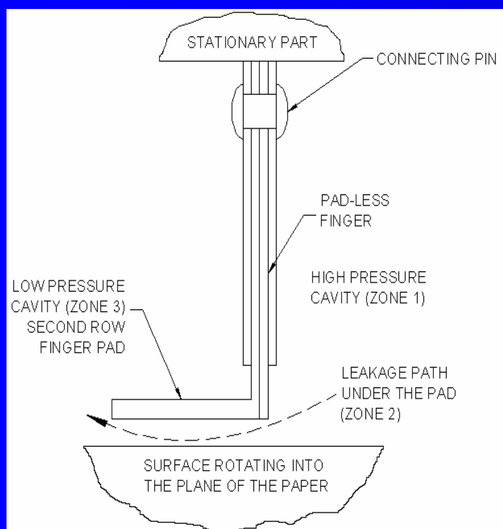
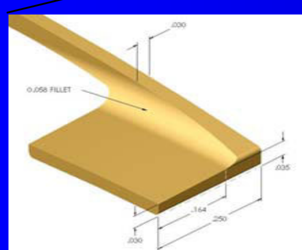
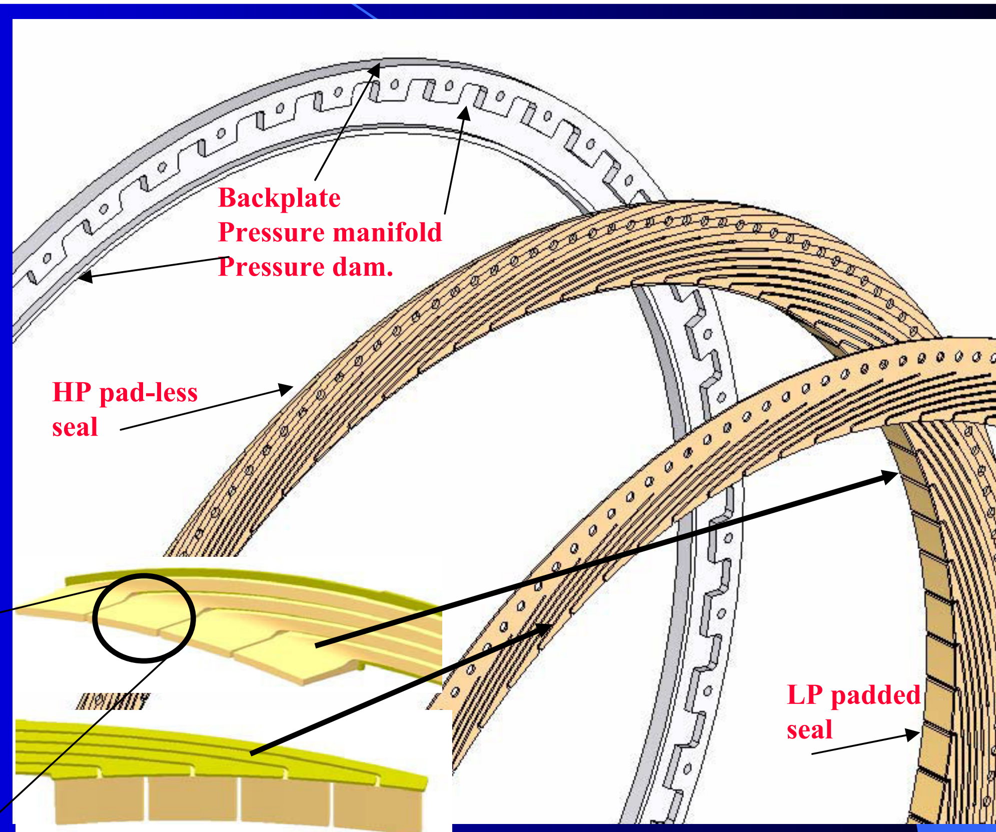
CONCEPT AND COMPONENTS



General Configuration





Full Wafer of Padded Fingers (8.5" ID, 9.666" OD, 81 Fingers) and details (b, c) of the Arrangement of the High and Low Pressure Fingers

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ACTUAL HARDWARE

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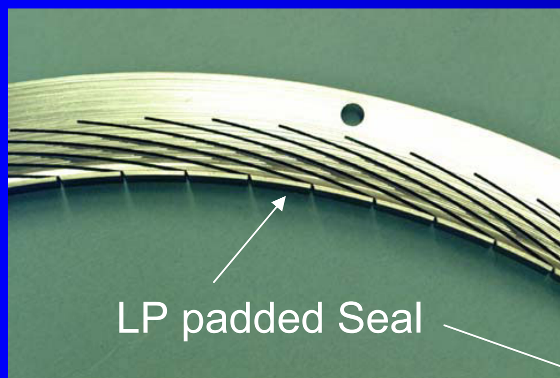

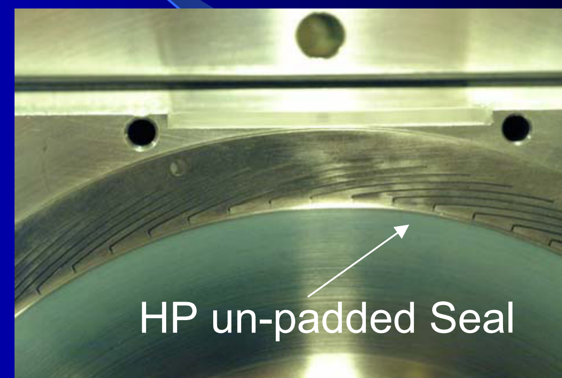

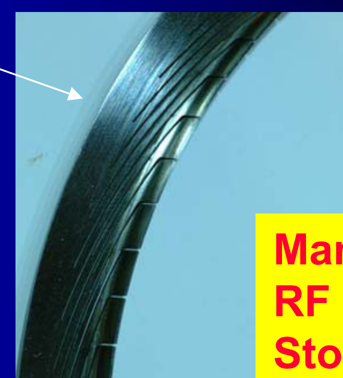

Manufactured by:
RF Cook
Stow, OH 44224

Padded and Unpadded Sections of HP- and LP-seals

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DESIGN PARAMETERS

(Variations in the Design of the Finger Stick and Foot)

Besides sealing, the other main goal of a successful finger seal design is to exhibit appropriate compliance to outside forces. The ability of the seal to ride or float along the rotor without rubbing or excessive heating is essential to the successful operation of the seal.

The compliance of the finger must only occur in the radial plane;

The seal needs to be as sturdy as possible in the axial direction.

The compliant finger that moves radially outward with rotor growth and motion has to be able to ride the rotor back down as the rotor diameter recovers or the rotor moves "away".

Thus there is an optimum stiffness for the finger;

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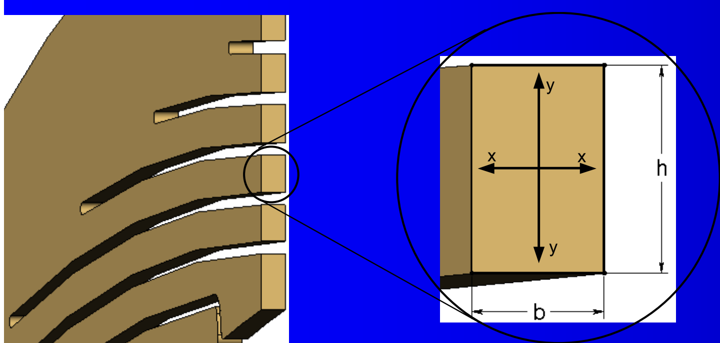
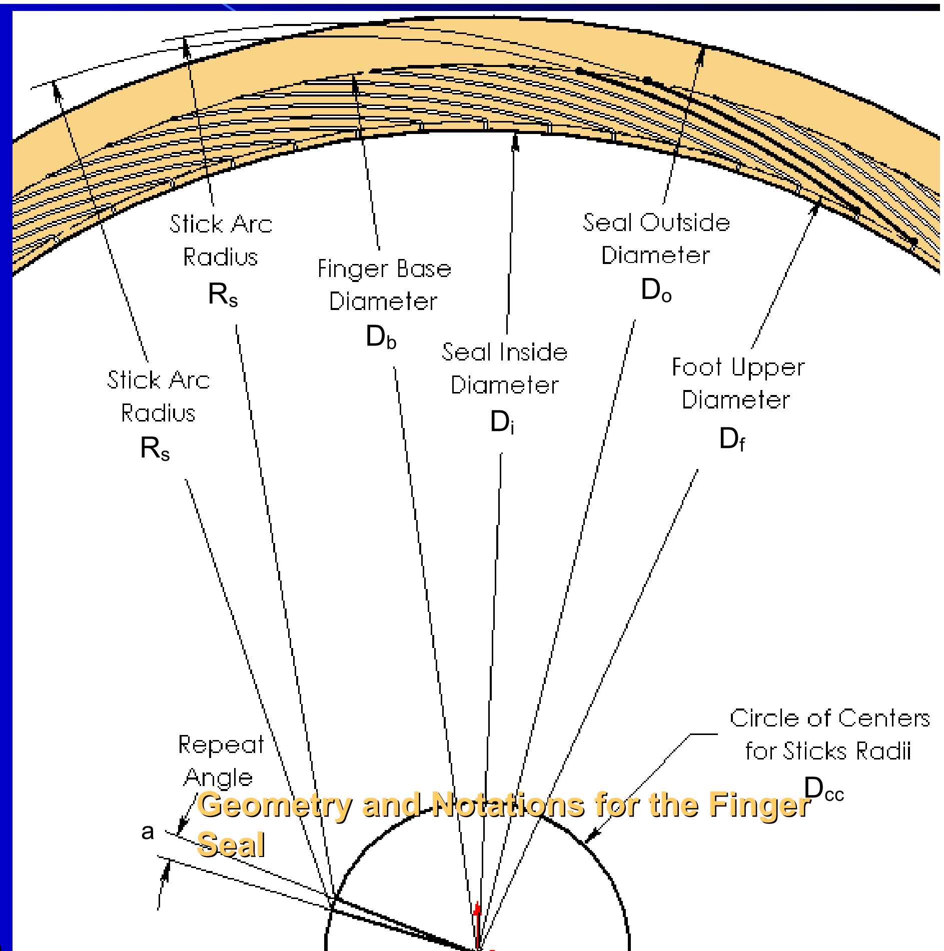
DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

1. D_{cc} Stick Arcs Circle of Centers.
2. R_s Stick Arc Radius.
3. D_b Finger Base Diameter.
4. D_f Foot Upper Diameter.
5. 'a' Finger Repeat Angle.
6. l_s Finger Interstice Width.
7. L_c Circumferential Foot Length.
8. 'b'-Laminate thickness.



View of Finger Stick Cross-Section



Geometry and Notations for the Finger Seal

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DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

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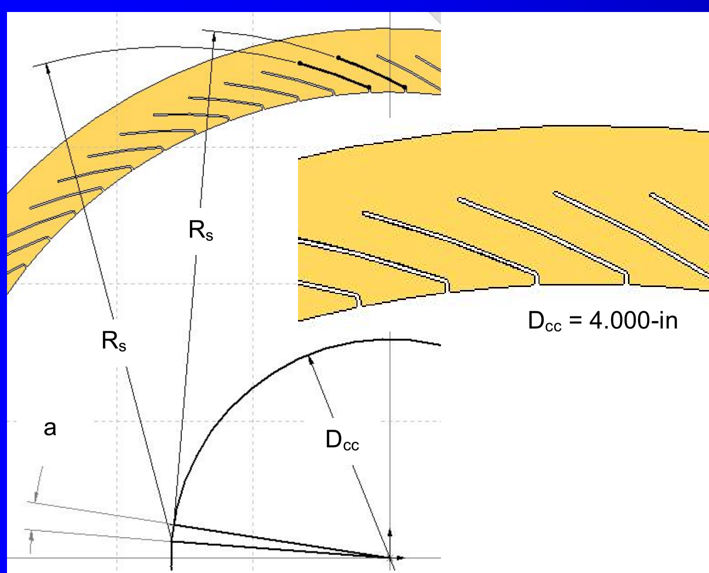
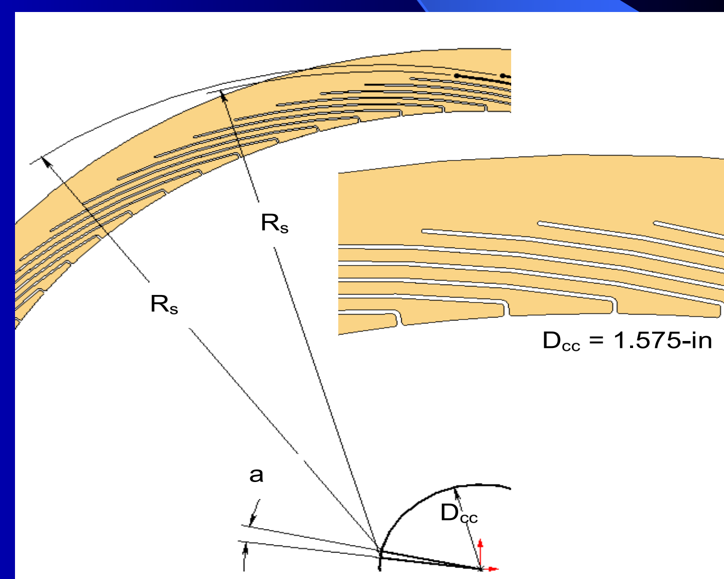
1) D_{cc} Stick Arcs Circle of Centers

When the diameter of the circle of centers (D_{cc}) of the finger stick arcs was increased, while all other dimensions remained the same, the sticks became thicker and pointed more directly toward the center of the seal.

The two figures show the change in the shape of the finger stick when the circle of centers was increased to the diameter of (a) D_{cc} = 4.000-in from (b) D_{cc} = 1.575-in





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DESIGN PARAMETERS (cont'd)

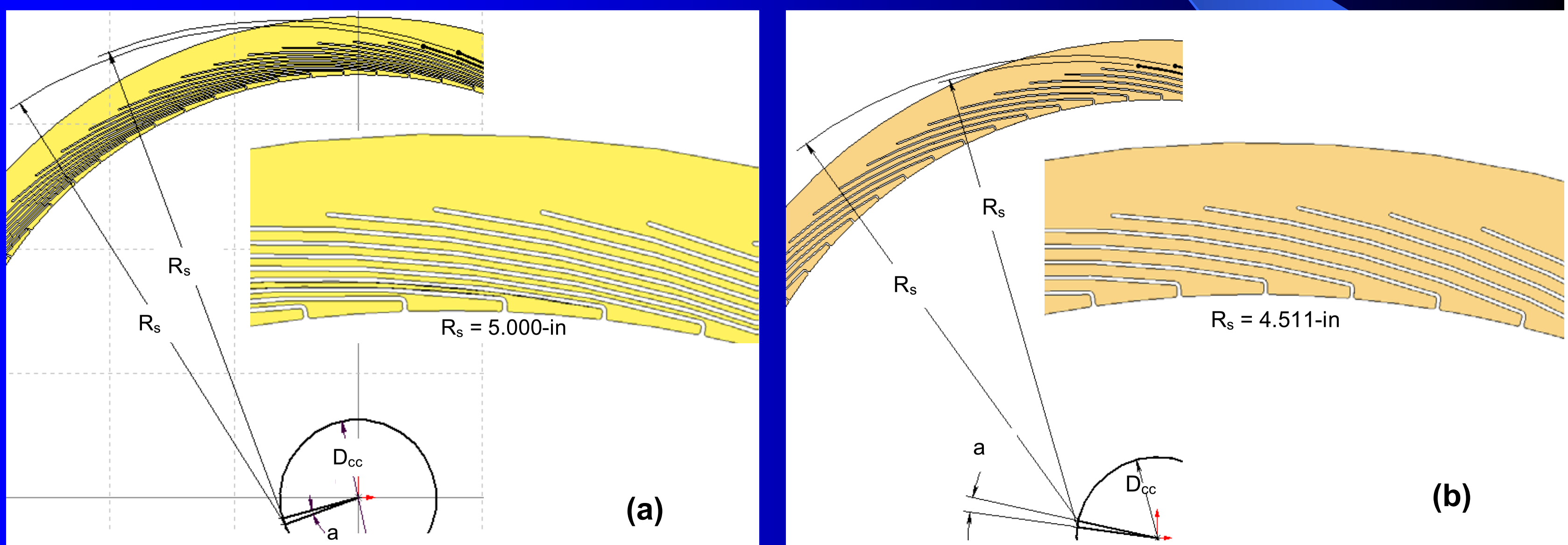
(Variations in the Design of the Finger Stick and Foot)

(2) R_s Stick Arc Radius.

The two figures (a) and (b) show the change in the shape of the finger stick when the arc radius was increased to Rs = 5.000-in from R_s = 4.511-in.

NOTE:

The increase in R_s, while keeping D_{cc} constant, caused the sticks to curve more concentric with the inside diameter of the seal, and consequently make the stick length much longer.



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DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

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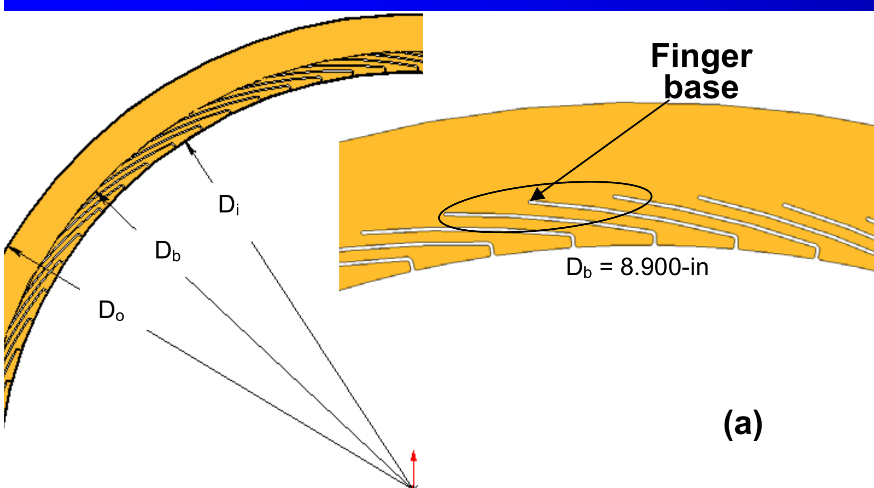
(3) D_b Finger Base Diameter.

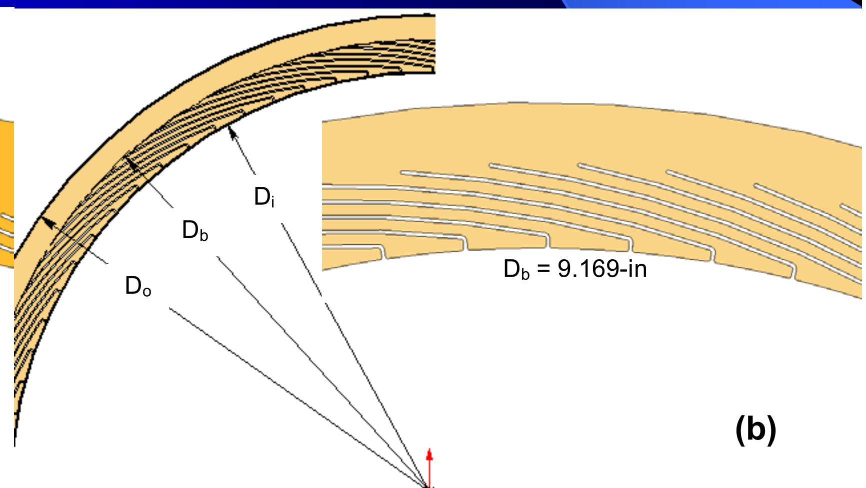
Figures (a) and (b) shows the seal in which the finger base diameter had been changed to (a) Db = 8.900-in. from (b) Db = 9.169-in.

NOTE:

When the finger base diameter, D_b, was changed, the stick length, L_{st}, changes. With all other dimensions kept constant, this variation *only* altered the length of the stick; the cross-sectional height, h, and the angle at which it attaches to the pad (foot) remained the same.



(a)



(b)

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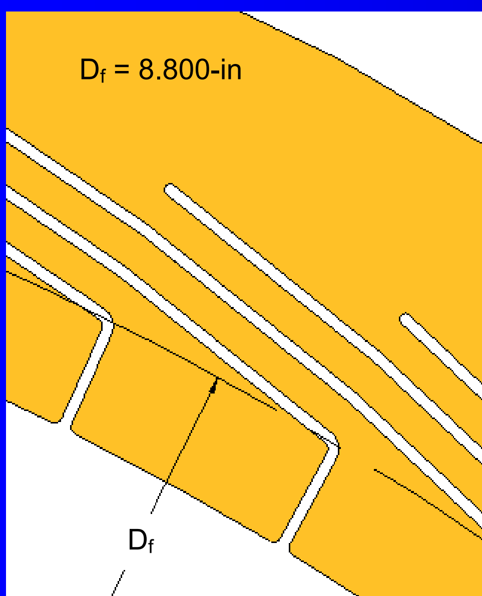
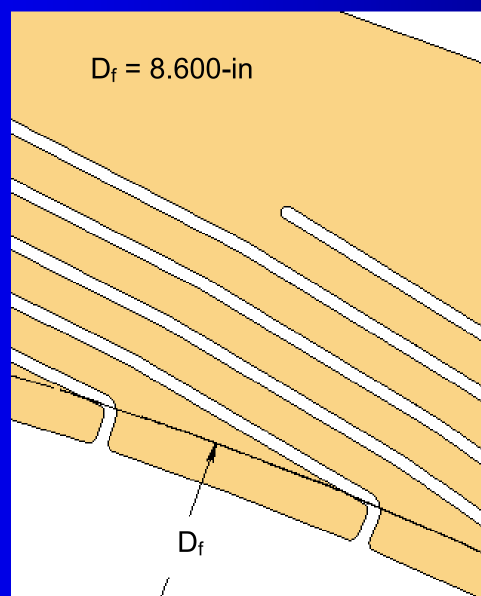
DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

4) D_f Foot Upper Diameter.

Figures (a) and (b) shows the altered foot geometry as the upper foot diameter was changed to (a) Df = 8.800-in from (b) Df = 8.600-in. The mass of the foot can be altered by changing the upper foot diameter, Df.





NOTE #1:

Altering the mass does not affect the equivalent stiffness of the finger, but it does have an impact on the finger dynamics.

increasing D_f also shortened the effective stick length, L_{st}, which significantly affects the finger stiffness.

NOTE #2:

D_b also affects the finger stiffness length L_{st} (see previous slide)

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DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

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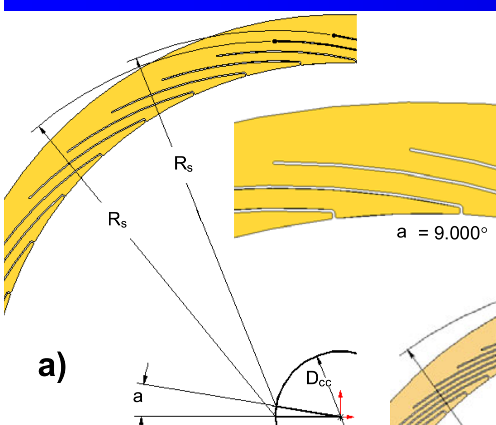
(5) 'a' Finger Repeat Angle.

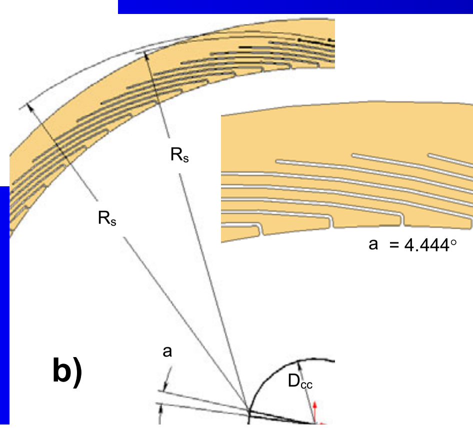
Figures (a) and (b) shows the change to a 40 finger seal, (a) a = 9.000° repeat angle, from an 81 finger seal, (b) a = 4.444° repeat angle. It is the repeat angle, a, of the finger stick arcs that determines how many individual fingers will be in the total seal.

From the standpoint of the stick stiffness, the change in 'a' will cause a significant change in h; doubling the height increased the area moment of inertia, and consequently the stiffness by eight fold, as summarized in the following Table for an increase in a to 9.000°.

a)



b)



	Symbol	Original Value	Value change with the Increase of 'h'
Effective Stick Length	L_{st}	1.6108-in	SAME
Cross-section Base	b	0.030-in	SAME
Cross-section Height	h	0.045-in	0.090-in
Area Moment of Inertia	I_{xx}	2.28×10^{-7}-in^4	1.822×10^{-6}-in^4
Modulus of Elasticity	E	31×10^{6}-psi	SAME
Stick Stiffness	k_{stick}	5.07- lbf/in	40.55 - lbf/in

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DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

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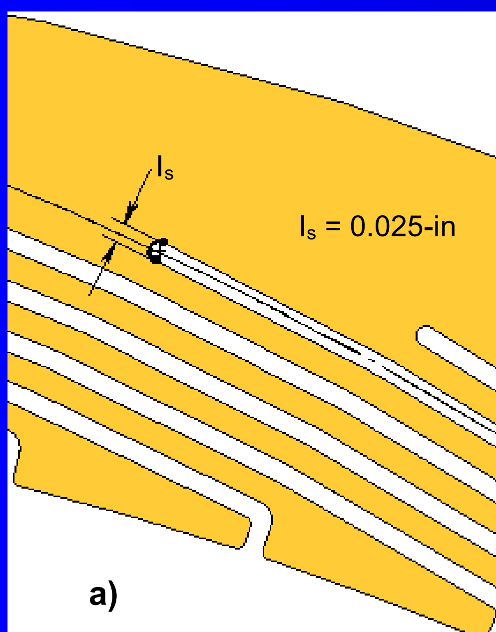
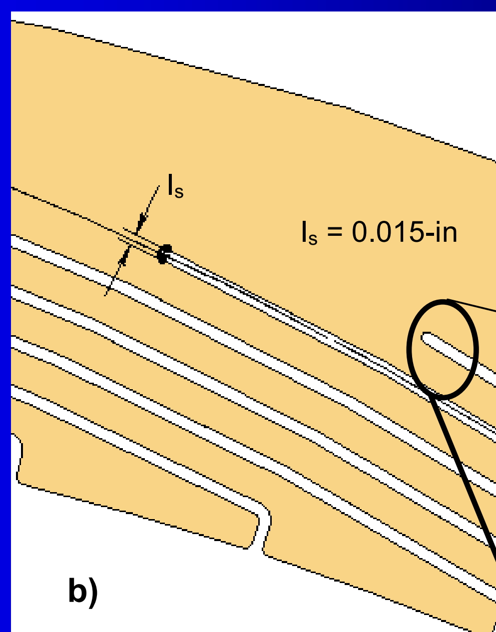
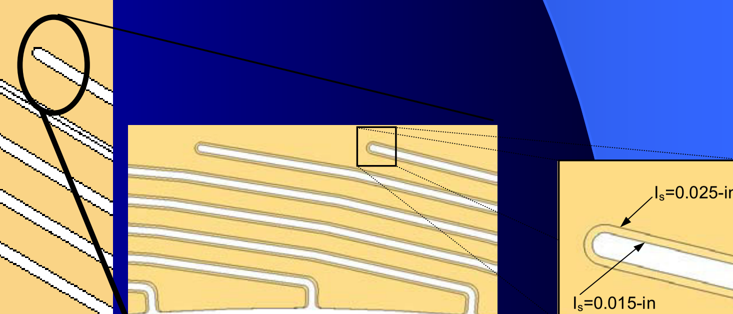
(6) Is Finger Interstice Width

Figures (a) and (b) shows a finger seal with a change to an (a) Is = 0.025-in interstice from an (b) Is = 0.015-in interstice between fingers The interstices, I_s, (cutouts) between the individual fingers are what give the fingers the ability to move independently of each other.







Detail of interstice

NOTE:

The added space between the fingers allows the seal to open to a greater maximum diameter, but it also allows greater potential leakage.

Thus one has to optimize between freedom of movement and minimum leakage.

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DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

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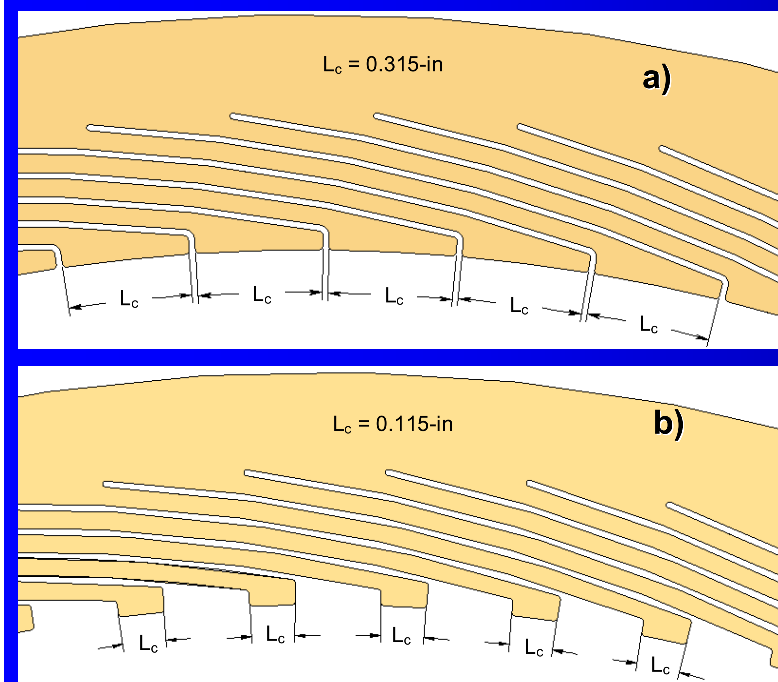
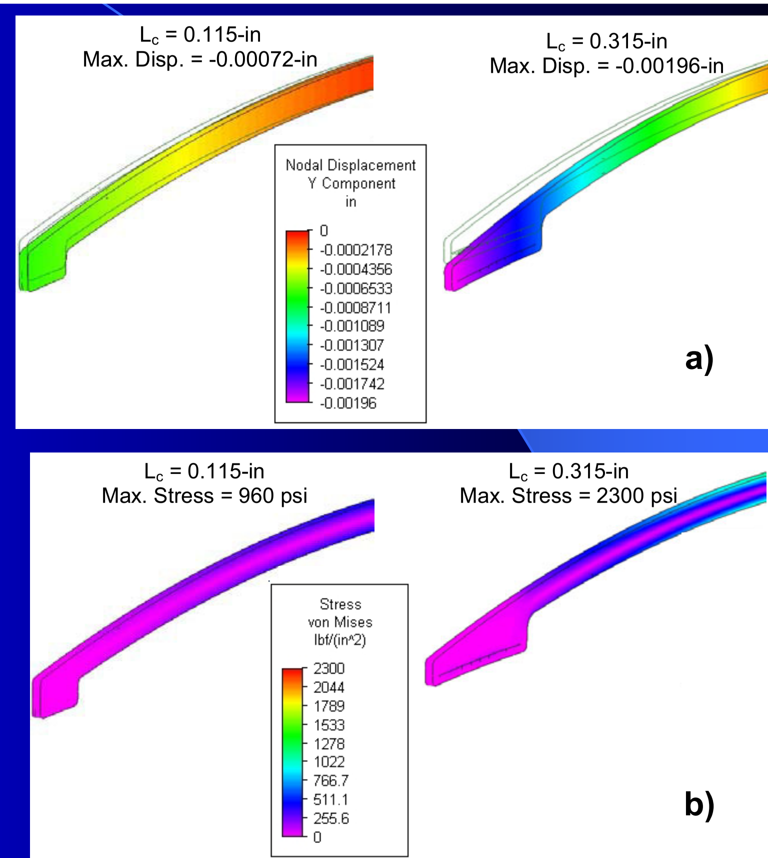
(7) L_c Circumferential Foot Length.

Figures (a) and (b) show a foot whose toe and heel were removed such that the arc length is reduced to (a) Lc = 0.115-in from (b) Lc = 0.315-in. Keeping all other parameters constant, the circumferential arc length, Lc, of the foot itself was considered for optimization





Resultant Contours Comparisons for a Change in Lc to 0.115-in from 0.315-in: (a) Deflection Dither, (b) Stress Dither

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DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

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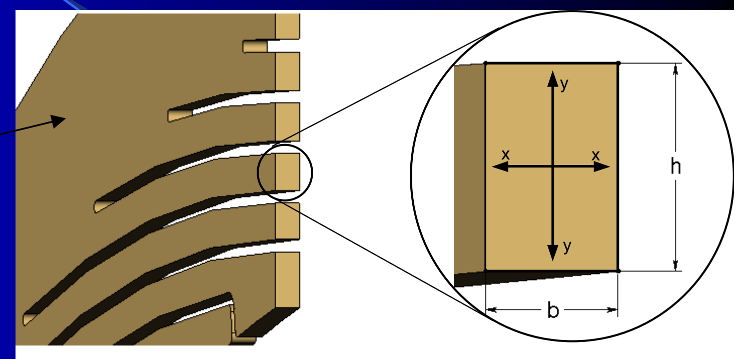
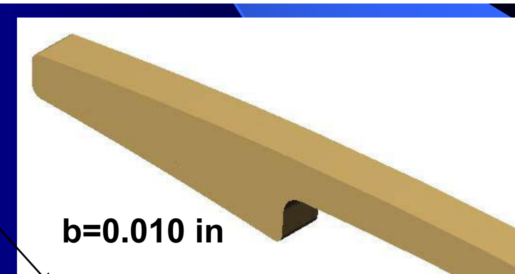
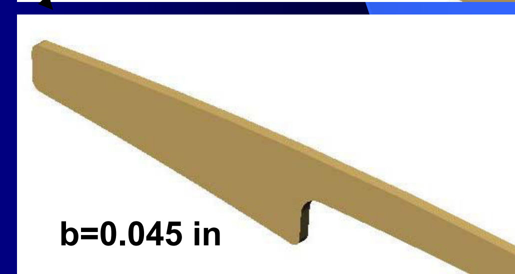
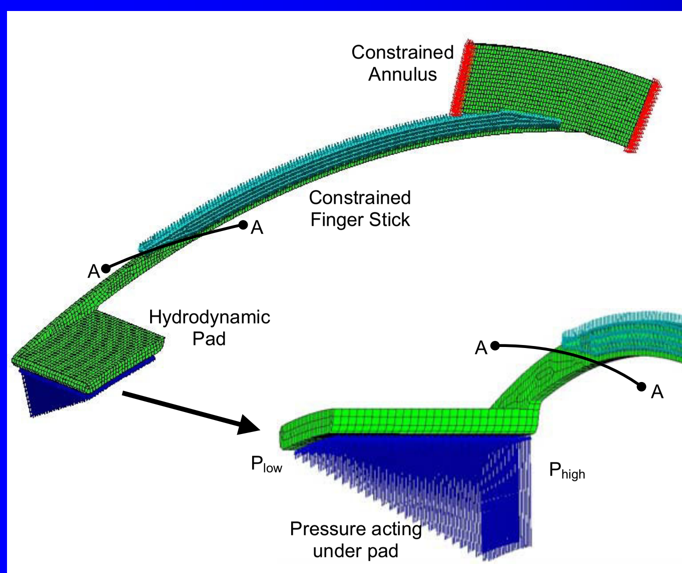
(8) b-Laminate thickness.

The final geometric variation of the finger portion that was evaluated was the cross-sectional thickness, b, of the individual finger laminates. Stiffness values, k_{stick}, were determined for a cross-sectional thickness ranges from b = 0.010" to b = 0.045".









FEM Loading and Boundary Conditions for Investigation of Finger Out-of-Plane Twisting as a function of Finger Thickness, b

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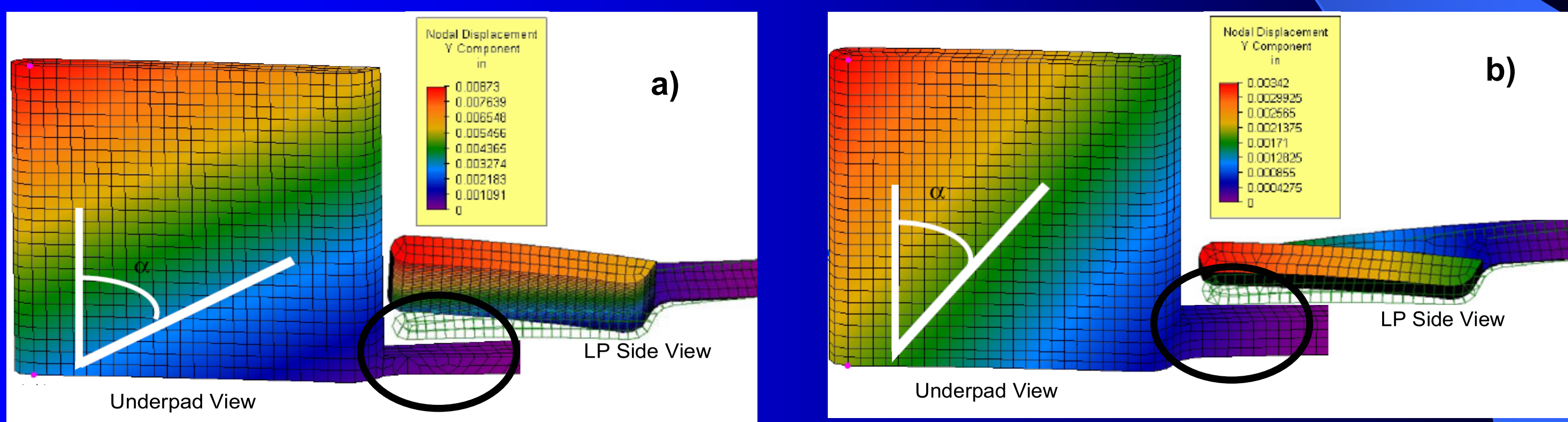
DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

Variations in Finger Pad Design

The finger seal obtains its hydrodynamic lifting capabilities from the pattern of the padded fingers underside, which "rides" the surface of the shaft. The objective in the design of the pad was to determine an optimal configuration that would enable the pad portion to lift from the rotating rotor and to run on a thin film of air during operation while minimizing the leakage rate

The desirable motion of the pad is one that is in sync with the motion of the stick while minimizing its rotation out-of-plane with respect to the stick. If the pad rotated around its heel, it could potentially both open the clearance for leakage and "dig" into the shaft at the origin of the pad rotation. Therefore the design of the pad had to minimize this situation.



Radial Out-of-Plane Twisting as Viewed from Underneath the Pad and from the Low-Pressure Side: (a) Stick Thickness of b=0.015-in, (b) Stick Thickness of b=0.030-in

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DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

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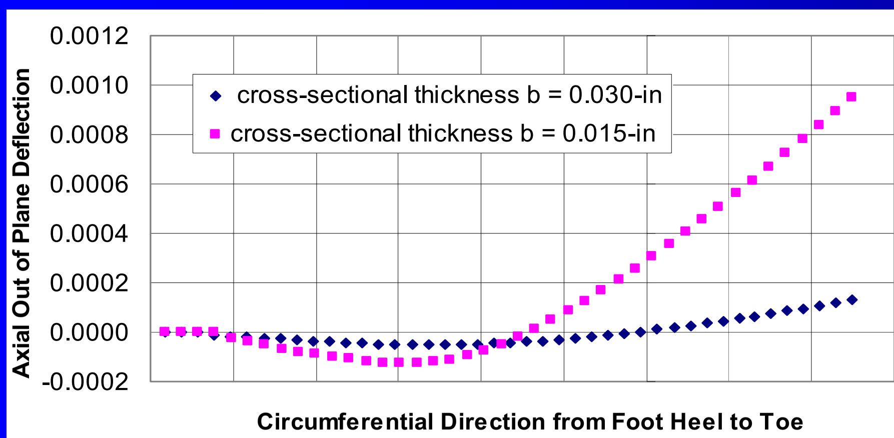
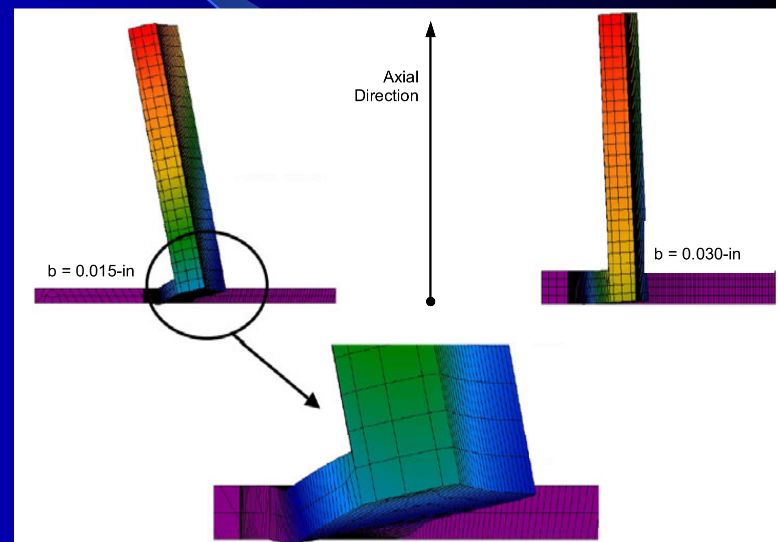
Variations in Finger Pad Design



Shape of the underpad surface Axial Out-of-Plane Twisting for Stick Thickness of b=0.015-in and b=0.030-in



Another view of pad and stick deformation

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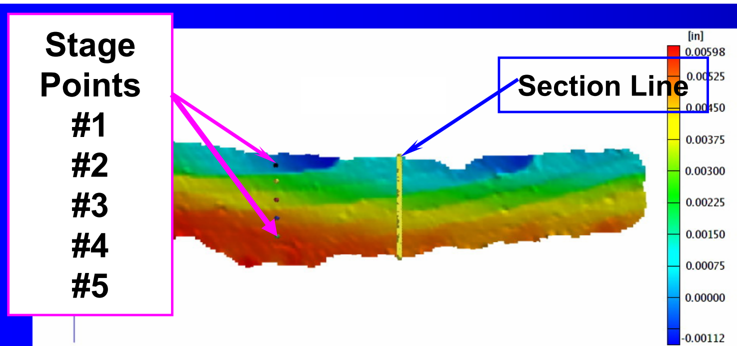
FINGER BEHAVIOR WITH ROTATING SHAFT AND AXIAL PRESSURE DIFFERENTIAL Δp=5 PSI

x-, y- and z- Displacements



Experimental Conditions:
Rotation: 7000 RPM
Axial pressure: 0 to 5 PSI

Photos of the fingers (the region shown in the above pictures) are taken by two cameras from different angles at the same time. The x (circumferential), y (radial), and z (axial) displacements are obtained by analyzing the pairs of the images.

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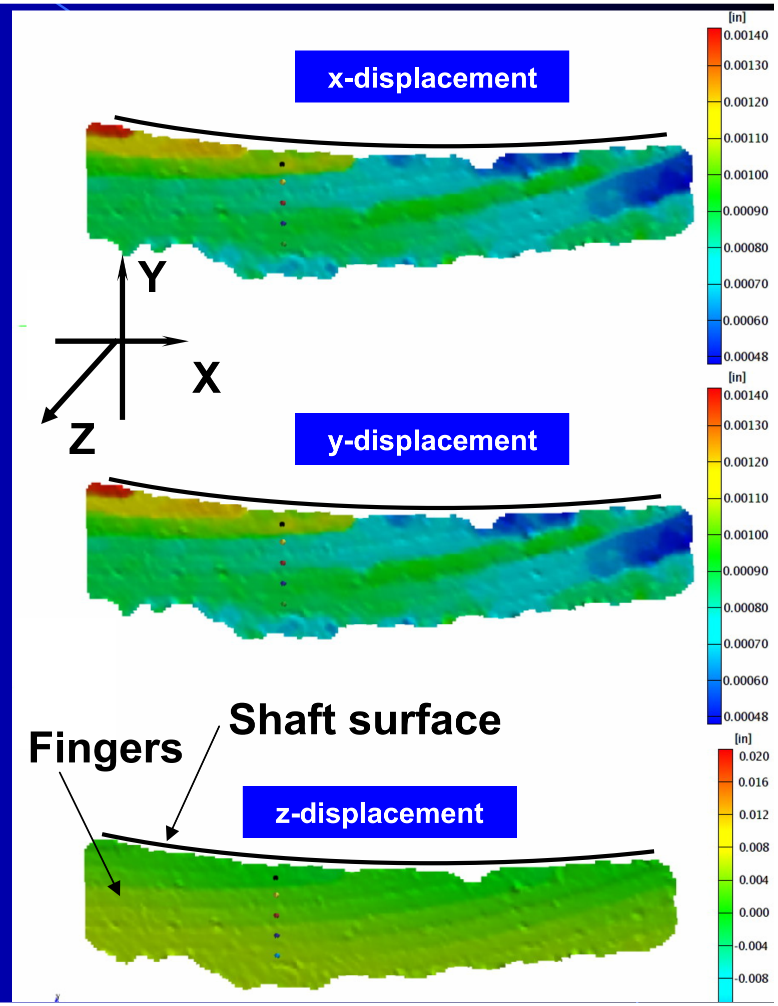

Fingers Motion and Deformation Animation

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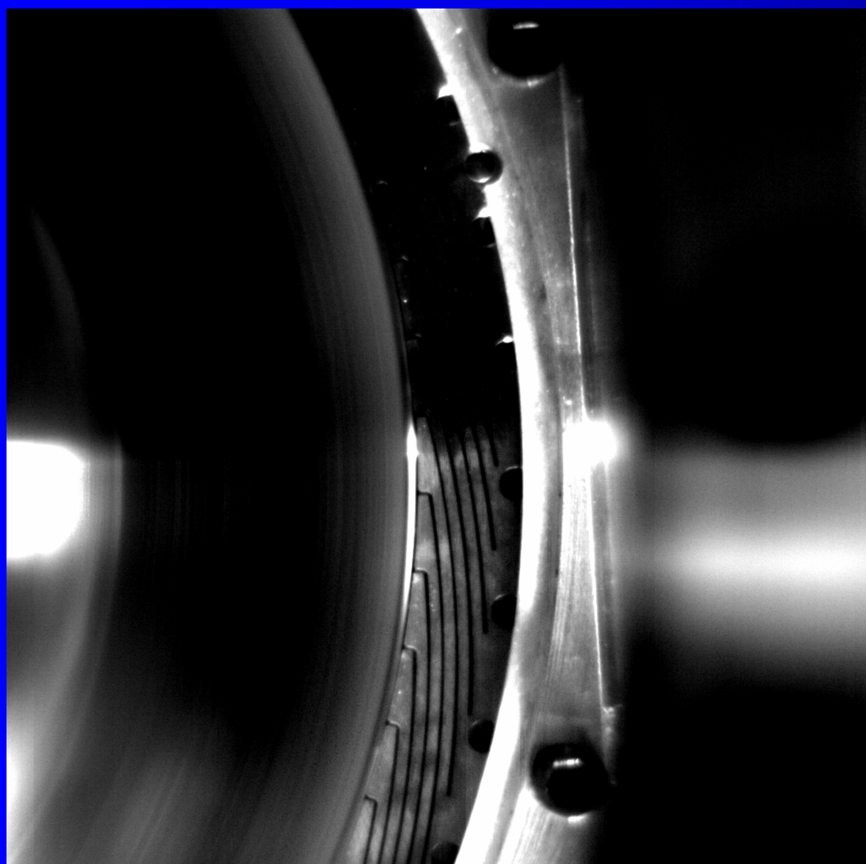
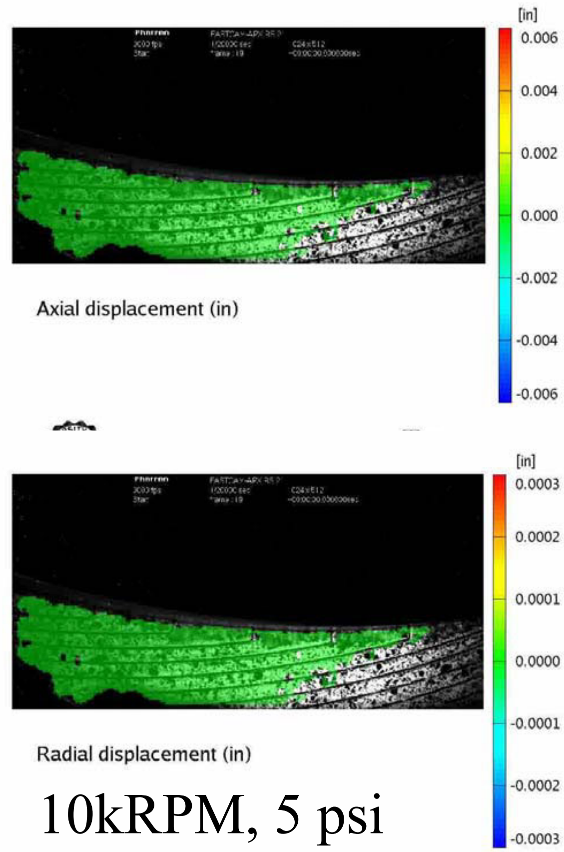


10,000 RPM



10kRPM, 5 psi

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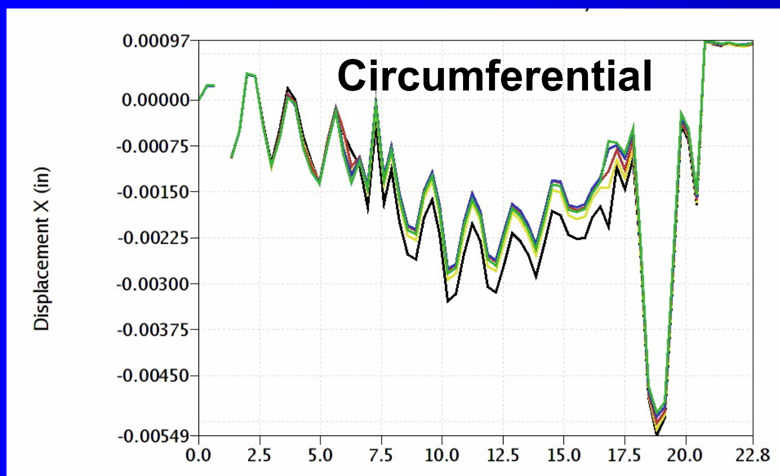
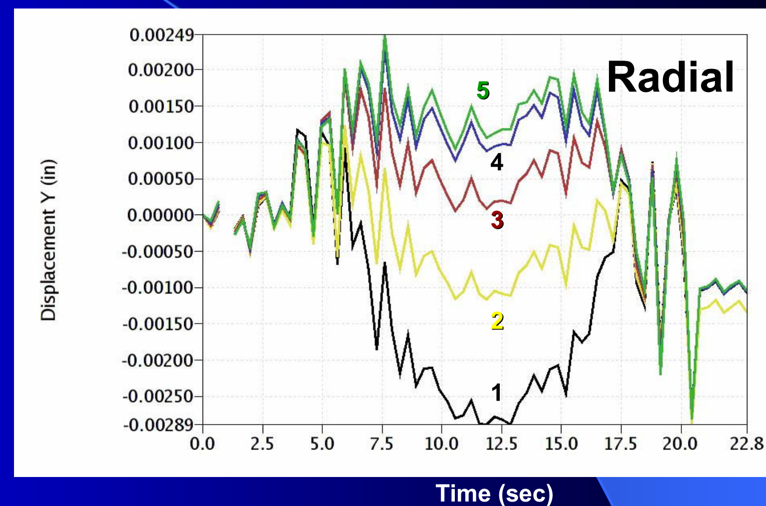
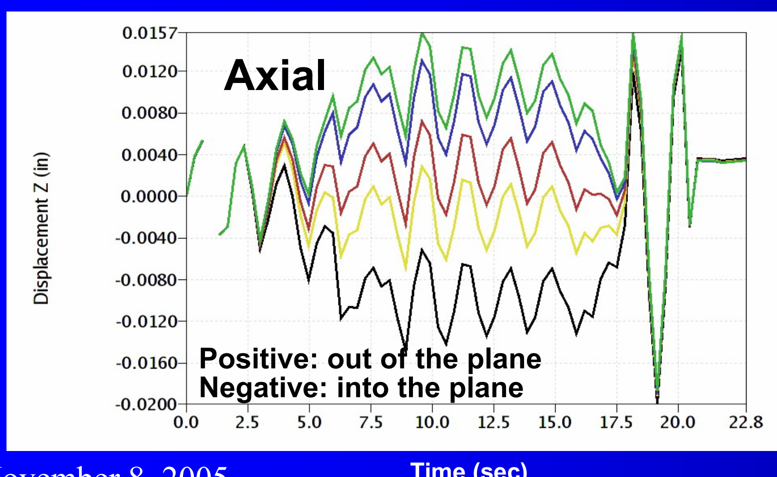
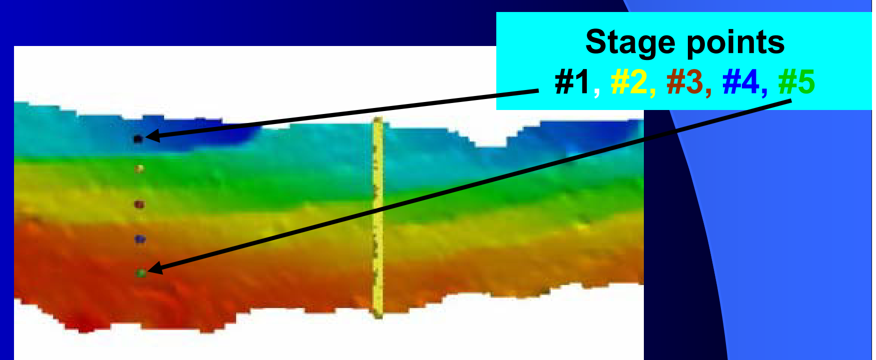
FINGER BEHAVIOR WITH ROTATING SHAFT AND AXIAL PRESSURE DIFFERENTIAL Δp=5 PSI

Time History Displacement of The Stage Points









The color of the stage points # corresponds to the color of the curves above

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CONCLUDING REMARKS (1)

Finger Behavior with Rotating Shaft and Axial Pressure Differential

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- All the fingers vibrate because of the rotation of the shaft. Lifting force on the pad is very sensitive to the clearance between the pad and the shaft surface.
- In one coordinate direction, all the fingers move in the same manner
- At different radial locations, the x-displacement varies in the same manner
- The y- and z- displacements are different at different radial locations
- The z-displacement is smallest at the root of the fingers and at the back plate supporting point

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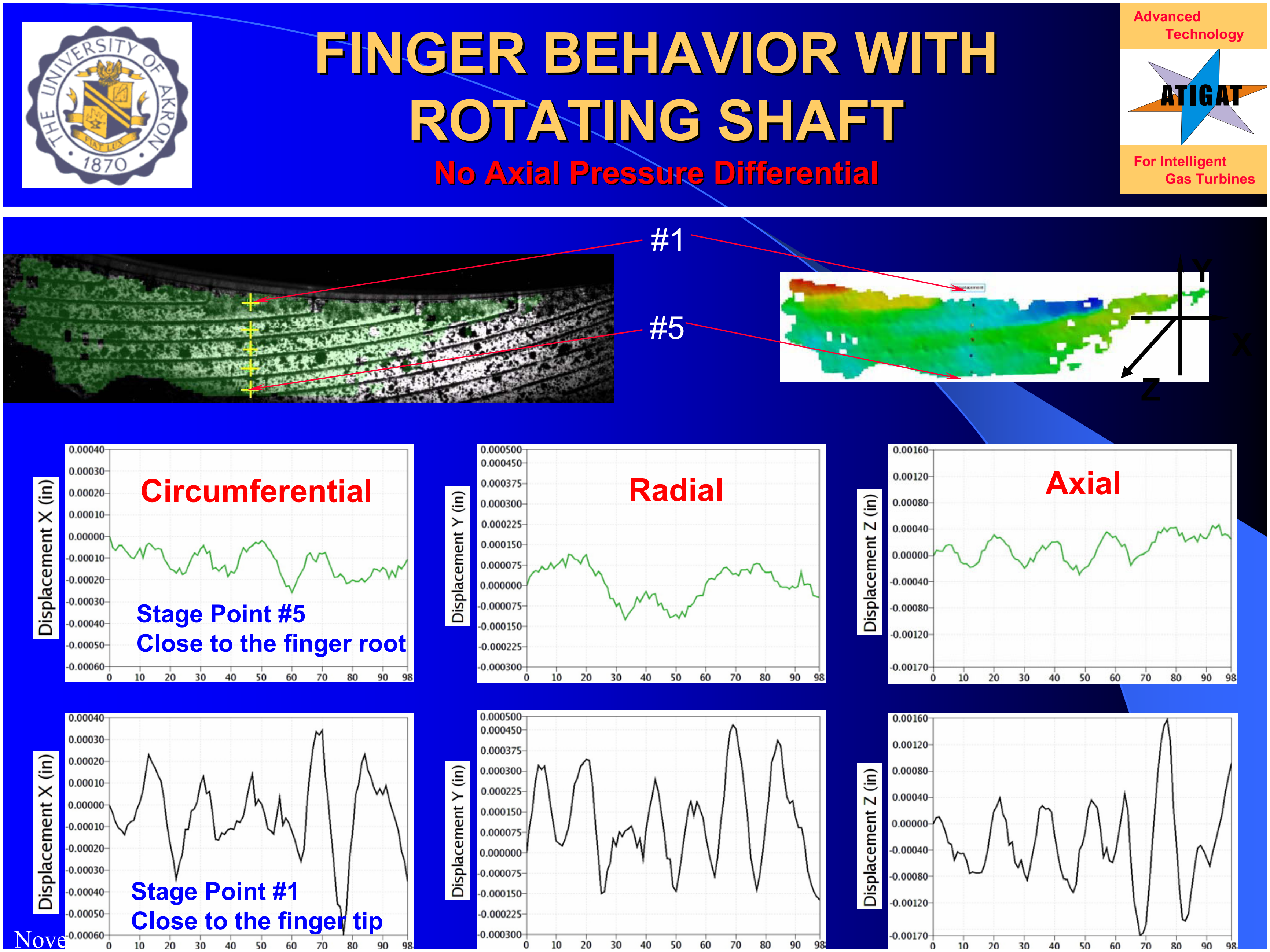
FINGER BEHAVIOR WITH ROTATING SHAFT
No Axial Pressure Differential
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#1
#5
Circumferential
Radial
Axial
Stage Point #5
Close to the finger root
Stage Point #1
Close to the finger tip
Displacement X (in)
Displacement Y (in)
Displacement Z (in)
Nove

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CONCLUDING REMARKS (2)

Finger Behavior with Rotating Shaft and No Axial Pressure Differential

- With the shaft rotating while no axial pressure drop, all the fingers move/vibrate independently. There is no phase correlation observed between the vibrations of the fingers.
- The displacement decreases from the finger tips to the finger roots
- At one location, the displacement magnitude of the vibration in three (x-, y-, z-) directions are roughly the same
- The movements of the fingers proved that all the fingers are lifted by the pressure build up under the bad due to the rotation of the shaft.

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FINGER BEHAVIOR WITH AXIAL PRESSURE DIFFERENTIAL

Axial Pressure Shock: 0-20-0 PSI, No Shaft Rotation,

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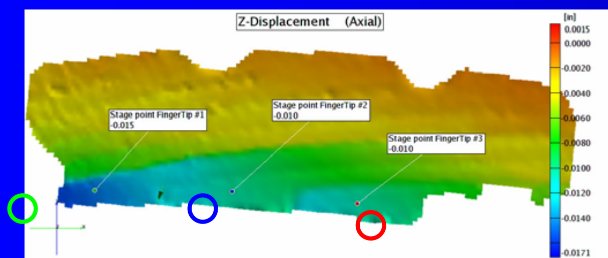
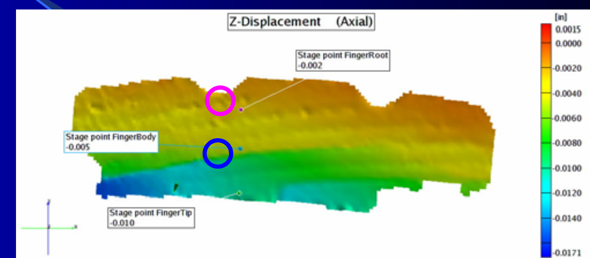
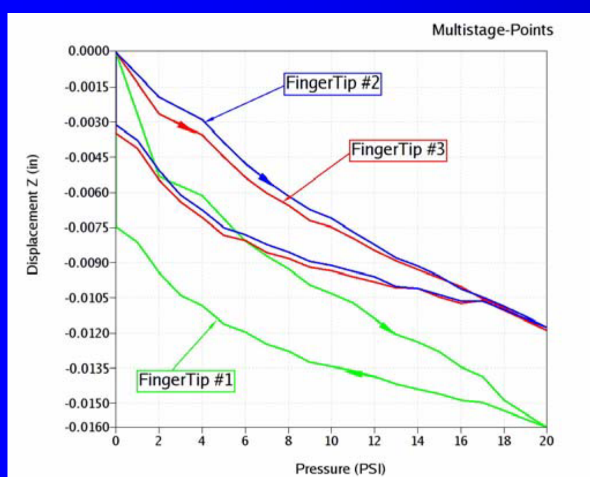
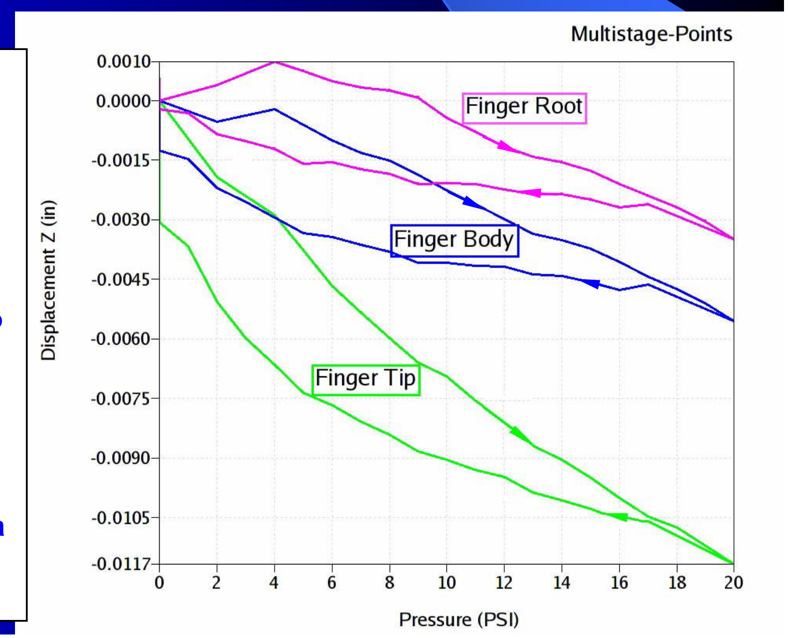






From initial state, pressure was increased from 0 to 20 psi and then decreased to 0 psi. The test was to investigate the finger behaviors under such a pressure shock



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CONCLUDING REMARKS (3)
Finger Behavior with Axial Pressure Differential, No Shaft Rotation.
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• With axial pressure drop only , all the finger moves in the same manner since all the fingers subject to roughly the same axial flow and axial pressure drop
• The deformation/bending of the fingers are three-dimensional.
• Displacement distributions shows sharp jump between the fingers, which indicates that they cam move independently.
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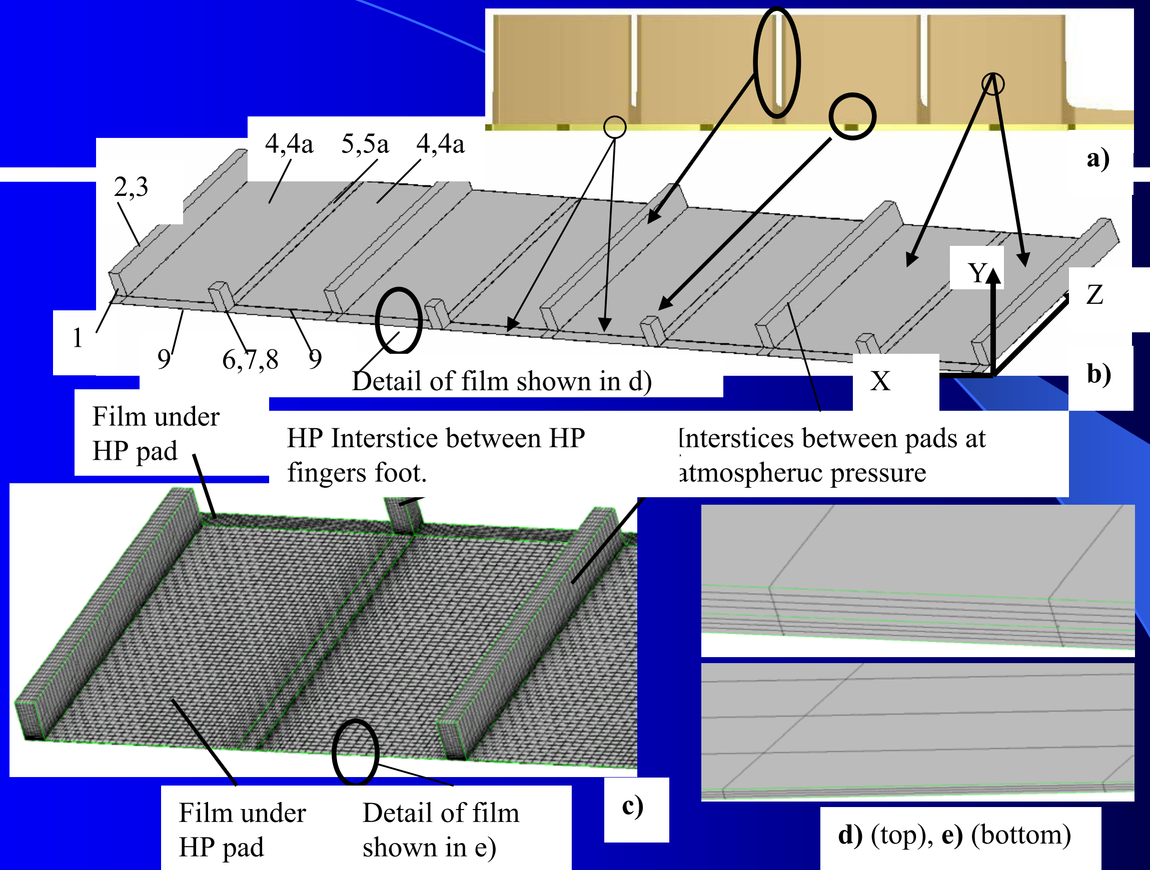
COMPUTATIONAL GRID



Grid Details for the Pressure, Flow and Temperature Calculations.
a) Solid representation of the two rows of fingers viewed from below
b) Corresponding representation of the fluid film contained between the rotor and the assembly of fingers.
c) Detail of the cell structure in the fluid film below and in-between HP and LP pads.
d) Fluid film grid structure under the HP finger
e) Fluid film grid structure under the LP finger

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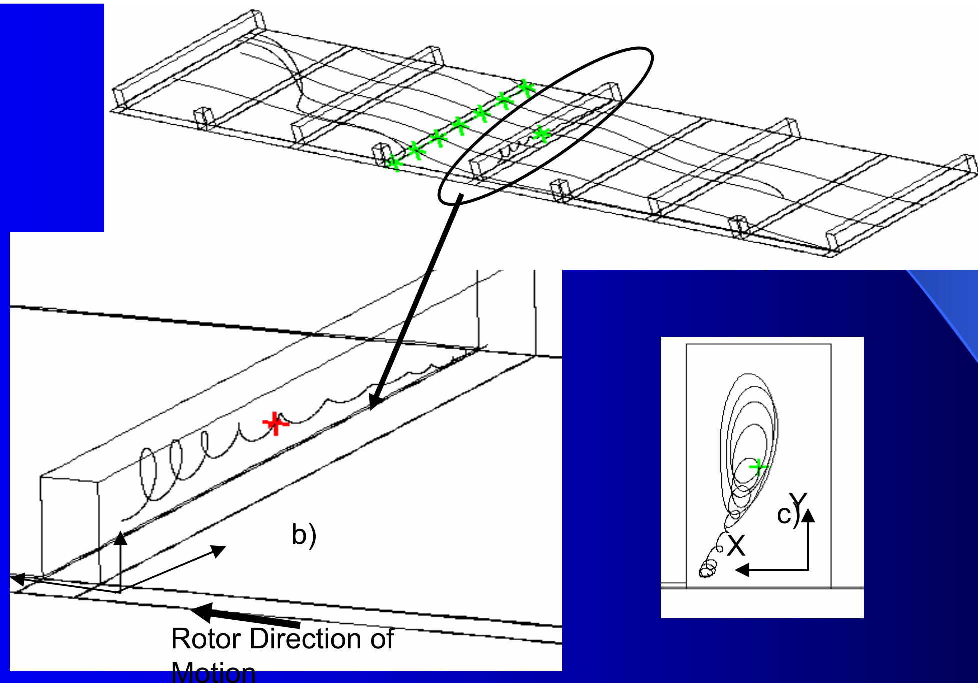
General 3-D Flow Paterns



Flow trajectories visualized with individual 4-finger cell showing circumferential flow. a) tracers showing circumferential flow; b) 3-D flow between low pressure fingers, c) frontal view of flow in b)

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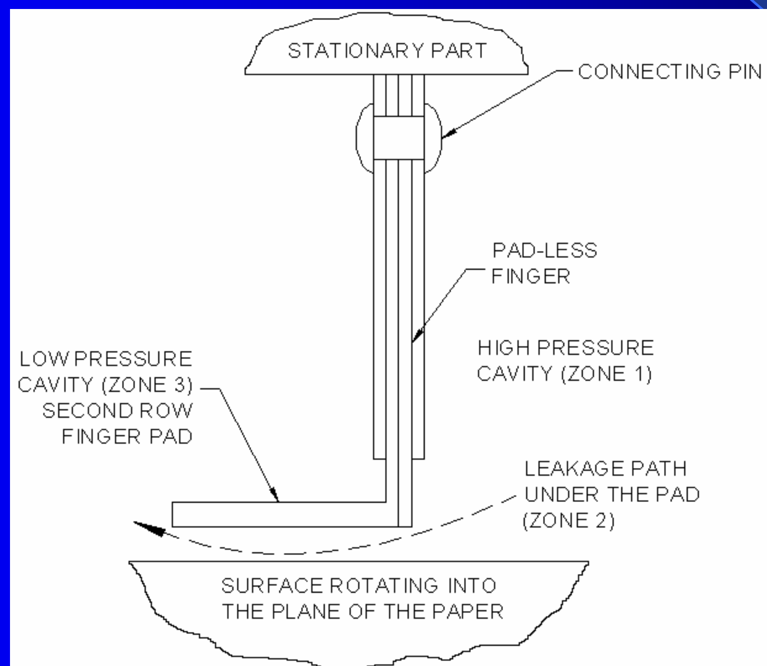
THERMOFLUID BOUNDARY CONDITIONS



Boundary conditions for the Finger Seal. Schematic Cross Section with Two Rows of Padded Low- and Pad-less High Pressure Fingers

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PRESSURES: INCOMPRESSIBLE vs. PGL

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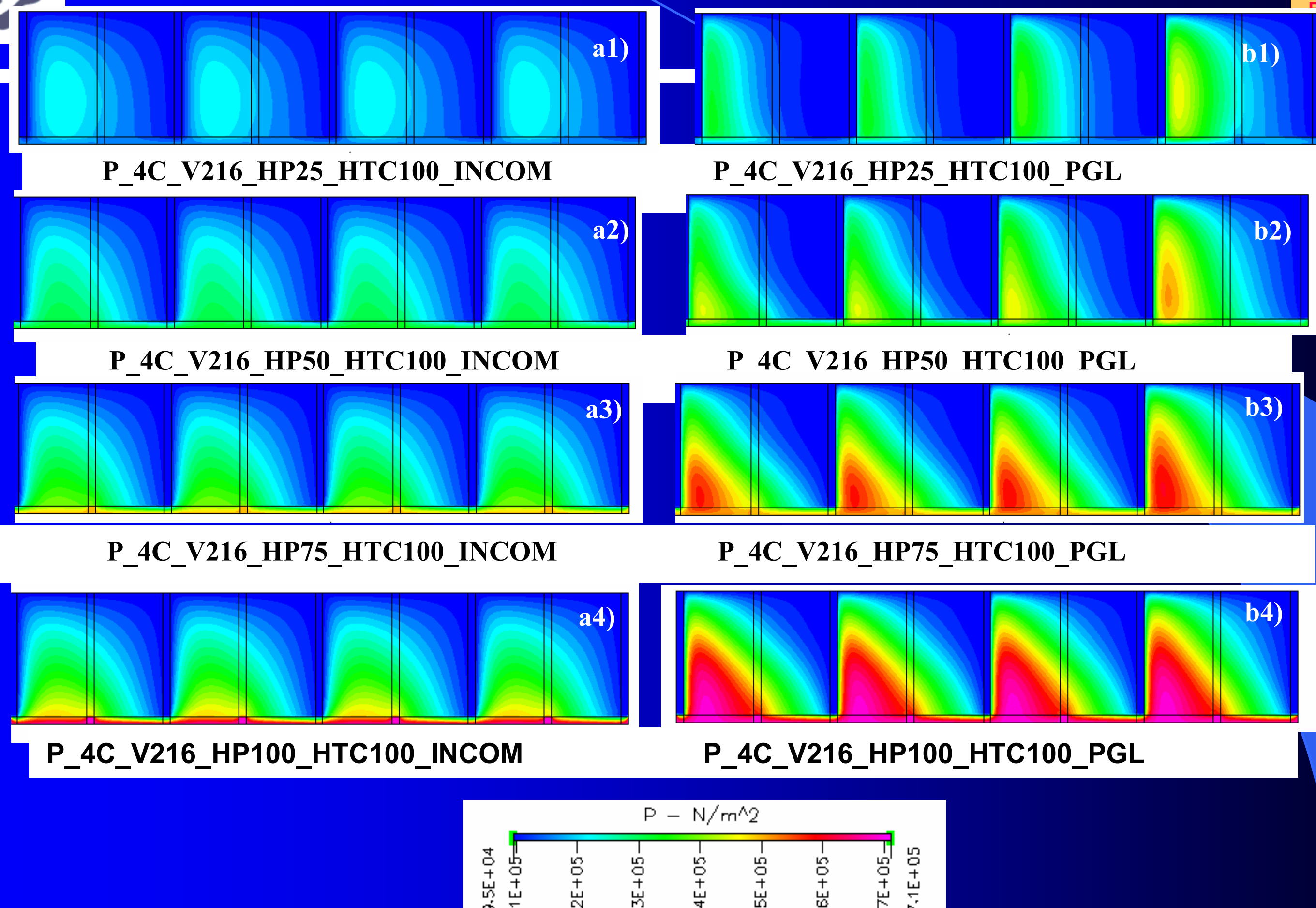

Comparison between pressure magnitude development under the fingers when incompressible(ρ ,μ=const) and perfect gas laws are used.

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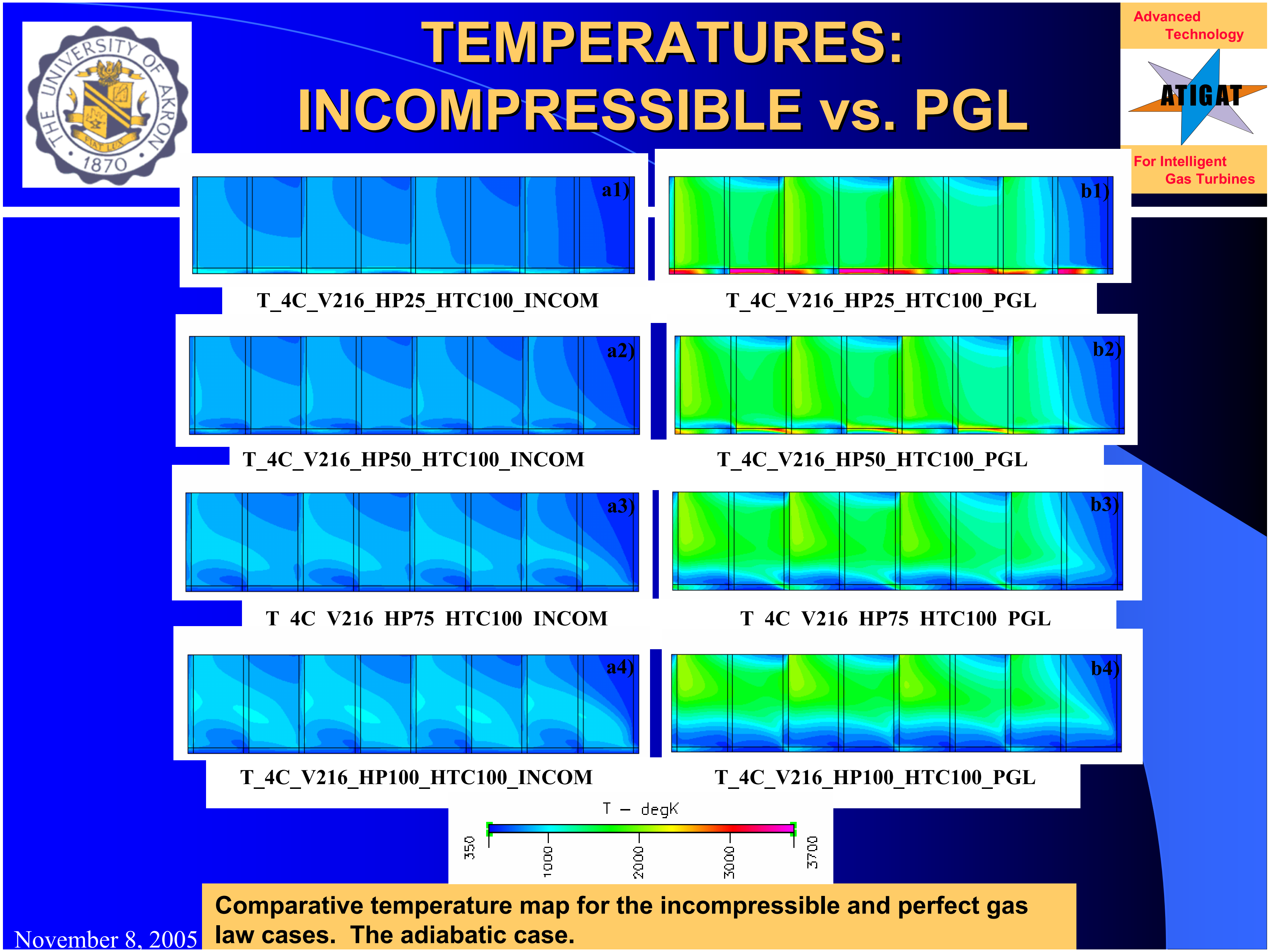

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TEMPERATURES:
INCOMPRESSIBLE vs. PGL
a1)
T_4C_V216_HP25_HTC100_INCOM
b1)
T_4C_V216_HP25_HTC100_PGL
a2)
T_4C_V216_HP50_HTC100_INCOM
b2)
T_4C_V216_HP50_HTC100_PGL
a3)
T_4C_V216_HP75_HTC100_INCOM
b3)
T_4C_V216_HP75_HTC100_PGL
a4)
T_4C_V216_HP100_HTC100_INCOM
b4)
T_4C_V216_HP100_HTC100_PGL
T – degK
350
1000
2000
3000
3700
Comparative temperature map for the incompressible and perfect gas law cases. The adiabatic case.
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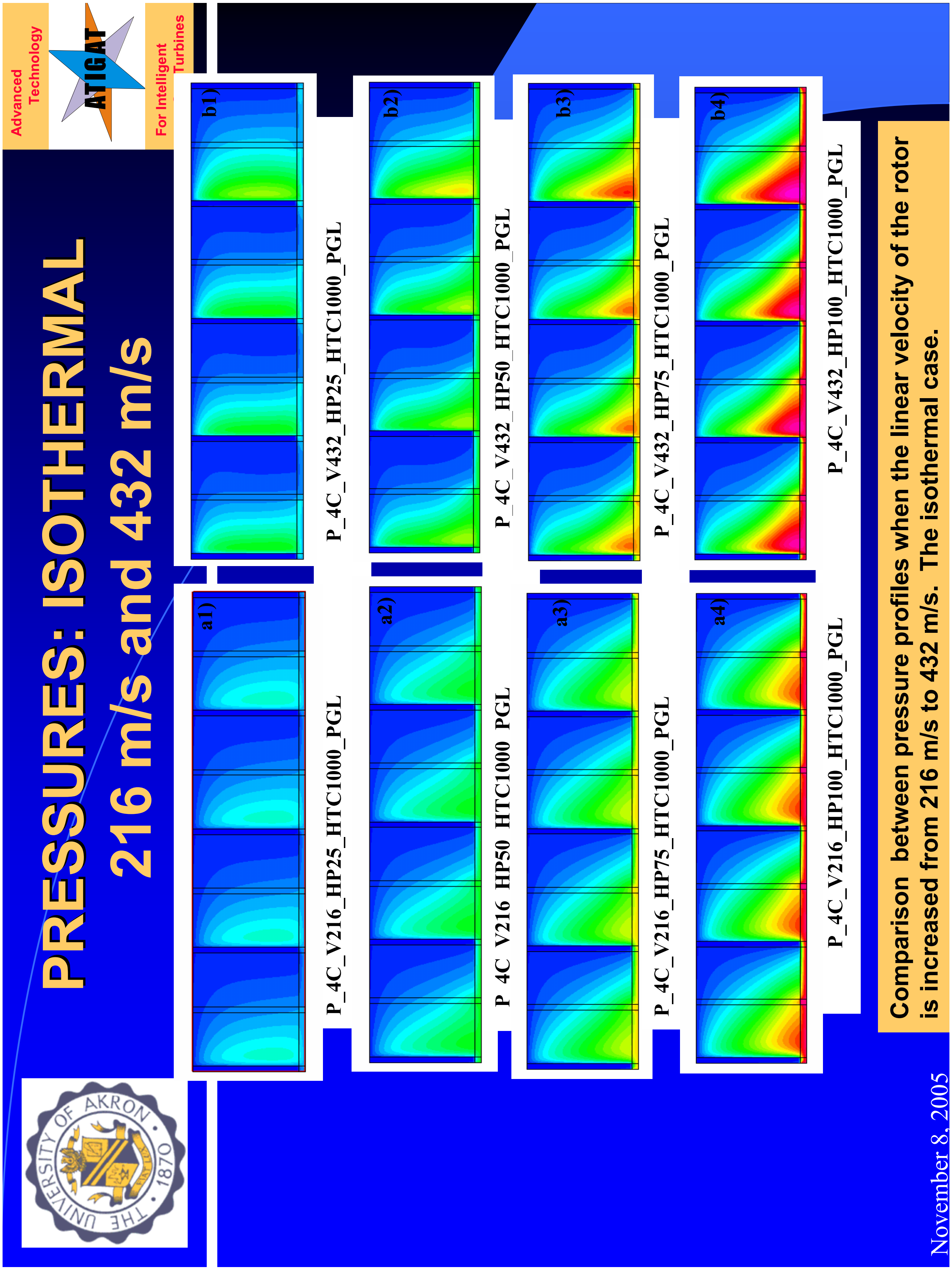

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PRESSURES: ISOTHERMAL
216 m/s and 432 m/s
a1)
P_4C_V216_HP25_HTC1000_PGL
b1)
P_4C_V432_HP25_HTC1000_PGL
a2)
P_4C_V216_HP50_HTC1000_PGL
b2)
P_4C_V432_HP50_HTC1000_PGL
a3)
P_4C_V216_HP75_HTC1000_PGL
b3)
P_4C_V432_HP75_HTC1000_PGL
a4)
P_4C_V216_HP100_HTC1000_PGL
b4)
P_4C_V432_HP100_HTC1000_PGL
Comparison between pressure profiles when the linear velocity of the rotor is increased from 216 m/s to 432 m/s. The isothermal case.
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TEMPERATURES:

ALMOST ISOTHERMAL (1000 W/m²K)
216 m/s and 432 m/s

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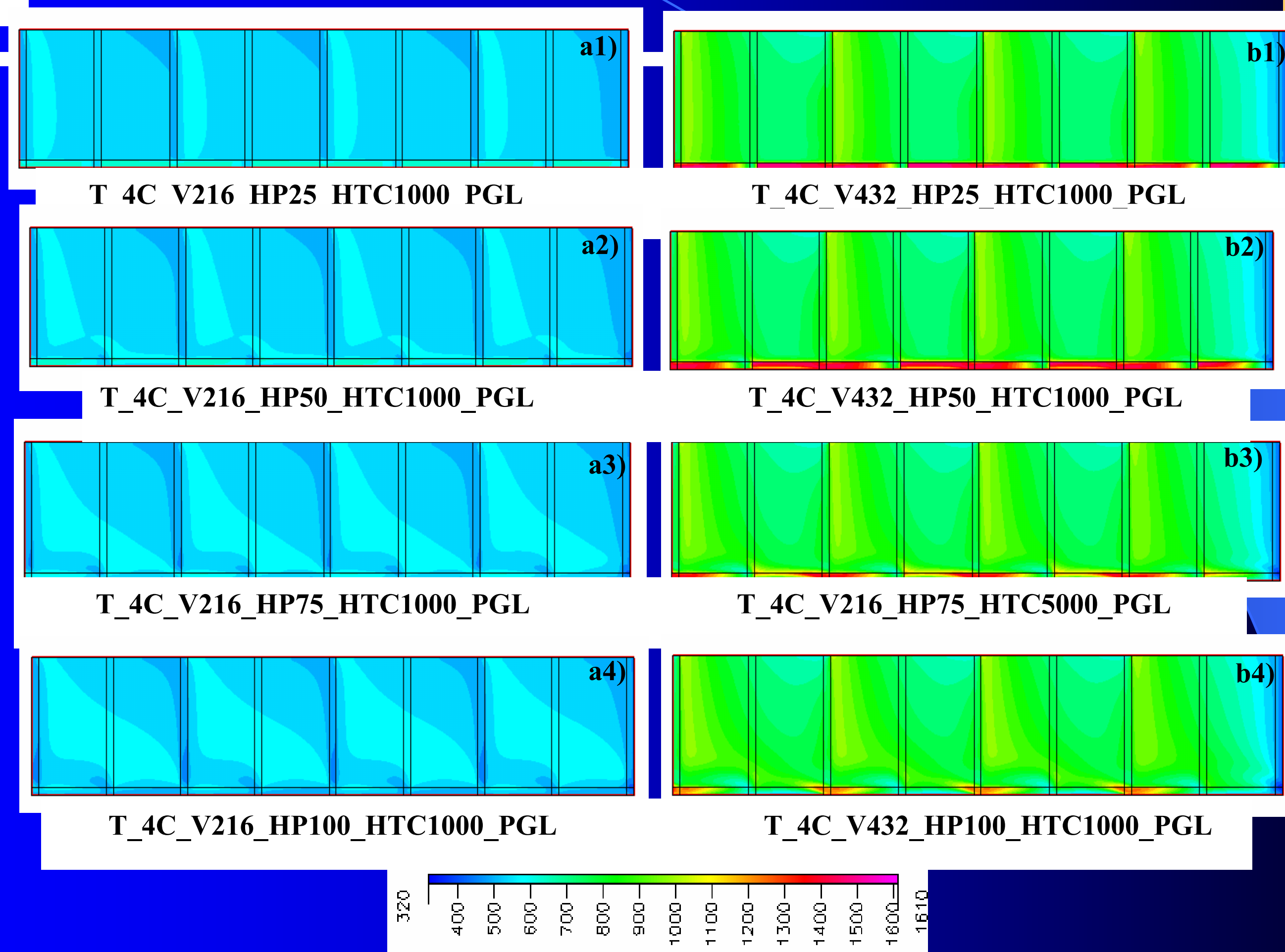

Temperature development when the angular velocity is varied from 216 m/s linear, to 432. The almost isothermal case.

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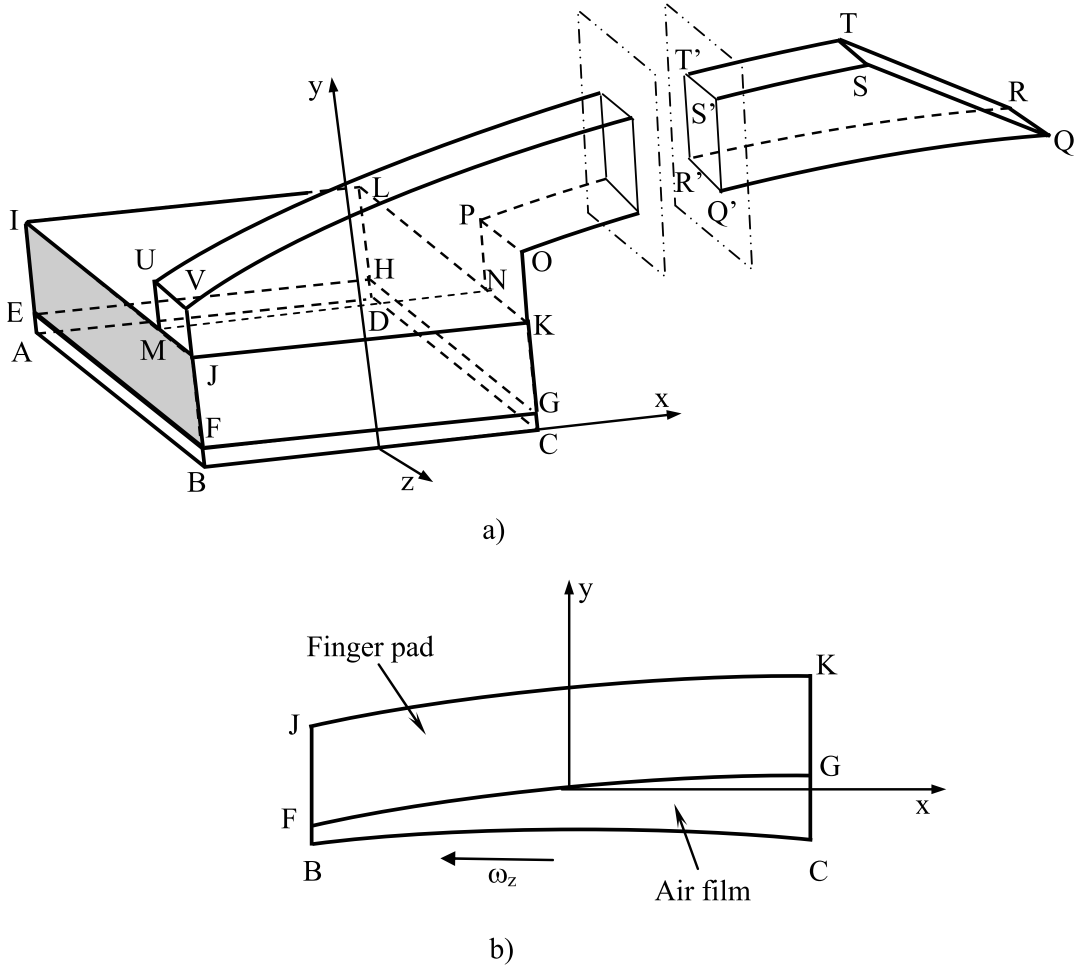
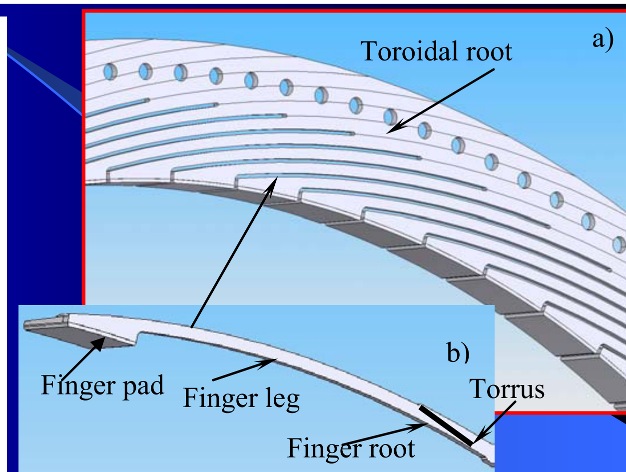
Single Finger Geometry (Solid-Fluid Interaction)





Moving Finger

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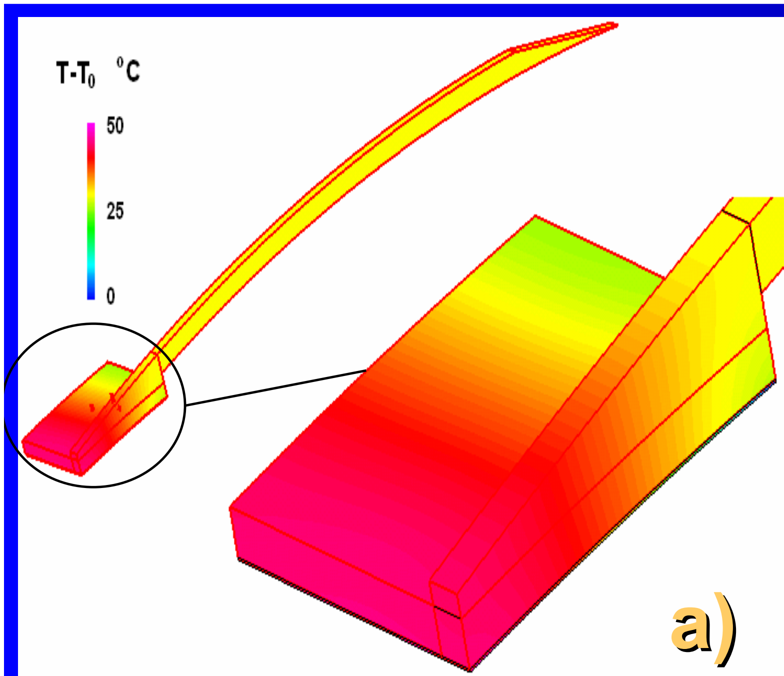

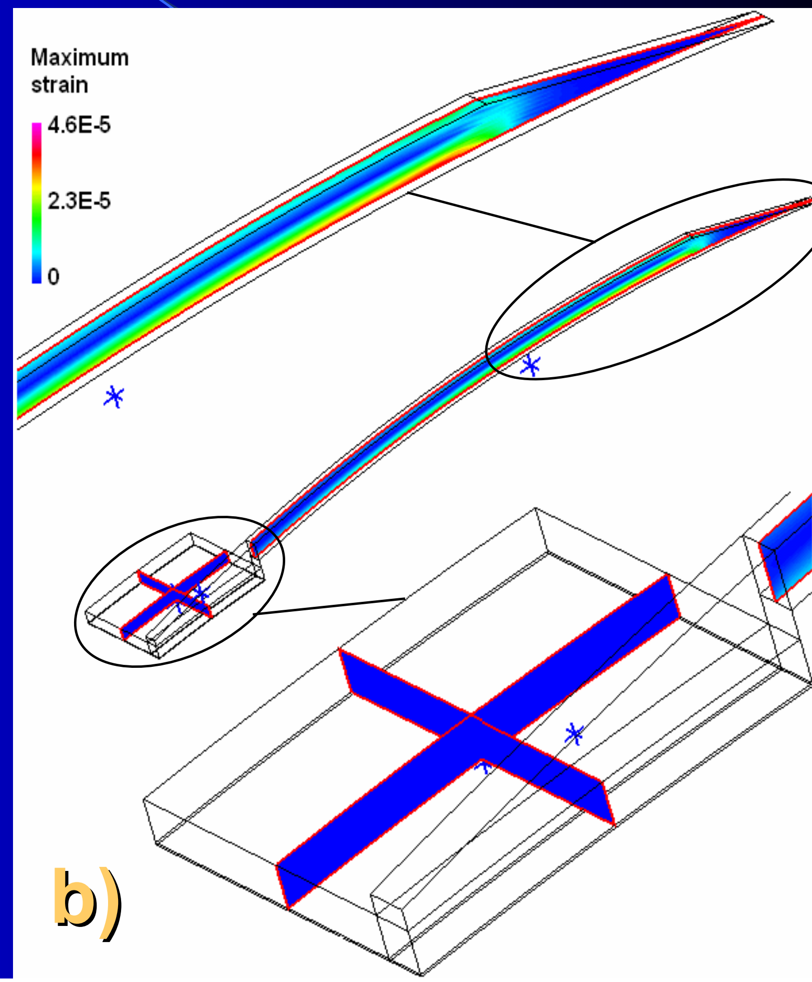

Temperature (a) and strain (b) in the finger pad and leg. Adiabatic conditions on finger and rotor surfaces.

Rotor rotates at 30000 rpm

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Lift of the pad central section with angular velocity

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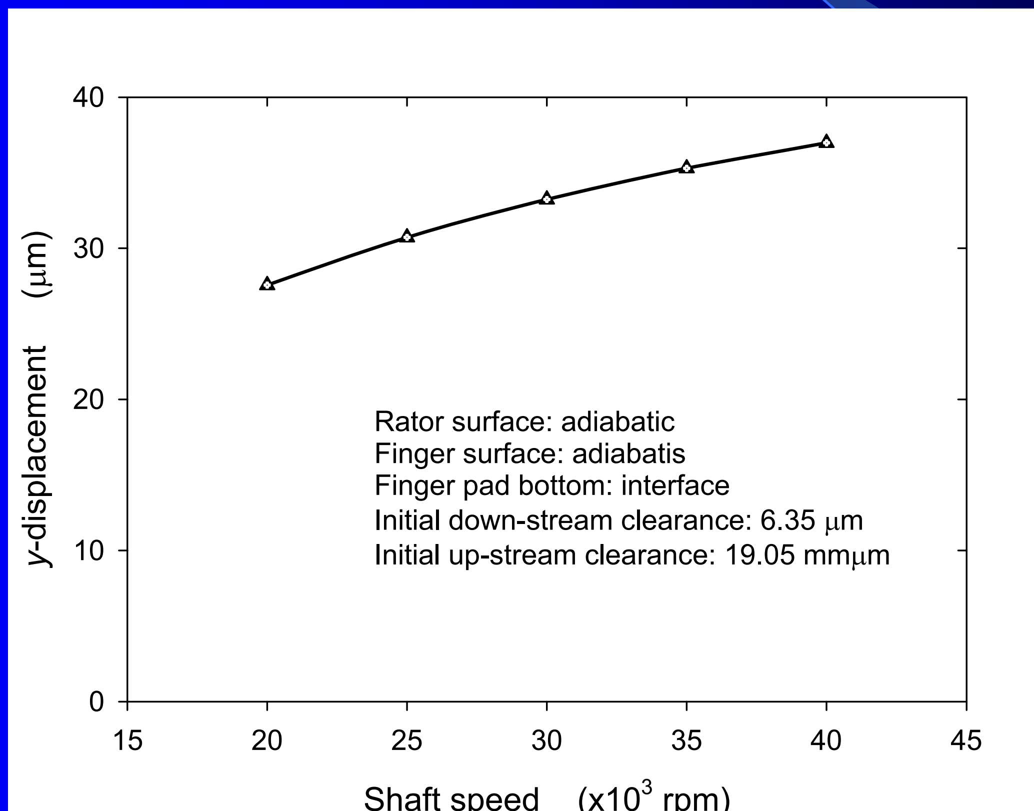

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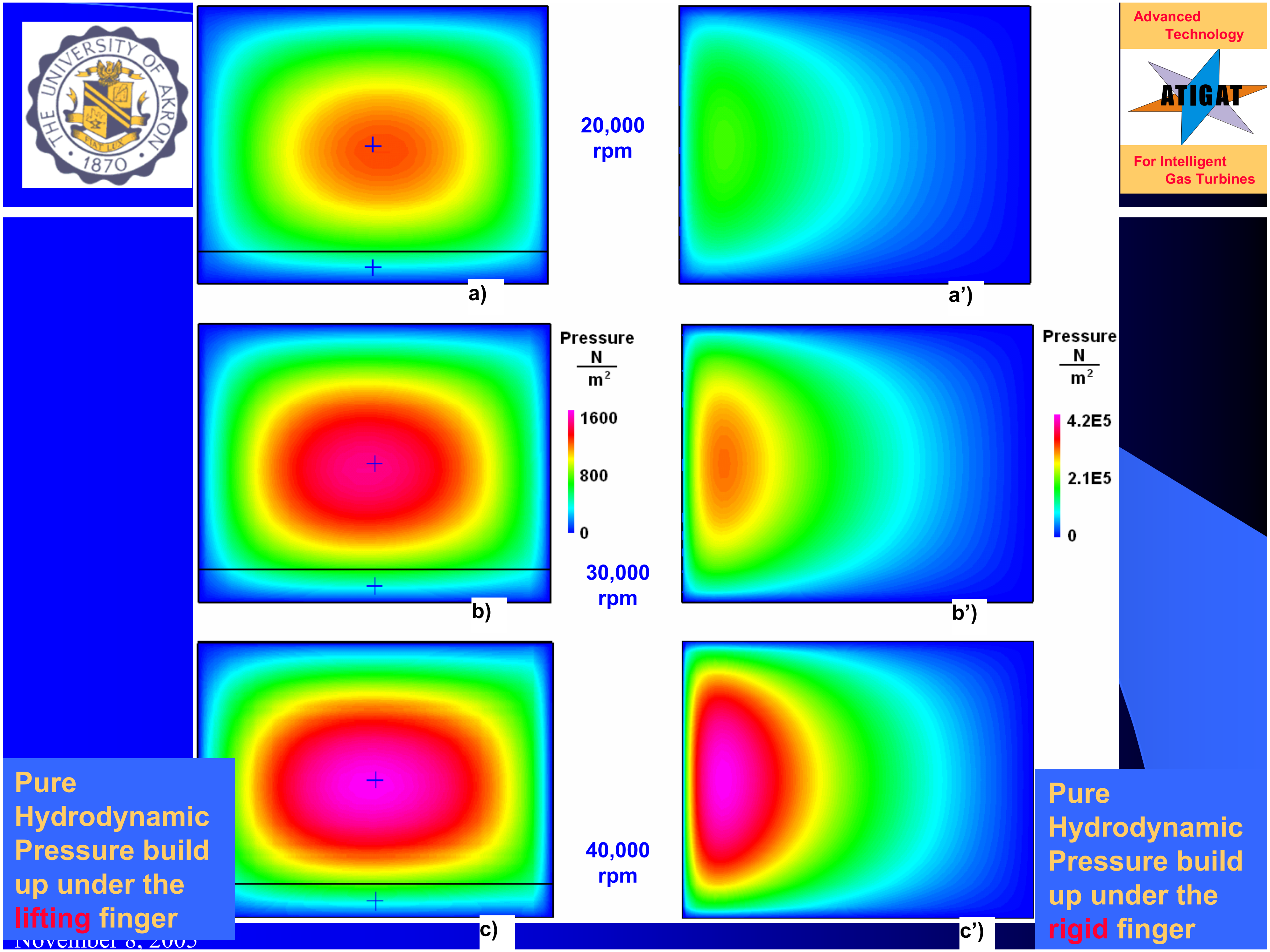

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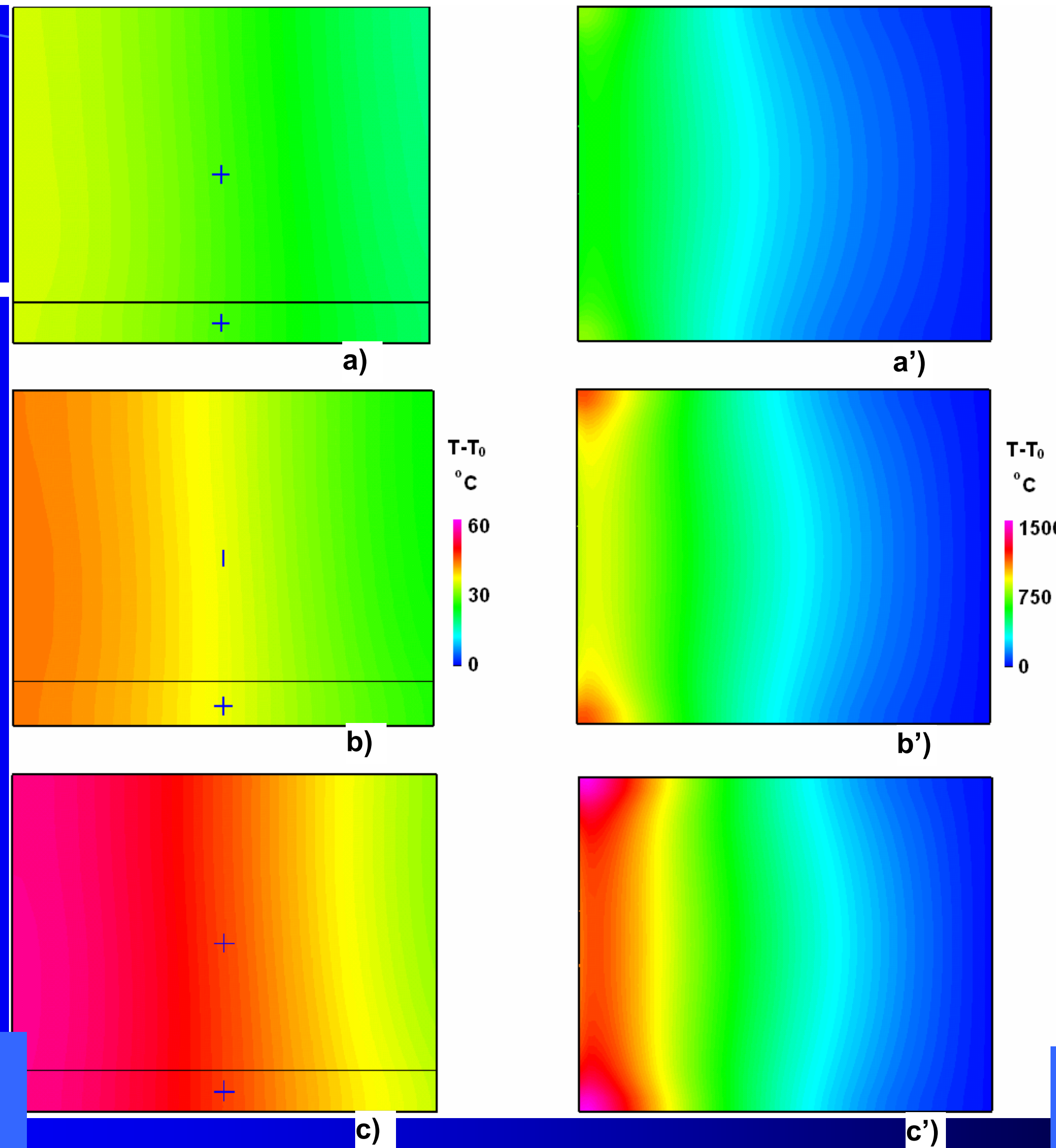
20,000 rpm
a)
a')
Pressure
N/m2
1600
800
0
30,000 rpm
b)
Pressure
N/m2
4.2E5
2.1E5
0
b')
40,000 rpm
c)
c')
Pure Hydrodynamic Pressure build up under the lifting finger
Pure Hydrodynamic Pressure build up under the rigid finger



Pure Hydrodynamic Temperature build up under the lifting finger

Rtor and pad upper surface are adiabatic. The pad itself allows 3-D energy transfer

Pure Hydrodynamic Temperature build up under the rigid finger

Comparison between adiabatic and thermal conditions

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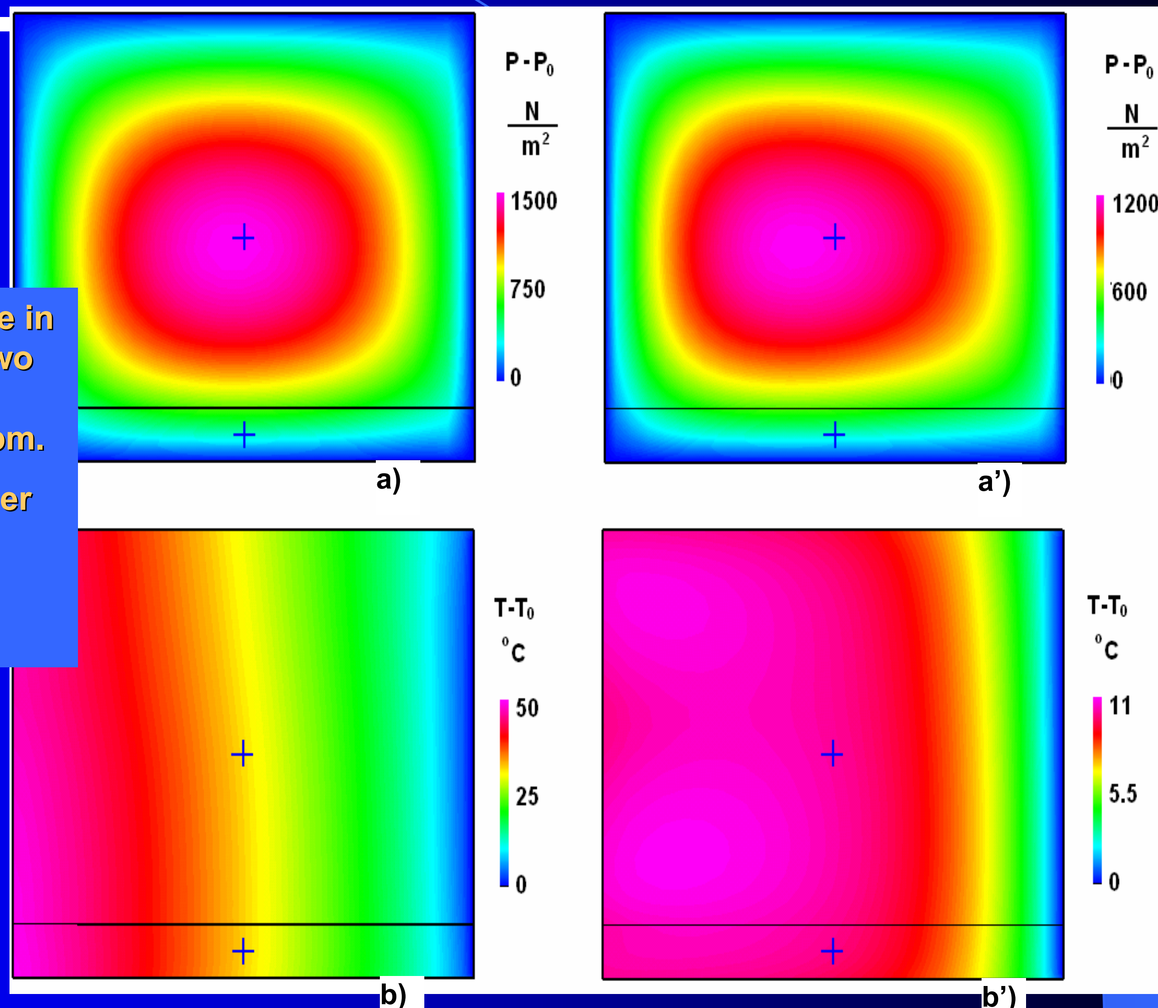

The pressure and temperature in the center of the air film for two thermal boundary conditions with rotor rotating at 30000 rpm.

(a, b) Adiabatic rotor and finger surfaces.

(a', b') Isothermal rotor and finger surfaces at T_0.

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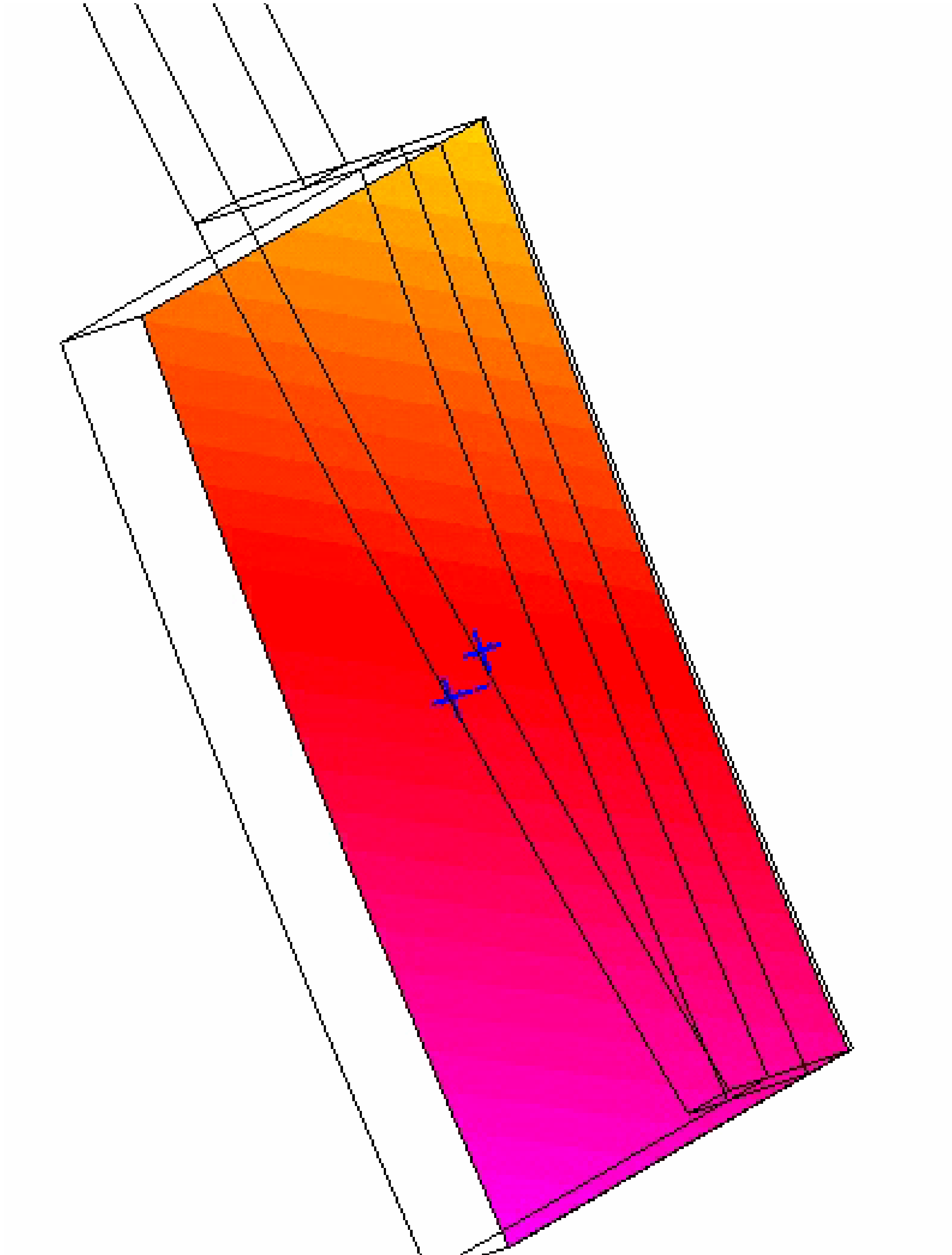

EQUIVALENT DYNAMIC MODEL

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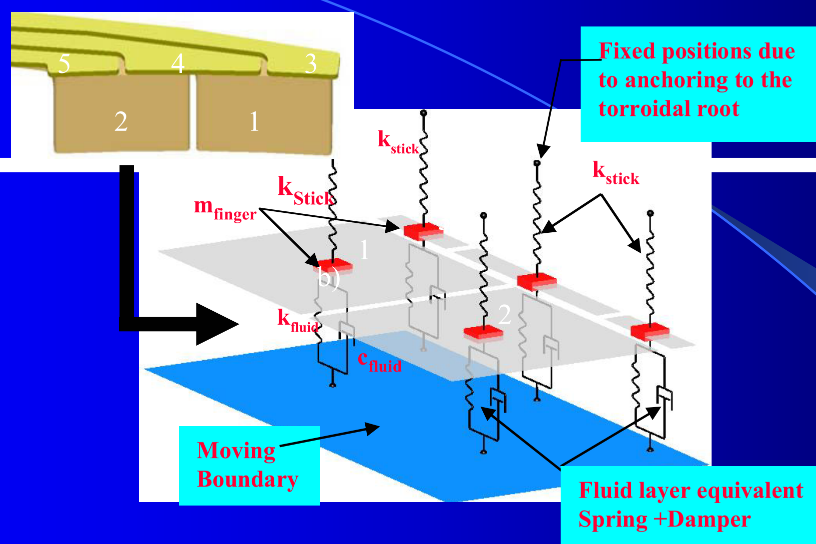
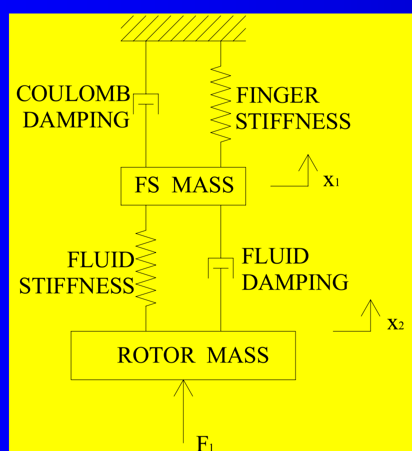
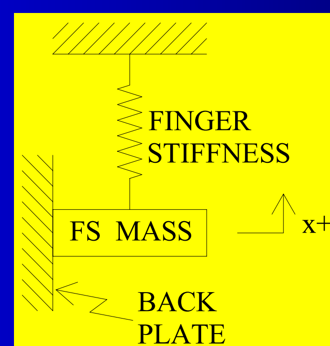


a)



b)



c)

Solid model and Equivalent Spring-Mass-Spring/Damper representation for use in the equation of motion simulation

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FINGER DYNAMICS-2
Free Vibration
Stiffness is varied

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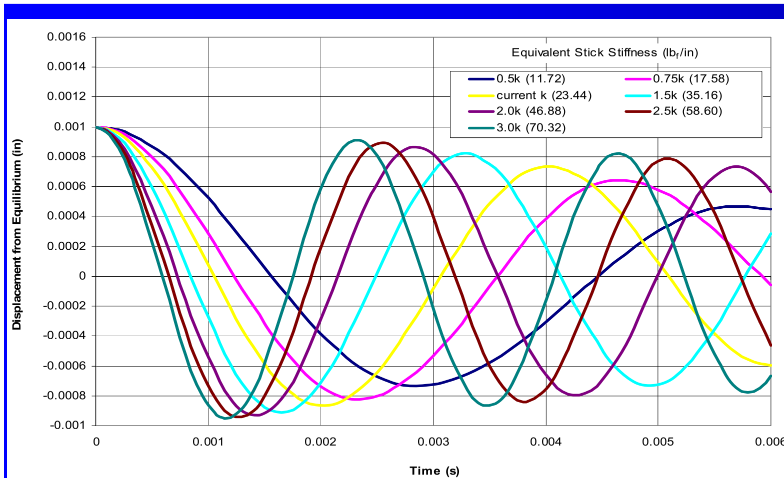
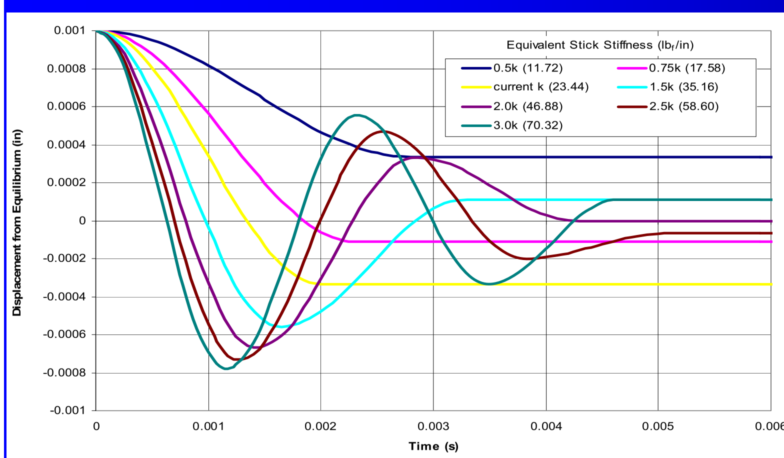
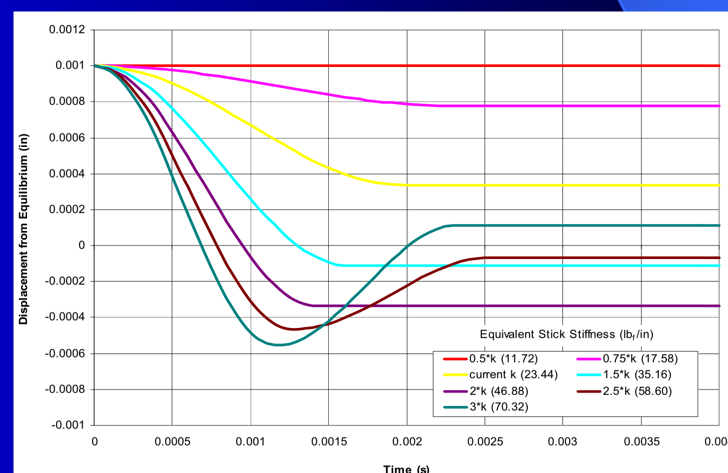


a)

Finger assembly free vibration when k_{SEqu} is varied: a) Δp_C=6.9 kPa (1psi); b) Δp_C=34.5 kPa (5psi); c) Δp_C=69 kPa (10psi);



b)



c)

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FINGER DYNAMICS

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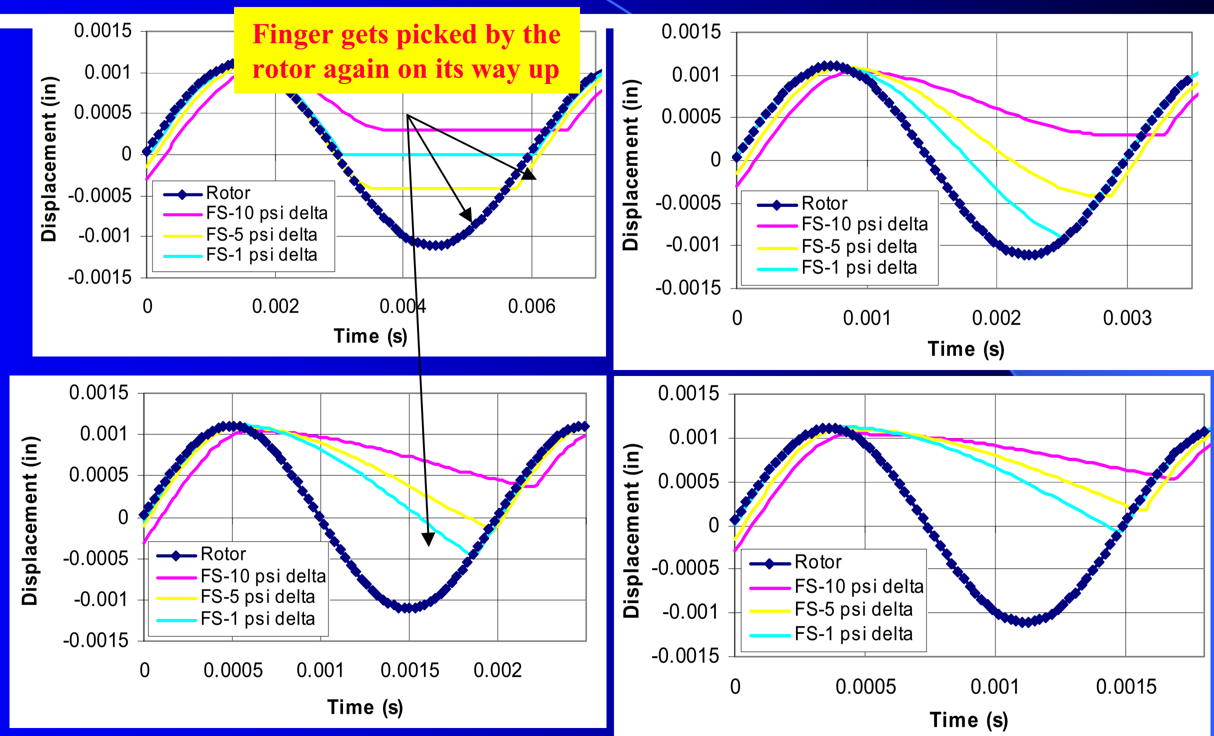

Finger following the rotor when Coulomb damping force and rotor angular velocity is varied. Finger stiffness is $k_{SEqu} = 3.58\frac{N}{m}(20.44\frac{lbf}{in});$

a) 10,000 rpm(108 m/s); b) 20,000 rpm (216 m/s); c) 30,000 rpm (324 m/s); d) 40,000 rpm (432 m/s)

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SOME EXPERIMENTAL WORK

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DIARGAMS OF THE TEST SECTION
Overall inatallation
Electric, Oil and Air Circuits

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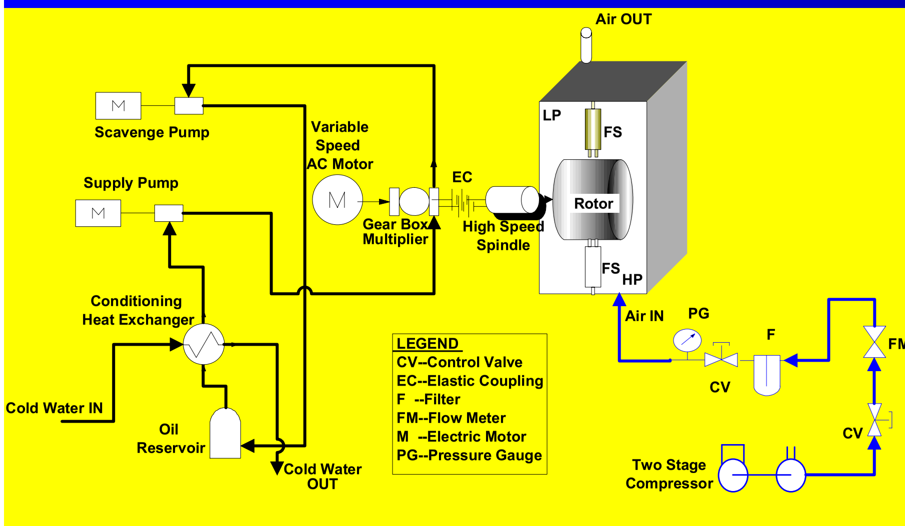

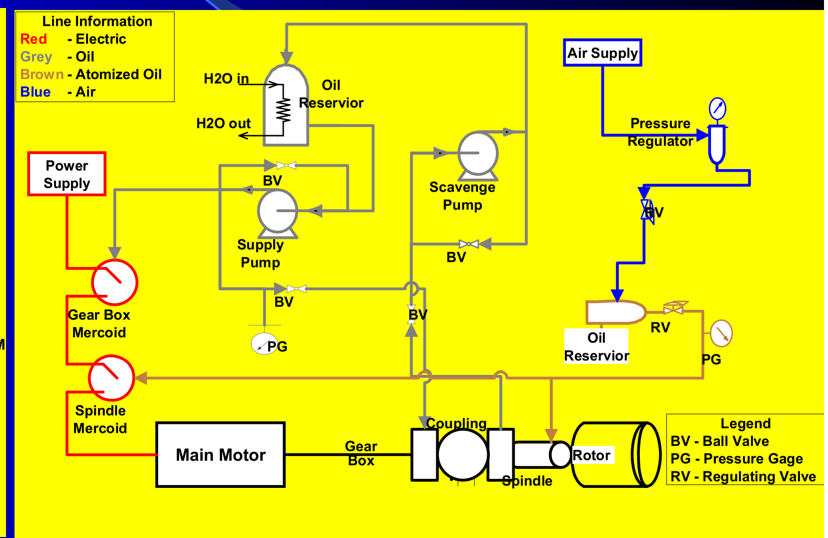

Overall inatallation

Electric, Oil and Air Circuits

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EXPERIMENTAL INSTALLATION

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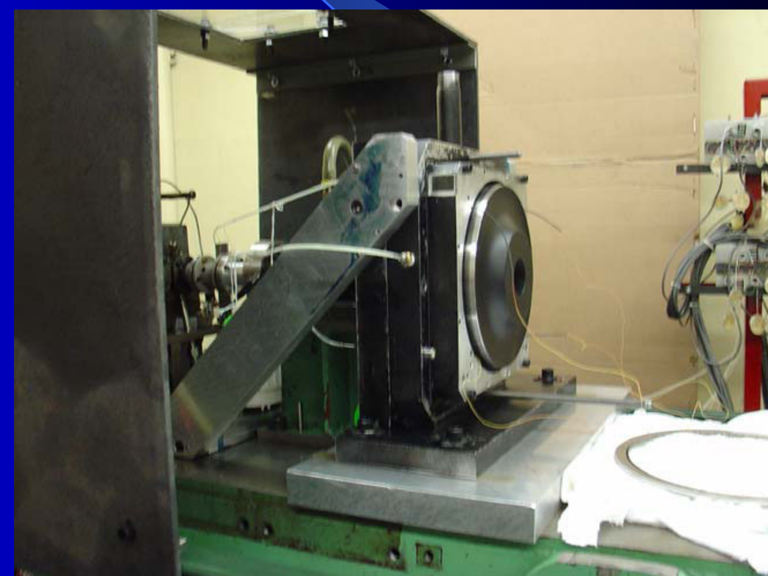
ATIGAT

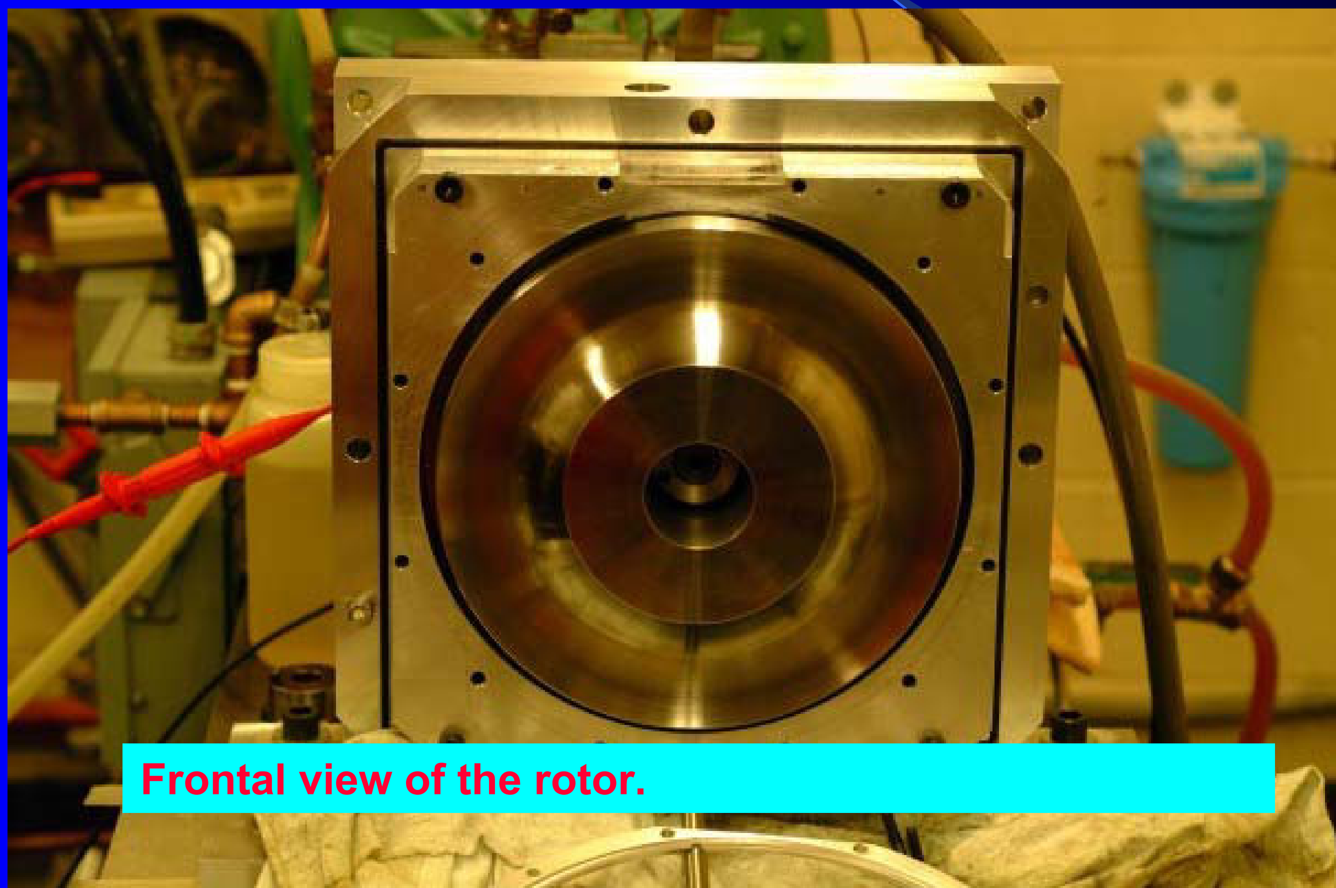
Drive Train



Rotor Section

November 8, 2005

ROTOR: FRONTAL VIEW



Frontal view of the rotor.

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ROTOR SURFACE

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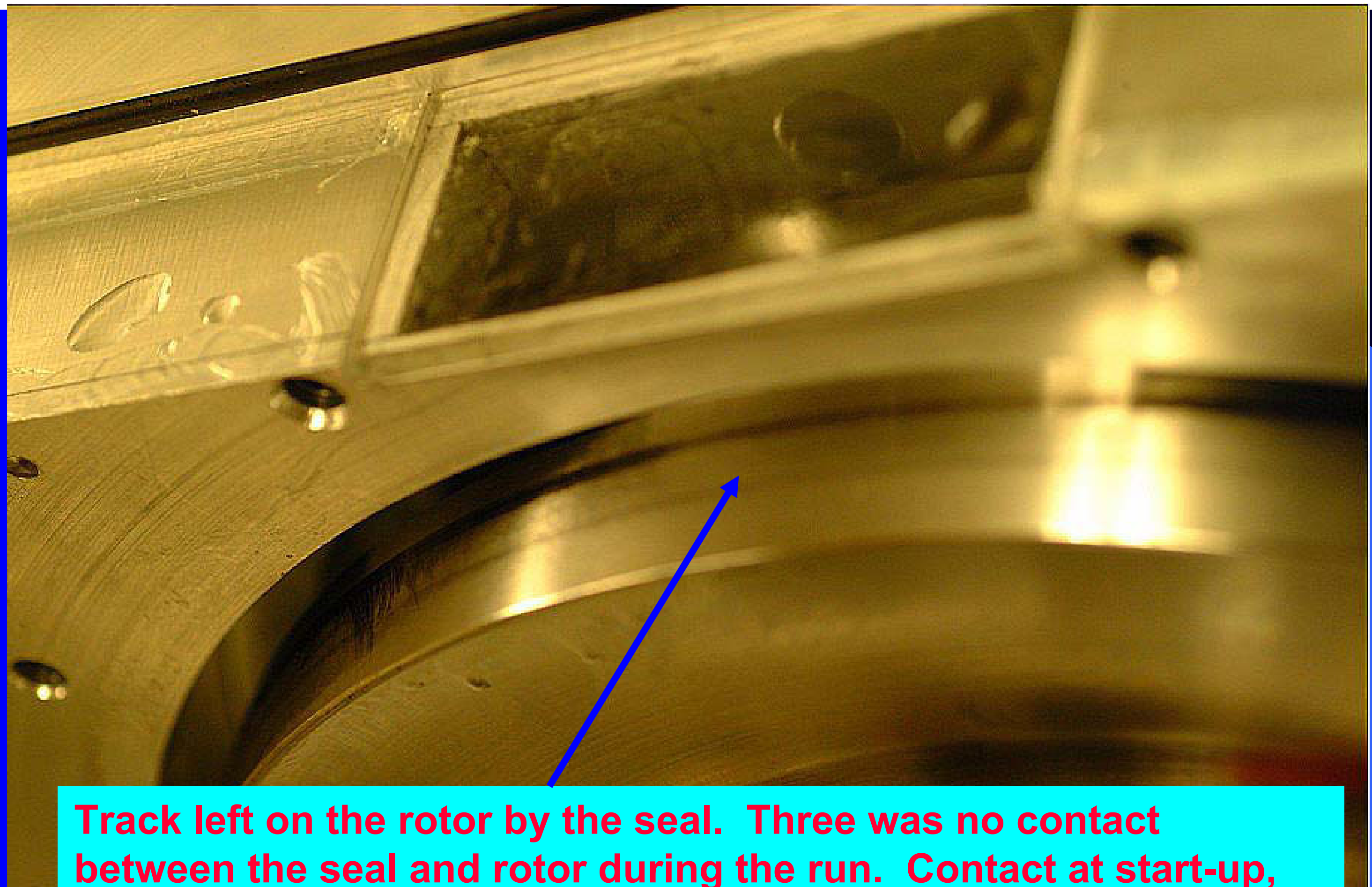
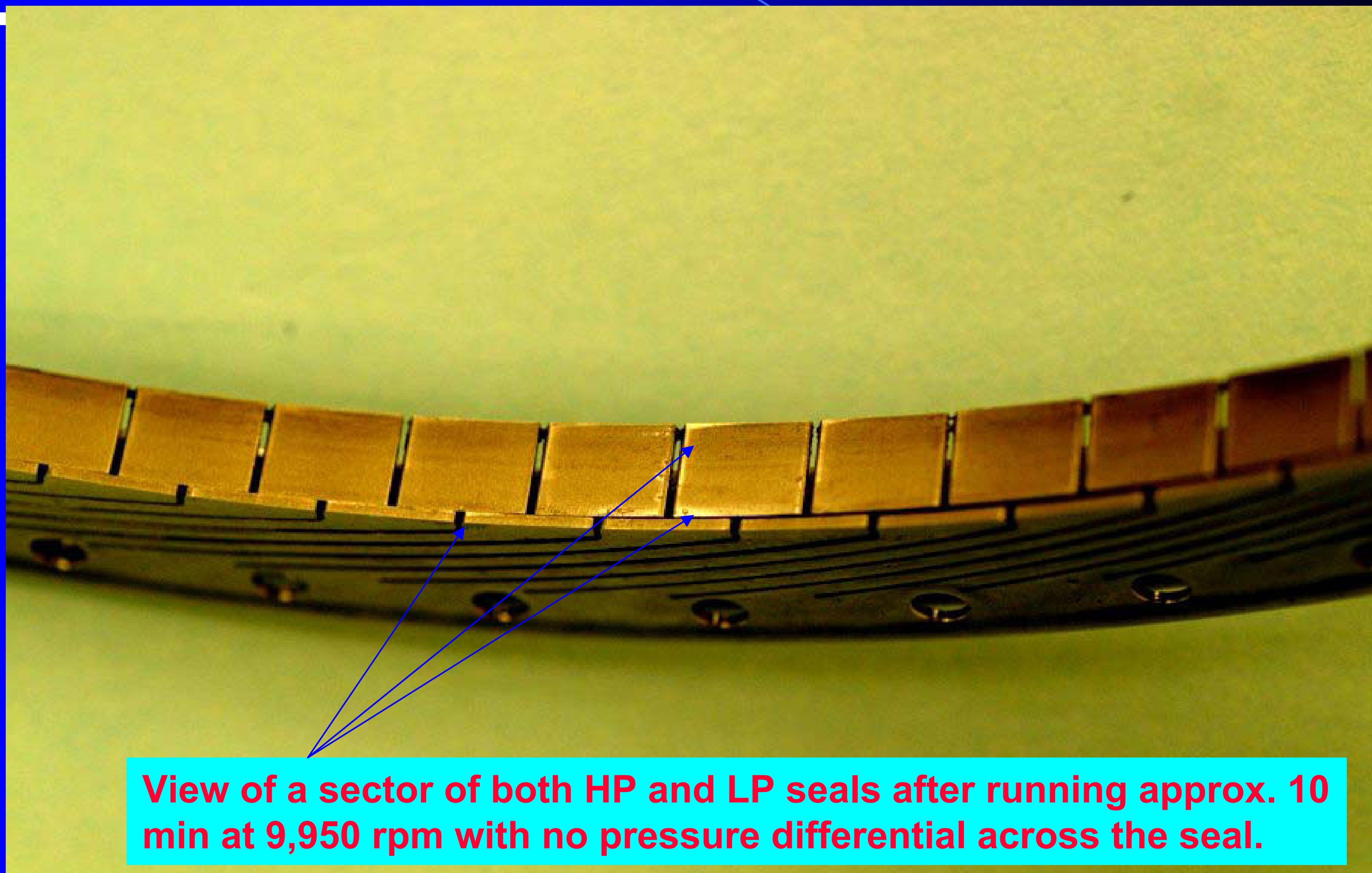
For Intelligent Gas Turbines



Track left on the rotor by the seal. Three was no contact between the seal and rotor during the run. Contact at start-up, liftoff-no contact, contact again at coast-down

November 8,

FINGERS' PAD UNDERSURFACE



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FINGERS' PAD UNDERSURFACE DETAILS

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Enlarged view of two pads after the 10 min. run

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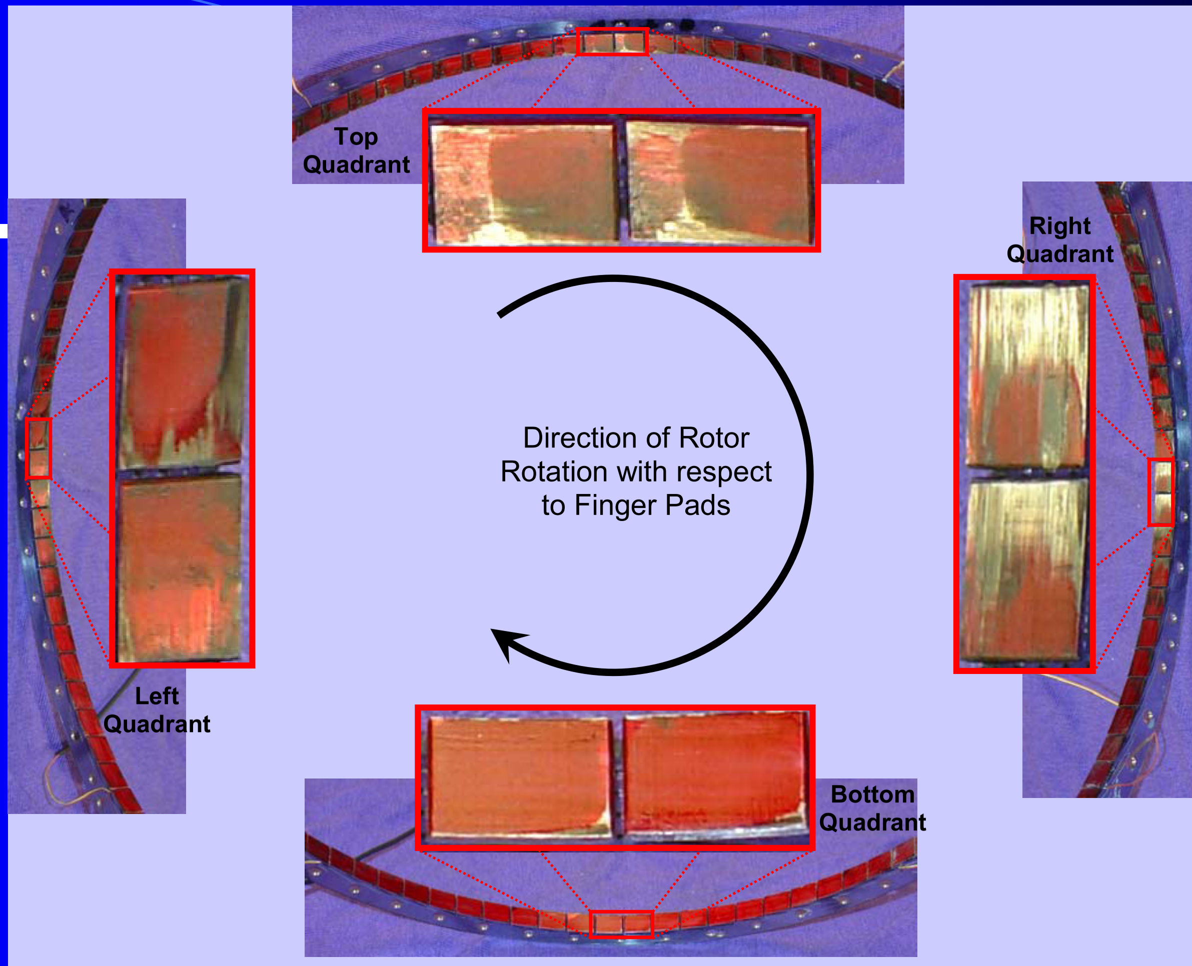

LP Finger Underside Pads Surface Showing Ink Wear Marks after a Total Run Time of 97 min at a nominal speed of 9,950 rpm; This included 4 start-ups and 4 coast-downs. Seal Quadrants Positioned as Viewed from the Low-Pressure Side

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LEAKAGE FLOW PERFORMANCE SUPERIMPOSED ON ROTATION , TEMPERATURE AND PRESSURE DIFFERENTIAL

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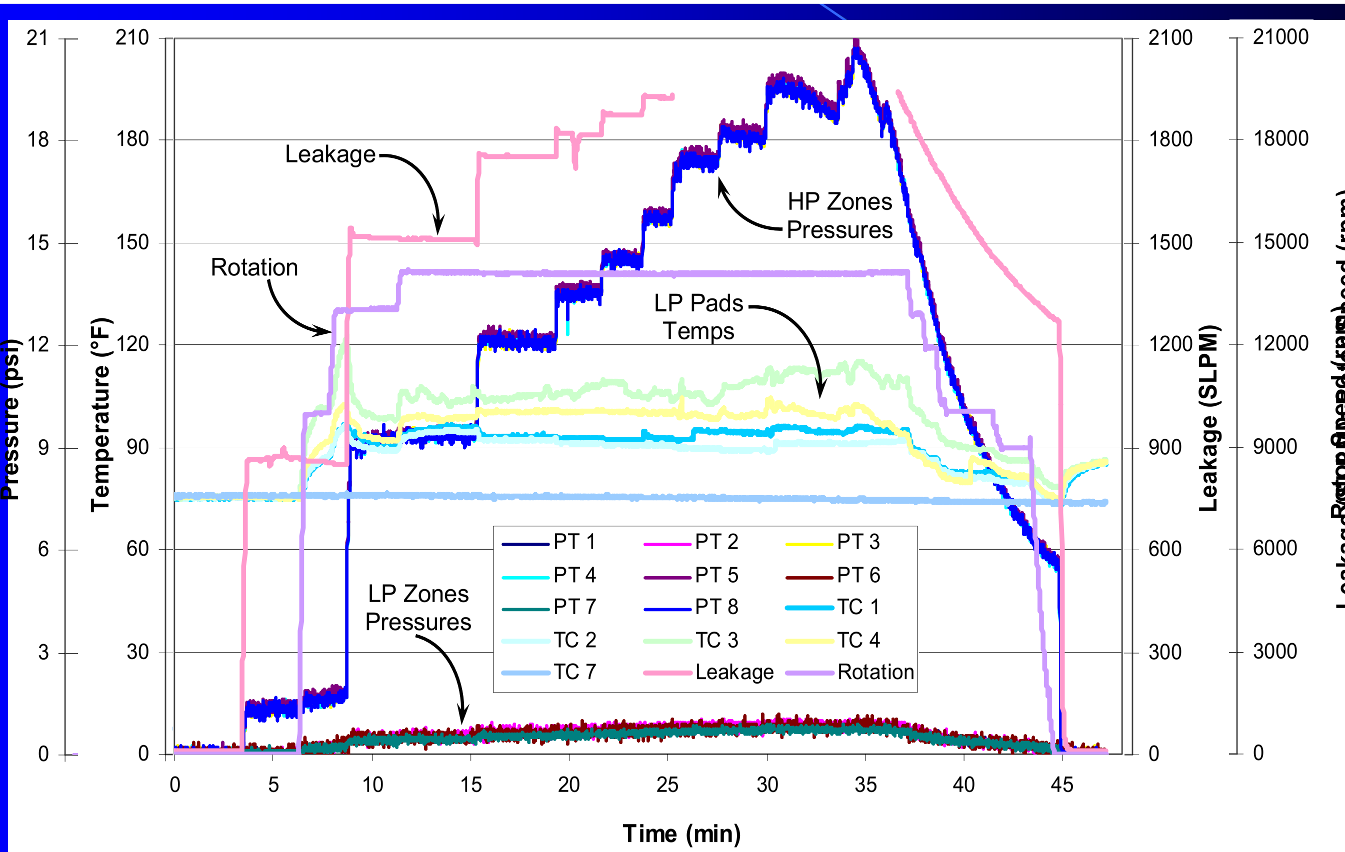

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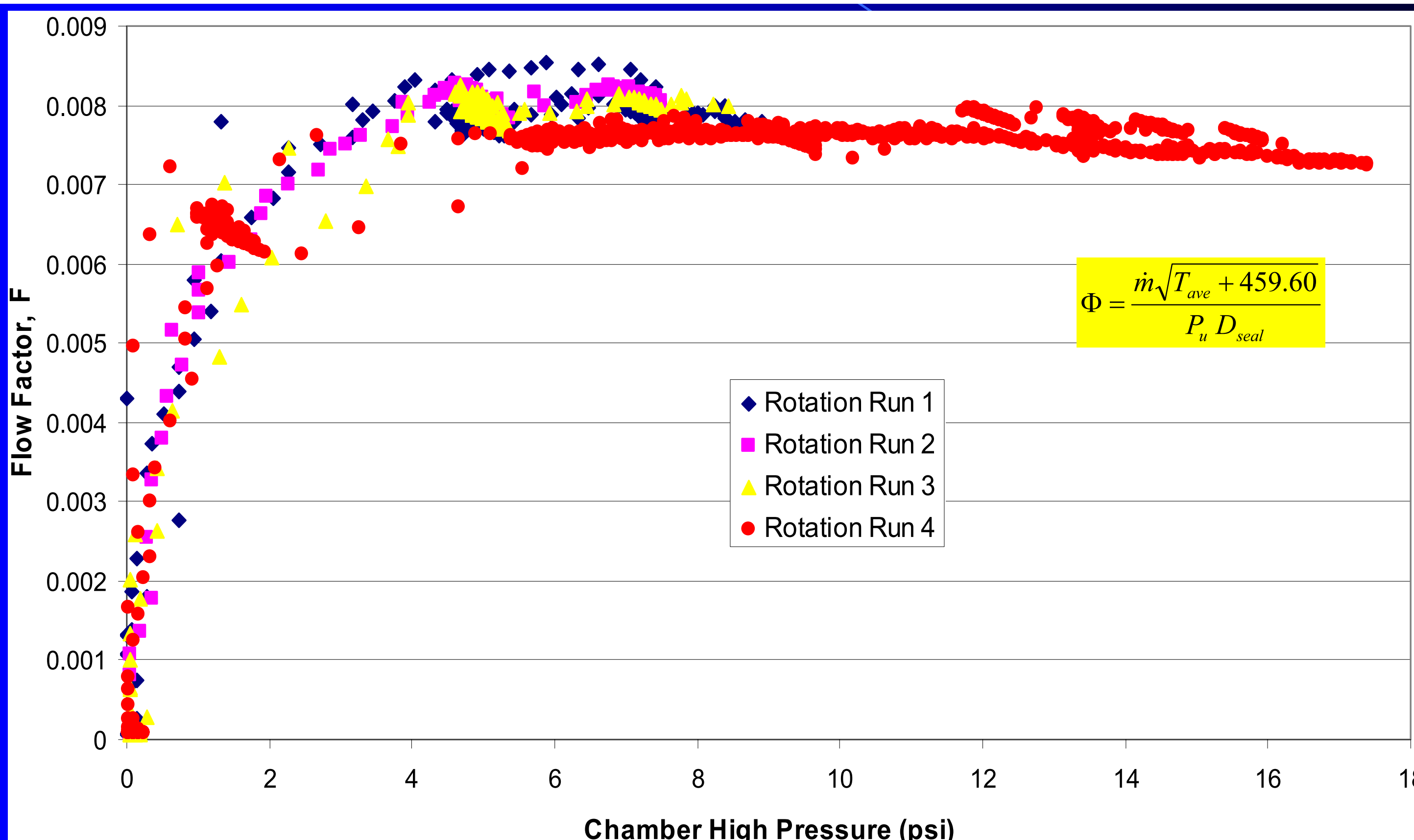
FLOW FACTOR vs. PRESSURE DIFFERENTIAL

Advanced Technology For Intelligent Gas Turbines



November 8, 2005

GAS TURBINE ENGINE CARBON OIL SEALS COMPUTERIZED ASSEMBLY

Robert Lee
Axiam Incorporated
Gloucester, Massachusetts

AXIAM
INCORPORATED

Gas Turbine Engine
Carbon Oil Seals
Computerized Assembly

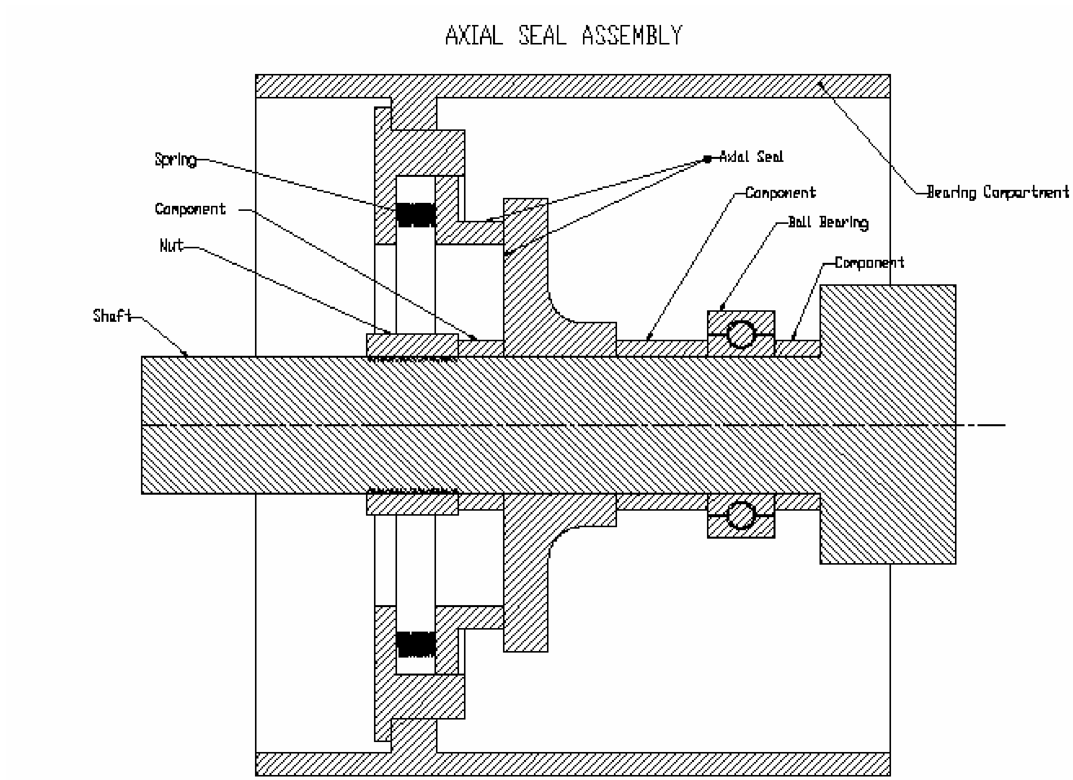
AXIAM
BEARING & SEAL
STACK ASSEMBLY
SOFTWARE AND PROCEDURES

AXIAM INCORPORATED

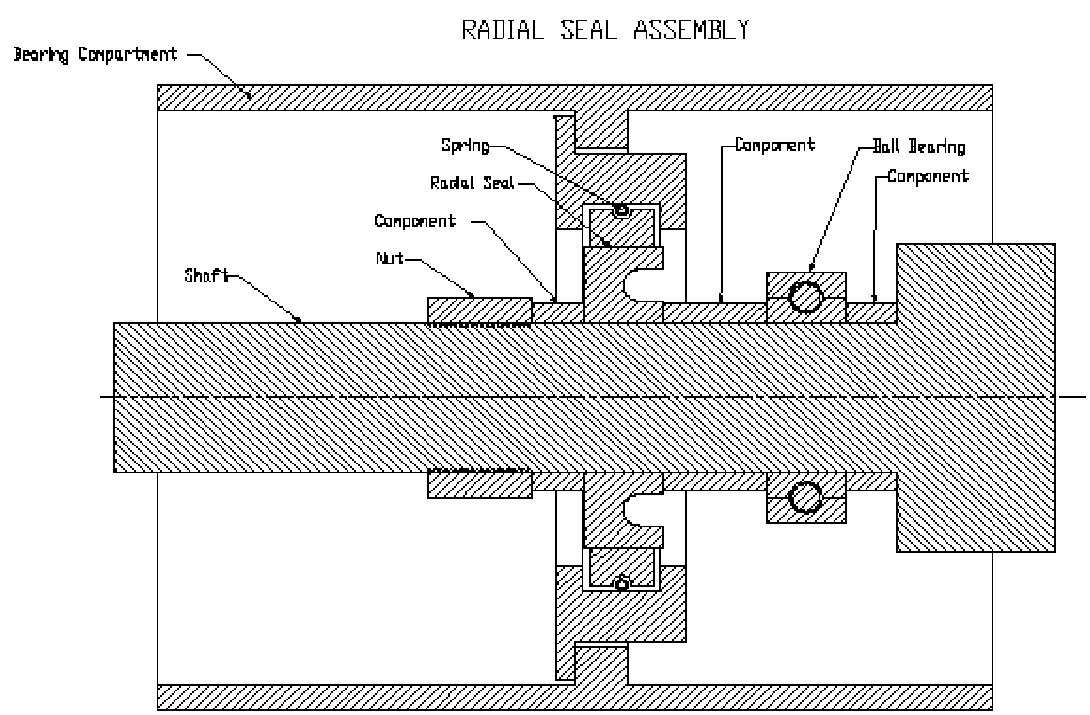
GOALS

1) REPEATABLE ASSEMBLY PROCESS
2) ACCURATE ASSEMBLY PROCESS
3) MINIMIZE SEAL RUNOUT
4) DESIGN TO ENGINE CENTERLINE OF ROTATION, IE” BEARINGS

Axial Seal Assembly



Radial Seal Assembly



GAS TURBINE SEAL LEAKS

- POTENTIAL PROBLEMS CAUSING OIL LEAKS

- 1) INCORRECT PART DATUMS
- 2) MISSING PART GEOMETRY
- 3) ENGINE VIBRATION
- 4) SEAL HYSTERESSES
- 5) INCORRECT ASSEMBLY PROCEDURES
- 6) ACCUMULATION OF TOLERANCES

INCORRECT PART DATUMS

In a bearing compartment there are a series of parts when assembled determine the location of the bearing and seal as related to the centerline of rotation.
We see part datums that do not establish A coincident path from the bearing to the seal.

Missing Part Geometry Controls

Part geometry controls missing on drawings:

Concentricity

Roundness

Flatness

Circumferential Waviness

Engine Vibration

High engine vibration can cause severe oil leakage

- Case: Navy EA6B "Prowler"
- Engine: J52-408

Engine vibration level approaching 6Mils

- Low Rotor shafts breaking due to oil coking

Seal Hysteresis

The inability of the seal to respond fast enough to the rotating element

Radial Seal: Sensitive to housing air pressure
Sensitive to seal runout ?

Axial Seal: Very sensitive to seal perpendicularity to shaft

Incorrect Assembly Procedures

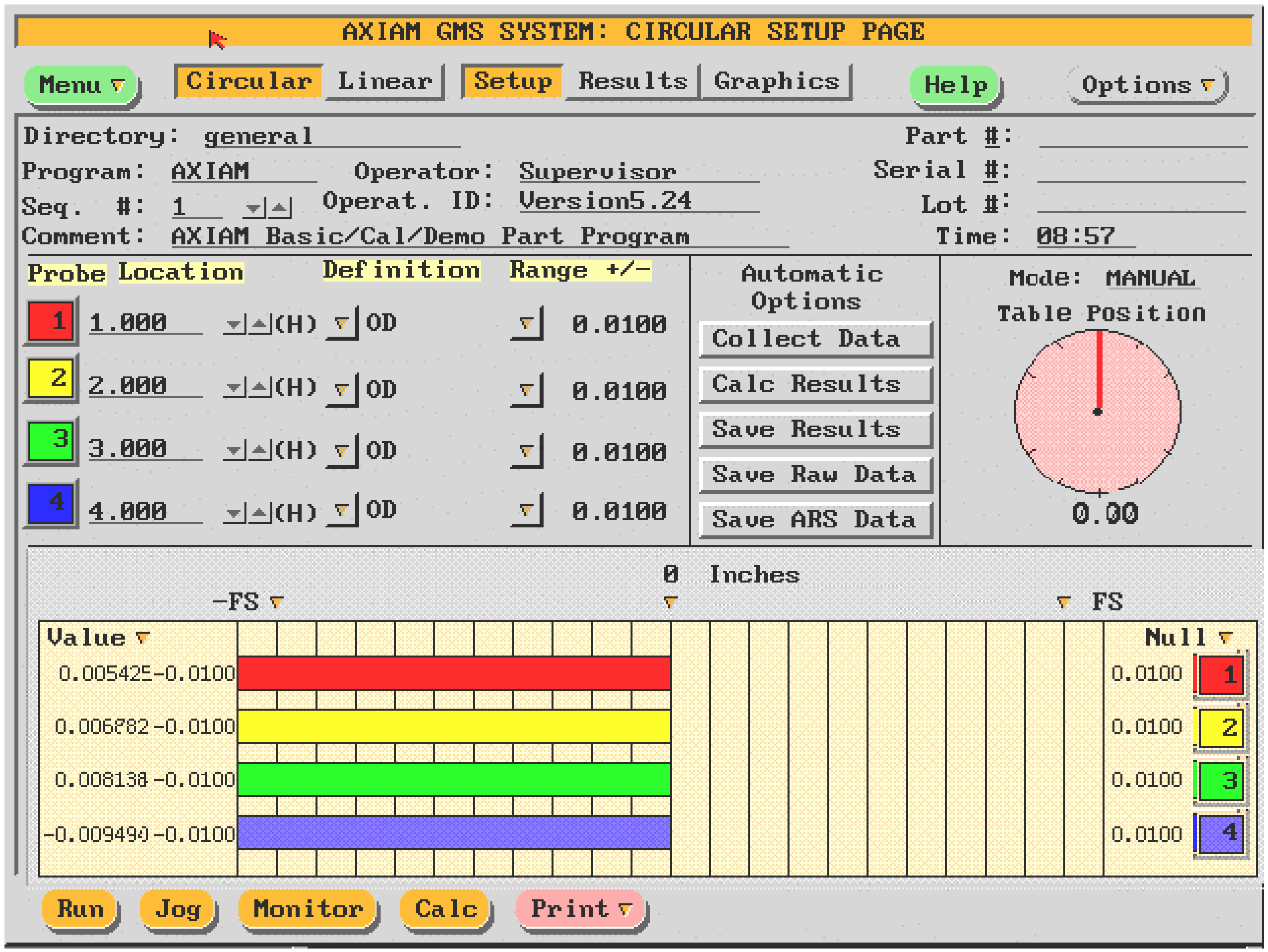
Parts not fully seated

Parts heated or cooled to incorrect temperature

Part fits are incorrect

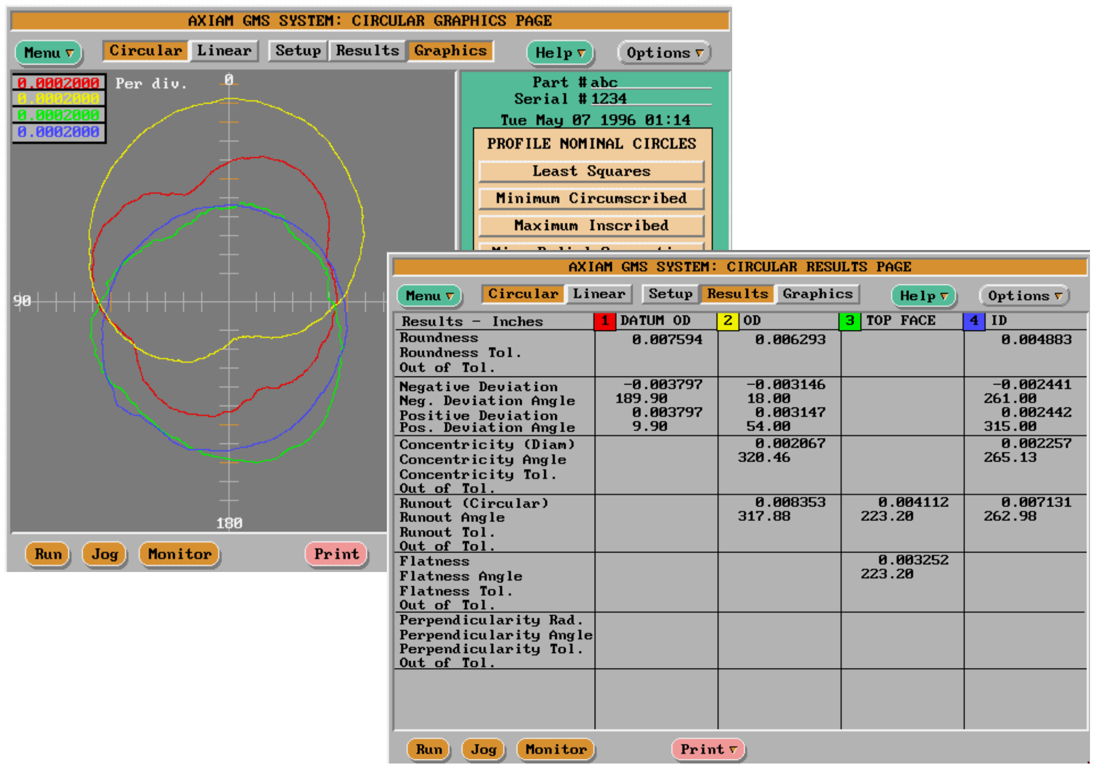
Not being aware that assembly procedures are sometimes time sensitive

GMS-4000 Software Part Inspection Setup



GMS-4000 Output Page

GMS 4000^{TM} Software Measurements



Rotor Output Sheet

```
Program: 8thspcr     Operator:                      Part #: 773168
Seq.  #: 1        Operator ID:                    Serial #: RG5695
Comment: Fwd End Up                                    Run #: 3
Date Data Collected 11/17/98 12:34
  Table rotation CW.
Date Tue Nov 17 1998                                  Time: 12:35
```

Probe Configuration	#1 RED OD	#2 Yellow TOP FACE	#3 Green DATUM OD	#4 Blue DATUM RF
Height	2.570000	2.670000	0.100000	0.000000
Angle	0.000000	0.000000	0.000000	0.000000
Radius	7.750000	7.650000	7.710000	7.610000
Range	0.0200	0.0100	0.0200	0.0100
Waviness Filter	50	50	50	50
Centering Method	LSC	LSC	LSC	LSC
Results - Inches				
Roundness	0.024036		0.025814	
Roundness Tolerance				
Out of Tolerance				
Negative Deviation	-0.012968		-0.013560	
Neg. Deviation Angle	254.34		245.16	
Positive Deviation	0.011068		0.012254	
Pos. Deviation Angle	337.14		161.28	
Eccentricity (radius)	0.000279			
Eccentricity Angle	146.16			
Eccentricity Tol.				
Out of Tolerence				
Runout (Circular)	0.023888	0.002668		
Runout Angle	156.60	329.04		
Runout Tolerance				
Out of Tolerance				
Flatness		0.002379		0.002841
Flatness Angle		329.04		174.06
Flatness Tolerance				
Out of Tolerance				
Perpendicularity Rad.	0.000279			
Perpendicularity Angle	146.16			
Perpendicularity Tol.				
Out of Tolerance				

Typical CMM Output

Alternet Results Page

Rotor Output Sheet (cont'd)

Program: 8thspcr Operator: Part #: 773168
Seq. #: 1 Operator ID: Serial #: RG5695
Comment: Fwd End Up Run #: 3
D̄ate Data Collected 11/17/98 12:34
:e Tue Nov 17 1998 Time: 12:35

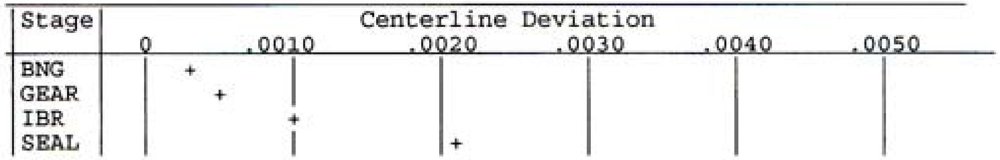
Table rotation CW.
Results - Inches

	PROBE	NOMINAL	ACTUAL	MIN.TOL.	MAX.TOL.	OUT TOL
Biplane Deviation	2	.000000	.000452			
Biplane Deviation Angle	2		37.07			
Center Line Deviation	1	.000000	.000279			
Center Line Dev. at Angle	1		146.16			

AXIAM Bearing Stack Report

```
DIRECTORY                                          Part #    SEAL25ASSY
PROGRAM              25SEAL                      Serial #    NOINDEX
OPERATOR                                            Run #     1
DATE STACKED 05/19/05 11:30
DATE PRINTED Thu May 19 2005          Time  11:30
```

RESULTS SECTION



Stage	Build Angle	Spline Tooth	Biplane Deviation Amount	Biplane Deviation Angle	Centerline Deviation Amount	Centerline Deviation Angle
BNG	0		0.000000	0.00	0.000250	180.00
GEAR	0		0.000500	0.00	0.000500	180.00
IBR	0		0.001451	0.00	0.001009	180.00
SEAL	0		0.001917	0.00	0.002144	180.00

Greatest centerline deviation = 0.002144

INPUT SECTION

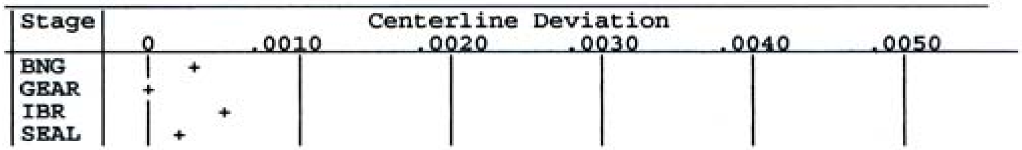
Stage	Part Number	Serial Number	Biplane/Perp.Plane Amount	Biplane/Perp.Plane Angle	Center Line Deviation Amount	Center Line Deviation Angle
BNG	4315875		0.000000	0.00	0.000250	180.00
GEAR	4317132		0.000500	0.00	0.000250	180.00
IBR	4322504		0.001000	0.00	0.000500	180.00
SEAL	4314924		0.000500	0.00	0.000500	180.00

Stage	Height (in)	Radius (in)	Spline Teeth	Index	Index Angle
BNG	0.75	2.85	0	YES	0.00
GEAR	0.10	2.85	0	NO	0.00
IBR	0.10	2.57	0	NO	0.00
SEAL	2.25	2.51	0	NO	0.00

AXIAM Bearing Stack Report

```
DIRECTORY                                        Part #    SEAL25ASSY
PROGRAM                 25SEAL                 Serial #    INDEX
OPERATOR                                          Run #     1
DATE STACKED 05/19/05 11:29
DATE PRINTED Thu May 19 2005                  Time  11:29
```

RESULTS SECTION



Stage	Build Angle	Spline Tooth	Biplane Deviation Amount	Biplane Deviation Angle	Centerline Deviation Amount	Centerline Deviation Angle
BNG	0		0.000000	0.00	0.000250	180.00
GEAR	180		0.000500	0.00	0.000000	0.00
IBR	0		0.000549	0.00	0.000491	180.00
SEAL	180		0.000036	0.00	0.000232	180.00

Greatest centerline deviation = 0.000491

INPUT SECTION

Stage	Part Number	Serial Number	Biplane/Perp.Plane Amount	Biplane/Perp.Plane Angle	Center Line Deviation Amount	Center Line Deviation Angle
BNG	4315875		0.000000	0.00	0.000250	180.00
GEAR	4317132		0.000500	0.00	0.000250	180.00
IBR	4322504		0.001000	0.00	0.000500	180.00
SEAL	4314924		0.000500	0.00	0.000500	180.00

Stage	Height (in)	Radius (in)	Spline Teeth	Index	Index Angle
BNG	0.75	2.85	0	YES	0.00
GEAR	0.10	2.85	0	YES	0.00
IBR	0.10	2.57	0	YES	0.00
SEAL	2.25	2.51	0	YES	0.00

SEAL #2 MAX. ACCUMULATED TOLERANCES

PARTS	PT, NUMBER	MAX STACK BIPLANE DEVIATION	MAX STACK CENTERLINE DEV.	MAX STACK SEAL RUNOUT
# 2 SEAL			Tolerance=.0005	Tolerance= .001
BEARING	4317248	0.000500	0.000250	0.000500
COUPLING	4321831	0.001000	0.000517	0.001034
SPACER	4310500	0.001483	0.000845	0.001690
SEAL	4318437	0.001807	0.001408	0.002816

AXIAM STACK # 2 SEAL

PARTS	PT, NUMBER	BNG STACK BIPLANE DEVIATION	BNG STACK CENTERLINE DEV.	BNG STACK SEAL RUNOUT
# 2 SEAL			Tolerance=.0005	Tolerance=.001
BEARING	4317248	0.000500	0.000250	0.000500
COUPLING	4321831	0.000000	0.000517	0.001034
SPACER	4310500	0.000500	0.000517	0.001034
SEAL	4318437	0.000941	0.000005	0.000010

SEAL # 2.5 MAX. ACCUMULATED TOLERANCES

PARTS	PT, NUMBER	MAX STACK BIPLANE DEVIATION	MAX STACK CENTERLINE DEV.	MAX STACK SEAL RUNOUT
# 2.5 SEAL				
BALL BEARING	4315875	0.000000	0.000250	0.000500
BEVEL GEAR	4317132	0.000500	0.000500	0.001000
IBR DISC	4322504	0.001451	0.001009	0.002018
SEAL	4314924	0.001917	0.002144	0.004288

AXIAM STACK 2.5 SEAL

PARTS	PT, NUMBER	BNG STACK BIPLANE DEVIATION	BNG STACK CENTERLINE DEV.	BNG STACK SEAL RUNOUT
# 2.5 SEAL				
BEARING	4315875	0.000000	0.000250	0.000500
BEVEL GEAR	4317132	0.000500	0.000000	0.000000
IBR DISC	4322504	0.000549	0.000491	0.000982
SEAL	4314924	0.000036	0.000232	0.000464

SEAL # 3 MAX. ACCUMULATED TOLERANCES

PARTS	PT, NUMBER	MAX STACK BIPLANE DEVIATION	MAX STACK CENTERLINE DEV.	MAX STACK SEAL RUNOUT
# 3 SEAL				
BEARING # 3	4315875	0.000000	0.000250	0.000500
GEAR	4317132	0.000500	0.000500	0.001000
IBR	4322504	0.001456	0.001254	0.002508
SEAL	4314926	0.002747	0.001782	0.003564

AXIAM STACK # 3.0

PARTS	PT, NUMBER	BNG STACK BIPLANE DEVIATION	BNG STACK CENTERLINE DEV.	BNG STACK SEAL RUNOUT
# 3 SEAL				
BEARING	4315875	0.000000	0.000250	0.000500
GEAR	4317132	0.000500	0.000000	0.000000
IBR	4322504	0.000544	0.000246	0.000492
SEAL	4314926	0.000347	0.000244	0.000488

AXIAM

INCORPORATED

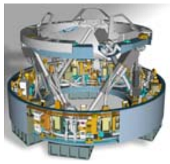
ADVANCED DOCKING BERTHING SYSTEM UPDATE

James Lewis
National Aeronautics and Space Administration
Johnson Space Center
Houston, Texas

Advanced Docking Berthing System Update
NASA Seal Workshop
GRC

November 8-9, 2005

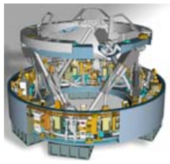
James Lewis, NASA-JSC/ES5 281-483-8954



Outline

- Background
- Future Program Needs
- Existing Systems
- Status
- Advanced Docking/Berthing System (ADBS) Overview
- Key Seal Requirements
- Early Seal Development Work

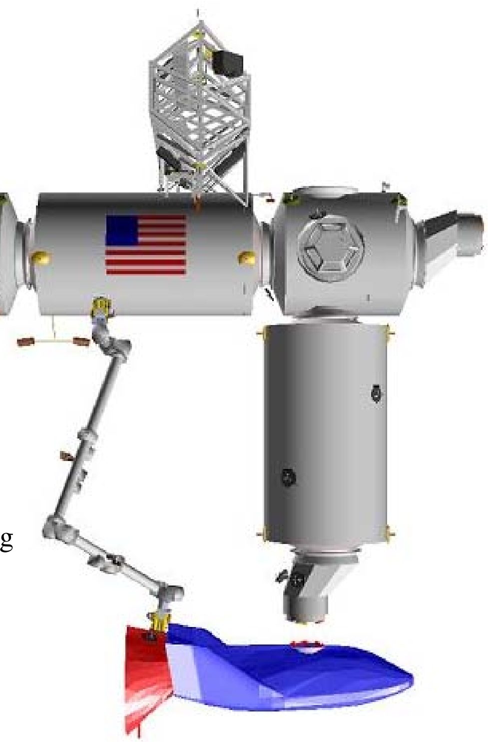
James Lewis, NASA-JSC/ES5 281-483-8954



Background

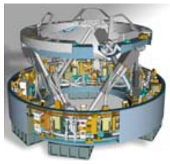
Berthing refers to mating operations where an inactive module/vehicle is placed into the mating interface using a Remote Manipulator System-RMS.

Docking refers to mating operations where an active vehicle flies into the mating interface under its own power.



RMS Berthing Depiction

James Lewis, NASA-JSC/ES5 281-483-8954



Future Needs

Future Mating System Capability Requirements:*

- A system able to support a variety of missions: CTV/CEV/CRV, lunar gateway, Moon, and Mars
- Lightweight, fault tolerant system that blends well into vehicle OML (aero)
- Capable of autonomous rendezvous & docking
- Berthing capable for modular assembly and vehicle swap-out
- Software reconfigurable for a range of vehicles and operations
- Fast separation for rapid release
- Modular for maintenance and servicing
- Constellation safety & reliability goals
- Adaptable to ISS
- Crew and large cargo transfer
- Power, data, and fluid transfer
- Vehicle to vehicle mating (CRV-CTV-others) requires androgynous interface

*-During FY06, with the Constellation Program and the CEV Project ramping up, detailed requirements development and documentation will occur.

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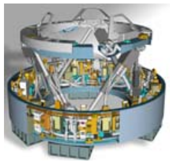
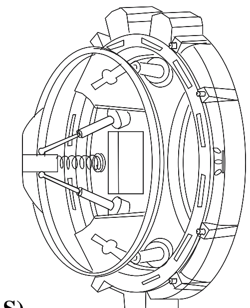
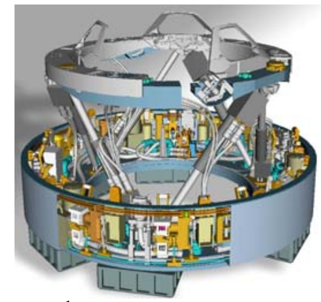


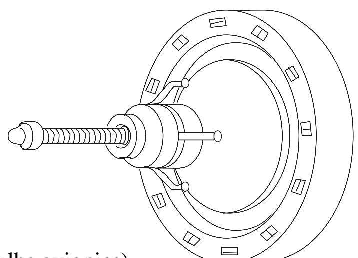
Existing Systems



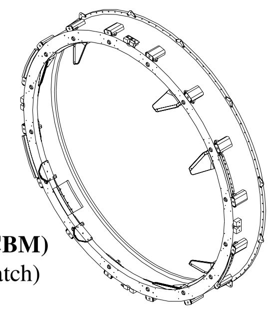
Androgynous Peripheral Docking System (APAS)
Weight: ~950 lbs (660 lbs APDA-6001 + 276 lbs avionics) (hatch not incl.)
Max OD: 69" dia
Hatch Pass Through: 31.38" dia
Source: JSC-26938, "Procurement Specification for the Androgynous Peripheral Docking System for the ISS Missions



Advanced Docking/Berthing System (ADBS)[1]
Weight: est. 750 lbs (includes electronics & hatch)
Max OD: 58" dia
Hatch Pass Through: 32" dia
Source: LIDS Project Group



Russian Probe
Weight: 700 lbs (550 lbs cone + 150 lbs avionics)
Max OD: 61" dia
Hatch Pass Through: 31.5" dia (approximate)
Source: Energia



Passive Common Berthing Mechanism (PCBM)
Weight: 680 lbs[2] (440 lbs PCBM + 240 lbs hatch)
Hatch Pass Through: 50" square
Max OD: 86.3" dia
Source: SSP 41004, Part 1, "Common Berthing Mechanism to Pressurized Elements ICD" & SSP 41015, Part 1, Common Hatch & Mechanisms To Pressurized Elements ICD

[1]ADBS currently under development
[2]Bulkhead hatch ring structure not included

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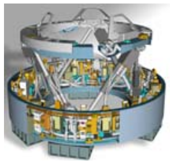

Existing Systems

Limitations of existing systems:

- Do not meet 2-fault tolerant, time-critical release requirement for crewed vehicles
  - APAS for Shuttle relies on 96 bolt EVA to meet 2nd fault tolerance
  - CBM powered bolts in nominal ops are not time critical and are single fault tolerant
- Unique active & passive halves: precludes vehicle-to-vehicle mating using like pairs
- Do not support autonomous operations
  - No automatic mating of fluid, power (APAS does have a power/data connector) and forced air umbilicals
  - CBM cannot mate to unmanned vehicles; requires RMS grappling and berthing
- Standard ISS racks cannot pass through existing docking ports
- Significant velocities required to provide alignment & capture forces
- Crit-1 operations supported by intensive training & analysis
- High part count / mechanical complexity with single point failures (reliability and failure tolerance problems)
- Berthing mechanisms do not dock and docking mechanisms do not berth
- Russian systems are supplied by a foreign vendor with substantial economic concerns
  - Purchase of additional units banned by Iran Missile Proliferation Sanctions Act of 1997
  - Very limited access to engineering data
- Systems designed and/or certified for very few cycles and short exposure life

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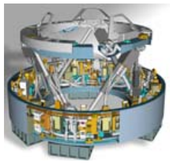
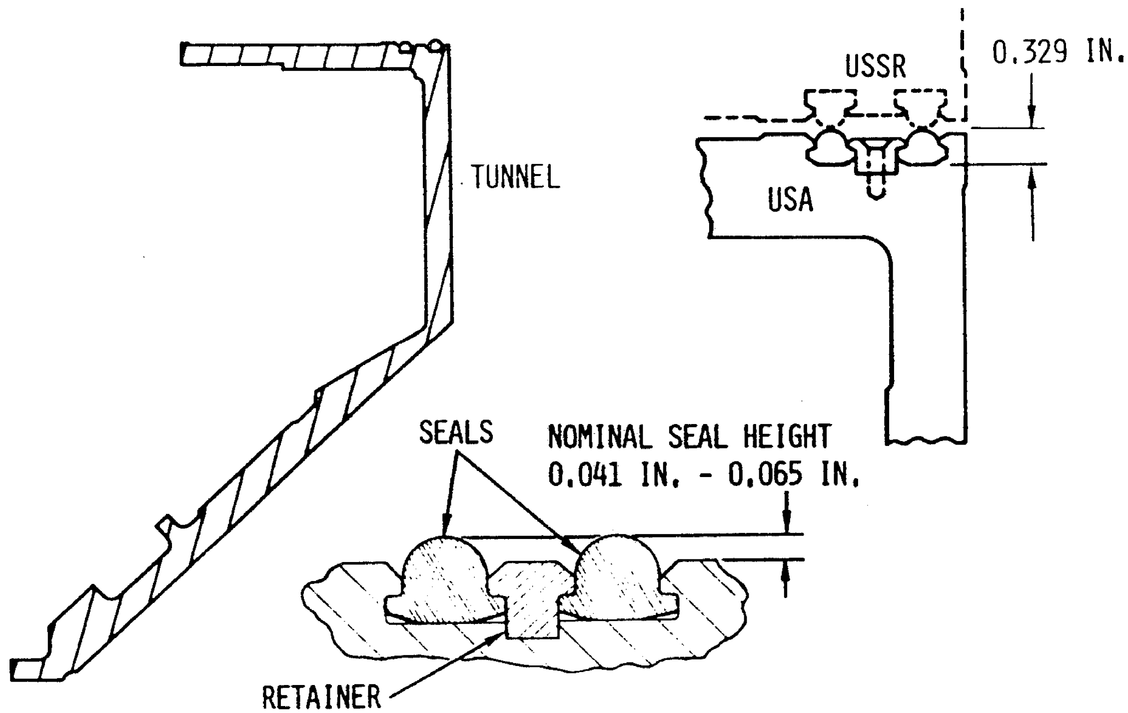


Existing System Seals



Apollo Soyuz Test Program
Docking System Interface Seal Diagram

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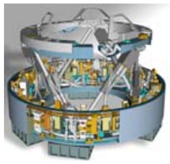

Current Status

Advanced Mating System Development Activities

– In FY05 the Exploration Systems Technology Maturation Program selected the JSC advanced mating systems development to continue as an in-house project.

– In FY06, as a result of ESAS Study (60 Day Study) the CEV Project (within the Constellation Program) has chosen to continue the project as a GFE Flight Hardware development effort.

  – new requirement for CEV to travel and dock with the ISS in 2011/12 in support of retiring the Shuttle and reducing the gap of time where US does not have any US based crew launch capability.

– As before, long-duration compatible seal-on-seal technology (seal-on-seal to support androgynous interface) has been identified as a risk mitigation item.

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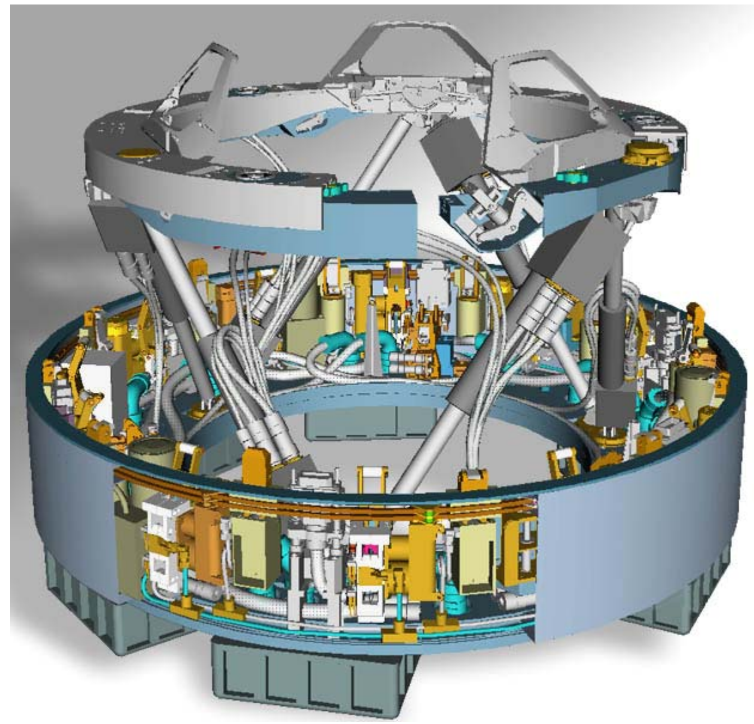
ADBS Overview

A Next-Generation Mating Mechanism

- Designed specifically to take advantage of modern electromechanical technology
- Incorporates the lessons learned and experiences from previous/current mating mechanism development and use
- Desensitizes mating mechanism operations and performance from other vehicle systems requirements
- Supports both docking and berthing operations
- Supports autonomous rendezvous & mating
- Aligned with NASA Strategic Plan



CAD Image

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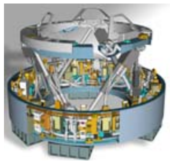

Key Seal Requirements

- Seal-on-seal interface
  - ASTP did it.
  - Russian APAS has it.
- Very low leak rate
  - Long-duration pressurized volumes requiring minimal atmospheric volume loss
- Long life
  - Long-duration exposed periods
  - Long-duration mated periods
  - LEO, deep-space and lunar/Mars environments
  - May also be a potential for high mate/demate cycle life
- Redundancy
- Damage tolerance

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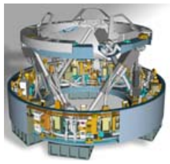
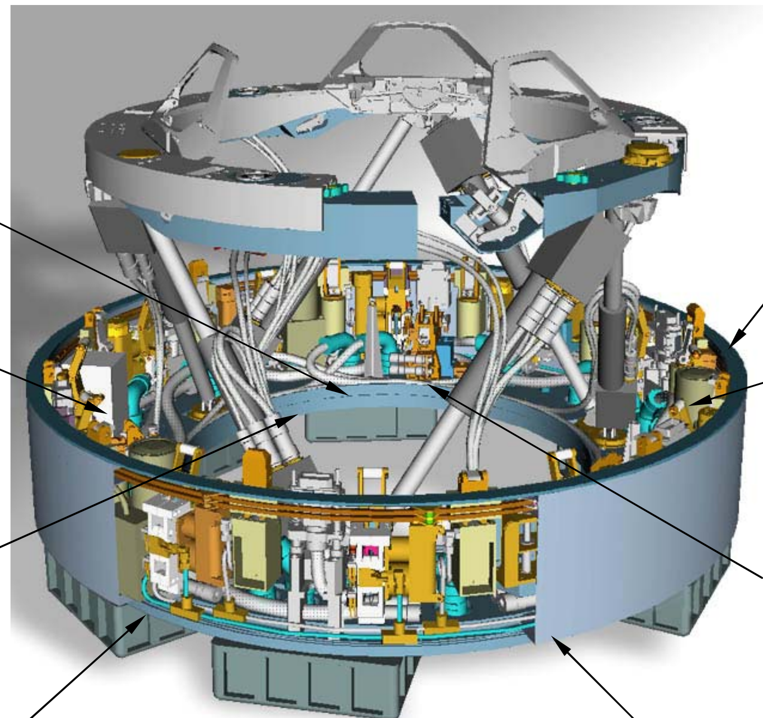
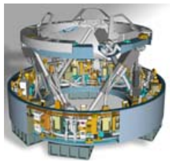


ADBS Seal Locations



James Lewis, NASA-JSC/ES5 281-483-8954



Early ADBS Seal Development

To preserve the fully androgynous design concept the seal design approach baselined was a seal-on-seal implementation similar to the Apollo Soyuz (ASTP) seals.

Subscale seal-on-seal elastomeric development with Parker Inc.

- Quick development and testing to evaluate seal-on-seal potential
- 2 cross-sections (flat top and elliptical) and 2 different durometer silicon materials
- Helium leak testing and seal load force testing completed in July 2001
- Adhesion testing

Test results

- Leak rates comparable to ISS CBM seals with offset of 0.050 inches and no gapping (~20 configurations tested)
- Compression force testing showed that “flat top” slightly higher than “elliptical” for the 70 durometer at (96 & 87 lb/in) and for the 50 durometer at (46 & 42 lb/in). Results indicated that seal-on-seal in the “acceptable” range for use.
- Adhesion test results pending; series of “buttons” molded from each material are currently mated and compressed for eventual separation and inspection at TBD regular intervals of time.

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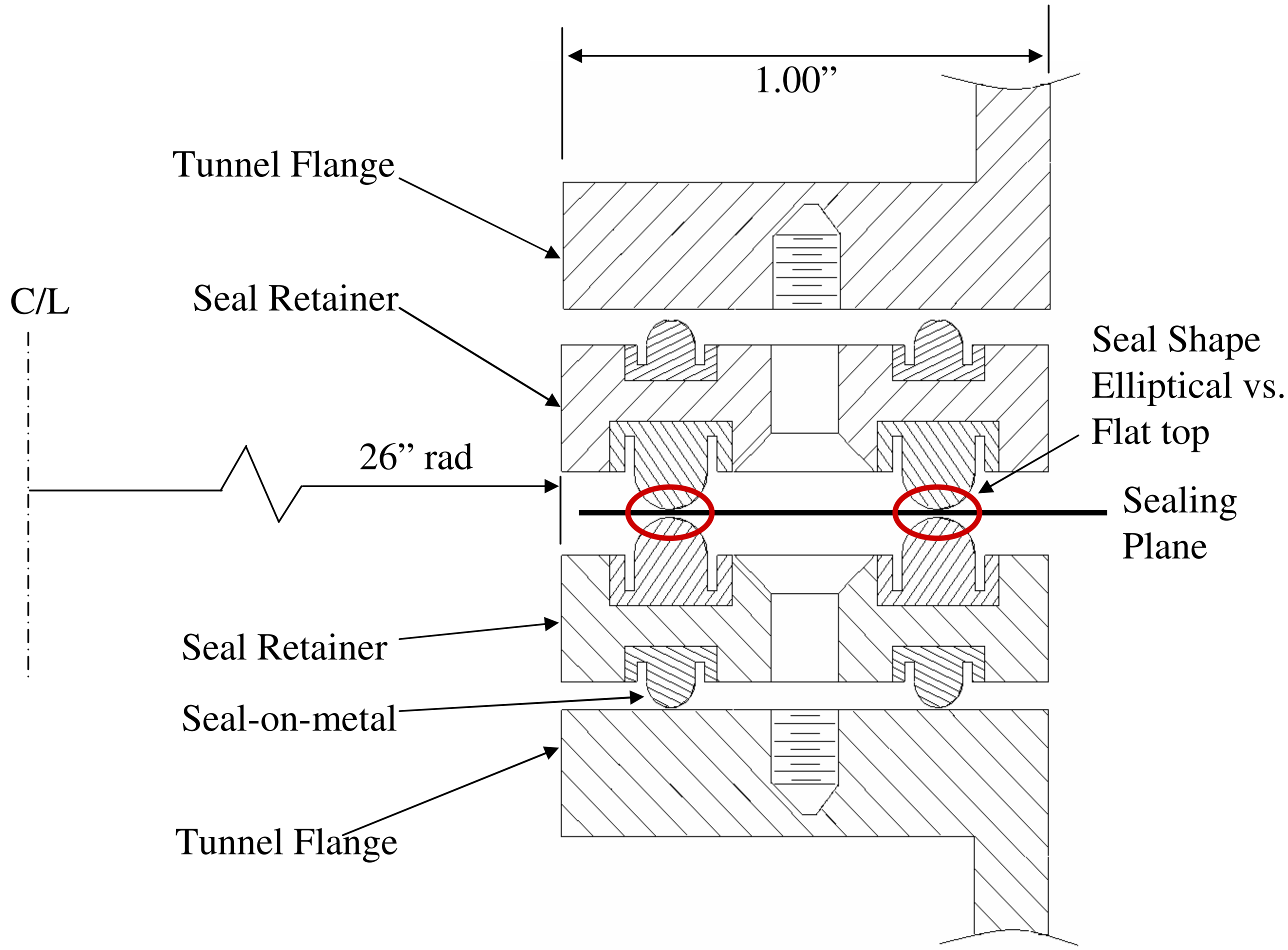
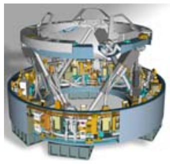
RRU Interface Seal Concept



James Lewis, NASA-JSC/ES5 281-483-8954



Early ADBS Seal Development

Conclusions

- GRC Seal Team has been working since Feb and has some early results
- They are currently establishing the processes and development plans for the next few years.

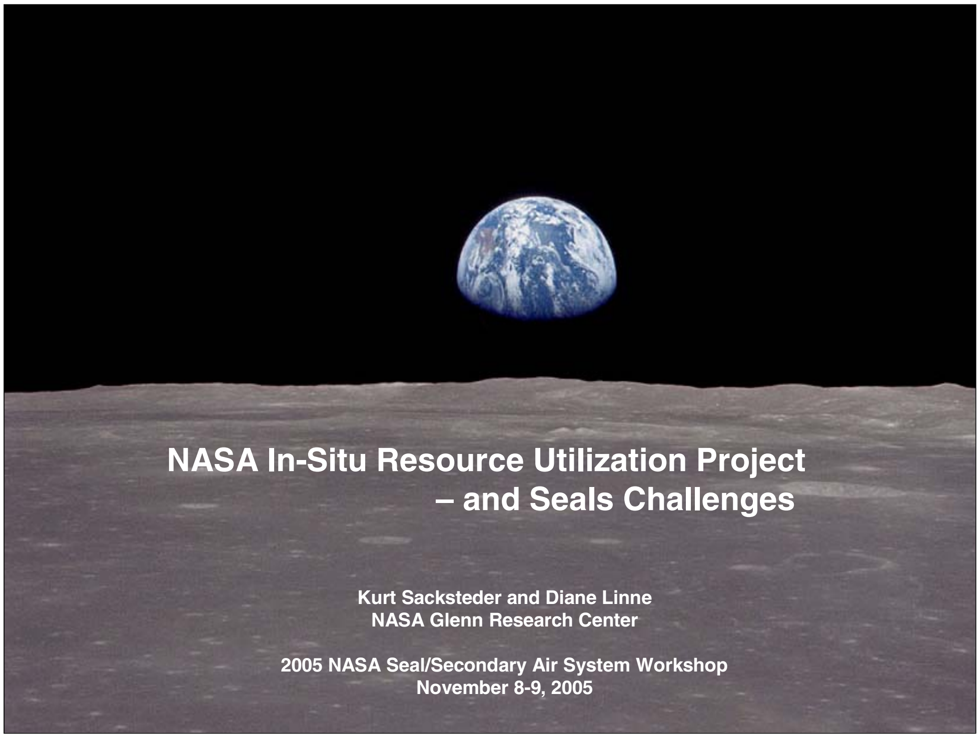
Forward work

- Evaluating early space flight demonstration opportunity on private space modules.
  - Move forward with a full scale development seal purchase for the RRU
  - Continue long duration seal material characterization and test program
- Need to establish baseline seal cross-section design
  - Optimize seal to guarantee optimal sealing: percent of fill, squeeze, crown profile and height, if elastomeric
  - Establish total potential seal mismatch: misalignment, thermal expansion, flange deflection
  - Establish on-orbit/lander environment requirements & acceptable seal force and leak rate
  - Determine full scale hardware development approach.
- Evaluate concepts and results for full-scale implementation
  - Evaluate design upward scaling
- Continue to investigate alternate seal materials
  - Metallic seals
  - Hybrid metallic/elastomeric

James Lewis, NASA-JSC/ES5 281-483-8954

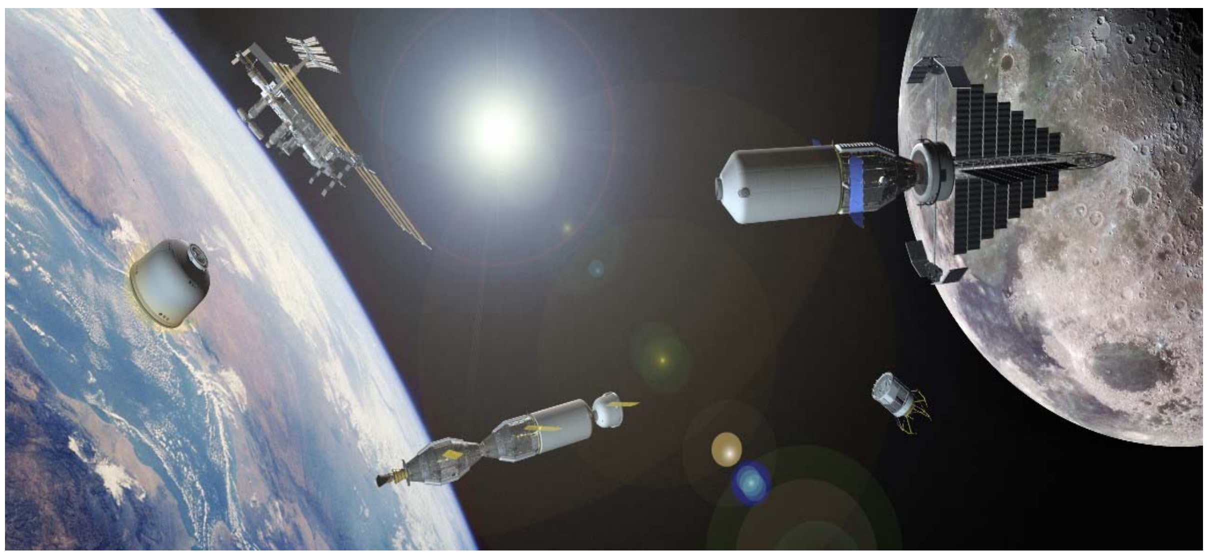
NASA IN-SITU RESOURCE UTILIZATION PROJECT—AND SEAL CHALLENGES

Kurt Sacksteder and Diane Linne
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio



New Space Exploration Vision

- **On January 14, 2004, the President announced a new vision for NASA**
  - Implement a *sustained and affordable* human and robotic program to explore the solar system and beyond;
  - Extend *human presence* across the solar system, starting with a human return to the Moon in preparation for human exploration of Mars and other destinations;
  - Develop the *innovative technologies*, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and
  - Promote *international and commercial participation* in exploration to further U.S. scientific, security, and economic interests.



"Making use of the Moon's abundant resources…"

Kurt Sacksteder, NASA GRC, Kurt.Sacksteder@nasa.gov

What Are Space Resources?

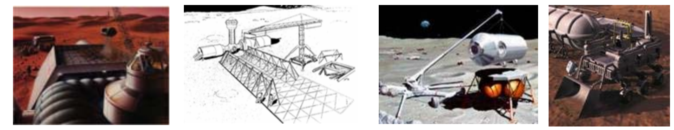
- **Traditional material resources including**:
  - Water from the soil or atmosphere
  - Atmospheric gases (CO_2, O_2, N_2, etc.)
  - Volatile species from the solar wind or comets (H_2, He, H_2O, CH_4, etc.)
  - Minerals/metals (Fe, Ti, Ni, Si, etc.)
- **Energy**
  - (Near) Continuous sunlight for electrical/thermal power and stable thermal control
  - (Near) Continuous Darkness for cryogenic fluid storage, scientific instruments and stable thermal control
- **Environment**
  - Vacuum/Dryness
  - Micro/Partial Gravity
  - High Thermal Gradients
- **Location**
  - Stable Locations for Earth/Sun/deep-space observations, mission staging
  - Isolation from Earth's electromagnetic noise, storage of duplicate vital information
  - Isolation for Earth to conduct hazardous testing (nuclear, biological, etc.) and extraterrestrial sample curation & analysis, etc.

In-Situ Resource Utilization exploits these resources, creating products & services that significantly reduce the mass, cost, & risk of extended-duration space exploration

Space Resource Utilization for Exploration

Mission Consumable Production

- **Propellants for Lander/Ascent Vehicles, Surface Hoppers, & Aerial Vehicles**
- **Fuel cell reagents for mobile** (rovers, EVA) & stationary backup power
- **Life support consumables** (oxygen, water, buffer gases)
- Gases for science equipment and drilling
- Bio-support products (soil, fertilizers, etc.)
- Feedstock for in-situ manufacturing & surface construction



Surface Construction

- **Radiation shielding for habitat & nuclear reactors from in-situ resources or products** (Berms, bricks, plates, water, hydrocarbons, etc.)
- **Landing pad clearance**, site preparation, roads, etc.
- Shielding from micro-meteoroid and landing/ascent plume debris
- Habitat and equipment protection

Manufacturing w/ Space Resources

- **Spare parts manufacturing**
- Locally integrated systems & components (especially for increasing resource processing capabilities)
- High-mass, simple items (chairs, tables, replaceable structure panels, wall units, wires, extruded pipes/structural members, etc.)

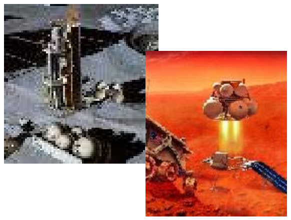
Space Utilities & Power

- **Storage & distribution of mission consumables**
- Thermal energy storage & use
- **Solar energy** (PV, concentrators, rectennas)
- **Chemical energy** (fuel cells, combustion, catalytic reactors, etc.)

Kurt Sacksteder, NASA GRC, Kurt.Sacksteder@nasa.gov

National Aeronautics and Space Administration

ISRU Enables Affordable, Sustainable & Flexible Exploration

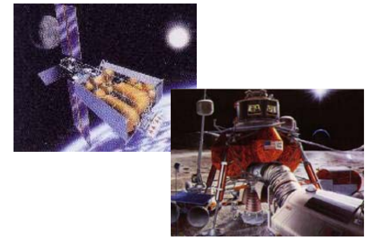


Mass Reduction

Propellant Production

- Reduces Earth to orbit mass by 20 to 45% for Mars missions
- 3.5:1 to 4:1 mass savings leverage from Moon/Mars surface back to Low Earth Orbit

Cost Reduction



- Reduces number and size of Earth launch vehicles
- Allows reuse of transportation assets
- Minimizes DDT&E cost

Space Resource Utilization

Risk Reduction & Flexibility

- Fewer Earth launches & reduced mission operations
- Reduced dependence on Earth
- Common hardware & mission consumables
- In-situ fabrication of spare parts for sustainable self-sufficiency
- Dissimilar redundancy
- Radiation & Plume Shielding

Enables Space Commercialization

- Material handling and processing technologies
- Infrastructure for space commercialization
- Propellant/consumable depots at Earth-Moon L1 & Lunar Surface

Expands Human Presence

- Increase surface mobility and extend missions
- Habitat & infrastructure construction
- Consumables for propellant, life support, power, etc.
- Substitute infrastructure cargo for Earth-source propellant & consumables

Kurt Sacksteder, NASA GRC, Kurt.Sacksteder@nasa.gov

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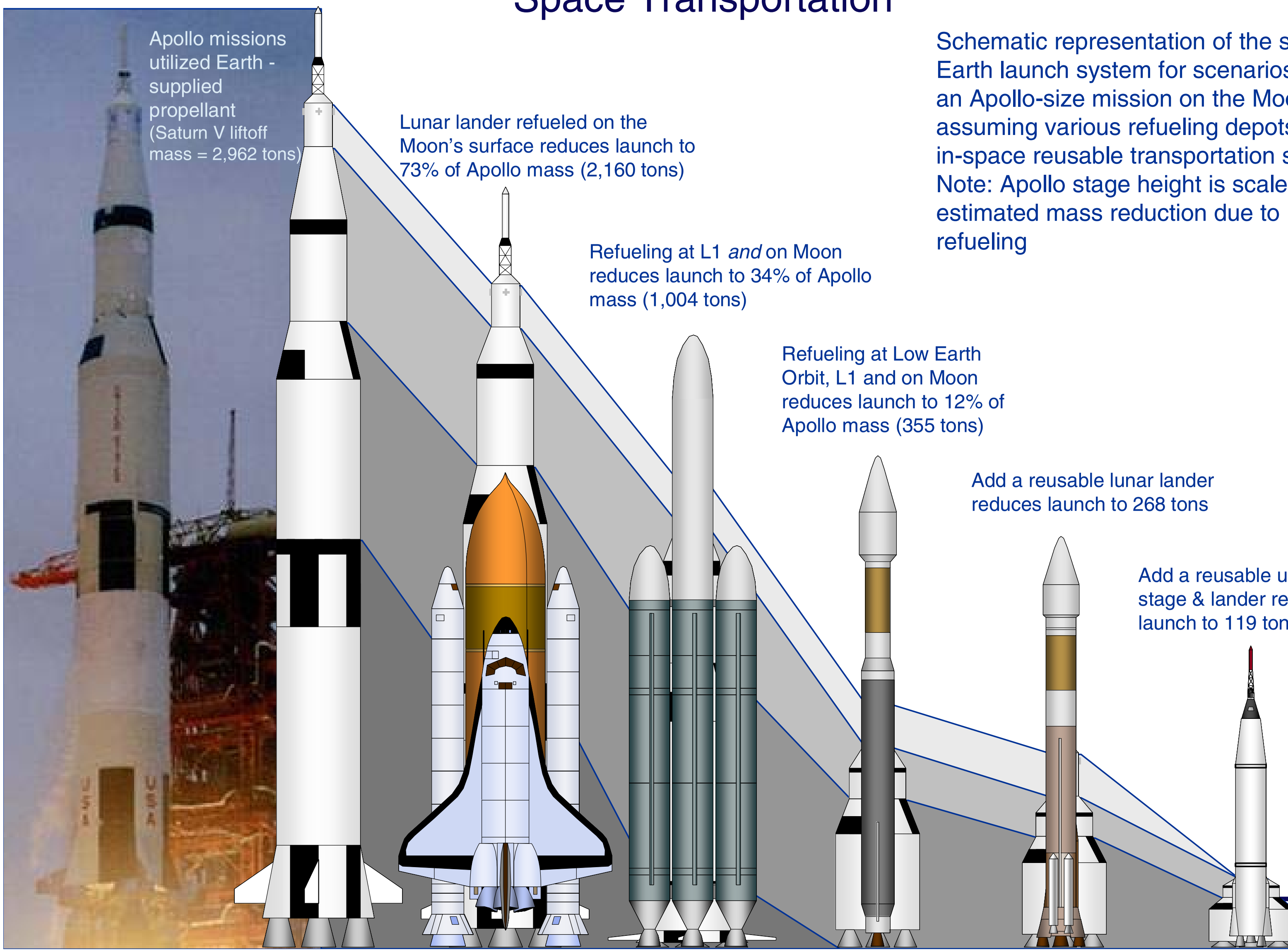
Propellant from the Moon Could Revolutionize Space Transportation

Schematic representation of the scale of an Earth launch system for scenarios to land an Apollo-size mission on the Moon, assuming various refueling depots and an in-space reusable transportation system. Note: Apollo stage height is scaled by estimated mass reduction due to ISRU refueling



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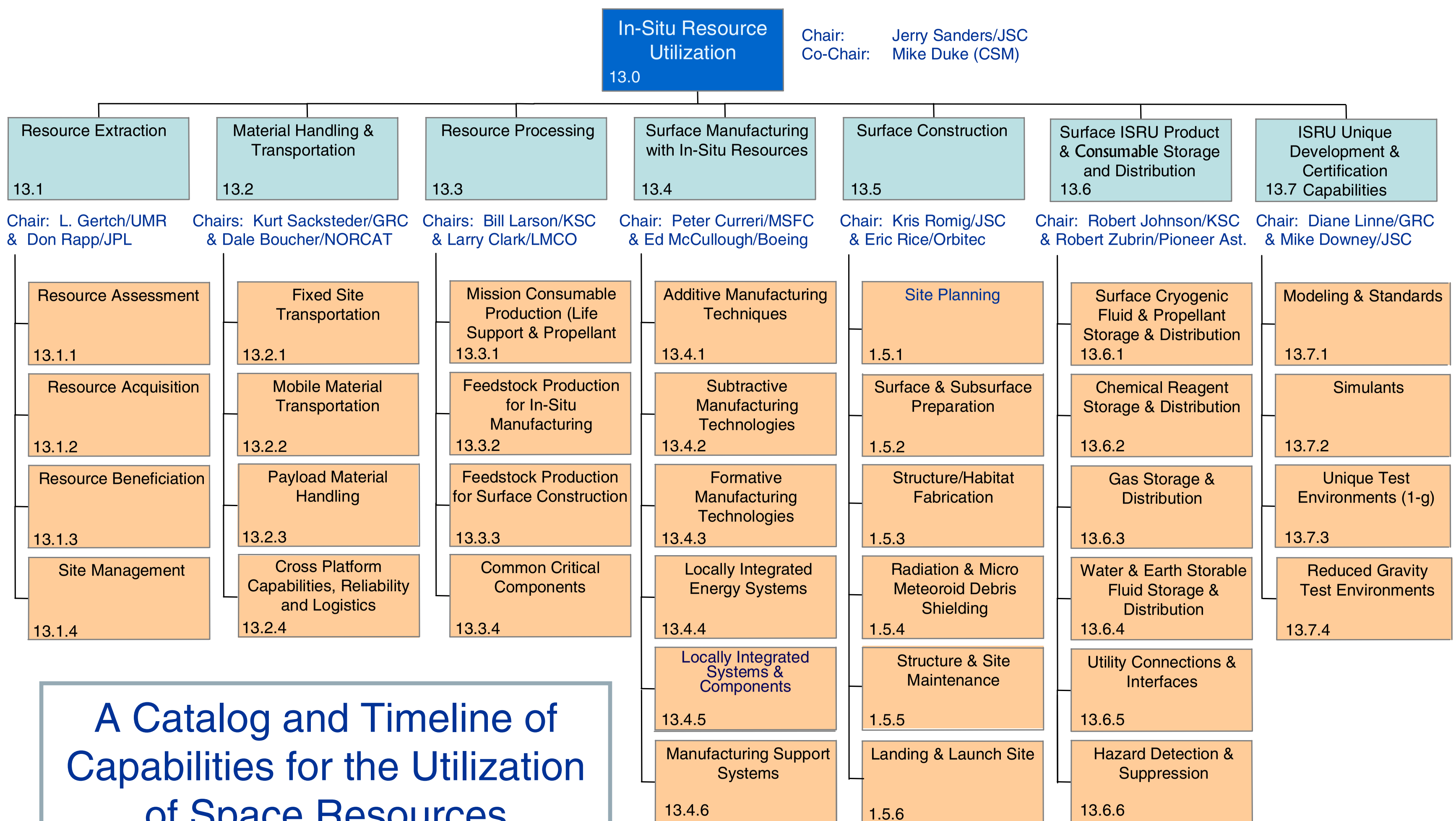
NASA ISRU Capability "Roadmap" Study, 2005



A Catalog and Timeline of Capabilities for the Utilization of Space Resources

Kurt Sacksteder, NASA GRC, Kurt.Sacksteder@nasa.gov

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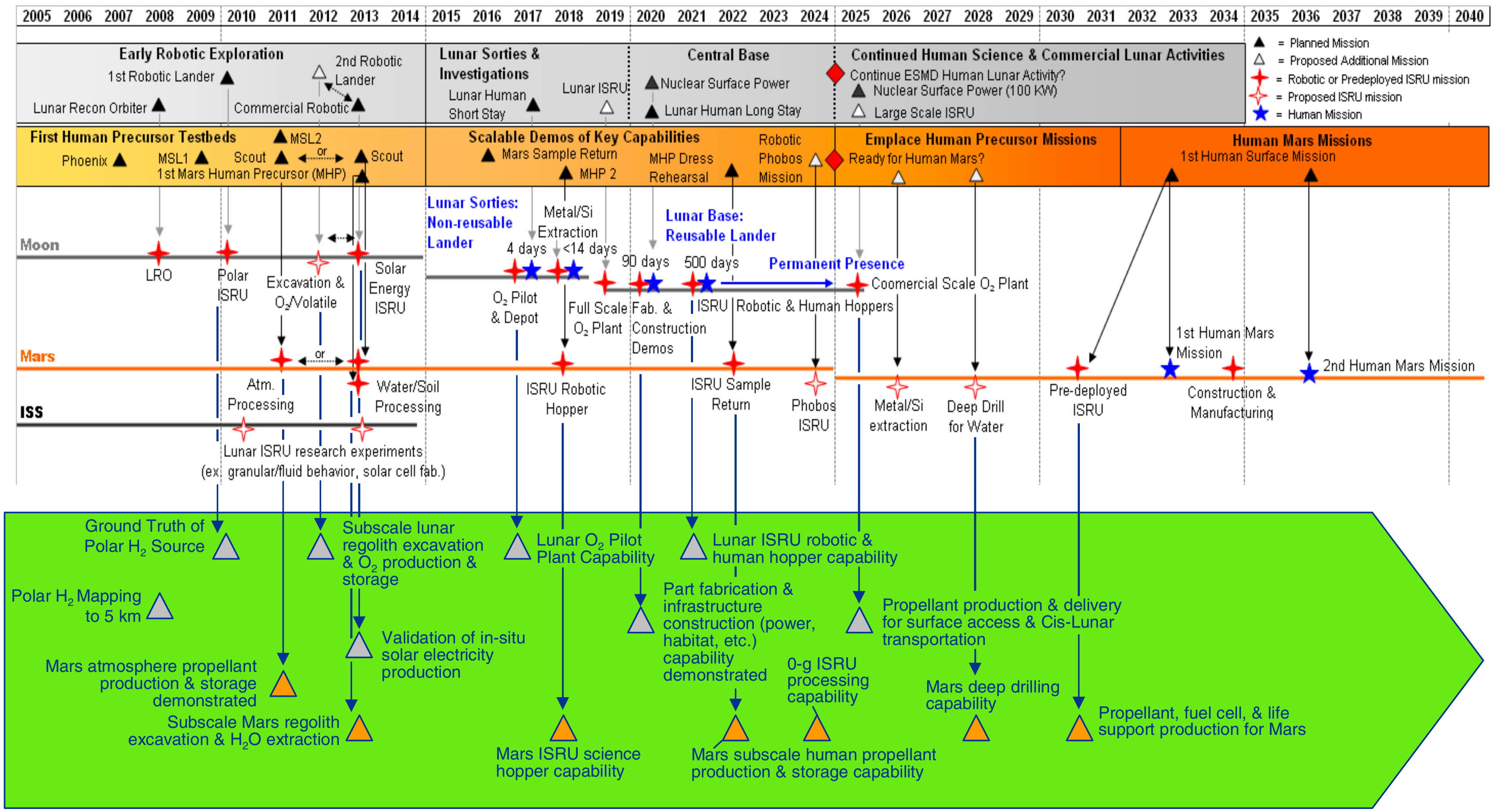
Timeline for ISRU Capability Implementation



In-Situ Resource Utilization must earn acceptance for mission critical roles in crewed missions through convincing demonstrations early in the Exploration timeline

Kurt Sacksteder, NASA GRC, Kurt.Sacksteder@nasa.gov

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Lunar ISRU Implementation Approach

Lunar Mission Assumptions with ISRU (Lunar Exploration Analysis Group-LEAG)

- Robotic precursors identify resources and validate critical processes
- Early human missions (4 to 14 days) gain system & operational experience until a candidate long-term site is selected
  - Pre-deployed ISRU/mission assets before human missions
- Develop infrastructure at one base for Mars mission ‘dress rehearsals’ (90 day & 500 day) and sustained human presence in space
  - Traverse or hop to other locations for short term science mission objectives

Initial Capabilities

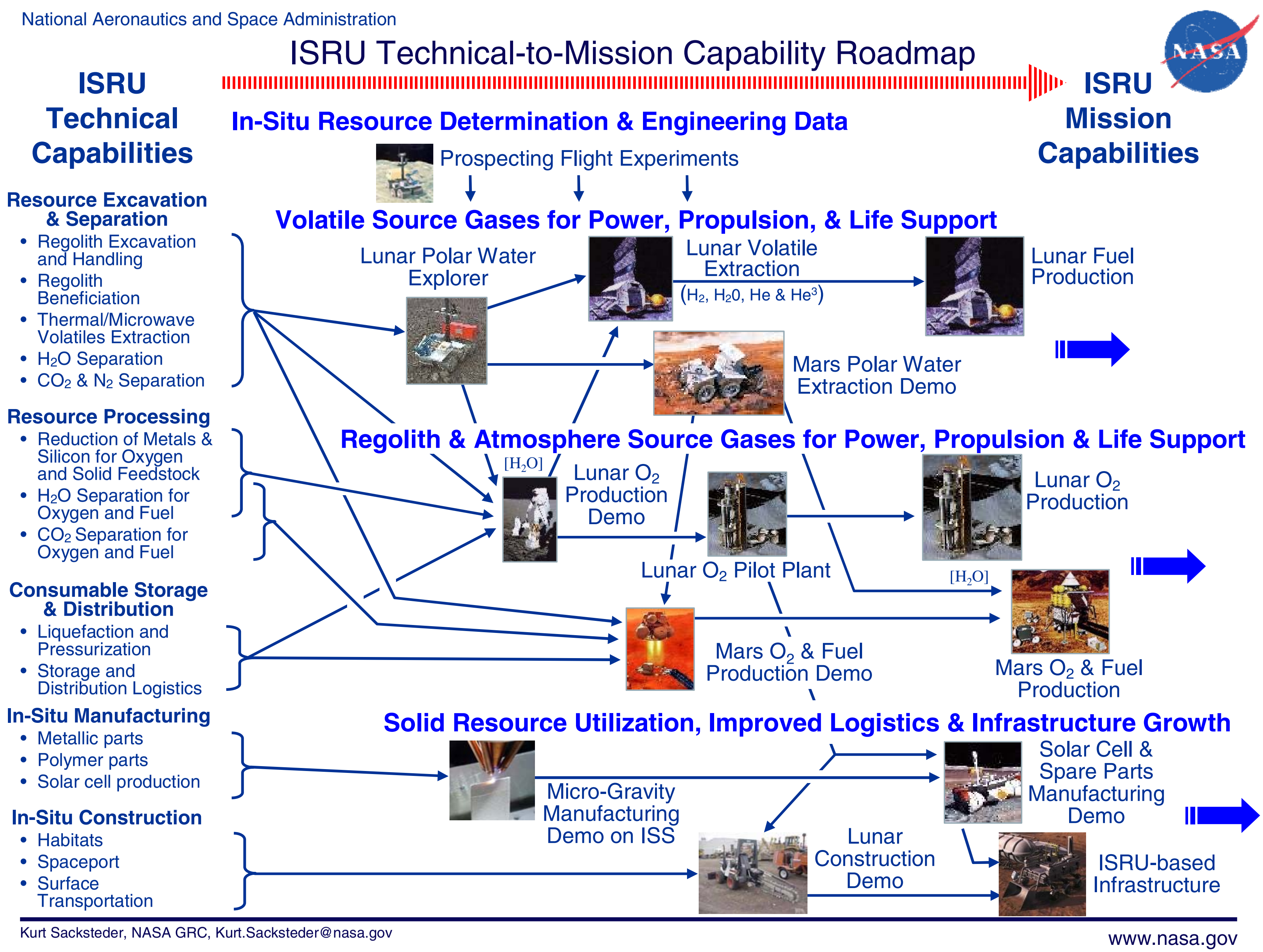
- Surface regolith excavation and manipulation
  - Excavation for volatile extraction and regolith processing
  - Berms and shielding for radiation and plume protection
  - Site/landing pad preparation and road/dust mitigation
- Extraction & recovery of useful volatiles from surface resources (H_2, CO, N_2, H_2O)
- Oxygen (O_2) production from regolith processing
- Production/regeneration of fuel cell reagents
- Cryogenic storage & transfer

Mid-Term ISRU Capabilities

- In-situ fabrication and repair
- Space Power
- Thermal energy storage & use

Long-Term Lunar Capabilities

- In-situ manufacturing of complex parts and equipment
- Habitat and infrastructure construction (surface & subsurface)
- Life Support System – bio support (soil, fertilizers, etc.)
- Helium-3 isotope (^3He) mining


National Aeronautics and Space Administration
ISRU Technical-to-Mission Capability Roadmap
ISRU Technical Capabilities
ISRU Mission Capabilities
Resource Excavation & Separation
• Regolith Excavation and Handling
• Regolith Beneficiation
• Thermal/Microwave Volatiles Extraction
• H_2O Separation
• CO_2 & N_2 Separation
Resource Processing
• Reduction of Metals & Silicon for Oxygen and Solid Feedstock
• H_2O Separation for Oxygen and Fuel
• CO_2 Separation for Oxygen and Fuel
Consumable Storage & Distribution
• Liquefaction and Pressurization
• Storage and Distribution Logistics
In-Situ Manufacturing
• Metallic parts
• Polymer parts
• Solar cell production
In-Situ Construction
• Habitats
• Spaceport
• Surface Transportation
In-Situ Resource Determination & Engineering Data
Prospecting Flight Experiments
Volatile Source Gases for Power, Propulsion, & Life Support
Lunar Polar Water Explorer
Lunar Volatile Extraction
(H_2, H_20, He & He^3)
Lunar Fuel Production
Mars Polar Water Extraction Demo
Regolith & Atmosphere Source Gases for Power, Propulsion & Life Support
[H_2O]
Lunar O_2 Production Demo
Lunar O_2 Pilot Plant
Lunar O_2 Production
[H_2O]
Mars O_2 & Fuel Production Demo
Mars O_2 & Fuel Production
Solid Resource Utilization, Improved Logistics & Infrastructure Growth
Micro-Gravity Manufacturing Demo on ISS
Solar Cell & Spare Parts Manufacturing Demo
Lunar Construction Demo
ISRU-based Infrastructure
Kurt Sacksteder, NASA GRC, Kurt.Sacksteder@nasa.gov
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ISRU Resources & Products of Interest

LUNAR RESOURCES

MARE REGOLITH

Ilmenite - 15%

FeO•TiO_2	98.5%

Pyroxene - 50%

CaO•SiO_2	36.7%
MgO•SiO_2	29.2%
FeO•SiO_2	17.6%
Al_2O_3•SiO_2	9.6%
TiO_2•SiO_2	6.9%

Olivine - 15%

2MgO•SiO_2	56.6%
2FeO•SiO_2	42.7%

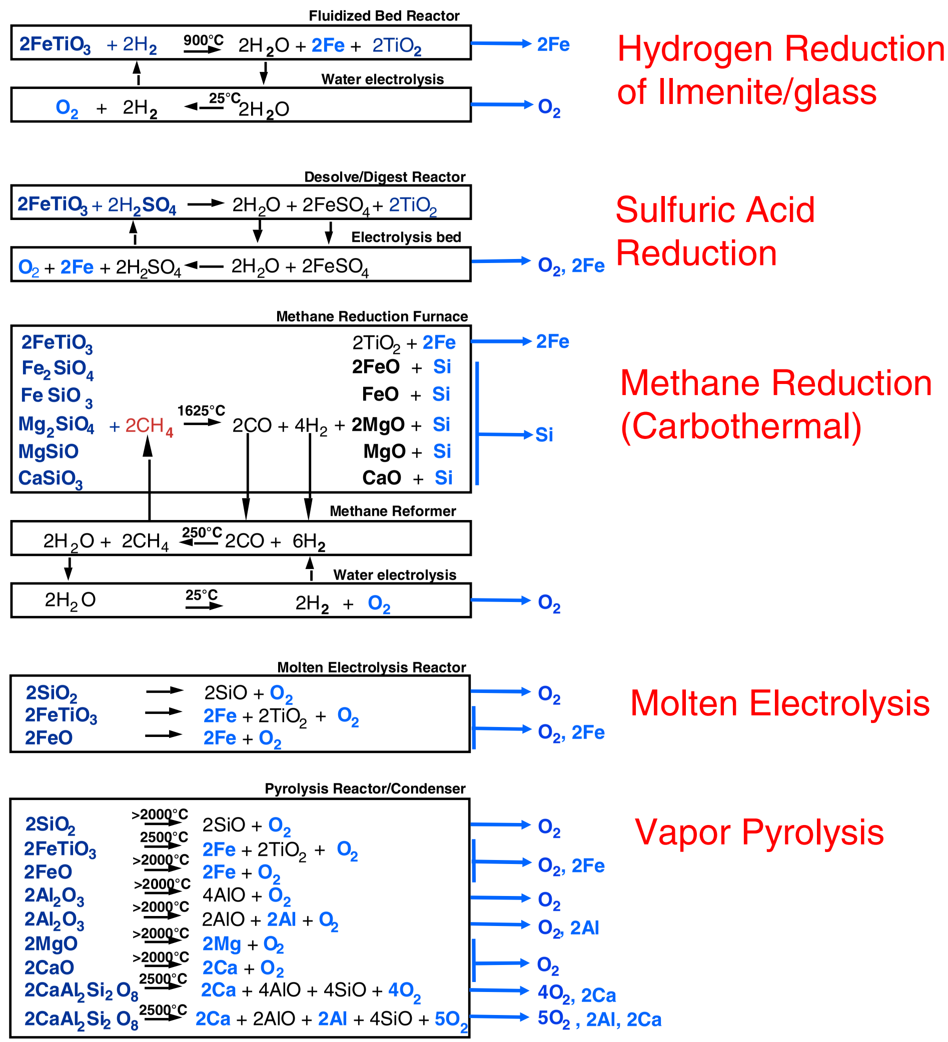
Anorthite - 20%

CaO•Al_2O_3•SiO_2	97.7%

VOLATILES (Solar Wind & Polar Ice/H_2)

Hydrogen (H_2)	50 - 150 ppm
Helium (He)	3 - 50 ppm
Helium-3 (^{3}He)	10^{-2} ppm
Carbon (C)	100 - 150 ppm
Polar Water (H_2O)/H_2	1 - 10%

→ Thermal Volatile Extraction



Kurt Sacksteder, NASA GRC, Kurt.Sacksteder@nasa.gov

Challenging Seals Requirements for ISRU

The Moon is a Harsh Environment

- Temperatures from 40K (-230C) to 450K (150C)
- High Vacuum, 10^{-10} mm Hg
- Dust: abrasive, static cling, etc.
- Partial gravity

Initial ISRU Capabilities

- Surface regolith excavation and manipulation – mechanism bearings and regolith abrasion
  - Excavation for volatile extraction and regolith processing
  - Berms and shielding for radiation and plume protection
  - Site/landing pad preparation and road/dust mitigation
- Extraction & recovery of useful volatiles from surface resources (H_2, CO, N_2, H_2O) – encapsulate regolith during excavation and heating
- Oxygen (O_2) production from regolith processing – high temperature reactors and reagent recovery systems
- Production/regeneration of fuel cell reagents – fuel transfer operations
- Cryogenic storage & transfer – valves and other plumbing issues

Kurt Sacksteder, NASA GRC, Kurt.Sacksteder@nasa.gov

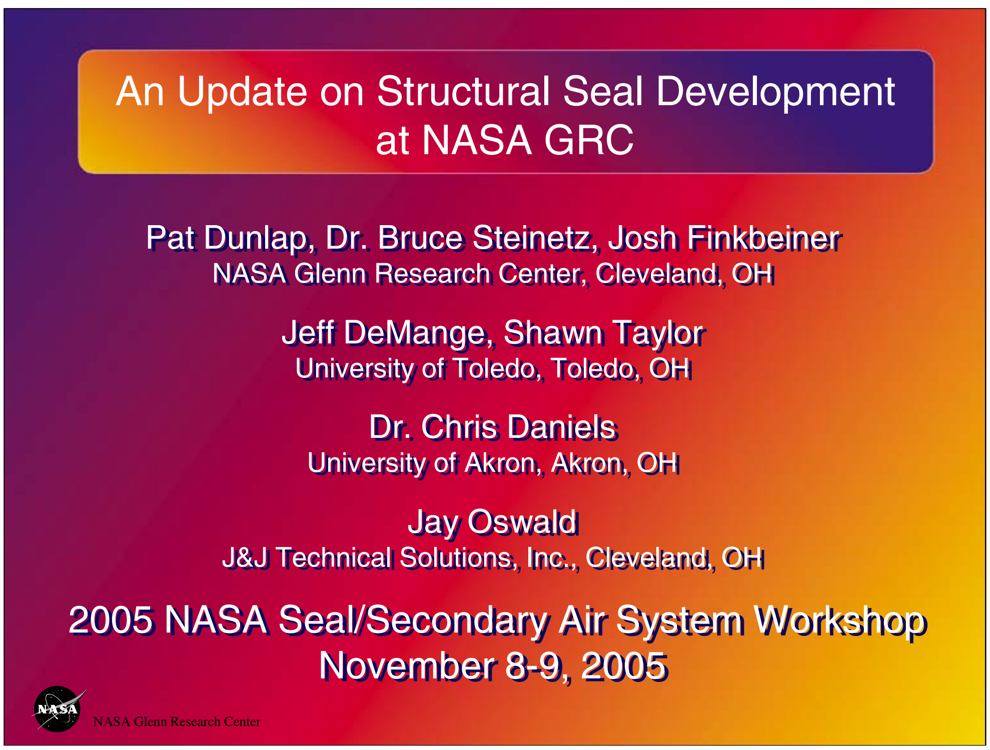
AN UPDATE ON STRUCTURAL SEAL DEVELOPMENT AT NASA GRC

Pat Dunlap, Bruce Steinetz, and Josh Finkbeiner
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Jeff DeMange and Shawn Taylor
University of Toledo
Toledo, Ohio

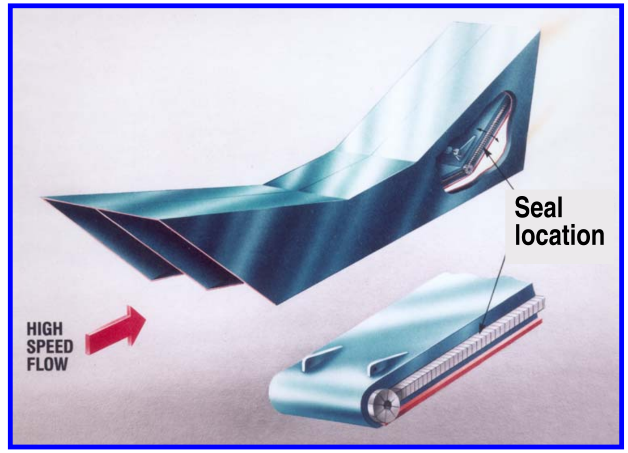
Chris Daniels
University of Akron
Akron, Ohio

Jay Oswald
J&J Technical Solutions, Inc.
Cleveland, Ohio

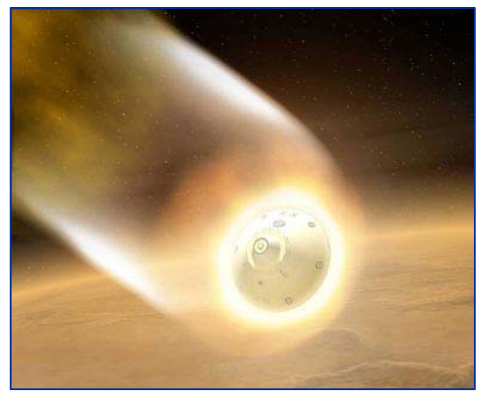


Introduction & Background

- Advanced structural seals are required on future hypersonic vehicles and on vehicles and systems for NASA's Exploration Initiative
  - Dynamic seals:
    - Control surfaces
    - Landing gear doors
    - Access panels and doors
    - Hypersonic engine ramps and panels
  - Static seals:
    - Docking/berthing system seals
    - Leading edge panel joints
    - Acreage thermal protection system (TPS) joints
    - Heatshield joints and interfaces

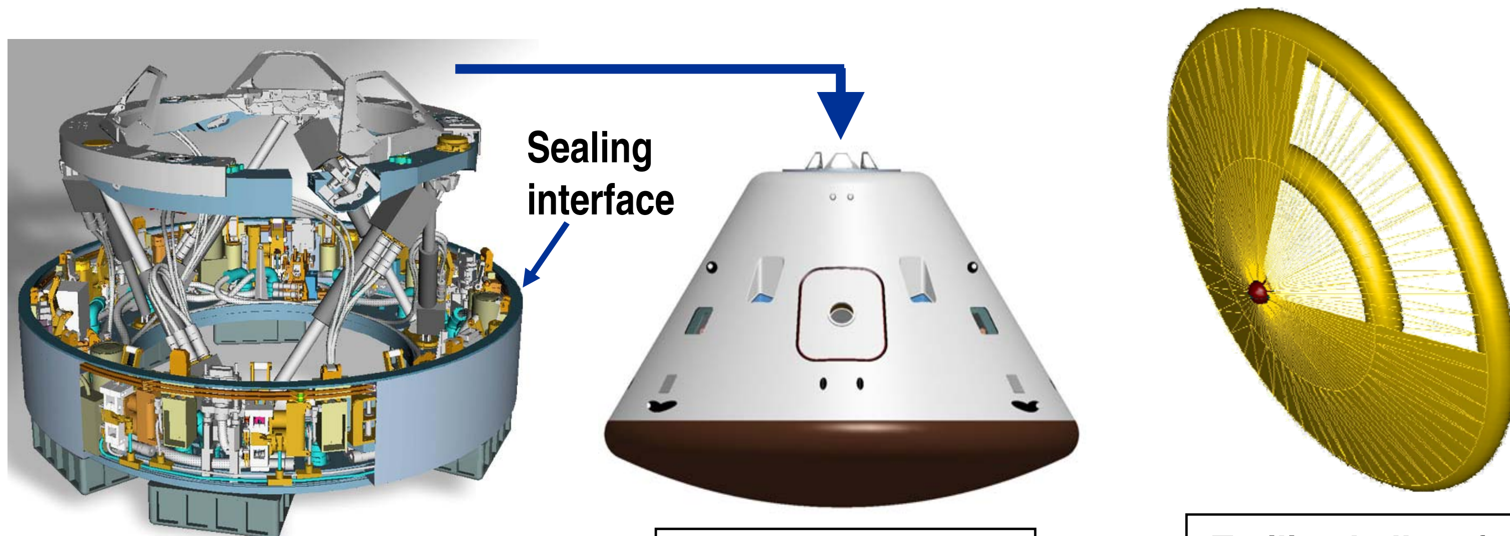


Hypersonic engine seals



Heatshield seals

GRC Structural Seals Team Research Areas



Advanced Docking/Berthing System

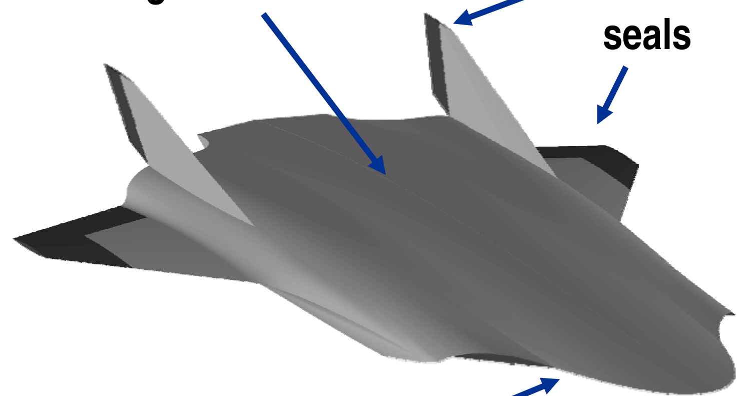
Crew Exploration Vehicle (CEV)

Trailing ballute for aerocapture

- GRC Structural Seals Team developing seals for NASA's Exploration Initiative:
  - Advanced Docking/Berthing System (ADBS) for CEV (JSC)
  - CEV TPS Advanced Development (LaRC, Ames)
  - Aerocapture Technology Development (MSFC)
  - Deployable Skirt System (Northrop Grumman)

Research Areas & Objective

- GRC Structural Seals Team also developing seals for hypersonics programs:
  - Falcon program (Lockheed Martin, DARPA, JSC)
  - X-43C Direct Connect Combustor Rig (ATK GASL, LaRC)



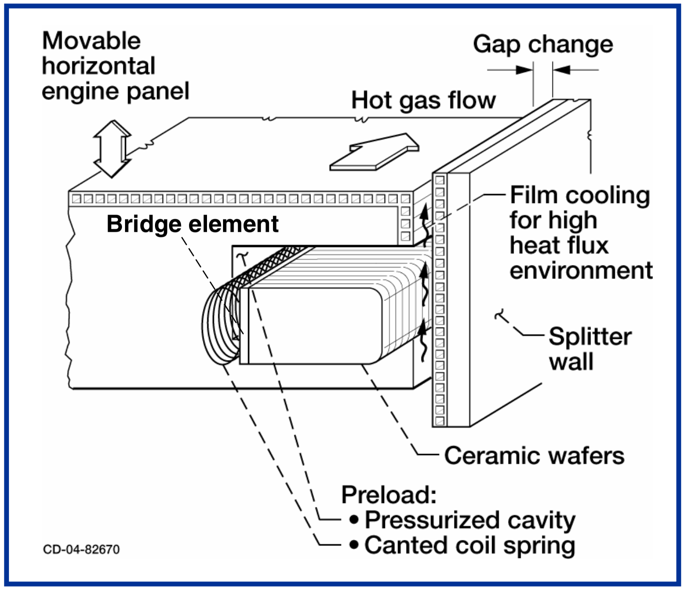
Falcon vehicle

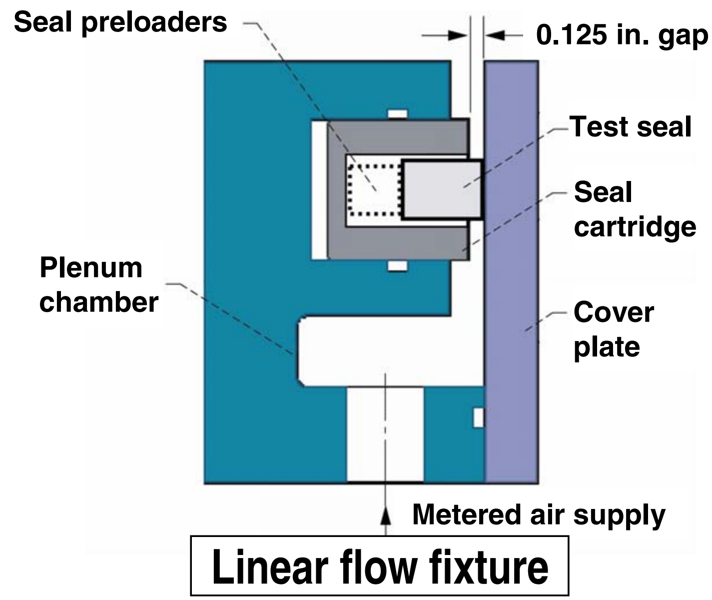
<u>Objective</u>: Develop sealing systems that meet vehicle/system requirements and demonstrate performance in relevant environments

Presentation Outline

- Wafer seals
- Spring tube seals
- High temperature seal preloaders: TZM canted coil springs
- Arc jet test rig

Wafer Seal Geometry/Flow Investigations

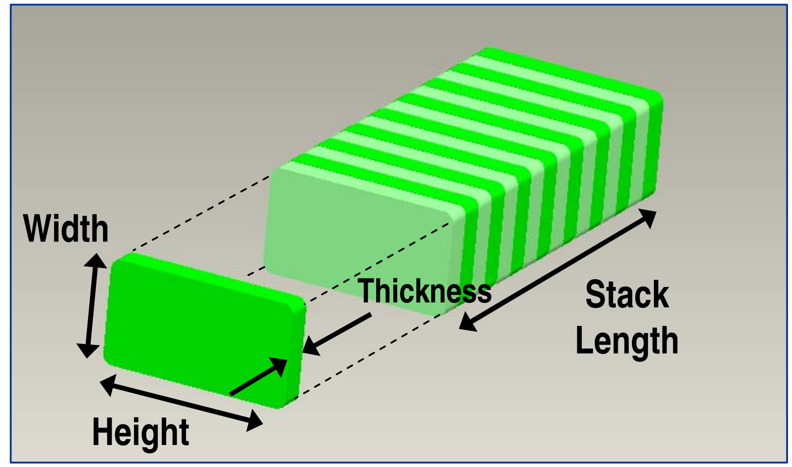


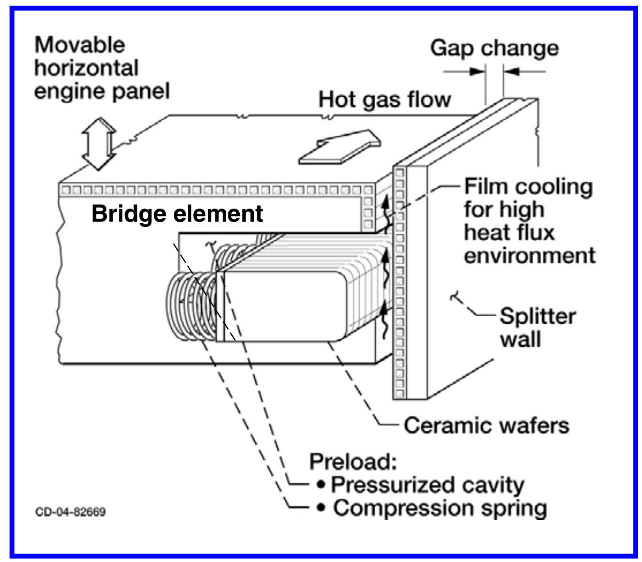


- Previous tests revealed that wafer seal installation factors influenced flow rates
- Objective: Improve understanding of wafer sealing system
- Approach: Parametric studies of performance (flow tests)
  - Design of experiments (DOE) study to evaluate variables that affect seal installation
  - Wafer seal geometry study

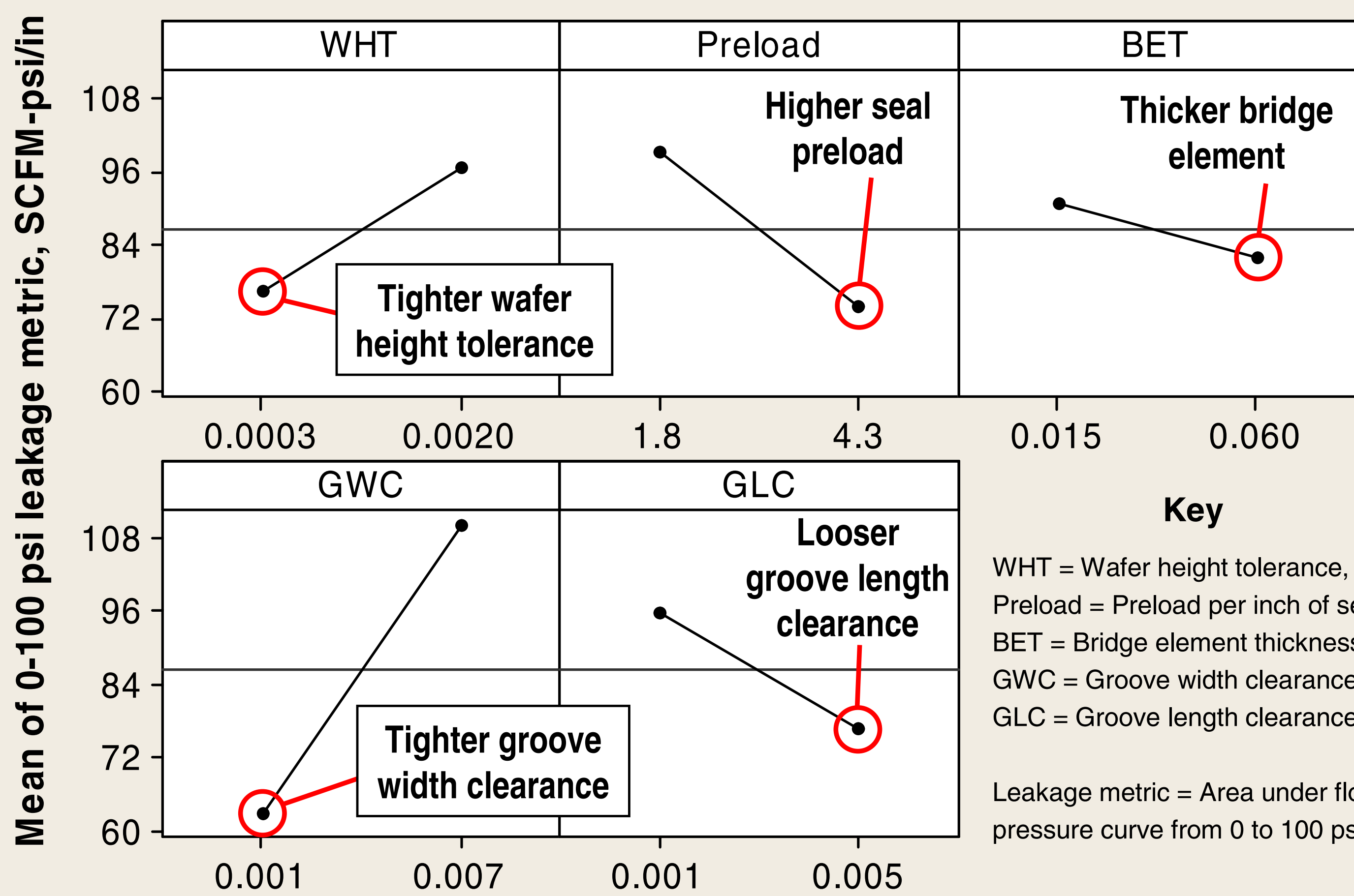
Wafer Seal Installation DOE Study

- Wafer geometry: 0.5 in. wide x 0.92 in. long x 0.125 in. thick
- Five factors evaluated at two levels
  - Wafer height tolerance: 0.0003 and 0.0020 in.
  - Preload: 1.8 and 4.3 lbf per inch of seal
  - Bridge element thickness: 0.015 and 0.060 in.
  - Groove width clearance: 0.001 and 0.007 in.
  - Groove length clearance: 0.001 and 0.005 in.
- Test matrix:
  - 16 trials
  - Fractional factorial design (Resolution V)
  - Tests performed in random order to minimize biases





Results of Wafer Seal Installation DOE Study

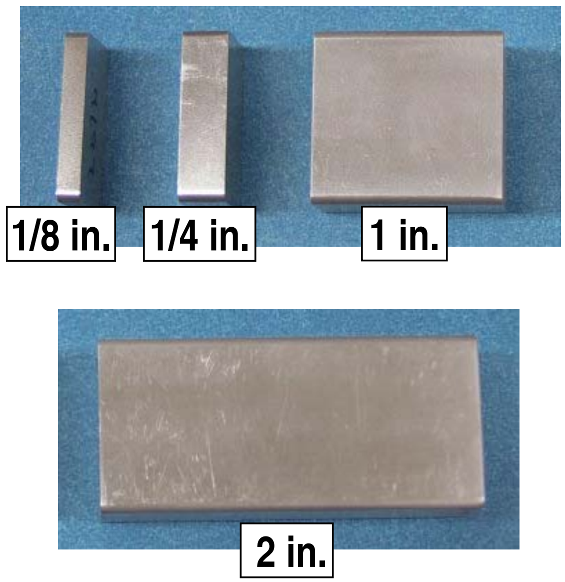


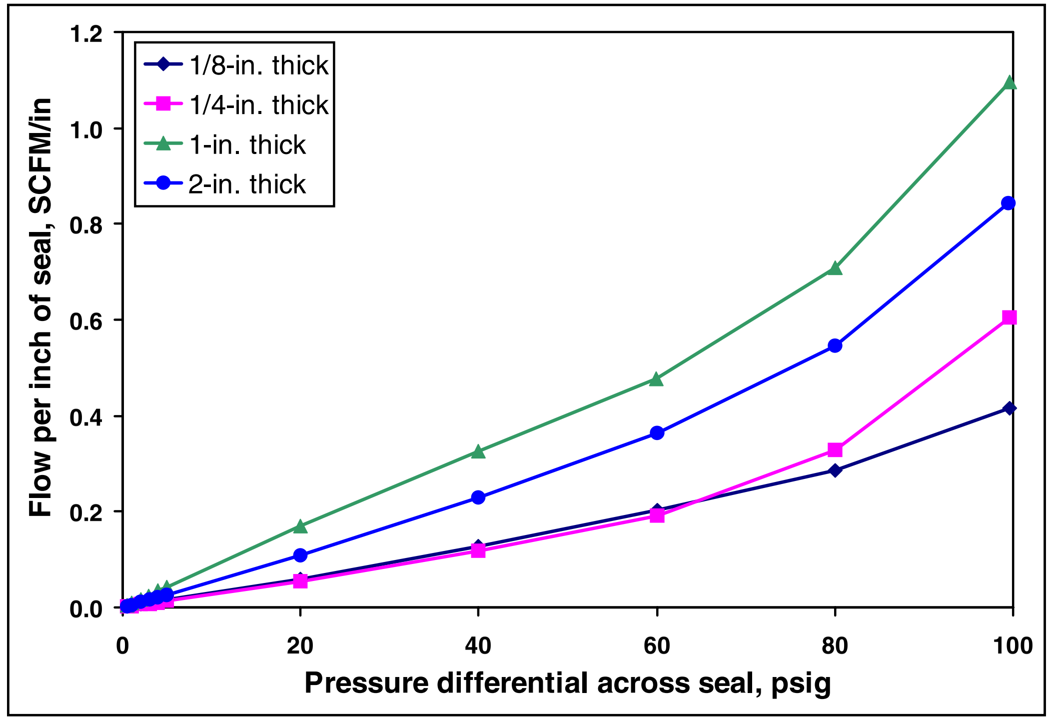
Key

WHT = Wafer height tolerance, in.
Preload = Preload per inch of seal, lbf/in.
BET = Bridge element thickness, in.
GWC = Groove width clearance, in.
GLC = Groove length clearance, in.

Leakage metric = Area under flow vs. pressure curve from 0 to 100 psig

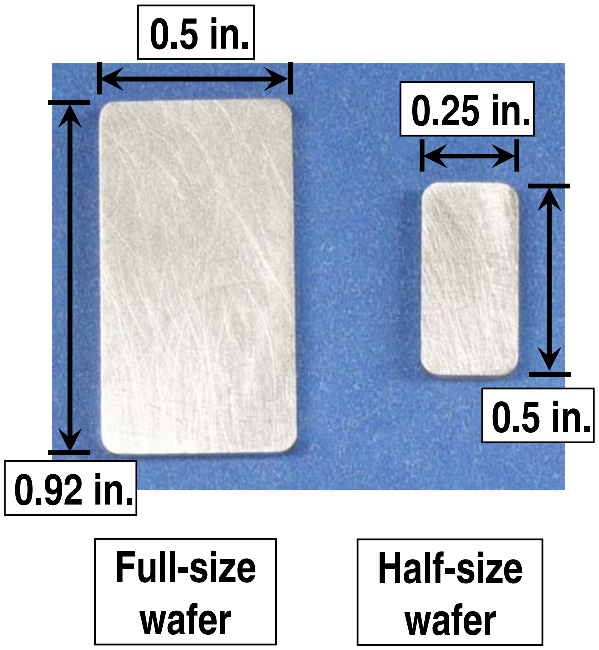
Wafer Geometry Study: Thickness Variations

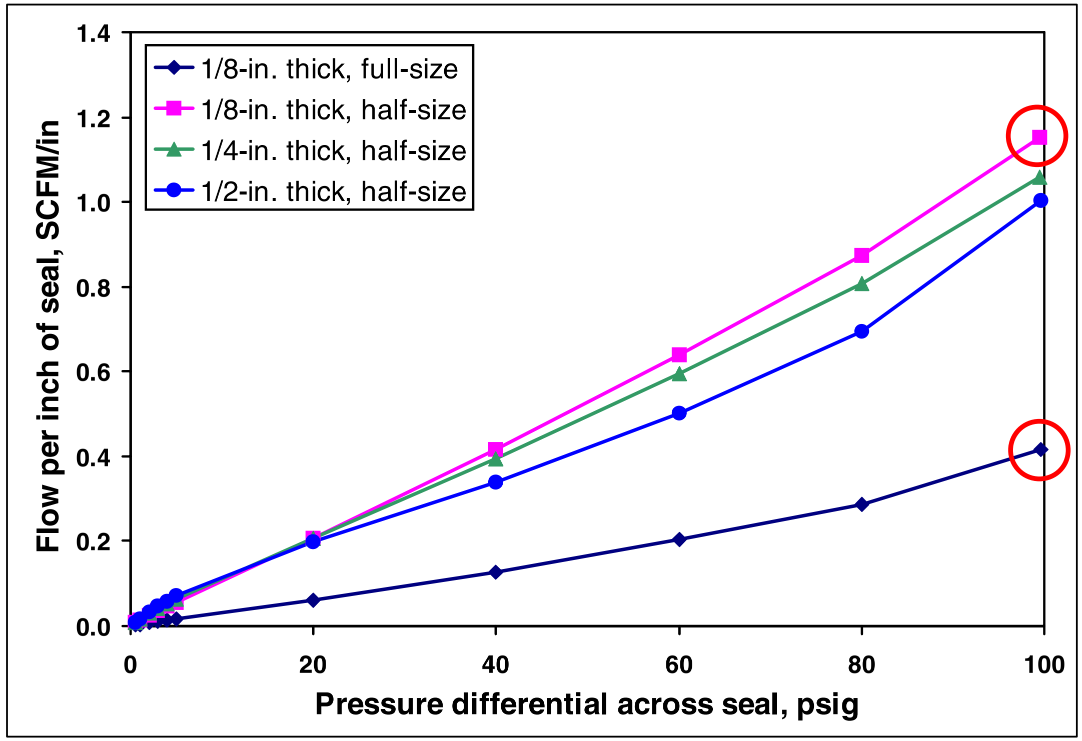




- Motivation: Thicker wafers have lower part count, lower leakage rates?
- Comparable leakage rates for 1/8-in. and 1/4-in. thick wafers: can reduce part count 2X by using 1/4-in. thick wafers
- Higher flow rates for 1-in. and 2-in. thick wafers, less able to conform to wafer misalignments and sealing surface distortions

Wafer Geometry Study: Full-Size vs. Half-Size Wafers

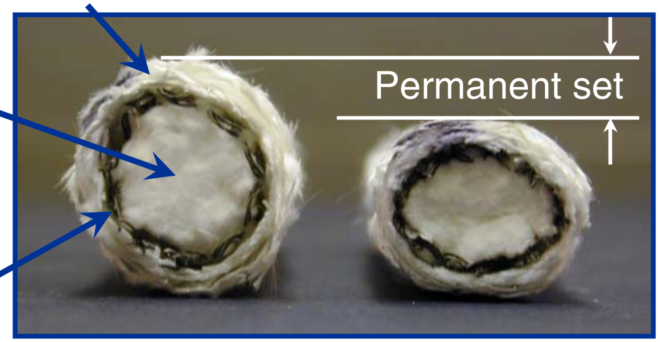




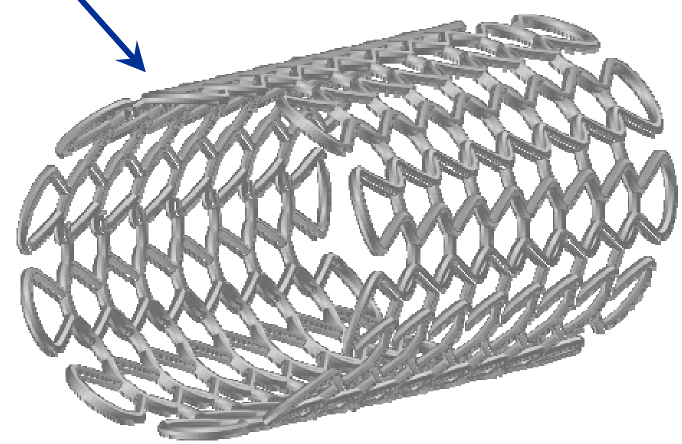
- Motivation: Smaller wafers occupy less space, weigh less, fit in tighter locations
- Flow rates for half-size wafers ~3X those for full-size wafers (1/8-in. thick)
- Can reduce part count 4X for half-size wafers by using 1/2-in. thick wafers vs. 1/8-in. thick (similar flow rates)

Spring Tube Seal Development

- Objective: Improve resiliency of spring tube seals at high temperatures
- Approach: Substitute Rene 41 as material for knitted spring tube vs. Inconel X-750 in baseline design



Loss of resiliency in baseline seal



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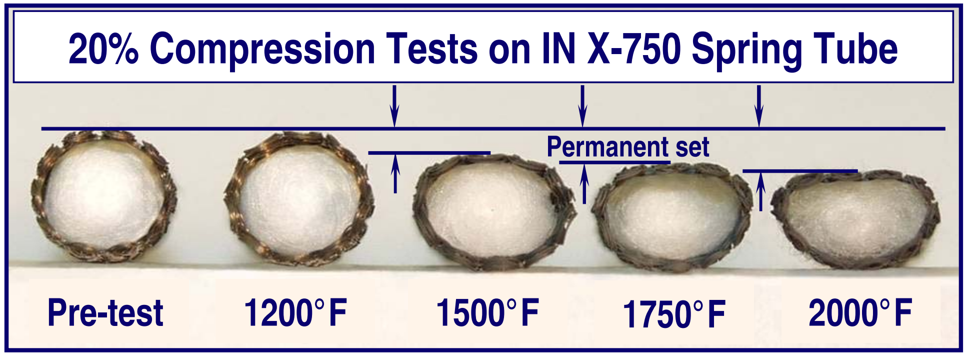
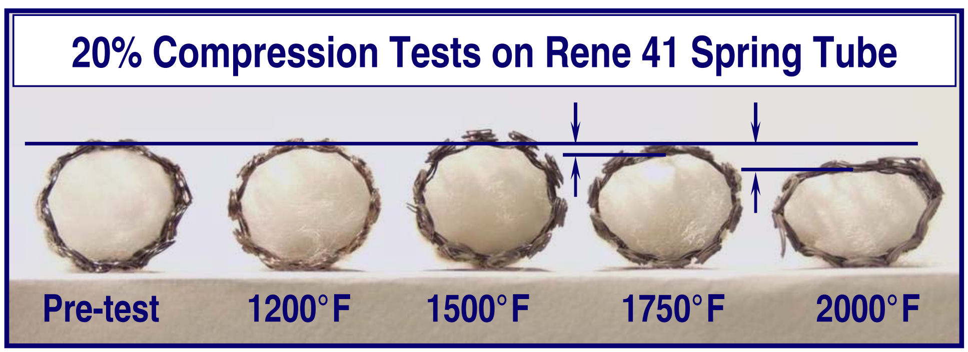
Resiliency Improvement for Rene 41 Spring Tube



Significant permanent set for Inconel at 1500°F



No visible permanent set for Rene until 1750°F

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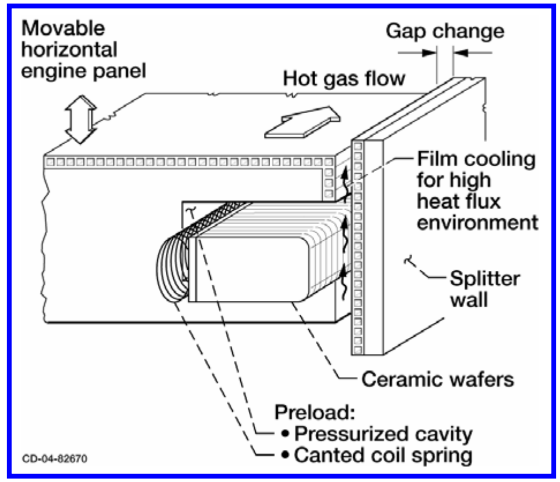
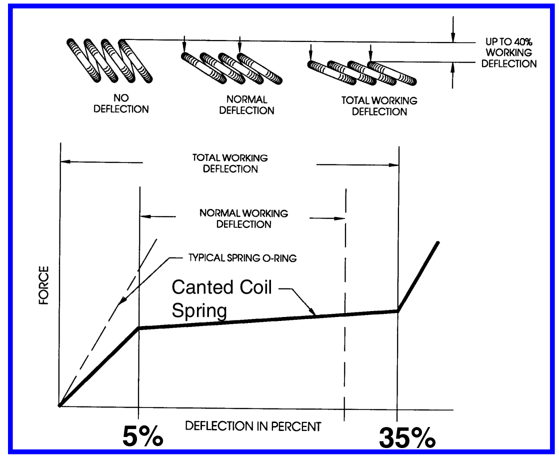
Spring Tube Seals: Go-Forward Plan

- Testing to-date has been on spring tubes by themselves
- Work in progress:
  - Fabricating seals with Rene 41 spring tubes for evaluation (Jackson Bond Enterprises, LLC)
- Future work
  - Perform hot compression tests on new seals to evaluate if resiliency improvements translate to full seals
  - Fabricate and evaluate seals with Kanthal A1 wire overbraid instead of Nextel fabric (improved durability)
  - Fabricate and evaluate seals with engineered cores instead of Saffil (improved resiliency and lower flow rates)

High Temperature Seal Preloader Development: TZM Canted Coil Spring

- Objective: Develop preload devices that provide/augment seal resiliency at high temperatures
- Approach: Pursuing high temperature TZM canted coil springs
  - Unique load vs. displacement curve provides nearly constant force over large range
  - Large working deflection

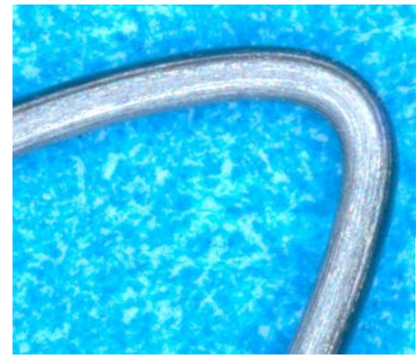




Large working deflection of canted coil spring

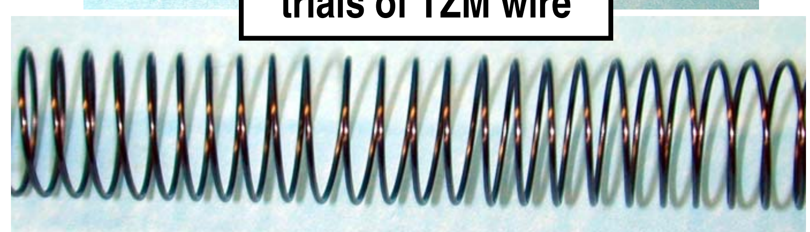
TZM Canted Coil Spring Development

- Recent accomplishments
  - Successfully fabricated split-free 0.025-in. diameter TZM wire with better than expected strength and ductility (Rhenium Alloys, Inc.)
  - Successfully cold-coiled TZM wire into representative spring geometries
- Work in progress
  - Wire coating trails using platinum
  - Wire tensile tests at room temperature and 2300°F
- Future work
  - Assess platinum coating durability via bend tests at 2300°F in air
  - Coil TZM wire into canted coil configuration and perform compression tests to evaluate resiliency



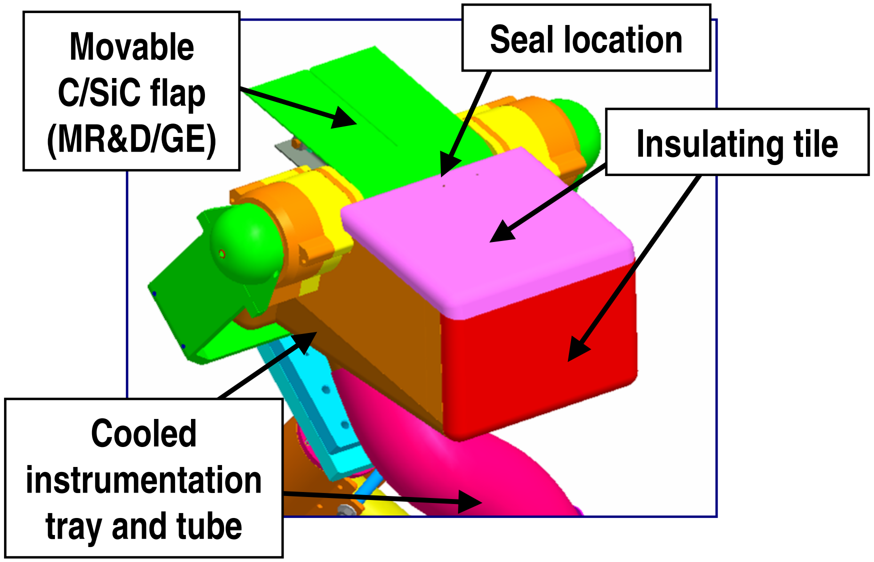
Split-free TZM wire

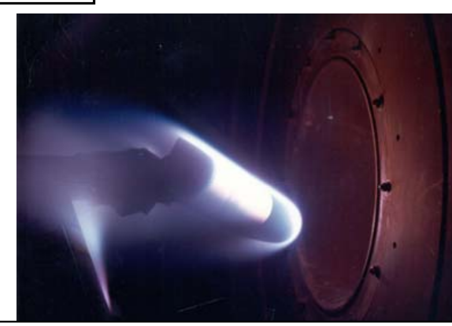
Successful coiling trials of TZM wire



Arc Jet Test Rig Development

- Objective
  - Evaluate seals under simulated reentry heating conditions in JSC arc jet using GRC-developed test fixture
- Features
  - Unique GRC design permits testing of different seal and flap designs/materials
  - Modular seal cartridges enable rapid exchange of seal specimens
  - Motor-driven flap moves during testing to simulate flight
  - Adjustable angle-of-attack and yaw angle permit investigation of different flow conditions
  - Instrumentation records temperatures and pressures around seal and flap
  - Cooled subassembly permits time-at-temperature tests

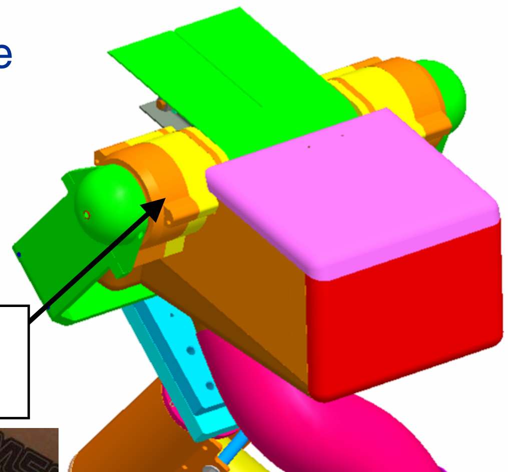


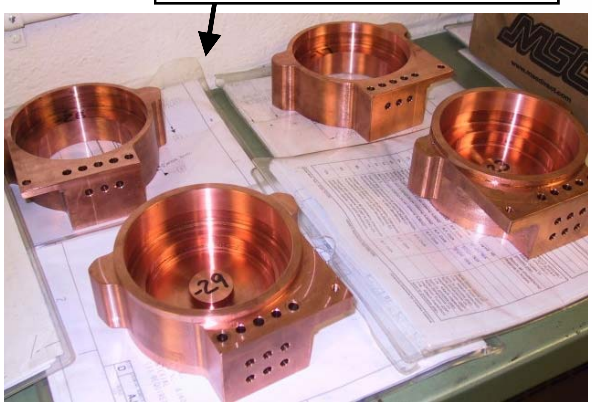


Typical arc jet test at JSC

Arc Jet Test Rig – Status

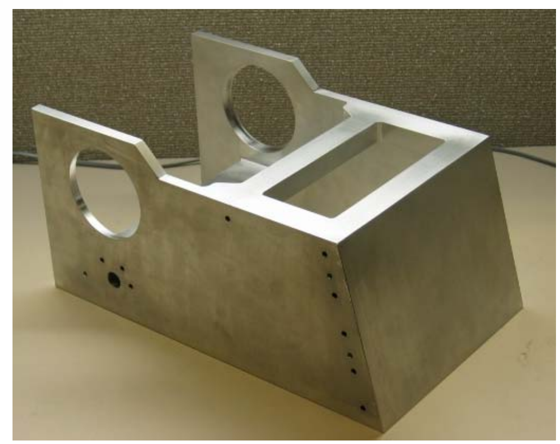
- Fabrication is underway (Cook Manufacturing Co.)
- Schedule:
  - Complete test fixture fabrication and assembly: 1Q FY06
  - Perform tests at JSC: FY06-07





Cooled copper motor and brake housings

Wax model of sidewall showing cooling channels



Aluminum mockup of leading edge

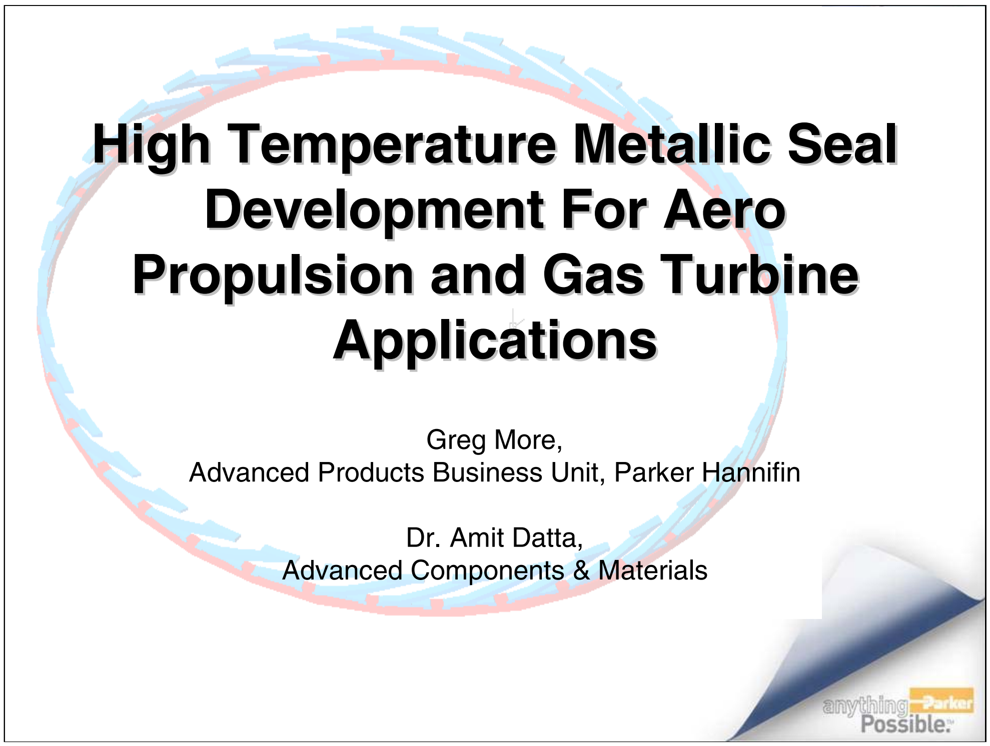
Summary

- GRC Structural Seals Team developing key seal technologies for NASA's Exploration Initiative and hypersonics programs
- More details in presentations to follow…

HIGH TEMPERATURE METALLIC SEAL DEVELOPMENT FOR AERO PROPULSION AND GAS TURBINE APPLICATIONS

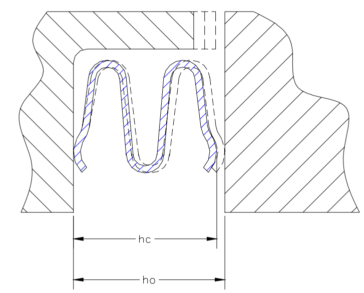
Greg More
Parker Hannifin
North Haven, Connecticut

Amit Datta
Advanced Components & Materials
East Greenwich, Rhode Island



High Temperature Static Seal Development

- Industry Requirements – Industry is requiring seals to operate at higher and higher temperatures.
  - Greater efficiency
  - Reduced cooling air requirements
- Seal Problem – Traditional seal designs and materials experience stress relaxation. Over time seals loose their ability to maintain contact with moving flanges.
- Solution – High temperature seal development program
  - Multiphase program with incremental increases in seal operating temperatures

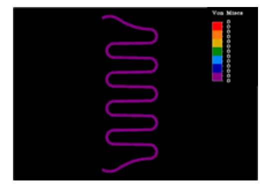


Seal gap is created resulting from stress relaxation at elevated temperatures. The original seal height ho is reduced to hc creating a gap when the flange moves away from the compressed condition.

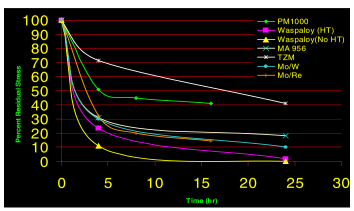
Program Review

High temperature seal development program review

Phase I : Improved traditional sheet metal seal design and analysis

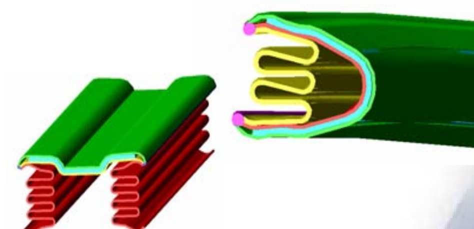


Phase II : Higher temperature sheet metal materials and improved thermal processing



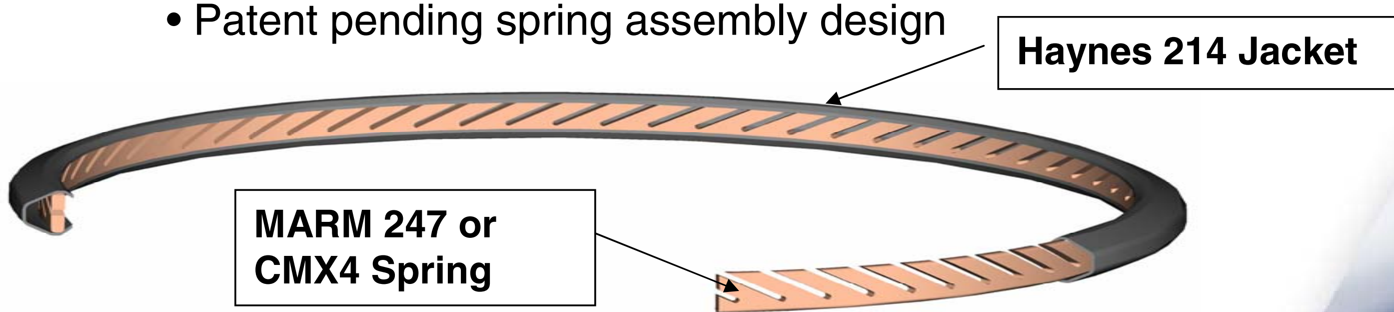
Phase III :Thermally insulated seals

Phase IV : High temperature single crystal material spring element



Phase IV : Innovative Seal with Blade Alloy Spring

- In order to achieve next temperature range a different, non-traditional sealing, methodology is utilized
- Utilize a high temperature spring material that is currently used, well known, and has good operating experience in the Gas Turbine industry
- Outer jacket performs sealing function
  - Thin cold formable alloy jacket provides a continuous sealing surface
- Inner spring provides high temperature load and elastic recovery
  - Cast blade alloy spring energizer for operation up to 1800 °F
  - Patent pending spring assembly design



Phase IV : Innovative Seal with Blade Alloy Spring

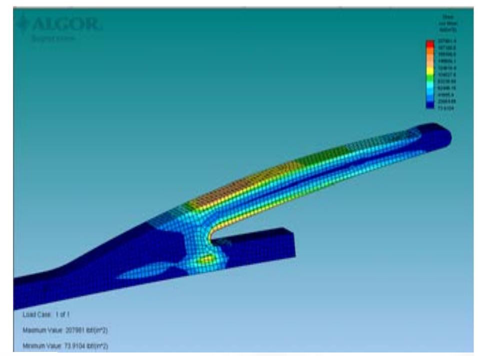
Cast Blade alloys have extremely high strength

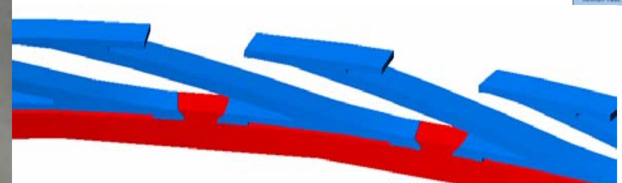
Alloy	Temperature,º F	Yield Strength,ksi	Elongation,%
MARM 247, poly crystal	1400	130	12
CMX4, Single crystal	1600	114	18
INCO 718,poly crystal	1472	100	10
Waspaloy,poly crystal	1600	75	35

- Blade alloys also have superior creep and stress rupture strength compared to cold formable superalloys. Hence, blade alloys have higher resistance to stress relaxation.
- Manufacturing Challenge - Blade alloys are only available in the cast condition (poly or single crystal)

Spring Design

- Prototype I
  - Solid ring machined from a single casting
  - Basic finger design, not optimized with FEA
  - Opportunities for design and manufacturability enhancements
- Prototype II
  - Independent finger and support ring configuration
    - Improved DFM and lower manufacturing cost
    - Fine tune spring load and seal load
      - Adjust number of the number of fingers
  - FEA optimized finger configuration
  - Significantly improved stress relaxation characteristics



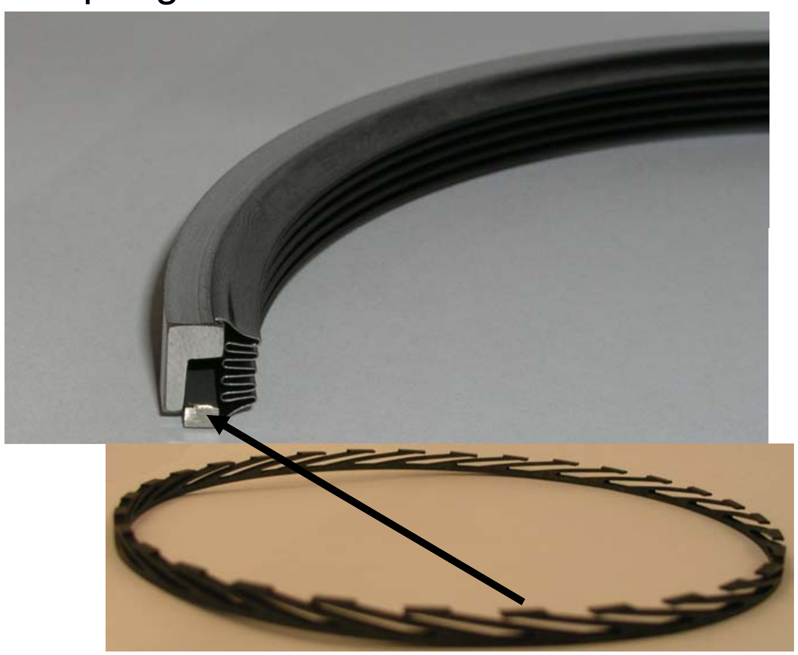


Phase IV : Innovative Seal with Blade Alloy Spring

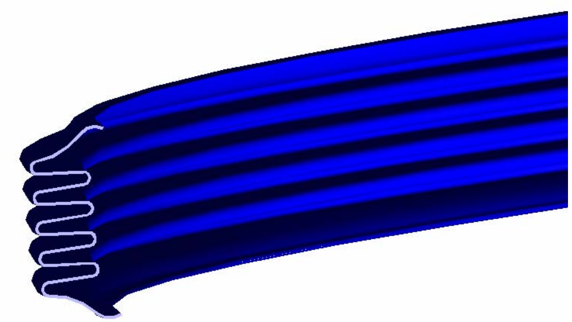
Cross Sectional comparison of high temperature sealing designs

High temperature modular seal

- Standard E-Seal with blade alloy spring



Traditional E-Seal produced from high temperature Waspaloy alloy



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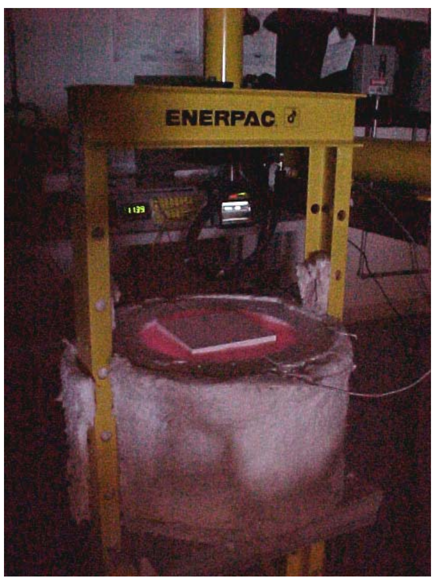
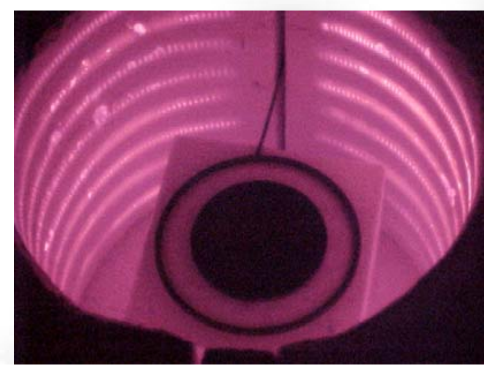
Phase IV : Innovative Seal with Blade Alloy Spring

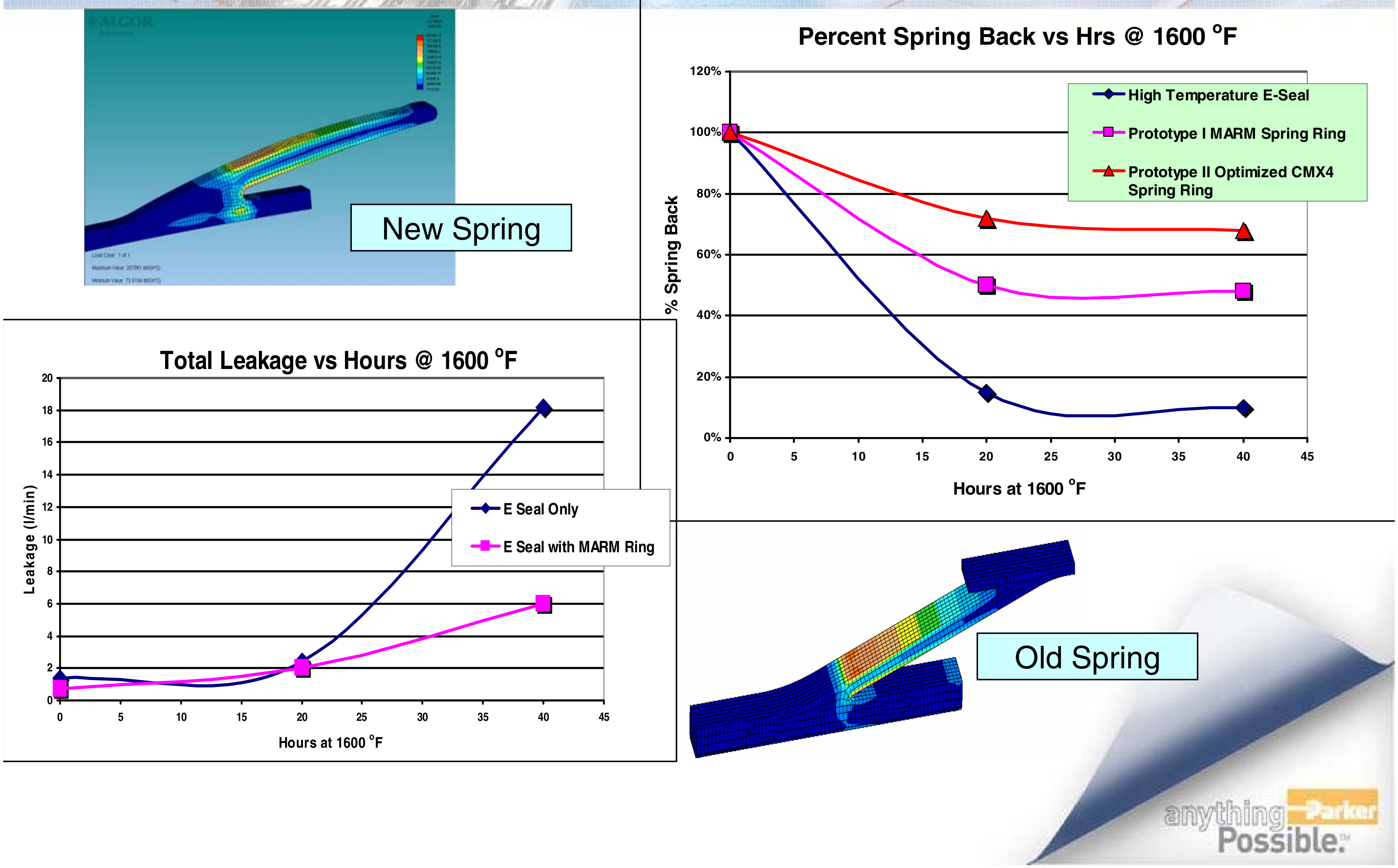
Performance testing experimental procedure:

- Stress relaxation
  1. Seals were compressed 12% between flanges and heated to 1600 ^{o}F for specified time periods
  2. After each exposure, seals were cooled to room temperature to measure change in seal free height
  3. Change in seal free height is then used to calculate usable seal springback
- Leakage testing
  – Identical to steps 1 – 3 above and seals were room temperature leakage tested as step 4



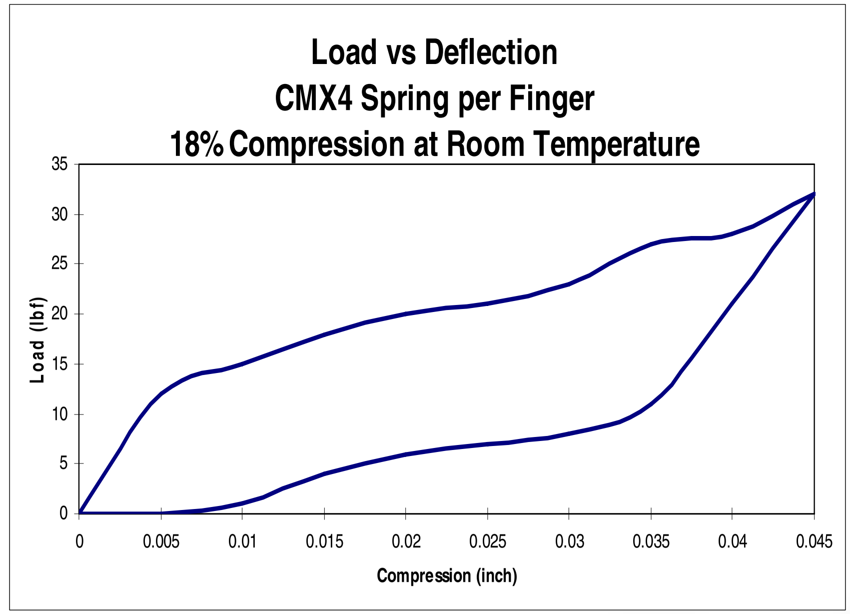


Phase IV : Testing Results



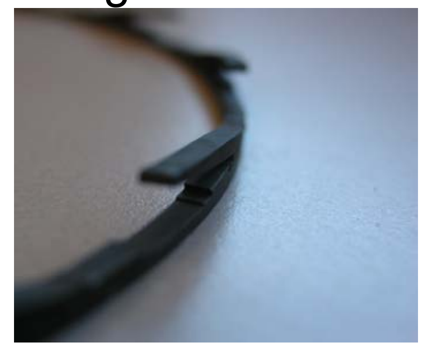
Seal Seating Load

- An important design feature of the modular manufacturing process is seal seating load tune-ability
  - Seal seating load can be adjusted
  - This combination yield a seal seating load of 19 lb/inch of seal circumference
    - Comparable with a traditional E-Ring type seating load
  - Other loading levels could be selected based on hardware and desired leakage rate
- As can be seen from the load vs deflection curve, the FEA optimization worked well and resulted in a large elastic operating range



Spring Seal Manufacturing

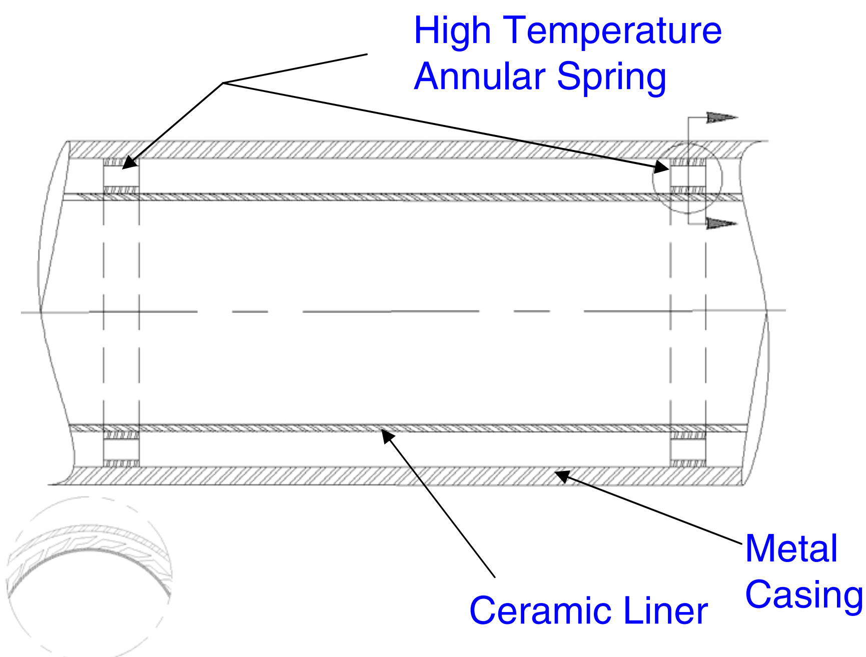
- Thought and effort has been applied to reduce manufacturing costs and lead times
- Modular manufacturing approach
- Seal outer sheet metal jacket
  - Standard E or U type seal cross section
  - No special tooling or processing are required
- Inner spring
  - Single crystal spring finger can be investment cast in near net shape
  - Spring finger geometry will be fixed independent of seal diameter
    - Spring fingers can be held in inventory for a fast seal manufacturing process
    - Retaining ring diameter will set spring assembly diameter
  - Spring material is readily available and is currently widely used and accepted
  - Retaining ring will be machined from a lower cost alloy
    - Stresses within retaining ring are comparably low, therefore commonly used superalloys such as Inconel 718 can be used
  - Spring fingers can be easily joined (welded or brazed) to the spring ring
  - Number of fingers will govern overall seal seating load
- Patent pending manufacturing and processing approach



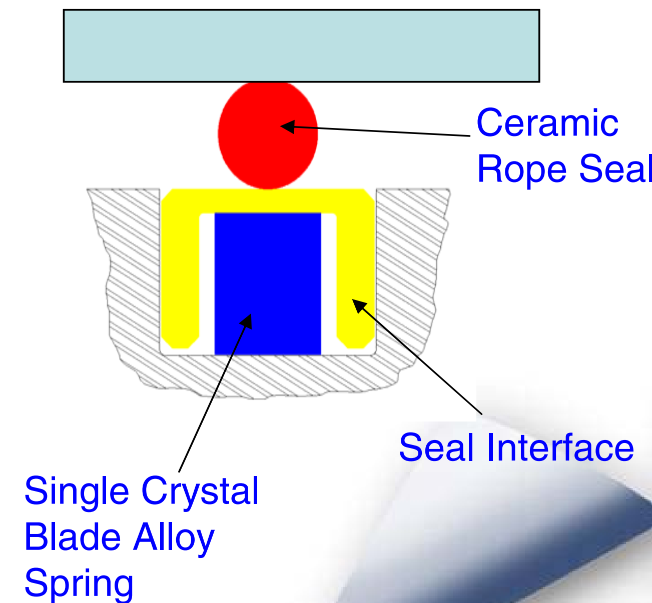
Other Applications for High Temperature Spring Design

Transition fastener between metal and ceramic components with a large α-mismatch

Combustor CMC liner– low load, large deflection spring at 1800F



Low-load/ high deflection spring energizer for extremely high temperature (>2000F) ceramic sliding seal



Conclusions

- The Ultra High Temperature seal program has successfully progressed and developed industry accepted high temperature static seal solutions
- The next phase of higher operating temperature seals is progressing well
  - First prototype showed very promising results
  - Second prototype proved further enhancements were possible
    - Modular design can be used to create a cost effective and rapid turn around solution
    - Seal seating load can be adjusted to match the desired application
    - Additional stress relaxation resistance was available through spring optimization
- Future activities
  - Stress relaxation testing at 1600 °F shows good usable performance, next phase will be to perform testing at 1700 °F and 1800 °F
  - Slight further optimization of the spring fingers and manufacturing of cast fingers preparing for full product launch

Questions ?

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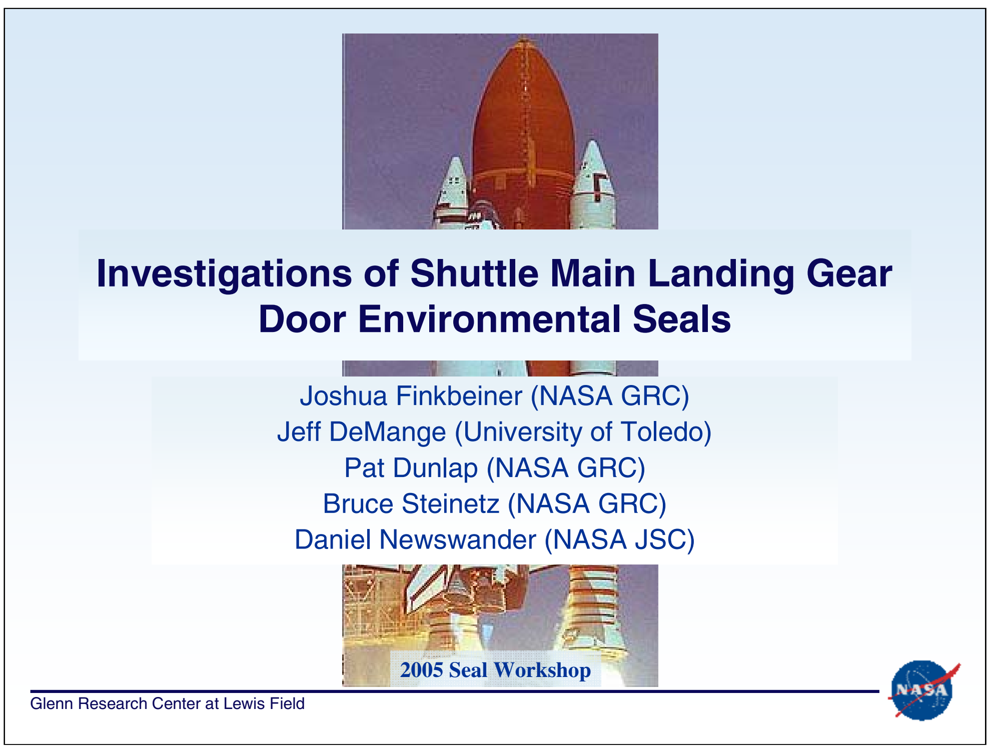
INVESTIGATIONS OF SHUTTLE MAIN LANDING GEAR DOOR ENVIRONMENTAL SEALS

Joshua Finkbeiner
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Jeff DeMange
University of Toledo
Toledo, Ohio

Pat Dunlap and Bruce Steinetz
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Daniel Newswander
National Aeronautics and Space Administration
Johnson Space Center
Houston, Texas



Overview

- CAIB investigation and request for examination of Main Landing Gear (MLG) door seals
- NASA GRC's involvement in investigation
- Description of MLG door environmental seals
- Results from compression testing
  - Exploratory (installation/mounting conditions)
  - Systematic
- Results from flow testing
- Seal performance conclusions

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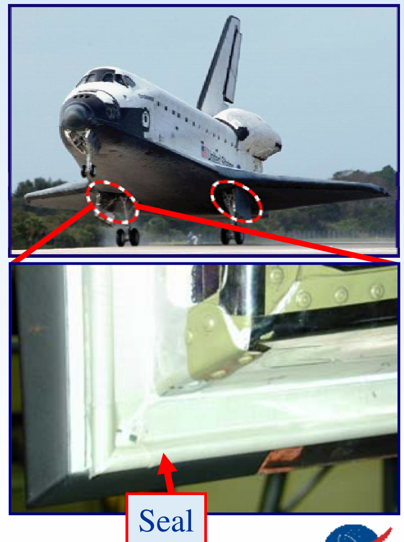
Investigation of Main Landing Gear Door Seals

- Columbia Accident Investigation Board (CAIB) requested investigation of MLG door environmental seals
  - Assess potential contribution of seals to loss of STS-107
  - Assess safety issues of seals for future flights
- Environmental seals provide pressure-blocking capability to MLG doors
- Upstream thermal barrier not investigated in this study



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The Columbia Accident investigation Board (CAIB) requested an investigation into the MLG door seals. Initially, the MLG door seals were thought to have been a potential contributor to the loss of Columbia. These suspicions were later found to be untrue, but the seals remained as a cause for concern in future flights.

MLG door seals comprised of thermal barrier and environmental seal. This study focuses on the environmental seal for the MLG door. Photograph shows the installed environmental seal on the MLG door. Tape behind seal is removed before door closure.

Findings from Investigation of MLG Door Seals

- Installation and maintenance procedures problematic
  - Seal compression specified in certification documents
  - Compression procedures not specified in installation/rigging drawings
  - Seal maintenance procedures not specified between flights
- Damage to seals
  - Permanent deformation of seal bulb from OV-103
  - Clay compression test demonstrated seals did not meet certified compression requirements

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The investigation into the Shuttle MLG door seals found several problems with the seals.

First, the installation and maintenance procedures were found to be potential problems. The seal certification documents specified the minimum amount of compression to be applied to the seals (after maximum flight deflections of the MLG door), but neither the seal installation drawings nor the door rigging drawings provided any procedure to ensure that this minimum compression be met. Furthermore, no maintenance drawings or procedures existed for the seals, such that there were no documented means to ensure that the seals continued to be compressed to their certified compression levels, either by adjustment or measurement & replacement of the seals.

In addition, the investigation found that the seals installed on OV-103 (Shuttle Discovery) were permanently deformed and damaged from repeated use. The damaged varied from a small amount of deformation ("good", right) to heavy deformation ("bad", left). Clay compression tests demonstrated that the damaged seals did not meet certified seal compression requirements.

Replacement of Seals and Subsequent Problems

- Steps to satisfy seal certification documentation
  1. Old (Rev. M) seals replaced with new (Rev. P) seals
  2. Shims added to sealing surface to ensure proper seal compression
- Modifications prevented full closure of MLG door
  – Door retraction mechanism linkage near-overload
  – Previous experience (ca. 1991) demonstrated that overload conditions damaged door retraction linkage mechanism
- NASA Johnson Space Center (JSC) requested testing of MLG Environmental Seals at NASA Glenn Research Center (GRC)

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Several steps were taken to alleviate the potential problems with the environmental seals.

The old Rev. M seals were replaced with new Rev. P seals to eliminate permanent deformation. In addition, constant-thickness shims were added to the sealing surface (MLG bay) to ensure that the seals would always be compressed to their certified amounts after accounting for maximum flight deflections of the MLG door.

However, after making these modifications, the MLG doors could not be closed. The modified seals generated loads approaching mechanical limits on the door retraction mechanism linkages. Previous experience (ca 1991) had demonstrated that higher preloads caused damage to the linkage, and thus engineers were reluctant to increase the preload on the linkages to close the MLG door.

At this point, NASA JSC requested that NASA GRC conduct tests of the MLG environmental seals.

Involvement of NASA GRC

- Exploratory compression testing to assist in closing MLG doors
  - Understand mounting and setup effects on seal loading
  - Provide options for reduction in seal loading
- Systematic testing
  - Fill out seal performance database
    - Compression
    - Flow (0%-63% compressions)
  - Determine new seal (Rev. P) performance relative to old seal (Rev. M) performance

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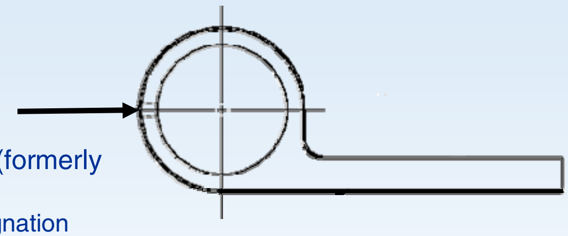
NASA GRC's testing of the MLG seals was performed in two parts with two primary goals.

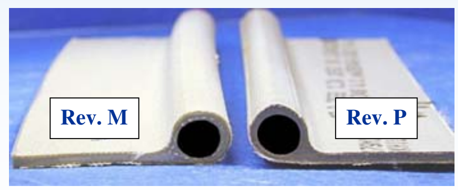
First, exploratory tests were conducted on the seals to understand the loading characteristics of the seals. These exploratory tests were to investigate installation variables on the seals and would ultimately provide options to reduce the amount of load generated by the seals.

After the exploratory tests, a series of systematic tests were conducted. The seal performance database was incomplete in both compression and flow data, and GRC's testing rectified this. In addition, the GRC tests determined the performance of the new Rev. P seal relative to the old Rev. M seal. If the Rev. P performance closely matched Rev. M performance, the new seal would be shown to meet the certification requirements and would not have to be recertified (a lengthy procedure).

Description of MLG Environmental Seal

- Silicone rubber core
- Nomex fabric overwrap
- Vent holes every 6 in.
- Two revisions
  - Rev. M - old revision (formerly flown)
    - Nomex fabric impregnation
    - Higher stiffness
  - Rev. P - new revision (installed on STS-114)
    - Material slightly darker than Rev. M
    - No Nomex impregnation
    - Lower stiffness





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The Orbiter MLG environmental seal is made of a hollow bulb section attached to a solid tail section. Both are composed of silicone rubber (ZZ-R-765, Class IIIa, Grade 50) overwrapped with Nomex fabric.

Since the seals are designed to work in space (i.e. vacuum conditions), vent holes are included every 6 in. in the front of the seal bulb. These holes allow pressure in the interior of the bulb to vent to ambient pressure, preventing damage to the seals.

Two revisions of the seal were tested in this study. The old type of seal, Rev. M, was removed from OV-103 during the initial investigation of the seals. It features an additional Nomex fabric impregnation of the silicone rubber material, particularly in the bulb.

The new seal revision, Rev. P, lacks the Nomex fabric impregnation of the silicone rubber. The lack of Nomex impregnation leads to a seal which is less stiff to the touch than the old Rev. M seal. The Rev. P seal material is also a slightly darker color than Rev. M, indicating a possible change in composition of the silicone rubber.

Damage to Rev. M Seals Removed from OV-103

- Seal samples removed from starboard MLG door
- Samples represented extremes of damage
  - "Good" seal deformed ~0.035 in.
  - "Bad" seal deformed ~0.110 in. - 0.160 in.
- Sample locations
  - "Bad" seal taken from hinge side of door
  - "Good" seal taken from rear of door

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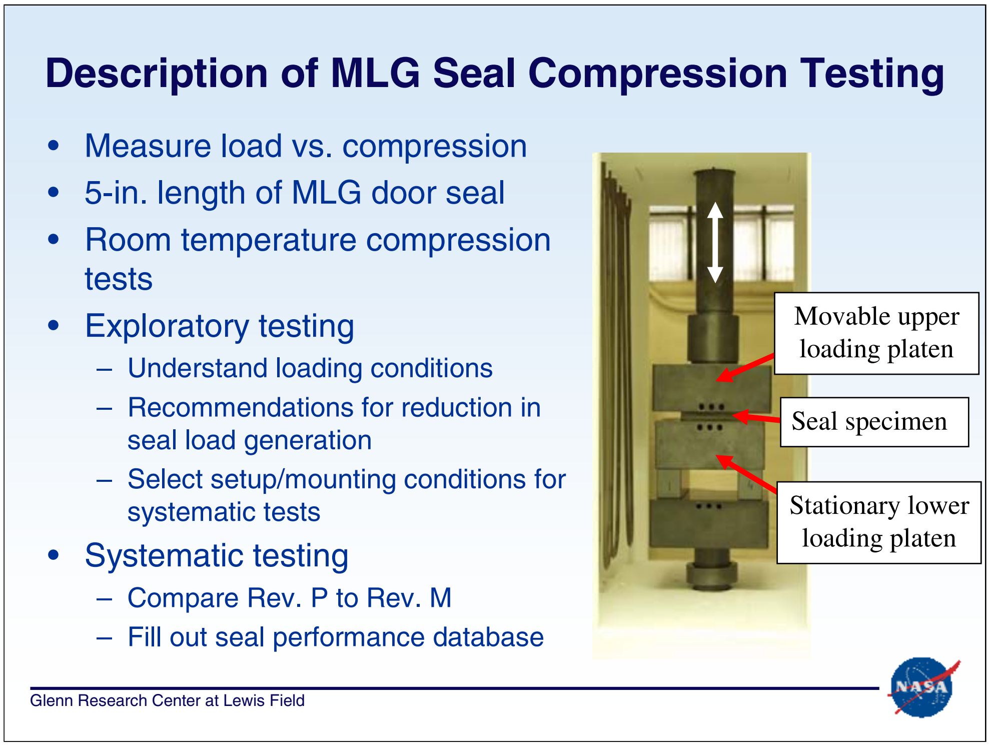
In addition to the as-received Rev. M and Rev. P seals tested in this study, seals removed from the starboard MLG door of OV-103 were also investigated. Specimens representing the extremes of damage to the Rev. M seal were taken. The "good" specimen was measured to be deformed approximately 0.035 in. relative to a pristine specimen, while the "bad" seal showed heavy damage with deformations varying between 0.110 in. and 0.160 in.

The "bad" seal was taken from locations along the hinge line of the door, while the "good" seal was removed from the rear of the door.



Compression testing on the MLG seals was conducted in NASA GRC's Compression Rig. The rig consists of a movable upper and stationary lower loading platens. The seal specimen is placed between the two platens and compressed by the upper platen. Generated load is measured by a load cell in-line with the lower platen, and compression is measured by an LVDT connected to the upper platen. All compression specimens in this study were 5 in. in length.

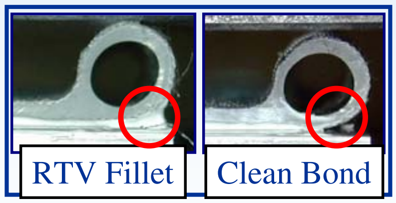
The first set of tests were exploratory tests to better understand the mounting conditions of the MLG seals. After these tests, GRC provided JSC/KSC with recommendations to decrease seal load generation and allow closure of the MLG doors.

The systematic testing was performed to compare Rev. M seals to Rev. P seals and demonstrate that the Rev. P seals serve as an acceptable substitute for the Rev. M seals. Additionally, the systematic tests were designed to fill out the seal performance database for future reference.

Exploratory Testing Variables

- Effect of Groove

- Effect of RTV fillet



- Effect of loading speed
  - 0.002 in/sec
  - 0.200 in/sec

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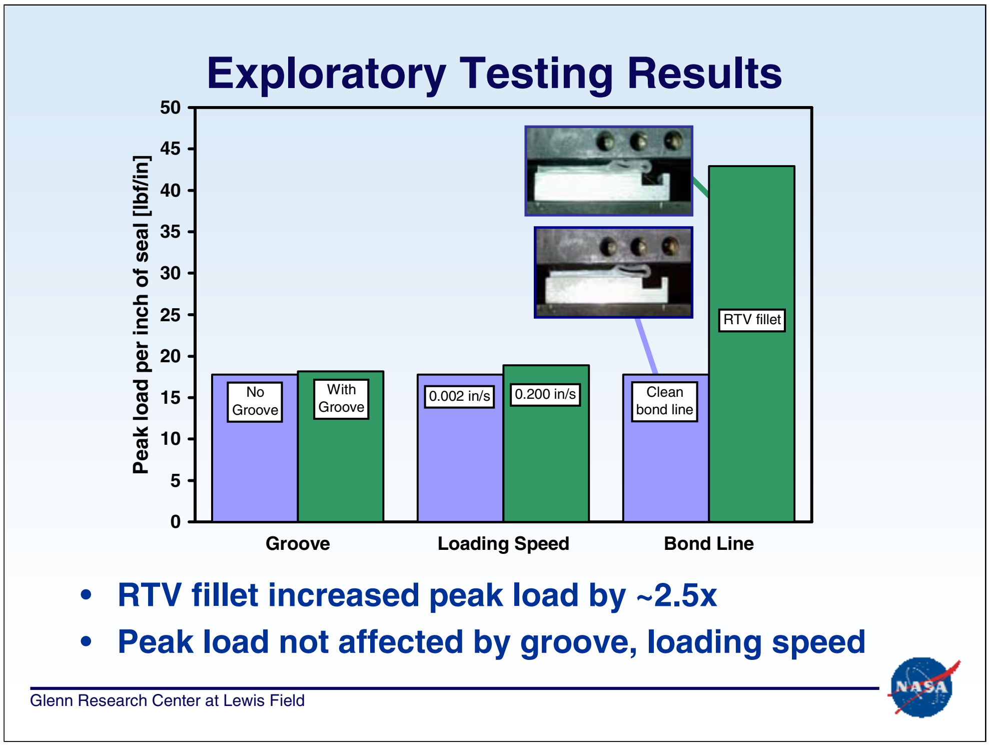
Three variables were examined during the exploratory tests. First, the presence of a groove adjacent to the seal bulb was evaluated. Actual Orbiter mounting conditions include the groove.

Second, the presence of an RTV fillet under the seal bulb was examined. Excess RTV was observed along the seal bulb in the newly-installed seals on OV-103.

Finally, the speed at which the seals were loaded was varied between 0.002 and 0.200 in/sec. The doors typically close quickly, so that the faster loading speed is believed to be a better representation of Orbiter conditions than the slow speed.



Compression results for exploratory tests with only the first cycles of each test shown. The graph is % compression vs. load generated in the seal, and the arrows indicate the different paths for loading and unloading portions of the testing cycle. The first five tests show results which are nearly identical, demonstrating that the presence of the adjacent groove and the seal loading speed do not affect the test results. The sixth test (blue curve) demonstrates that the presence of the RTV fillet increases the load by as much as a factor of three.

Findings from Exploratory Tests

- Implications for Return to Flight
  - GRC recommended removal of RTV fillets from OV-103 seals
  - Seal installation procedure amended to include removal of excess RTV
- Systematic test variables selected as:
  - 0.200 in/sec loading
  - Groove adjacent to seal bulb
  - No RTV fillet

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GRC recommended to JSC/KSC that removal of excess RTV from under the seal bulb would reduce generated loads and possibly allow MLG door closure. The seal installation procedures were amended to include the removal of excess RTV.

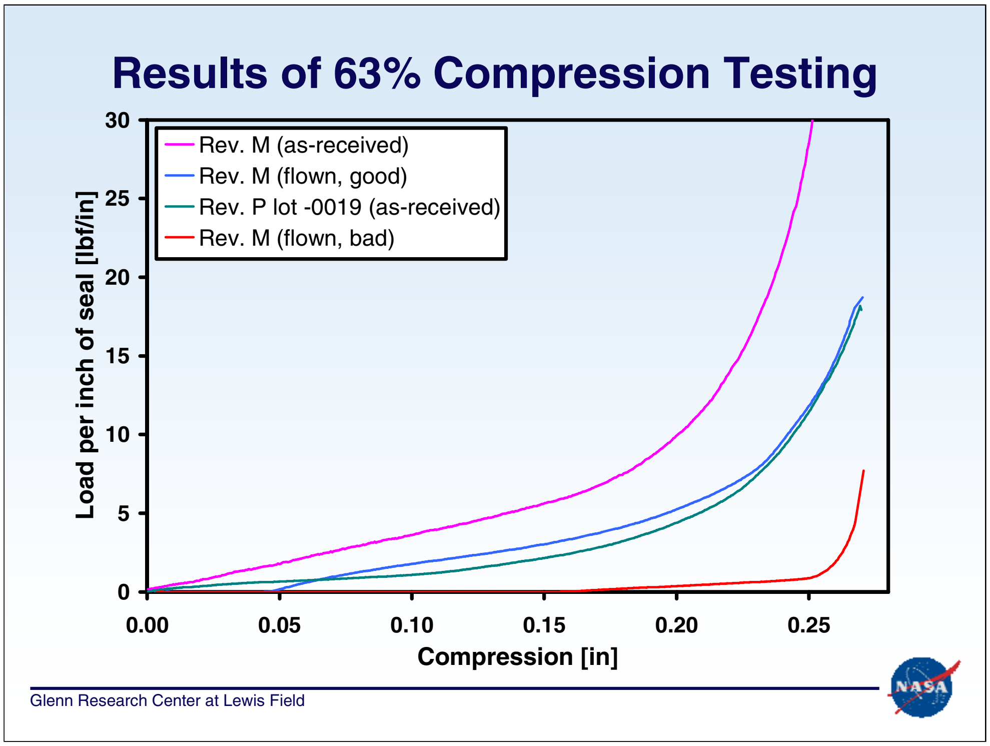
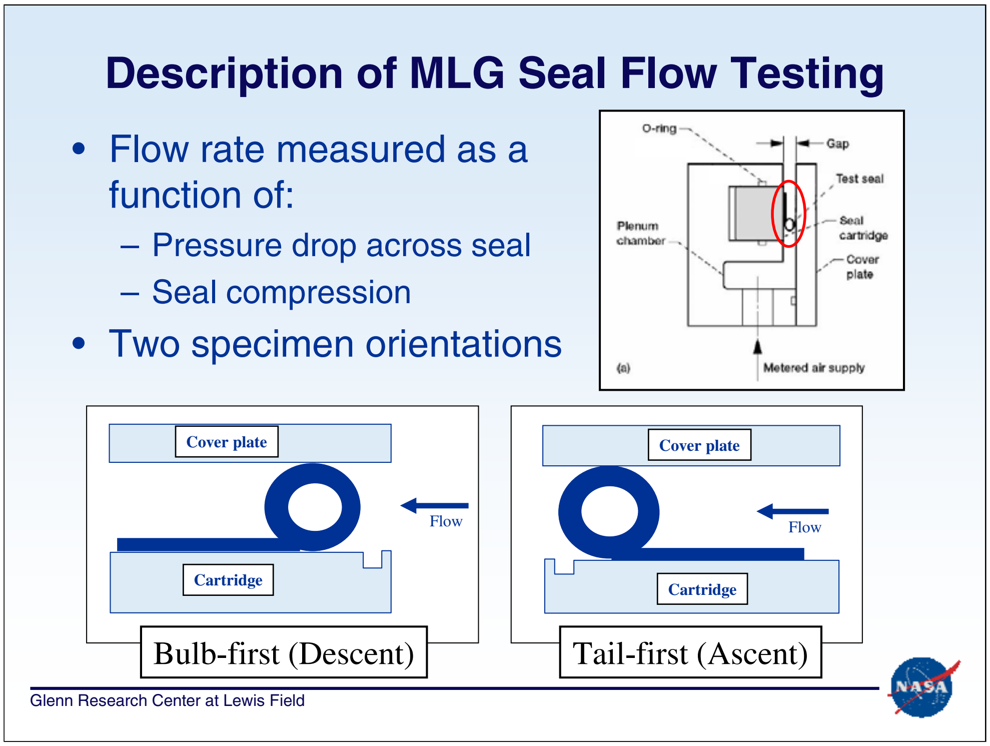


Chart shows results from four seals (two as-received, two flown) for systematic compression tests. The graph is compression distance [in] vs. generated load per inch of seal. The as-received Rev. M data is plotted twice: once in its as-measured state, and once shifted to the right (i.e. higher compression) by 0.035 in.

The as-received Rev. M specimen demonstrated the highest loads of the specimens tested, and the "bad" flown Rev. M demonstrated the lowest. With approximately 0.160 in. of permanent set, the "bad" flown specimen did not generate load until the upper platen contacted the bulb.

The as-received Rev. P data falls far below the as-received Rev. M specimen and is even lower than the "good" flown seal data. The reduction in generated load may be due to the lack of Nomex impregnation of the seal bulb. The as-received Rev. M seal generated five times the load of the as-received Rev. P seal for 63% compression.

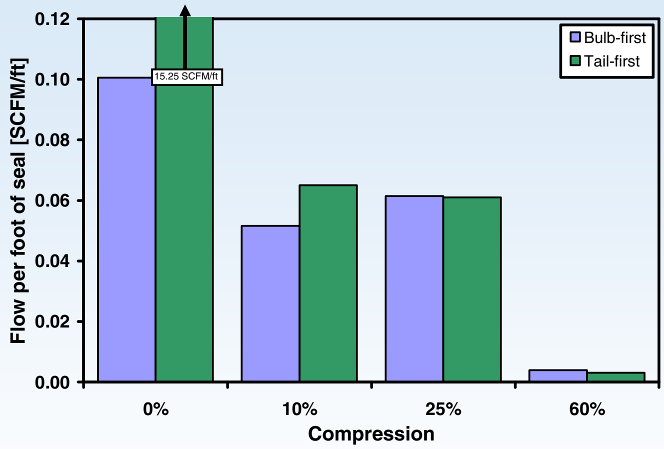
What does this mean? Rev. P seals may be used as replacements for Rev. M seals without danger of overloading Shuttle structures. As-received Rev. P seals can be expected to generate lower loads (as much as five times) than as-received Rev. M seals. Permanent deformation in the seal bulb reduces the load generated by the seal.



Seals in the bulb-first orientation are pressurized similarly to those on shuttle descent when the pressure outside the MLG bay exceeds that inside the bay.

Seals in the tail-first orientation are pressurized similarly to those during shuttle ascent when the pressure inside the MLG bay exceeds that outside the bay.

Flow Test Results (Rev. P Seal)



- Bulb-first (descent) flow rates below 3 SCFM/ft leakage limit
- Tail-first (ascent) flow rates much higher at low compressions
- Effect of orientation disappears by 25% compression

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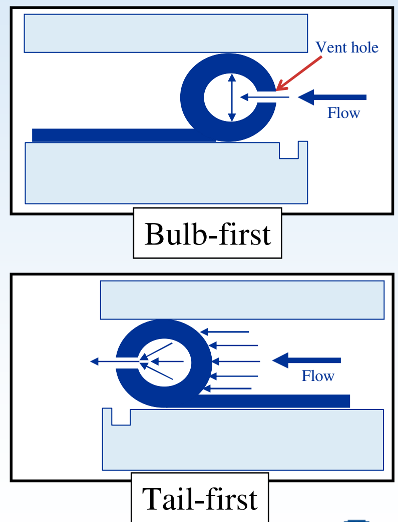
Seal Bulb Pressurization Effects

- Bulb inflation occurred via vent holes in bulb-first orientation
  - Stagnation pressure raised bulb pressure
  - Improved bulb contact along sealing surface
- Bulb deflation occurred via vent holes in tail-first orientation
  - Pressure along rear of seal bulb deflated bulb
  - Bulb deflation opened gap along sealing surface



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Flow Testing Summary

- Bulb-first seals met flow certification requirements
  - Leakage below 3 SCFM/ft for all compressions
  - Bulb inflation reduced seal leakage rates
- Tail-first seals met flow certification requirements for higher compression levels
  - Leakage below 3 SCFM/ft for compressions greater than 5%
  - Bulb deflation may have increased leakage rate below 5% compression
- Plateau or increase in Rev. P flow data between 10-25% compression

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Actions Taken by JSC/KSC

- Removal of excess RTV allowed closure of starboard door
- Two actions to successfully close port-side door
  - Custom-thickness shims added to sealing surface (replaced constant-thickness shims)
  - Door retract link shortened to increase preload
- Future steps to ensure compliance with certifications
  - Seal installation procedures amended to include removal of excess RTV
  - Seal deformation to be checked between flights

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Conclusions

1. Excess RTV at bond line increased peak loads by ~3x
2. As-received Rev. P seals generated less load than as-received Rev. M seal
3. Leakage rates of Rev. P seals were below 3 SCFM/ft leakage limit for compressions greater than 5%
4. Seal bulb inflation may improve seal performance during reentry pressurization

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Systematic Compression Tests

- Basic compression tests
  - 63% compression
  - Held for 30 seconds, then released
  - Repeated once
- 31-day test
  - 63% compression for 31 days (uninstrumented)
  - Measured load at discrete compression levels

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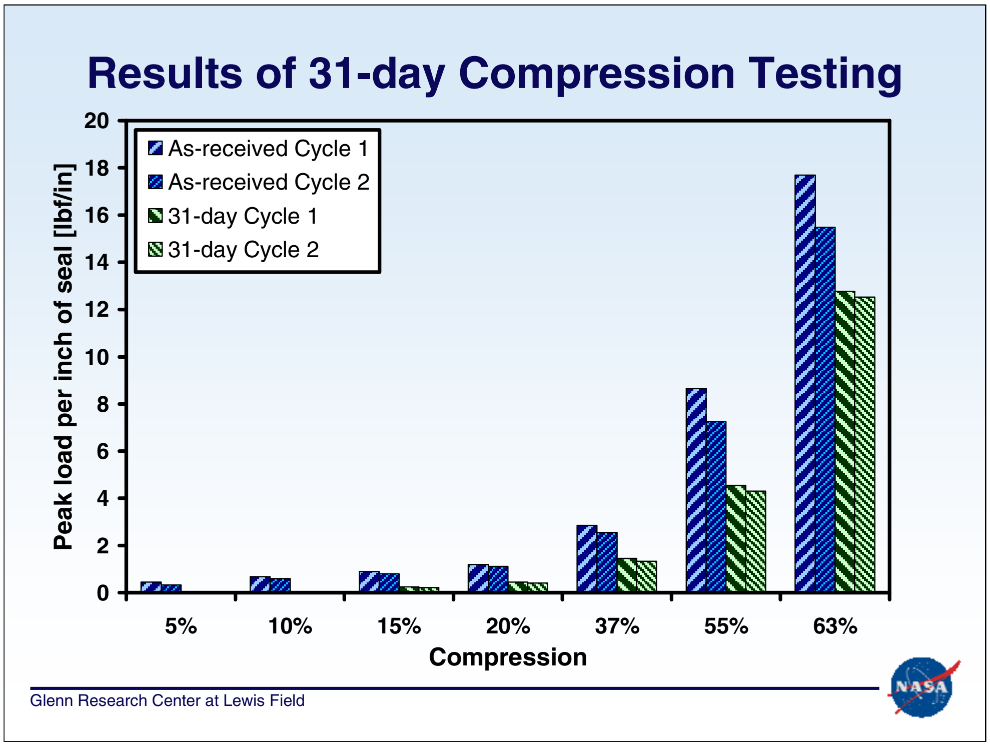


This graph shows the peak load per inch of seal vs. discrete compression levels applied to the seals for each of the two loading cycles. Both seal previously held at 63% compression for 31 days and an as-received control specimen are shown. The as-received specimen was measured to have 0.050 in. (12%) permanent deformation after release from the 31-day compression fixture.

The control specimen generated small amounts of loads immediately, while the 31-day compressed specimen did not generate any measurable load until 15% compression. Since the 31-day specimen was found to have 12% permanent deformation after the compression, the upper platen of the fixture did not contact the seal for 5% and 10% compression and generated no load for these displacements. Meanwhile, at 63% compression, the first cycle of the post-compression specimen generated 80% of the load of the as-received specimen.

Of particular interest was the drop-off in load of the as-received specimen between the first and second loading cycles and the relatively small load reduction in the compression specimen. If load drop-off is assumed to be proportional to permanent deformation, the data indicates that a seal with permanent deformation takes on new deformation more slowly than a pristine seal.

What does this mean? Seals held at compression for 31 days will take on some permanent deformation (0.050 in. in this test). However, the rate at which the seals take on permanent deformation appears to decrease as the seal takes on more deformation.

ELASTOMERIC SEAL DEVELOPMENT FOR ADVANCED DOCKING/BERTHING SYSTEM

Christopher Daniels
University of Akron
Akron, Ohio

Jay Oswald
J&J Technical Solutions, Inc.
Cleveland, Ohio

Patrick Dunlap and Bruce Steinetz
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Presentation Overview

- ADBS Overview
  - →Seal evaluation criteria
  - →Candidate seals
  - →Environments
  - →Historical data
  - →Elastomers
- Test Fixtures and Results
  - →Compression set
  - →Adhesion testing
  - →Small-scale flow test
  - →Full-scale flow test
- Numerical Simulation
- Summary
- Future Work

Brief ADBS System Overview

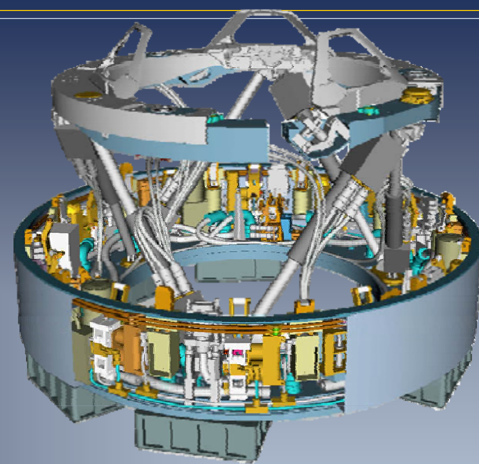
What is the ADBS?

System under development by Johnson Space Center (JSC) to:

- Provide androgynous pressurized interface permitting autonomous docking/berthing between space vehicles and structures
- Reduce impact loads between two mating space craft.
- Become new Agency standard for docking/berthing systems.

What are the Sealing Challenges?

- Androgynous configuration requires seal-on-seal mating at the interface between systems
- Seals must survive exposure to space environment



Criteria for evaluating candidate seals

- Environmental and operating temperature compatibility
  - →Environment: -100 to 100°C
  - →Operation: -50 to 50°C
- Compatibility to vacuum environment (low outgassing)
  - →Total mass loss (TML): <1%
  - →Collected volatile condensable materials (CVCM): < 0.1%
- Material stability when exposed to Atomic Oxygen (AO) and Ultraviolet radiation (UV)
- Compression force required to produce adequate seal
  - →Less than 100 lbf / linear inch
- Leak rate
  - →Less than 0.044 lbm / day
- Resistance to mechanical damage / ability to seal after damage
  - →Debris
  - →Micrometeoroids

Types of Candidate Seals

Two types of seals are being considered:

	Elastomeric Seals	Metallic Seals
		
Ability to form adequate seal	Excellent	Good
Long term resistivity to space environments		
AO / UV	TBD	Excellent
Micrometeroids	TBD	TBD
Compression load required	TBD: initially low / expected to rise	TBD
Ability to perform under gapping / misalignment	TBD	TBD
Space application experience	<30 days on Shuttle / ISS	None known
Adhesion	Some expected	None expected

Environmental Exposures

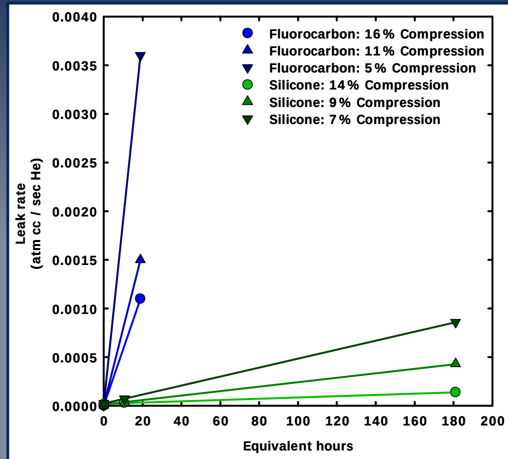
- As the Agency standard for docking systems, the ADBS is expected to operate
  - →In low Earth orbit (LEO)
  - →On Moon
  - →On Mars

Low Earth Orbit	Moon	• Mars
• Atomic Oxygen	• Ultraviolet radiation	• Ultraviolet radiation
• Ultraviolet radiation	• Vacuum	• Near vacuum
• Vacuum	• Micrometeroids	• Micrometeroids
• Micrometeroids	• Dust	• Dust / Debris
	• Temperature (-233 to 123°C)	• Temperature (27 to -128°C)

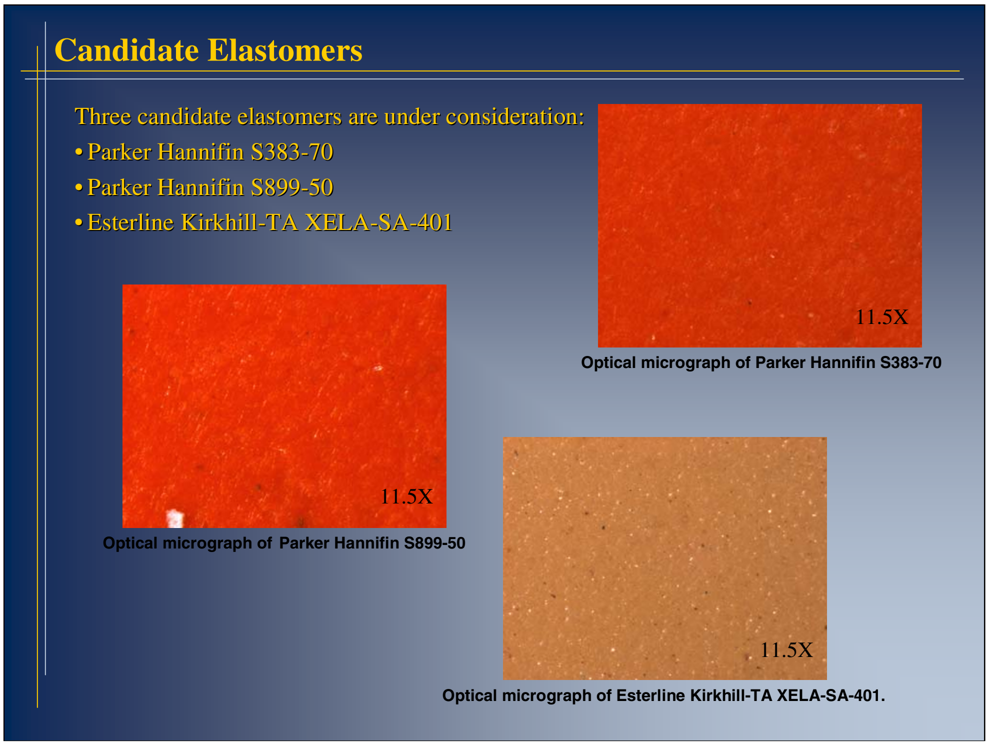
- To determine the effects of AO and UV, elastomer samples will be tested
  - →As-received
  - →After AO exposure
  - →After AO + UV exposure

Historical Data

- Material evaluation completed for the Common Berthing Mechanism (CBM) / International Space Station (ISS)
- Fluorocarbon elastomers are unacceptable for use in environments where Atomic Oxygen (AO) and Ultraviolet radiation (UV) are present
- Leakage from silicone elastomer seals increased linearly when exposed for up to 181 hours of AO and UV.
- Leakage increased up to 3200% for Silicone seals exposed to 181 equivalent hours.



*J.R. Christensen, et al. "Atomic Oxygen effects on seal leakage," 20th Space Simulation Conference, (1998): 195-206.



All three are silicone rubber. The PH S383-70 has a durometer of 70; the PH S899-50 has a durometer of 50; the EK is the softest material having a durometer of 38.

Compression Set Testing

- Determines the ability of elastomeric compounds to retain elastic properties after prolonged compression.
- Testing per ASTM Standards D395 (Test Method B) and D1414.
- Tests to be completed
  - → As-received ✓
  - → After exposure to AO
  - → After exposure to AO + UV

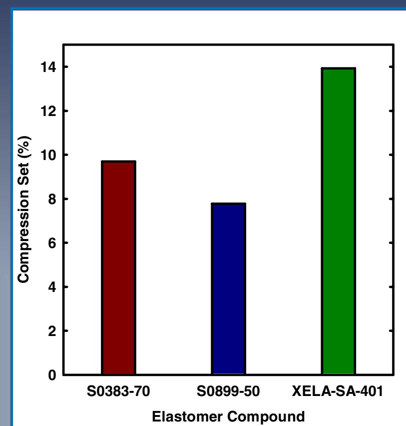
Photo of the Compression Set Fixture

Compression Set Results

- O-ring specimens have been tested per ASTM Standards D395 (Test Method B) and D1414.
  - →Parker-Hannifin silicone S0383-70
  - →Parker-Hannifin silicone S0899-50
  - →Esterline Kirkhill silicone XELA-SA-401

- The specimen were tested in the as-received condition and have not been exposed to atomic oxygen nor ultra-violet radiation.

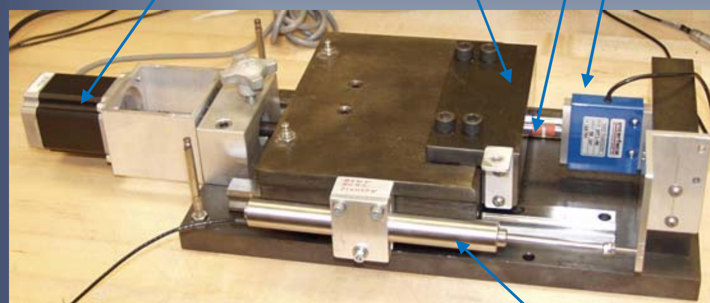
- Test conditions
  - →25% Compression
  - →70 hours at room temperature
  - →Surfaces were unlubricated
  - →Compression set results (median)
    - S0383-70: $C_B = 9.7\%$
    - S0899-50: $C_B = 7.8\%$
    - XELA-SA-401: $C_B = 13.9\%$



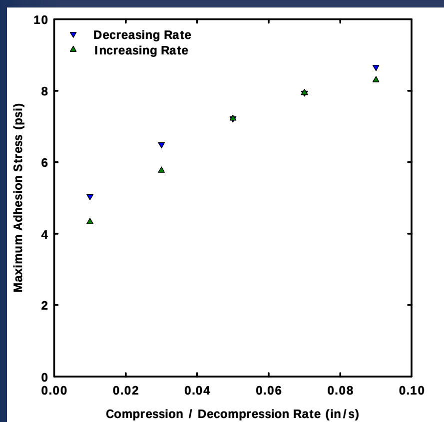
Compression set test results of o-ring specimen (AS 568A size 309) manufactured from Parker-Hannifin S0383-70, Parker-Hannifin S0899-50, and Esterline Kirkhill XELA-SA-401 compounds.

Adhesion Testing

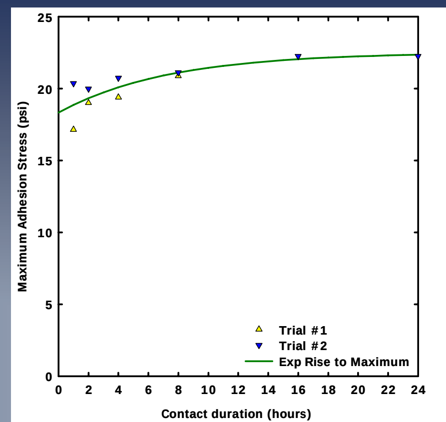
- Quantify adhesion between two elastomeric samples before and after exposure to Atomic Oxygen and Ultraviolet radiation.
- Measures compression and adhesion forces as a function of displacement at a given compression / decompression rate



Sample Adhesion Test Results



Adhesion test results showing effects of compression / decompression rate on adhesion for XELA-SA-401.



Adhesion test results showing effects of contact period on adhesion for XELA-SA-401.

- Adhesion increases with increased compression / decompression rate
- Adhesion increases with increased contact duration, but levels off.

Small Scale Flow Testing

- Quantify seal performance
  - →Of 2-309 size o-rings
  - →Leakage
  - →Before and after exposure to AO and UV
- Configuration
  - →Seal against flat metal plate
- Pressure boundary conditions
  - →Internal pressure
  - →External vacuum
- Temperature conditions
  - →Room temperature

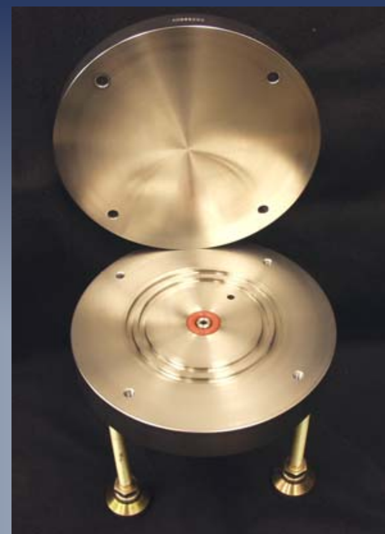
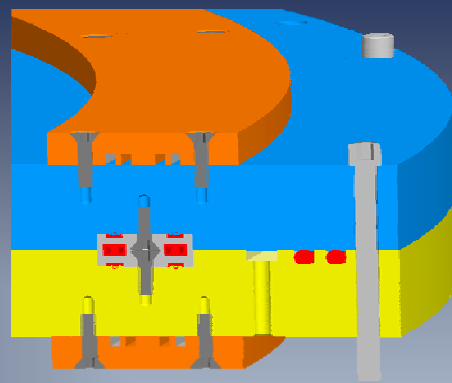


Photo of the Small-scale Flow Fixture
with sample o-ring installed.

Full Scale Flow Testing

- Quantify seal performance
  - →Leakage
  - →Compressive load required
  - →Separation force required
- Under representative conditions
  - →Full-scale (ϕ54”) seal-on-seal configuration
  - →Pressure boundary conditions
    - Internal pressure
    - External vacuum
  - →Temperature conditions
    - Minimum temperature: -50C
    - Maximum temperature: 50C
    - Temperature gradients
  - →Seal-to-seal alignment
    - Up to 0.050 inch axial misalignment
    - Angular misalignment (gapping)



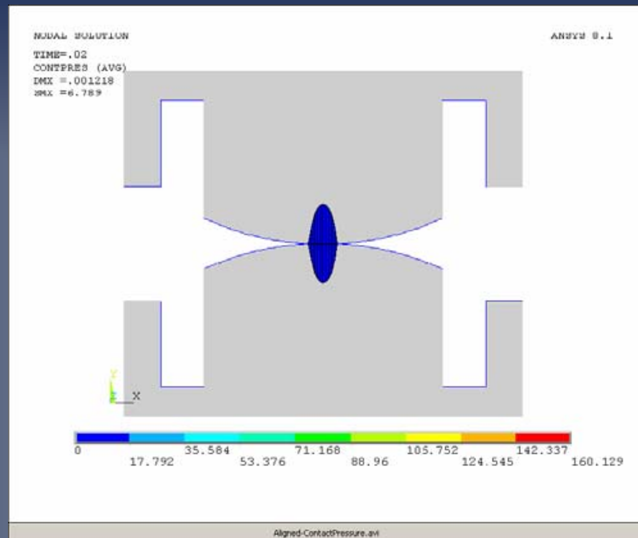
Full-scale Flow Fixture.

Numerical Modeling

- Preliminary model of contact pressure generated as the seal interacts with its replicate
- Model includes
  - →Properties obtained using adhesion test fixture
  - →Friction
  - →Misalignment of seals
- Many alternate configurations can be modeled as processing is fast (<60s) for 2-D cases
  - →Seal geometry
  - →Axial misalignments
- Model is linear elastic, not hyperelastic
  - →Does not support true incompressibility
  - →Difficult to converge
  - →Hyperelasticity most closely models rubber material
    - Close to ideally elastic
    - Strongly resists volume changes
    - Very compliant in shear
    - Shear response is strongly temperature dependent
- Planning to switch to hyperelastic model after obtaining needed material properties

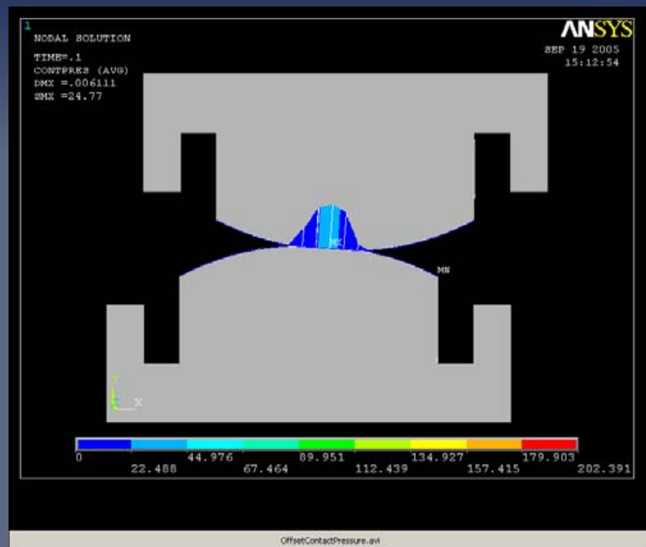
Common Berthing Mechanism: Numerical Simulation

- Configuration:
  Parker-Hannifin
  Gask-O-Seal
- Aligned
- Linear elastic model
  - → E = 230 psi
  - → $\nu = 0.4999$
  - → $\mu s = 0.8$



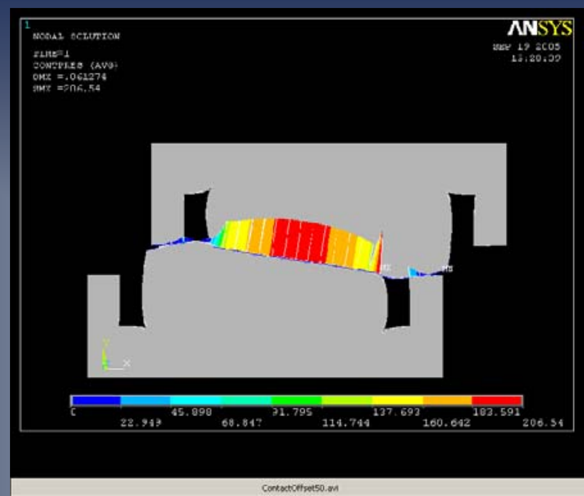
Common Berthing Mechanism: Numerical Simulation

- Configuration: Parker-Hannifin Gask-O-Seal
- Misaligned 0.025 inch
- Linear elastic model
  - → E = 230 psi
  - → $\nu = 0.4999$
  - → $\mu s = 0.8$



Common Berthing Mechanism: Numerical Simulation

- Configuration: Parker-Hannifin Gask-O-Seal
- Misaligned 0.050 inch
- Linear elastic model
  - → E = 230 psi
  - → ν = 0.4999
  - → μs = 0.8



Summary

- Elastomeric seals are being considered for application to the Advanced Docking / Berthing System.

- Currently, three candidate elastomers are being evaluated.

- To meet the unique requirements of the ADBS, several test fixtures have been built to determine each elastomer's
  - → Environmental and operating temperature compatibility
  - → Material stability when exposed to Atomic Oxygen and Ultraviolet radiation
  - → Adhesion force required to separate
  - → Compression set
  - → Leak rate

- These results will be compared with those from the metallic seal development to determine the final seal design

Future Work

- Complete compression set, adhesion, and small-scale flow tests
  - →Baseline
  - →After Atomic Oxygen (AO) exposure
  - →After AO + Ultraviolet radiation (UV) exposure

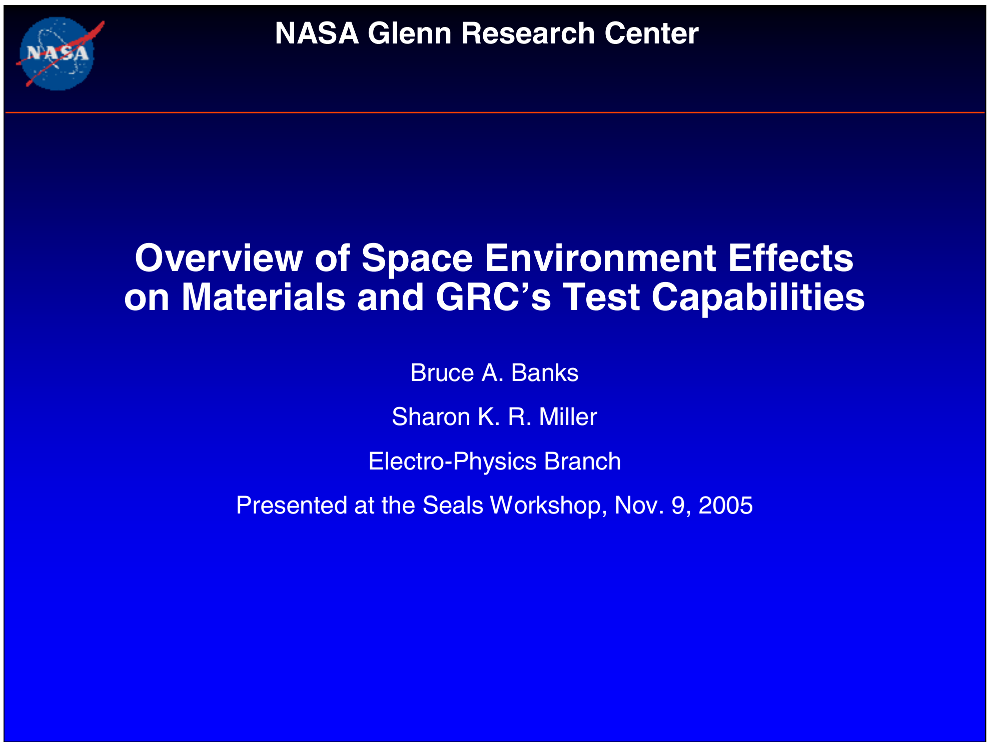
- Down-select between competing concepts and materials based on requirements.

- Perform full-scale flow tests to assess:
  - →Full scale seal-on-seal leakage
  - →Temperature effects
  - →Effects of axial offset
  - →Effects of seal-to-seal gapping (angular misalignment)

- Perform numerical simulations to predict seal leakage
  - →Seal geometries
  - →Misalignments

OVERVIEW OF SPACE ENVIRONMENT EFFECTS ON MATERIALS AND GRC'S TEST CAPABILITIES

Bruce A. Banks and Sharon K.R. Miller
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio



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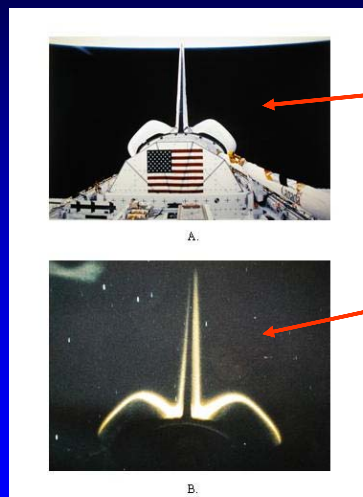
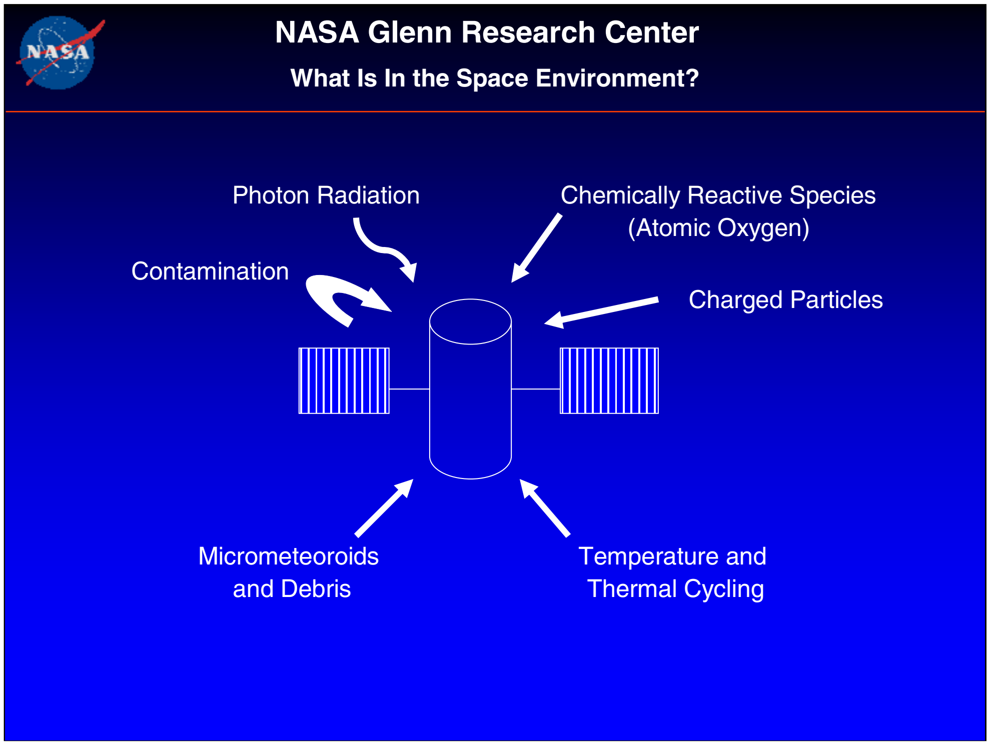
Evidence of Environmental Reactions



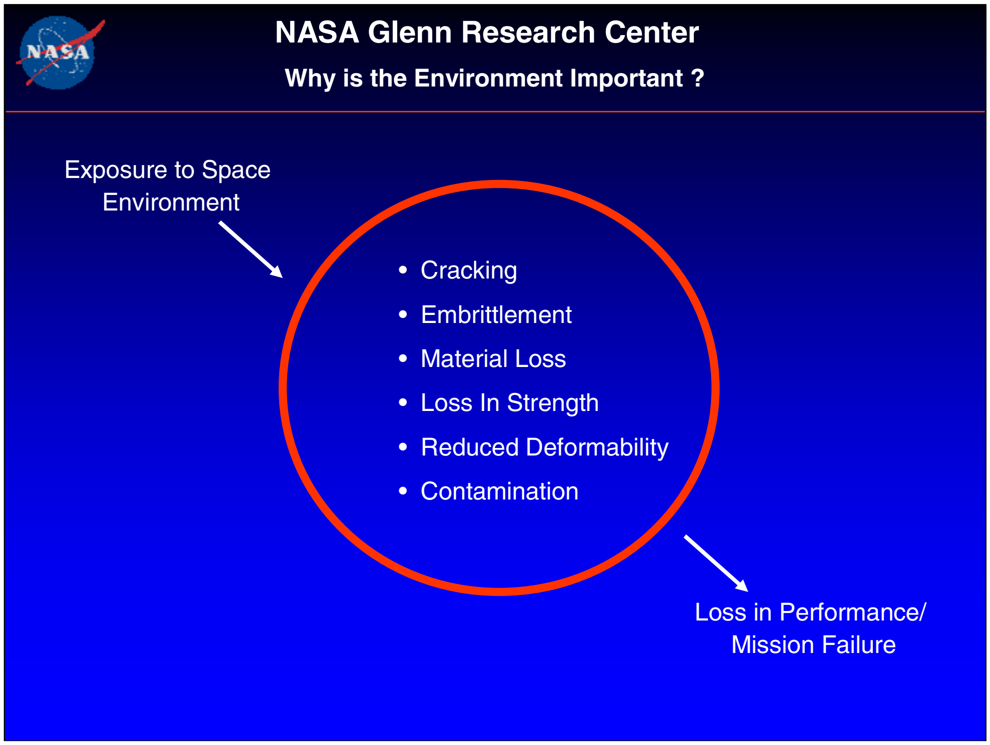
Daytime Photo of Shuttle Bay

Time Exposure of Shuttle Bay at Night

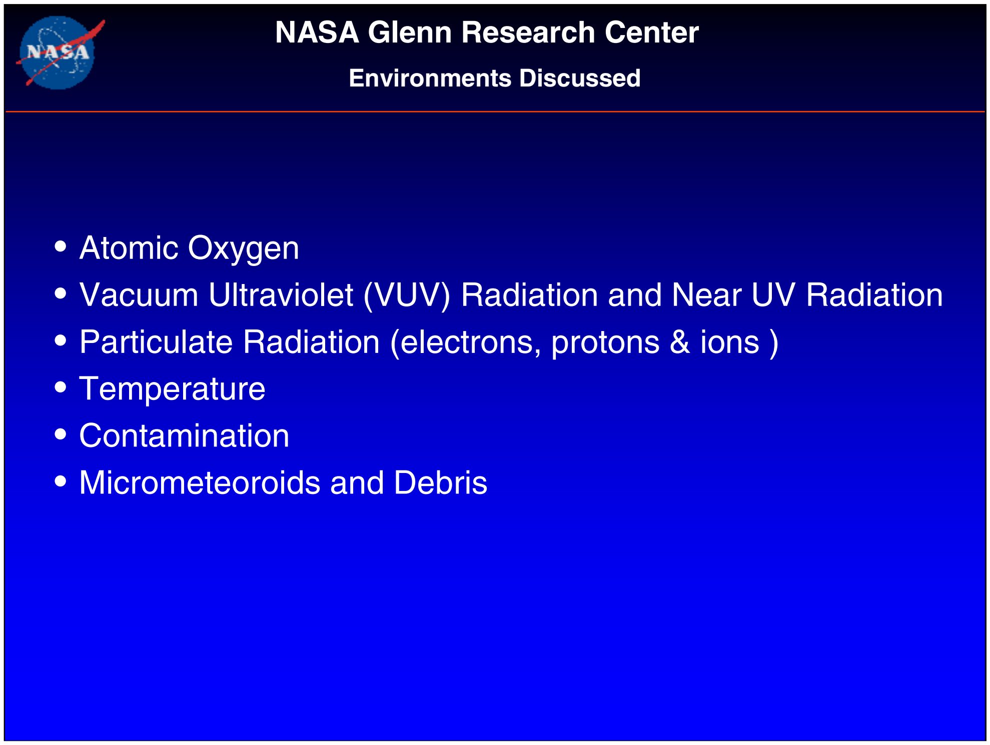
Evidence of the interaction of the space environment with spacecraft surfaces can be seen from this time exposure image of the shuttle bay at night. The glow around the tail section is caused by the impact of atomic oxygen and other low Earth orbit (LEO) environment species on the shuttle surface creating short lived excited species that emit visible radiation.



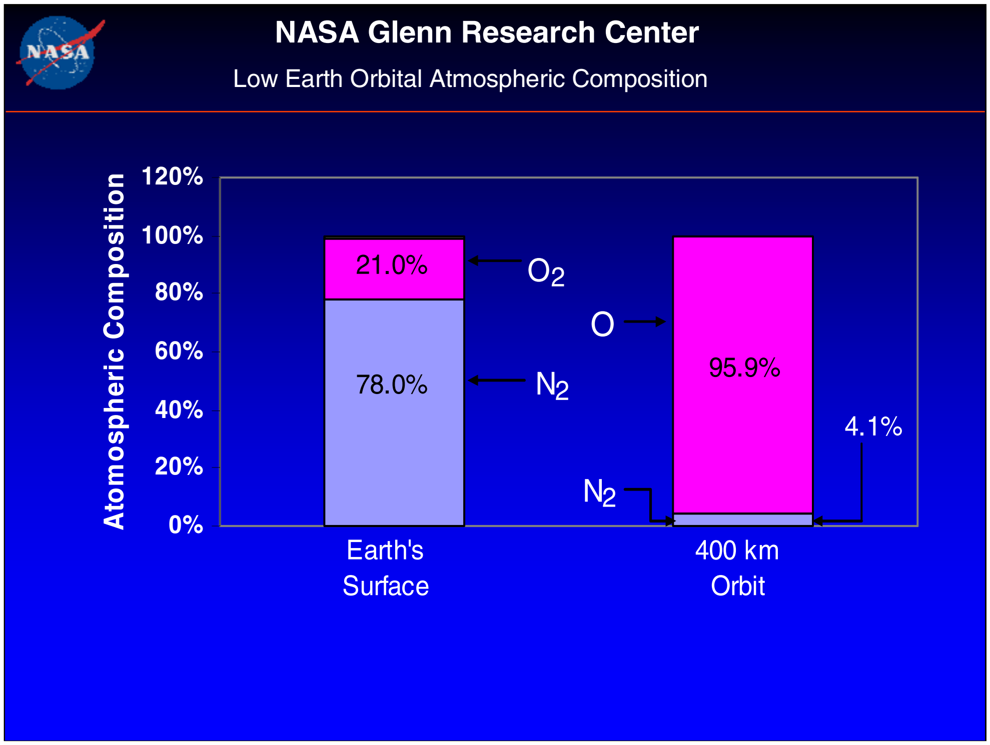
The space environment contains chemically reactive species such as atomic oxygen, photon radiation, charged particles, and micrometeoroids. It also contains man made or self generated debris and contamination. The thermal flux from the sun and traveling of spacecraft into areas of planetary shadow create heating and thermal cycling which also affects spacecraft performance. What environmental constituent is of concern for a particular mission is highly dependent on where the spacecraft will fly and the desired mission life.



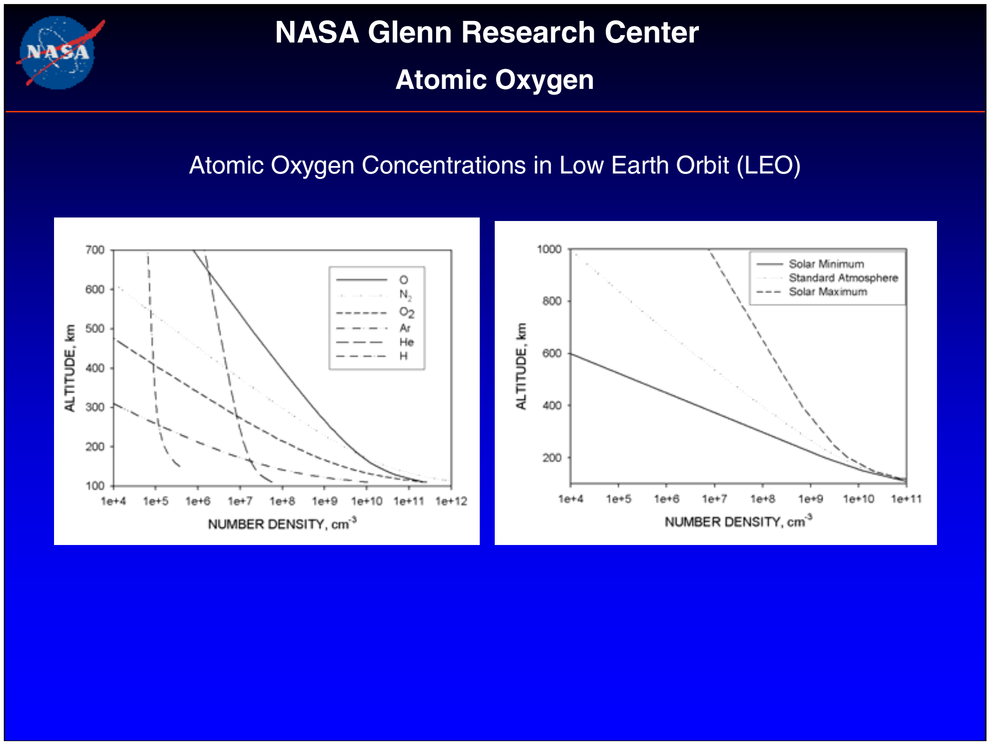
Why is the space environment important for seals? Exposure to the space environment over time can lead to cracking and embrittlement of polymer and silicone seals, loss of seal material, reduction in the strength of the material, and increased hardness which lowers the deformability. Ejecta from micrometeoroid and debris impacts depositing on seals can provide places where leaks can occur. In addition, the seals themselves can produce contamination which can deposit on sensitive optics or thermal control surfaces if the seal material contains too high of a level of condensable volatile components. All of these can lead to loss in performance and ultimately failure of the mission.



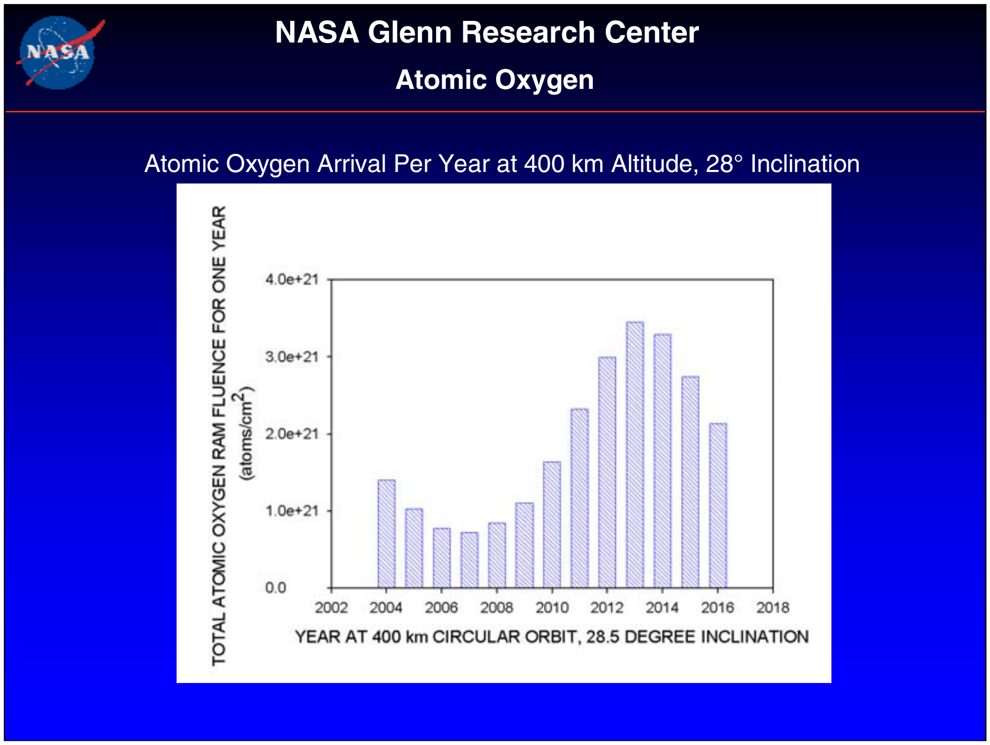
This presentation focuses on the main environments that are experienced in Earth orbit, although many of these are applicable to other planetary and transitional environments as well. In some cases, the environments can combine to produce synergistic effects that produce damage to materials beyond that seen in either environment alone. This has been observed for particulate radiation in combination with solar heating.



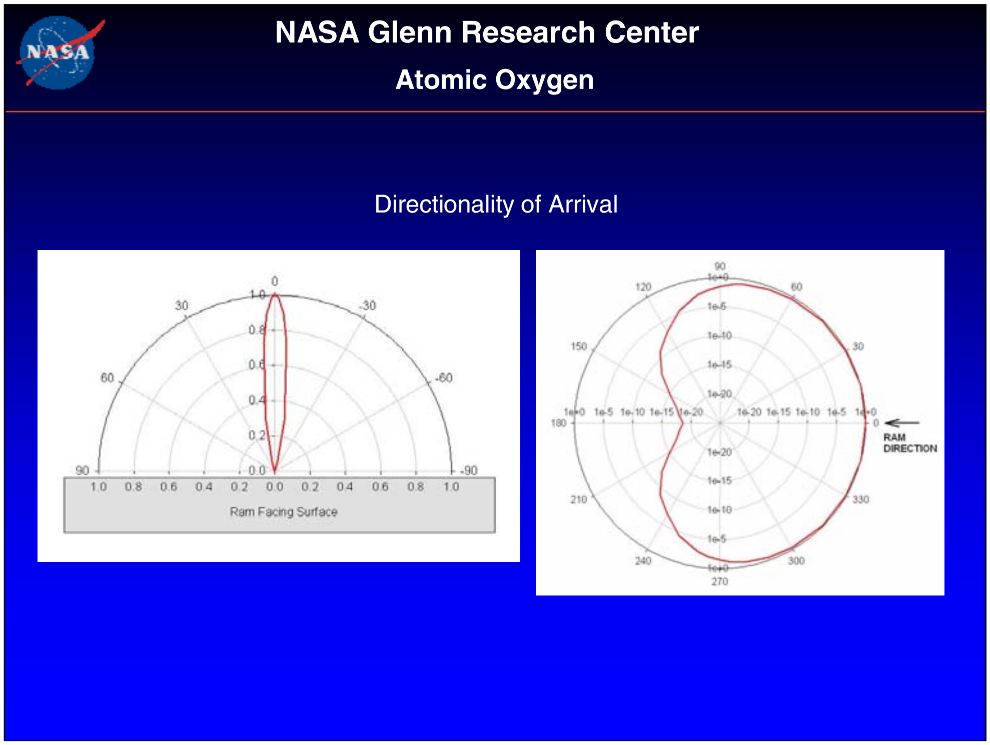
At the surface of the earth, the primary constituent of the atmosphere is molecular nitrogen, as the altitude increases, the amount of nitrogen decreases and atomic oxygen becomes the predominant component of the atmosphere.



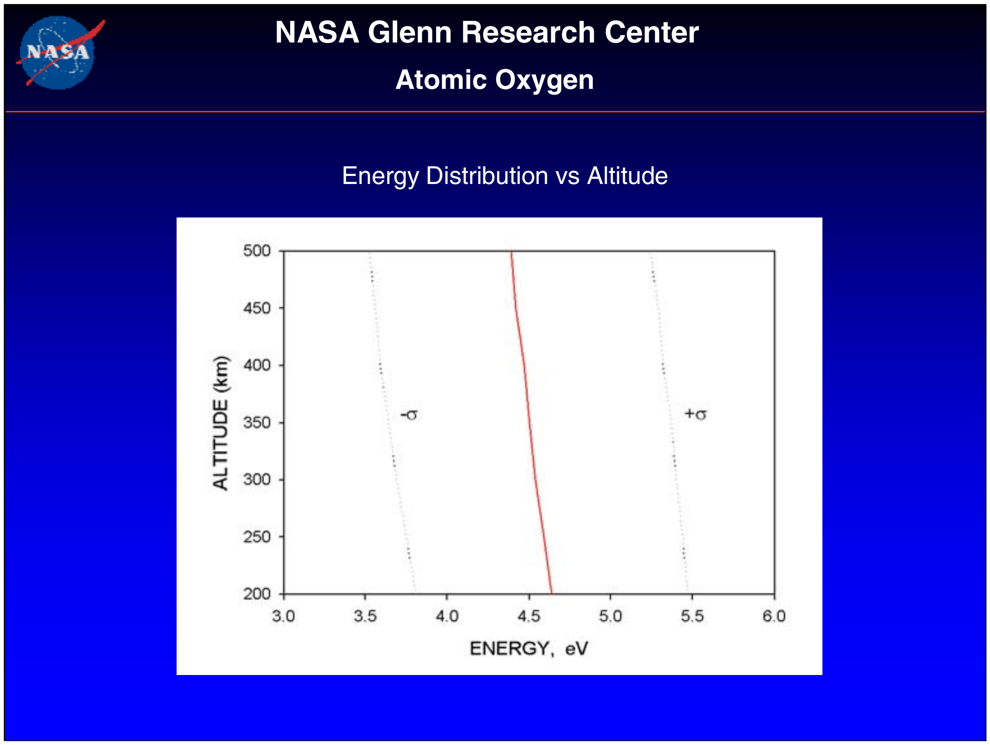
The altitudes at which atomic oxygen are dominant are between 180 and 650 km. The amount of atomic oxygen present is highly dependent on solar activity and is highest during periods of elevated sun spot activity.



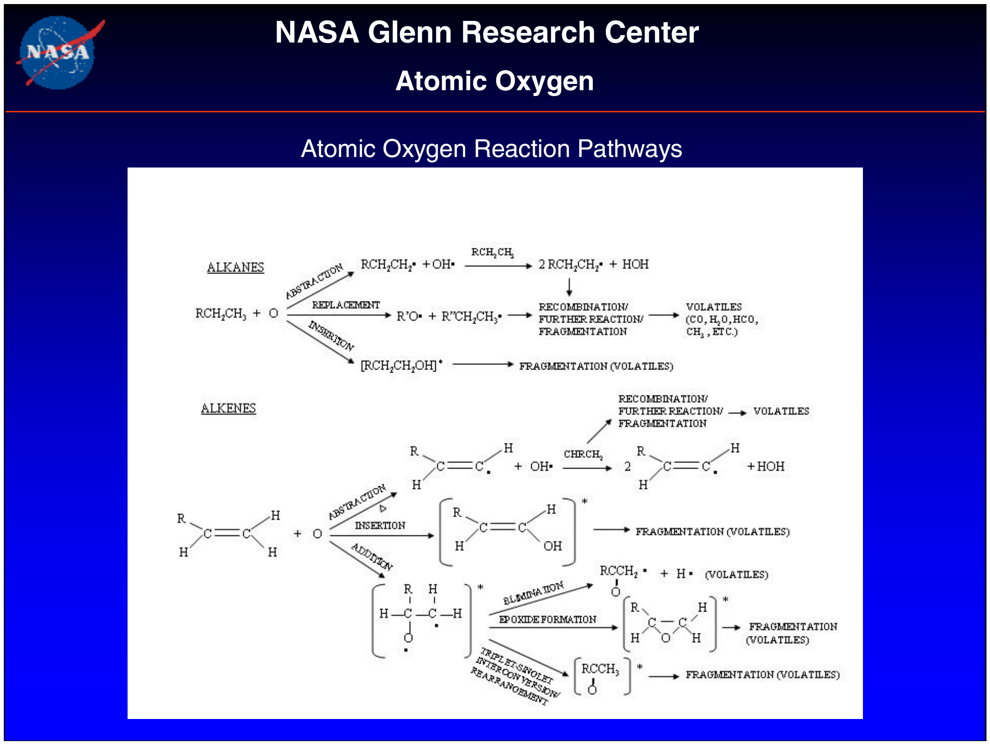
Solar activity varies over an 11 year cycle. Atomic oxygen concentrations arriving at spacecraft surfaces also follow this 11 year cycle.



As a spacecraft orbits the Earth at velocities on the order of 7.7 km/sec, it runs into the atomic oxygen ("ram" atomic oxygen). If the spacecraft is in an orbit that has zero inclination, then the average angle of attack is perpendicular to surfaces whose surface normal points in the direction of travel. Most spacecraft have orbits which are inclined with respect to the Earth's equatorial plane. This causes the average angle of attack of the atomic oxygen to sinusoidally vary around the orbit as a result of the vectoral addition of the orbital spacecraft velocity vectors. In addition, atomic oxygen atoms have thermal velocities associated with their Maxwell-Boltzman distribution (which can be as high as 1000K) actually allowing some atomic oxygen atoms to catch up with the trailing surfaces of the spacecraft producing a small arrival flux which is orders of magnitude lower than the ram flux. The figure on the left shows the arrival of atomic oxygen with respect to the ram arrival for a ram facing surface as a function of angle for a spacecraft orbiting at 400 km altitude with a 28.5 degree angle of inclination. The figure on the right is for the same altitude and inclination, but shows the flux as a function of angle around the spacecraft. This will vary with altitude and angle of inclination.



The impact energy of the arriving atomic oxygen in LEO is dependent upon the orbital spacecraft velocity vector, the Earth’s atmospheric co-rotation velocity vector, and the thermal velocity vector. This results in an energy distribution that varies as a function of altitude at a fixed inclination and thermosphere temperature. The plot above is for 28.5 degree inclination and 1000K thermosphere.



These energies combined with the reactivity of the atomic oxygen allow the breaking of most organic polymer bonds and the subsequent formation of volatile species by a variety of pathways.

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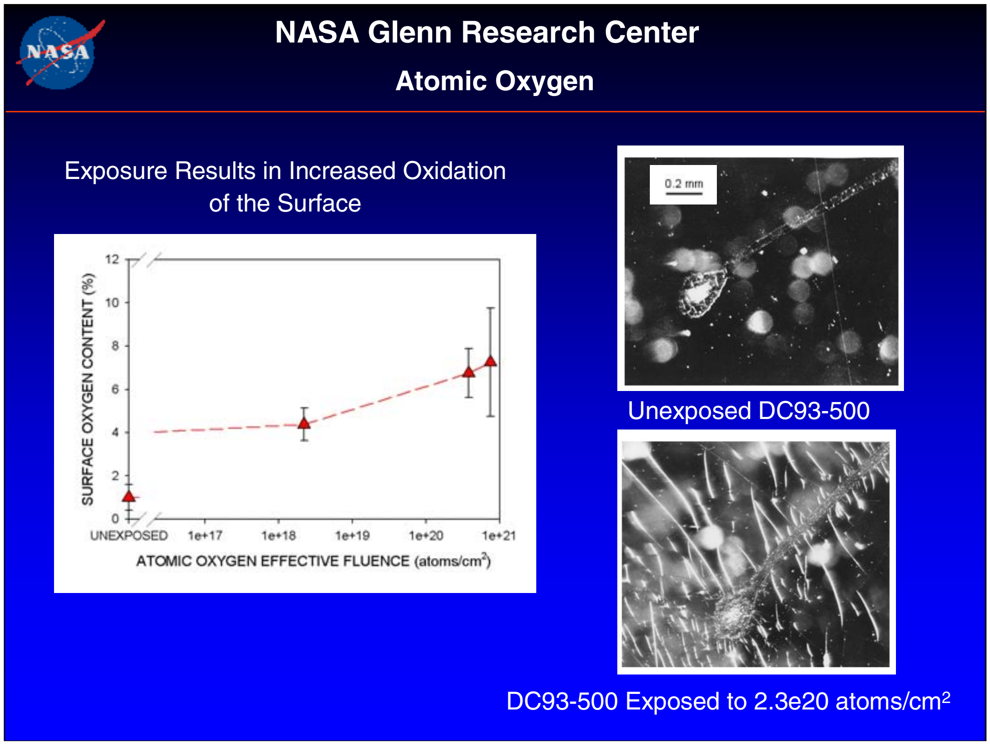
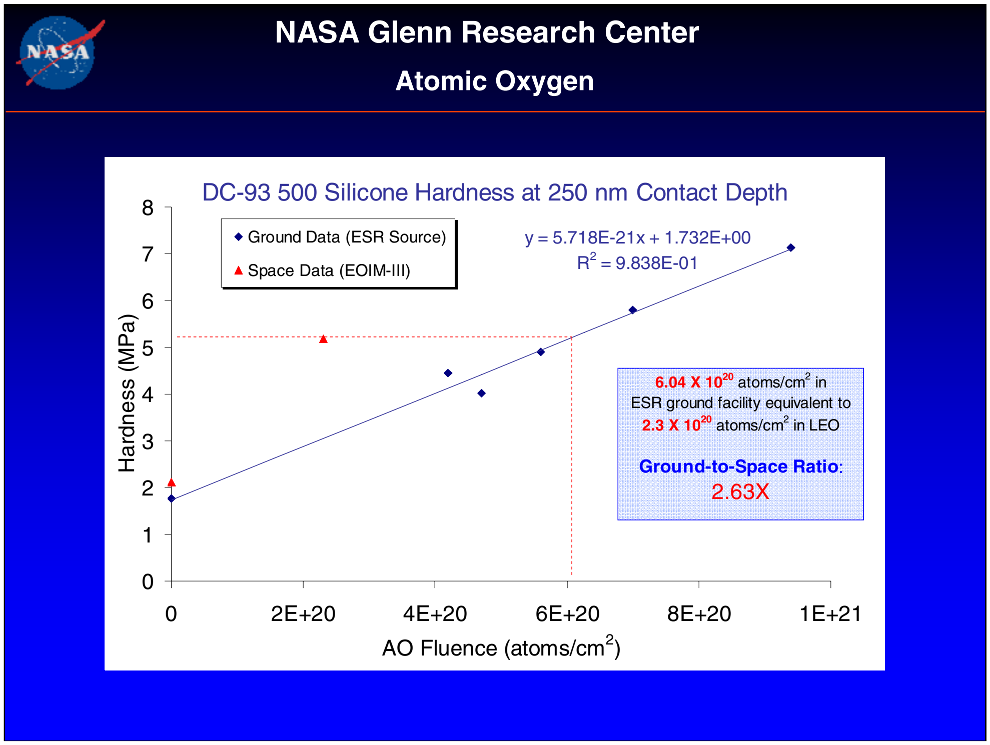
Atomic Oxygen

Materials International Space Station Experiment
After 4 Years in Low Earth Orbit

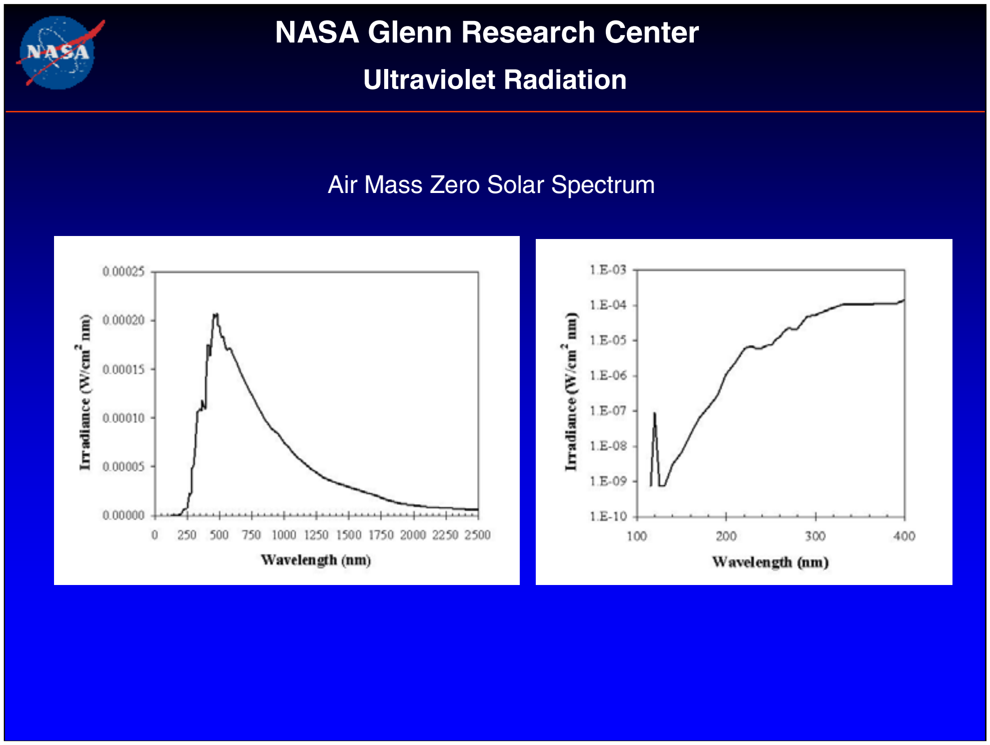
The loss of material through reaction with atomic oxygen has been the focus of several flight experiments. This is an example of an experiment tray that was recently retrieved after flying four years on the International Space Station in an attempt to better understand the reactions that occur and enable quantification of material durability in LEO for future missions.



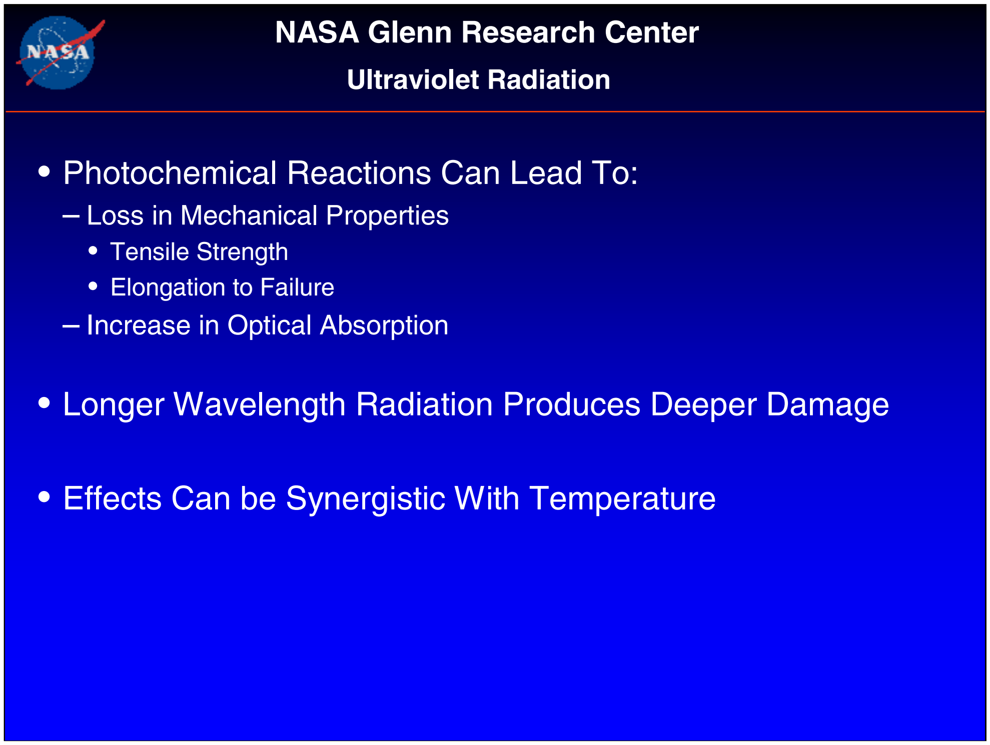
Surfaces of polymers exposed to atomic oxygen develop an increase in oxygen content as shown in the figure on the left. Oxidation of surfaces of silicones such as that shown on the right causes removal of methyl groups and gradual conversion of the surface to silica. This frequently results in shrinkage and crack formation in the exposed silicones as they are transformed from the lower modulus silicone into higher modulus silica. This cracking can continue through branch cracking as the cracks open up and expose more silicone to oxidation.



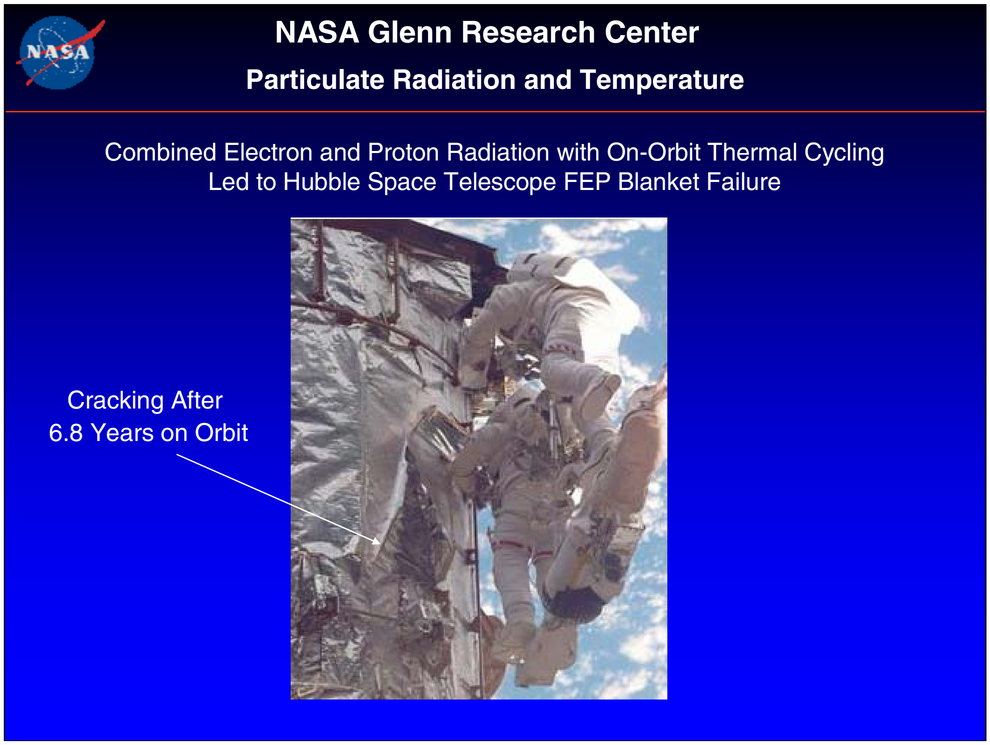
The hardness of silicones also increases as the conversion from silicone to silica takes place with increasing atomic oxygen arrival. The plot above shows this trend and how the surface hardness measured from space exposed samples can be used to estimate the equivalent dose that would be needed in a ground based exposure facility to achieve the same level of damage.



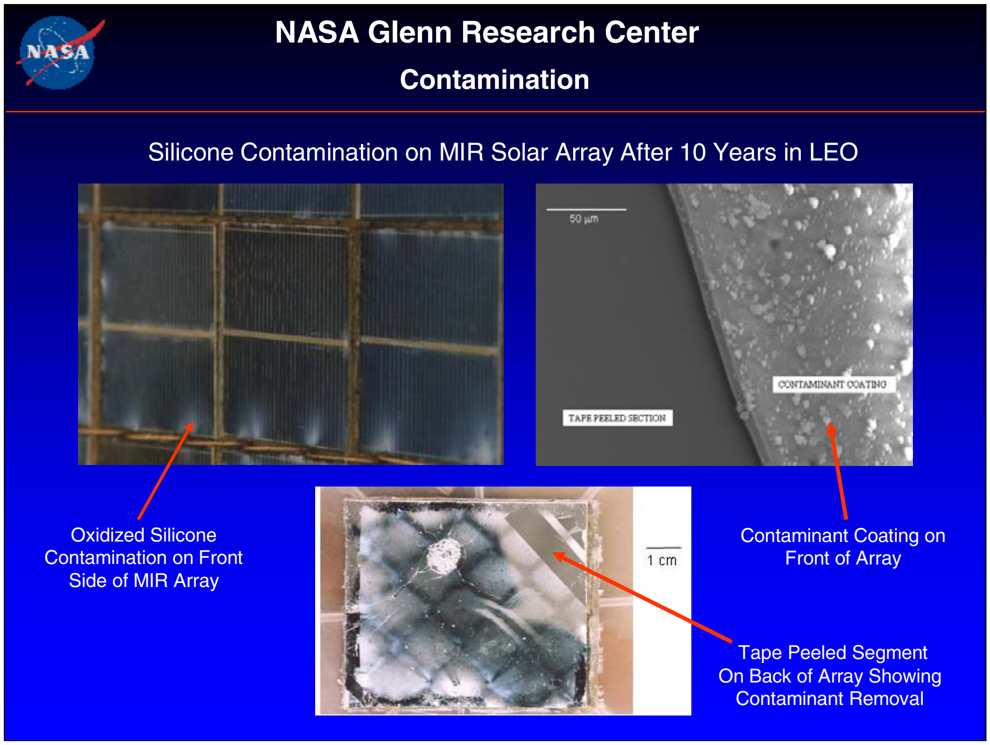
Photon radiation is defined by the Air Mass Zero solar spectrum, which is the irradiance that is measured as a function of wavelength at one astronomical unit from the sun as shown in the figure on the left. The greatest damage is produced by the ultraviolet radiation portion of the spectrum which is shown in the right figure. Ultraviolet radiation can further be subdivided into vacuum ultraviolet radiation (VUV) (100-200 nm) and near UV (NUV) radiation (200-400 nm). The VUV radiation produces surface damage while the NUV radiation can penetrate more deeply.



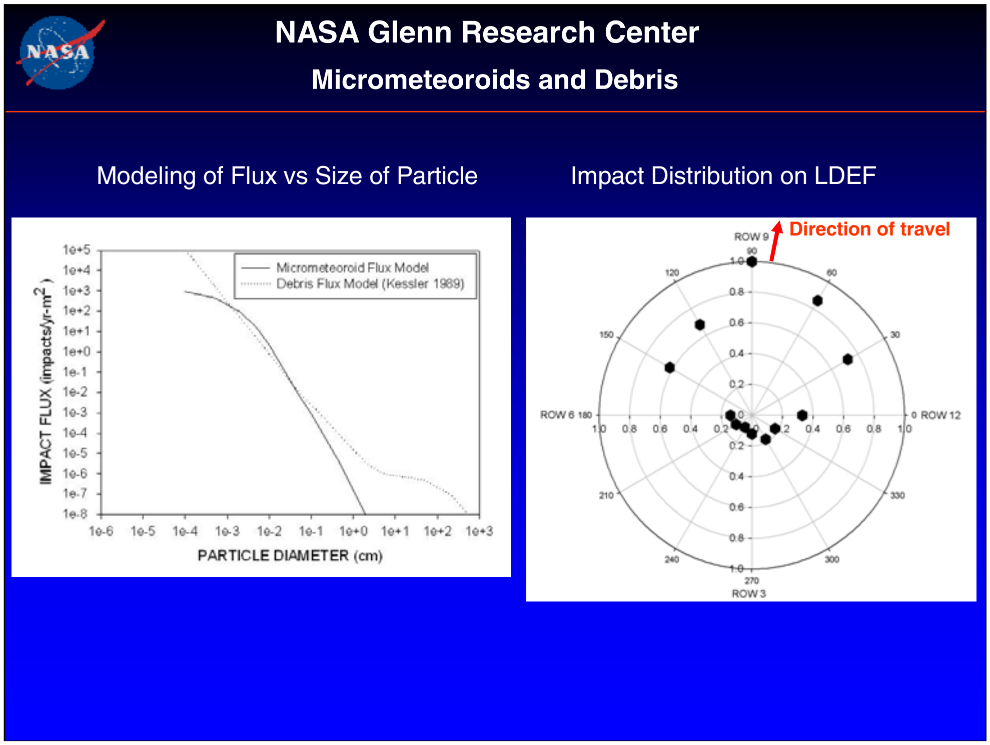
Photochemical reactions consist predominantly of chain scissioning in polymers and formation of absorbing color centers. Both can lead to loss in performance through reduced mechanical properties or overheating which can both result in mission failure. These effects can also be accelerated by exposure to ultraviolet radiation in combination with temperature elevation.



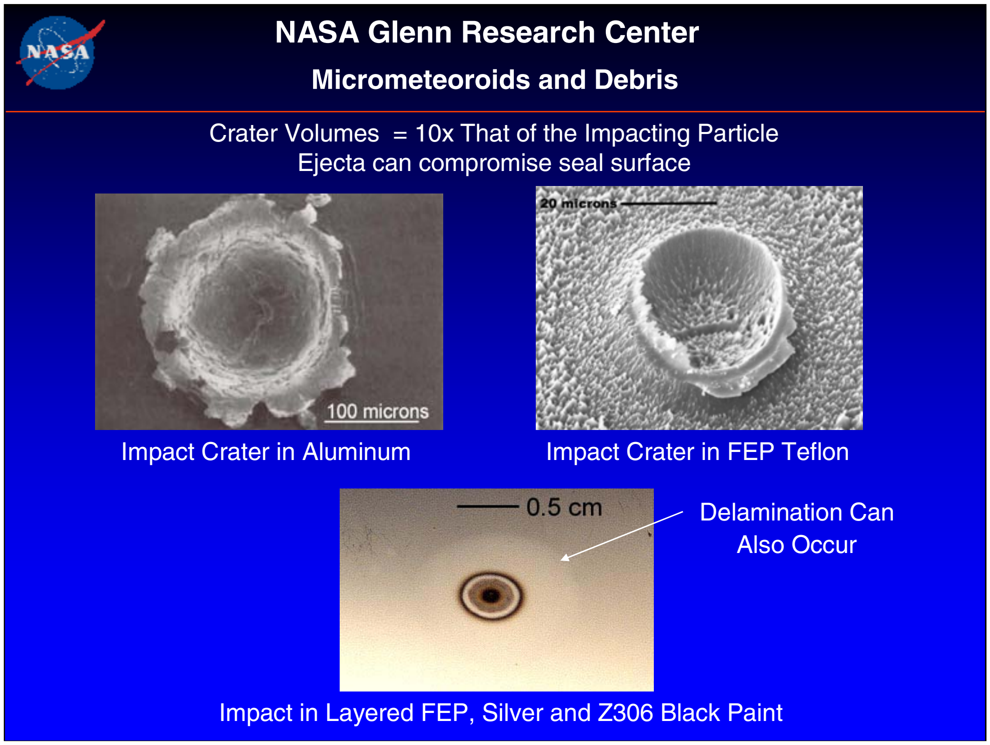
Synergistic effects can also be observed for polymers exposed to electron and proton radiation at elevated temperature. This combined exposure produces more severe damage than either environment alone. This type of exposure is believed to have caused the cracking and tearing of the FEP Teflon thermal blanket cover on the Hubble Space Telescope after 6.8 years on orbit.



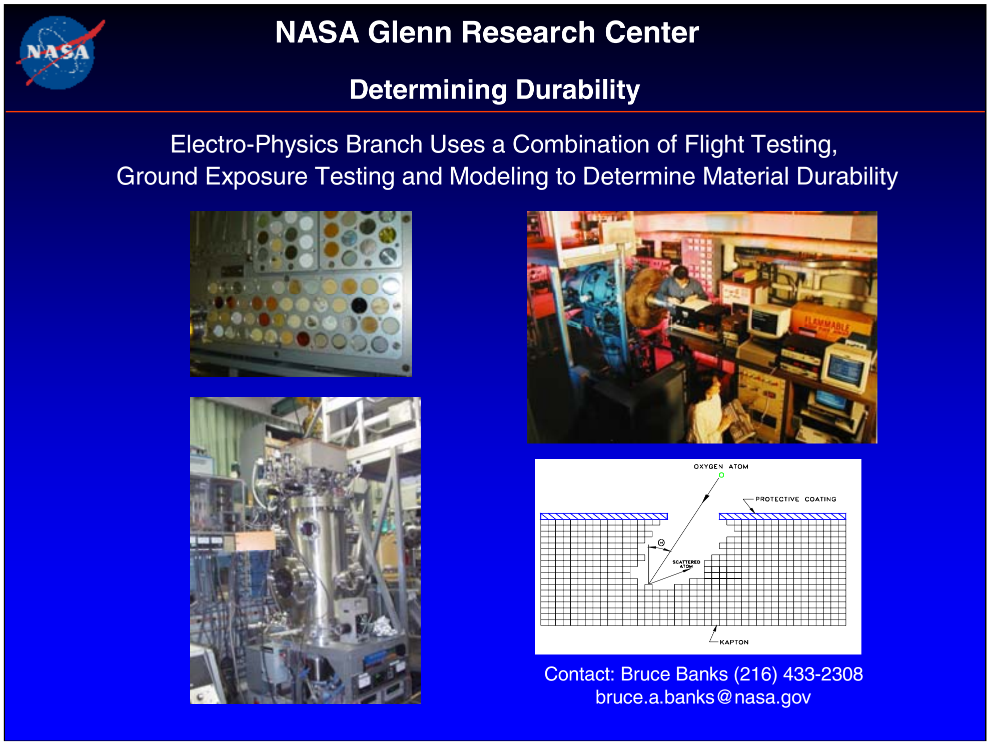
Silicone seals and other silicone containing materials should be used with caution in the space environment. The silicone fragments that are volatilized in the vacuum of space can land and be fixed on other surfaces by ultraviolet radiation or oxidation by atomic oxygen. In an atomic oxygen environment the layers can build forming a thick contaminant like that observed on the MIR solar array as shown in the top left and right images. The contaminant layer here was produced as a result of volatilized and fixed silicone fragments from the silicone adhesive bonding the array together. The contaminant on the front of the array stayed fairly clear and was thick (up to 4.6 microns thick). If the deposition of silicone fragments, however, is accompanied by hydrocarbon deposition, a much more optically absorbing coating can result. The contamination on the back side of the MIR solar array was more tan in appearance for this reason as shown in the lower figure. The diamond pattern on the back of the cell is caused by contaminant being deposited where there was a fabric net stretched across the back. Areas where the net covered were protected from atomic oxygen attack which prevented the conversion of silicone to silica. The contaminant could be removed by tape peeling for thickness measurement which on the back side was about 1.24 microns thick. To reduce the occurrence of this, low outgassing materials with low volatile condensable materials are needed. Testing for compliance can be done using ASTM E-595. Not all materials listed as being “space qualified” do meet this requirement. Some silicone seals failed the outgassing test due to an incomplete cure , but were sold as “space qualified”.



Micrometeoroids are of extraterrestrial origin and will have a flux which is reasonably constant with time with an average velocity near 20 km/sec. Orbital debris is of man-made origin and has an average velocity of 8.7 km/sec. Because of the man-made origin and atmospheric drag, orbital debris flux is highly dependent upon the world's spacecraft launch frequency and occurrences of orbital breakups. Size distribution models for both are contained in the figure on the left. The figure on the right contains a polar plot of the combined micrometeoroid and debris impacts on the LDEF satellite (a space environment reaction exposure free flyer) which was in orbit 69 months. It illustrates the nonuniformity of impacts around a spacecraft with a fixed orientation relative to the ram velocity direction.



The impact of micrometeoroid or orbital debris particles with spacecraft materials is sufficiently energetic to cause vaporization of the impacting particle as well as produce an impact crater of volume 10x that of the impacting particle. Impacts shown on the top left and right were in bulk materials (aluminum on the left and atomic oxygen textured FEP Teflon on the right). Laminated materials can experience delamination of a significant area around the impact site as shown in the lower figure. The likelihood of large impacts on seal surfaces which will affect their performance, however, is much lower than the potential for seal problems caused by sputter ejecta from impacts landing on the seal surface.



The Electro-Physics Branch at NASA Glenn Research Center has been involved with evaluating the durability of materials and understanding environment interactions for over 20 years. A combination of flight experiments (upper left figure), ground based exposure facilities, and environmental modeling provide a well rounded approach to material durability evaluation and prediction for future missions. Ground based testing includes atomic oxygen exposure facilities (large and small area thermal facilities and directed atomic oxygen with and without VUV radiation (upper right figure)), VUV and NUV exposure facility (lower left figure), and thermal cycling facility with and without UV radiation.

A lunar dust exposure facility is also being brought on-line. Material reactions in these facilities is compared to that observed in space. The lower right figure shows a sample output from a Monte Carlo model developed to predict the extent of reaction of scattered atomic oxygen entering a coating defect or a recessed portion of a spacecraft.

Further information about the environment, and testing can be obtained at http://www.grc.nasa.gov/www/epbranch/ephome.htm or contacting Bruce Banks, Chief of the Electro-Physics Branch at bruce.a.banks@nasa.gov, (216)-433-2308

METALLIC SEAL DEVELOPMENT FOR ADVANCED DOCKING/BERTHING SYSTEM

Jay Oswald
J&J Technical Solutions, Inc.
Cleveland, Ohio

Christopher Daniels
University of Akron
Akron, Ohio

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

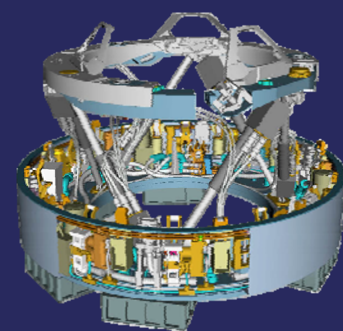
Outline of Presentation

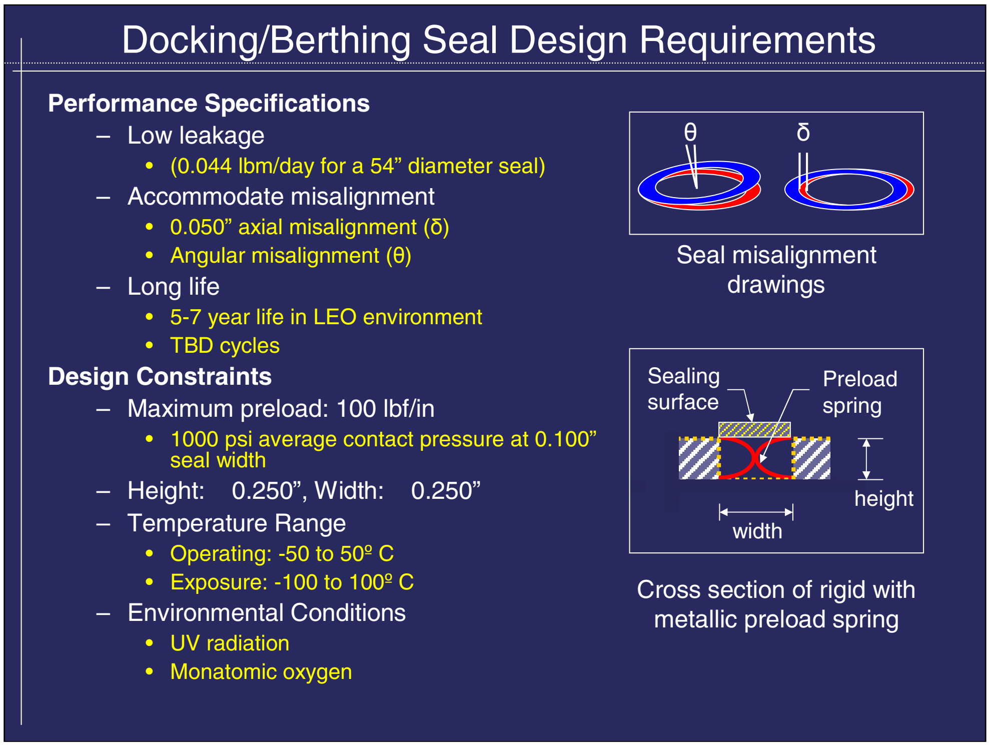
- Introduction
  - Advanced Docking/Berthing System (ADBS) Background
  - ADBS Seal Design Requirements
  - ADBS Unique Challenges
- Approach
  - Initial Design
  - Second Generation
    - Experiments
    - Analytical
  - Advanced Metallic Seal Concepts
    - Flexible Metallic Seals
    - Rigid Metallic Seals
  - Future Work
- Summary

ADBS Background

System under development by JSC to:

- Provide gender neutral (androgynous) interface permitting docking/berthing between any two space vehicles
- Become new agency standard for docking/berthing systems





Life

Duration of cycles (how long the seals stay in contact)

Metallic Seal Challenges/Benefits

Challenges:

- Develop metallic sealing surface
  - Meets leakage goals
  - Avoids wear
  - Does not cold weld in vacuum
  - Tolerates axial misalignment
- Develop preload element
  - Deforms elastically
    - Conforms to angular misalignment
  - Provides necessary preload
  - Does not allow secondary leakage behind seal

Benefits:

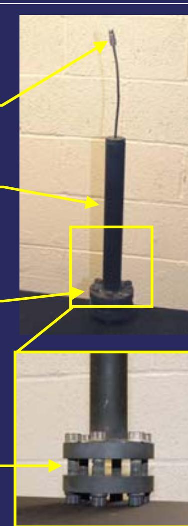
- Metallic surface is more stable than polymer
  - Will not degrade in space environment
- Not expected to outgas
- Early investigations show low contact force required for adequate seal

Transition to approach

Defined design goals -> look at the approach

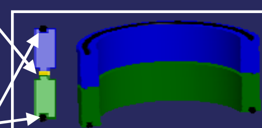
Preliminary Metallic Seal Test

- Test surface on each of two metal parts (ϕ2.5”) were ground flat
  - Ra ~ 12-14 μin
- Gold coated with ion plating process
  - gold thickness ~ 40 μin
- Sealing surfaces were mated in test fixture
- Seal leakage approached target leakage goal
  - Further refinements necessary



Grips of test fixture.

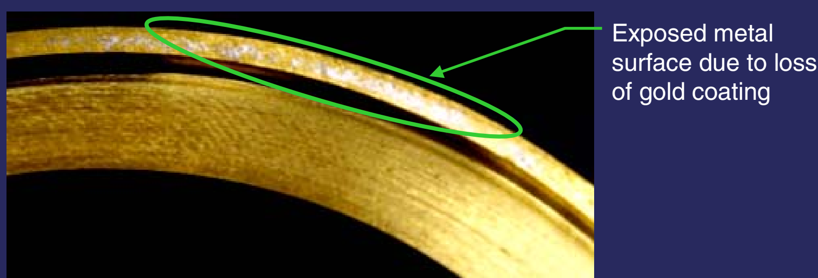
Seal surface pair after gold plating.



Test seal surface pair.

Metallic Seal Results/Lessons Learned

- Metallic surface seal was near the leakage goal
- Gold surface will not survive multiple cycles
- Possible improvements to seal surface
  - Flatness
  - Surface finish (Ra)



Damage on gold plated surface after mating cycle.

Second Generation Prototype

- **Metallic seals were fabricated in-house out of Stainless Steel Type 304.**
  - Turned on lathe
  - Hand lapped on a granite surface using progressively finer diamond lapping film, (30, 6, 1, and 0.5 micron)
  - Surface roughness measured to be Ra 1 µin
  - Ultrasonically cleaned with
    - Ethanol
    - Hexane
  - Hand cleaned with acetone
- **Dimensions are**
  - 1.492 inch I.D.
  - 1.692 inch O.D.
  - 0.100 inch seal land width

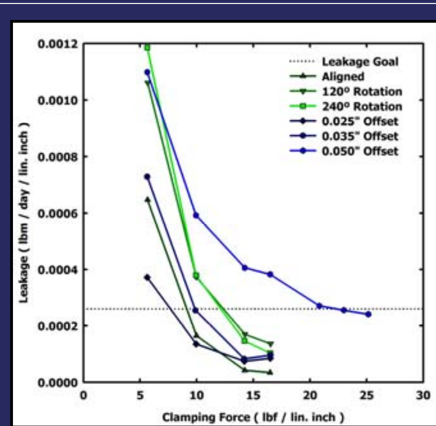
Sealing Surfaces

Photo of the metallic seals.

Second Generation Results

- **Second generation met leakage goal with very low required contact pressure**
  - **Metallic surface design functions well with any angular orientation**
  - **Accommodates axial offsets of 0.050"**
- **Seal needed to be manufactured to very tight tolerances to function properly**

- **Further analysis required to determine which tolerances are important:**
  - Surface finish
  - Flatness



Flexible metallic seal test results showing the effects of metallic surface thickness on leakage rates.

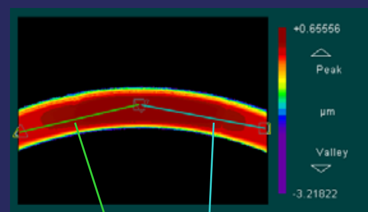
Average seal surface roughness
- Ra = <1 μin, σ = n/a

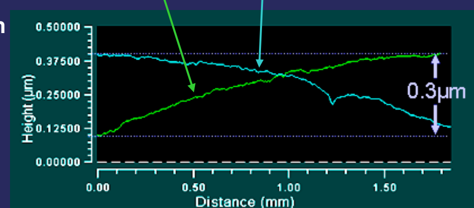
Flatness of seal surface
- Flat to 12 μin

Metallic Seal Development: Experimental Analyses

- POST- FLOW TEST ANALYSES
- **An estimate of fabrication tolerances was needed for future iterations of metallic seal designs**
- **An optical comparator was used to determine the surface conditions of a seal fabricated using simple techniques**
- **Measurements showed a wavy surface with**
  - –Amplitude = 0.3 µm ≈ 12 µin
  - –Wavelength = 4 mm ≈ 0.150 in
- **These parameters formed the basis for the subsequent numerical analyses**

Surface condition measurements showing a top view of the metallic seal surface and the variation from flat around the seal.





Surface condition measurements at two locations showing variation from flat across the metallic seal surface.

Metallic Seal Development: Analytical Model

Description of the Analyses

- **ANSYS used to model circumferentially wavy seal surface, with**
  - Variable seal thickness
  - Constant wave amplitude
- **Seal material**
  - Generic steel
  - (E = 30×10^6 psi)
- **Force applied**
  - 100 lbf / linear inch

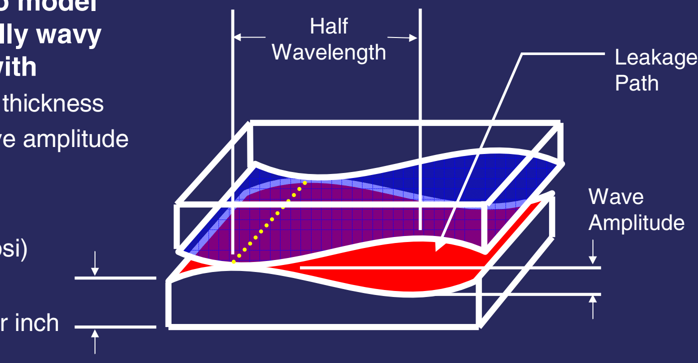
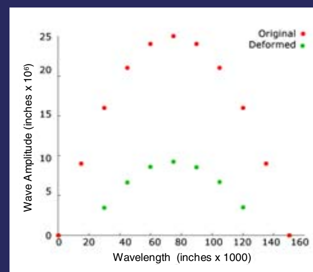


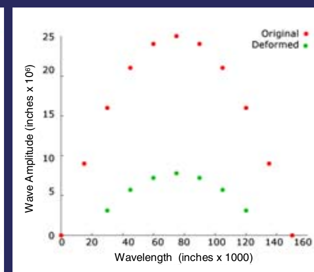
Diagram of the parameters used in the ANSYS model.

Numerical Analyses: Effect of Seal Thickness

- **Seal wavelength is constant for each case (0.150 inch)**
- **Wave amplitude is constant for each case (25×10^{-6} inch)**
- **Seal thickness is variable (0.040 - 0.070 inch)**
- **A force of 100 lbf / linear inch reduces the amplitude of the original wave, thereby reducing the gas leakage path.**
- **Under these conditions, a seal with a thickness of 0.040 inch is fully compressed, thereby minimizing the leakage path.**

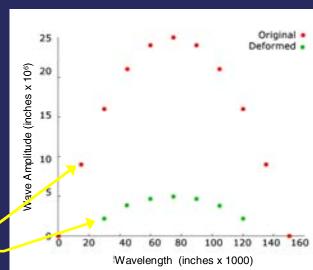


Seal thickness = 0.070 inch

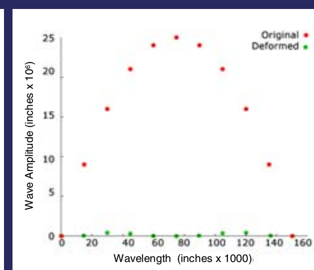


Seal thickness = 0.060 inch

Original Leakage Path
Reduced Leakage Path



Seal thickness = 0.050 inch



Seal thickness = 0.040 inch

Advanced Metallic Seal Concepts

- Feasibility of metal-to-metal androgenous seals has been demonstrated
- Techniques to minimize surface irregularities must be examined

Two concepts investigated:

- **Flexible metal interface with elastomeric preloader**
  - Flexibility will accommodate any surface irregularities from the mating surface
- **Rigid metal interface with elastomeric preloader**
  - Rigidity of the metal surface will prevent irregularities (waves) from occurring

Photo of flexible metal interface concept test specimens

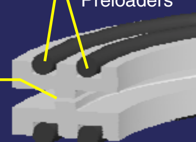


Diagram of rigid metal interface concept test specimens

Photo of rigid metal interface concept test specimens

Flexible Metallic Seals: Performance

- **Conforming metallic surfaces are well suited to make a suitable seal**
- **Circular shims of various thicknesses were bonded to of square o-rings**
  - Shims: Stainless Steel 18-8
  - Adhesive: Loctite 404

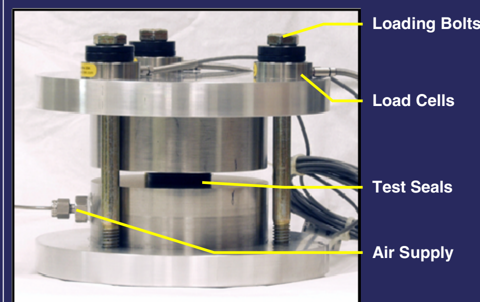
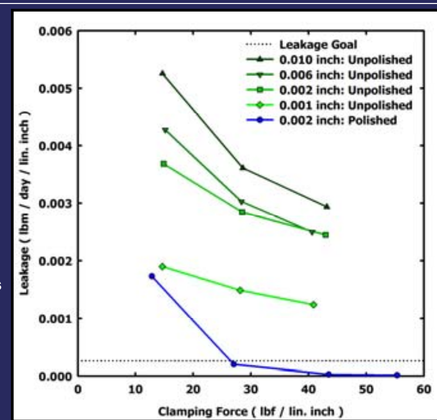


Photo of the test fixture.



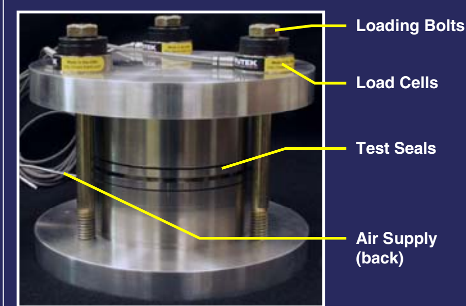
Graph of the flexible metallic seal test results showing the effects of metallic surface thickness on leakage rates.

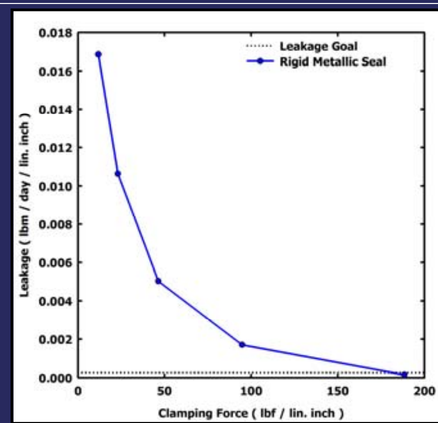
Seal	Ra (µin)	σ
0.010 inch: Unpolished	11.6	7.1
0.006 inch: Unpolished	8.6	2.2
0.002 inch: Unpolished	8.6	2.7
0.001 inch: Unpolished	12.7	5.9
0.002 inch: Polished	<1	n/a

Table showing the surface roughness of the flexible metallic seals.

Rigid Metallic Seal: Performance

- Rigid metallic surfaces are not suited for a suitable seal
- Seal does not conform to surface irregularities
- A uniform surface over a 54" diameter seal would be impossible to manufacture



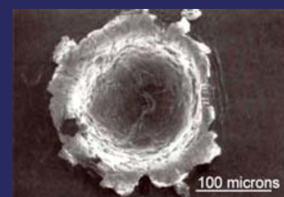


Graph of the rigid metallic seal test results showing the effect of clamping force on leakage rates.

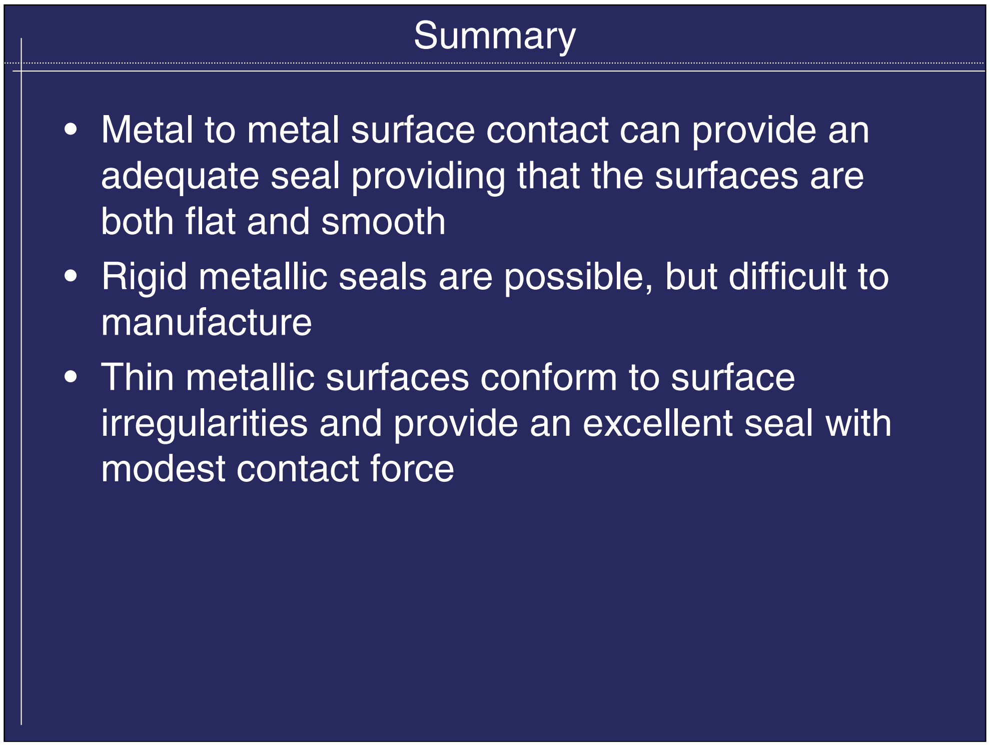
Average seal surface roughness
- Ra = <1 μin, σ = n/a

Future Work

- Investigate effects of environmental conditions on metallic surfaces
  - AO, UV, debris, micrometeoroid impacts
- Investigate whether smooth metallic surfaces will cold weld at low temperatures at 100 lbf/in contact force (1000 psi contact pressure)
- Develop full scale flexible metallic seal for further testing



Aluminum impact crater from micrometeoroid



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John Lucero – NASA GRC

MAPPING OF TECHNOLOGICAL OPPORTUNITIES—LABYRINTH SEAL EXAMPLE

Dana W. Clarke, Sr.
Applied Innovation Alliance, LLC
West Bloomfield, Michigan

All technological systems evolve based on evolutionary sequences that have repeated throughout history and can be abstracted from the history of technology and patents. These evolutionary sequences represent objective patterns and provide considerable insights that can be used to proactively model future seal concepts. This presentation provides an overview of how to map seal technology into the future using a labyrinth seal example.

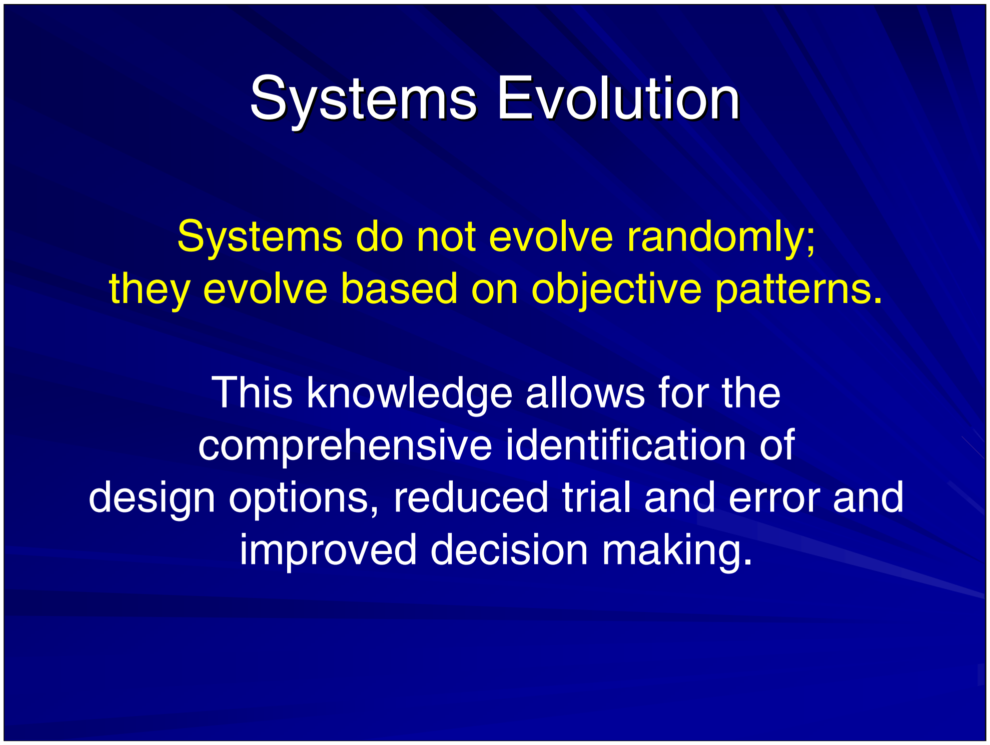
The mapping process delivers functional descriptions of sequential changes in market/consumer demand, from today's current paradigm to the next major paradigm shift. The future paradigm is developed according to a simple formula: the future paradigm is free of all flaws associated with the current paradigm; it is as far into the future as we can see.

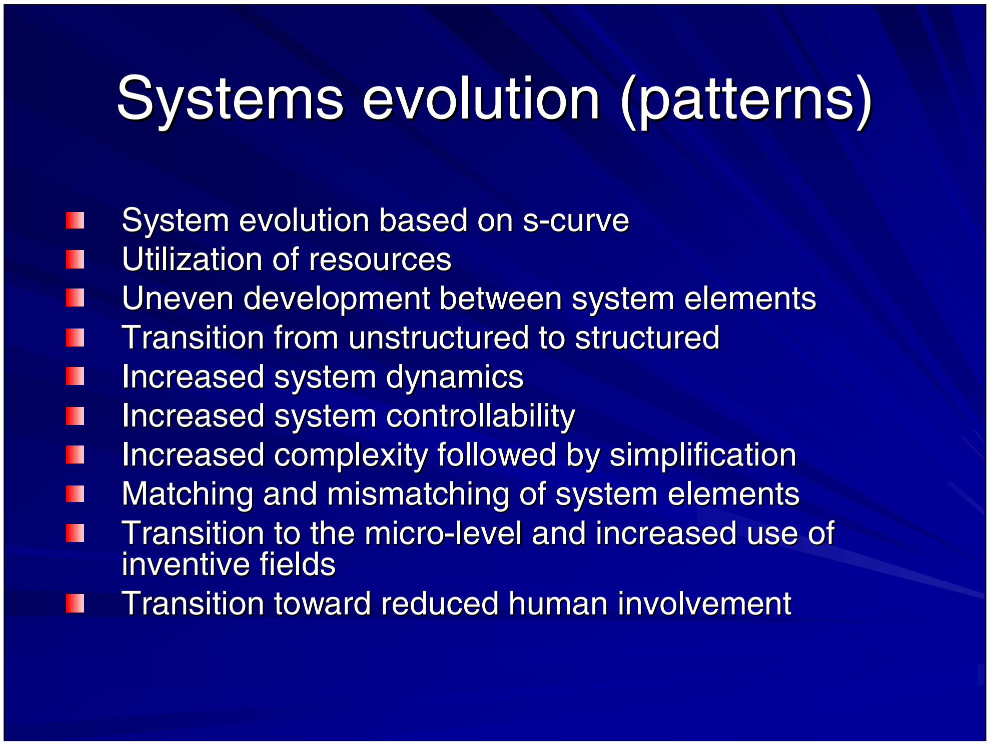
Although revolutionary, the vision of the future paradigm is typically not immediately or completely realizable nor is it normally seen as practical. There are several reasons that prevent immediate and complete practical application, such as:

- Some of the required technological or business resources and knowledge not being available;
- Availability of other technological or business resources are limited; and/or
- Some necessary knowledge has not been completely developed.

These factors tend to drive the Total Cost of Ownership or Utilization out of an acceptable range and revealing the reasons for the high Total Cost of Ownership or Utilization which provides a clear understanding of research opportunities essential for future developments and defines the current limits of the immediately achievable improvements.

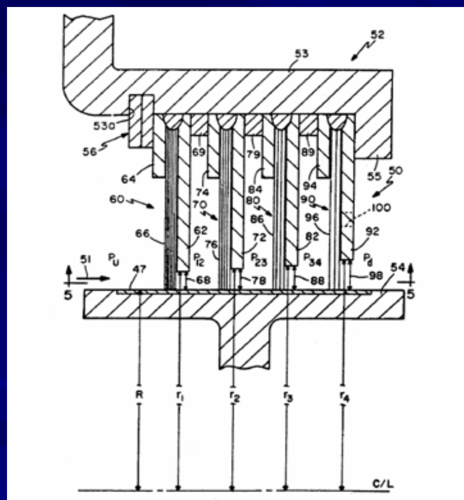
The typical roots of high Total Cost of Ownership or Utilization lie in the limited availability or even the absence of essential resources and knowledge necessary for its realization. In order to overcome this obstacle, step-by-step modification of the current paradigm is pursued to evolve from the current situation toward the ideal future, i.e., evolution rather than revolution. A key point is that evolutionary stages are mapped to show step-by-step evolution from the current paradigm to the next major paradigm.


Systems Evolution
Systems do not evolve randomly;
they evolve based on objective patterns.
This knowledge allows for the
comprehensive identification of
design options, reduced trial and error and
improved decision making.



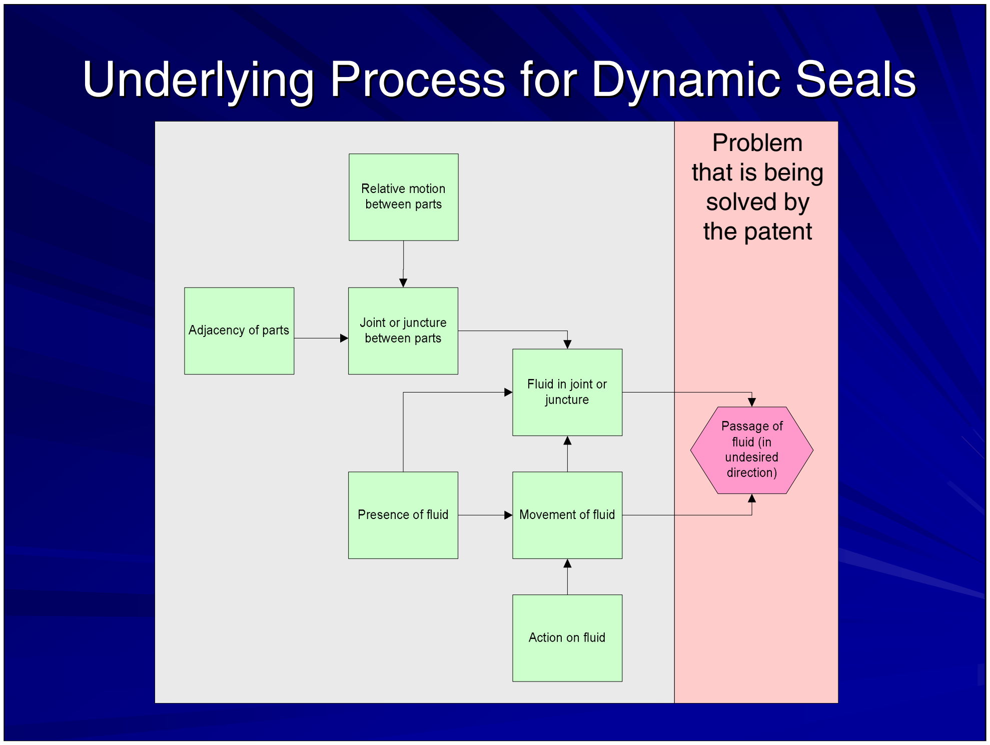
These evolutionary patterns are based on research of the history of technology and patents that was conducted in the Soviet Union by Genrich Altshuller between 1946 and 1985. All evolving systems transition through these patterns of evolution.

Labyrinth Seal - Steam Turbine Application
U.S. Patent 5,106,104

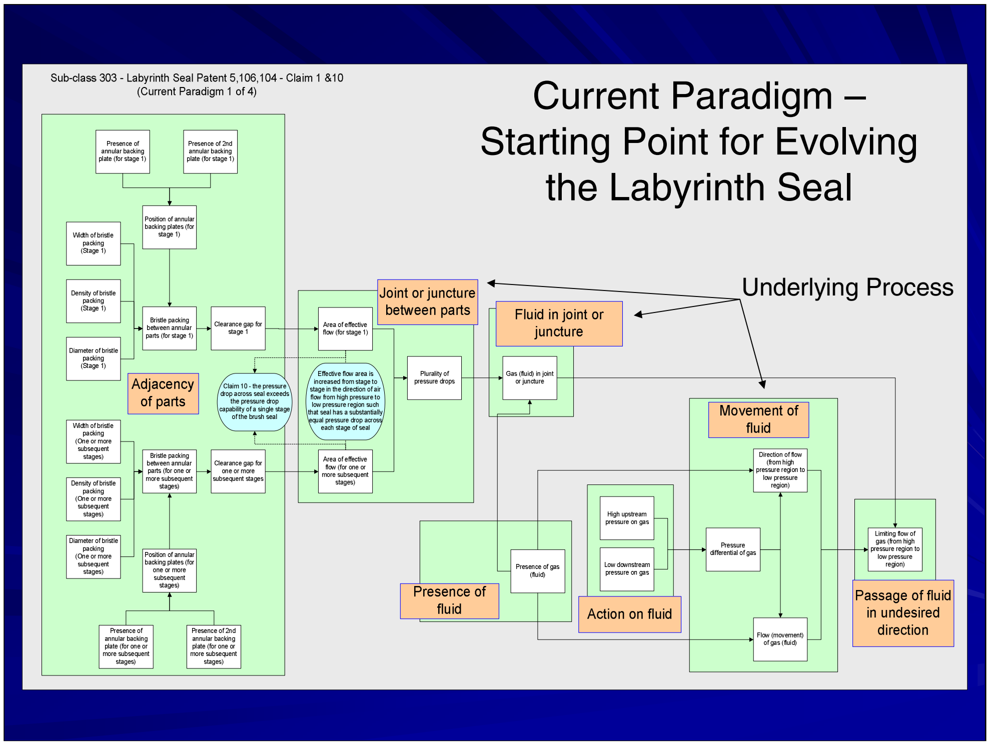


Abstract
A multiple stage brush seal having a controlled distribution of pressure drops across each stage of the seal is provided. The pressure drop across each stage is controlled by one or a combination of the following structural arrangements: increased clearance gaps, reduced bristle packing, and venting holes in the seal stage backing plate.

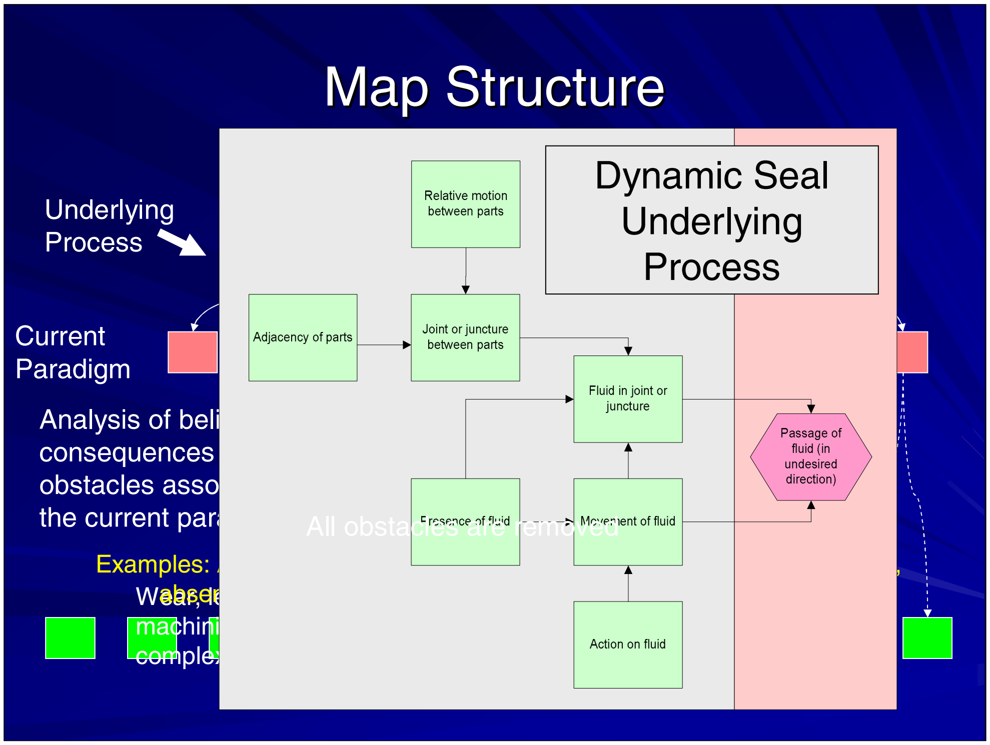
This US patent was selected as the result of researching highly cited labyrinth seal patents. It was chosen as one of several possible baselines for analysis of the evolution of labyrinth seals.



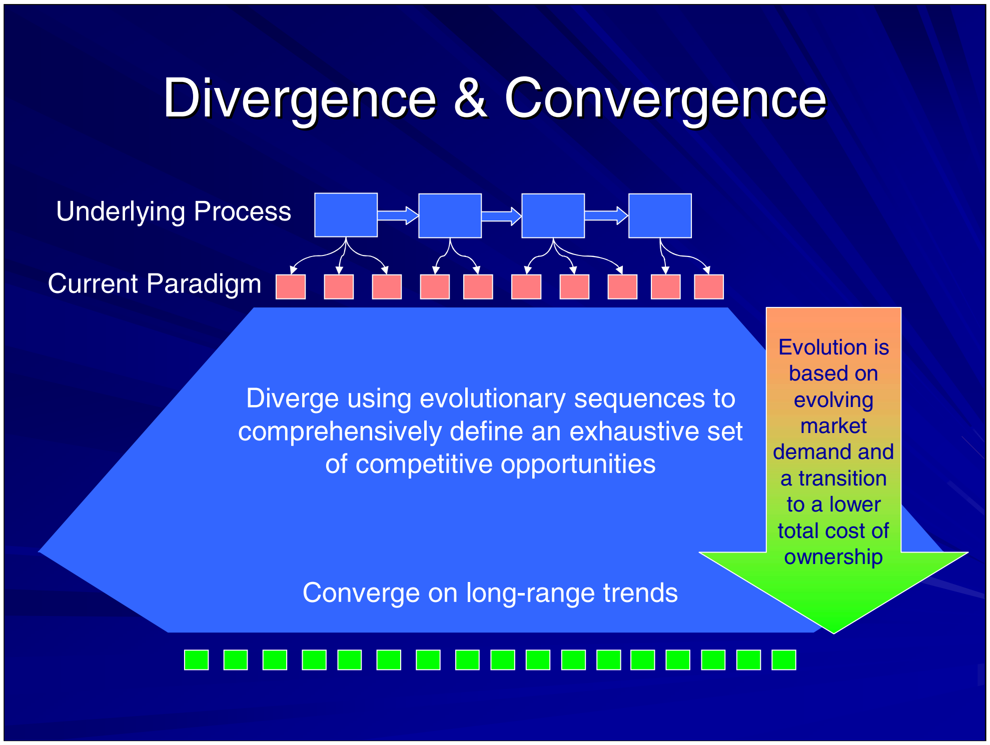
Since a labyrinth seal is a dynamic seal we need to look at dynamic seals in general. The underlying process provides a generic model for all dynamic seals. This model is a combination of functions, events and conditions that allow the objective of counteracting the passage of fluid in an undesired direction.



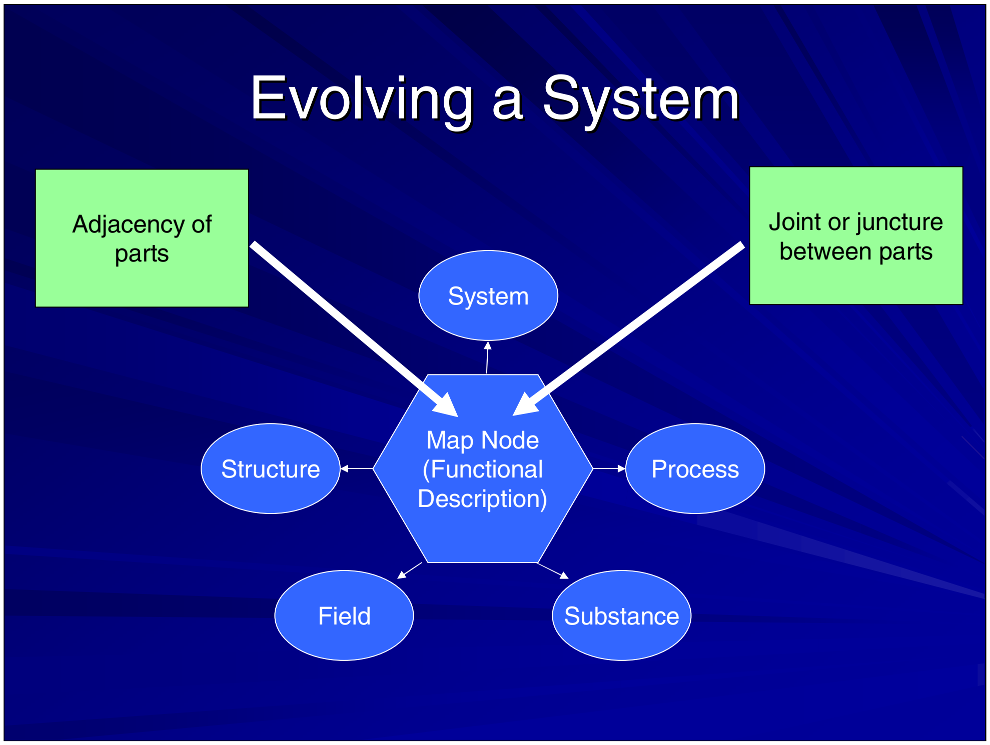
Analysis of US patent 5,106,104 claims provides details and a foundation for understanding how the patent relates to the underlying process of dynamic seals.



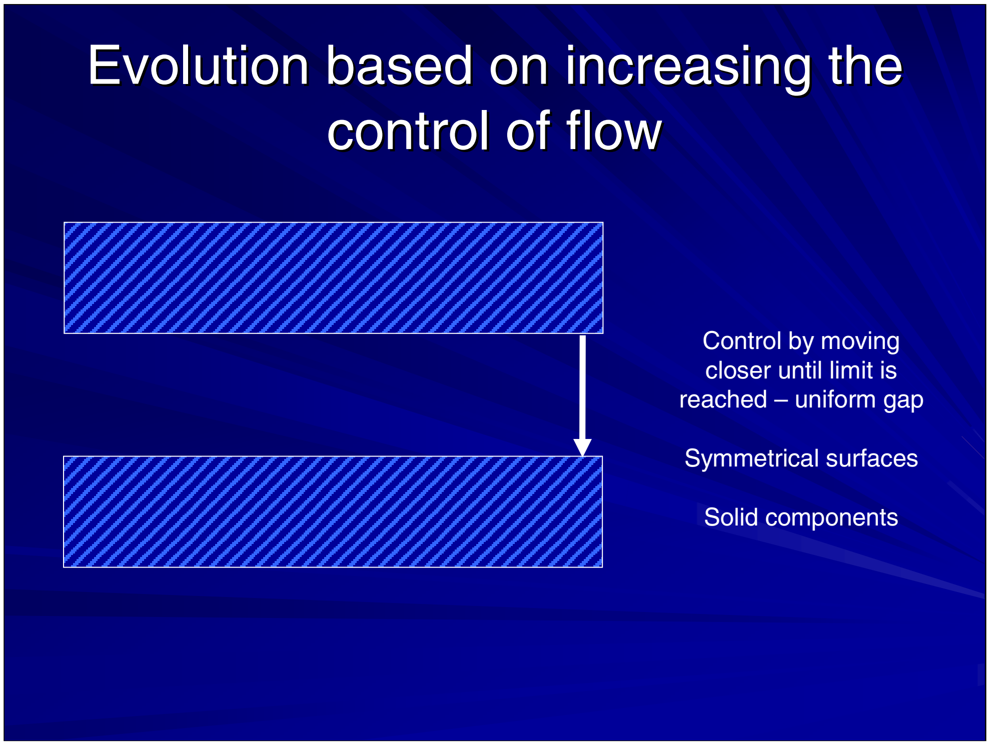
Once the underlying process and the current paradigm have been defined, the current paradigm is analyzed to identify the beliefs associated with the current paradigm. Each belief has potential consequences and there are some barriers (obstacles) to overcoming the consequences. In all probability, someone, somewhere is or will try to remove the obstacles. The theoretical removal of the obstacles results in the identification of long-range trends. The long-range trends, also known as "lighthouses on the horizon", are as far as we can see into the future based on the evolution of the current paradigm. This defines the direction of work for working on evolving the labyrinth seal. The gap created between the current paradigm and the long-range trends is filled by comprehensively mapping the possibilities.



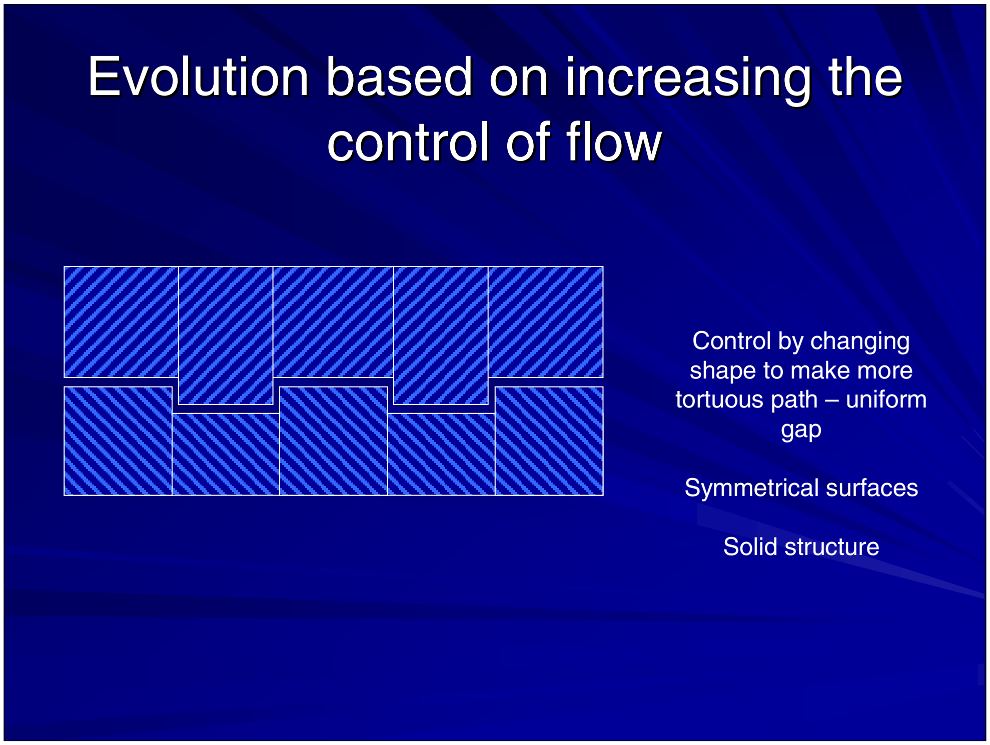
Mapping is a process of divergence, defining all of the possibilities, and convergence, focusing on achieving the long-range trends. Beginning with a bounded starting point, underlying process, and a bounded end-point, based on the elimination of obstacles.



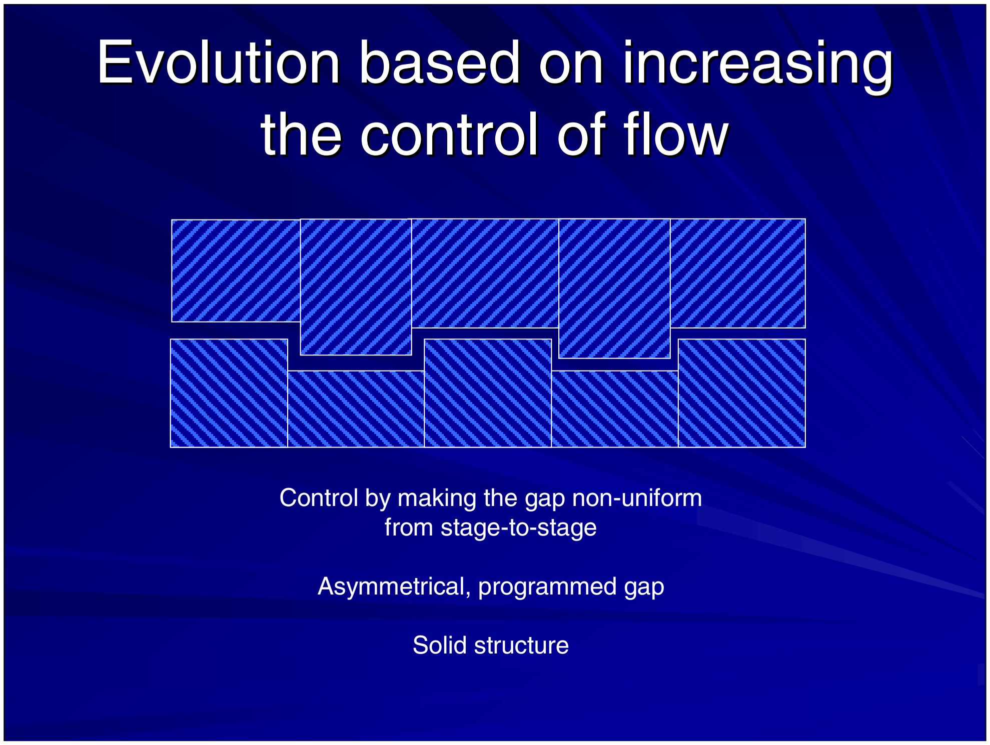
Evolving the functions, events and conditions associated labyrinth seal starts by looking at the functions, events and conditions associated with the underlying process and the labyrinth seal design. Systems are evolved based on five key areas – system, structure, field, substance and/or process.



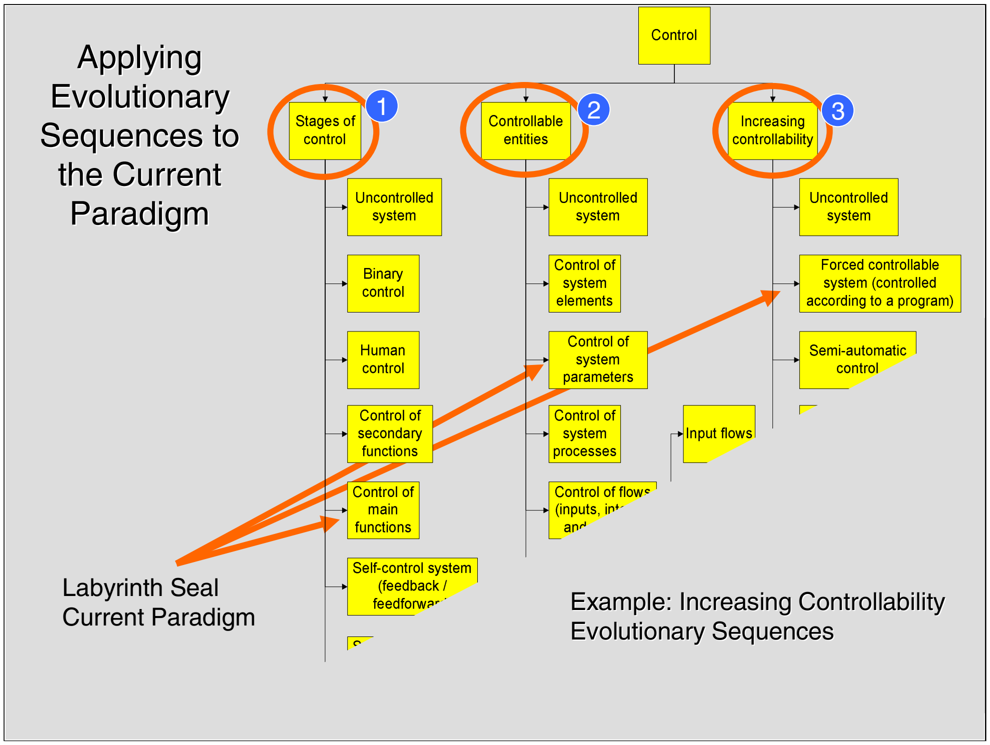
Looking at the history of seals and the evolution to labyrinth seal design we find that the process started with parallel surfaces and control was improved by moving the two surfaces toward each other. This process is limited by the ability to control the manufacture of the two surfaces. The closer the surfaces the better the control of flow through the seal.



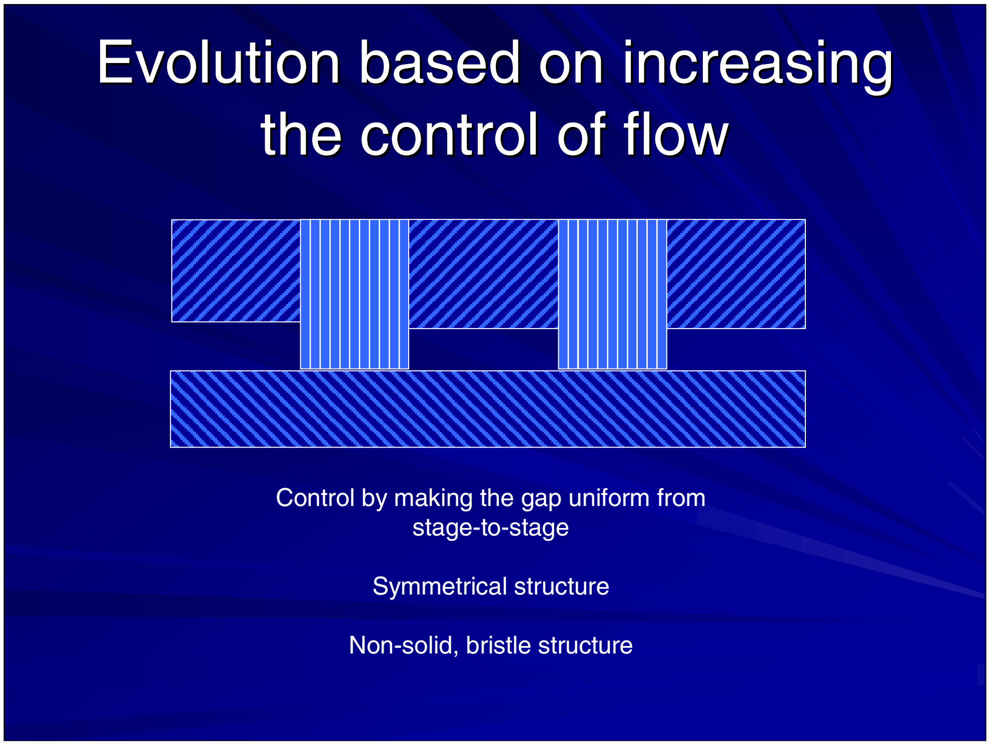
Over time seal designers realized that a more tortuous path would help restrict the flow. In the first designs the gap thickness was still uniform but performance was improved.



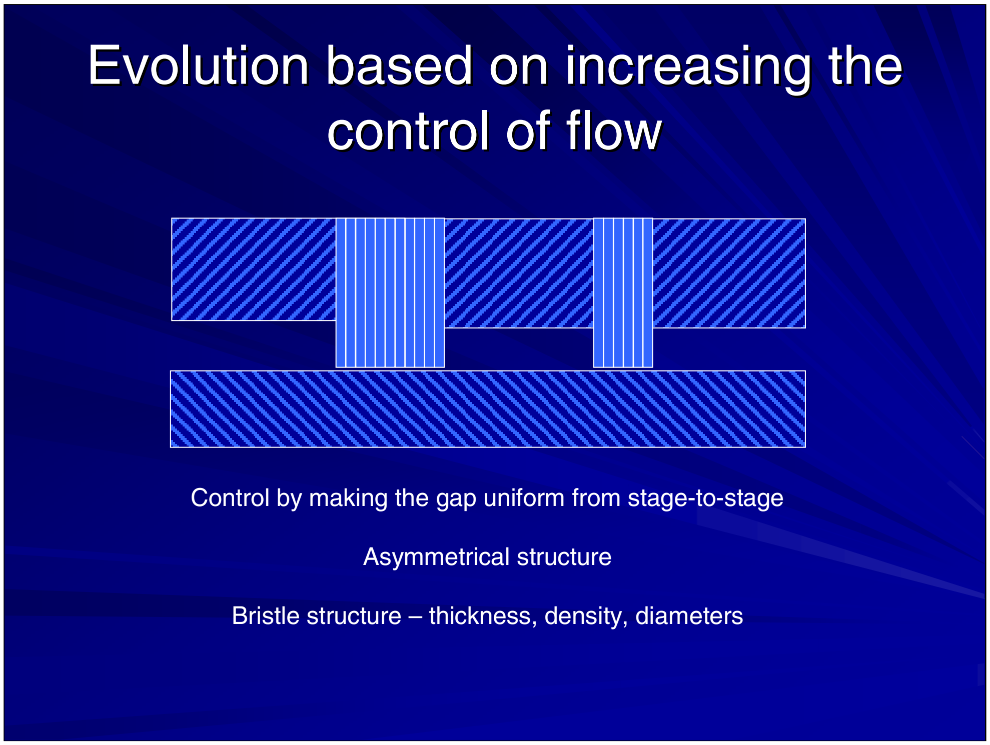
Next, designers realized that they could change the gap thickness and manage the pressure drop between the stages of the labyrinth seal. At this point, the design based on the use of solid, machined materials has reached a point of diminishing returns but there is a need to continue to refine the functionality of the seal.



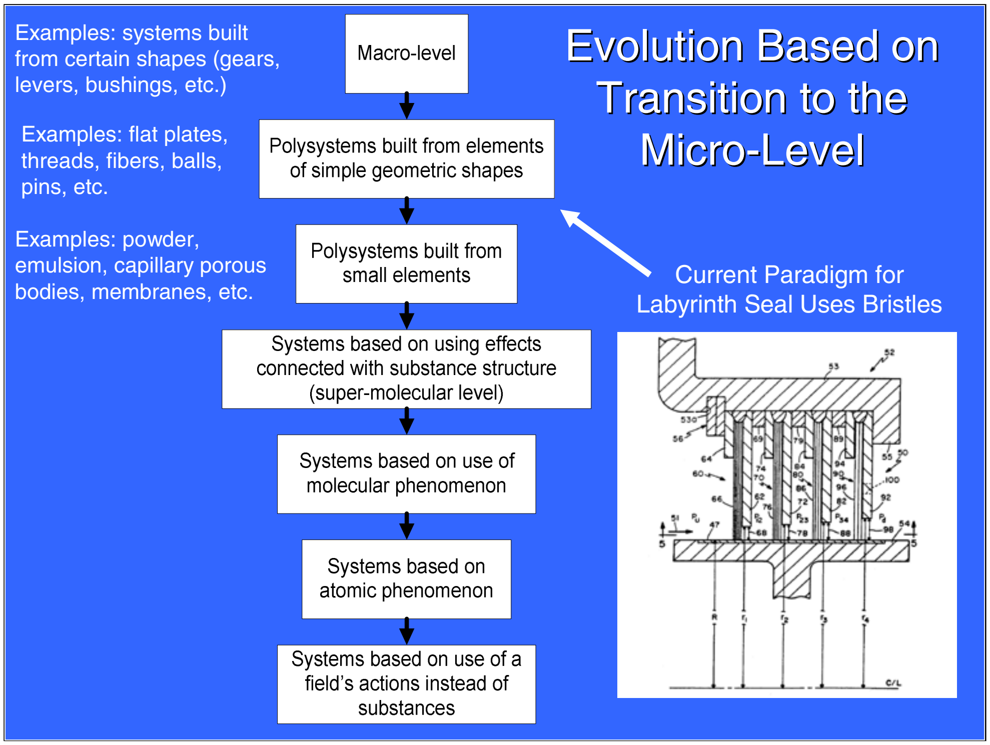
The last three slides are an example of how the labyrinth seal design has evolved based on the control of a process. Research of patents has revealed evolutionary sequences that provide details on how systems have evolved throughout history. These sequences can be used to reduce the amount of trial and error performed in evolving technology to the next generation.



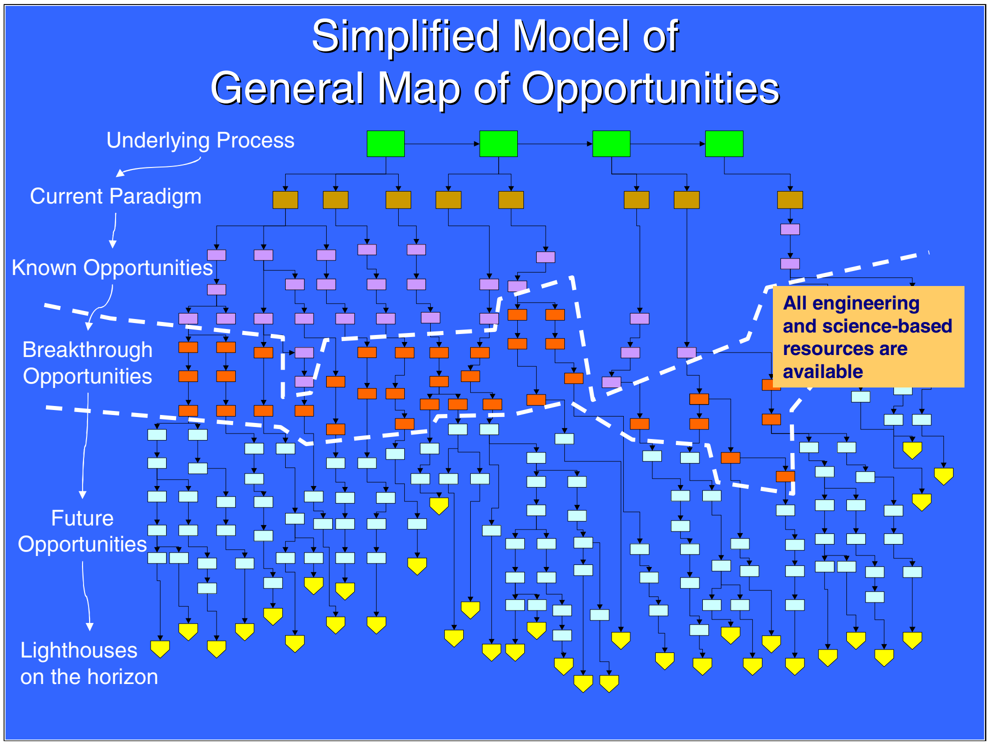
There are several evolutionary paths that systems take. Evolution can also take the path of transitioning from a solid system to the micro-level (use of energy fields). This diagram shows the transition from a solid to poly-system built from elements of simple geometric shapes.



Again, designers realized that they can control the flow from stage to stage by changing the bristle configuration – thickness of the bristle package, density of the bristles and diameters of the bristles.



Additional research reveals that the selected labyrinth seal has only evolved to the second of seven possible levels of evolution.



Step-by-step identification and resolution of problems coupled with the structured use of evolutionary sequences provides a means of identifying a comprehensive set of possible scenarios for the evolution of any technological system. The map development reveals known opportunities, breakthrough opportunities and future opportunities and can be used to leverage capital investments, focus the energy of scientists and engineering and continuously evolve systems from generation-to-generation.

Benefits of Mapping Technological Opportunities

- Research Benefits
  – Advance understanding of specific technologies
  – Discover new technological opportunities
  – Focus creative energy based on natural system evolution
  – Improve definition of research path(s)
  – Provide logic behind research initiatives
- Business Benefits
  – Enhance product value
  – Develop a continuous flow of new high value products
  – Develop continuous differentiation of products
  – Maximize technology reuse to speed product development
  – Maximize capital investment utilization

Accelerates the processes associated with innovation

Presented by:
Dana W. Clarke, Sr.
Applied Innovation Alliance, LLC
dclarke@aia-consulting.com
(248) 682-3368

2005 NASA Seal/Secondary Air System Workshop
Attendee Listing

Last	First	Company	City	St	Zip	Phone	Email
Anderson	John	Allied Aerospace	Newport News	VA	23606	757.873.5277	janderson@alliedaerospace.com
Artiles	Tony	Pratty & Whitney	East Hartford	CT	06108	860.557.1218	antonio.artiles@pw.utc.com
Assion	Joe	Analex Corp.	Cleveland	OH	44135	216.433.6712	jassion@grc.nasa.gov
Backlund	Shayler	ATK	Brigham City	UT	84302	435.863.2108	shayler.backlund@atk.com
Banks	Bruce	NASA Glenn Research Center	Cleveland	OH	44135	216.433.2308	bruce.a.banks@nasa.gov
Barnes	Steve	Parker Hannifin	Mayfield	OH	44124	216.896.3217	sbarnes@parker.com
Bond	Bruce	Jackson Bond Enterprises, LLC	Rochester	NH	03867	603.335.7913	brucebond@metrocast.net
Braun	Minel (Jack)	University of Akron	Akron	OH	44325	330.972.7734	mjbraun@uakron.edu
Cabe	Jerry	Belcan Corporation	Cincinnati	OH	45242	513.985.7386	jcabe@belcan.com
Christiansen	Rich	NASA Glenn Research Center	Cleveland	OH	44135	216.433.5308	Richard.Christiansen@nasa.gov
Chupp	Ray	GE Global Research	Niskayuna	NY	12309	518.387.7550	raymond.chupp@crd.ge.com
Clarke	Dana	Applied Innovation Alliance, LLC	West Bloomfield	MI	48323	248.682.3368	dclarke@aia-consulting.com
Daniels	Chris	NASA Glenn Research Center	Cleveland	OH	44135	216.433.6714	christopher.c.daniels@grc.nasa.gov
Datta	Amit	Advanced Components & Materials Inc.	E. Greenwich	RI	02818	401.885.5064	ADatta@worldnet.att.net
DeCastro	Jonathan	NASA Glenn Research Center	Cleveland	OH	44135	216.433.3946	jonathan.decastro@grc.nasa.gov
Delgado	Irebert	NASA Glenn Research Center	Cleveland	OH	44135	216.433.3935	irebert.r.delgado@nasa.gov
DeMange	Jeffrey J.	NASA Glenn Research Center	Cleveland	OH	44135	216.433.3568	Jeffrey.Demange@nasa.gov
Diaz	Steven	Rolls-Royce Corporation	Indianapolis	IN	46241	317.230.6348	steven.w.diaz@aadc.com
DiCarlo	James	NASA Glenn Research Center	Cleveland	OH	44135	216.433.5514	james.a.dicarlo@nasa.gov
Dong	Zhifeng (Phil)	GE Aircraft Engines	Cincinnati	OH	45215	513.243.4901	phil.dong@ae.ge.com
Donovan	Eric	LibertyWorks	Indianapolis	IN	46242	317.230.8224	jz1887@aadc.com
Dunlap	Patrick	NASA Glenn Research Center	Cleveland	OH	44135	216.433.3017	patrick.h.dunlap@nasa.gov
Eberly	Eric	NASA Marshall Space Flight Center	MSFC	AL	35812	256.544.2092	eric.a.eberly@nasa.gov
Engelmann	Rainer	Rexnord Ind., Inc.	Wheeling	IL	60090	847.229.2858	rainer.engelmann@rexnord.com
Erker	Art	NASA Glenn Research Center	Cleveland	OH	44135	216.433.2911	arthur.erker@analex.com
Finkbeiner	Joshua	NASA Glenn Research Center	Cleveland	OH	44135	216.433.6080	joshua.finkbeiner@nasa.gov
Flaherty	Andrew	Rexnord	Wheeling	IL	60090	847.229.2807	andy.flaherty@rexnord.com
Garrard	Doug	ATA - Aerospace Testing Alliance	Arnold Air Force Base	TN	37389	931.454.3300	Doug.Garrard@arnold.af.mil
Geisheimer	Jon	Radatec, Inc.	Atlanta	GA	30308	404.526.6037	jong@radatec.com
Glahn	J. Axel	Pratt & Whitney	East Hartford	CT	06108	860.565.9286	glahnja@pweh.com
Gravereaux	Stephen J.	Parker Hannifin	North Haven	CT	06473	860.658.6200	sjgravereaux@parker.com
Grondahl	Clayton	CMG Tech, LLC	Rexford	NY	12148	518.371.5050	cmgtech@earthlink.net
Grudier	Michael	The Boeing Company	Huntington Beach	CA	92647	714.372.9977	michael.a.grudier@boeing.com
Gupta	Hemant	Esterline Technologies/TA Aerospace	Valencia	CA	91355	661.775.1190	hgupta@kirkhill-ta.com
Harmon	Crystal	Pratt & Whitney	North Olmsted	OH	44070	440.734.3990	crystal.harmon@pw.utc.com
Hebert	Ryan	Florida Turbine Technologies, Inc.	Jupiter	FL	33477	561.746.3317	rhebert@fttinc.com
Hendricks	Robert C.	NASA Glenn Research Center	Cleveland	OH	44135	216.977.7507	robert.c.hendricks@nasa.gov
Herron	William L.	General Electric	Cincinnati	OH	45215	513.243.7445	william.herron@ae.ge.com
Higgins	Amy	PerkinElmer Fluid Sciences	Beltsville	MD	20705	301.902.3533	amy.higgins@perkinelmer.com
Holloway	Gary	Diversitech Inc.	Cincinnati	OH	45246	513.772.4447	gary.holloway@diversitechinc.com
Jasklowski	Chris	The Boeing Company	Seattle	WA	98124	425-342-6897	chris.t.jasklowski@boeing.com
Johnson	Dexter	NASA Glenn Research Center	Cleveland	OH	44135	216.433.6046	Dexter.Johnson@grc.nasa.gov
Justak	John F.	Advanced Technologies Group	Stuart	FL	34994	772.283.0253	jjustak@advancedtg.com
Kamibayashiyama	Julian	Parker Composite Systems Sealing Div.	San Diego	CA	92139	619.671.3272	jkamibayashiyama@parker.com
Kane	Daniel	Pratt & Whitney	E. Hartford	CT	06108	860.557.1853	daniel.kane@pw.utc.com
Keith	Theo G.	NASA Glenn Research Center	Cleveland	OH	44135	216.433.3944	theo.g.keith@nasa.gov

2005 NASA Seal/Secondary Air System Workshop
Attendee Listing

Last	First	Company	City	St	Zip	Phone	Email
Koch	Peter	US Air Force	WPAFB	OH	45433	937.255.7319	peter.koch@wpafb.af.mil
Krawiecki	Stephen	Diversitech Inc.	Cincinnati	OH	45246	513.772.4447	stephe.krawiecki@diversitech.com
Lattime	Scott	The Timken Company	Canton	OH	44706	330.471.2284	scott.lattime@timken.com
Lee	Robert	Axiam Inc.	Gloucester	MA	01930	978.281.3550	robert.lee@axiam.com
Lombardi	Louis	Dresser-Rand	Olean	NY	14760	716.375.5311	Louis_M_Lombardi@dresser-
Long-Davis	Mary Jo	NASA Glenn Research Center	Cleveland	OH	44135	216.433.8708	maryjo.long-davis@nasa.gov
Makhobey	Mark	Car-Graph, Inc.	Tempe	AZ	85281	480.894.1356	mmakhobey@car-graph.com
Martin	Katherine	NASA Glenn Research Center	Cleveland	OH	44135	216.433.2406	katherin.martin@nasa.gov
McNickle	Alan	Stein Seal Company	Kulpsville	PA	19443	215.256.0201	AlanMcNickle@steinseal.com
Mehta	Jayesh	TK Engineering	Cincinnati	OH	45246	513.552.5091	Jayesh.mehta@ae.ge.com
Mikulic	John	NASA Glenn Research Center	Cleveland	OH	44135	216.433.3868	john.j.mikulic@nasa.gov
Miller	Sharon	NASA Glenn Research Center	Cleveland	OH	44135	216.433.2219	sharon.k.miller@nasa.gov
Moll	Randy	Dresser-Rand	Wellsville	NY	14895	585.596.3491	randy_w_moll@dresser-rand.com
More	D. Greg	Advanced Products Company	North Haven	CT	06473	203.985.3141	gmore@advpro.com
Nagpal	Vinod	N&R Engineering	Parma Hts.	OH	44130	440.845.7020	vnagpal@nrengineering.com
Oswald	Jay	NASA Glenn Research Center	Cleveland	OH	44135	216.433.6411	jay.oswald@grc.nasa.gov
Pakkianathan	Stanley	PerkinElmer	Beltsville	MD	20705	301.902.3457	stanely.pakkianathan@perkinelmer.co
Paolillo	Roger	Pratt & Whitney	East Hartford	CT	06108	860.557.1460	roger.paolillo@pw.utc.com
Pickett	Paul	Solar Turbines, Inc.	San Diego	CA	92186	619.544.5420	pickett_paul_e@solarturbines.com
Proctor	Margaret	NASA Glenn Research Center	Cleveland	OH	44135	216.977.7526	margaret.p.proctor@nasa.gov
Ransom	David	Southwest Research Institute	San Antonio	TX	78238	210.522.5281	david.ransom@swri.org
Robbie	Malcolm	NASA Glenn Research Center	Cleveland	OH	44135	216.433.5490	malcolm.g.robbie@grc.nasa.gov
Rose	Steve	Flowserve Corp.	Temecula	CA	92592	951.719.4412	srose@flowserve.com
Sacksteder	Kurt	NASA Glenn Research Center	Cleveland	OH	44135	216.433.2857	kurt.r.sacksteder@nasa.gov
Sak	Wojciech	GE - Advanced Mechanical Design	Cincinnati	OH	45215	513.243.8875	wojciech.sak@ae.ge.com
Seitzer	Ken	GE Aviation	Cincinnati	OH	42515	513.243.2534	kenneth.seitzer@ae.ge.com
Shaughnessy	Dennis	Pratt & Whitney	East Hartford	CT	06108	860.557.1675	dennis.shaughnessy@pw.utc.com
Shivakumar	Kunigal	North Carolina A&T University	Greensboro	NC	27411	336.334.7411	kunigal@ncat.edu
Short	John	Perkin Elmer	Warwick	RI	02888	401.781.4700	john.short@perkinelmer.com
Shpargel	Tarah	QSS, NASA Glenn Research Center	Cleveland	OH	44135	216.433.2644	tarah.shpargel@grc.nasa.gov
Singh	Jay	QSS, NASA Glenn Research Center	Cleveland	OH	44135	216.433.8883	Mrityunjay.Singh@grc.nasa.gov
Steinetz	Bruce	NASA Glenn Research Center	Cleveland	OH	44135	216.433.3302	bruce.m.steinetz@nasa.gov
Stevens	Mark	NASA Glenn Research Center	Cleveland	OH	44135	216.433.2529	Mark.A.Stevens@nasa.gov
Subramanian	Mani	ASE Technologies, Inc.	Cincinnati	OH	45241	513-563-8855	mani@asetech.com
Sulda	Erik	TurboCare	Chicopee	MA	01022	413.593.0500	esulda@turbocare.com
Taylor	Shawn	CWRU - NASA GRC	Cleveland	OH	44135	216.433.3166	shawn.c.taylor@grc.nasa.gov
Trabert	Chuck	PerkinElmer	Warwick	RI	02888	401.473.2220	Chuck.Trabert@PerkinElmer.com
Trudell	Jeff	NASA Glenn Research Center	Cleveland	OH	44135	216.433.5303	jeffrey.j.trudell@nasa.gov
Tyburski	Timothy	NASA Glenn Research Center	Cleveland	OH	44135	216.433.8616	timothy.tyburski@nasa.gov
Vasagar	Manik	Stein Seal Company	Kulpsville	PA	19443	215.256.0201	manikvasagar@steinseal.com
Verbus	Richard	Analex, NASA Glenn Research Center	Cleveland	OH	44135	216.433.3758	Richard.J.Verbus@nasa.gov
Wong	Gordon	The Boeing Company	Huntington Beach	CA	92647	714.372.5039	gordon.f.wong@boeing.com
Wu	Charley	Pratt & Whitney	East Hartford	CT	06108	860.565.9383	wucc@pw.utc.com
Zheng	Xiaoqing	PerkinElmer	Warwick	RI	02888	401.473.2274	Xiaoqing.Zheng@PerkinElmer.com
Zuchowski	Brian	Lockheed Martin Aeronautics Co.	Palmdale	CA	93599	661.572.5353	brian.zuchowski@lmco.com

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6. AUTHOR(S)

Bruce M. Steinetz and Robert C. Hendricks, editors

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National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135−3191

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13. ABSTRACT *(Maximum 200 words)*

The 2005 NASA Seal/Secondary Air System workshop covered the following topics: (i) Overview of NASA's new Exploration Initiative program aimed at exploring the Moon, Mars, and beyond; (ii) Overview of the NASA-sponsored Propulsion 21 Project; (iii) Overview of NASA Glenn's seal project aimed at developing advanced seals for NASA's turbomachinery, space, and reentry vehicle needs; (iv) Reviews of NASA prime contractor, vendor, and university advanced sealing concepts including tip clearance control, test results, experimental facilities, and numerical predictions; and (v) Reviews of material development programs relevant to advanced seals development. Turbine engine studies have shown that reducing high-pressure turbine (HPT) blade tip clearances will reduce fuel burn, lower emissions, retain exhaust gas temperature margin, and increase range. Several organizations presented development efforts aimed at developing faster clearance control systems and associated technology to meet future engine needs. The workshop also covered several programs NASA is funding to develop technologies for the Exploration Initiative and advanced reusable space vehicle technologies. NASA plans on developing an advanced docking and berthing system that would permit any vehicle to dock to any on-orbit station or vehicle. Seal technical challenges (including space environments, temperature variation, and seal-on-seal operation) as well as plans to develop the necessary "androgynous" seal technologies were reviewed. Researchers also reviewed tests completed for the shuttle main landing gear door seals.

14. SUBJECT TERMS

Seals; Turbine; Clearance control; Materials; Analyses; Experimental; Design; Docking mechanism; Space vehicles; Leakage; Hypersonic

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