NASA/CP—2007-214995/VOL1

2006 NASA Seal/Secondary Air System Workshop

October 2007

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2006 NASA Seal/Secondary Air System Workshop

Proceedings of a conference held at and sponsored by
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November 14–15, 2006

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

October 2007

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Executive Summary
Volume 1

The 2006 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 NASA's new fundamental aeronautics technology 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 fundamental aeronautics project is developing advanced technologies for subsonic rotary and fixed-wing aircraft and supersonic and hypersonic aircraft. 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 for subsonic aircraft. General Electric presented an approach for a fast-acting thermal active clearance control system. NASA Glenn researchers presented efforts underway to develop new Active Clearance Control (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. Vibro-meter 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 a Low Impact Docking System (LIDS) that would become the Agency's standard for docking and berthing for the Exploration Initiative. 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 seal technologies employed by the Apollo command module that serve as an excellent basis for seals for NASA's new Crew Exploration Vehicle (CEV).

Contents

OVERVIEW OF NASA GLENN SEAL PROJECT

Bruce M. Steinetz, Patrick J. Dunlap, Jr., and Margaret P. Proctor
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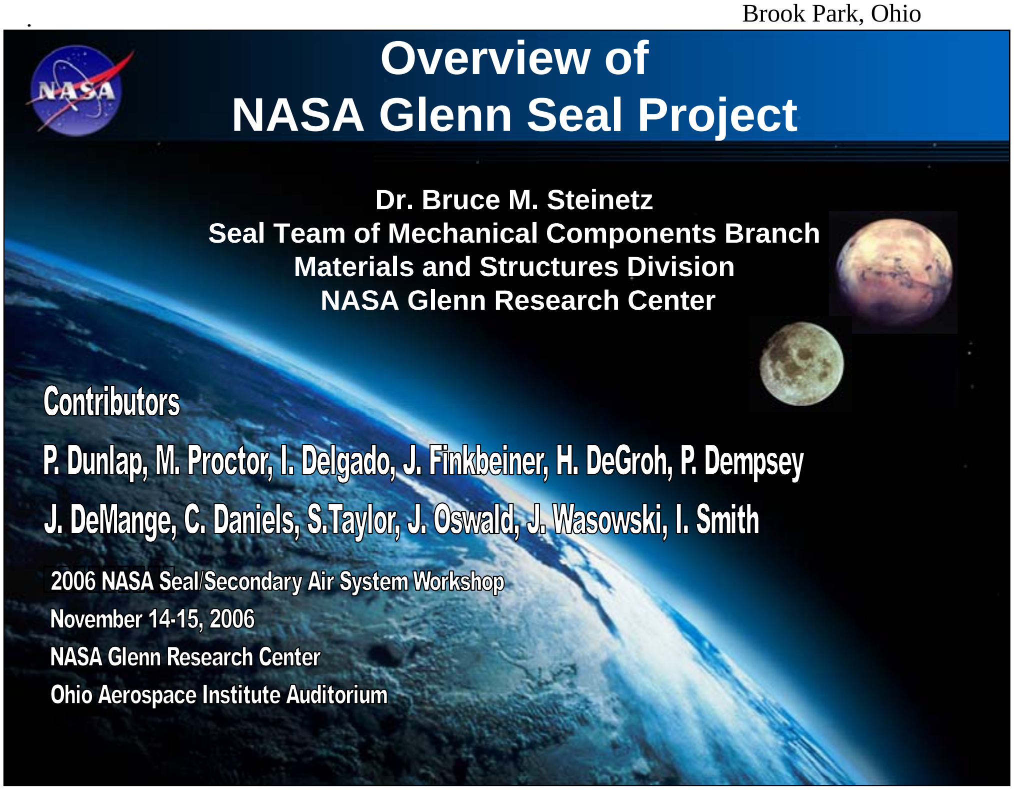

NASA Glenn hosted the Seals/Secondary Air System Workshop on November 14-15, 2006. At this workshop NASA and our industry and university partners shared their respective seal technology developments. We use these workshops as a technical forum to exchange recent advancements and "lessons-learned" in 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 as Sensitive But Unclassified (SBU) under International Traffic and Arms Regulations (ITAR).

The first day of presentations included overviews of current NASA programs. Mr. Smith reviewed the goals and objectives of NASA's new Exploration Initiative targeting both robotic and manned missions to the Moon, Mars and beyond. Ms. Anita Liang reviewed project plans and objectives of the Fundamental Aeronautics Project aimed at developing technologies for rotorcraft, sub-sonic fixed wing, supersonic and hypersonic systems.

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.

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. Seitzer presented an overview of GE's current work in developing improved turbine active clearance control concepts. 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 at temperatures up to ~1200°F. 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.

Workshop Agenda
Tuesday, Nov. 14, Afternoon

Turbine Seal Development Session II	**1:15-2:55**
Application of Non-metallic Fiber Brush Seals to Barrier Sealing Applications (*Withdrawn)*	Dr. Eric Ruggiero and Mr. Mark Lusted/GE Global Research Center
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
Large Diameter Non-Contacting Face Seal Development	Dr. Xiaoqing Zheng, G. Berard /Eaton-Centurion Mechanical Seals
Brush Seal Design Option Evaluation Results	Mr. Chuck Trabert, X. Zheng, J. Duquette Eaton-Centurion Mechanical Seals
Forming a Turbomachinery Seals Working Group An Overview and Discussion	Ms. Margaret Proctor/NASA GRC
Break	**2:55-3:10**
Turbine Seal Development Session III	**3:10-5:00**
Experimental Implementation & Results of Four Types of Non-Contacting Finger Seals.	Mr. Ian Smith/Analex Corp. and Dr. Minel J. Braun/Univ of Akron
Force Balance Determination of a Film Riding Seal Using CFD	Mr. John Justak/Advanced Technologies Group, Inc
Robustness of Modeling of Out of Service Gas Mechanical Face Seal	Dr. Itzhak Green/Georgia Institute of Technology
A Rapid Survey of the Compatibility of Selected Seal Materials with Conventional and Semi-Synthetic Jet Fuel	Mr. John Graham, R. Striebich, Univ. of Dayton Research Inst., D. Minus, W. Harrison/Propulsion Directorate AFRL
Adjourn	
Group Dinner: 100th Bomb Group	**6:00-?**

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Seal Team

Mr. Delgado provided an update on comparisons he and Ms. Proctor are making for labyrinth, annular, brush, and finger seal power loss and leakage characteristics. Representatives from Eaton presented leakage data of brush seals and early performance assessments of large diameter non-contacting face seal under development. Ms. Proctor presented a status update on an a turbomachinery working group formation. She is evaluating whether such a working group would be beneficial to the community.

Dr. Braun and Ian Smith presented investigations into a non-contacting finger seal under development by NASA GRC and University of Akron. Mr Justak presented CFD work being used to understand the force balance in a film-riding H-seal assessing fluid dynamic effects on gap sizes. Dr. Green presented modeling work of seals that have seen actual service conditions where worn face conditions exist. Mr. Graham presented results assessing compatibility of seal materials currently in operation within the Air Force with semi-synthetic jet fuels blended from JP-8 and Fisher-Tropsch fuels, with an aim to reduce dependence on foreign oil supplies.

Workshop Agenda

Wednesday, Nov. 15 Morning

Registration at OAI	**8:00-8:30**
Space Systems Development	**8:30-10:00**
Future Space Vehicle Docking/Berthing Mechanism and Seal Needs: An Update	Mr. Brandon Burns, Mr. J. Lewis, /NASA Johnson Space Center
CEV Project Overview and Seals Challenges	Mr. Matt Parke, Mr. Warren "Hunts" Kretsch/Lockheed-Martin
Falcon Vehicle Program Objectives and Seal Challenges: An Update	Mr. Brian Zuchowski, V. Bodepudi/Lockheed-Martin
Development, Evaluation, and Qualification of Low-Temperature Seal Materials for RSRM Use	Mr. Neal Carter/ATK Thiokol
Break	**10:00-10:15**
Structural Seal Development Session I	**10:15-12:30**
Overview of LIDS Docking and Berthing System Seals	Dr. Christopher Daniels/Univ. of Akron, P. Dunlap, H. DeGroh, B. Steinetz/NASA GRC, J. Oswald/J&J Technical Solutions, I. Smith/Analex Corp.
Space Environments Effects on Candidate LIDS Seal Materials	Mr. Henry deGroh,/NASA GRC, C. Daniels/Univ. of Akron, P. Dunlap, J. Dever, S. Miller/NASA GRC, D. Waters/ASRC Aerospace Corp, B. Steinetz/NASA GRC
FEA Modeling of Elastomeric Seals for LIDS	Mr. Jay Oswald/J&J Tech. Solutions, C. Daniels/Univ. of Akron
Overview of CEV Heatshield Interface Seals Development	Mr. Pat Dunlap, B. Steinetz, J. Finkbeiner/NASA GRC, J. DeMange, S. Taylor/Univ. of Toledo
Apollo Seals: Basis for CEV Seal Development	Mr. Josh Finkbeiner, Patrick Dunlap, et al/NASA GRC
Lunch OAI Sun Room	**12:30-1:30**

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NASA is developing a standardized system for docking and berthing for future exploration system vehicles, including as the Crew Exploration Vehicle (CEV). Mr. Brandon Burns presented the goals and objectives of this Low Impact Docking Systems (LIDS) project, headed by NASA JSC. Dr. Daniels presented an overview of the extensive seal and seal test fixture development underway at NASA Glenn to support the LIDS development project. Mr. DeGroh presented GRC's efforts to characterize the effects of space environments (atomic oxygen, ultraviolet and particle radiation) on LIDS seal performance (compression set, leakage, and adhesion). Mr. Oswald presented GRC's approach of performing structural analyses of elastomer seal loads in a seal-on-seal configuration. He also presented experimentally measured data supporting the hyperelastic constitutive models used to perform the finite element modeling.

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. Neal Carter presented work ATK Thiokol is doing with the seal vendors to reduce the operating temperature capability of Viton O-ring seals to help with cold launch conditions for the Space Shuttle.

Mr. Dunlap presented an overview of the structural seal development activities underway for the Crew Exploration Vehicle heat shield. GRC has been tasked to develop a seal for the heat-shield to command module interface, evaluate its performance under simulated conditions and make a recommendation to the prime contractor, Lockheed-Martin. Mr. Finkbeiner presented an summary of the seal technologies used for the Apollo capsule that serve as good reference points for the CEV seal designs.

Workshop Agenda
Wednesday, Nov. 15, Afternoon

Structural Seal Development Session II	**1:30-3:00**
An Update on High Temperature Structural Seal Development at NASA GRC	Mr. Jeff DeMange/Univ. of Toledo, P. Dunlap, B. Steinetz, F. Ritzert/NASA GRC,
Development and Evaluation of High Temperature Gaskets for Hypersonic and Reentry Applications	Dr. Jay Singh/OAI, T. Shpargel/ASRC Aerospace/NASA GRC
High Temperature Metallic Seal Development: An Update	Dr. Amit Datta/Advanced Components and Materials G. More/Parker Co.
Survey of Dust Issues for Lunar Seals and the RESOLVE Project	Ms. Margaret Proctor, P. Dempsey/NASA GRC

Tour of NASA Seal Test Facilities **3:15-4:15**

Must have NASA/Seal Workshop badge for tour

Adjourn

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Mr. DeMange presented high temperature structural seal development efforts underway at GRC for future hypersonic and re-entry vehicles. Dr. Singh reviewed materials developments for high temperature 1800+F gasket materials. Mr. More and Dr. Datta presented recent progress in developing higher temperature metal seals that incorporate single-crystal blade alloy finger preloaders capable of 1600+°F operation. Ms. Proctor reviewed the key issues seal designers face for lunar seals that must operate in a dusty environment – including a reaction chamber seal for the RESOLVE project.

Outline

- Seal Team Organization and Members
- Turbine Seals
  - Challenges
  - Ongoing GRC Projects
    - » Shaft Seals
    - » Clearance Management
- Space Exploration Seals
  - Ongoing GRC Projects
    - » Docking and Berthing Seals
    - » CEV Heat Shield Interface Seals (see Volume 2)
    - » Surface Operation Seals
- Hypersonic Vehicle Seals
  - Development Goals
  - Challenges

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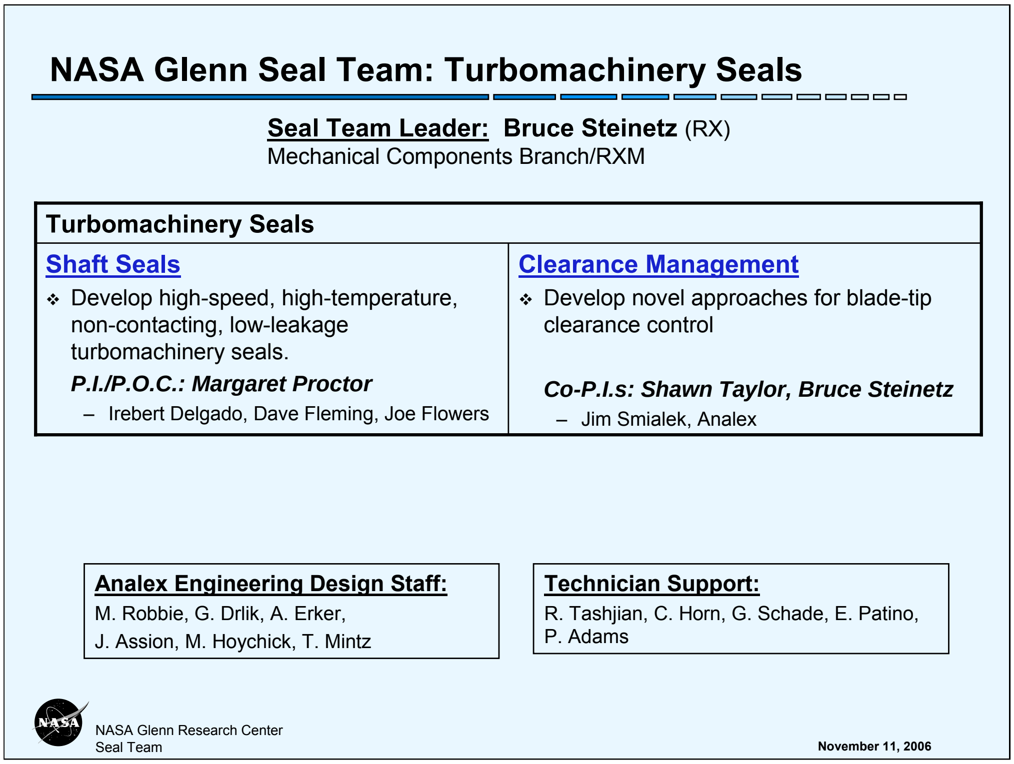
The presentation is divided into these major discussion areas.

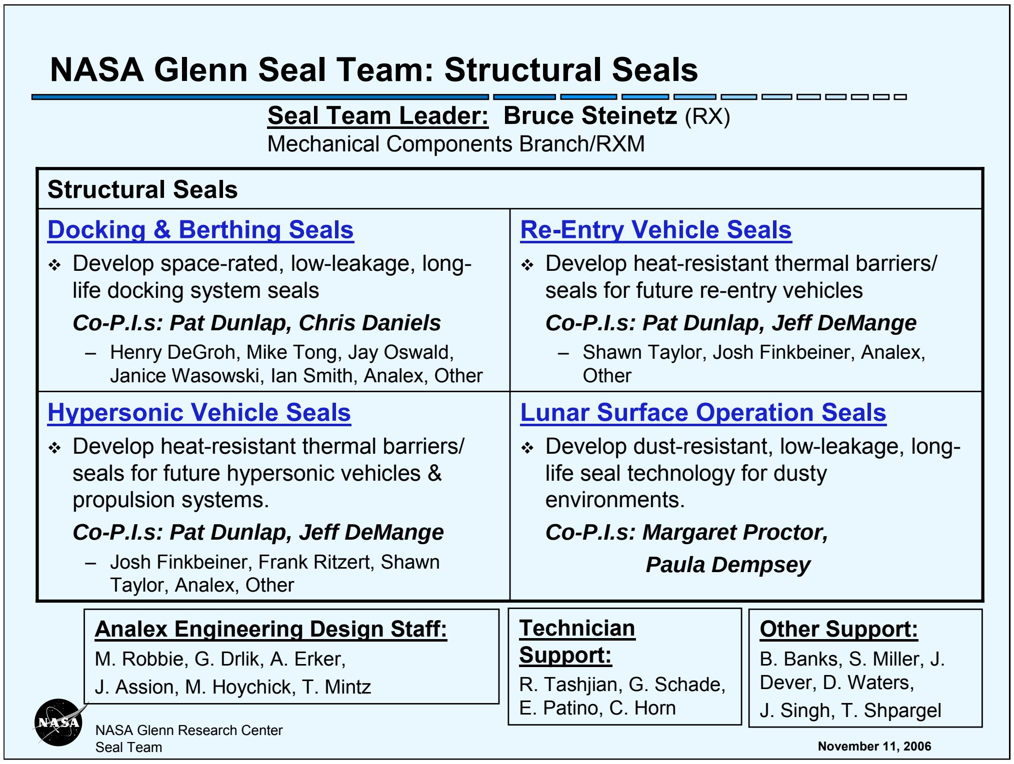


The Turbomachinery Seal Team is divided into two primary areas. The principal investigators and supporting researchers for each of the areas are shown in the Table.

As NASA pursues research in Fundamental Aeronautics, advanced seal development is important. Two key areas that NASA Glenn is contributing to include the following:

+ Non-contacting shaft seals are being developed to reduce leakage enabling lower specific fuel consumption and emissions and increase engine service lives.

+ Novel approaches for clearance management are being pursued to reduce specific fuel consumption and emissions and increase engine service lives. Both active clearance control system and passive “smart” material approaches are being pursued.



The Structural Seal Team is divided into four primary areas. The principal investigators and supporting researchers for each of the areas are shown in the slide.

As NASA pursues the Vision for Space Exploration, advanced seal development is critical. Four key areas that NASA Glenn is contributing to include the following:

+ Docking and berthing seals are being developed to ensure that vehicles can dock and prevent leakage of limited astronaut cabin pressure air.

+ Re-entry vehicle heat shield and penetration thermal barriers/seals are being pursued to ensure hot plasma re-entry gases due not compromise the function of the thermal protection system.

+ Technology for dust resistant, surface operation seals is being investigated for space suits, airlocks, quick disconnects, robotic experimental payloads and the like. Dust resistant seals exhibiting low-leakage, and long life are essential to ensure long-term mission success.

+ Hypersonic vehicle and propulsion system thermal barriers/seals are being developed to enable future single-stage and two-stage access-to-space options.

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

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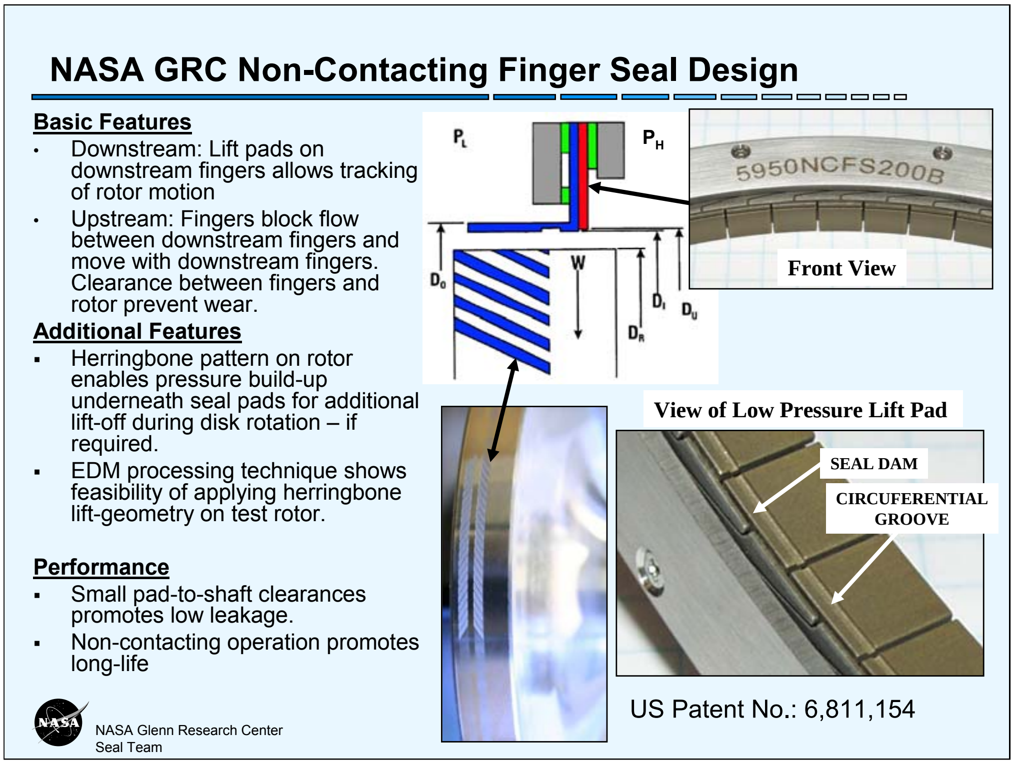
Seal Team

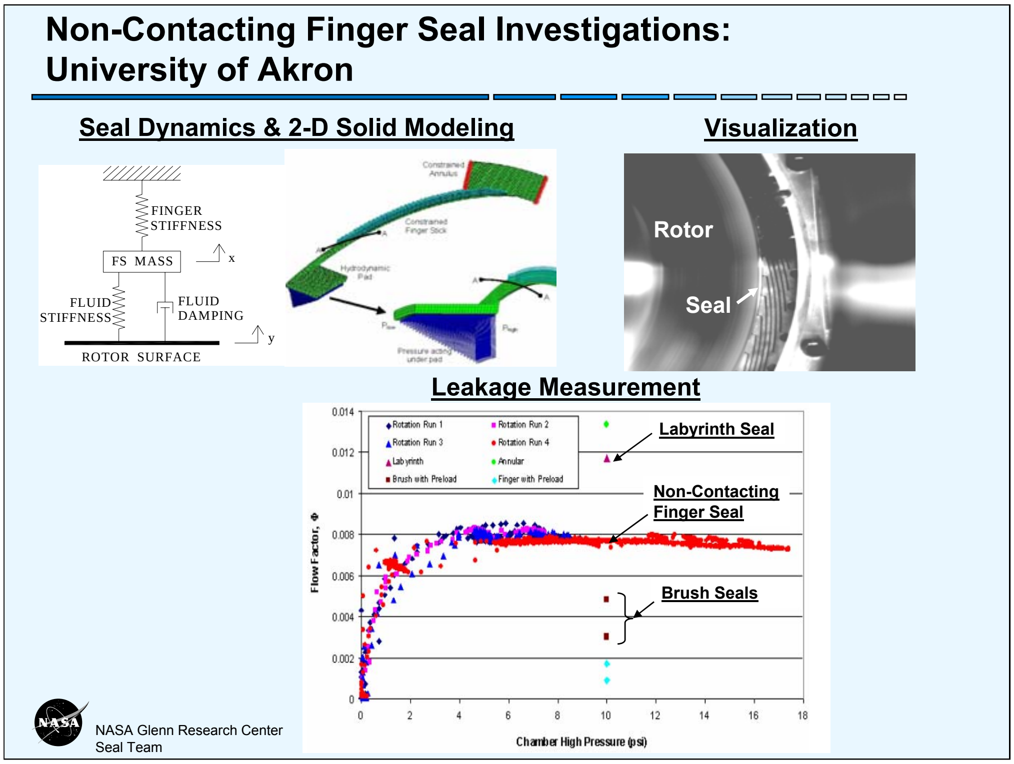
Designers of future turbine engine seals face ever increasing challenges (Steinetz and Hendricks, 1998) including high temperature, high speed operation, the need to operate for long lives with little or no wear while minimizing heat generation. One of NASA GRC’s turbine engine seal goals is to develop 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 Electro Discharge Machining process.



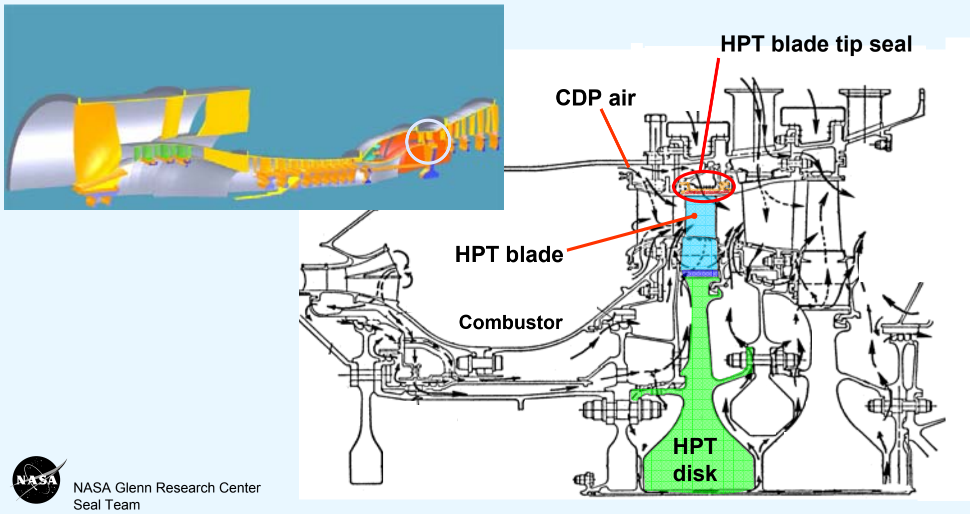
Dr. J. Braun and his team at the University of Akron is performing analyses and tests of this GRC concept through a cooperative agreement (Braun et al, 2003). University researchers developed an equivalent spring-mass-damper system to assess lift characteristics under dynamic excitation. Fluid stiffness and damping properties were obtained utilizing CFD-ACE+ (3-D Navier-Stokes code) and a perturbation approach. These stiffness and damping properties were input into the dynamic model expediting the solution for design purposes. 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

Turbine Clearance Management Goal

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



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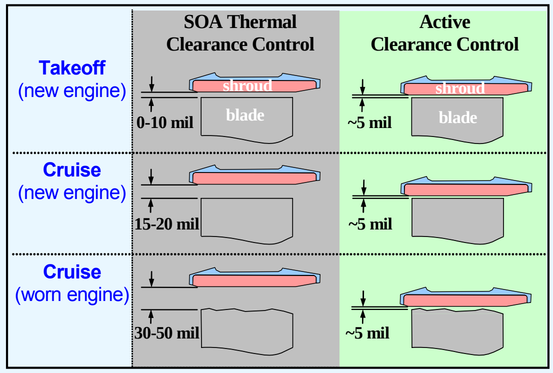
Seal Team

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 engine efficiency goals. Large SFC and emissions improvements are achievable by improving blade tip clearances in the high pressure turbine.

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)**.

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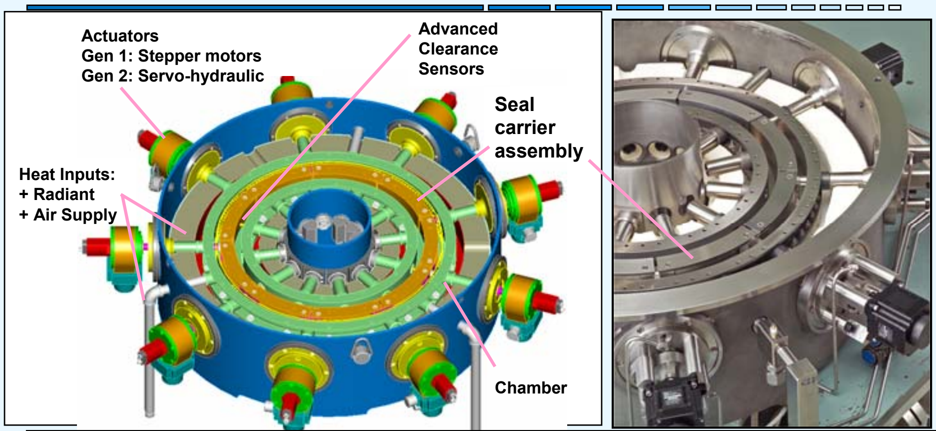
Seal Team

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.

Active Clearance Control Concept & Evaluation Test Rig



Purpose:

- Evaluate ACC kinematic system + actuator response and accuracy under engine simulated 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 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

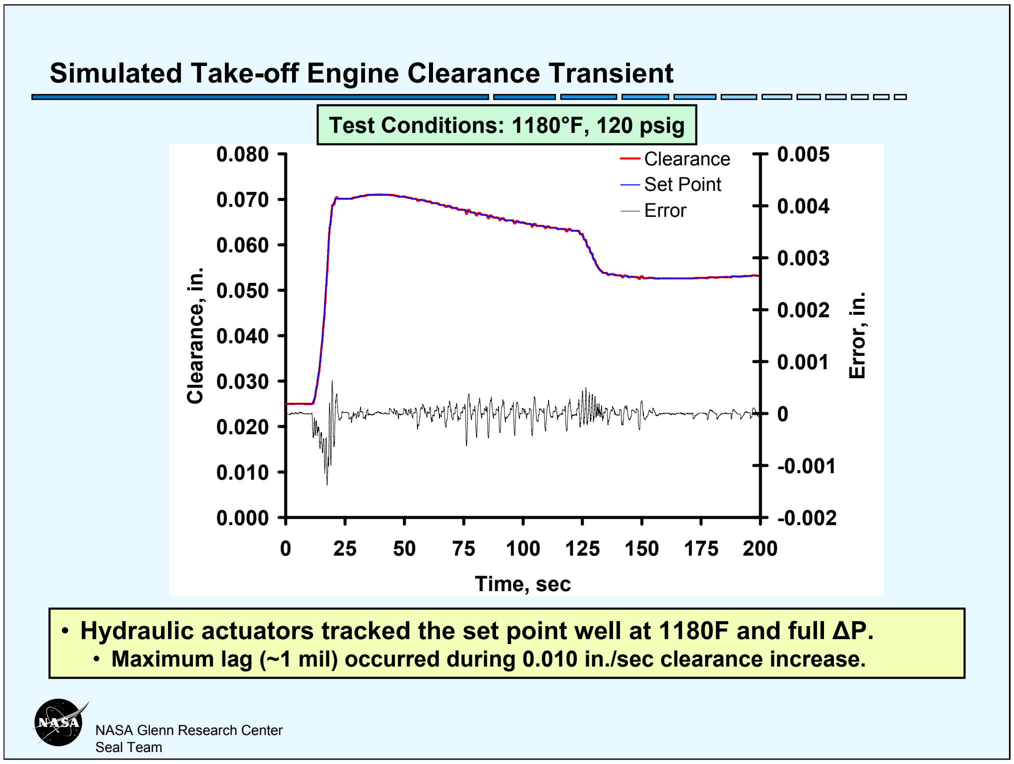
•System concentricity and synchronicity

•Component wear

•Secondary seal leakage

•Clearance sensor response and accuracy

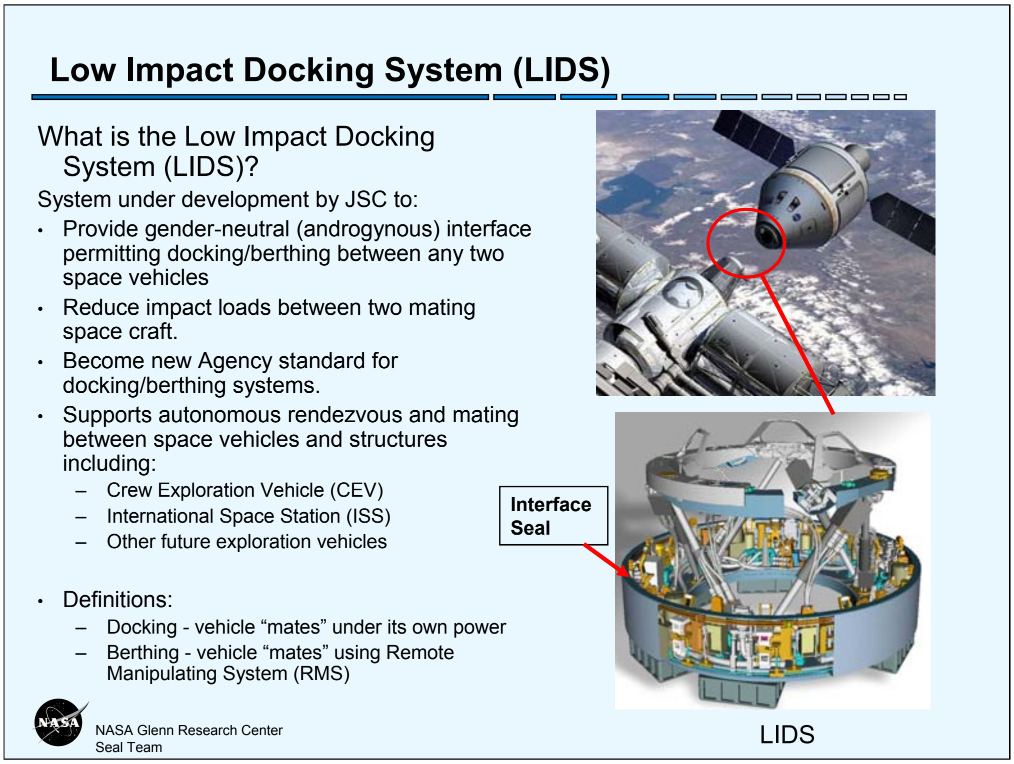
The results of this testing will be used to further develop/refine the current system design as well as other advanced actuator concepts. More details regarding this test rig can be found in Taylor, et al 2006 (in this Seal Workshop Proceedings), Taylor et al, 2006, Steinetz et al, 2005, and Lattime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



The installation of the new servo-hydraulic actuation package onto the ACC test rig enabled the system to easily track a simulated engine clearance profile at the full design pressure differential of 120 psig while at 1180°F. The maximum error observed between the commanded setpoint clearance and the measured control clearance was only 0.0012 in. noted at the start of the profile's 0.010 in./s clearance transient. Error was calculated by subtracting the commanded setpoint clearance from the measured control clearance. This evaluation shows that the ACC concept is capable of tracking an engine clearance transient profile under engine-like temperature and pressure conditions, while maintaining an acceptable level of error. If a commercial controller was implemented in place of the PC based controller used in this laboratory study, the communication lag that exists between the PC and the NI motion controllers would be eliminated. This would likely reduce observed clearance error to less than 0.001 in.

Exploration Systems:
Seals Challenges and Project Supported

CEV Docking and Berthing System



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 a Low Impact Docking System (LIDS) that has several important features:

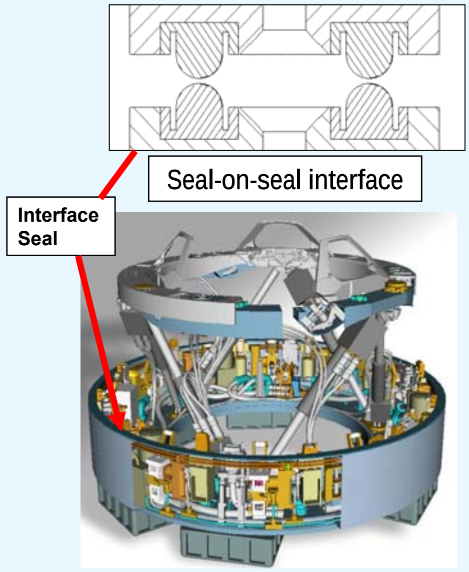
+ The system will be androgynous or gender-neutral permitting docking and berthing between any two space vehicles, giving NASA and the astronauts maximum mission planning flexibility.

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

For additional information regarding the LIDS project and system, see Brandon Burns' presentation in this 2006 Workshop Proceedings.

Advanced Docking and Berthing System: Seal Challenges

- Seal on seal interface for androgynous system
- Extremely high reliability: Man rating
- Size: Large diameters ≥ 54”, Small Width <1.5”
- Extremely low leakage rates: 0.01 lb/day
- Temperature: -50°C to +50°C and thermal gradients
- Exhibit low forces: Sealing & Adhesion
- Long mating periods and repeated docking



NASA Glenn Research Center
Seal Team

A unique seal challenge posed by the androgynous LIDS 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.

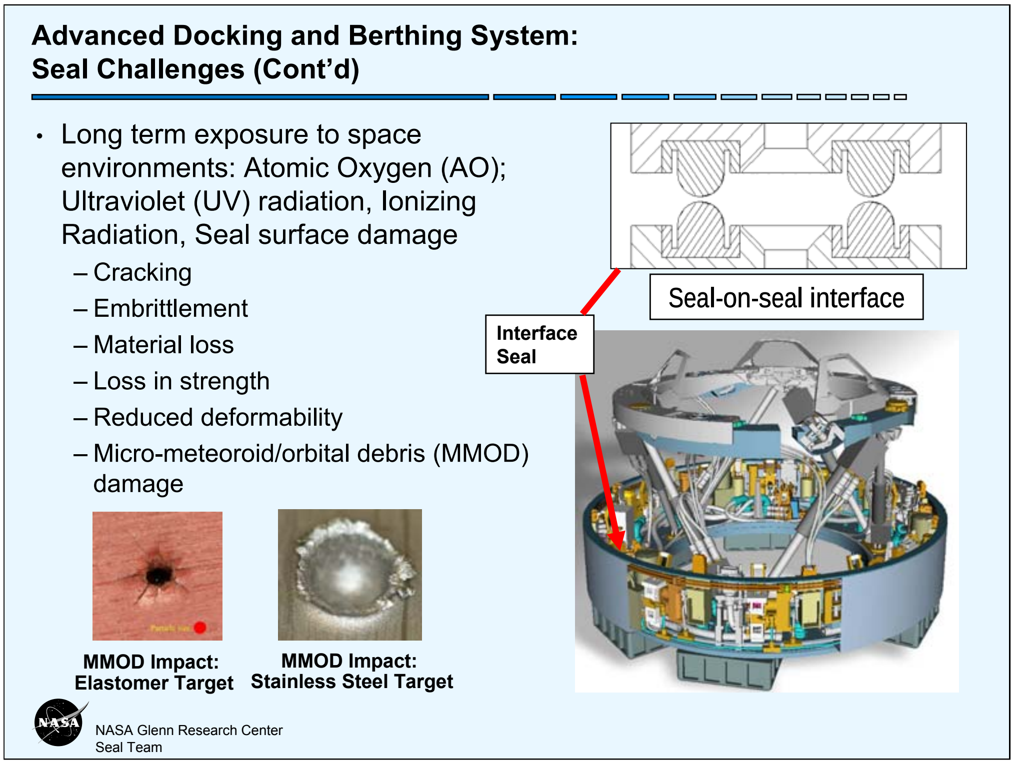
Challenges posed by this new system include:

Extremely high reliability: for man rating

Relative large diameter ≥ 54”

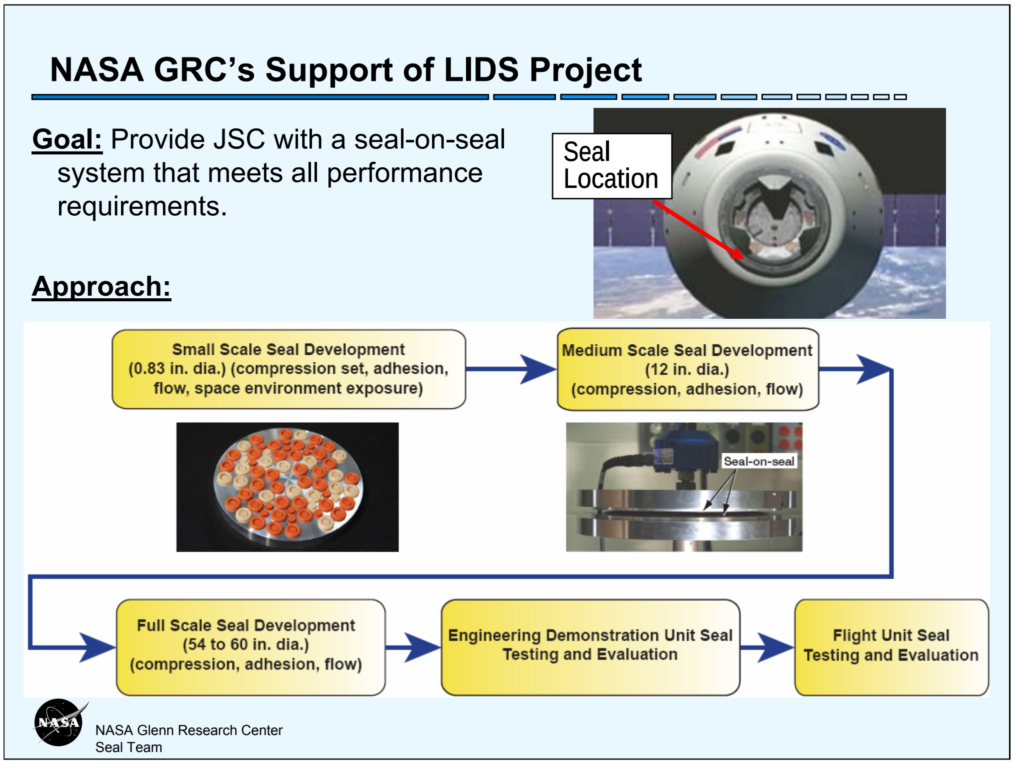
Extremely low leakage rates: <0.01 lb/day

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



Additional seal challenges posed by this new system include:

Long term exposure to space environments: Atomic Oxygen (AO); Ultraviolet (UV) radiation, Seal surface damage due to micro-meteors and orbital debris (MMOD). The lower images show the results of small 0.5 mm particles impacting silicone rubber and stainless steel targets at hyper-velocities (7.5 km/sec). NASA Glenn is implementing test programs to evaluate the effects of each of these environments on seal performance.



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

The following elements are planned during the development project:

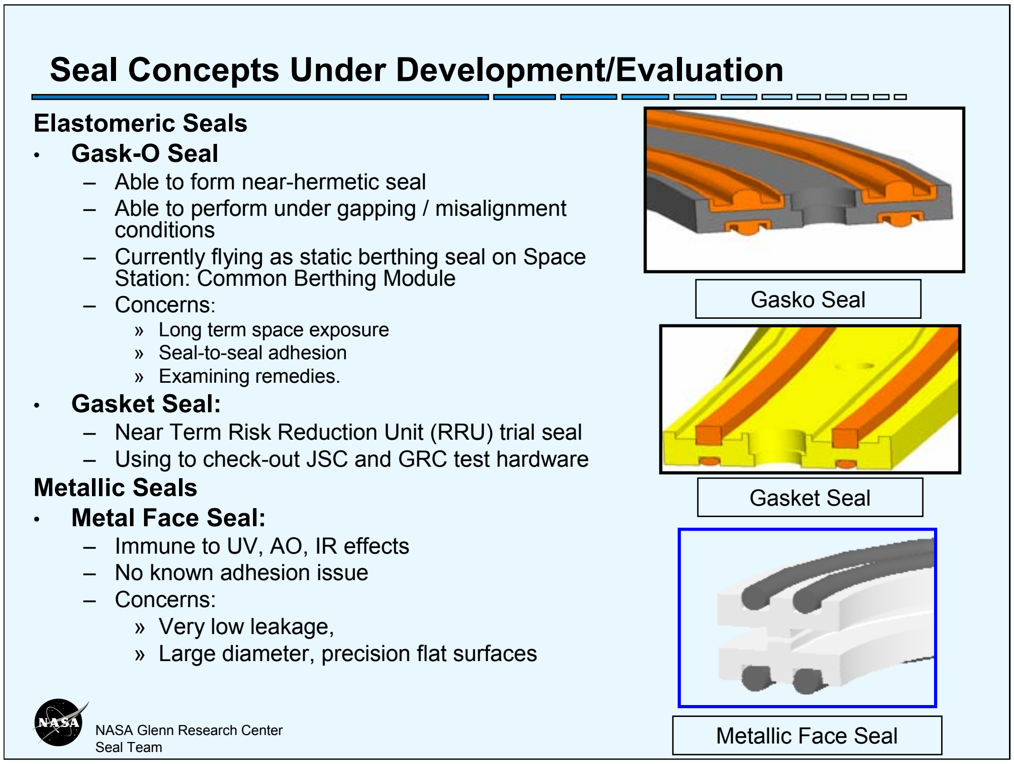
+ Perform coupon-level and small-scale environmental exposure and flow tests of candidate sub-scale seals

+ 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



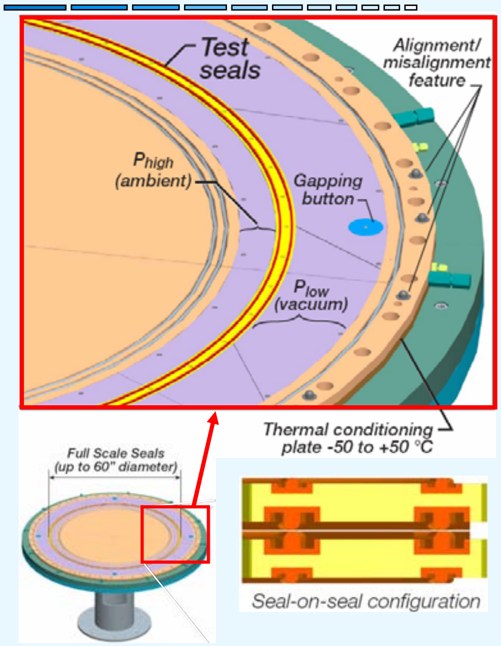
Several competing seal concepts are being evaluated including elastomeric (both gasket and molded Gask-O) seals and metallic seals shown. As shown in the chart, each type of seal comes with its own attributes and concerns.

Full Scale LIDS Seal Test Rig Development

Goal: Evaluate full-scale seal leakage rates under anticipated thermal, vacuum, and engagement conditions

Features:

- Static seal-on-seal or seal-on-plate configurations
- Seal diameters:
  - Risk reduction unit............................54”
  - Engineering demonstration unit ....58”
  - Flight unit..TBD
- Simulated environmental conditions
  - Thermal -50 °C to +50 °C
  - Simulates: Vehicle seal in: sun or shade
- Pressure (ΔP)
  - Operational: Ambient pressure to vacuum
  - Pre-flight checkout: 15 psig to ambient
- Engagement conditions
  - Vehicle alignment/misalignment (±0.060”)
  - Gapping: Non-uniform clamping engagement (0.040”)



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Seal Team

NASA Glenn has designed and is fabricating a new test fixture which will be used to evaluate the leakage of candidate full-scale seals under simulated thermal, vacuum, and engagement conditions. This includes testing under seal-on-seal or seal-on-plate configurations, temperatures from -50 to 50°C (-58 to 122°F), operational and pre-flight checkout pressure gradients, and vehicle misalignment (+/- 0.381 cm (0.150 in.)) and gapping (up to 0.10 cm (0.040 in.)) conditions.

Elastomer Material Property Characterization

Goal: Acquire basic material property data at temperatures required for FEA modeling:
- Constitutive properties (e.g. Hyper-elastic properties)
- Other

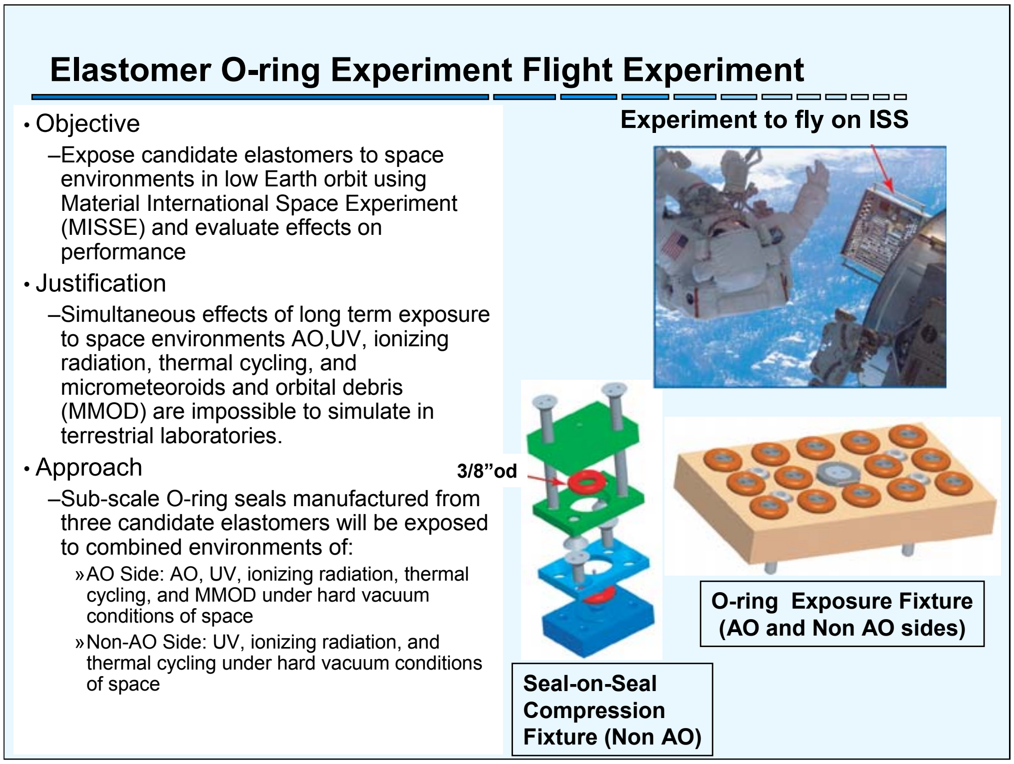
- Three materials:
  - Parker Hannifin S0383-70
  - Parker Hannifin S0899-50
  - Kirkhill-TA XELA-SA-401
- Stress vs. Strain for temps: -50, 23, 50 & 125°C
- Hyperelastic material tests -50, 23, 50 & 125°C
  - Uniaxial strain
  - Compression & tension
  - Pure shear
  - Biaxial extension
  - Volumetric compression
- Friction (elastomer on self) -50, 23, 50 & 125°C
- Material properties
  - Coefficient of Thermal Expansion
  - Heat Capacity
  - Density
- Other properties (Mullins effect, etc.)
- Allows for material constitutive law selection

Photograph of biaxial extension test

Partner Organization:
Axel, Ann Arbor, MI

NASA Glenn Research Center
Seal Team

Silicone compounds exhibit hyper-elastic behavior. To aid in the finite element modeling of the silicone seals, Glenn contracted Axel of Ann Arbor Michigan to acquire basic constitutive constants at temperatures of -50, 23, 50 & 125°C. This is the first known time that this property data has been acquired for the Parker Hannifin S0383-70, Parker Hannifin S0899-50, and Kirkhill-TA XELA-SA-401compounds, being considered for the LIDS seals. This property data is being used by the Seal Team to properly model the load displacement characteristics of the seals (see also Jay Oswald's presentation in this 2006 Seal Workshop Proceedings)



NASA Glenn has also designed and built hardware to fly on a Materials International Space Station Experiment (MISSE-6) scheduled to fly in February, 2008. In these tests both fully exposed (right hand figure) and fully compressed seals (left figure) will be flown on the International Space Station to characterize the effects of space environments on candidate seal materials. The O-rings being flown include seals made from Parker Hannifin S0383-70, Parker Hannifin S0899-50, and Kirkhill-TA XELA-SA-401compounds. Pre- and post-flight performance characteristics will be measured including leakage flow, adhesion, compression set, and durometer.

Surface Operations:
In-Situ Resource Utilization
Seal Challenges

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 valuable resources 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.

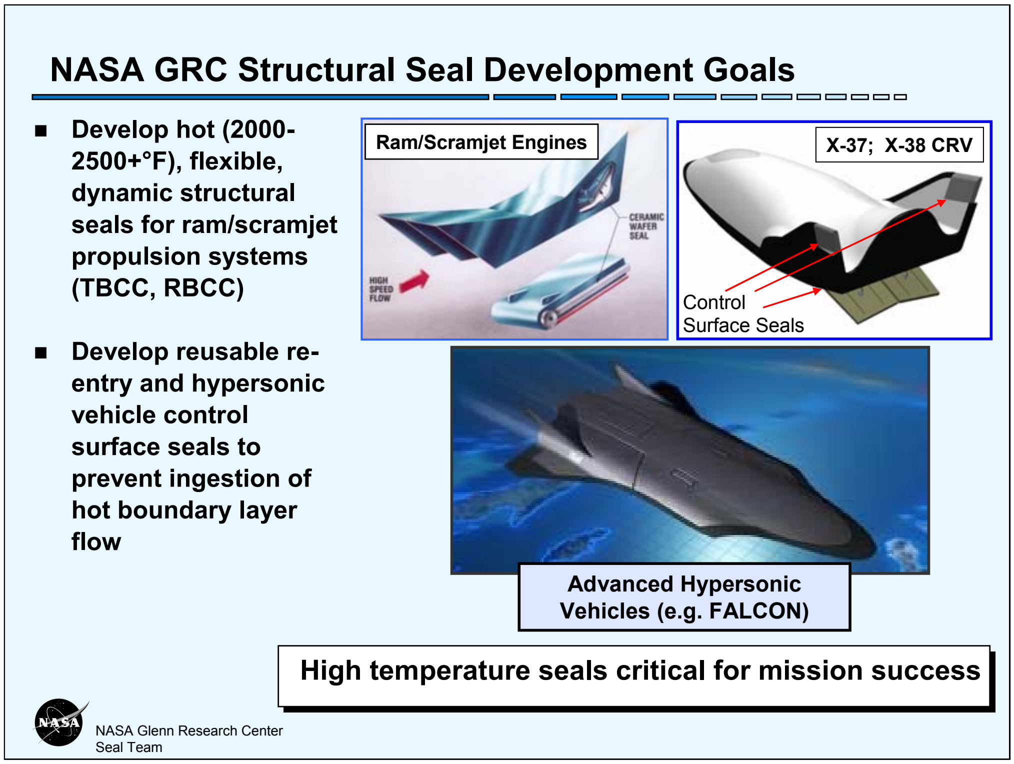
Some of the technologies under consideration, include production of mission critical consumables including:

+ 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.

Hypersonic Vehicle:
Goals and Seal Challenges



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 2006, 2005, 2004, and 2003, et al; and DeMange 2006 and 2003, et al; for further details.

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.

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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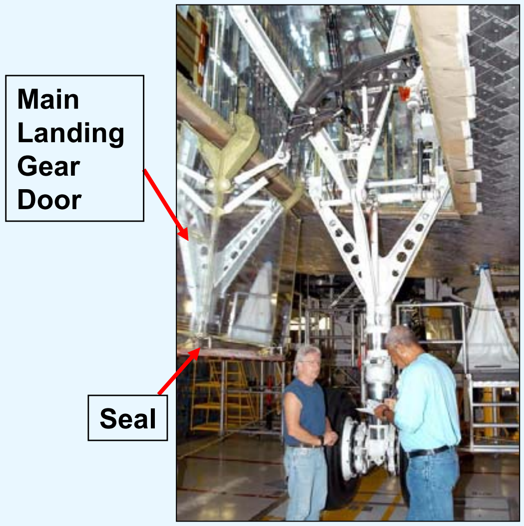
Seal Team

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.

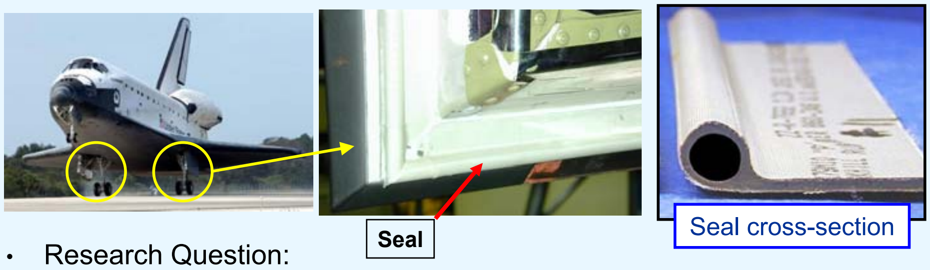
Oswald et al 2005, performed finite element analyses on various spring tube designs defining desirable knit parameters to minimize stress while still supporting the necessary loads. Taylor et al 2005, identified the benefits of Rene'41 material over conventional Inconel X-750. Substituting specially 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 all while resisting the extreme heat fluxes shown in this NASA GRC hydrogen rocket test chamber.

Space Shuttle Main Landing Gear Door Seal Assessments



Shuttle Main Landing Gear Door Seal:
Long Term Compression Tests



- Research Question:
  - How well do environmental seals perform (e.g. recover) after a long term compression?
- Objective:
  - Measure seal spring-back (e.g. recovery) after hold periods to aid NASA JSC and KSC engineers with seal operations and maintenance planning.
- NASA Johnson Space Center requested testing of MLG environmental seals at GRC
  - Compress seals for 1 hr, 1 day, 1 and 3 month durations at various levels of compression level
  - Assess seal recovery via non-contacting laser recovery test fixture

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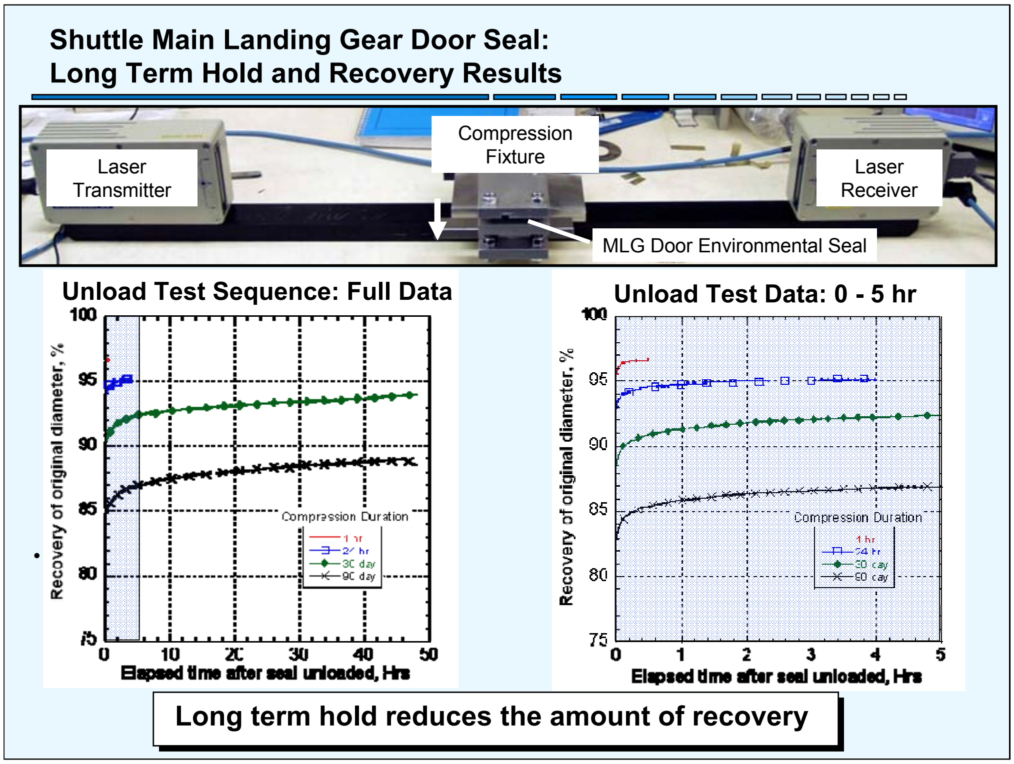
Seal Team

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. Additional details of these tests can be found in Finkbeiner, 2005 et al.

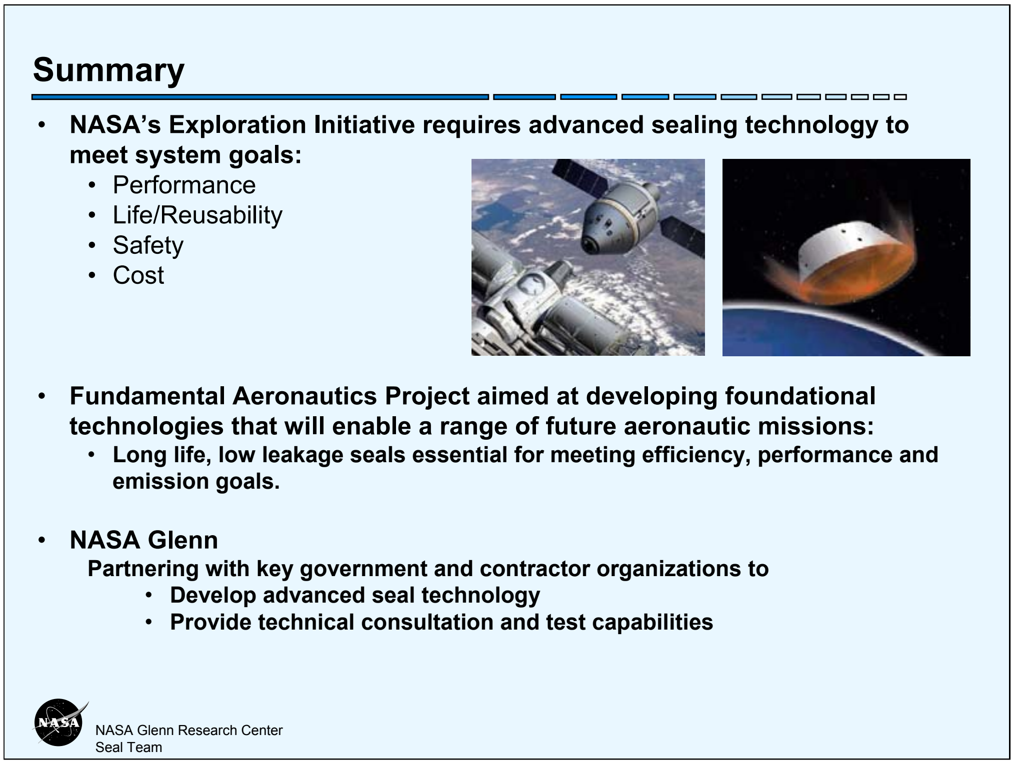


JSC asked GRC to evaluate the time for the seal bulb to recover from long term compression hold times of 1 day, 30 days, and 90 days, simulating periods of time the seals may be compressed prior to and during flight.

Example observations of seal recovery after 30 day hold include the following (Data recorded for 48 hrs. after compression shim removed)

Seal recovered more gradually

- ~86% recovery within first 0.25 sec
- ~90% recovery within 5 min
- ~94% recovery after 48 hrs



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.

Advanced docking system seals need to be very robust resisting space environmental effects while exhibiting very low leakage and low compression and adhesion forces.

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

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NASA Glenn Research Center
Seal Team

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NASA Glenn Research Center
Seal Team

VISION FOR SPACE EXPLORATION

Bryan K. Smith
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

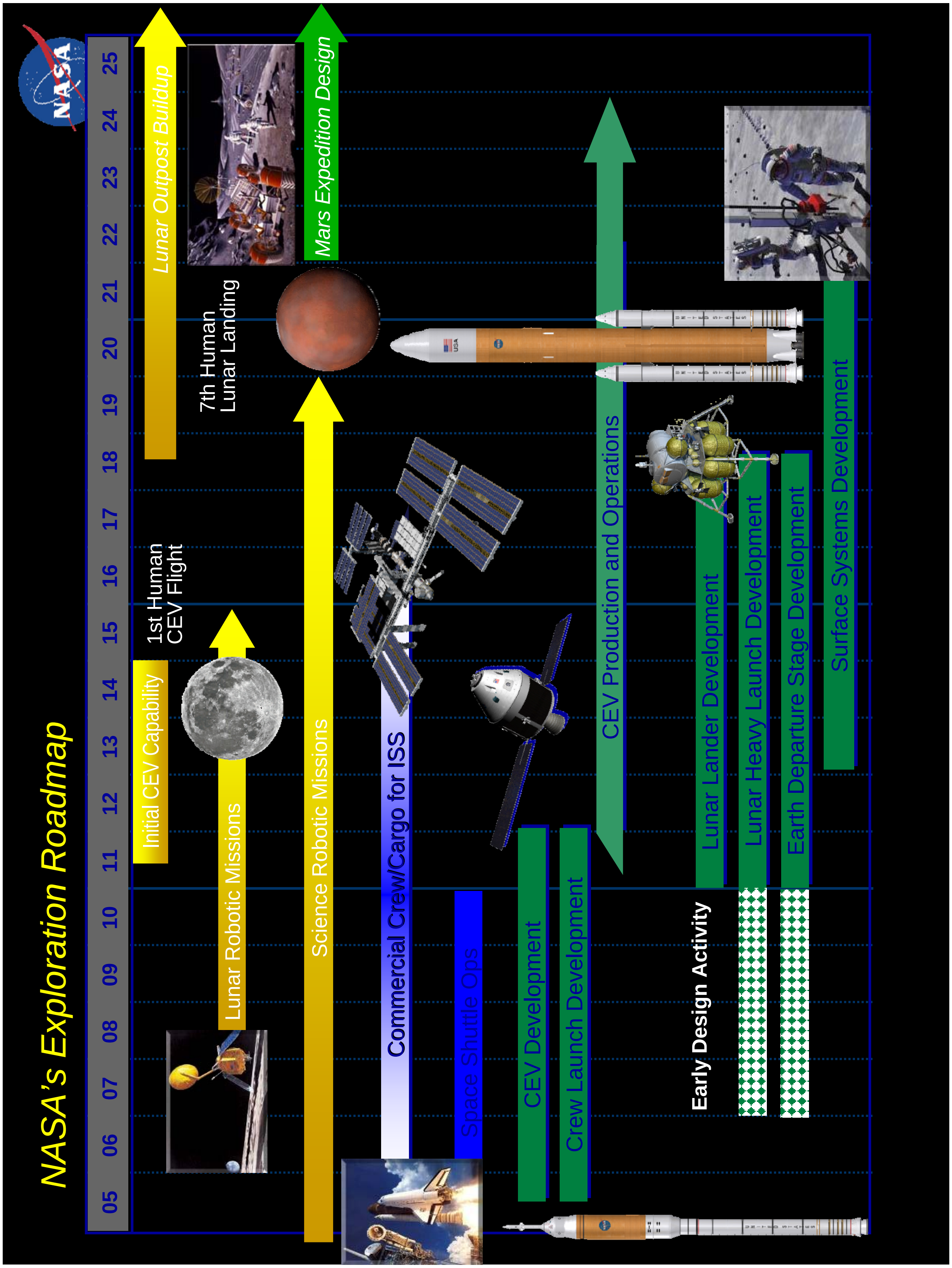
A Bold Vision for Space Exploration

- Complete the International Space Station
- Safely fly the Space Shuttle until 2010
- Develop and fly the Crew Exploration Vehicle (by 2014)
- Return to the moon (by 2020)
- Sustained and affordable human and robotic program
- Develop innovative technologies, knowledge, and infrastructures
- Promote international and commercial participation

"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



NASA's Exploration Roadmap
05
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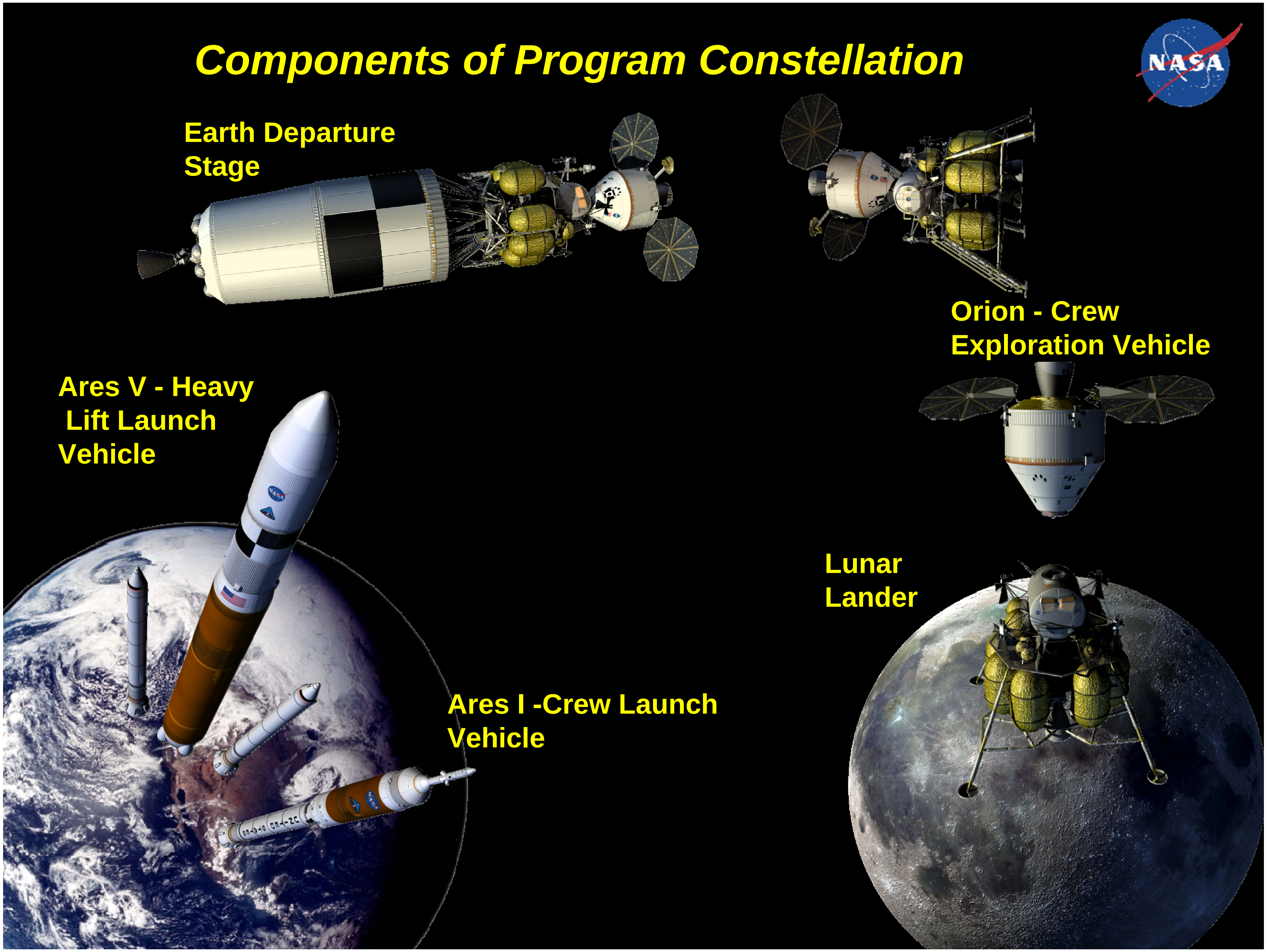
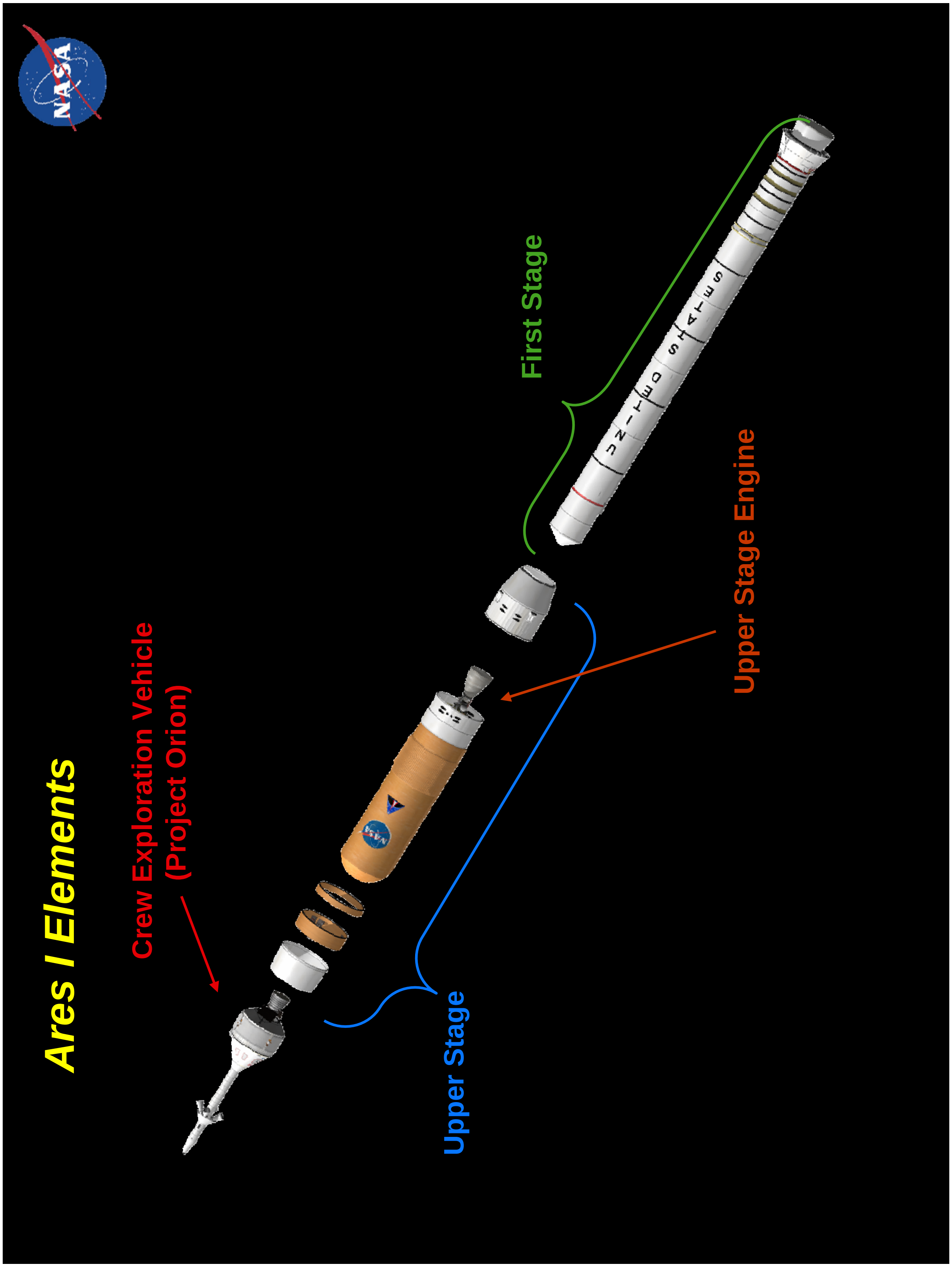
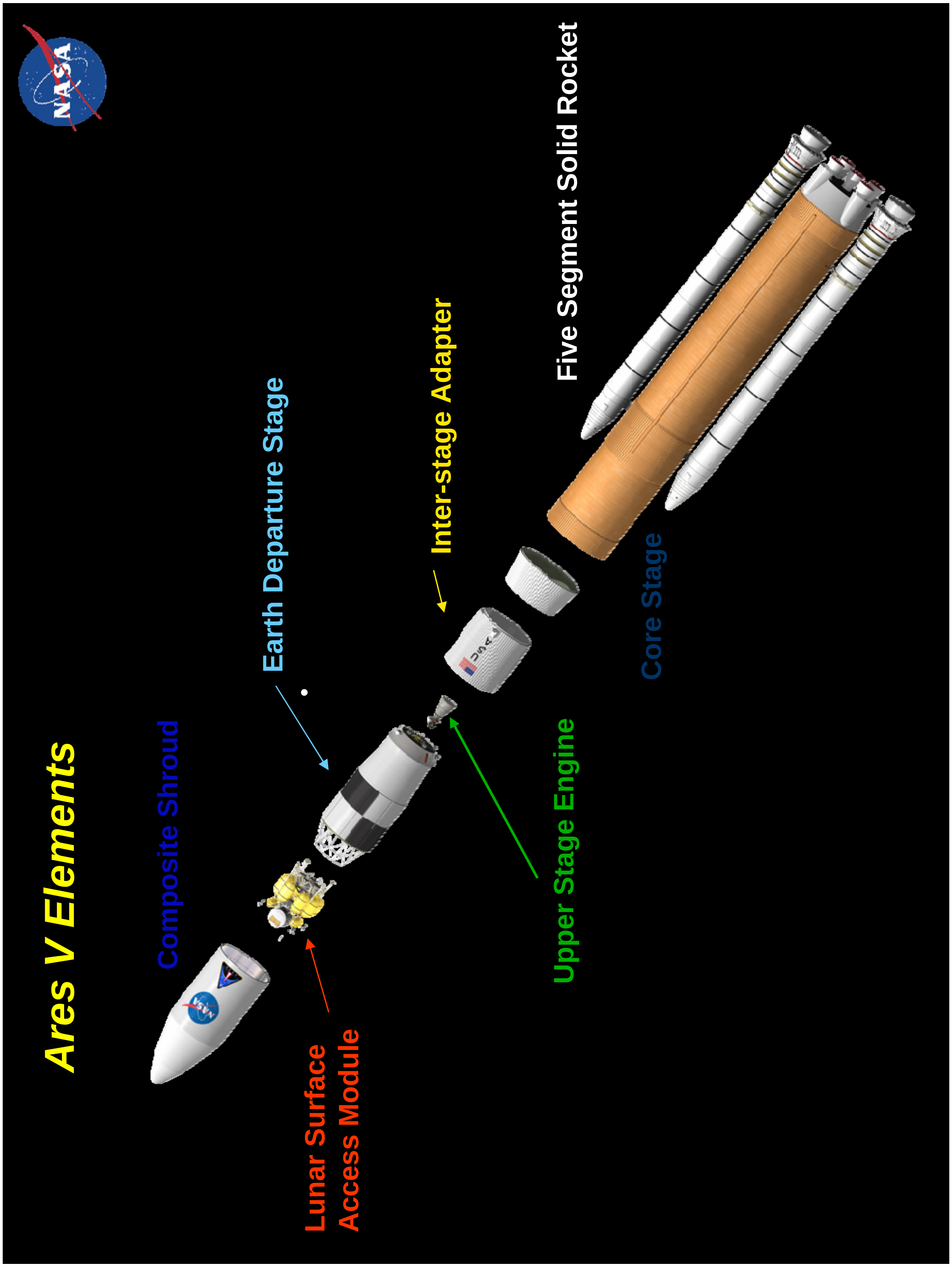
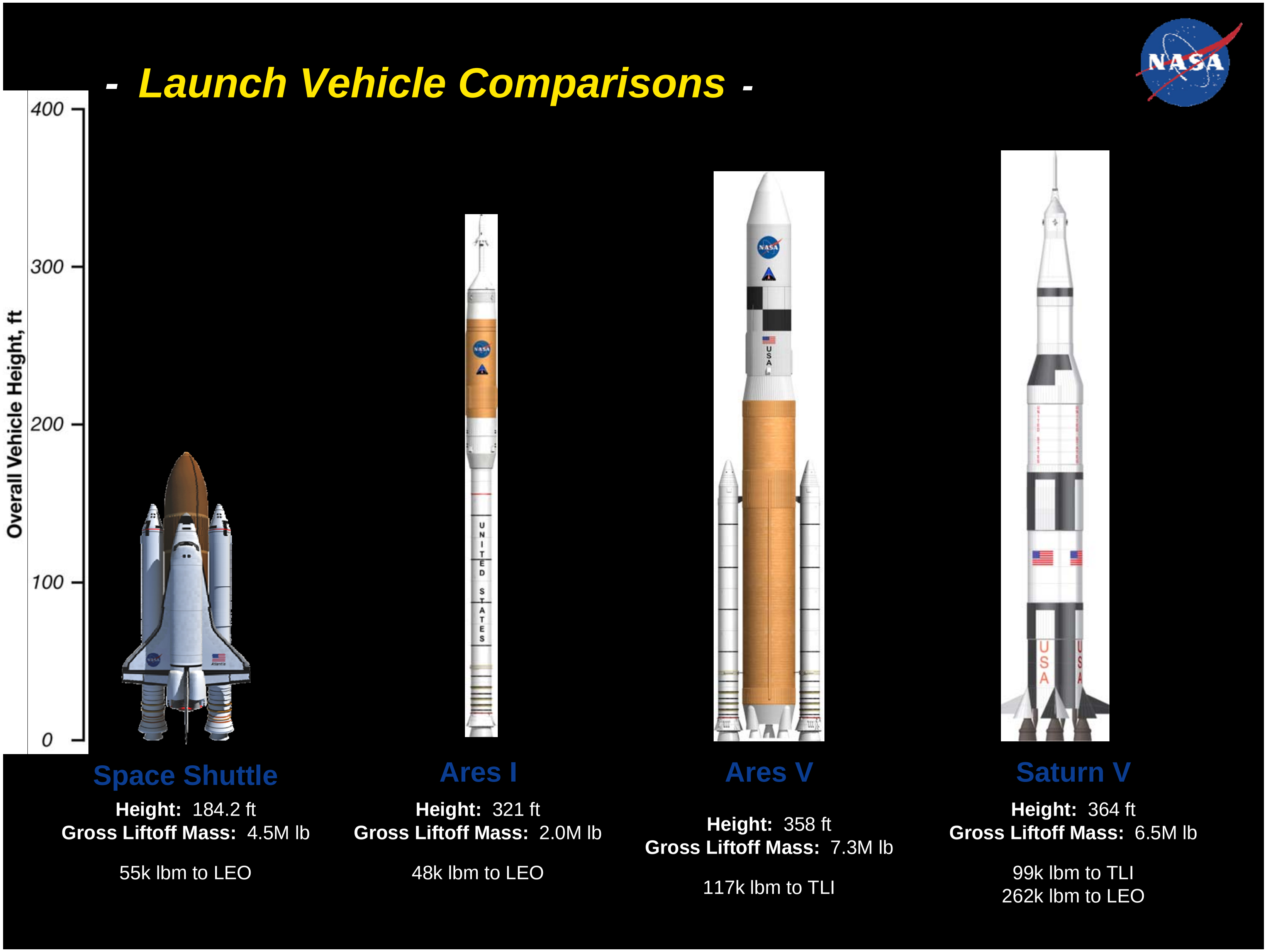
Initial CEV Capability
1st Human CEV Flight
Lunar Outpost Buildup
Lunar Robotic Missions
7th Human Lunar Landing
Science Robotic Missions
Mars Expedition Design
Commercial Crew/Cargo for ISS
Space Shuttle Ops
CEV Development
Crew Launch Development
CEV Production and Operations
Early Design Activity
Lunar Lander Development
Lunar Heavy Launch Development
Earth Departure Stage Development
Surface Systems Development

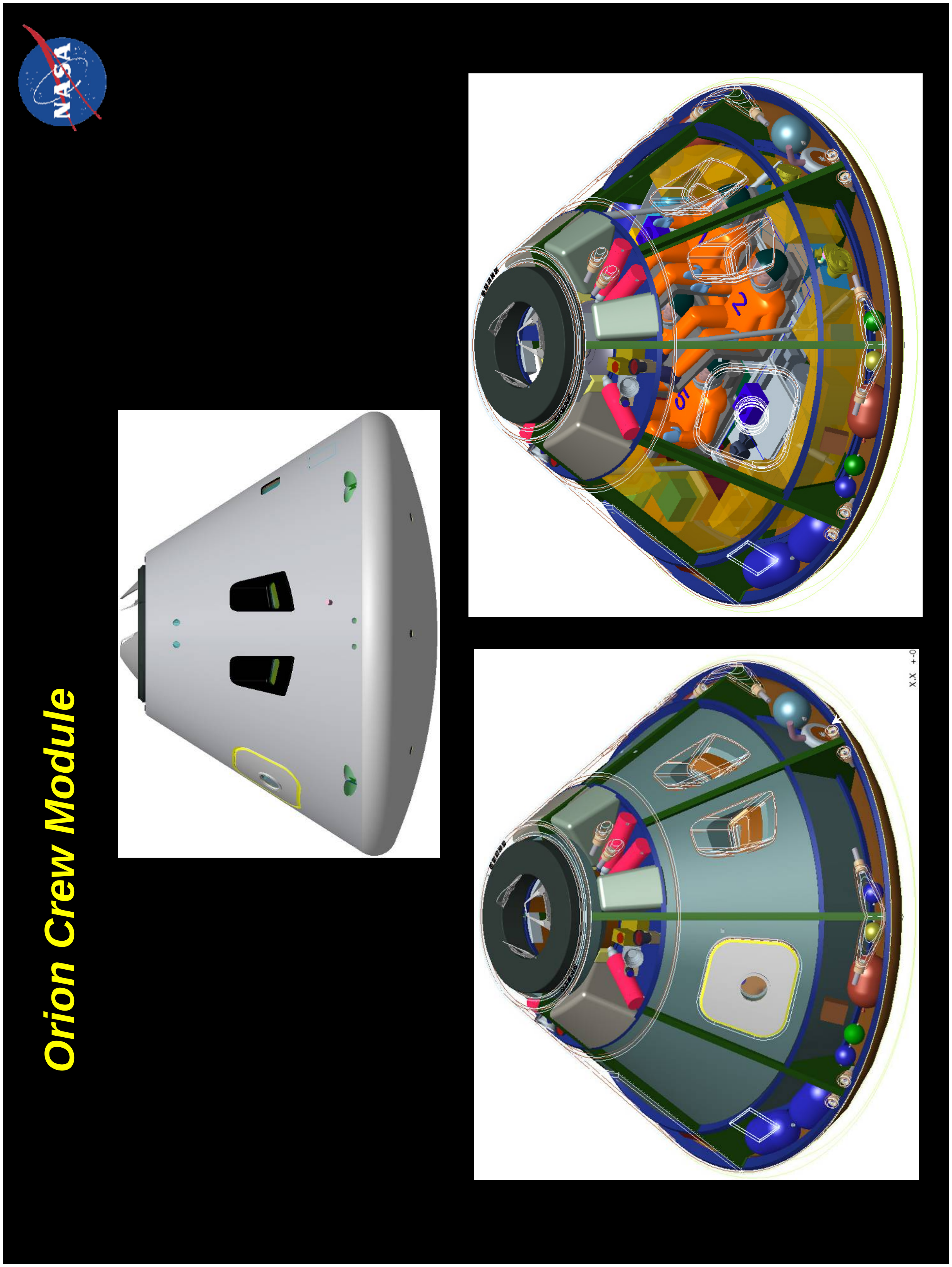

Components of Program Constellation
Earth Departure Stage
Orion - Crew Exploration Vehicle
Ares V - Heavy Lift Launch Vehicle
Lunar Lander
Ares I -Crew Launch Vehicle

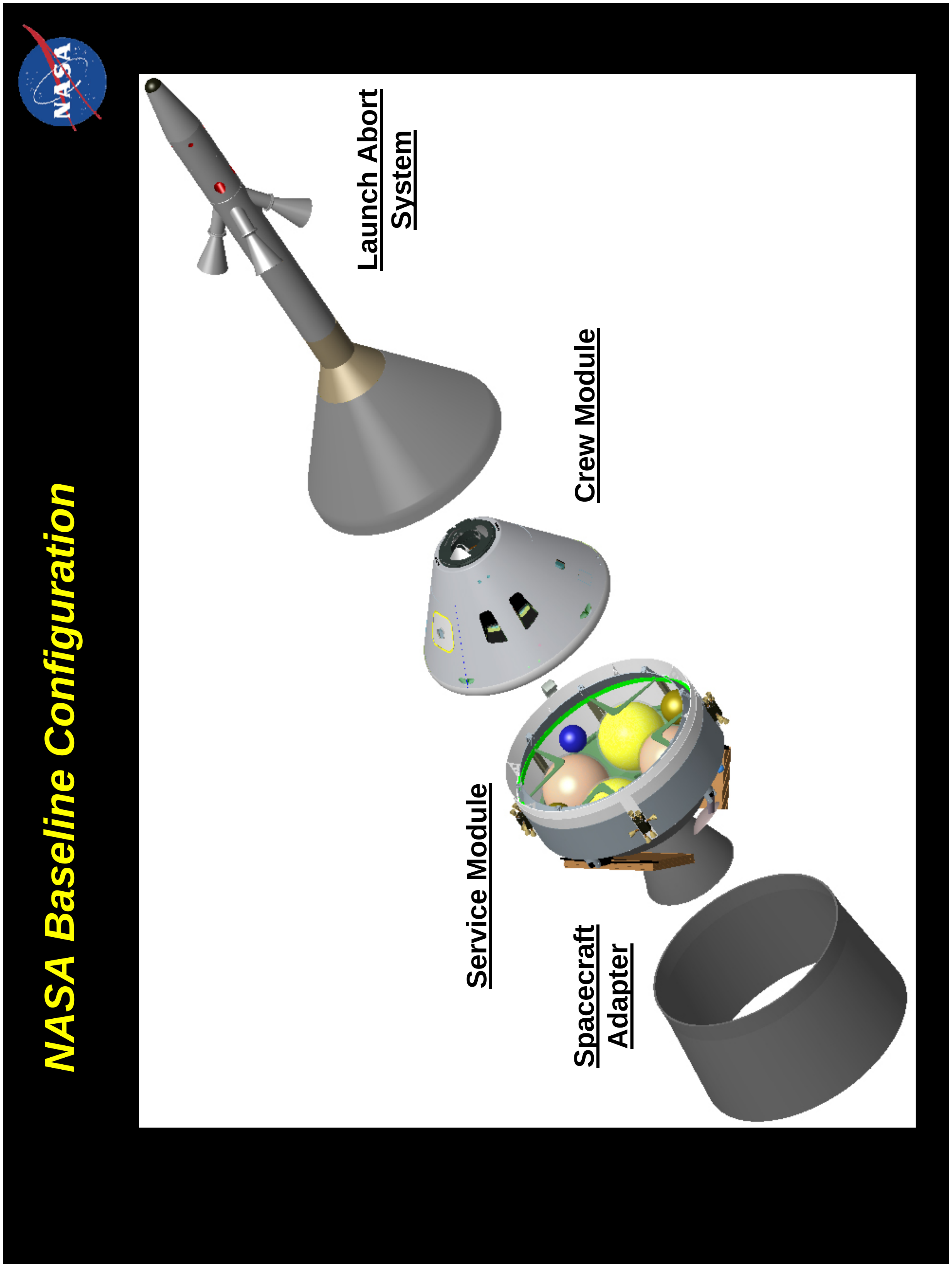

Ares I Elements
Crew Exploration Vehicle
(Project Orion)
Upper Stage
Upper Stage Engine
First Stage


Ares V Elements
Composite Shroud
Lunar Surface
Access Module
Earth Departure Stage
Upper Stage Engine
Inter-stage Adapter
Core Stage
Five Segment Solid Rocket



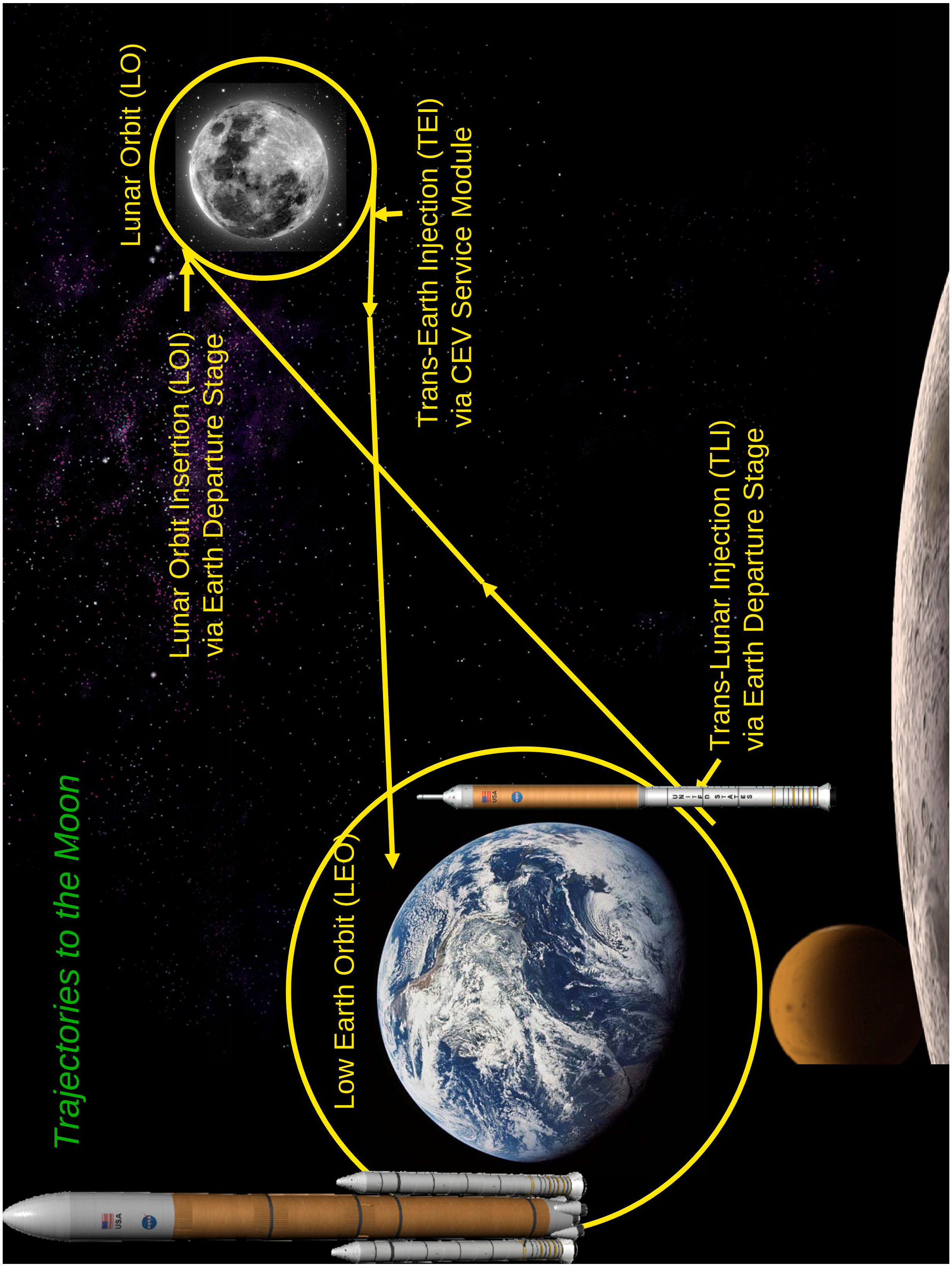
- Launch Vehicle Comparisons -
Overall Vehicle Height, ft
400
300
200
100
0
Space Shuttle
Height: 184.2 ft
Gross Liftoff Mass: 4.5M lb
55k lbm to LEO
Ares I
Height: 321 ft
Gross Liftoff Mass: 2.0M lb
48k lbm to LEO
Ares V
Height: 358 ft
Gross Liftoff Mass: 7.3M lb
117k lbm to TLI
Saturn V
Height: 364 ft
Gross Liftoff Mass: 6.5M lb
99k lbm to TLI
262k lbm to LEO


Orion Crew Module


NASA Baseline Configuration
NASA
Launch Abort System
Crew Module
Service Module
Spacecraft Adapter

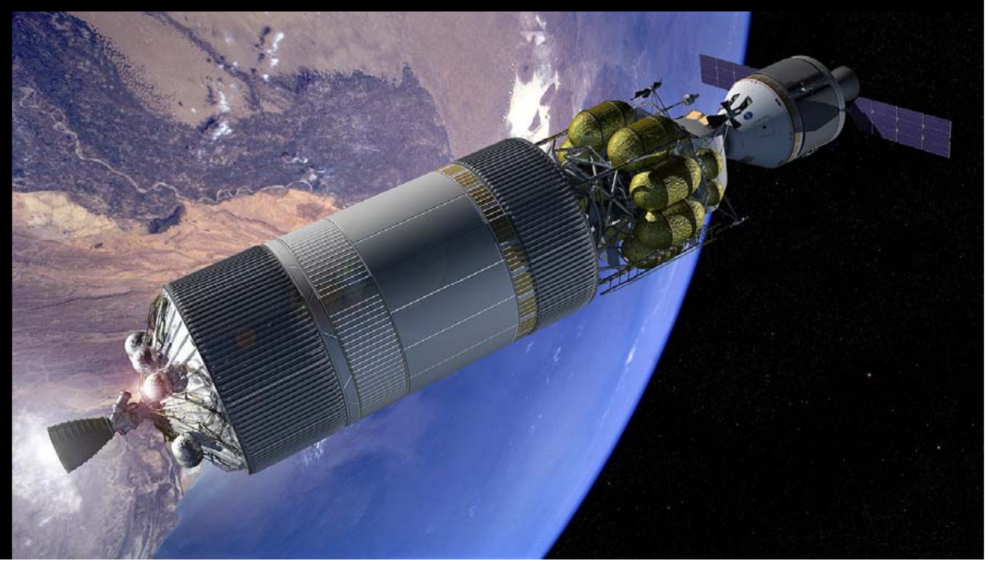
Orion will travel to the Space Station

- Transport up to 6 crew members on Orion for crew rotation
- 210 day stay time
- Emergency lifeboat for entire crew
- Deliver supplies


Trajectories to the Moon
Lunar Orbit (LO)
Trans-Earth Injection (TEI)
via CEV Service Module
Lunar Orbit Insertion (LOI)
via Earth Departure Stage
Trans-Lunar Injection (TLI)
via Earth Departure Stage
Low Earth Orbit (LEO)

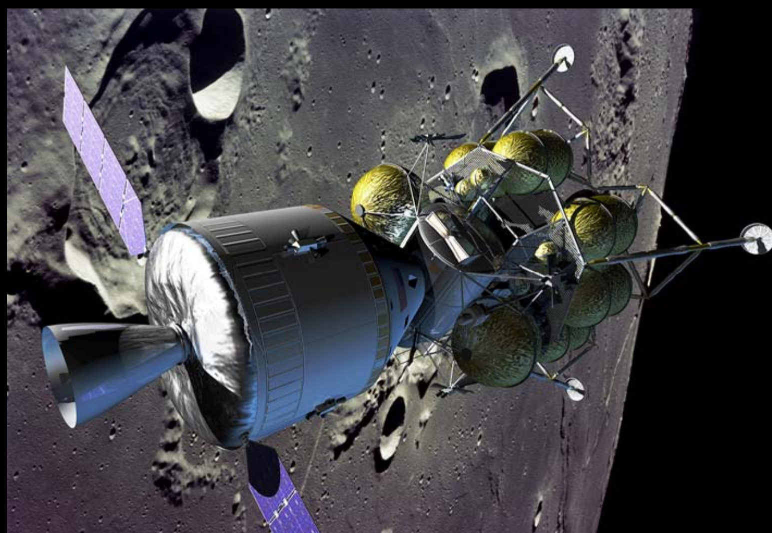
Orion Lunar Mission – Getting There

- Orion docks with the Earth Departure Stage (EDS) in Earth Orbit



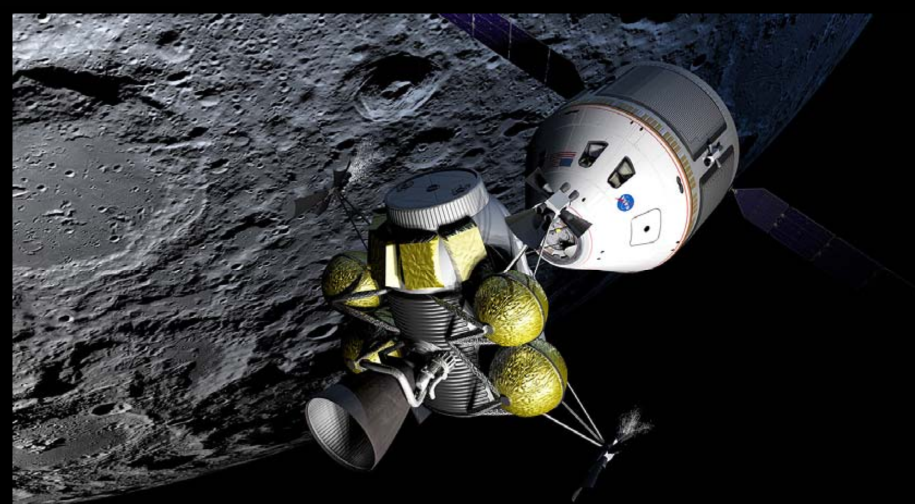
- Earth Departure Stage (EDS) travels to Moon with :
  - Lunar Surface Access Module (LSAM)
  - Orion: up to 4 crew

Orion Lunar Mission – Arriving There



- **Orion and Lander travel to Moon**
- **Lander descends to lunar surface for up to 7 days**

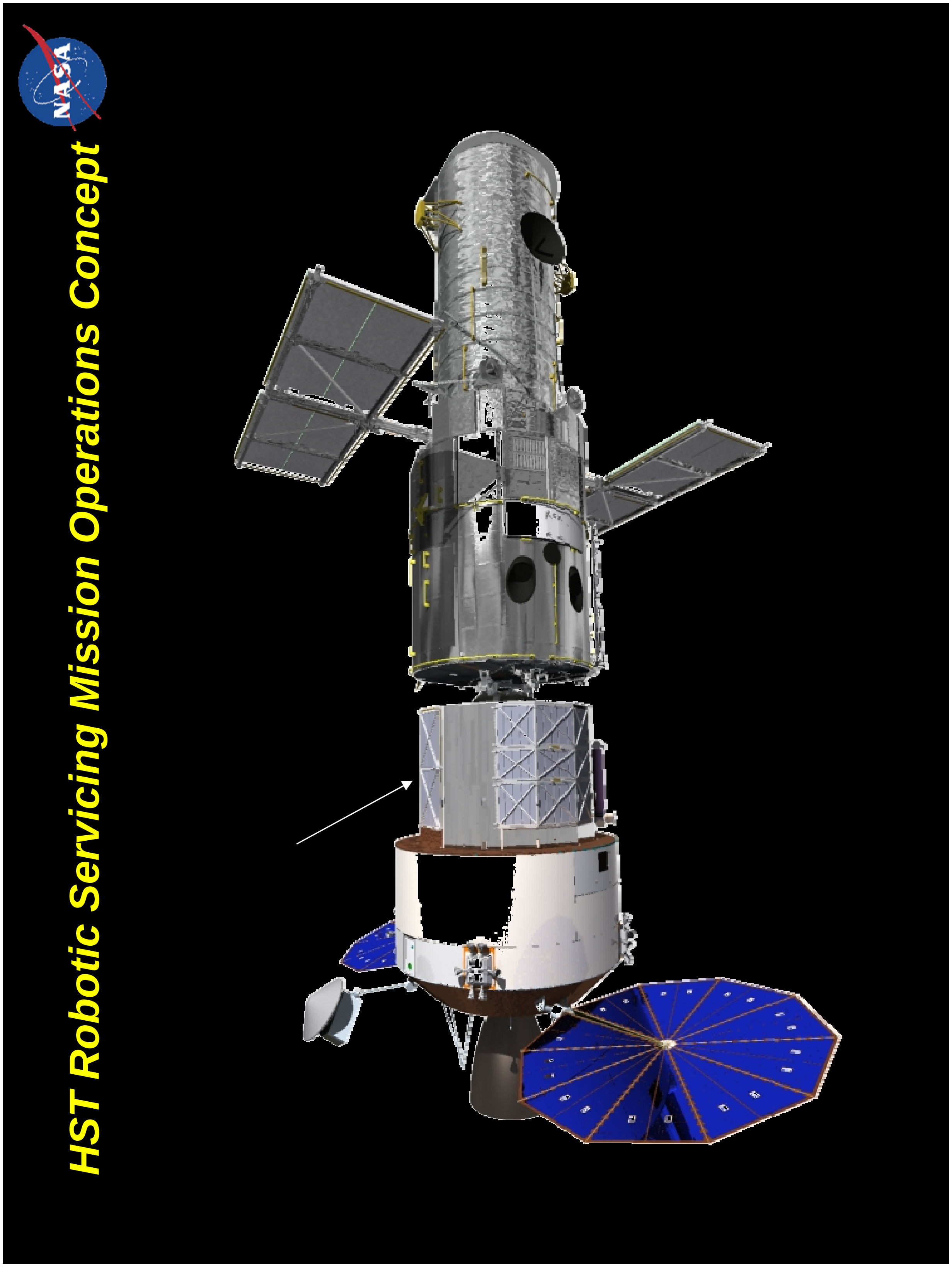
- **Lander upper stage returns to Orion in lunar orbit**



CEV Lunar Mission – Coming Home

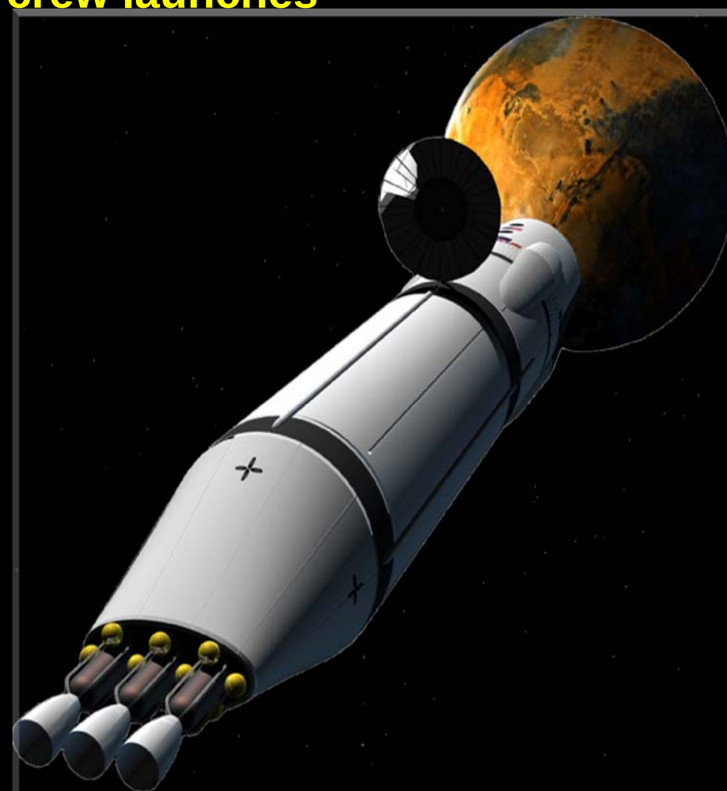
- Orion provides Earth return trajectory

- Command Module capsule reenters atmosphere
- Parachute descent
- Land in water or on land


HST Robotic Servicing Mission Operations Concept

How We Will Get to Mars

- 4 to 5 assembly flights to low Earth orbit
- Mars surface outpost before the crew launches
  - Electricity
  - Shelter
  - Supplies
- 180 day transit time to/from Mars
  - 6 crew members
- 500 days on the surface
  - Food, Oxygen and water



Glenn Research Center's Two Campuses

Cleveland (Brook Park and Fairview Park)
- 350 acres
- 1707 civil servants and 1367 contractors

Plum Brook (Sandusky)
- 6400 acres
- 9 civil servants and 87 contractors


Thank you

RESHAPING NASA'S AERONAUTICS PROGRAM

Anita D. Liang
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Reshaping NASA's Aeronautics Program

Anita Liang
NASA Glenn Research Center
Cleveland, OH

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The Three Principles

- We will dedicate ourselves to the mastery and intellectual stewardship of the core competencies of Aeronautics for the Nation in all flight regimes.
- We will focus our research in areas that are appropriate to NASA's unique capabilities.
- We will directly address the R&D needs of the Next Generation Air Transportation System (NGATS) in partnership with the member agencies of the Joint Planning and Development Office (JPDO).

Re-shaping Aeronautics

OLD		NEW
Vehicle Systems	→	Fundamental Aeronautics
Aviation Safety and Security	→	Aviation Safety
Airspace Systems	→	Airspace Systems

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Re-shaping Aeronautics

- **Fundamental Aeronautics Program (FAP)**
  - We will conduct long-term, cutting-edge research in the core competencies of aeronautics in all flight regimes, producing knowledge/data/capabilities/ design tools that are applicable across a broad range of air vehicles.
  - Four thrust areas:
    - Hypersonics
    - Supersonics
    - Subsonics: fixed wing
    - Subsonics: rotary wing
- **Aviation Safety Program (AvSP)**
  - We will build upon our unique safety-related research capabilities to…
    - Improve the inherent safety attributes of new and legacy vehicles.
    - Overcome aircraft safety technological barriers that would otherwise constrain the full realization of the NGATS.
- **Airspace Systems Program (ASP)**
  - We will directly address the Air Traffic Management R&D needs of the NGATS as defined by the Joint Planning & Development Office (JPDO).
- **Aeronautics Test Program (ATP)**
  - We will protect and maintain our key research and test facilities.

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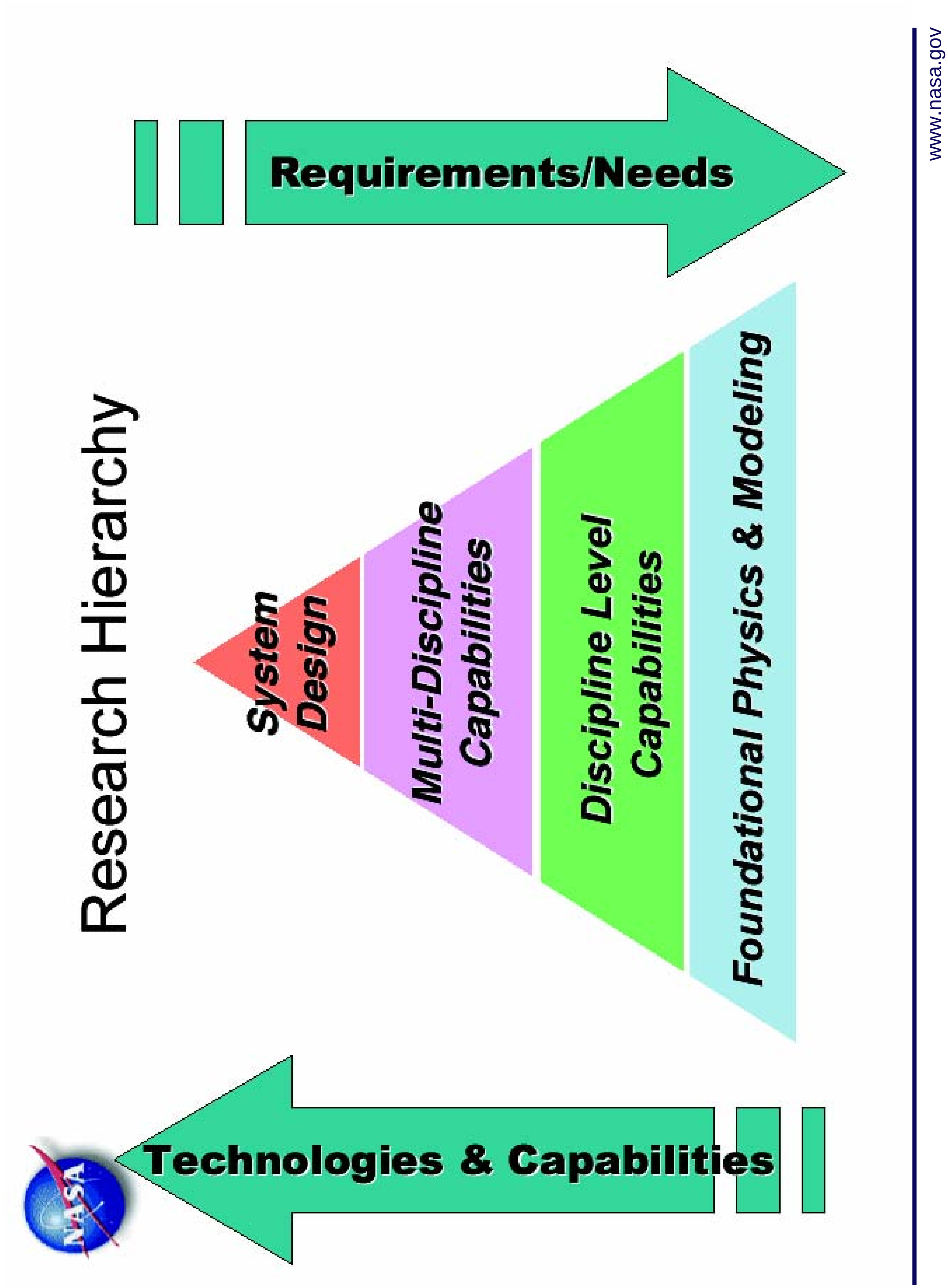

Research Hierarchy
Requirements/Needs
System Design
Multi-Discipline Capabilities
Discipline Level Capabilities
Foundational Physics & Modeling
Technologies & Capabilities
www.nasa.gov

Approach

Use Space Act Agreements to collaborate with industry; Establish partnerships with other Govt agencies (FAA, DOD, JPDO).	**Develop system-level capabilities to enable our civilian and military partners to develop revolutionary systems to meet their needs.** **Level 4**
NASA development of multidisciplinary methods and technologies.	**Integrate methods and technologies to develop multi-disciplinary solutions.** **Level 3**
NASA development of discipline-related solutions.	**Leverage the foundational research to develop technologies and analytical tools focused on discipline-based solutions.** **Level 2**
Use NASA Research Announcements (NRAs) to solicit proposals for foundational research in areas where NASA needs to enhance its core capabilities.	**Conduct foundational research to further our fundamental understanding of the underlying principles.** **Level 1**

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Impact on Partnerships

- NASA will take responsibility for the intellectual stewardship of the core competencies of Aeronautics for the Nation.
  - Ensures the availability of a world class resource (personnel, facilities, knowledge and expertise) ready to be drawn upon by our Government partners (e.g., DoD, FAA, JPDO) and by the private sector.
- University partnerships
  - We will integrate students and faculty as true partners in our research projects.
    - Enables replenishment of workforce at both NASA and in industry.
  - Full and open competition for funds.
- Industry partnerships
  - We will shift from near-term, evolutionary procurements to long-term, intellectual partnerships.
    - Ensures ability to provide long-term, stable investment in capabilities that will benefit all of industry.

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Four-Step Planning Process

Step 1: Assess the long-term research needs and goals in Fundamental Aeronautics and establish technical roadmaps to accomplish those goals.

Step 2: Solicit information on key areas of interest from the external community and determine opportunities for collaboration through an RFI

Step 3: Define research proposals at the field centers

Step 4: Issue a NASA Research Announcement to solicit proposals for foundational research

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Planning Details and Status

Step 1: Technical Roadmaps

- Conducted workshops to develop 10-year schedule/milestone roadmaps for each Project in each Program.
- Cross-cutting workshops held to identify research areas of overlap and collaboration across Projects and Programs.
- Workshop results presented to Government partners (DoD, FAA and JPDO).
- Roadmaps presented at 2006 AIAA Reno Conference and subsequently posted on NASA website.

Step 2: Request for Information

- Released RFIs to solicit interest from industry to collaborate at the system level. The RFIs:
  - Expressed interest in collaborations in pre-competitive research to benefit industry broadly.
  - Stated that Industry work would be conducted on a non-reimbursable basis.
- All RFI responses (~ 240 total) were provided to targeted Projects for consideration as part of their research proposal submissions.

  RFI Release……………………….. 3 Jan 2006
  RFI Responses Due:……………..31 Jan 2006

Step 3: Proposals

- Researchers develop proposals that include partnerships with industry & OGA.
- Proposals underwent HQ peer-review. Peer-review panels included Government SMEs from:

- USAF	- FAA	- US Army
- DARPA	- JPDO	- NOAA

- Proposals underwent a simultaneous, independent review conducted by the 4 research centers
- Proposals were evaluated based on the following criteria: Technical Plan, Resource Allocation, Management Plan & Partnership Plan

Step 4: NRA

- Proposals that are approved will release NASA Research Announcements (NRAs) for foundational research.

  NRA Est Release…………………..……. 24 May 2006
  NRA Response ………………………. 7 July 2006
- NRAs will provide full and open competition.
- NRAs reviewed and selections will be announced by end of 2006.
- Prepare for Phase 2 NRA Release

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Fundamental Aeronautics

Research Thrusts

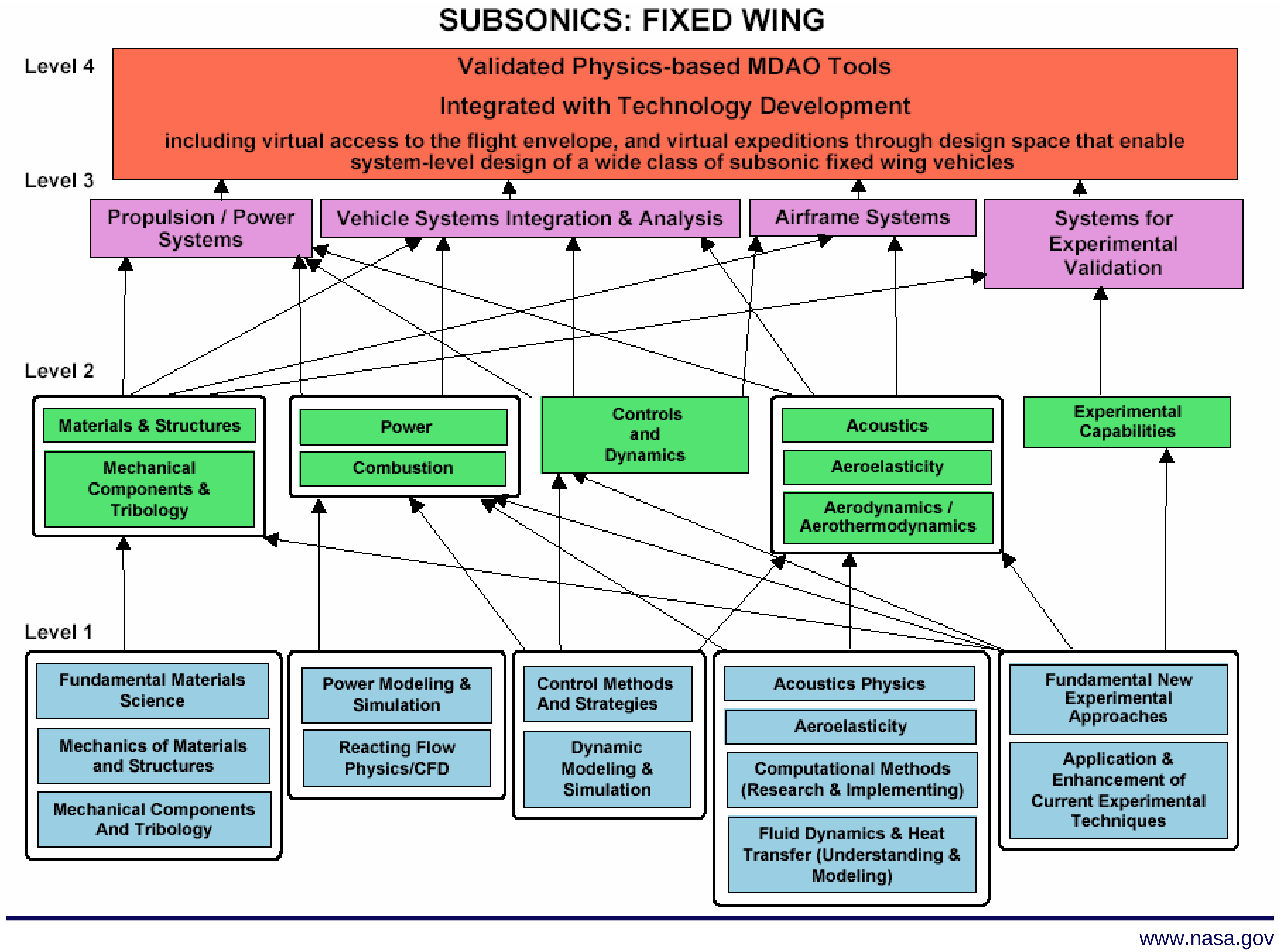
Hypersonics	Subsonics: Rotary Wing	Subsonics: Fixed Wing	Supersonics

Objective

- Development of system-level, multi-disciplinary capabilities for both civilian and military applications
- Provide long-term investment in research to support and sustain expert competency in critical core areas of aeronautics technology

Results

- Technology innovation and integrated, multidisciplinary analysis tools to:
  - Provide rapid evaluation of new concepts and technology
  - Accelerate the application of new technology to a wide array of vehicles
  - Reduce the environmental impact and increase the public benefit of future aircraft: lower emissions, less noise, higher efficiency, safer operation


SUBSONICS: FIXED WING
Level 4
Validated Physics-based MDAO Tools
Integrated with Technology Development
including virtual access to the flight envelope, and virtual expeditions through design space that enable system-level design of a wide class of subsonic fixed wing vehicles
Level 3
Propulsion / Power Systems
Vehicle Systems Integration & Analysis
Airframe Systems
Systems for Experimental Validation
Level 2
Materials & Structures
Mechanical Components & Tribology
Power
Combustion
Controls and Dynamics
Acoustics
Aeroelasticity
Aerodynamics / Aerothermodynamics
Experimental Capabilities
Level 1
Fundamental Materials Science
Mechanics of Materials and Structures
Mechanical Components And Tribology
Power Modeling & Simulation
Reacting Flow Physics/CFD
Control Methods And Strategies
Dynamic Modeling & Simulation
Acoustics Physics
Aeroelasticity
Computational Methods (Research & Implementing)
Fluid Dynamics & Heat Transfer (Understanding & Modeling)
Fundamental New Experimental Approaches
Application & Enhancement of Current Experimental Techniques
www.nasa.gov

Subsonics Fixed Wing: Research Topics

Propulsion and Power Systems	Alternative propulsion and power concepts
	Materials and structures technologies for durable, active, multi-functional propulsion and power systems
	Advanced technologies for intelligent engines, and engine icing characteristics
Vehicle Integration and Analysis	Engine and airframe noise source decomposition
	Advanced control techniques and autonomous control architectures
	Aeroelastic analysis methods
Airframe Systems	Metallic, composite, and hybrid materials and structures, analysis methods for property characterization
	Multifunctional materials and structures concepts
	Advanced materials, processing and manufacturing technologies
	Expanded design space enabled by high-lift design, edge of envelope stability and control
	Enhanced physics-based noise prediction, integrated aerodynamic, acoustic, and structural advanced analysis tool
Systems for Experimental Validation	Autonomous testbeds
	High-fidelity piloted simulations, and instrumentation with new capabilities integrated into multidisciplinary system validated with flight tests as appropriate

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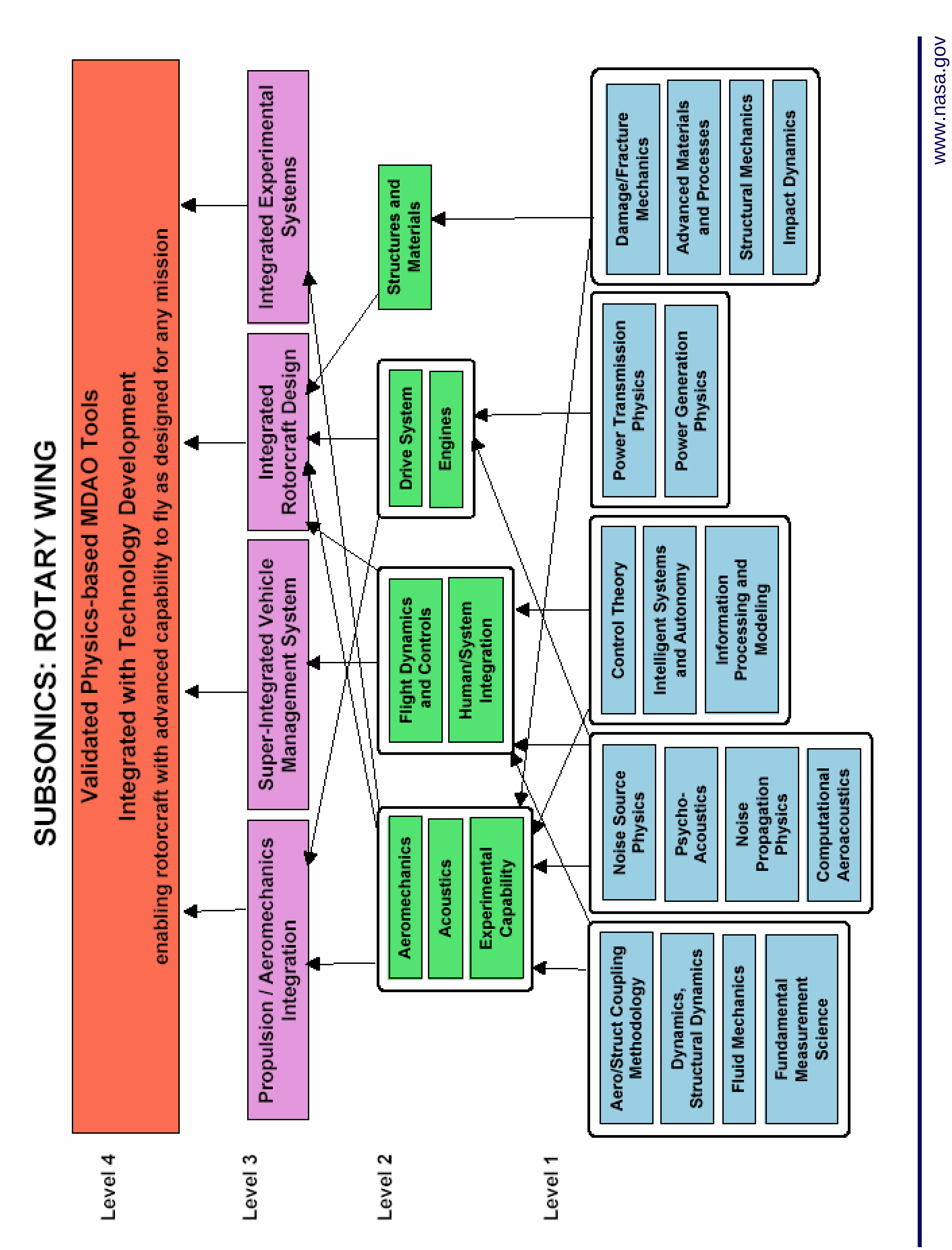

SUBSONICS: ROTARY WING
Level 4
Level 3
Level 2
Level 1
Validated Physics-based MDAO Tools
Integrated with Technology Development
enabling rotorcraft with advanced capability to fly as designed for any mission
Propulsion / Aeromechanics Integration
Super-Integrated Vehicle Management System
Integrated Rotorcraft Design
Integrated Experimental Systems
Aeromechanics
Acoustics
Experimental Capability
Flight Dynamics and Controls
Human/System Integration
Drive System
Engines
Structures and Materials
Aero/Struct Coupling Methodology
Dynamics, Structural Dynamics
Fluid Mechanics
Fundamental Measurement Science
Noise Source Physics
Psycho-Acoustics
Noise Propagation Physics
Computational Aeroacoustics
Control Theory
Intelligent Systems and Autonomy
Information Processing and Modeling
Power Transmission Physics
Power Generation Physics
Damage/Fracture Mechanics
Advanced Materials and Processes
Structural Mechanics
Impact Dynamics
www.nasa.gov

Subsonics Rotary Wing: Research Topics

Propulsion-Aeromechanics Integration	Variable speed drive systems
	Minimal or no-lubricant transmission concepts
	Life extension component technologies
	Alternative engine designs to address on-condition health management and interior noise
Super-Integrated Health Management System	Simulations and flight test to validate investigative results of active-control techniques
	Adaptive displays to address control system design capabilities
Integrated Rotorcraft Design	Aeromechanics and aeroacoustics predictive design capabilities for various size and flight regime operations
Integrated Experimental Systems	Methodology for real-time comparison of computational fluid- and structural-dynamics with experimental data
	Integrated diagnostic instrumentation systems into facilities for operational efficiency
	Simultaneous, multi-parameter diagnostic techniques that enable rapid testing and validation of rotorcraft behavior

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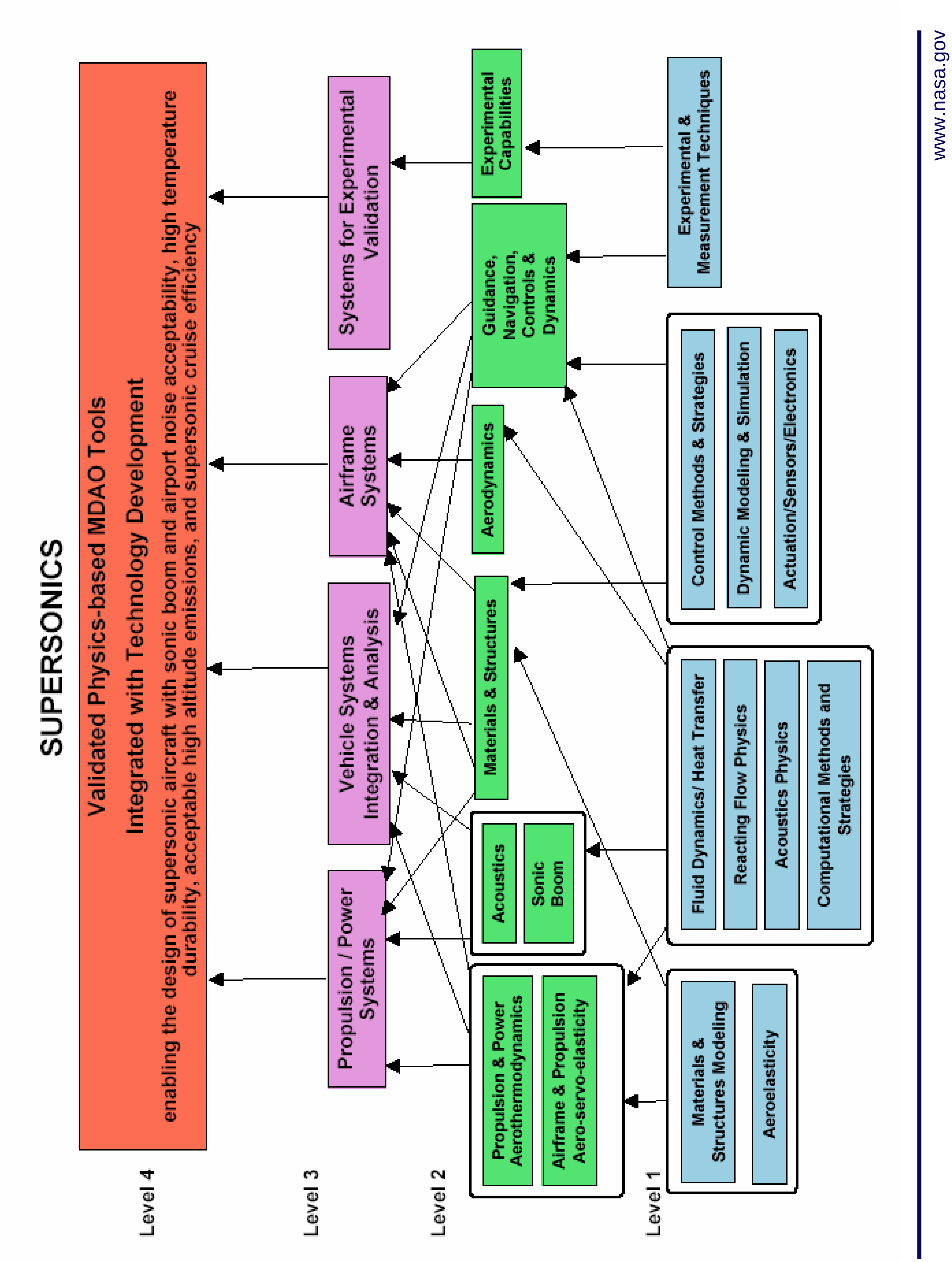
SUPERSONICS
Validated Physics-based MDAO Tools
Integrated with Technology Development
enabling the design of supersonic aircraft with sonic boom and airport noise acceptability, high temperature durability, acceptable high altitude emissions, and supersonic cruise efficiency
Level 4
Level 3
Level 2
Level 1
Propulsion / Power Systems
Vehicle Systems Integration & Analysis
Airframe Systems
Systems for Experimental Validation
Propulsion & Power Aerothermodynamics
Airframe & Propulsion Aero-servo-elasticity
Acoustics
Sonic Boom
Materials & Structures
Aerodynamics
Guidance, Navigation, Controls & Dynamics
Experimental Capabilities
Materials & Structures Modeling
Aeroelasticity
Fluid Dynamics/ Heat Transfer
Reacting Flow Physics
Acoustics Physics
Computational Methods and Strategies
Control Methods & Strategies
Dynamic Modeling & Simulation
Actuation/Sensors/Electronics
Experimental & Measurement Techniques
www.nasa.gov

Supersonics Research Topics

Propulsion and Power Systems	Tools to predict propulsion system noise, efficiency and high altitude emissions
	Reduced emissions combustor predictive capability
	Variable geometry nozzle aerodynamic predictive capability
	Multi-fidelity engine-aircraft structural simulation
	Ice accretion prediction
	High-pressure recovery predictive capability
	Low distortion and unstart mitigation inlets, integrated inlet-fan-nozzle predictive capability for steady-state and transient conditions
Vehicle Systems Integration and Analysis	Tools to predict integrated vehicle performance, noise and sonic boom,
	Installed propulsion system noise-performance trades for supersonic propulsion cycles, and integrated inlet-fan-nozzle
Airframe Systems	Tools to predict airframe noise, lift-drag, flight dynamics, stability and handling qualities
	High-fidelity computation method for achieving simultaneous gust and maneuver loads, ride quality due to elasticity, and flutter suppression control
Systems for Experimental Validation	Systems for experimental validation of capabilities for field noise measurements and techniques
	Requirements for national facilities to support propulsion and airframe systems tests

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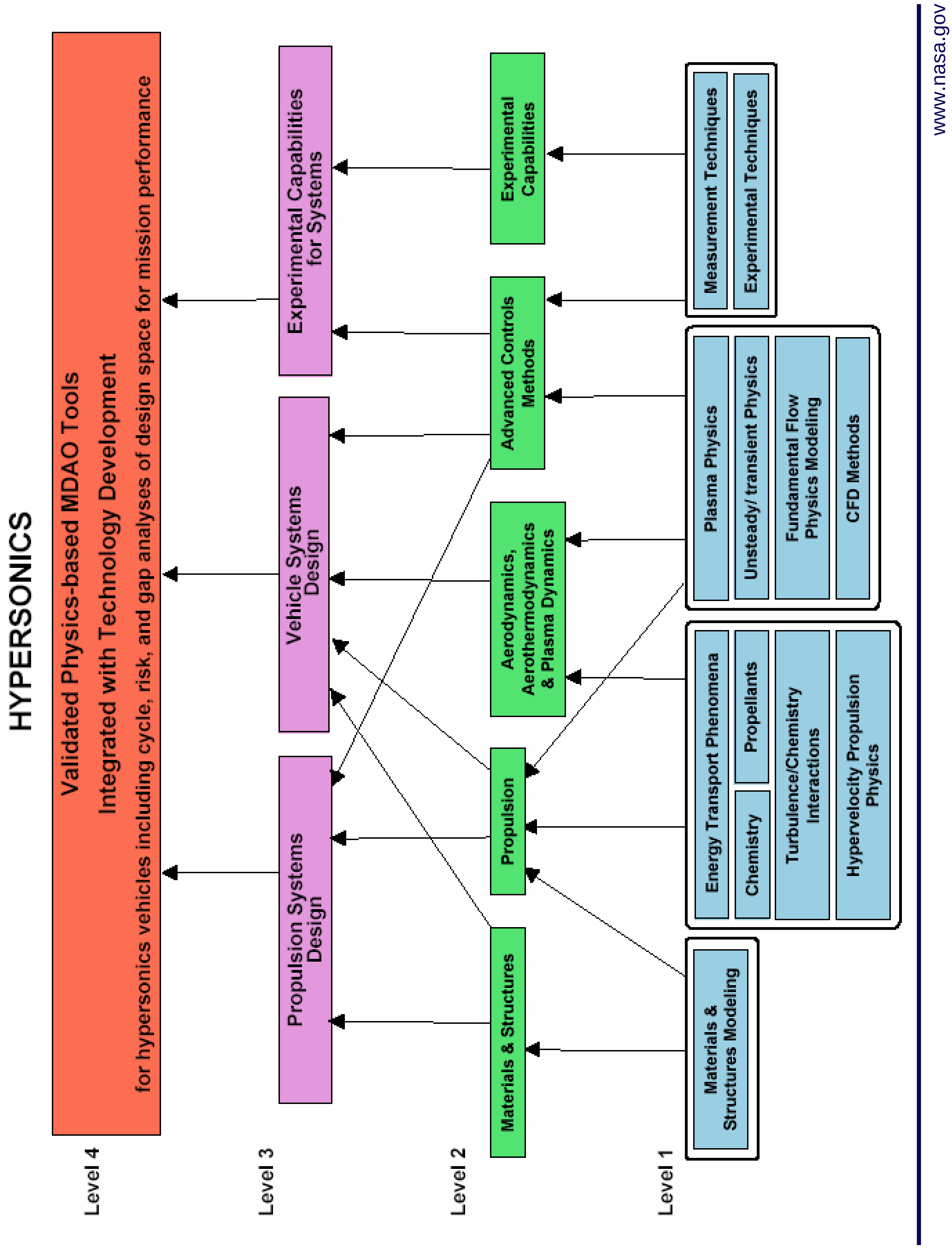
HYPERSONICS
Validated Physics-based MDAO Tools
Integrated with Technology Development
for hypersonics vehicles including cycle, risk, and gap analyses of design space for mission performance
Level 4
Level 3
Level 2
Level 1
Propulsion Systems Design
Vehicle Systems Design
Experimental Capabilities for Systems
Materials & Structures
Propulsion
Aerodynamics, Aerothermodynamics & Plasma Dynamics
Advanced Controls Methods
Experimental Capabilities
Materials & Structures Modeling
Energy Transport Phenomena
Chemistry
Propellants
Turbulence/Chemistry Interactions
Hypervelocity Propulsion Physics
Plasma Physics
Unsteady/ transient Physics
Fundamental Flow Physics Modeling
CFD Methods
Measurement Techniques
Experimental Techniques
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Hypersonics Research Topics

Propulsion Systems Design	Technology development for Turbine Based Combine Cycle (TBCC) and Rocket Based Combined Cycle (RBCC) propulsion systems to aid mode transition between low-speed and high-speed flowpaths, and address engine system thermal management and inlet operability
	Materials for cryogenic tanking applications
Vehicle Systems Design	Technologies to address the physics of combustion, hypersonic flows, and entry, descent and landing
	Lightweight high temperature materials for rotating and static components
	Structural durability analysis methods including deterministic and probabilistic life prediction techniques and non-destructive evaluation
	Material and structure alternatives for vehicle hot structures
	Methods and materials for developing improved thermal protection systems for extreme flight regimes of hypersonic flight
Experimental Capabilities for Systems	Methods for a single extreme environment sensor to measure multiple flow and structural values
	Optical sensors for flow characterization
	Multi-discipline control techniques for health monitoring
	Air data system allowing air-ground communication with the vehicle traveling Mach 12+ along the horizon

www.nasa.gov

Aviation Safety Program

Research Thrusts

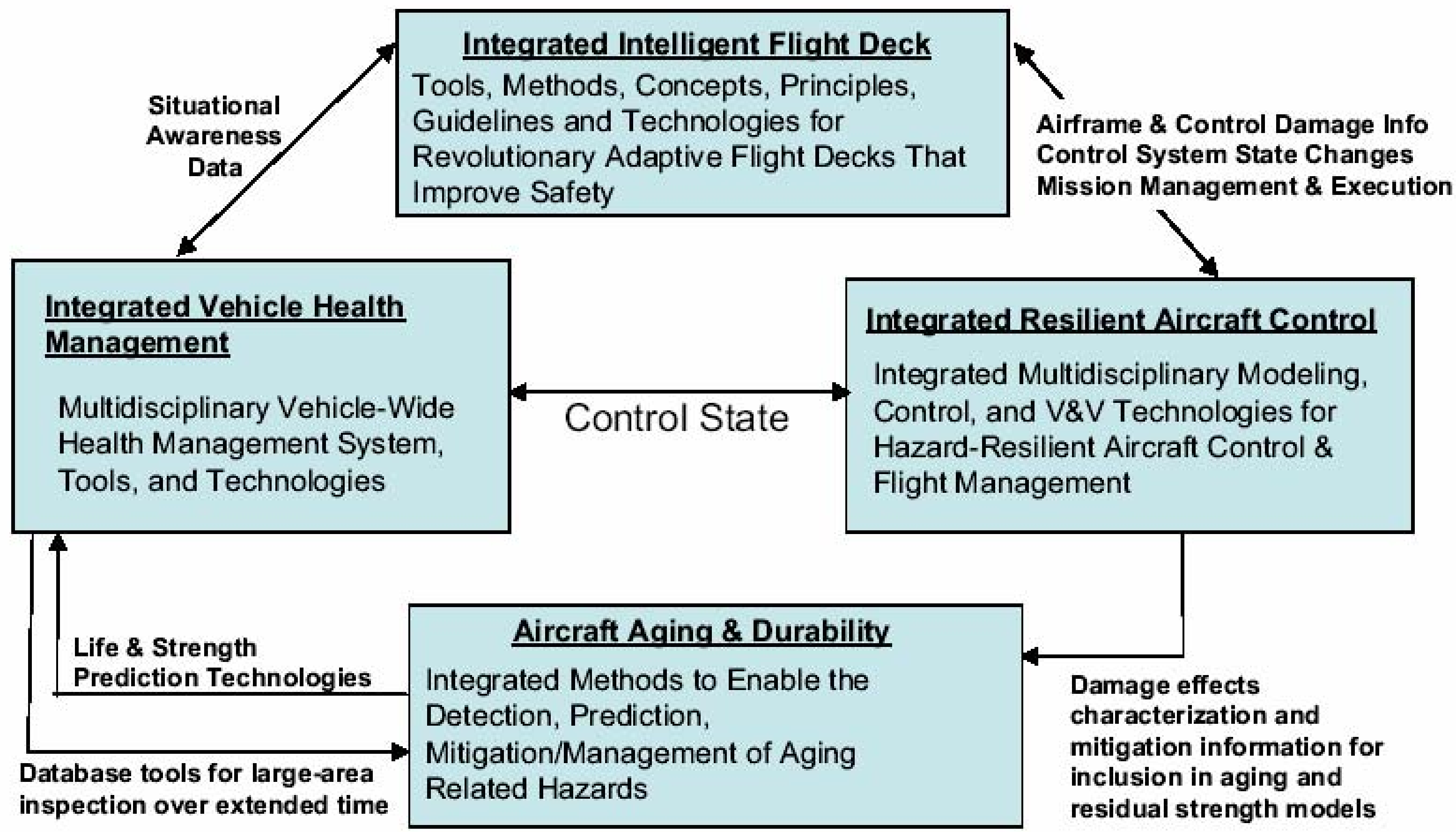
Integrated Vehicle Health Management	Integrated Intelligent Flight Deck	Integrated Resilient Aircraft Control	Aircraft Aging & Durability

Develop technologies, tools, and methods to:

- Improve inherent safety attributes of new and legacy vehicles
- Overcome safety technology barriers that would otherwise constrain full realization of the Next Generation Air Transportation System

Aviation Safety Program

Project Area Interdependencies - Examples



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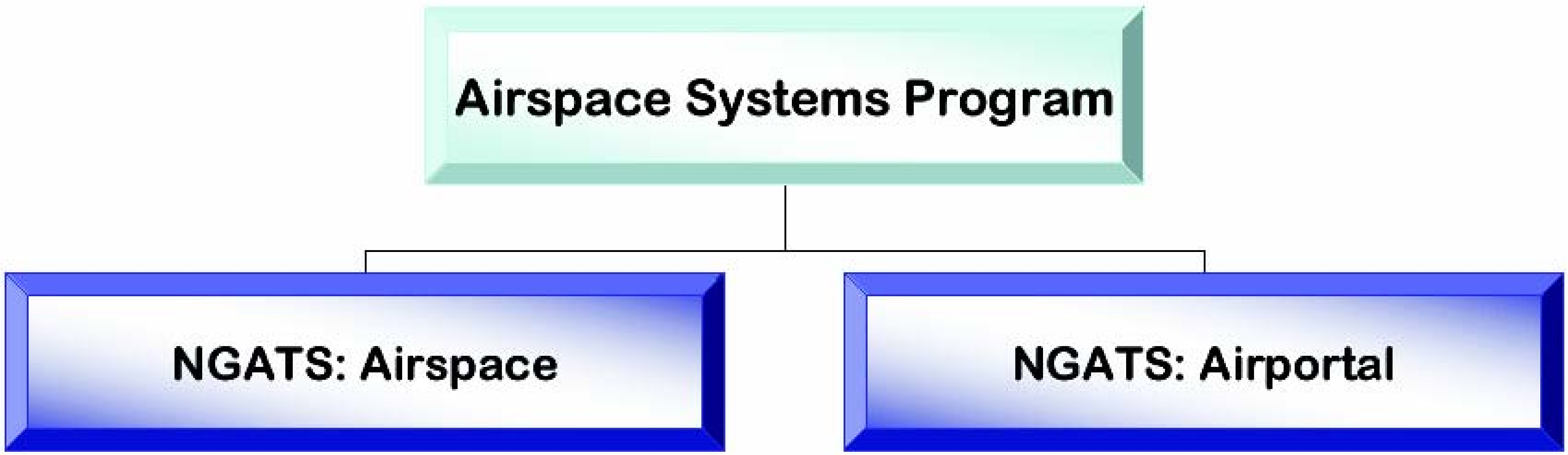
ASP Structure



Program Elements developed through a rigorous technical workshop process. Workshop participants comprised NASA Aeronautics' best and most experienced ATM technical experts.

AS Program Deliverables

Integrated Solutions for a Safe, Efficient and High-Capacity Airspace System

- **Evaluator: Strategic, NAS level**
- **4D Trajectory Operations: Strategic, NAS level**
- **Automated Separation Assurance**
- **Dynamic Airspace**

Integrated Solutions for Safe, Efficient and High-Capacity Airportals

- **Evaluator: Terminal and airport surface level**
- **4D Trajectory Operations: Terminal and airport surface level**
- **Super-Density Optimization**

- AS Program is aligned with JPDO plans as articulated through NGATS capabilities and roadmaps.
- Consistent with NGATS requirements, key AS Program elements will address:
  - Evaluator (Strategic and terminal area focused)
  - 4-D Trajectory Based Operations (Strategic and terminal area focused)
  - Automated Separation Assurance
  - Dynamic Airspace Configuration
  - Super-Density Surface and Terminal Area Traffic Optimization

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AS Program Deliverables (cont.)

- Airspace and Airportal deliverables will be integrated for gate-to-gate solutions.
  - Projects have been defined by domains.
  - Technical discipline overlap exists between these two projects.
  - Development of Airportal products will substantially leverage fundamental technology advances made in Airspace.
- Program elements were developed with a focus on technical R&D needs.
- Prioritization of efforts is essential.
  - ASP leadership has asked the JPDO to review the re-shaped ASP with regards to its relevance to NGATS goals and provide guidance for our final determination of work elements.

www.nasa.gov

Where to find more information?

www.aeronautics.nasa.gov

www.nasa.gov

GLOBAL ENERGY ISSUES AND ALTERNATE FUELING

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National Aeronautics and Space Administration

Global Energy Issues and Alternate Fueling

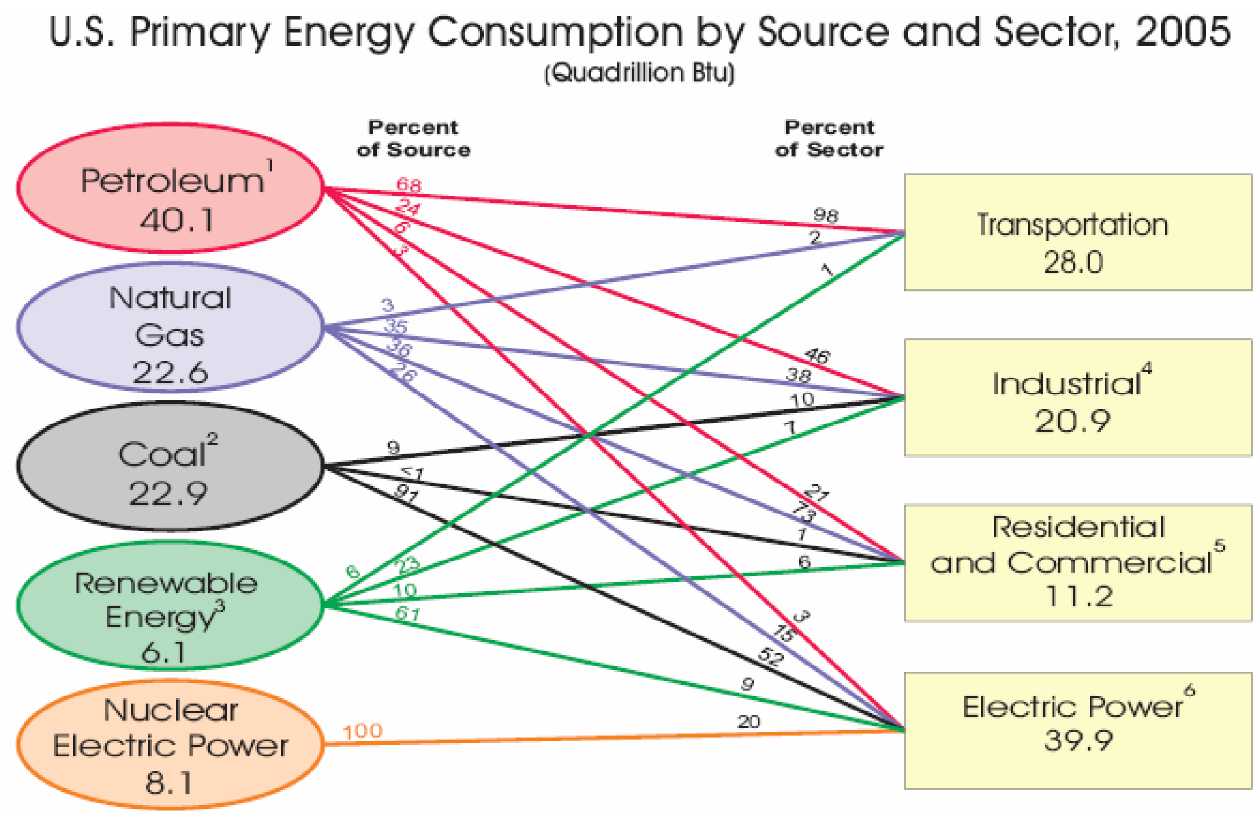
R.C. Hendricks
NASA –GRC

2006 NASA Seal/Secondary Air System Workshop
November 14-15, 2006
OAI Cleveland OH 44152

www.nasa.gov

National Aeronautics and Space Administration

US Uses about 100 Quad/year (1 Q = 10^{15} Btu)
World Energy Use: about 433 Q/yr



[1]Excludes 0.3 quadrillion Btu of ethanol, which is included in "Renewable Energy."
[2]Includes coal coke net imports.
[3]Conventional hydroelectric power, wood, waste, alcohol, geothermal, solar, and wind.
[4]Includes industrial combined-heat-and-power (CHP) and industrial electricity-only plants.
[5]Includes commercial combined-heat-and-power (CHP) and commercial electricity-only plants.
[6]Electricity-only and combined-heat-and-power (CHP) plants whose primary business is to sell electricity, or electricity and heat, to the public.

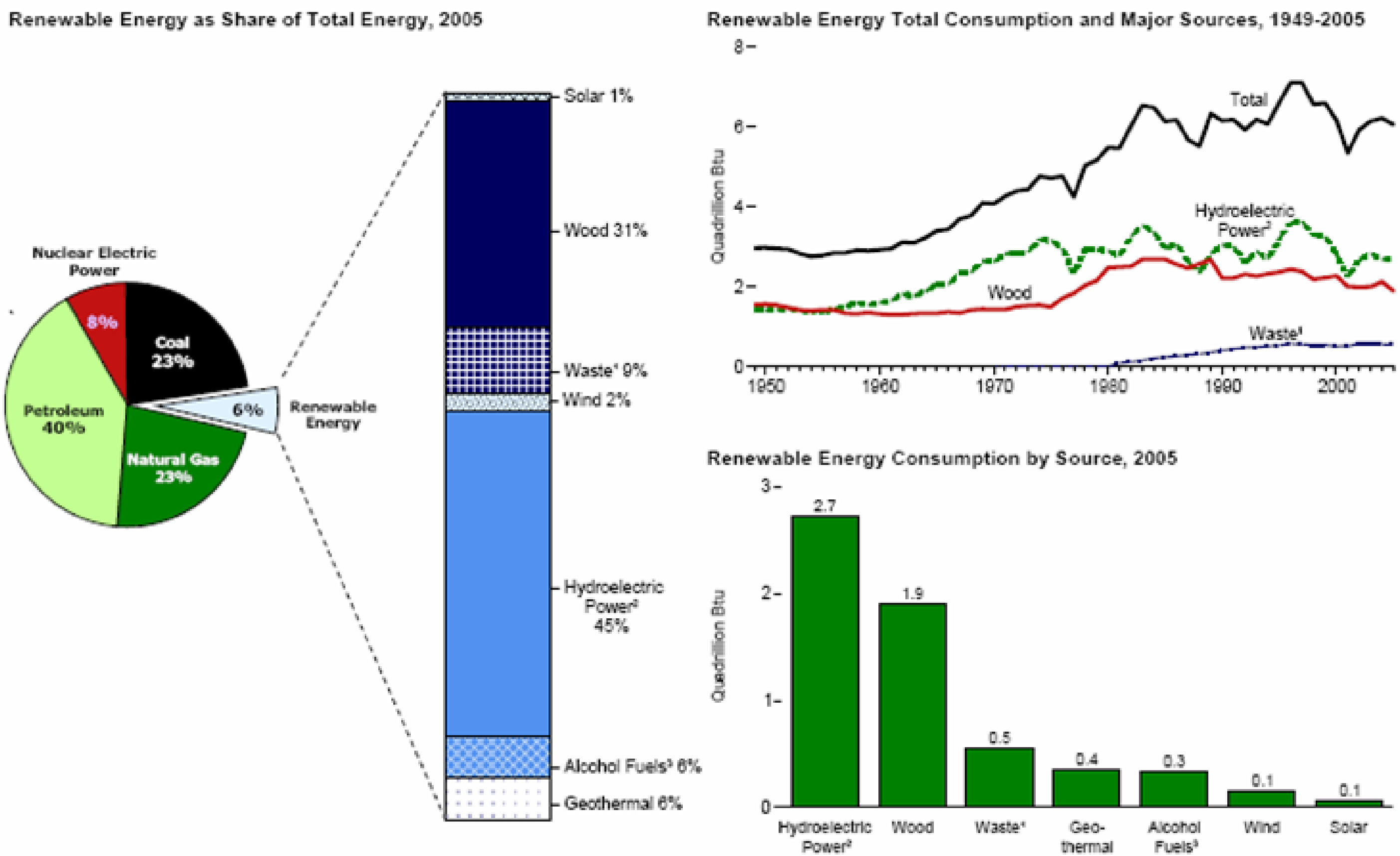
Note: Sum of components may not equal 100 percent due to independent rounding.

Source: Energy Information Administration, *Annual Energy Review 2005*, Tables 1.3 and 2.1b-2.1f.

http://www.eia.doe.gov/emeu/aer/pecss_diagram.html

www.nasa.gov

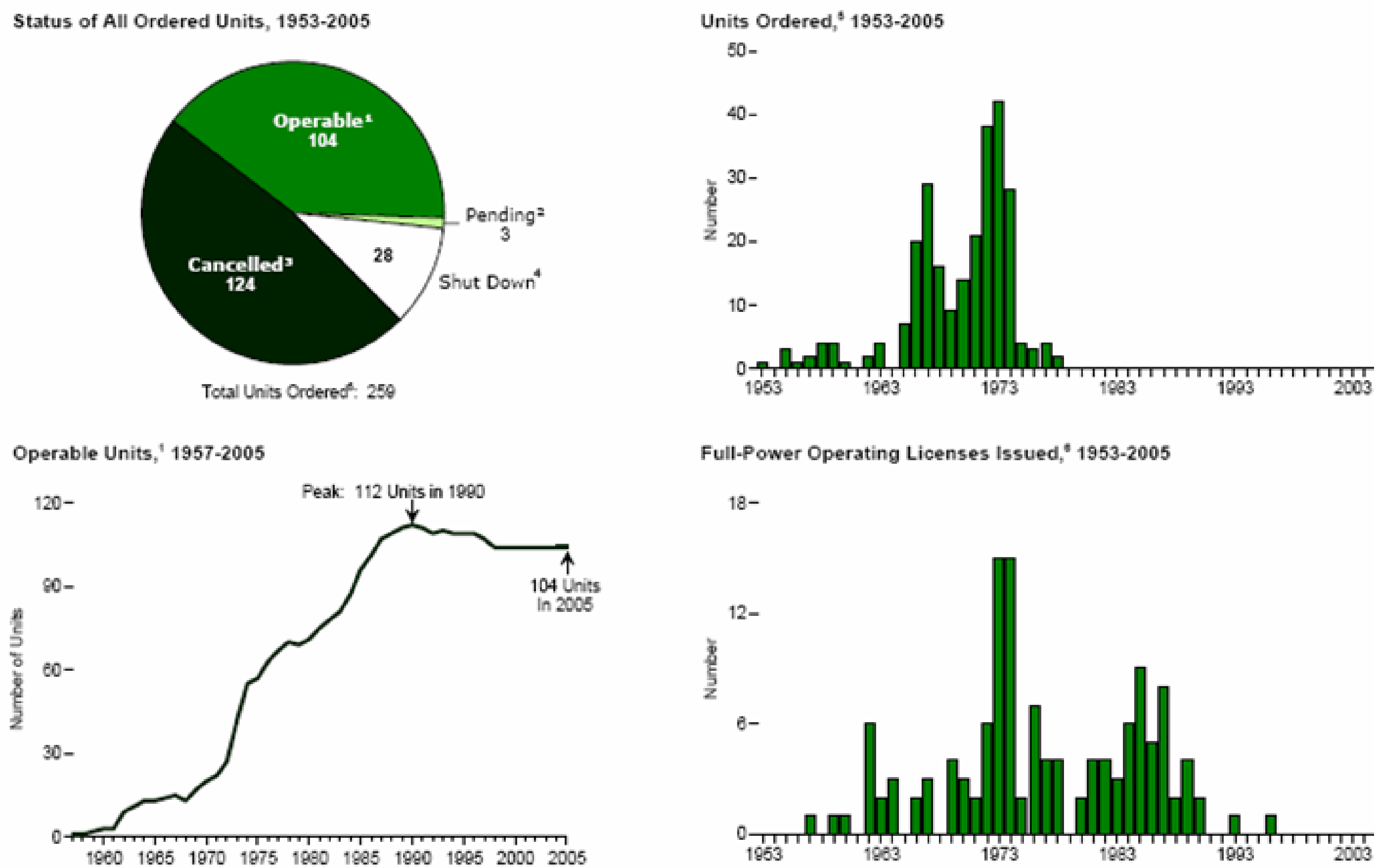
US Renewable Energy about 6%



[1] Municipal solid waste, landfill gas, sludge waste, tires, agricultural byproducts, and other biomass.
[2] Conventional hydroelectric power.
[3] Ethanol blended into motor gasoline.
Note: Because vertical scales differ, graphs should not be compared.
Sources: Tables 1.3 and 10.1.

http://www.eia.doe.gov/emeu/aer/pdf/pages/sec10_2.pdf

Nuclear Could Grow: Has Legacy Problems

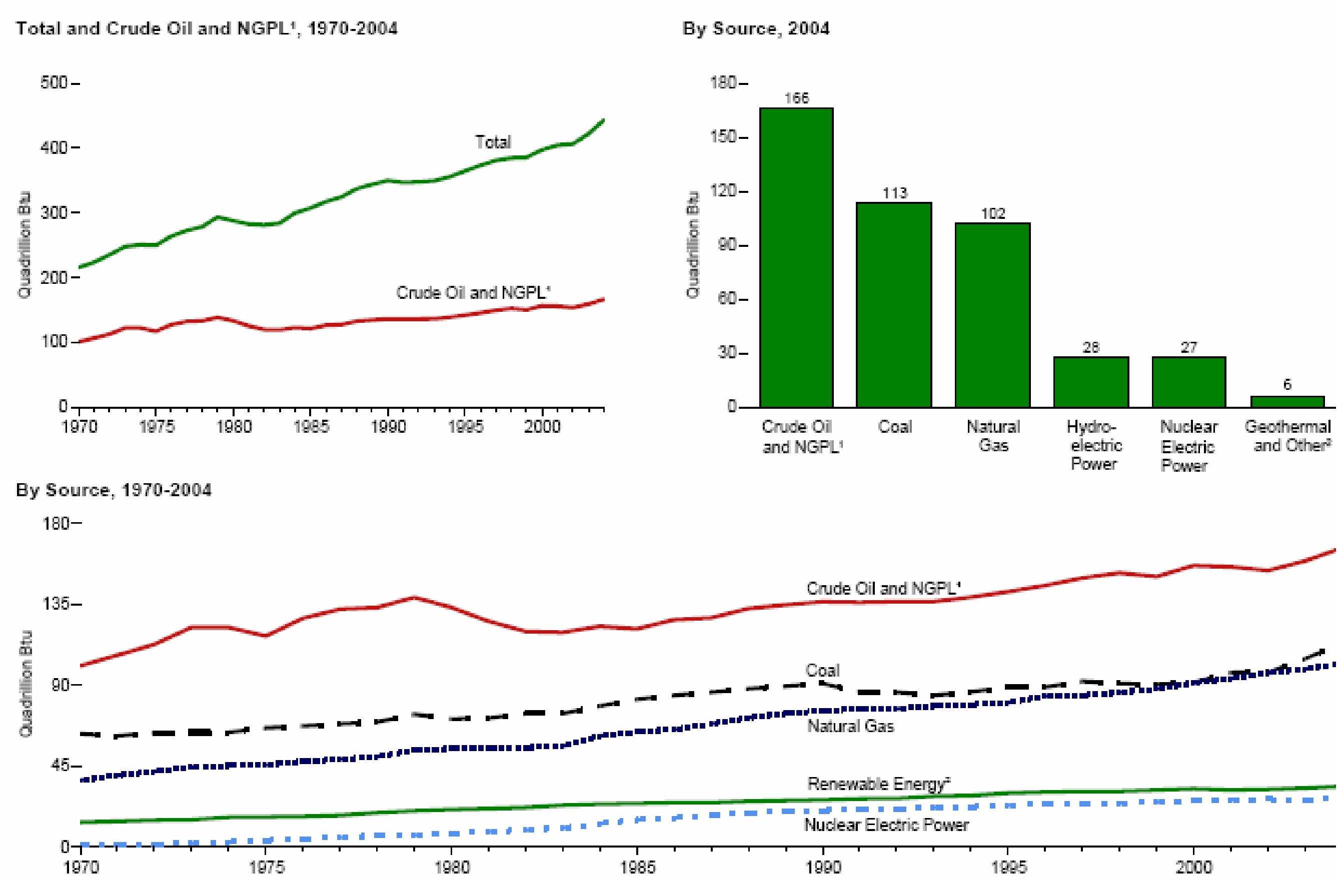


¹ Units holding full-power operating license, or equivalent permission to operate.
² Bellefonte 1 and 2 and Watts Bar 2, where construction has been stopped indefinitely.
³ Includes WNP 1; the licensee intends to request that the construction permit be cancelled.
⁴ Ceased operation permanently.
⁵ Placement of an order by a utility or government agency for a nuclear steam supply system.

⁶ Issuance by regulatory authority of full-power operating license, or equivalent permission.
Notes: • Data are at end of year. • Because vertical scales differ, graphs should not be compared.
Source: Table 9.1.

http://www.eia.doe.gov/emeu/aer/pdf/pages/sec9_2.pdf

Energy Sources Primarily NonRenewable Hydrocarbon



[1] Natural gas plant liquids.
[2] Net electricity generation from hydroelectric power, geothermal, wood, waste, solar, and wind. Data for the United States also include other renewable energy.

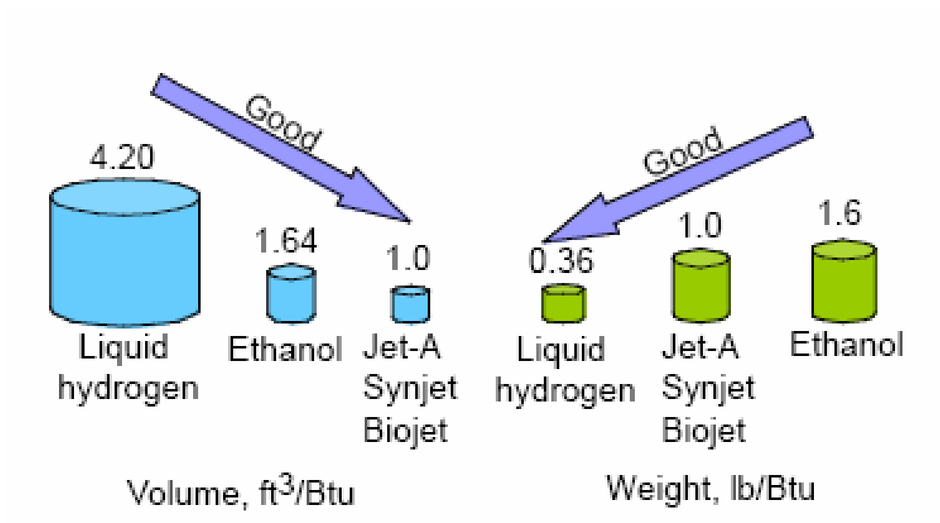
Notes: • Crude oil includes lease condensate. • Because vertical scales differ, graphs should not be compared.
Source: Table 11.1.

http://www.eia.doe.gov/emeu/aer/pdf/pages/sec11_2.pdf

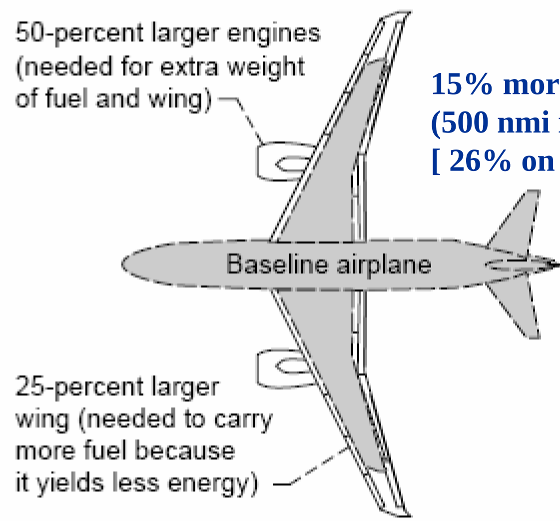
Notes

- Most renewable energy : wood and hydropower
- Small wind, solar and nuclear
- Stagnant nuclear growth, growing massive problem with aging reactor shutdown wastes and costs. Long lead time startup issues
- World Energy sources primarily hydrocarbon
- US: 76% Hydrocarbons only 6% renewable Energy distributed by 4 sectors (transportation, industrial, residential/commercial, electric)
- 28% US energy is transportation energy, 98% of which comes from petroleum
- Hydrocarbons emissions measured as CO2
- Fuels have major impact on aircraft design and use

Alternate Fuels Effect Aircraft Design

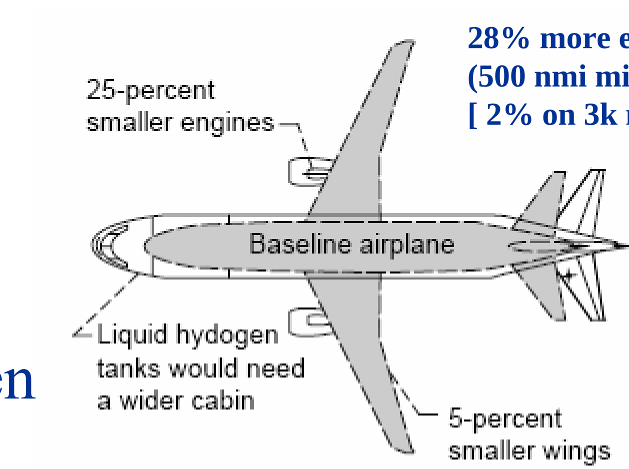


Ethanol



15% more energy use (500 nmi mission) [26% on 3k nmi mission]

Hydrogen



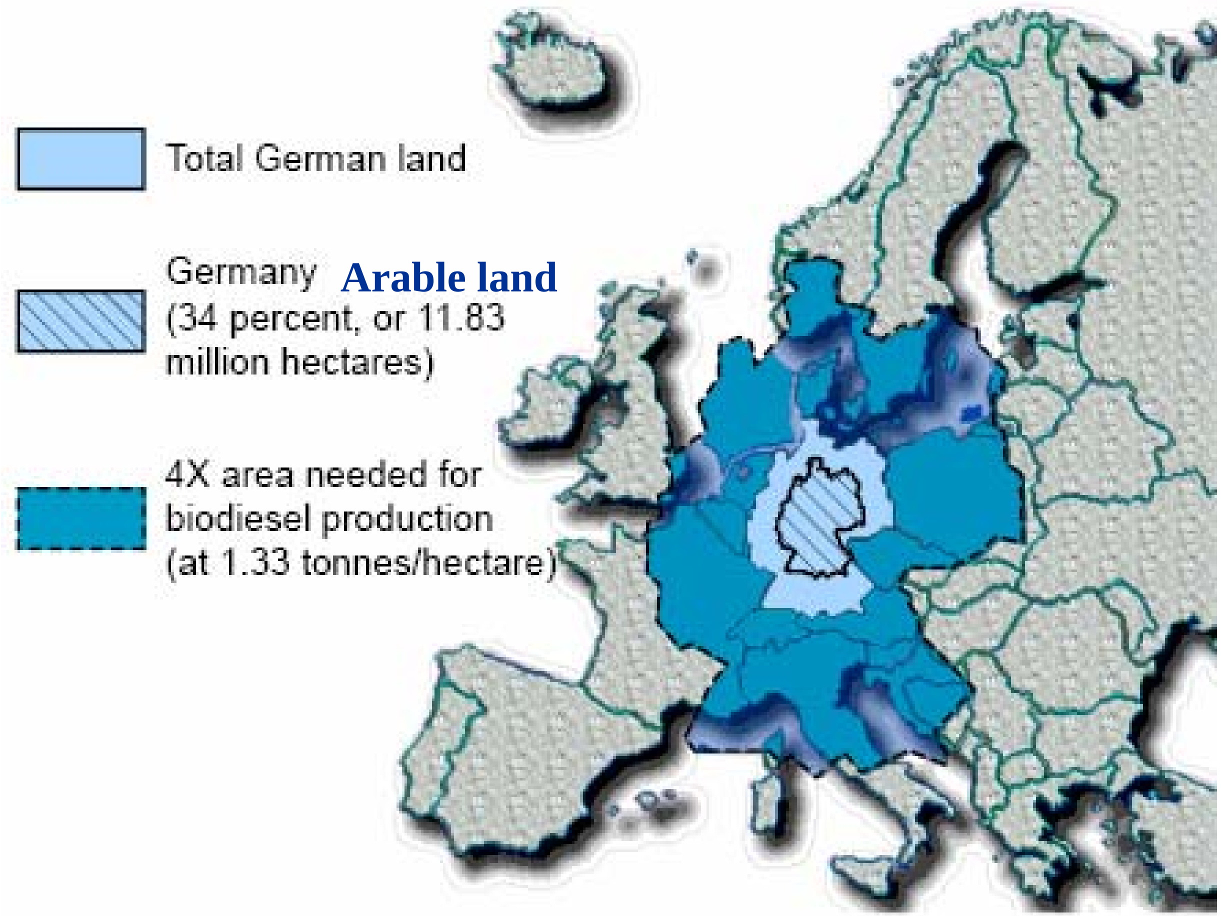
28% more energy use (500 nmi mission) [2% on 3k mni mission]

ICAS-2006-5.8.2 / NASA TM-2006-214365

Notes

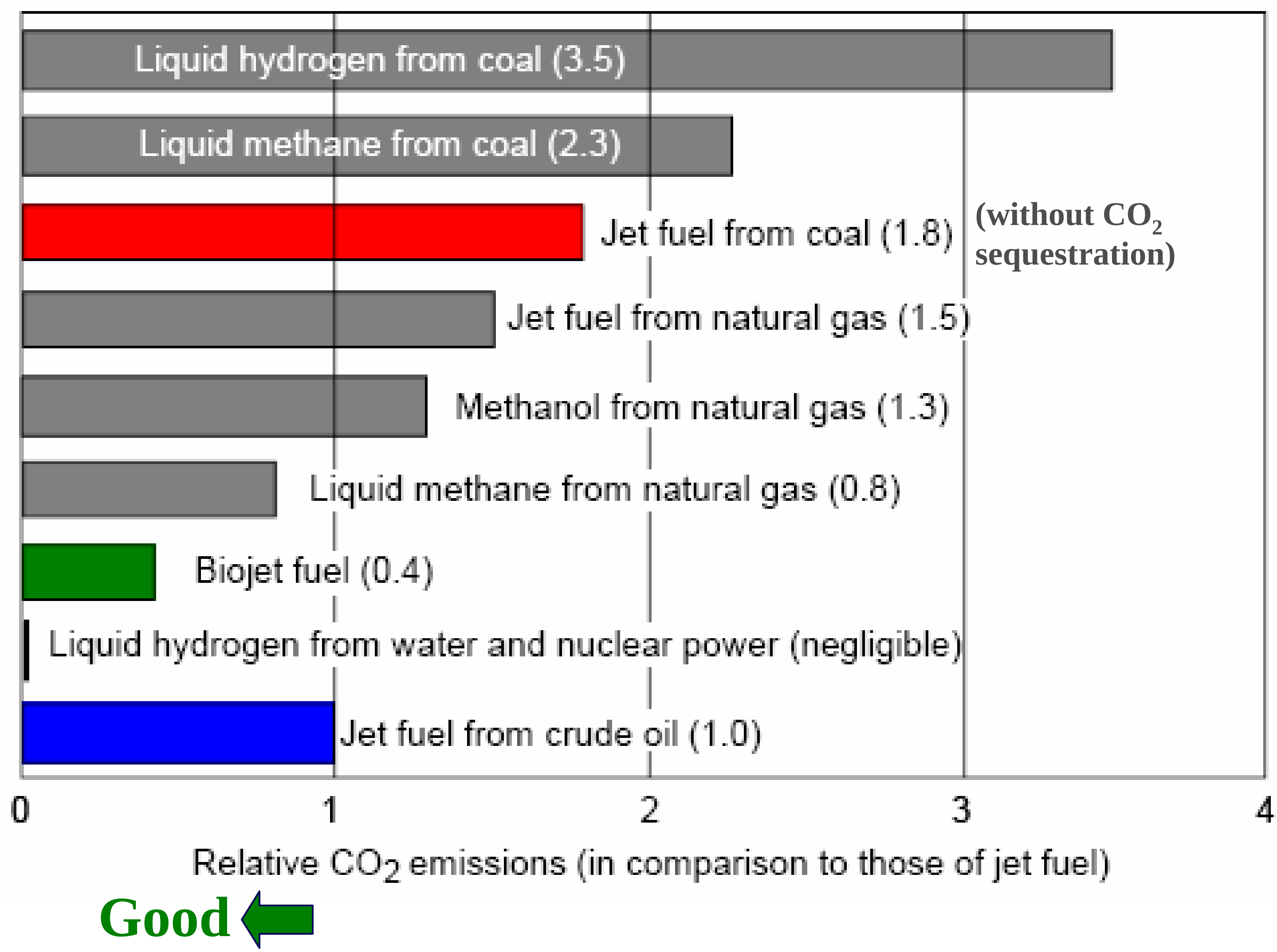
- Alternate fueling involves trade-offs in aircraft designs
- Renewable ethanol fuel requires larger engines and wings and 15% and 26% more fuel (than Jet A) for 500 nautical mile (nmi) and 3000 nmi missions.
- Hydrogen (liquid fuel) provides for smaller engines and wings yet requires 28% and 2% more fuel (than Jet A) for 500 nautical mile and 3000 nmi missions.
- New Logistics and support systems required
- Aircraft designers seeking drop in fuels suitable for both new and legacy aircraft
- Fuel line sealing becomes major issue to be resolved even for Fischer Tropisch (FT) hydrocarbon fuels
- Alternate fuels as ethanol, biodiesel become arable land intensive (food or fuel issues)

Conventional-Biomass Issue - Food or Fuel ?



ICAS-2006-5.8.2 / NASA TM-2006-214365

Alternate fuels must be environmentally benign



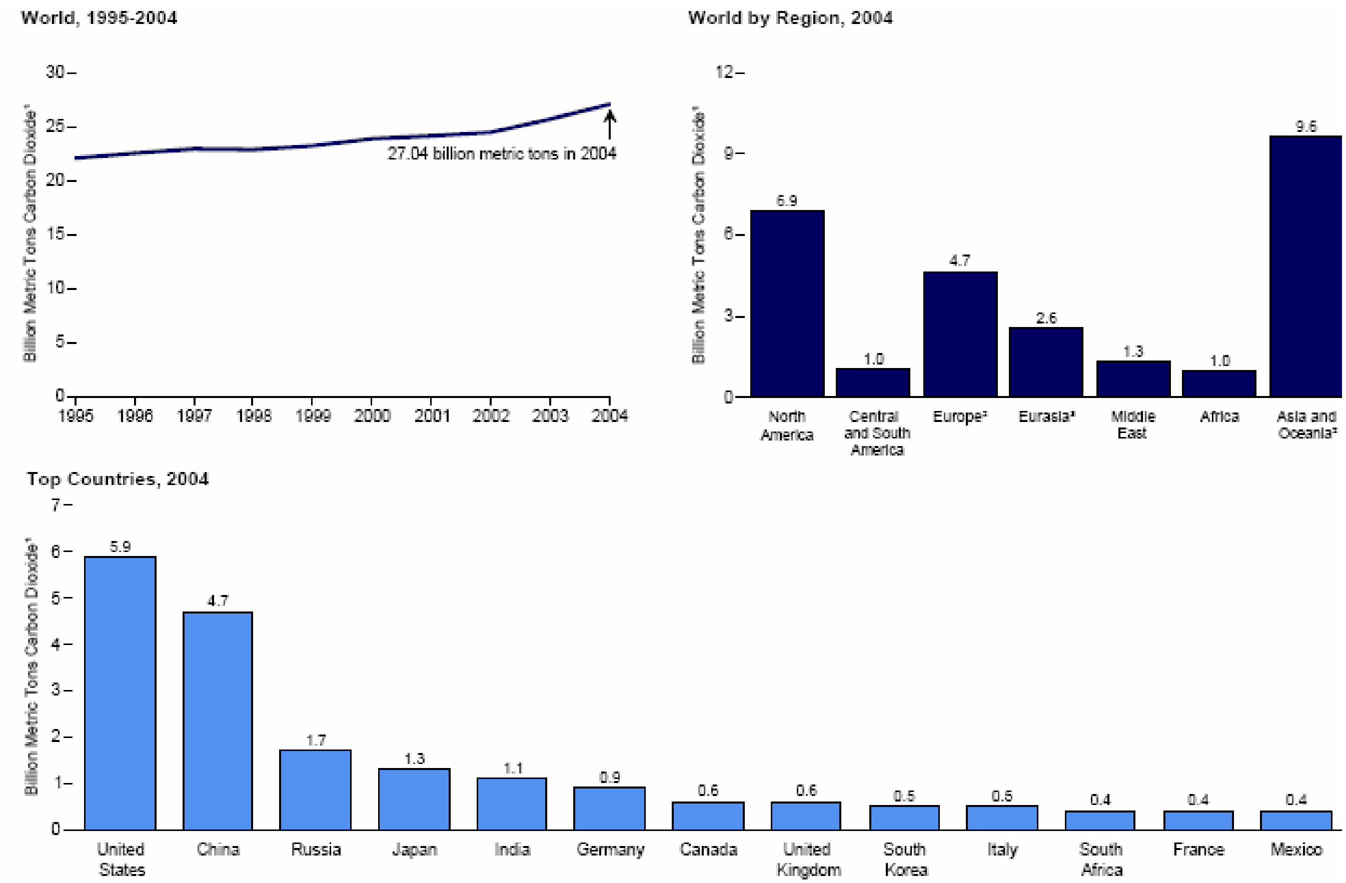
ICAS-2006-5.8.2 / NASA TM-2006-214365

Notes

- Germany mandated 5.75% biodiesel blends yet must import from Brazil to meet demand
- To meet annual diesel demand requires 4X German arable land (not a practical way)
- Emissions depend on methods for generating Alternate Fuels : Hydrogen from coal produces 3.5 x CO_2 than Jet-fuel, yet hydrogen as an alternate aircraft fuel produces negligible CO_2 emissions (but water may become a problem)
- Jet-fuel from coal (e.g., Sasol process) produces 1.6X Jet-fuel from petroleum-CO_2emissions
- World emissions are increasing with hydrocarbon use

National Aeronautics and Space Administration

World Carbon (CO2) Emissions Problem



[1] Metric tons of carbon dioxide can be converted to metric tons of carbon equivalent by multiplying by 12/44.
[2] Excludes countries that were part of the former U.S.S.R. See "U.S.S.R." in Glossary.
[3] Includes countries that were part of the former U.S.S.R. See "U.S.S.R." in Glossary.

Notes: • Data include carbon dioxide emissions from fossil-fuel energy consumption and natural gas venting and flaring. • Because vertical scales differ, graphs should not be compared.

Source: Table 11.19.

http://www.eia.doe.gov/emeu/aer/pdf/pages/sec11_38.pdf

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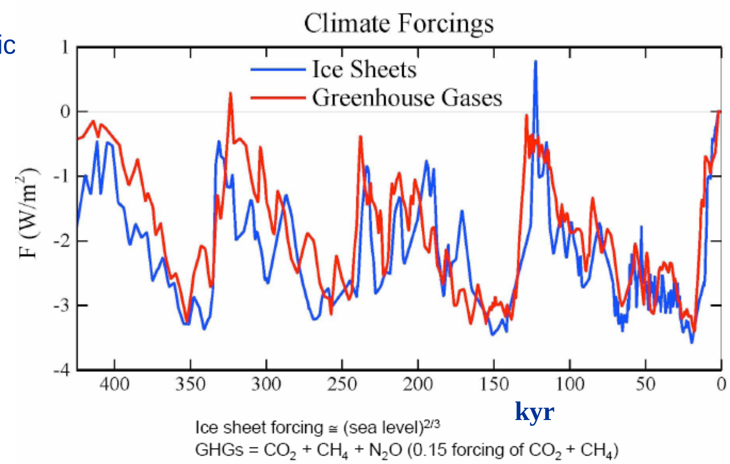
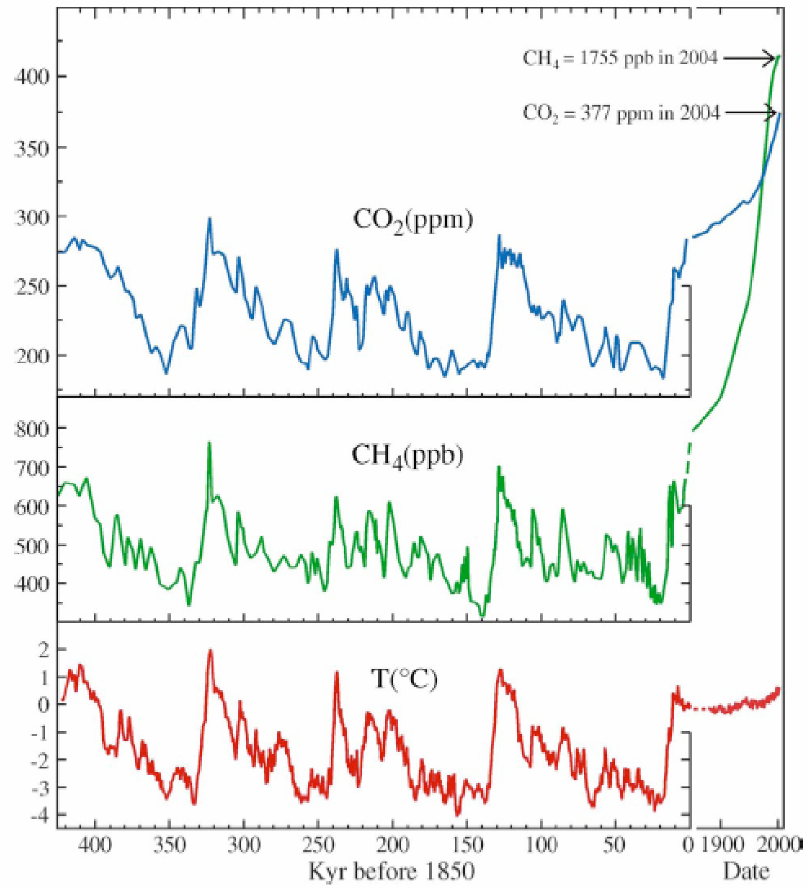
National Aeronautic

Planet Changing Emissions

Climate Forcing



Emissions



Hansen, J., Can We Still Avoid Dangerous Human-Made Climate Change?, World Science Forum, New York, NY, 9 November 2006

Metrics for "Dangerous" Change

Extermination of Animal & Plant Species

1. Extinction of Polar and Alpine Species
2. Unsustainable Migration Rates

Ice Sheet Disintegration: Global Sea Level

1. Long-Term Change from Paleoclimate Data
2. Ice Sheet Response Time

Regional Climate Change

1. General Statement
2. Droughts/Floods

Note Scale Change

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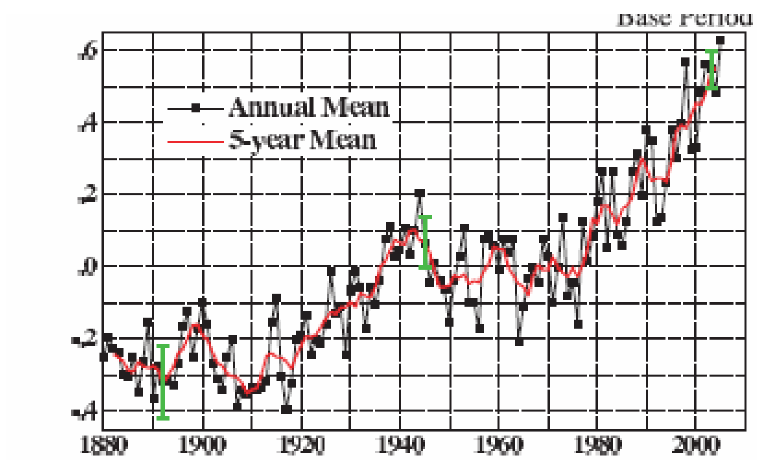
National Aeronautics and Space Administration

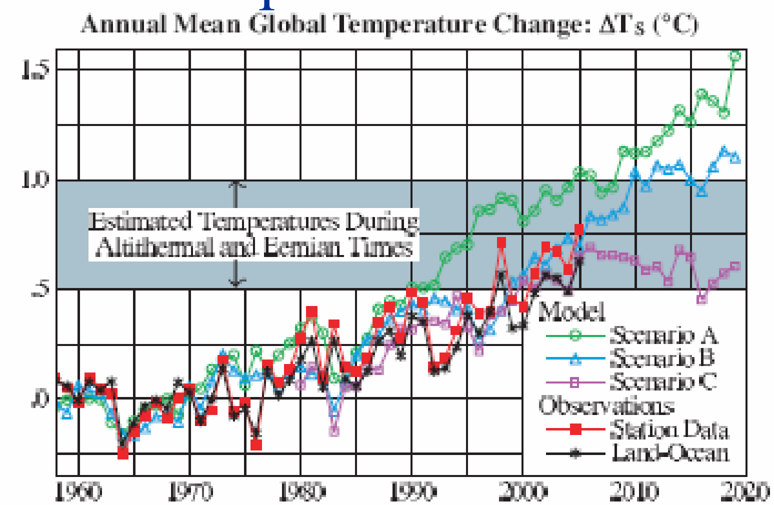
Jim Hansen's Global Warming Warnings

$T_{\text{Earth-surface}} \approx$ 1ºC of T_{max} of past 10^6 years

$\Delta T_{\text{Earth-surface}}$ = 0.2 ºC/decade for past 30 years

Earth warming +1ºC relative to year 2000 implies **dangerous climate change**, basis: likely effects of sea-level changes, extermination of species





A: Exponential GHG, C: Drastic emissions curtailment, B: Most plausible (close to real world)

BAU "Business-as-Usual" (between A & B) and AS "Alternate-Scenario" (similar to C)

Hansen, J., Sato, M., Ruedy, R. Lo, K., Lea, D.W., Medina-Elizade, M.; Global Temperature Change, PNAS Sept. 26, 2006, Vol. 103, No. 39, pp 14288-14293.
http://pubs.giss.nasa.gov/docs/2006/2006_Hansen_etal_1.pdf : accessed 25 September 2006

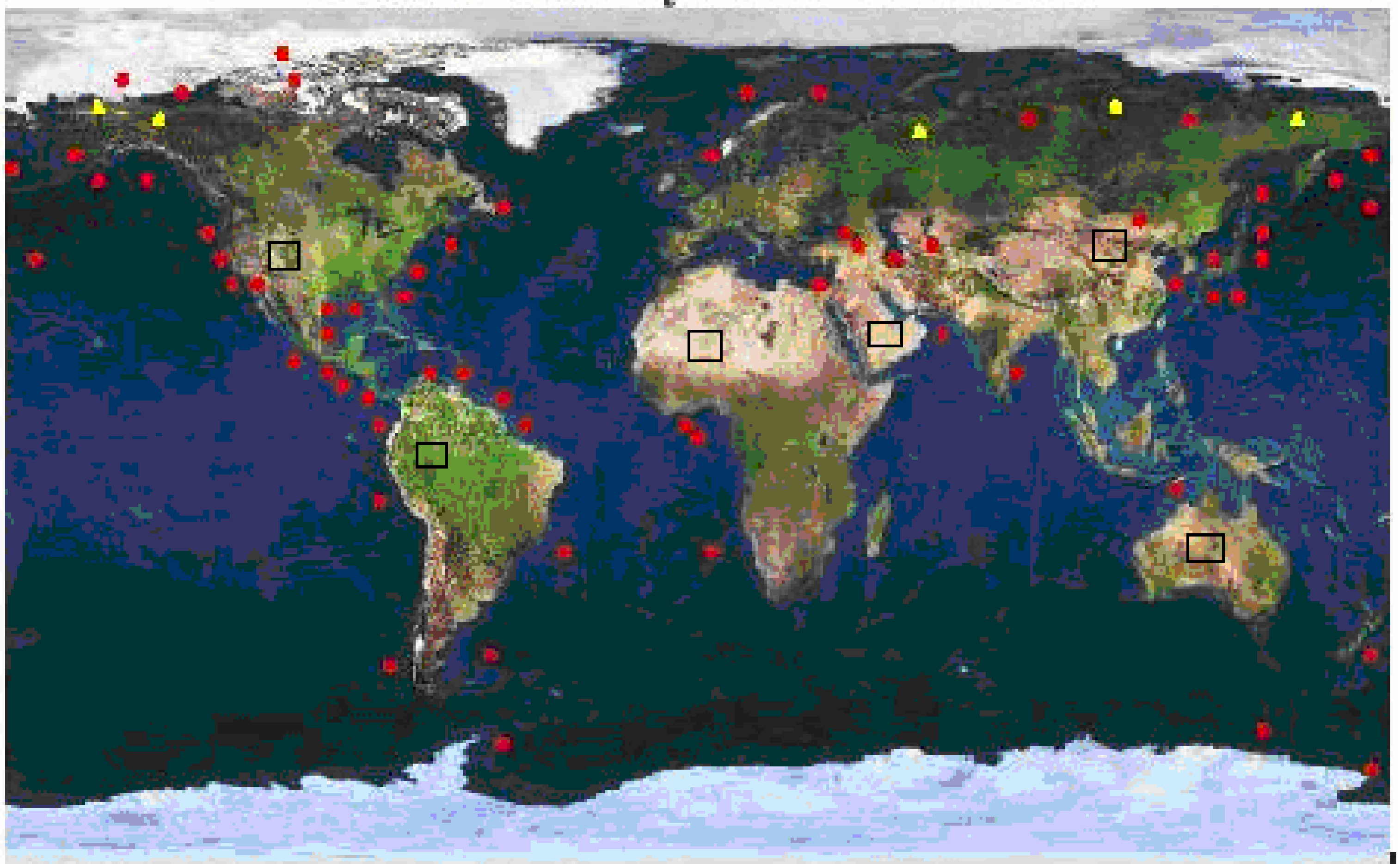
www.nasa.gov

Notes

- 80kyr cycles for CO_2 and CH_4 emissions are dwarfed by those from 1860's onward to present time
- Climate forcing Greenhouse Gases and Ice Sheets go hand in hand (compare the cycle periods) Ice heat of fusion factor in planet thermal response
- Metrics for Dangerous Change in planet Earth sources of data used to determine planet security alert [(Plant, Animal), (Ice, Sea Level), Climate]
- Extinction does not necessarily mean human, but could : Sea floor, ice, permafrost, stability issues
- Business as usual (BAU) is not an acceptable scenario as it impacts land surface and ocean temperatures which in turn impacts planet stability

National Aeronautics and Space Administration

Gas Hydrates (Clathrates), Solar & Biomass Locations



Gas Hydrate Locations in Ocean Sediment and Permafrost

ΔT_{Earth} Warming most prevalent in Northern Hemisphere

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

www.nasa.gov

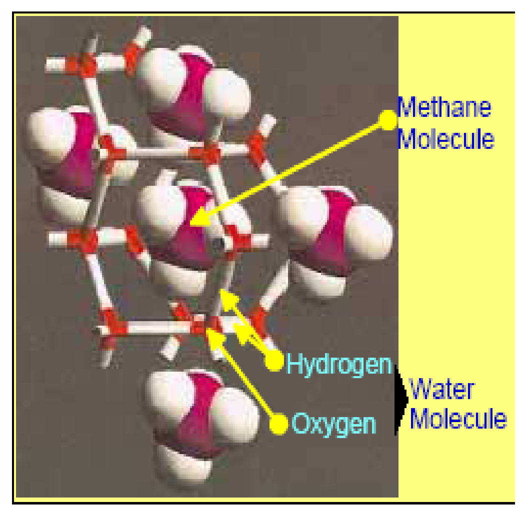
Global Energy Sector Response

Biotic theory petroleum (fossil): limits reserves perhaps 50 years
Abiotic theory hydrocarbon formation supports continuous oil formation deep within earth mantle: no finite bounds

Glaciered ice melts, rise in ocean temperatures and ocean levels impacts stability of methane hydrates, ocean floors, the coastal industrial and aviation complex and specie survival

Methane release (10 to 20 times more detrimental than CO_2)

Figure 1: Burning Methane Hydrate in the Lab. [1]



Notes

- Methane hydrates surround the Americas and Japan coastal regions and are distributed in the permafrost regions of the Northern Hemisphere (and maybe pervasive elsewhere ?)
- Methane hydrates are deep in the ocean or permafrost [150m to 1350m] and are extensive, but shallower or deeper in the Earth, they become gaseous as the temperature-pressure will not support clathrate or ice cage structure.
- At present geological time methane hydrates are stable to marginally stable within rock like structures or domes on ocean floor or permafrost regions
- Current mining (methane recovery) is by warming the hydrate or drilling through a gas dome of unknown pressure [major sealing issues]
- BAU-Global warming will eventually release methane which is 10 to 20 times worse than CO_2 as a greenhouse gas
- Methane Hydrate Stability Impacts Ocean Floor Stability

Ocean Floor Stability Disaster Example: 6200BC, 4000 $(km)^3$ slide off Norway sent 15m tsunami to Scotland and 90 000 $(km)^2$ muddy mid-Atlantic ocean (near shore residents and aquatic life probably would not have survived) http://www.discover.com/issues/mar-04/cover/?page=5 **(access 13Nov06)**

Global Energy Sector Response (cont'd)

- Nobel Laurent Prof. Richard E. Smalley (2005) proposed

• six 3.3 TW-year solar energy sites would meet energy demands of all nations (TW = 10^{12} W) {map squares}

• 100km x 100 km site 10.6 kW-hours/m^2/day at 10% solar cell efficiency and 50 year life

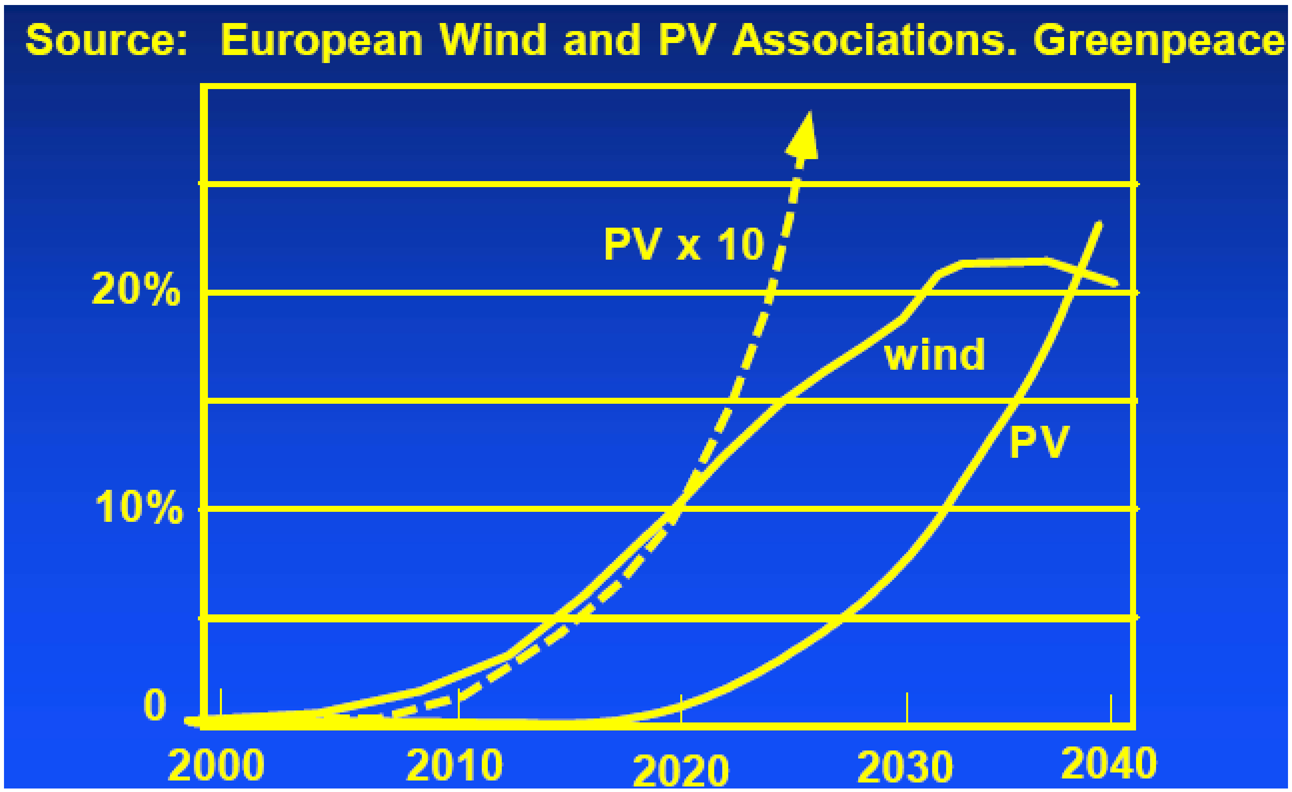
• \$3.50/W (\$300/m^2) to \$1/W (\$90/m^2) [10% cells]
• 3.3 TW-year PV cost (\$1 to \$3 trillion) or
8.5% < [PV-Cost]/GDP(2001) < 25.5% **(US GDP \$11.75 trillion)**

- Oil & Gas industry \$6 trillion : Energy Industry \$16 trillion, capital investment
- algae beds (20kgal-biodiesel/acre/yr) 20 X Smalley site. Can use brackish or fresh water, pond or column systems

Alternative Renewables

- Alternative Renewable Energy Sources Solar Wind. Diffuse yet pervasive; can supply ALL global energy
- Large land areas required mostly desert type where solar is prevalent (see squares on figure)
- Require less land than Algae Farms growing in fresh or brackish waters (ponds/columns) can capture CO_2
- Less expensive than pursuit of petroleum yet requires will of people of Earth to happen
- Renewable, diffusive PV and Wind energy sources are growing in Europe

Global Energy Sector Response (concl)



Stratospheric Sulfur Injection Global Cooling Switch

- "Pollution particles affect health and lead to more than 500,000 premature deaths per year worldwide. Through acid precipitation and deposition SO_2 and sulfates also cause various kinds of ecological damage" Paul J. Crutzen (Nobel Laureate)

- Crutzen's climate engineering involves
  - Injection of 1-2 Tg S (1 T gram = 10^9 kilogram)
  - SO_2 and sulfates formed reflect incident solar, cooling planet

Yet consider these issues.

- Reason for S removal
  - Reduce premature deaths - human and animal
  - Alleviate acid rains that destroy forests – plant matter

- Increasing S decreases biomatter CO_2 absorption

  Increasing CO_2 increases GHG warming, requiring more S release ?

- "The very best would be if emissions of the greenhouse gases could be reduced so much that the stratospheric sulfur release experiment would not need to take place. Currently, this looks like a pious wish." Paul J. Crutzen (Nobel Laureate)

- Experiments are to prove concepts - outcome uncertain

Notes

- **Crutzen's climate engineering involves stratospheric injection of 1-2 Tg S over 1-2 year planetary (cooling/warming switch)**
  Estimated costs are $25B-$50 B per injection; no cost basis provided.

- **Anthropogenetic effects are implied heat/cool control, yet unknown**
- **Implication of planet cycle lag response time could prove as extinction spiral.**

- **Freshwater addition and dilution of northern (southern) ocean salinity "stalls" warm equatorial current drivers and alter biomass production in ocean and costal areas. Hatun et al., Curry et al., realclimate.org : Global warming turns Global cooling.**

- **Policy makers Energy options - maintain business as usual (BAU), alternate scenario (AC), investing in solar farms provide long and short term energy. On these issues all life forms are involved; no one, including policy makers will be exempt.**

- **Social policy option, maximize profit or how many lifted from poverty, Energy policy option 6 solar stations supply world energy demand [policy options of Nobel Laureates, Muhammad Yunus (social) and Richard Smalley (global energy)]**

Crutzen, P.J. (2006) Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma?, An Editorial Essay, Climatic Change 77(3-4), Aug , pp 211-219.

Hatun H., Sandø A.B, Drange H., Hansen B. & Valdimarsson H. (2005) 'Inlfuence of the Atlantic Subpolar Gyre on the Thermocline Circulation', *Science*, vol 309, 1841-1844

Curry R. & Maurtizen C. (2005) 'Dilution of the Northern North Atlantic Ocean in Recent Decades', *Science*, vol 308, 1772-1774

http://www.realclimate.org/index.php/archives/2005/10/saltier-or-not/

Potential Global Energy Sector Response

1. Remove unstable methane hydrate sources before spontaneous release due to climate changes, convert to useful energy (work). Sequester CO_2 **(Carbon),** spent well injection? Clathrates? Plants ? Other use?
2. Move toward efficient diffuse-energy collection, conversion, storage, transmission systems
3. Increase renewable energy use, solar, wind, algae bio (general) both land and air power systems
4. Decrease hydrocarbon (“fossil” or abiotic) dependence (shift from BAU to AS)
5. Monitor shoreline dependence on global climatic changes with attendant response.

New Sealing and Fluid Flow Challenges

From tapping and capping hydrate domes to synthetic "drop-in" fuels in legacy aircraft, along with synthetic and bio fuels production, transmission, storage and use in transportation and ground based power industries, sealing and secondary flows remain key issues to their success

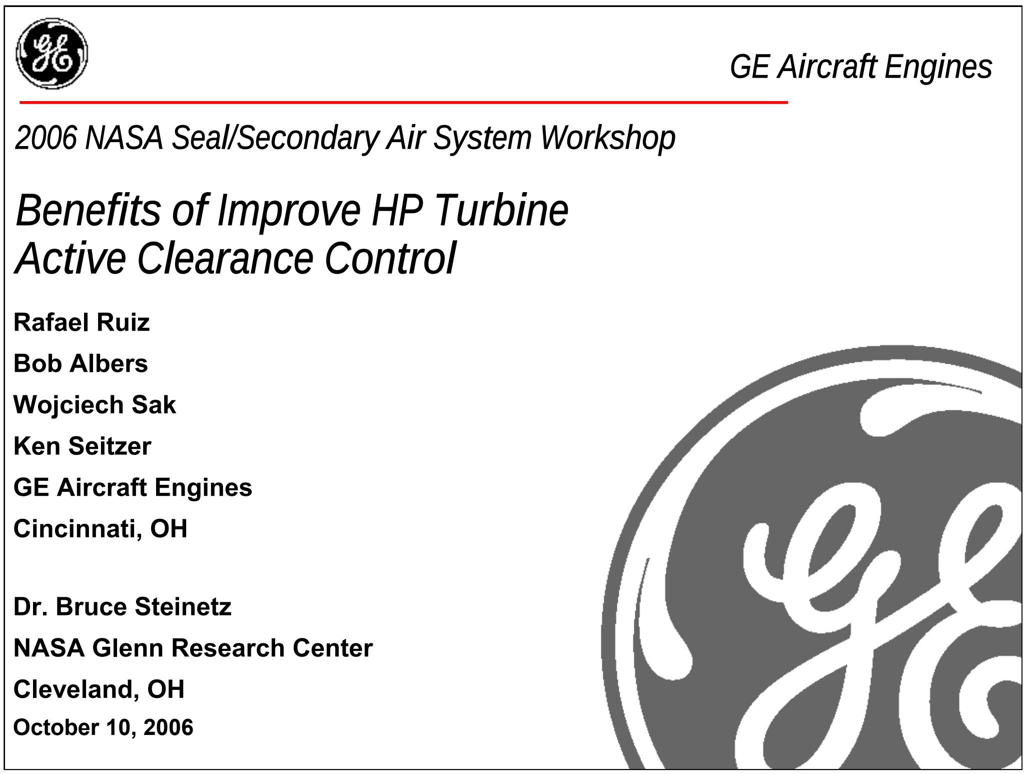
Different type of sealing issues

- Sequestering and sequestered emissions
- Deep well injection and sea-bed retention and stability
- FT and bio fuels materials compatibility
- Interface coatings, nanoparticulates, catalytic

BENEFITS OF IMPROVED HP TURBINE ACTIVE CLEARANCE CONTROL

Rafael Ruiz, Bob Albers, Wojciech Sak, and Ken Seitzer
General Electric Aircraft Engines
Cincinnati, Ohio

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



q *NASA Propulsion 21 HP Turbine Clearance Control Study*

Program Objective

Develop a high-pressure turbine (HPT) active clearance control system (ACC) to increase HPT efficiency throughout the engine operation range thereby reducing emissions.

Technical Challenges

- Minimize blade tip clearances through the entire engine operation
- Light blade tip to stator contact
- Reliable system

System Benefits

- Reduce emissions
- Reduce exhaust gas temperature during take off conditions

2 11/09/04 ***GE Aircraft Engines***

As part of the NASA Propulsion 21 program, GE Aircraft Engines was contracted to develop an improved high pressure turbine(HPT) active clearance control (ACC) system. The system is envisioned to minimize blade tip clearances to improve HPT efficiency throughout the engine operation range simultaneously reducing fuel consumption and emissions.

q *HP Turbine Active Clearance Control*

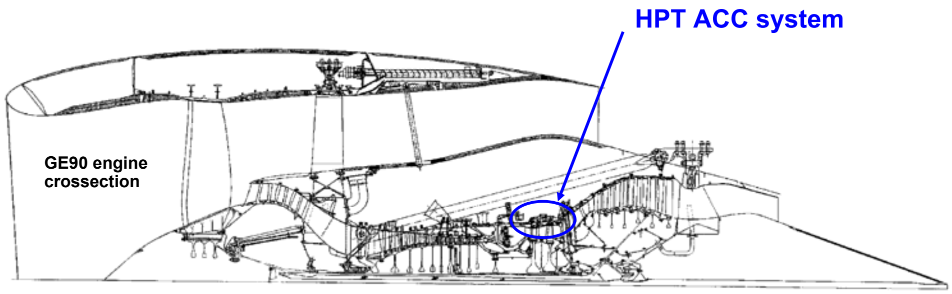
Background

- NASA HPT Propulsion 21 ACC program was worked ~ Phase I and II
  - Studied existing and potential ACC concepts
  - Benched marked systems
  - Started scoring existing system against existing systems
  - Focused study on fast acting systems
    - Thermal actuated
    - Mechanically actuated

- This presentation deals with mechanical and thermal systems

3 11/09/04 *GE Aircraft Engines*

q *Potential System Benefits for a Long Haul Aircraft*



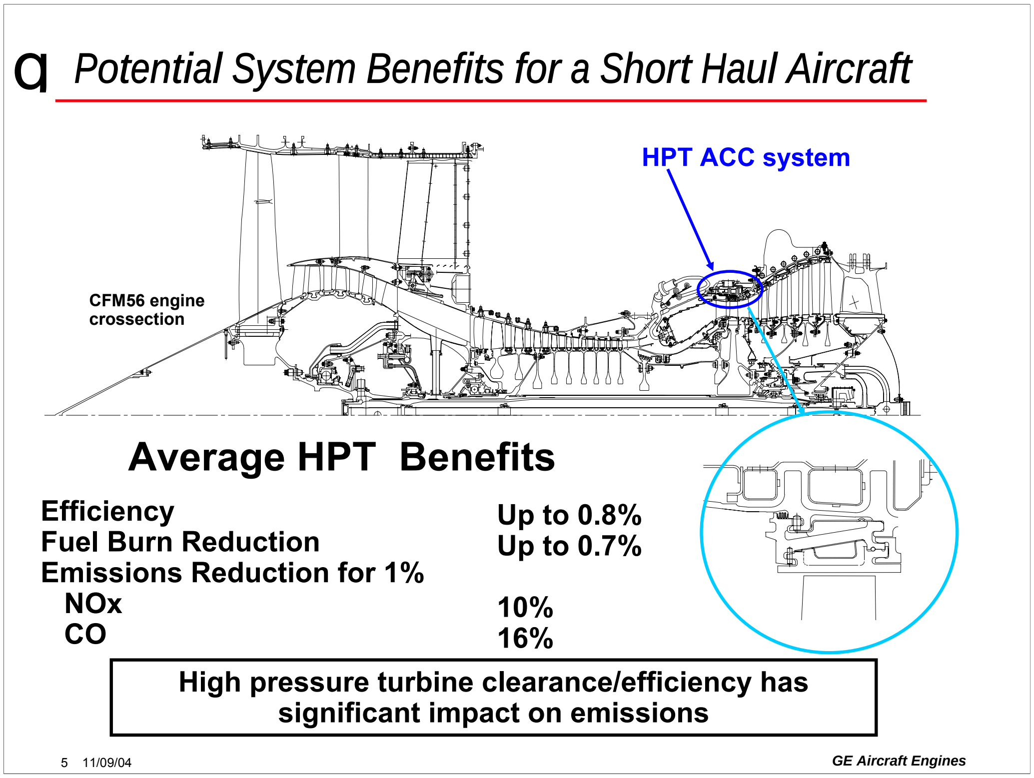
Average HPT Benefits

Efficiency	**Up to 0.9%**
Fuel Burn Reduction	**Up to 0.95%**
Emissions Reduction for 1%	
NOx	**10%**
CO	**16%**

High pressure turbine clearance/efficiency has significant impact on emissions

4 11/09/04 *GE Aircraft Engines*

This slide summarizes the potential benefits of improving the HPT ACC system on long haul aircraft engine. The HPT ACC system have the potential of increasing HPT efficiency up to 1%, depending if the engine is new or deteriorated. This efficiency gain will result in reduction of engine fuel burn and consequently emissions.



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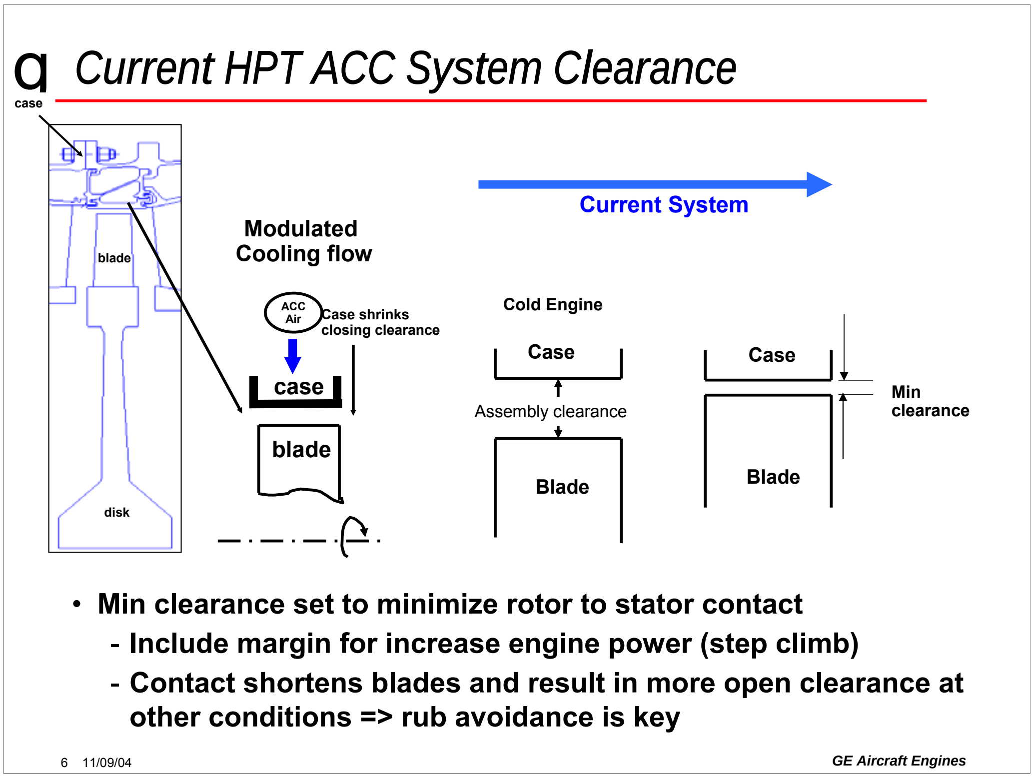
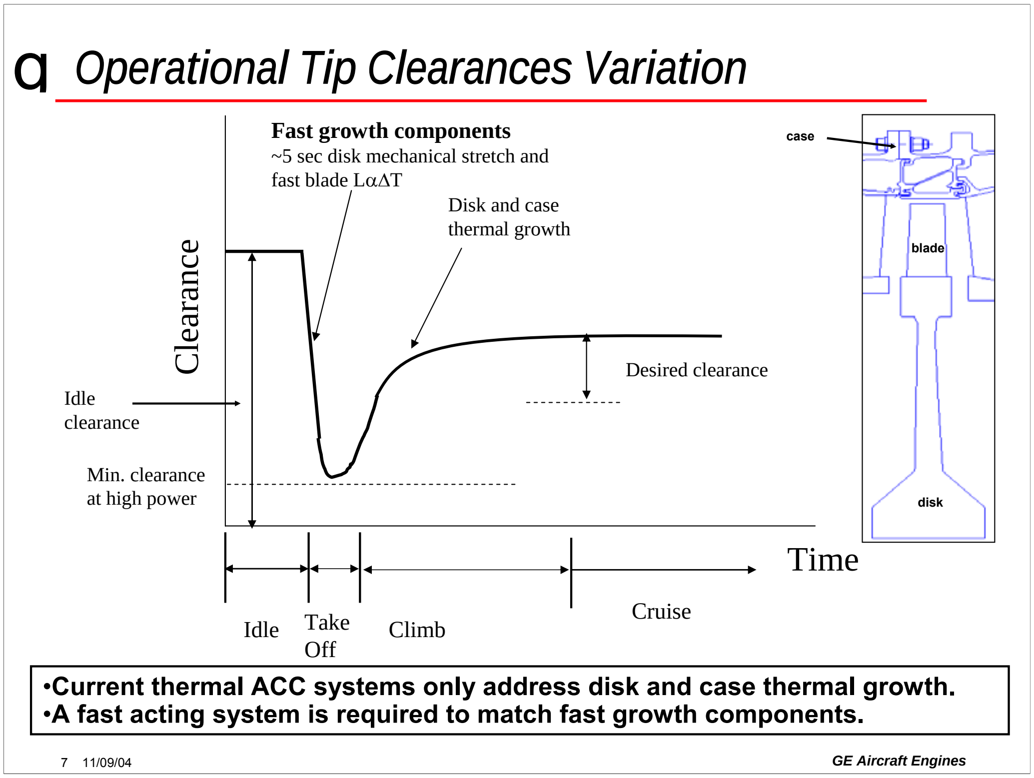


On today's engines, during engine operation, the HPT clearances are controlled by cooling the case using modulated cooling air flow. The cooling air, coming from engine bleed sources, will shrink the case, closing the clearances between rotor and case (some times called stator). The HPT modules are build with certain assembly clearances which it's magnitude depends on anticipated thermal and mechanical radial deflections of the rotor and stator during engine operation and the desired minimum clearance to protect against rubs during instantaneous increase in engine power.



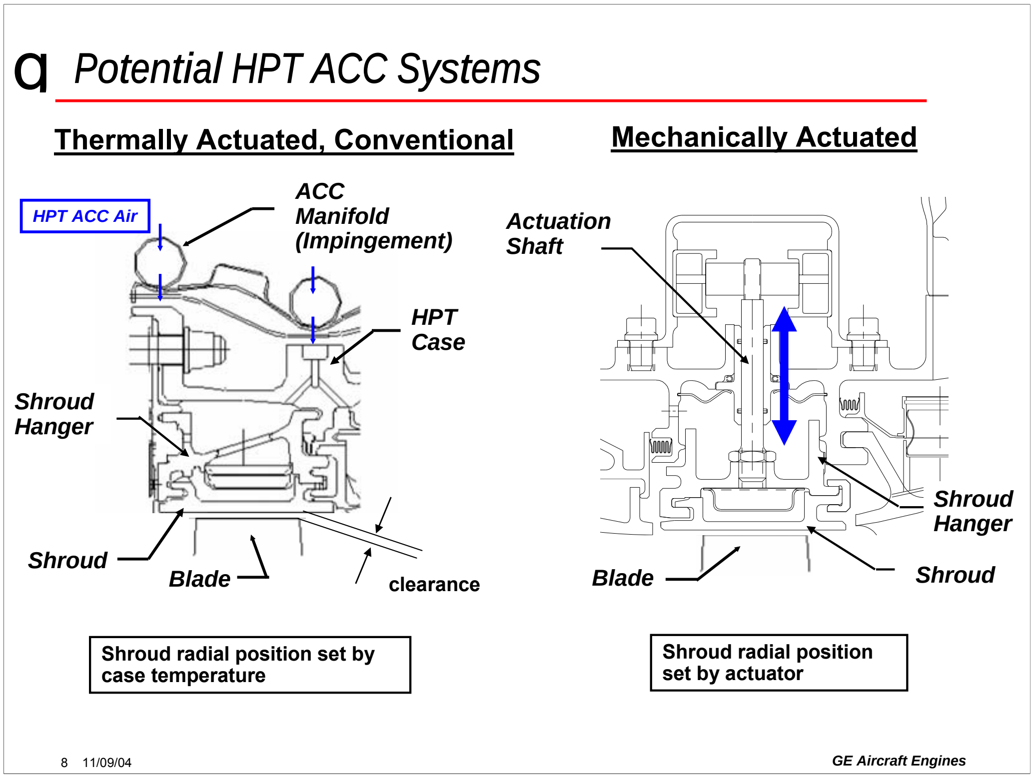
This slide shows how the HPT clearance varies overtime for idle, take off, climb and cruise conditions for a typical engine. The clearances are a function of the rotor and case thermal and mechanical radial growth.

Approximately, during the first five seconds into take off , the disk stretches mechanically and the blade expands thermally resulting in an instantaneous reduction in clearances. During this condition, the stator is not thermally fast enough to follow the rotor. Due to this reason, clearances are set more open during idle to avoid a rotor and stator contact during acceleration.

Following the initial acceleration, the stator and the disk grow thermally. At this point in time, the ACC system starts to modulate cooling air to match the case deflections with the rotor thermal deflections to minimize clearances during the thermal transient.

Once the engine reaches cruise condition, the stator and the rotor are nearly steady state and this is were the ACC air is fully used to close the clearances to maintain minimum clearances. Current HPT ACC systems are generally limited in clearance range capability.

A system the moves the stator as fast as the disk stretch and blade thermal growth is required for the HPT in order to operate near minimum clearances.



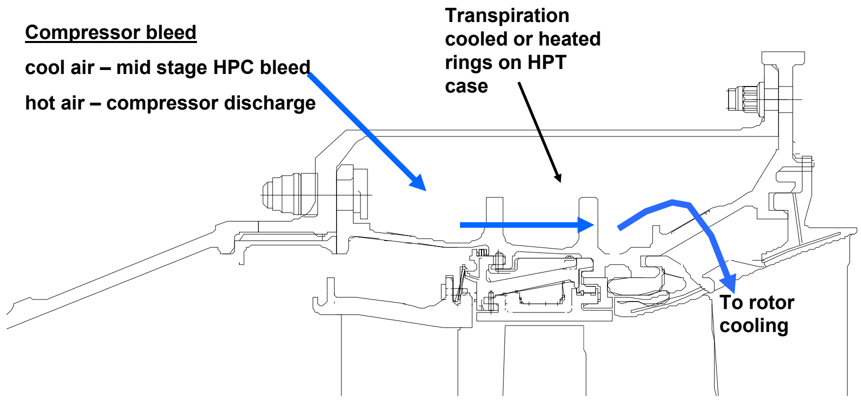
This slide gives a description of some of the ACC concepts studied, the thermal actuated and the mechanical actuated system.

Thermally actuated ACC system are used on today's production engines. In this system, the shroud, a segmented member, radial position is set by cooling the case using modulated cooling air from engine bleed sources. As was shown on previous slide, this system does not address the fast components during take off conditions. The system response is characterized by the thermal time constants.

On the other hand, the mechanical actuated system is a new revolutionary system. The concept behind this system is to control the radial position of individual shrouds by means of mechanical actuators, thereby setting clearance. This system in combination with a clearance sensor have the potential of addressing the fast components allowing the HPT to operate at near minimum clearances. The system response will depend on the response rate of the actuators.

q *Potential HPT ACC Systems –Cont'd*

Thermally actuated fast acting system



9 11/09/04 *GE Aircraft Engines*

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.

Increasing muscle – How it helps

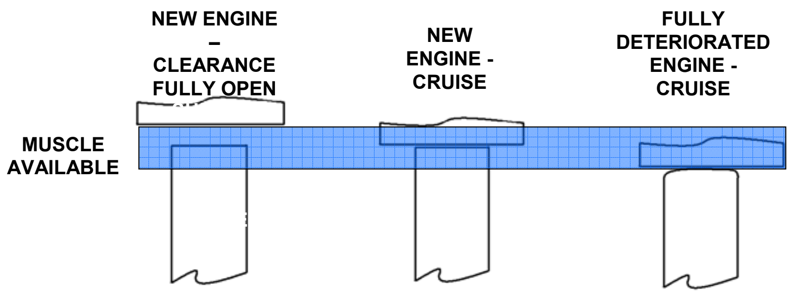
SYSTEM RANGE

•HPT CASE "MUSCLE"

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

•DETERIORATED ENGINE SYSTEM PERFORMANCE

Maintain new engine HPT clearance throughout engine life



Conventional ACC designs can use this to improve performance over time

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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

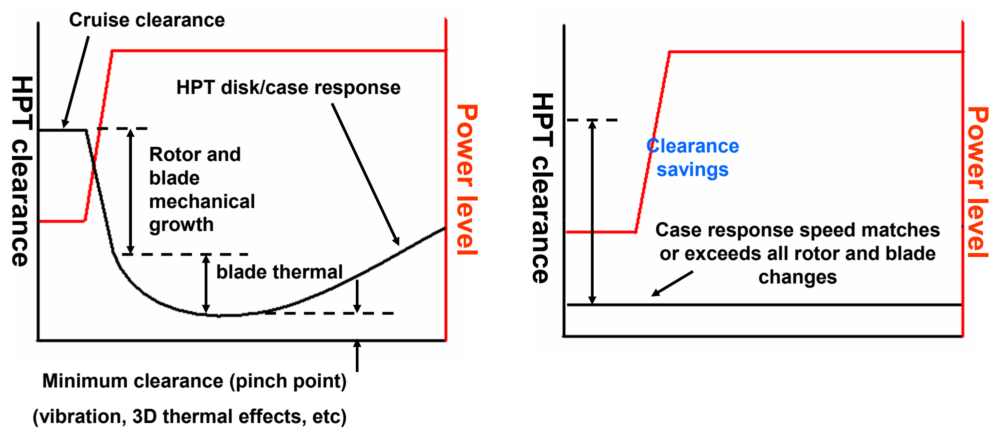
L - length of member

α – coefficient of thermal expansion

ΔT – temperature difference

Speed of Actuation – How it helps

•Deflection match throughout engine mission

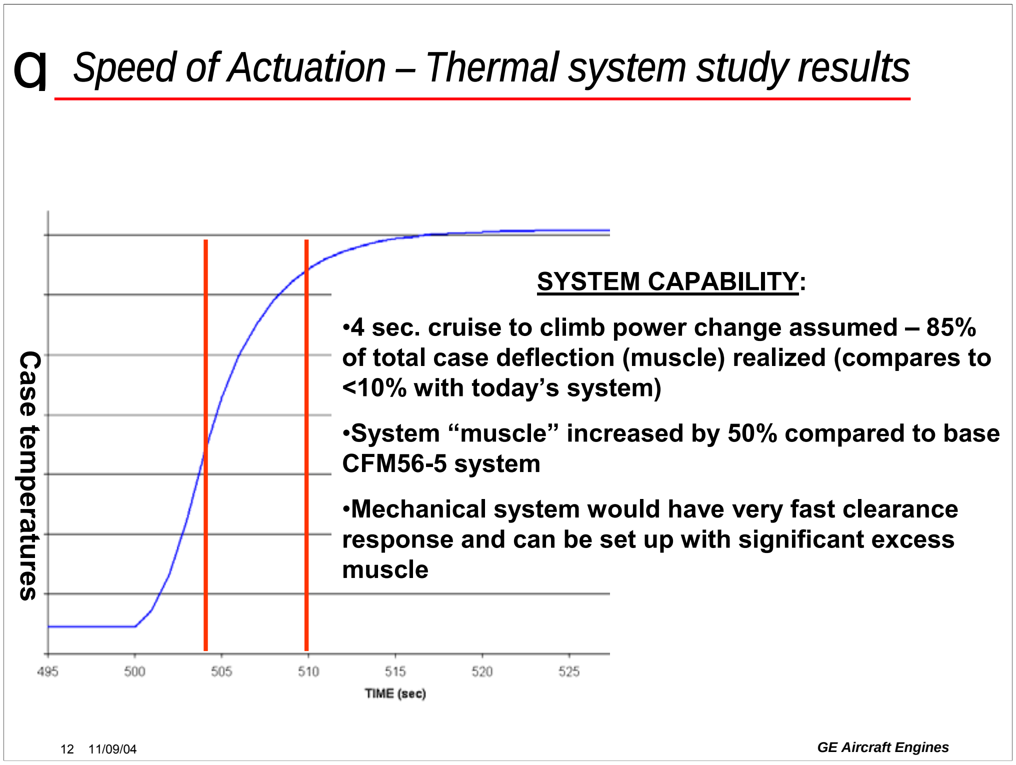


11 11/09/04

GE Aircraft Engines

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.

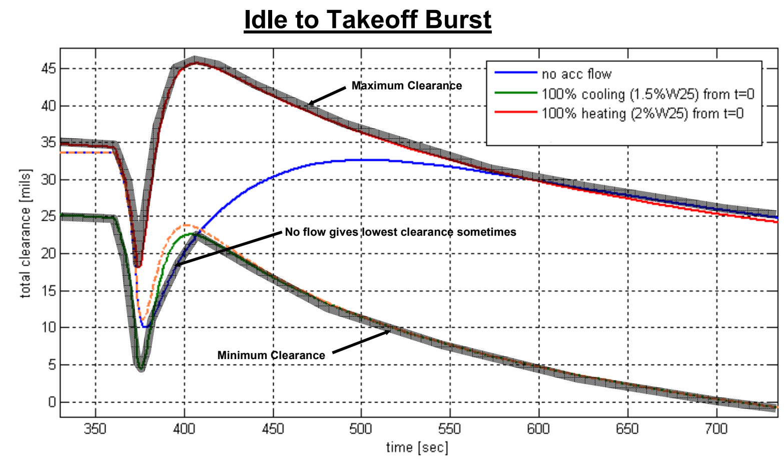


This is a result of analysis of a flight maneuver where speed was increased from cruise to climb. This type of change typically is executed to bring aircraft to a higher altitude. The reason for this change may be to make the flight more efficient as the aircraft burns off fuel, or to increase passenger 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 provided 44% of its entire thermal deflection range in this time. This 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.

q Control – What is the optimum Valve Schedule?

- *Fast acting system great for clearing step climb rub but less forgiving of improper valve control*



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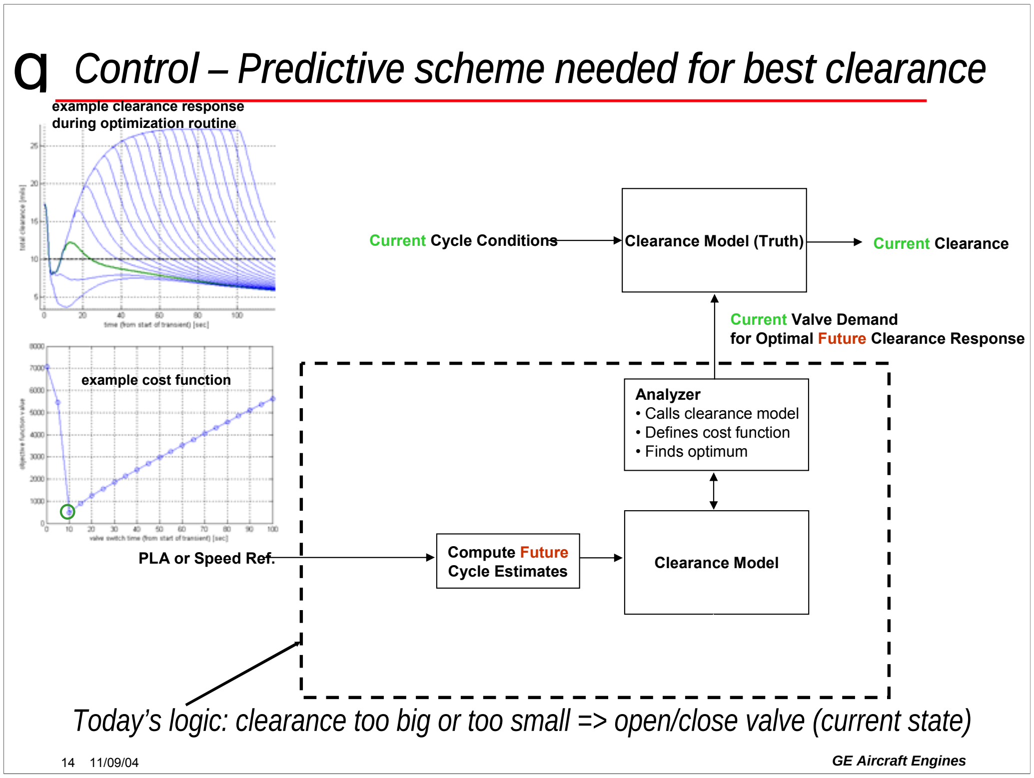
Control – Predictive scheme needed for best clearance
example clearance response
during optimization routine
example cost function
Current Cycle Conditions
Clearance Model (Truth)
Current Clearance
Current Valve Demand
for Optimal Future Clearance Response
Analyzer
• Calls clearance model
• Defines cost function
• Finds optimum
PLA or Speed Ref.
Compute Future
Cycle Estimates
Clearance Model
Today's logic: clearance too big or too small => open/close valve (current state)
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q Summary

- HPT clearance can significantly reduce fuel burn & emissions
- Current HPT ACC systems have potential for improvement
  - Fast thermal has most potential as next evolutionary step for aircraft
  - Fast mechanical could be used on land-based applications (wt)
- Additional work required to develop optimum systems
  - Work details of design
  - Rig test to demonstrate the system capability
  - Develop clearance sensor to reduce analytical uncertainty
  - Develop the control logic for the system
  - Engine demo test

15 11/09/04 **GE Aircraft Engines**

HIGH TEMPERATURE INVESTIGATIONS INTO AN ACTIVE TURBINE BLADE TIP CLEARANCE CONTROL CONCEPT

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University of Toledo
Toledo, Ohio

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

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

High Temperature Investigations into an Active Turbine Blade Tip Clearance Control Concept

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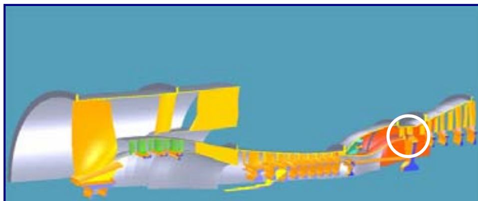
Mechanical, Industrial, and Manufacturing Engineering
Bruce Steinetz
NASA Glenn Research Center, Cleveland, OH
Structures and Materials Division
Jay Oswald
J&J Technical Solutions, Cleveland, OH

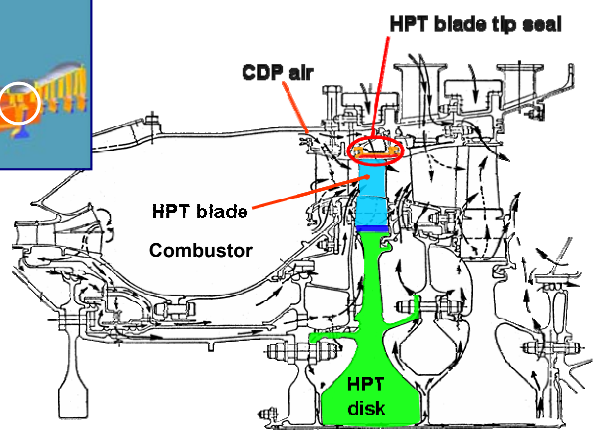
THE UNIVERSITY OF TOLEDO

Propulsion 21

Active Clearance Control (ACC) Objective

- Develop and demonstrate a fast-acting active clearance control system to:
  - Improve turbine engine performance
  - Reduce emissions
  - Increase service life

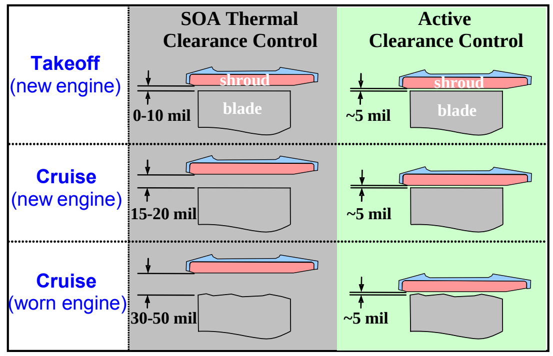




System studies have shown the benefits of reducing blade tip clearances in modern turbine engines. Minimizing blade tip clearances throughout the engine will contribute materially to meeting NASA's Ultra-Efficient Engine Technology (UEET) turbine engine project goals. NASA GRC is examining two candidate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

Benefits of Blade Tip Clearance Control

- **Fuel Savings & Reduced Emissions**
  - 0.010” tip clearance is worth ~0.8-1% SFC
  - Reduced NO_x, CO, and CO_2 emissions
- **Extended Life & Reduced Maintenance Costs**
  - Deterioration of exhaust gas temperature (EGT) margin is the primary reason for aircraft engine removal from service
  - 0.010” tip clearance is worth ~10 ºC EGT
  - Reduced turbine operating temperatures, increased cycle life of hot section components and engine time-on-wing (~1000 cycles)
- **Enhanced Efficiency/Operability**
  - Increased payload and mission range capabilities
  - Increased high pressure compressor (HPC) stall margin



Clearance Control Technology Promotes High Efficiency and Long Engine Life

You may ask why would we want to pursue this?

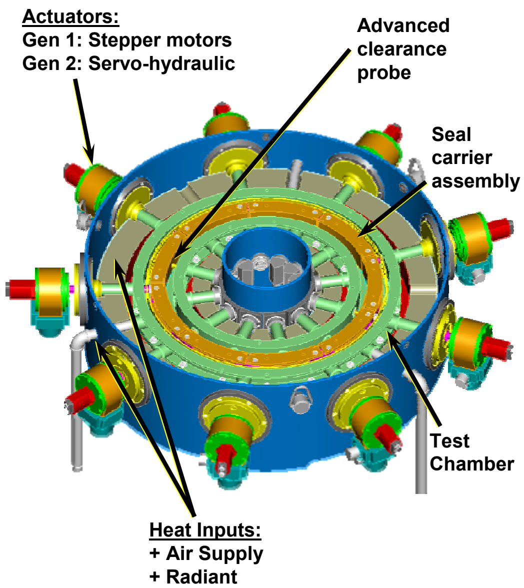
Well I am glad you asked: benefits of clearance control in the turbine section include lower specific fuel consumption (SFC), lower emissions (NOx, CO, CO2), retained exhaust gas temperature (EGT) margins, higher efficiencies, longer range (because of lower fuel-burn).

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

- Non-rotating environment for evaluating advanced seal, actuator and clearance probe concepts.
- Test conditions derived from an actual turbine engine.
- **Shroud ΔP:** 120 psig
- **Shroud backside temp.:** ~1200°F
- **Nominal stroke:** 0.190 in.
- **Nominal stroke rate:** 0.010 in./s
- **Clearance probes**
  - Current: Capacitance
  - Future: Microwave



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:

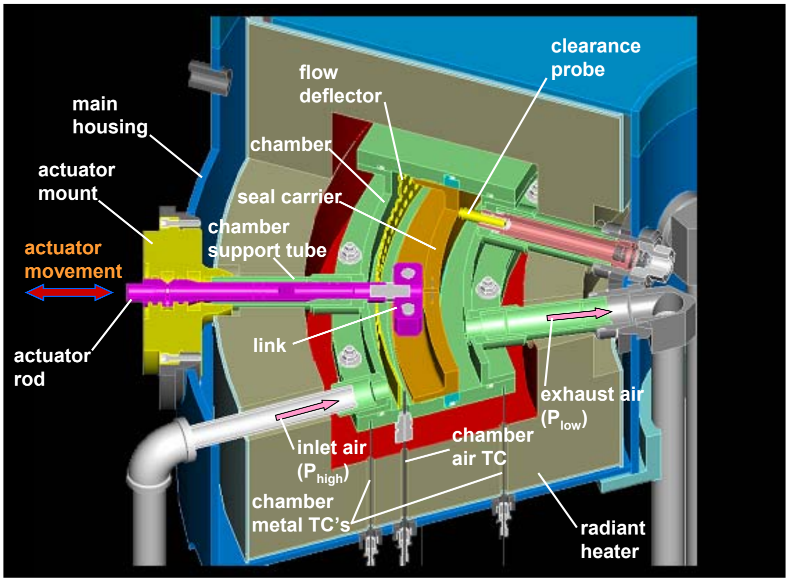
+ Individual component seal leakage rates and to compare them to an industry reference level at engine simulated pressures but at ambient temperature. High temperature tests are planned in the future.

+ Evaluate system leakage both statically and dynamically

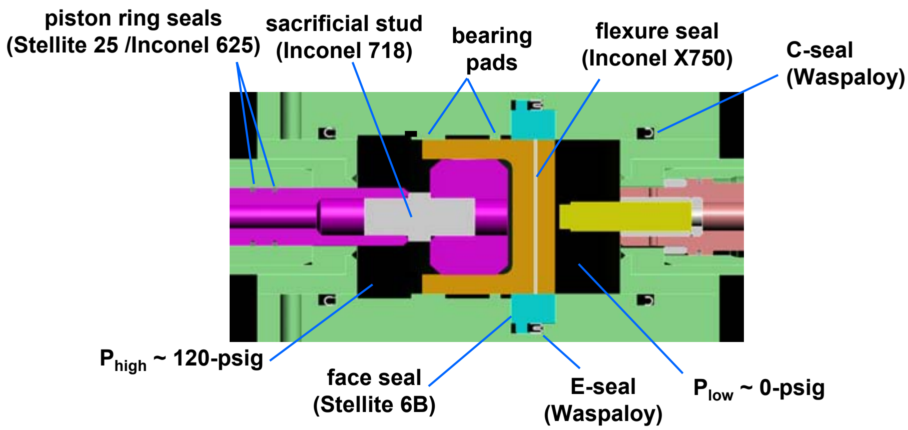
+ Evaluate candidate actuator's ability to position the seal carriers in a repeatable fashion

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

ACC Test Rig Components



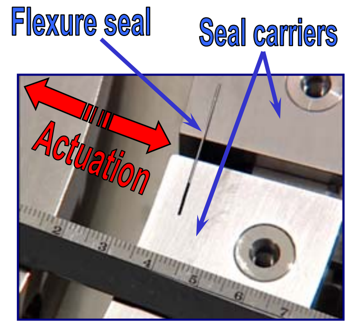
ACC Test Rig - Secondary Seals



Rig secondary seals maintain significant backpressure and create the desired P3 pressure differential across the seal shroud.

Test Rig Kinematics

ACC Test Rig With Cover Plate Removed



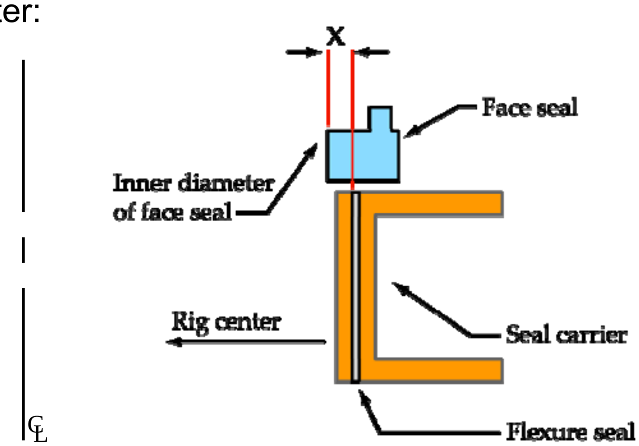
- Outward radial motion dilates the seal shroud.
- Inward radial motion contracts the shroud.

Study Objectives for Recent Testing

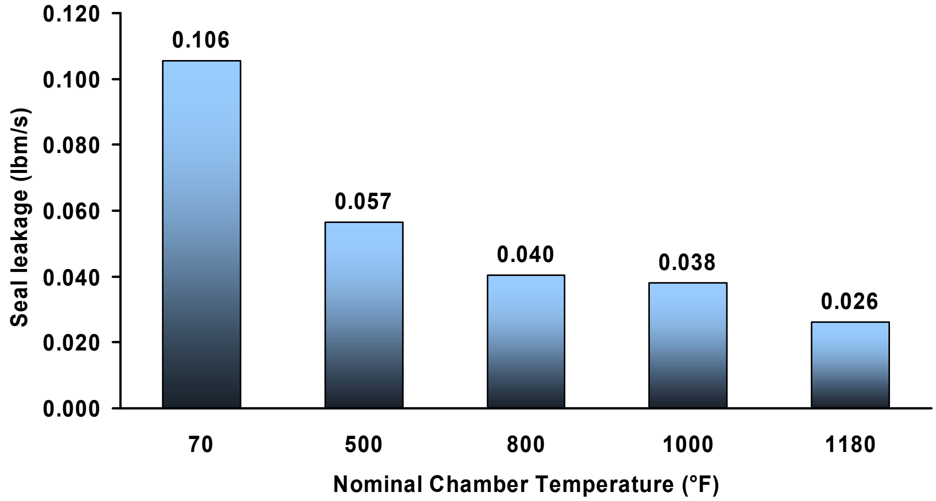
- Determine dependence of system leakage on:
  - Test pressure, temperature
  - Seal carrier position
  - Seal carrier direction of motion (inward vs. outward)
  - Actuation rate
- Quantify performance of the new servo-hydraulic actuators
  - Evaluate individual actuator accuracy and repeatability.
  - Evaluate system's ability to track simulated flight clearance profiles at full chamber pressure and temperature, utilizing closed-loop control with capacitance clearance sensors.

Test Procedures

- Test temperatures ranged from RT to ~1200°F (engine T3).
- Test pressures ranged from 60 to 120 psig (full engine ΔP).
- Hydraulic actuators evaluated on bench-top and on rig.
- Seal carrier position results presented in terms of "X" parameter:

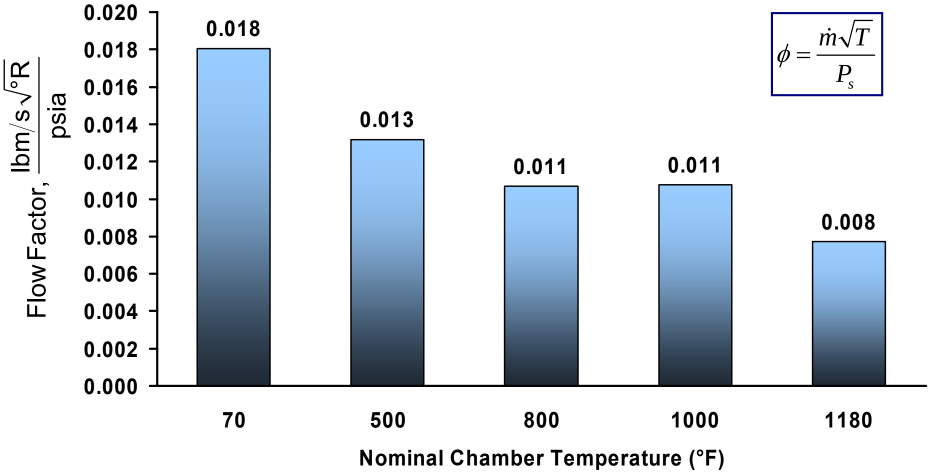


System Leakage vs. Temperature



Static leakage decreases with increasing temperature.

Flow Factor vs. Temperature



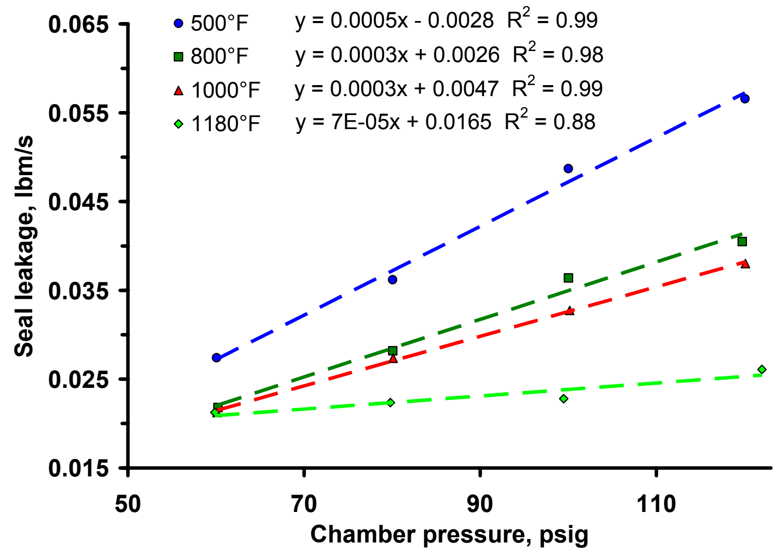
$$\phi = \frac{\dot{m}\sqrt{T}}{P_s}$$

<u>Flow factor generally decreases with increasing temperature:</u>

Increased test temperature results in:

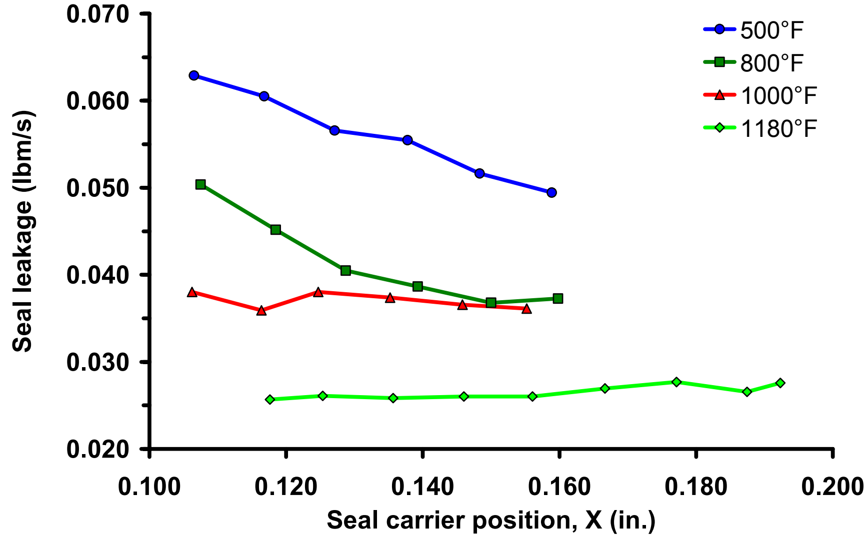
- Reduced secondary seal clearances
- Increased gas viscosity

Leakage Dependence on Pressure



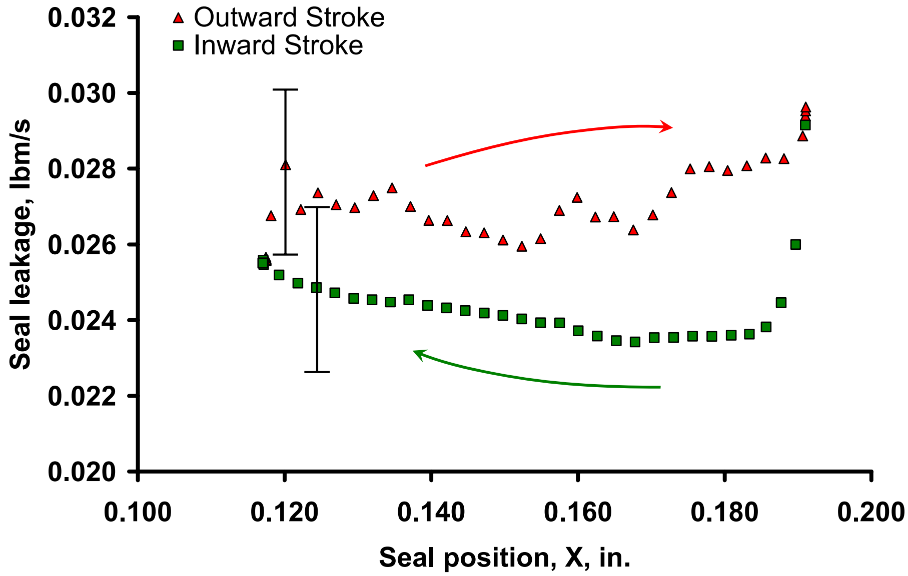
Static leakage: Linear dependence on pressure.

Leakage Dependence on Seal Carrier Position

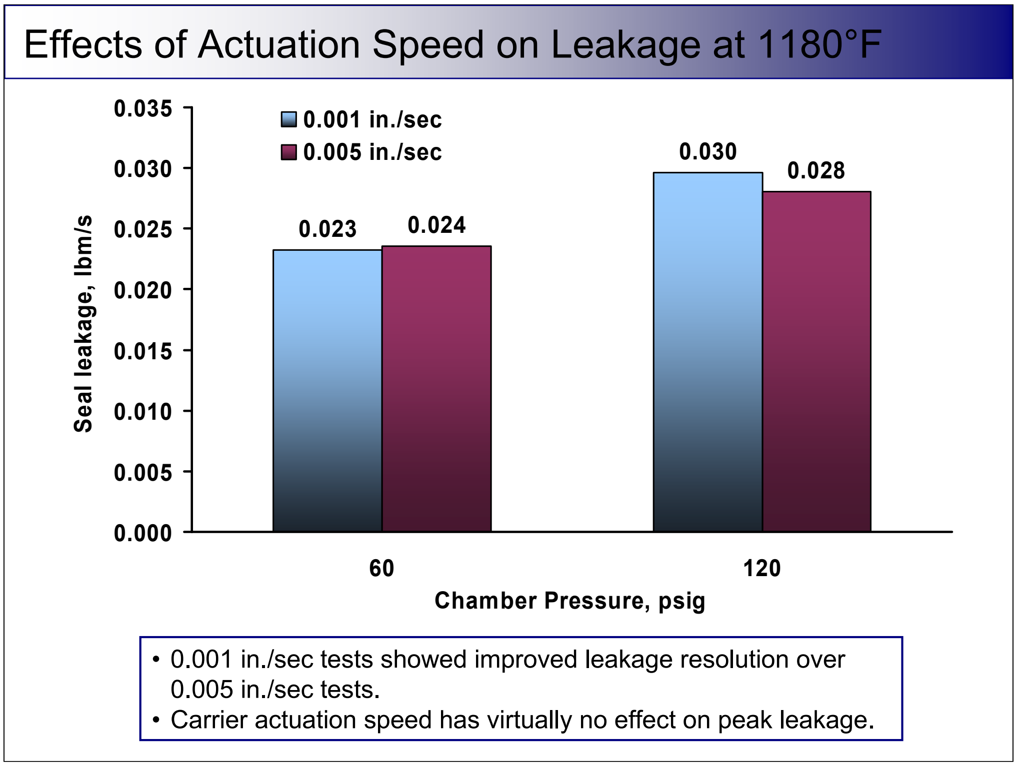


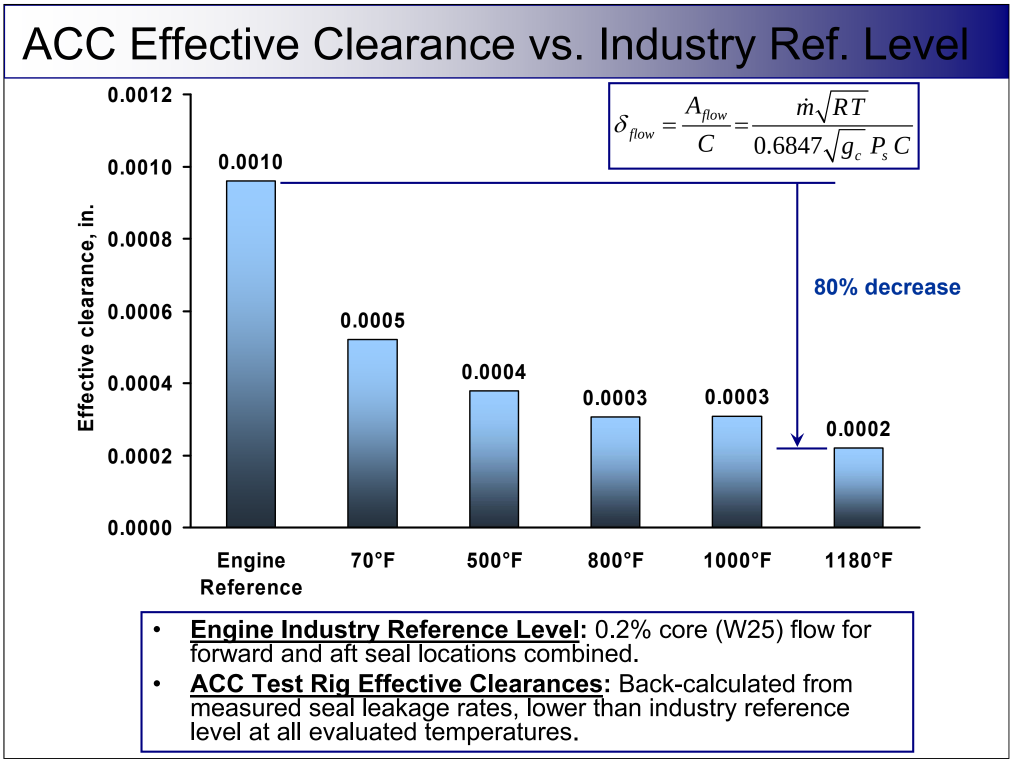
- At 500 and 800°F, leakage slightly lower at outward positions (larger X).
- Virtually no leakage dependence on position at 1000 or 1180°F.

Direction of Motion Effects at 1180°F



Overlap of leakage error in data sets indicates direction of motion has virtually no effect on leakage at 1180°F.

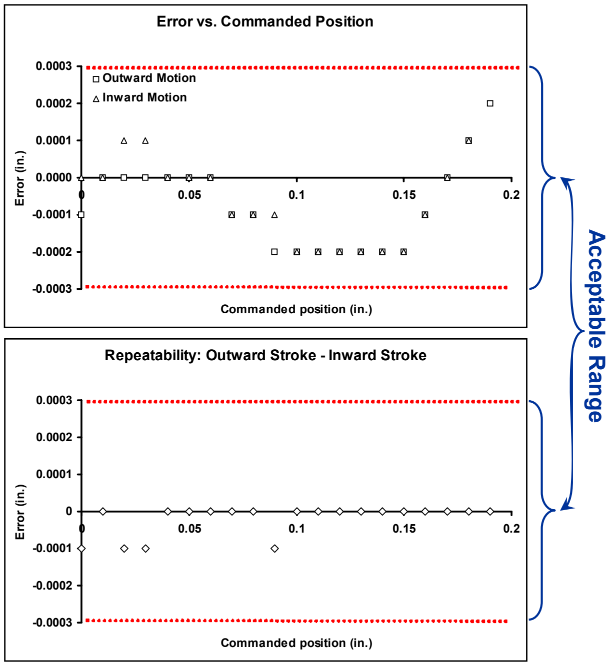

Effects of Actuation Speed on Leakage at 1180°F
0.001 in./sec
0.005 in./sec
Seal leakage, lbm/s
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0.023
0.024
0.030
0.028
60
120
Chamber Pressure, psig
• 0.001 in./sec tests showed improved leakage resolution over 0.005 in./sec tests.
• Carrier actuation speed has virtually no effect on peak leakage.

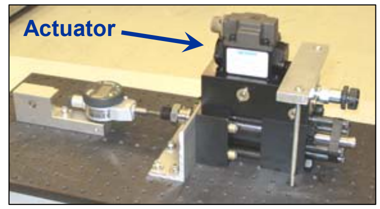


If one were to idealize the ACC system as an elastic structure (e.g. a rubber ring or band) that could move radially inward/outward, seals would only be required between the sides of the moving structure and the surrounding static structure. Engine designers have acknowledged that seals in these areas 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.

Actuator Positional Accuracy and Repeatability Tests





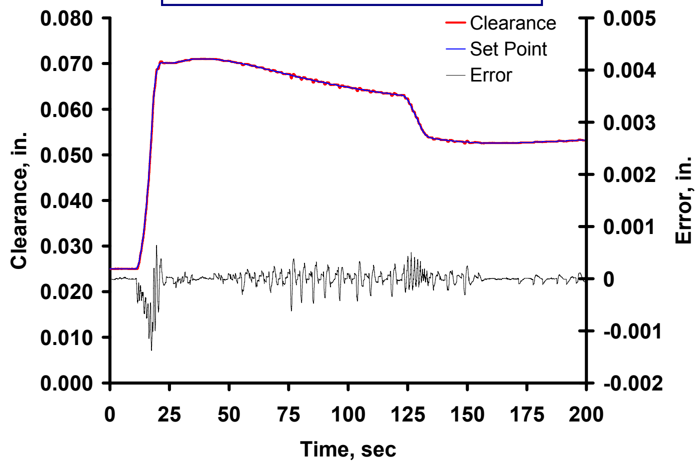
Actuator on Precision Test Fixture

Error vs. Commanded Position
Measured positional accuracy of ±0.0002 in. over 0.190 in. stroke range.

Measured Repeatability
≤ 0.0001 in. difference between outward and inward strokes for one cycle shows repeatability with virtually no hysteresis.

Simulated Take-off Engine Clearance Transient

Test Conditions: 1180°F, 120 psig



- **Actuators tracked the set point well.**
  - **Maximum lag (-0.0014 in.) occurred during 0.010 in./sec clearance increase.**
- **Due to 25 Hz control loop update rate, minimum possible error for 0.010 in./sec transient is 0.0004 in.**
- **Production control system using dedicated processor would easily reduce actuation error to <0.001 in.**

Conclusions

- System leakage:
  - Increases linearly with increasing pressure.
  - Decreases with temperature.
- Seal carrier position does not affect leakage at test temperatures ≥1000°F.
- Leakage dependence on seal carrier direction of motion negligible at elevated temperatures (≥1000°F).
- Actuation rate did not influence observed peak leakages.
- ACC effective clearance only 20% of industry reference level at 1180°F.
- Servo-hydraulic actuators accurate to ±0.0002 in. over 0.190 in. stroke range with a repeatability error of ≤ 0.0001 in.
- ACC system tracked simulated take-off flight clearance profile with ≤ 0.0014 in. error.

New Test Chamber Fabrication

New pressure vessel benefits:

- Overcomes weld-cracks found in existing pressure vessel
- Permits higher temperature operation for longer time periods

Shrink Fit of Tubes

Hydro Test of New Chamber

Acknowledgement

- Richard Tashjian, QSS

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MICROWAVE BLADE TIP SENSOR: AN UPDATE

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Vibro-Meter

Microwave Blade Tip Sensor: An Update

2006 NASA Seal/Secondary Air System Workshop
November 14, 2006

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Contents

- System Overview
- Probe Testing
- Measurement Accuracy and Testing
- Current System Status/Future Work

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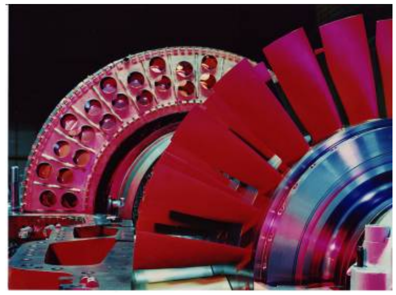
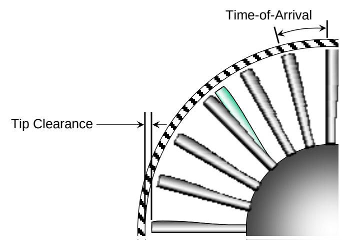
Microwave Displacement Sensor Overview

- Non-contact measurements
  - Tip clearance
  - Blade time of arrival
- Key Technology Features
  - First stage turbine environment (1300°C+ gas path using bleed air cooling)
  - "See through" combustion products, flaming natural gas, steam, etc.
  - Individual measurements from every blade
  - One size fits all (not limited by 1.5 times diameter)





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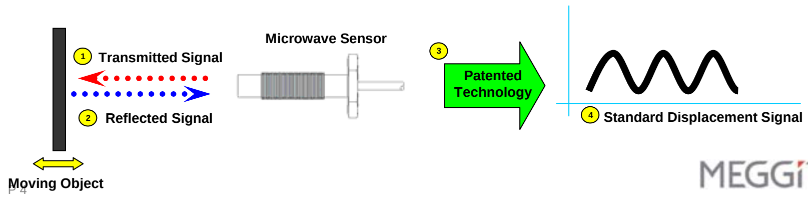
Technology Overview

- Electrical Performance
  - Phase-based microwave technique
  - Measures distance smaller than the transmitted wavelength (~5 cm)
  - High signal to noise ratios (active system)
  - Large bandwidths- able to measure waveforms at all speeds (turning gear to full RPM)
- Measurement
  - Resolution less than 0.025 mm
  - Large displacement ranges (up to 13 mm)
  - Self-calibration to eliminate effects of thermal growth



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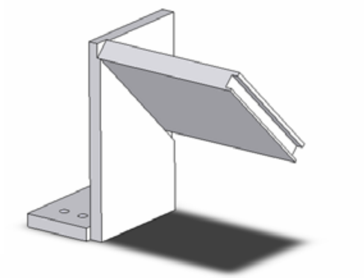
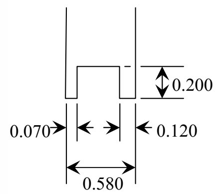
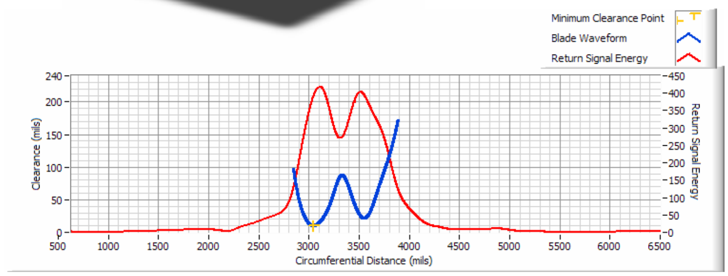
Example Measurements







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T2000 Rack Based System

- Land-based engines and tests
  - Aerospace ground tests
  - Power generating turbines
- Up to 12 channels (one channel per card)
- Minimum & average clearance to software or analog out
- 300MB/minute waveform data streamed to disk
- Future signal processing upgrades
  - Blade vibration
  - Blade health monitoring

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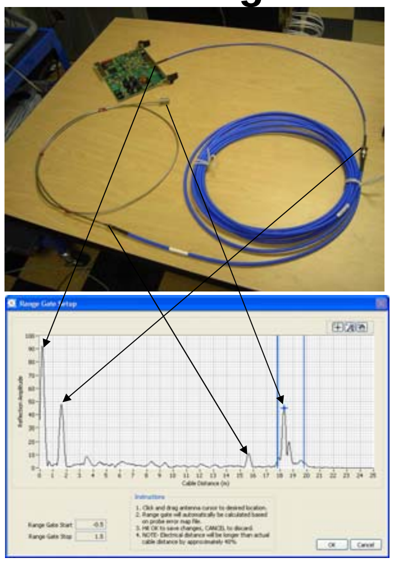
Sensor Diagnostics



- Sense changes in the cable
- Breaks in signal chain are localized very precisely—manifest as a parasitic signal return at a particular phase.
- Can be used to troubleshoot connections in the probe.
- Understand if changes are in the probe vs. in the reading.

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Sensor diagnostics is included with every product. Each connection from cable to cable is shown as a reflection visible in the TDR plot.

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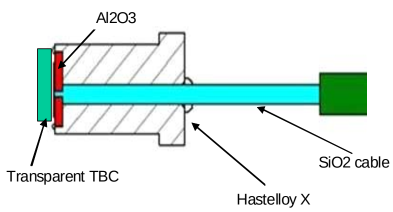
Probe



- Made from same/similar materials as first stage turbine
  - Alumina ceramics
  - Nickel-based alloys
- High temperature SiO_2 cable (900°C)
- Thermal/environmental protection of front face
- Low potential between center conductor and ground
  - No dielectric breakdown problems
- Fits into 0.5 inch hole

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Probe Testing

- Testing Focus
  - Cracking/separation due to coefficient of thermal expansion (CTE) mismatches and thermally induced stress
  - Oxidation of metal parts
- Internal laboratory testing
  - Isothermal bake to test oxidation
    - Initial 100 hour test at 800°C
    - 1000 hour interval
    - Go as long as we can
  - Thermal cycling to test CTE mismatches
    - Initial 20 cycles to 700°C
    - 300 cycles
    - Go as long as we can

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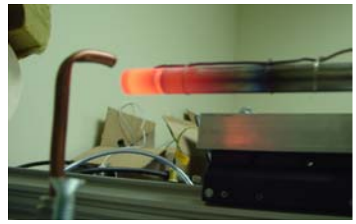
Thermal Cycling Rig

- Thermal cycling rig built to dip probe into a 900°C tube furnace
- Heat probe up slowly and then pull out to simulate a trip
- Thermocouple attached to probe for temperature monitoring
- Entire system automated to simulate a given temperature profile



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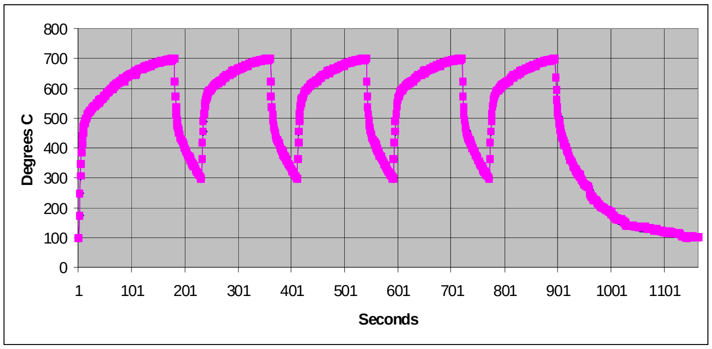
Thermal Cycling Profile

- Most rapid thermal changes seen during a trip
- Cycling profile defined similar to a engine trip condition
  - Trip with a hot restart
  - Start from a "cold" condition



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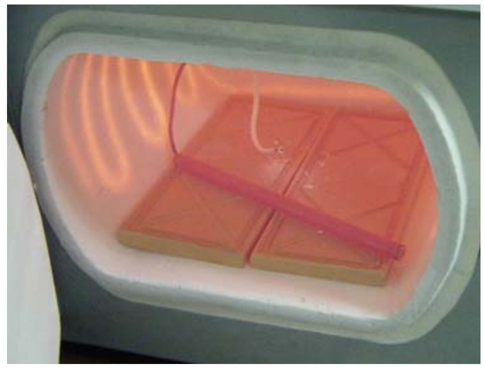
Isothermal Oven

- Oven capable of 900°C
- Hook cable up to network analyzer through instrumentation port
- Continuous logging of probe performance



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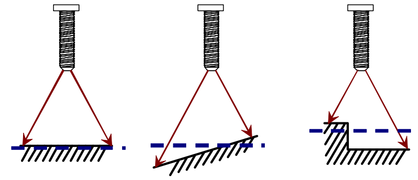
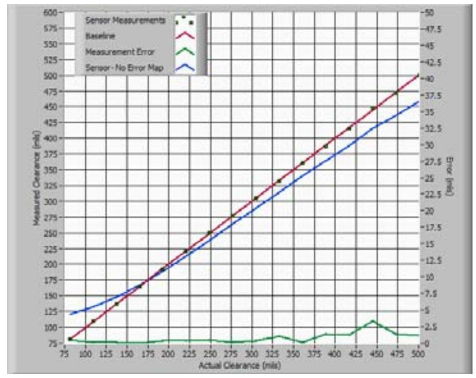
Spatial Filtering



- “Large spot size” sensors see multiple geometry features
- Measurement is a composite of everything within the spot size
- Lasers better able to approximate the true geometry, but only look at a single area- this may not be where the closest clearance is locate
- Microwave sensor measures “distance” directly but have to map the “average” clearance to the minimum clearance
- Use an error map to calibrate measured clearance to actual clearance



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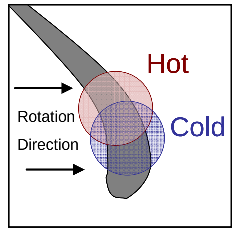
Measurement Accuracy- Axial Shifts

- Most sensors quote accuracy and linearity based upon a single calibrated target
- Real turbines have an additional complexity- axial shift due to thermal expansion and contraction of the rotor
- Geometry underneath the sensor changes
- With axial shifts, a perfectly linear sensor can give poor results
- Axial positions vary by stage and engine operating conditions
- This is probably more a problem in large frame power generating turbines than in aero applications



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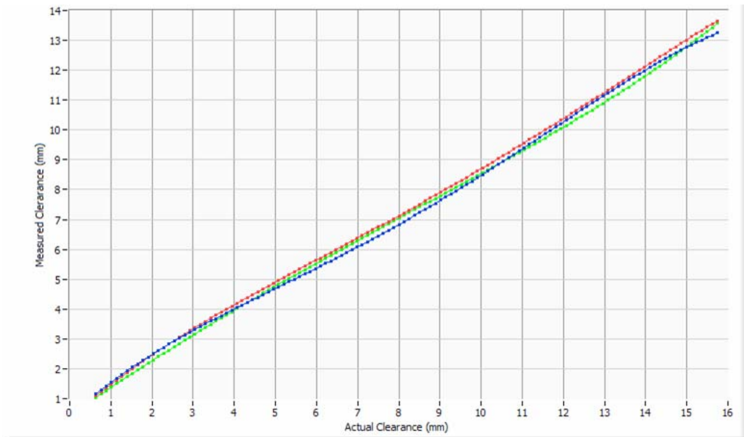
Example Changes Due to Axial Shift



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Accuracy Under Axial Shift Conditions

- Linearity could change several tenths of a millimeter across worse case axial shift conditions (large frame gas turbines)
- Signal processing techniques able to minimize this to +/- 0.1 mm or less
- Aero engine results expected to be more accurate (everything scales down)
- Continuing to investigate signal processing techniques to improve the measurement

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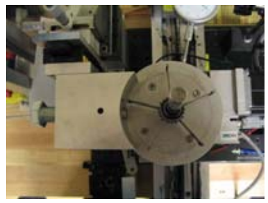
Measurement Repeatability Test



- Use rotary stage to rotate a synthetic blades in front of the sensor
- Five blades, each slightly different in height
- Rotary stage mounted on linear stage and moved to different clearances
- Look at the repeatability as function of distance

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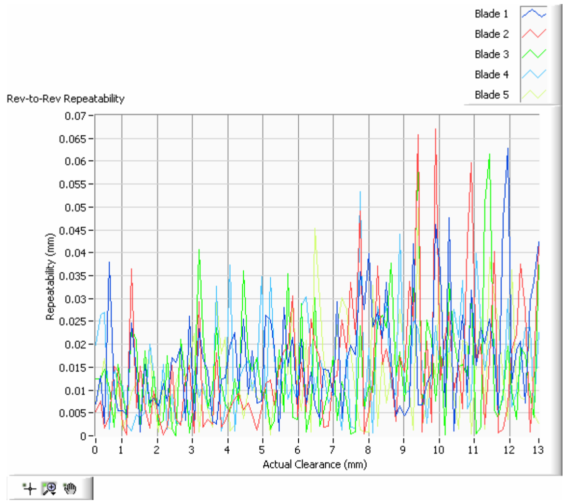
Measurement Repeatability Results



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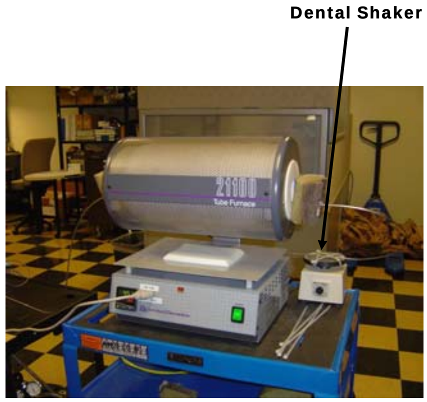
Vibration Testing

- Cable vibration can often induce extraneous signals into the measurement
- Industrial and aero turbines are vibration rich environments
- Simulate vibration and determine the effects
- Cable attached to a dental shaker
  - 60 Hz vibration frequency
  - Low, medium, high settings



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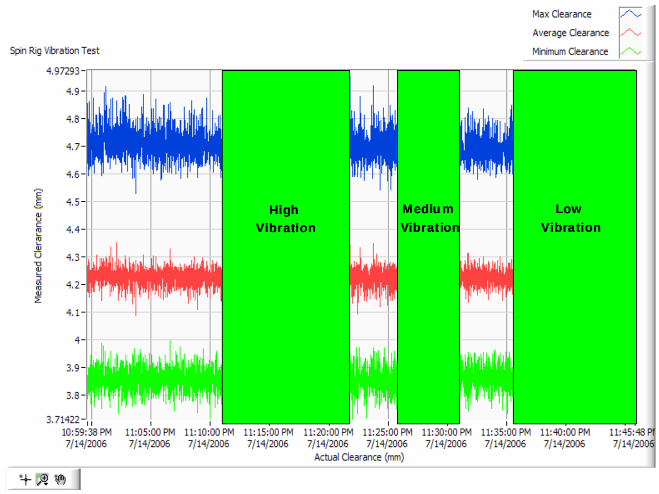
Vibration Testing- Time Domain Signal



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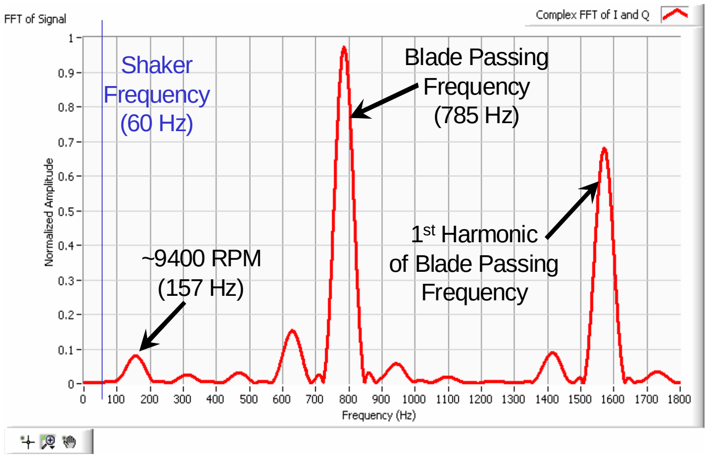
Vibration Testing- Frequency Domain



- No perceptible 60 Hz noise

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Current Status/Future Work

- Working on certifications for industrial market
- Completing next generation of probes with 12,000 hour design life Q1 2007
- Delivering prototype systems to several customers Q2 2007
- Delivered 2 channel prototype system to NASA Glenn
  - High Pressure Burner Rig testing in 2007
- Several large frame and aero gas turbines tests in 2007

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extreme environments

CONTINUED INVESTIGATION OF LEAKAGE AND POWER LOSS TEST RESULTS FOR COMPETING TURBINE ENGINE SEALS

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Continued Investigation of Leakage and Power Loss Test Results for Competing Turbine Engine Seals

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Prepared 2006 NASA Seal/Secondary Air System Workshop
Ohio Aerospace Institute, Cleveland, Ohio
Nov. 14-15, 2006

The authors would like to acknowledge NASA Glenn Research Center where all the testing was conducted, Bruce Steinetz who guided the design, procurement, and fabrication of the High Temperature, High Speed Turbine Seal Test Rig, and Joseph Flowers from the Army Research Lab who provided test and engineering support.

Motivation

- **Follow-up Study**
  - "Leakage and Power Loss Test Results for Competing Turbine Engine Seals" by Proctor and Delgado, (NASA/TM – 2004-213049)
- **Benefits**
  - Higher engine performance
  - Decreased specific fuel consumption
  - Increased thrust
  - Better investment towards performance gain than components, such as compressors and turbines.
- **Heat Generation and Power Loss**
  - Changes in engine air temperatures from stage to stage can negatively affect engine efficiencies.
  - Friction from contacting seals increases the amount of torque needed.
  - Advanced engines operate at very high temperatures. Excessive heat generation at the seal could expose downstream components to temperatures that exceed material capabilities.

This study is a follow-up on a previous paper published by the authors for the 2004 ASME Turbo Expo. Experimental labyrinth and annular seal data are included in this presentation.

Approach

- Conduct literature review
- Use previous and new baseline NASA seal experimental leakage and power loss data
- Adjust data to account for disk and bearing windage
- Compare experimental data with literature

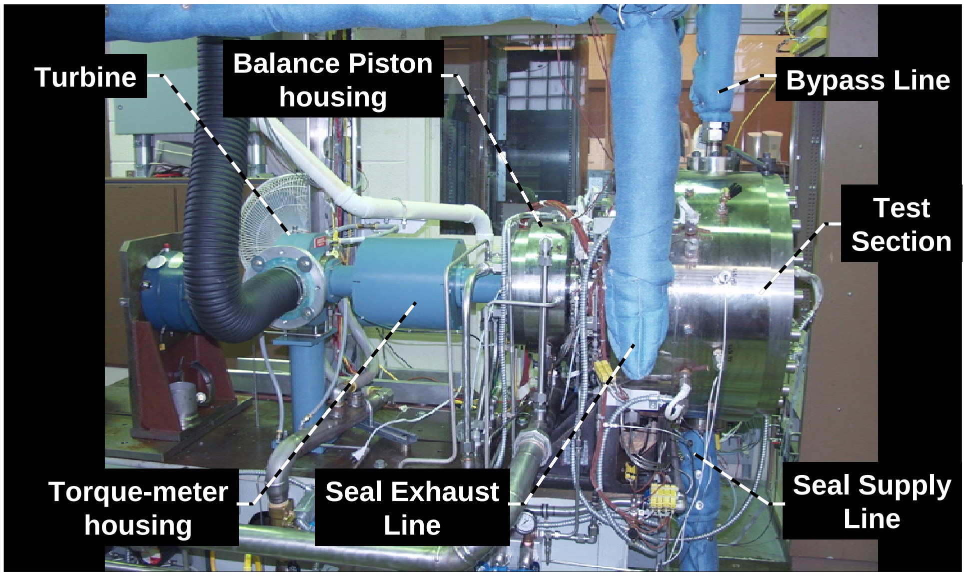
Previous brush and finger seal data are compared with new annular and labyrinth seal data. The results are also compared with literature. Finally, disk and bearing windage are accounted for and described in detail later in the presentation.

Literature Review

- 1987 – Windage effect of rim seals. (Hasser et al.)
  - Modelled wheel space cavity
  - Results agreed with full-scale engine and rig data
  - Results agreed with Daily & Nece axial spacing ratio
  - Results agreed with bolt drag effects
- 1989 – Laby. seal power dissipation. (McGreehan et al.)
  - Windage heating developed in first 2 pockets of a 5-knife labyrinth seal
  - Windage decreases with increasing swirl velocity ratio
- 1990 – Laby. seal recirculation zone. (Demko et al.)
  - Existence of a secondary recirculation zone in a labyrinth seal at high speeds
- 1996 – Laby. seal windage heating. (Millward et al.)
  - Seal power dissipation increases with increasing mass flow rate
- 2003 – Brush seal/shaft thermal effects. (Owen et al.)
  - Derived a power law relationship between mass flow rate, shaft temperature, and power dissipated

A review of the literature provided some labyrinth and brush seal data at comparable surface speeds, temperatures, and pressure ratios. This will be seen later in the presentation.

NASA Turbine Seal Rig



The NASA High Temperature High Speed Turbine Seal Test Rig located at NASA Glenn Research Center in Cleveland, Ohio is capable of testing current and advanced seals through 1500F, 250 psid, and >1000 ft/s.

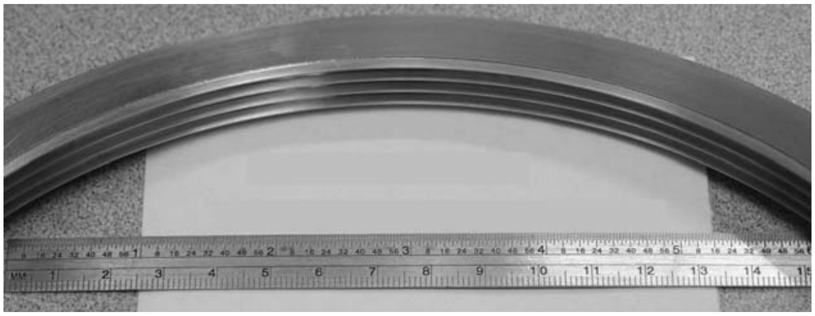
Annular Seal

- Material: Inco 625
- Seal Dia: 216 mm
- Seal Clearance: 0.3 mm

Note, each grid square is ¼ inch

A picture of the annular seal inner diameter.

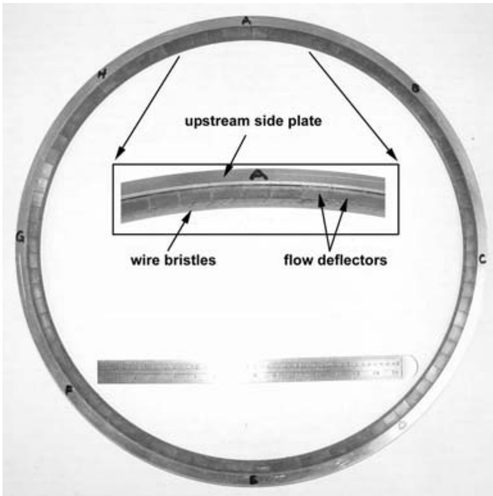
Labyrinth Seal



- Design : 4-Knife
- Material : Inco 625
- Seal Dia : 216 mm
- Seal Clr. : 0.3 mm
- Tooth height : 0.762 mm
- Pitch : 1.016 mm
- Tip width : 0.318 mm
- Tooth angle : 7.5°

This slide shows a picture of the 4-knife labyrinth seal used for baseline power loss data.

Brush Seal



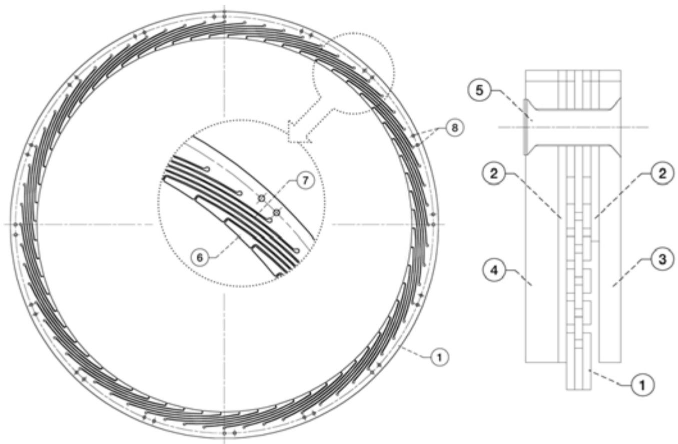
- Design w/Flow Deflector
- Material Haynes 25 Bristles
  Inco 625 Sideplates

- Seal Diameter 216 mm
- Seal Clearance ~ -0.1 mm

- Bristle lay angle 50°
- Bristle dia. 102 μm
- Density 68 wires/mm
- Fence height 1.27 mm

The brush seal supplied by Eaton has a flow deflector installed on the high pressure side. Power loss data taken previously is compared with current annular and labyrinth seal power loss data.

Finger Seal



1. Finger element
2. Spacer
3. Forward cover plate
4. Aft cover plate
5. Rivet
6. Finger contact pad
7. Finger
8. Indexing and rivet holes

- Design   Pressure-Balanced
- Seal Dia. 216 mm
- Seal Clr. -0.2 mm

The pressure-balanced finger seal was supplied by Honeywell.

Comparison of Test Seal Design Parameters

Seal Type	Material	Radial Clearance at 297K [mm]	Axial Length [mm]
Annular	Inco 625	0.3	11
4-knife labyrinth	Inco 625	0.3	11
Brush	Haynes 25 Bristles	-0.1	~1.0 bristle pack width
Finger	Haynes 25	-0.2	Similar to brush seal

This slide shows a quick glance at differences in material, radial clearance, and axial length for the four seals tested.

Seal Test Conditions

• 5 inlet air temperatures	• 297 K to 922 K 297, 533, 700, 811, 922 K (75, 500, 800, 1000, 1200°F)
• 5 pressure differentials	• 69 to 517 kPa 69, 138, 276, 345, 517 kPa (10, 20, 40, 50, 75 psid)
• 6 surface speeds	• 0 to 366 m/s 0, 113, 183, 274, 283, 366 m/s 0, 371, 600, 900, 928, 1200 ft/s

Not all conditions were obtained for each seal.

Self-Explanatory

Seal Flow Factor and Power Loss

- Seal Leakage (Flow Factor, ϕ)

$$\phi = \frac{\dot{m}\sqrt{T_{avg}}}{P_u D_{seal}}, \frac{kg-\sqrt{K}}{MPa-m-s}$$

- Seal Power Loss
  - Torquemeter has an absolute accuracy of 0.13%.
  - Tare Torque calibration curves (temperature, speed) used.
  - Frictional torque, M_o, due to test disk & balance piston included

$$M_o = C_{m,o}\rho\omega^2 a^2 /(4g) \qquad C_{m,o} = 0.102(s/a)^{1/10}/(\mathrm{Re}^{1/5})$$

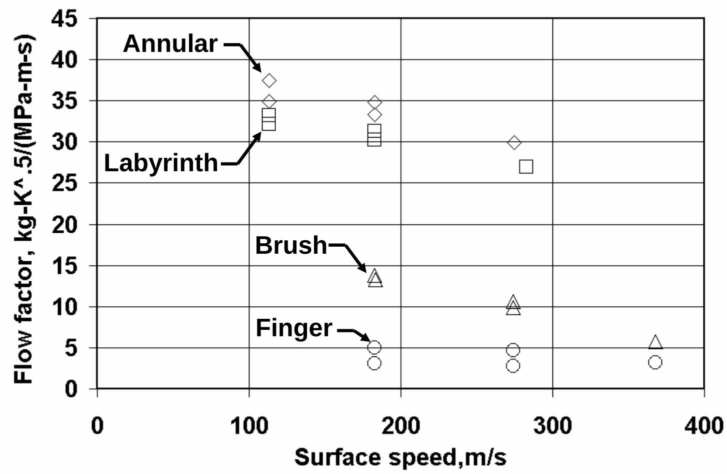
  - Test end bearing windage included

$$T = fD_1W/2$$

  - Seal Torque = (Torquemeter Torque) – (Tare Torque) – [(Test Disk Torque) + (Balance Piston Torque) + (Bearing Torque)]$_{\text{due to }\Delta p}$
  - Power loss = (Seal Torque) x (Angular Velocity)

Seal flow factor and power loss were calculated as shown. In addition disk and bearing windage are accounted for in the power loss calculations.

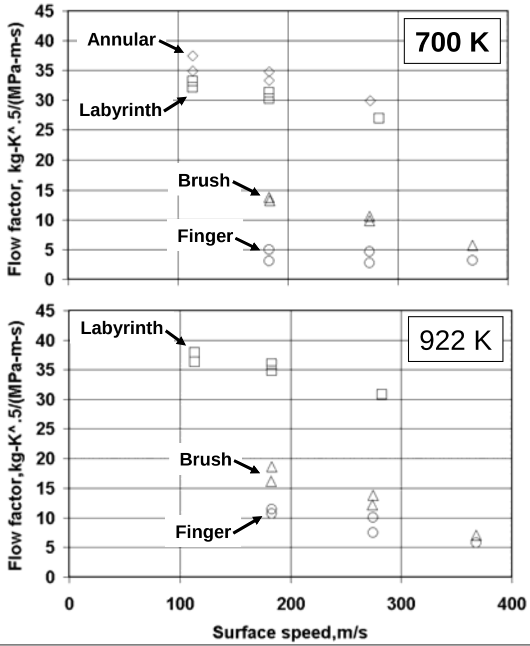
Flow Factor vs. Speed at 700 K and 276 kPa.



- Flow factor decreases with increasing surface speed.
- Flow factors influenced by large seal starting clearances (annular, labryinth) as well as seal pressure closing forces (i.e. brush, finger)

Flow factor is observed to decrease with increasing surface speed. However large starting clearances and seal pressure closing forces affect flow factor as well.

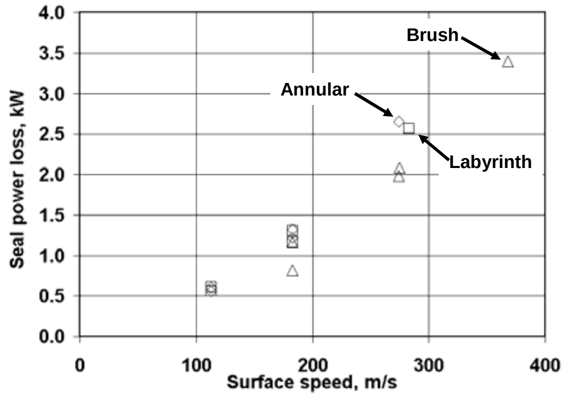
Flow Factor vs. Speed at 276 kPa and 700, & 922 K.



- Seals grow larger than disk due to coefficient of thermal expansion (CTE) mismatch
- Larger clearances result in larger flow rates
- Brush and finger seal leakage are 2-3 times less than annular and labyrinth seal leakage

Flow factor is observed to increase with increasing temperature. This is largely a result of CTE mismatch between the disk and seal. However brush and finger seals show 2-3 times less leakage than annular or labyrinth seals.

Seal Power Loss vs. Speed at 297 K and 276 kPa.



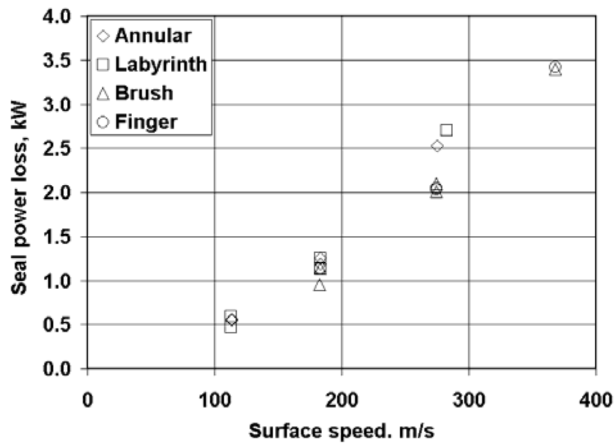
- Seal power loss increases with increasing surface speed
- Labyrinth seal data from Millward and Edwards is 2 to 3x higher (4 – 8 kW) at ambient temperature, 276 kPa, & 282 m/s

•Labyrinth Seal Design Differences

	NASA	Millward
Teeth	4	5
Radial CL	0.3 mm	1.12 mm
Pin/Pout	3.5	1.5
Axial Width	X	2X
Rotation?	No	Yes

Seal power loss is observed to increase with increasing surface speed. Labyrinth seal power loss data from Millward and Edwards are 2-3 times greater than the NASA labyrinth seal data. Differences in labyrinth seal design may explain the discrepancy.

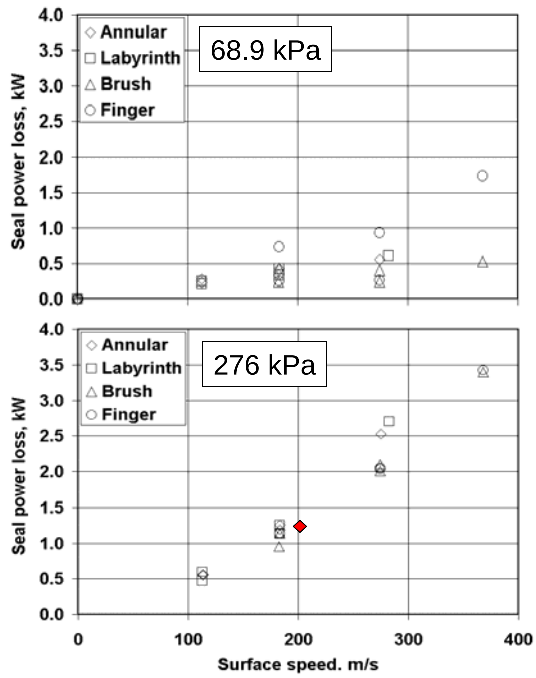
Seal Power Loss vs. Speed at 700 K and 276 kPa.



- For each seal, power loss varied by ±5% at most with increasing temperature.
- Annular and labyrinth seal power loss were consistently higher than brush or finger seal power loss at each test temperature.

Seal power loss was found to vary only 5% with increasing temperature.

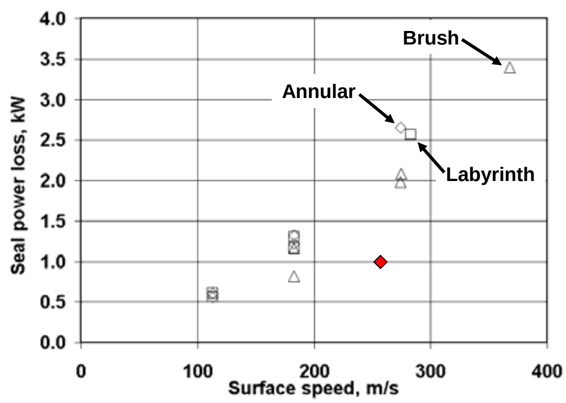
Seal Power Loss vs. Speed at 68.9 and 276 kPa at 700 K.



- Seal power loss increases with increasing seal pressure differential
- NASA 4-knife labyrinth seal power loss is comparable to McGreehan and Ko data (◆) (5-knife labyrinth @ 505 K with 0.19 mm radial clearance).

Seal power loss is observed to increase with increasing seal pressure differential. 5 knife labyrinth seal data from McGreehan and Ko are similar.

Seal Power Loss vs. Speed at 297 K and 276 kPa.



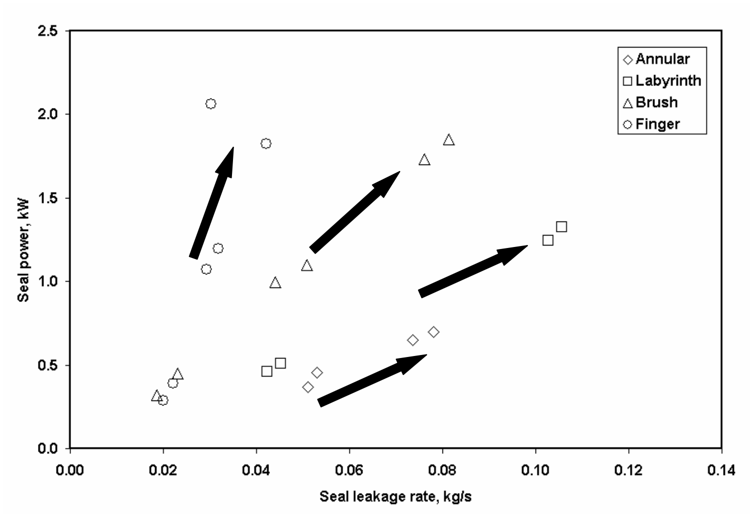
- NASA brush seal power loss is 2x that reported by Millward and Edwards (◆) at ambient temperature, 276 kPa, and 264 m/s
- Brush Seal Design Differences

	NASA	Millward
Radial CL	-0.1 mm	0 mm
Pin/Pout	3.4	1.3
Seal Dia.	216 mm	388 mm

- NASA brush seal flow rate (0.03 kg/s) is lower than Millward data (0.1 kg/s)
- Mass flow rate is proportional to seal diameter.

Differences in brush seal design may explain the discrepancy between the NASA data and that reported by Millward and Edwards. However, mass flow rate is found to be proportional to seal diameter.

Seal power loss vs. mass flow rate at 922 K and 183 m/s.



Seal power loss increases with mass flow rate.

Seal power loss is observed to increase with increasing mass flow rate.

Conclusions - Seal Leakage

- Seal leakage decreases with increasing surface speed due to reduced clearances from disk centrifugal growth.
- Annular and labyrinth seal leakage are 2-3 times greater than brush and finger seal leakage.
- Seal leakage rates increase with increasing temperature because of seal clearance growth due to different coefficients of thermal expansion between the seal and test disk.

Self-Explanatory

Conclusions - Seal Power Loss

- Seal power loss is not strongly affected by inlet temperature.
- Seal power loss increases with increasing surface speed, seal pressure differential, mass flow rate or flow factor, and radial clearance.
- The brush and finger seals had nearly the same power loss.
- Annular and labyrinth seal power loss were higher than finger or brush seal power loss. The brush seal power loss was the lowest and 15-30% lower than annular and labyrinth seal power loss.

Self-Explanatory

Future Work Needed

- Combined experimental/analytical effort
  - Compare CFD analyses with baseline seal experiments that obtain internal seal temperature and pressure measurements
- Test the effect of seal axial thickness
  - Brush & finger seals had lower power losses than annular and labyrinth seals possibly due to shorter axial lengths
  - Test a two-knife labyrinth with a shorter axial length
- Test the effect of preswirl on seal power loss
  - McGreehan and Ko found that preswirl in the direction of rotation reduces power loss

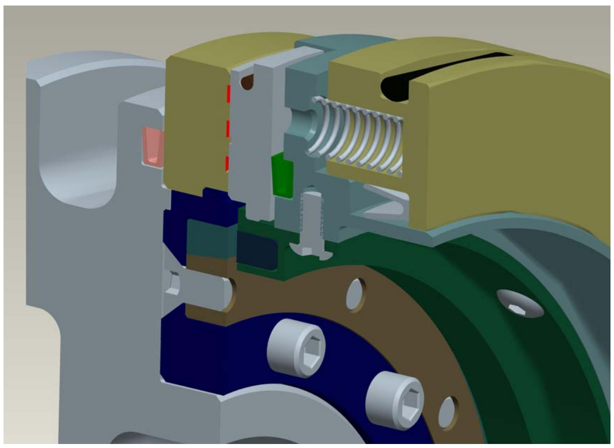
Self-Explanatory

ANALYSIS AND DESIGN OF A DOUBLE-DIVERT SPIRAL GROOVE SEAL

Xiaoqing Zheng and Gerald Berard
Eaton Aerospace
Warwick, Rhode Island

EATON

NASA
Seal/Secondary Air Delivery Workshop
November 14-15, 2006
Ohio Aerospace Institute (OAI)



Analysis and Design of a Double-Divert Spiral Groove Seal

Dr. Xiaoqing Zheng
and
Mr. Gerald Berard

Eaton Aerospace
Warwick, Rhode Island

Double Spiral Design Features

- Non-Contacting seal faces during static and dynamic operation
  - High temperature permanent magnets to prevent contact at startup/static conditions
  - Outwardly pumping spirals allow for self-correcting dynamic axial seal face tracking during seal face coning/dynamic conditions
- Insert segmentation with low leakage joints to accommodate larger sizes and enhance axial tracking and compliance
- Center feeding restrictive orifices allow insert segments to be adaptive to local waviness and coning

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Double Spiral Operational Features

- Low Leakage – Approximately 10 times less than a new brush seal
- Seal is always non-contacting therefore no wear and long life
- Low heat generation
- High speed capabilities

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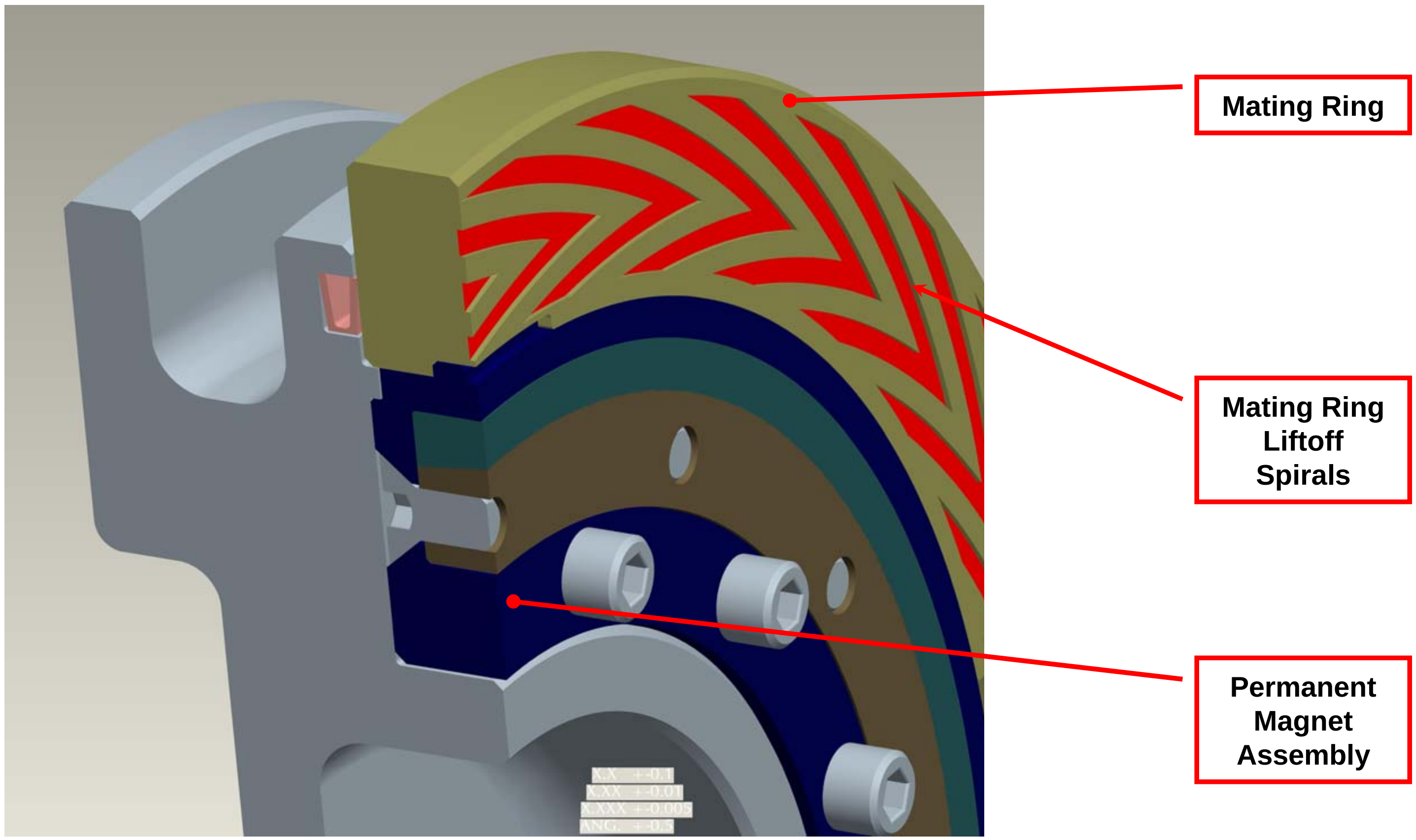
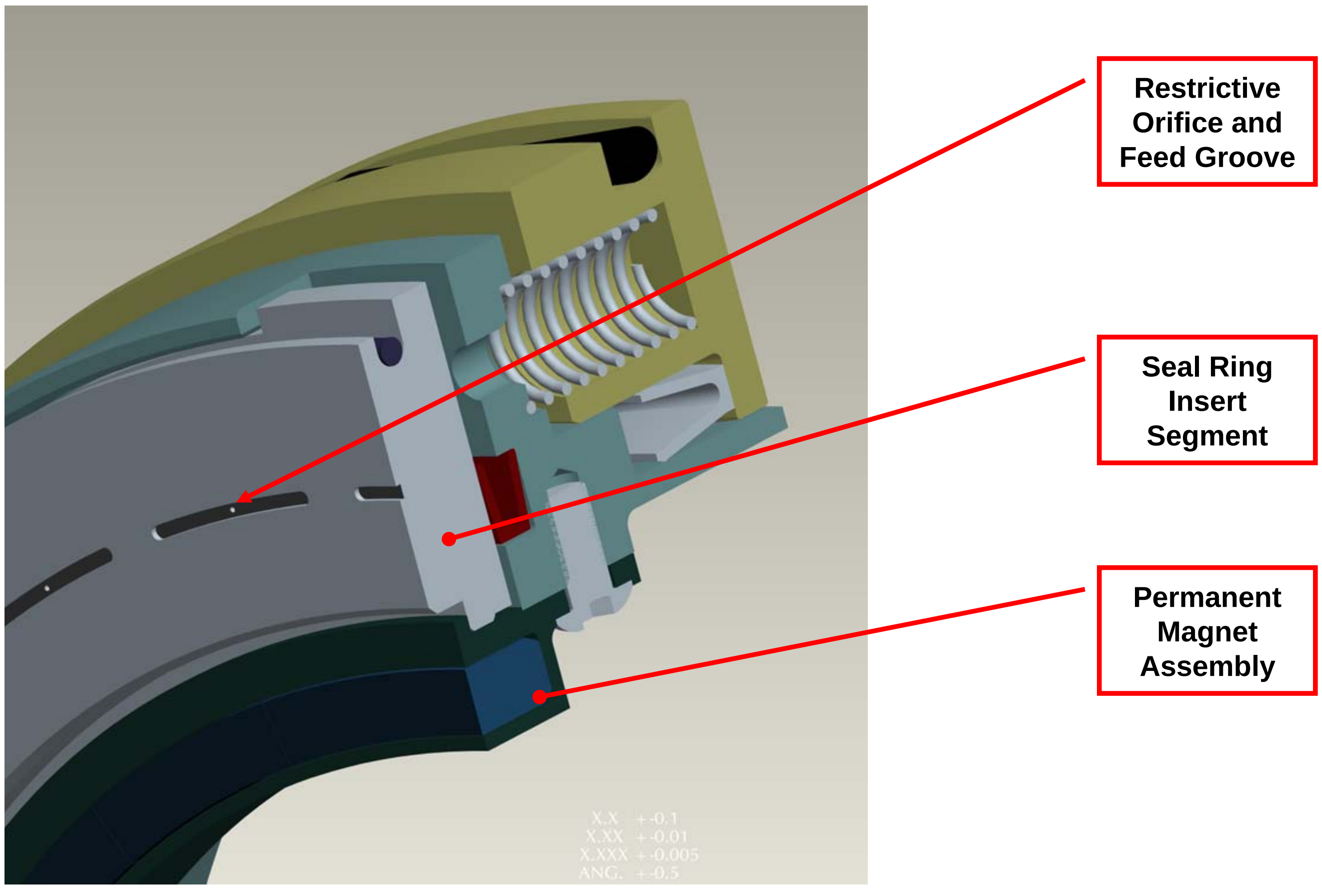
Mating Ring/Rotor Assembly



Design Features

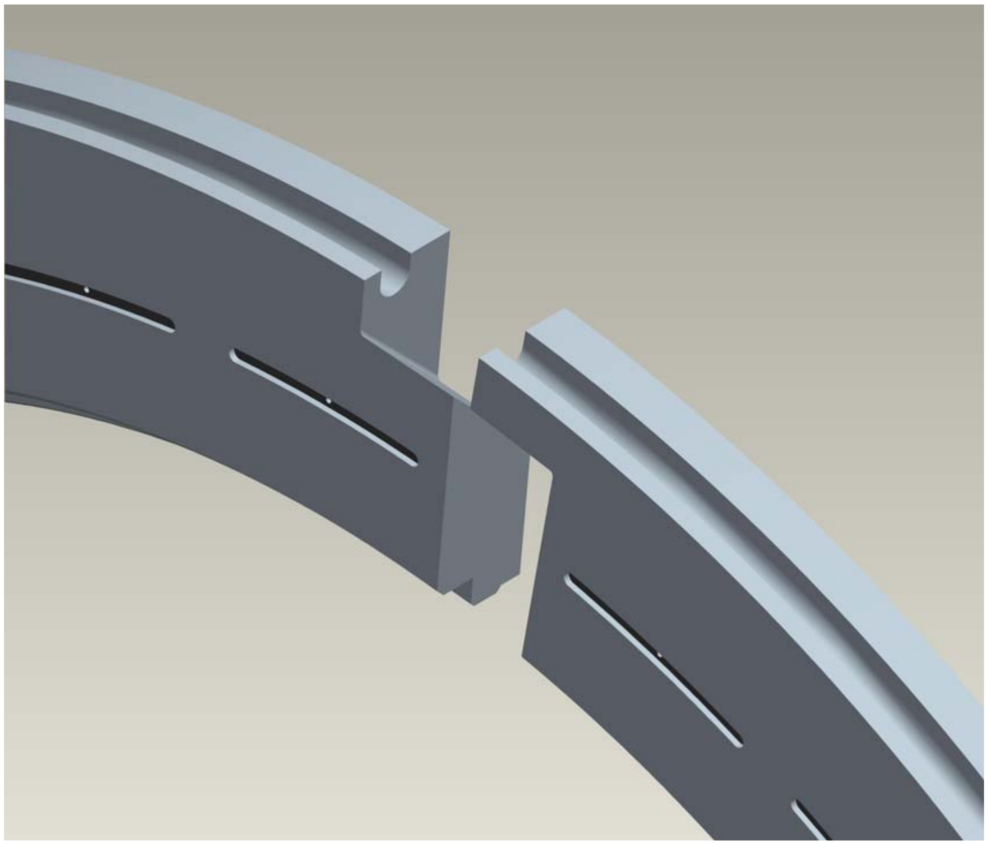
Seal Ring Assembly



Design Features

EATON

Insert Segment Joints



Machined inter-locking joints to minimize leakage and provide adaptability to larger diameters as well as provide axial compliance to rotor waviness

Design Features

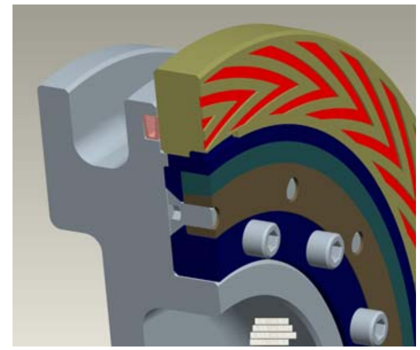
EATON

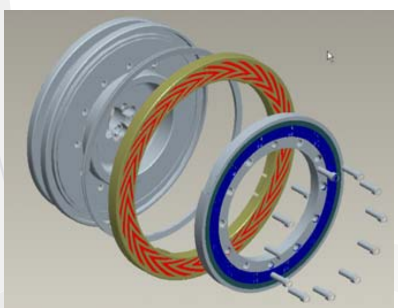
Rotor Assembly
Completed Prototype Parts

Titanium Rotor/
Shaft Adapter

Titanium/
Samarium Cobalt

Magnet Housing

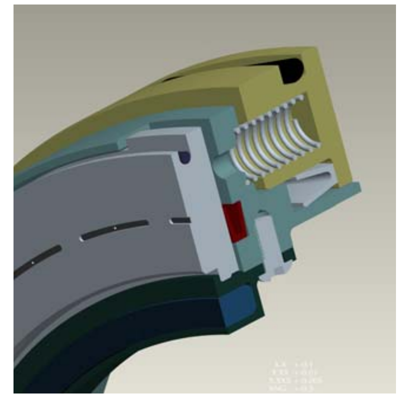




Stainless Steel
Mating Ring

Seal Assembly
Completed Prototype Parts

Stainless Steel Seal Ring Shell Assembly



Stainless Steel/ Samarium Cobalt Magnet Housing

Aluminum Seal Ring

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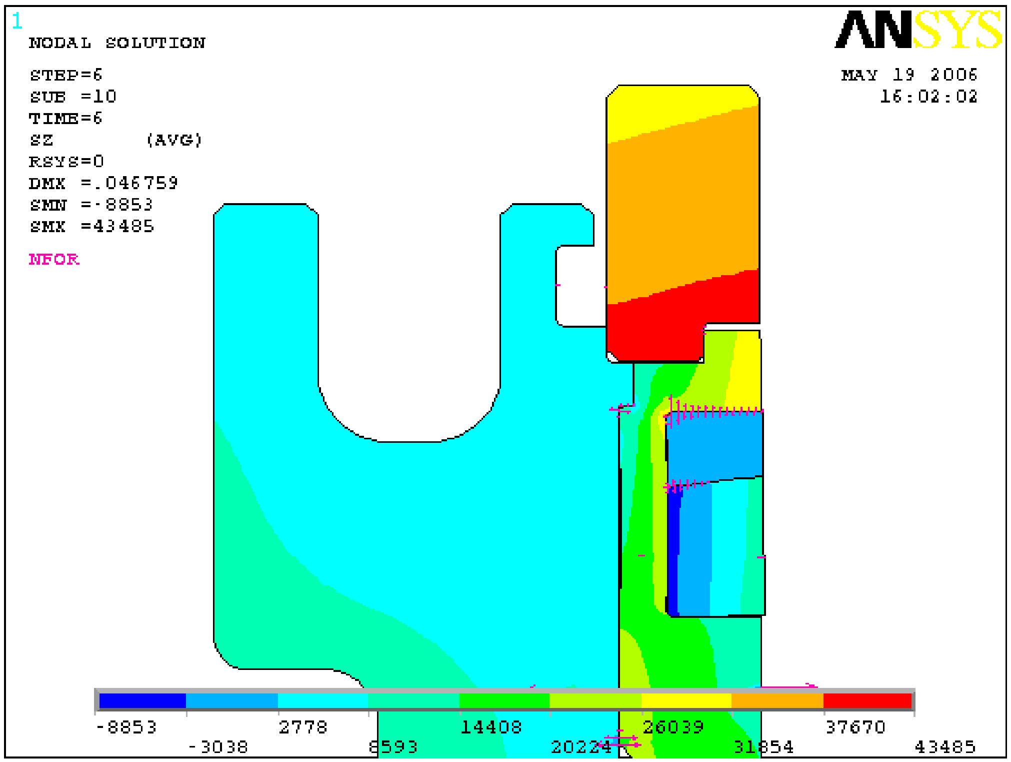
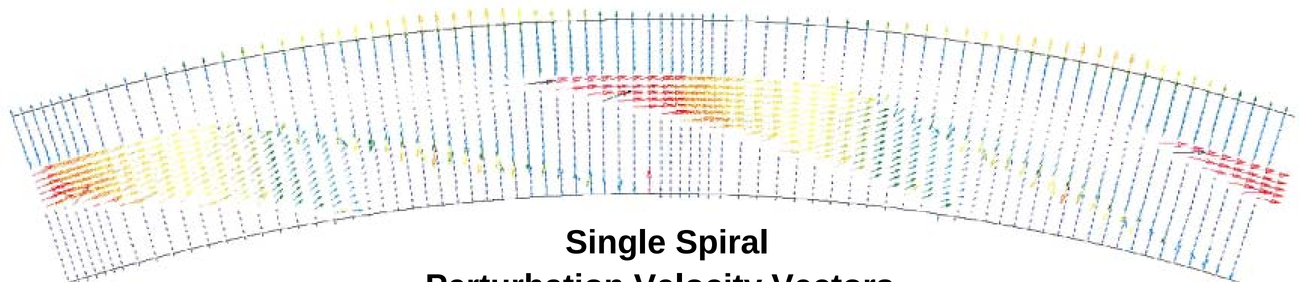
Finite Element Analysis



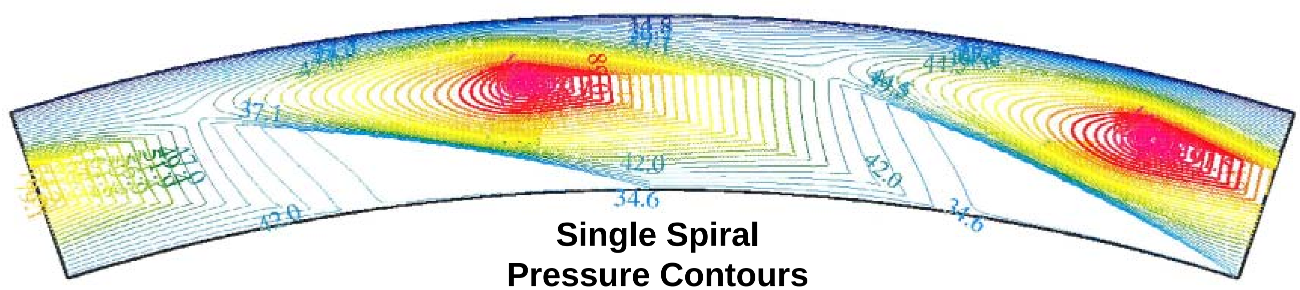
Von Mises Stress Plot at 15,000 RPM (PSI)

The Mating Ring/Rotor assembly were analyzed using ANSYS, a general purpose finite element analysis program

Computational Fluid Dynamics (CFD) Analysis



Single Spiral
Perturbation Velocity Vectors



Single Spiral
Pressure Contours

Seal face liftoff is calculated using Adina and a custom CFD code

Restrictive Orifice Design

1. Purposes:
   - Control leakage
   - Extend the range of high film stiffness
   - Improve film stiffness

2. Calculation of effectiveness
   - Empirical formula
   - Detailed CFD simulation
   - Integrated into double-spiral groove seal design code

Orifice CFD Model

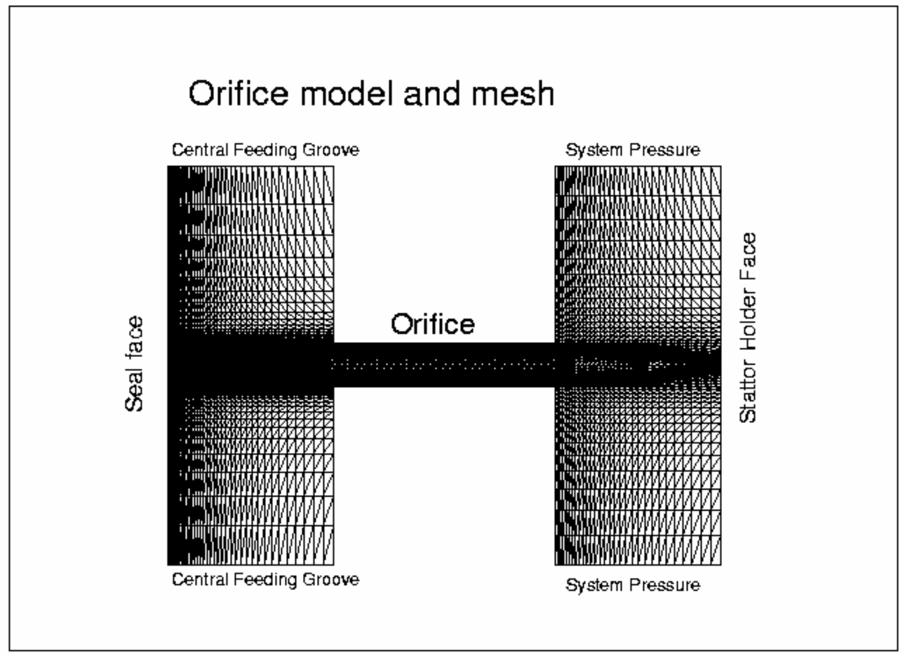
Governing Equation:

$$\frac{\partial U}{\partial t} + \nabla \bullet (F - G) - S = 0$$

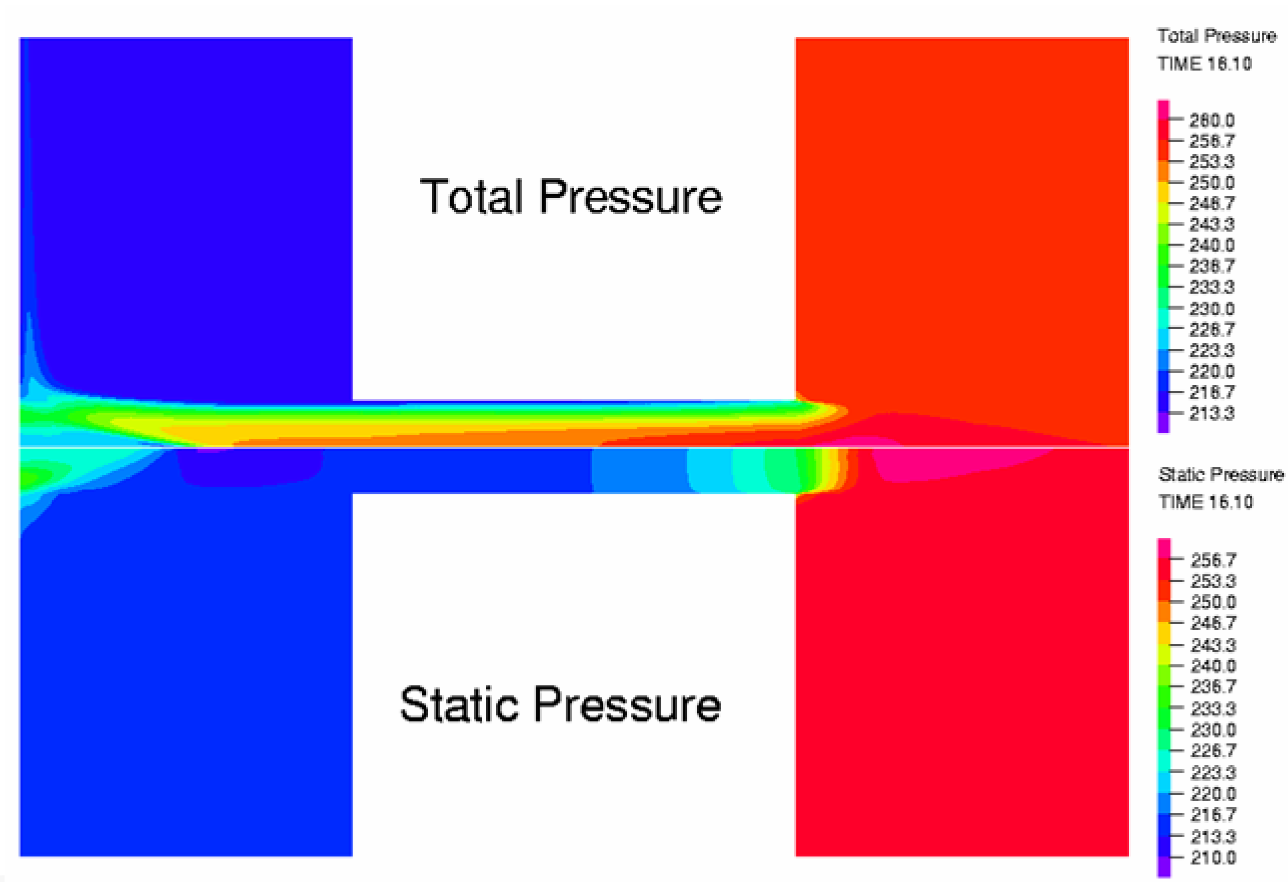
Where:

$$U = \begin{bmatrix} \rho \\ \rho v \\ \rho e \end{bmatrix} \qquad G = \begin{bmatrix} 0 \\ -pI + \tau \\ \tau \bullet v - q \end{bmatrix}$$

$$F = \begin{bmatrix} \rho v \\ \rho v v \\ \rho v h \end{bmatrix} \qquad S = \begin{bmatrix} 0 \\ f \\ f \bullet v + q_s \end{bmatrix}$$



Orifice Results



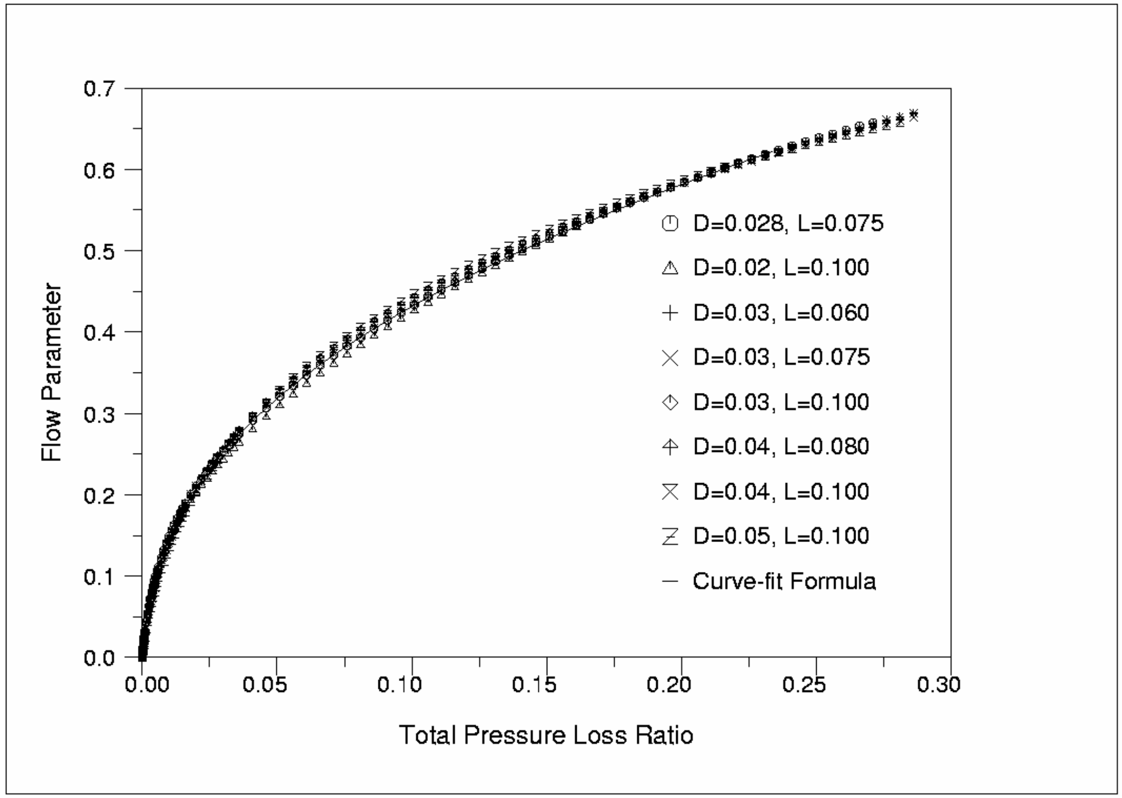
Restrictive Orifice

Flow parameter:

$$\phi = \frac{\dot{m}\sqrt{T^*}}{\frac{1}{4}\pi d^2 p^*_{Inlet} K}$$

Total pressure loss ratio:

$$\eta = \frac{p^*_{Inlet} - p^*_{Exit}}{p^*_{Inlet}}$$



Resulting Empirical formula:

$$\eta = 0.02756\ \phi + 0.1637\ \phi^2 + 0.8978\ \phi^3 - 0.4184\ \phi^4$$

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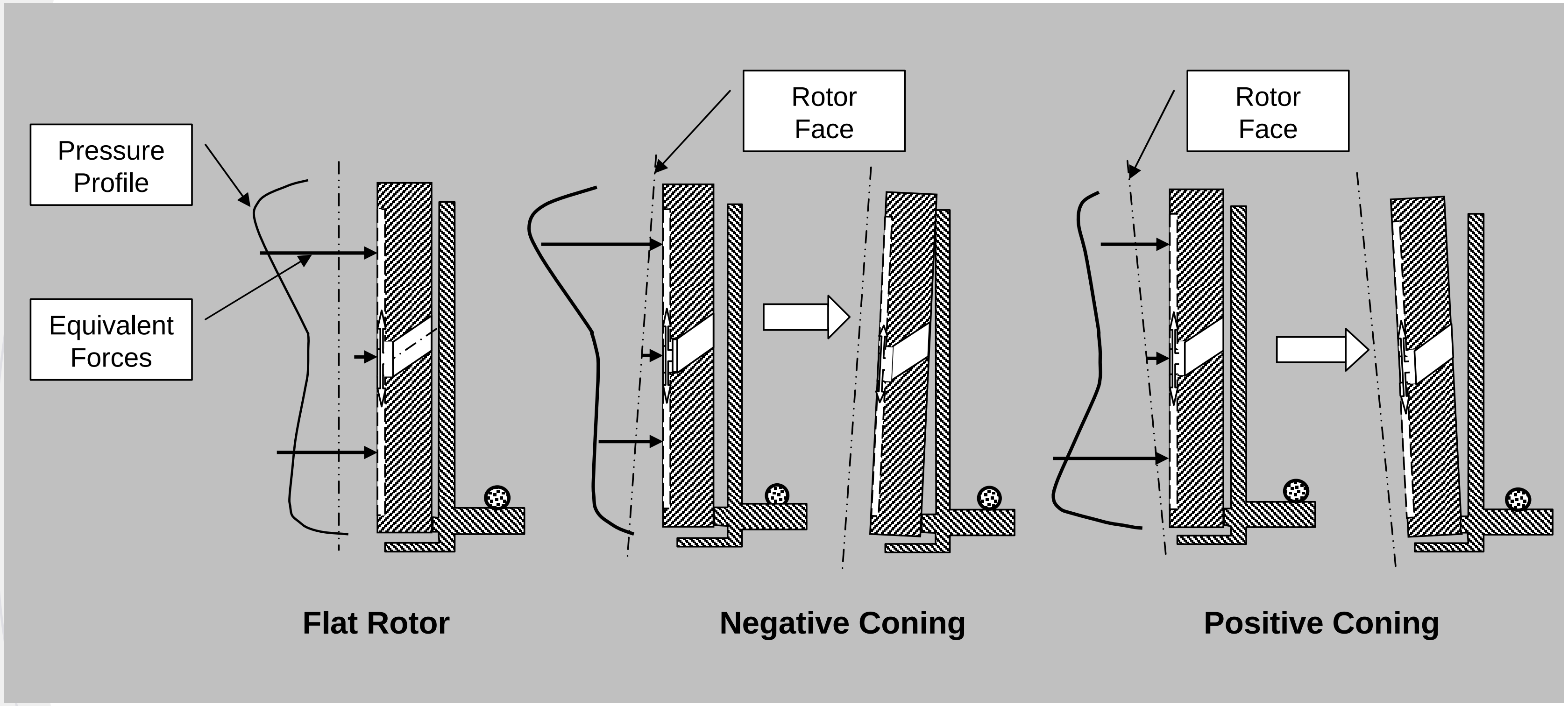
Seal Face Coning



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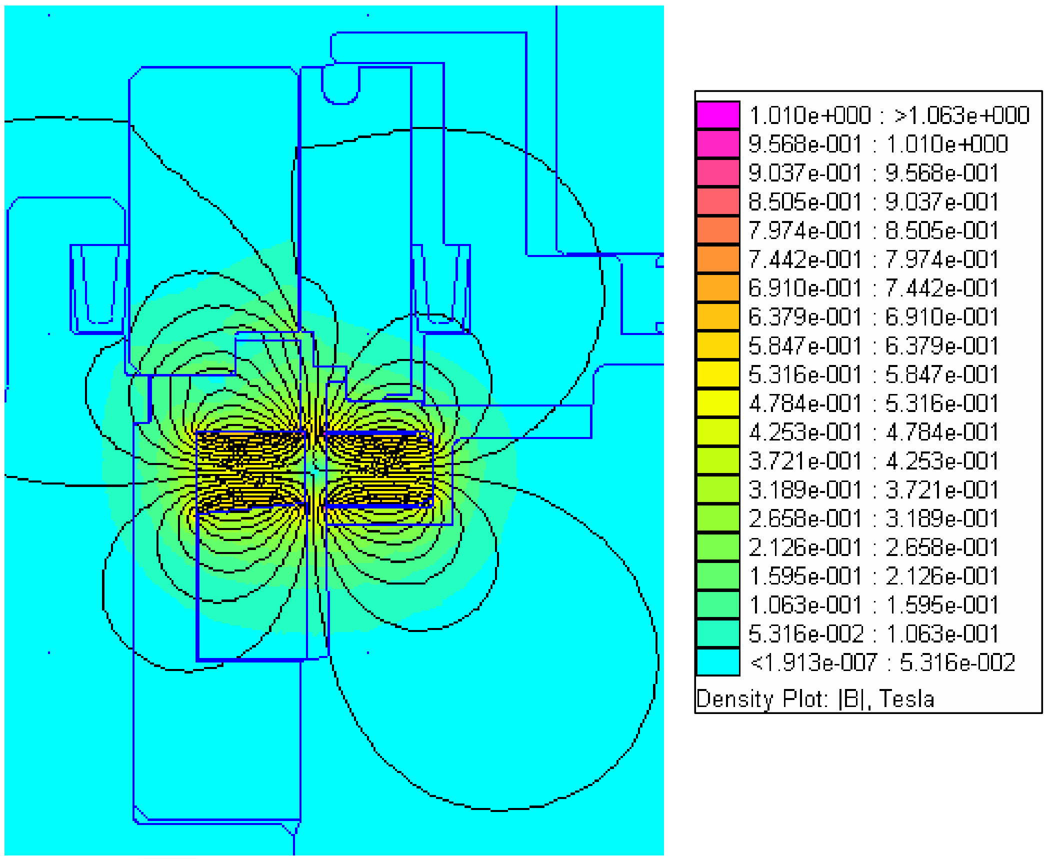
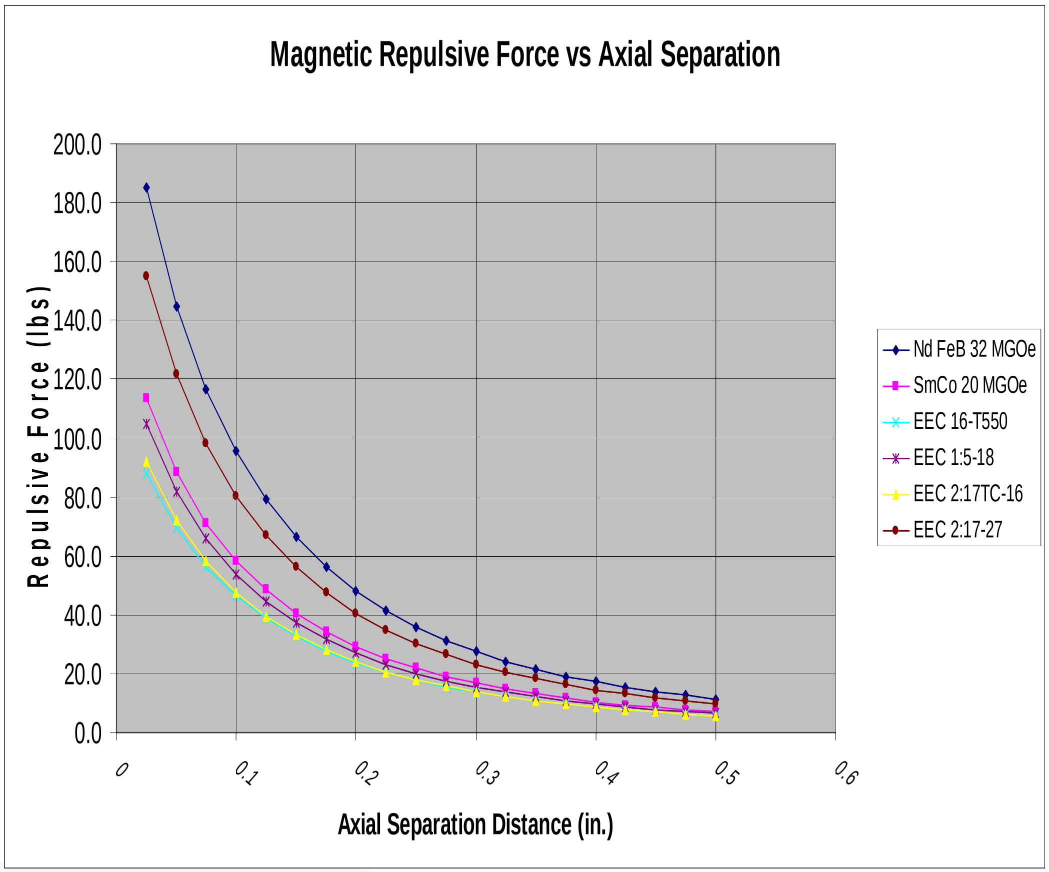
Permanent Magnet Analysis



Magnetic Analysis was conducted using various high temperature rare earth Samarium Cobalt with a maximum operating temperature of 550°C (1022°F)

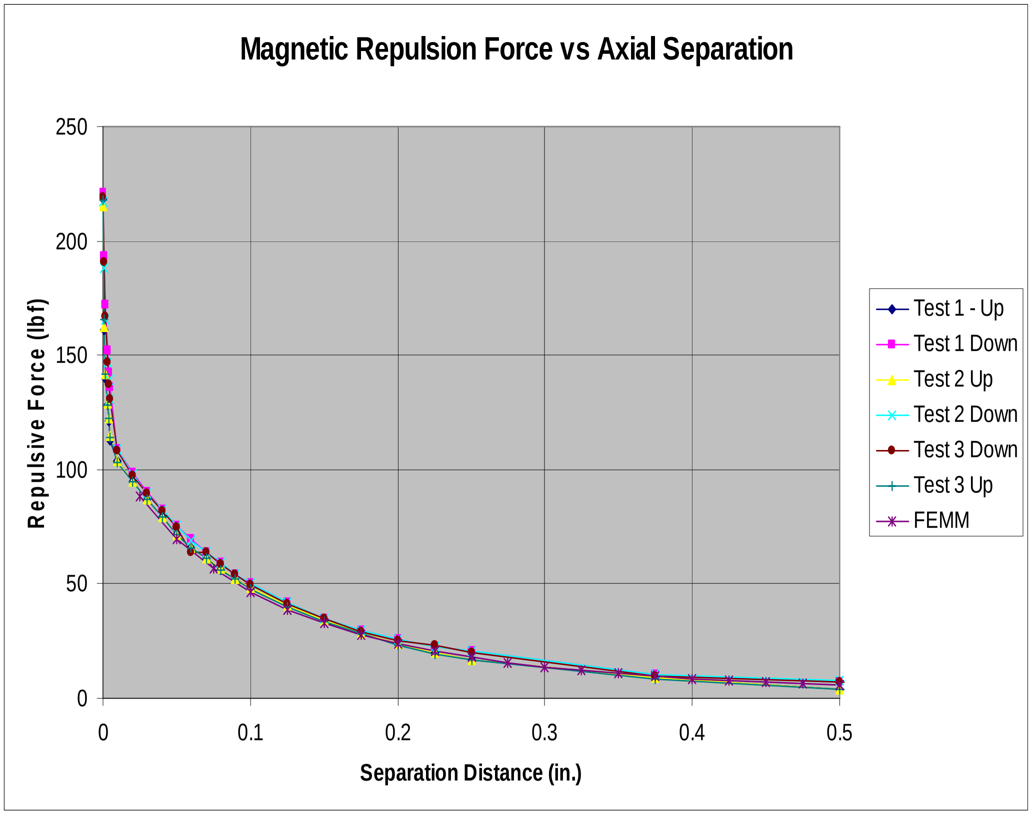
Magnetic Repulsive Force



Why Magnets?

Magnetic Repulsive Force is non-linear therefore the force dissipates significantly with increasing gap distance

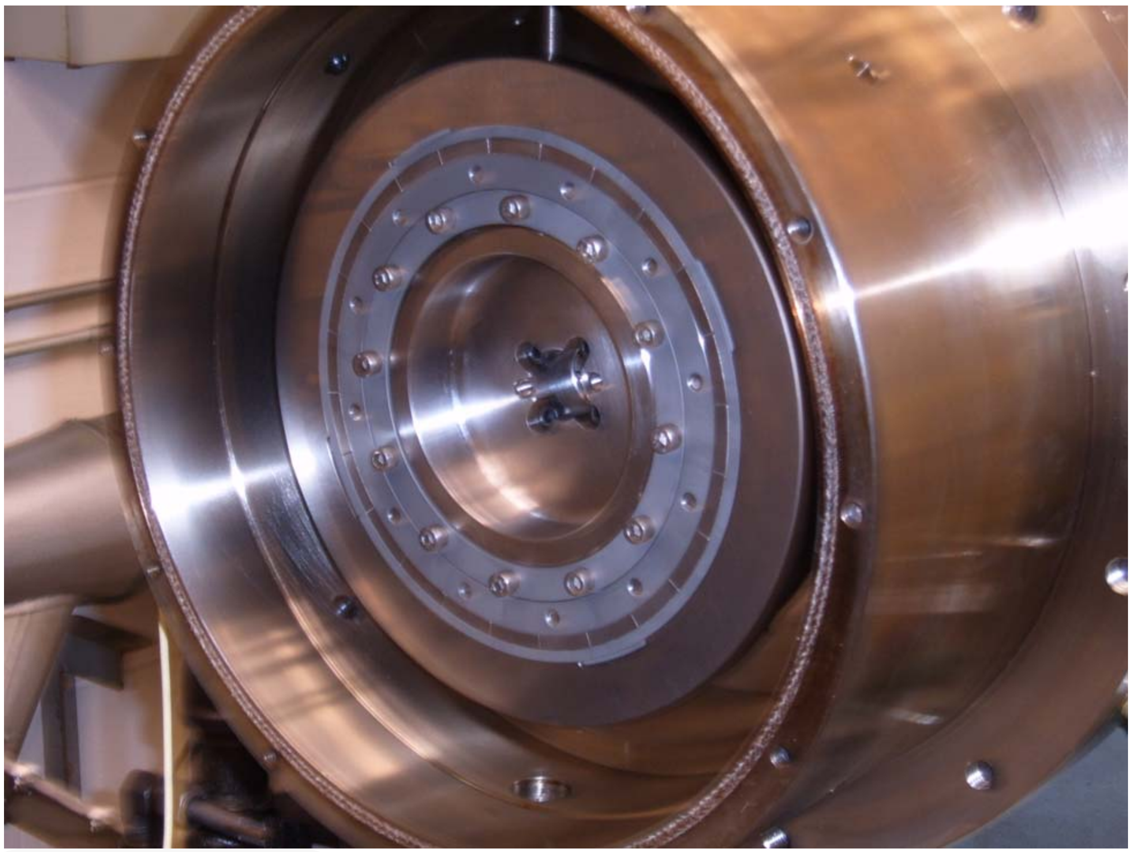
Magnetic Repulsive Test Results



Magnetic
Test Results

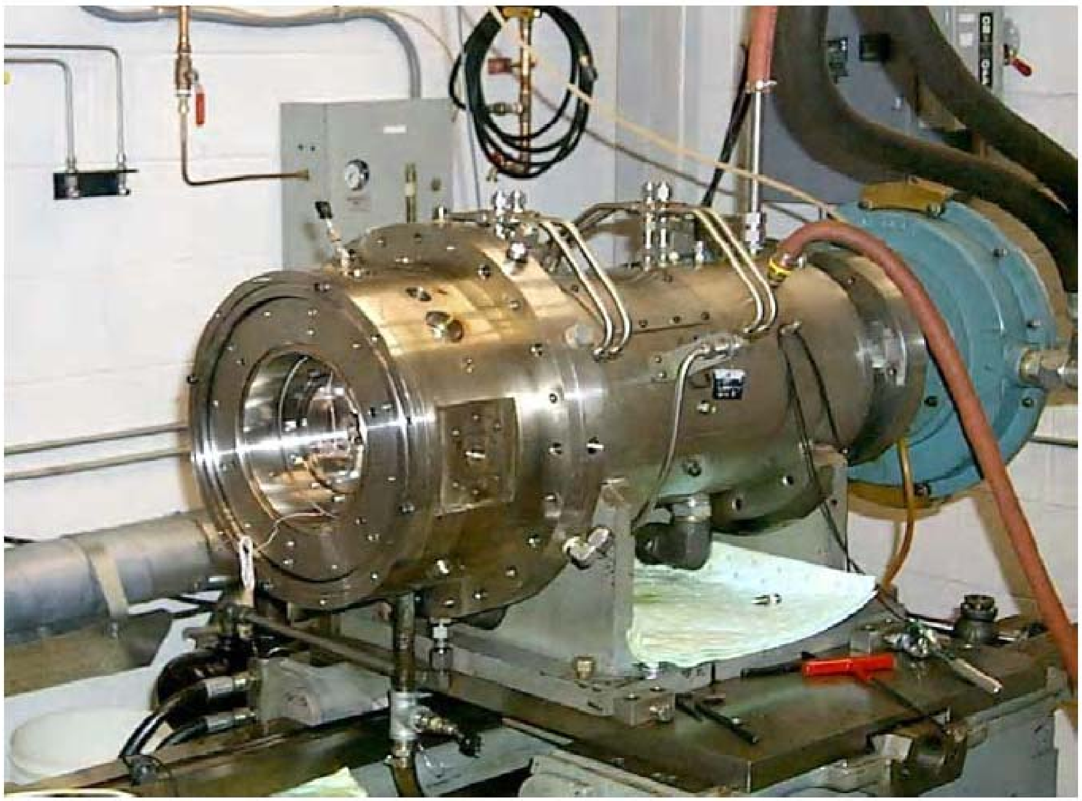
Comparison of Finite Element Analysis results to actual test results

Spin Testing



18,000 RPM Spin Test was conducted on the rotor/magnet assembly

Testing and Validation



- Testing and validation will be accomplished on the Warwick Aerospace Test Rig which has a 24,000 RPM, 1,000°F, 120 PSI capability

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FORMING A TURBOMACHINERY SEALS WORKING GROUP: AN OVERVIEW AND DISCUSSION

Margaret P. Proctor
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

National Aeronautics and Space Administration

Forming a Turbomachinery Seals Working Group: An Overview and Discussion

By
Margaret P. Proctor

Seals Team of the Mechanical Components Branch
Structures and Materials Division
NASA Glenn Research Center
Cleveland, OH

Presented at the
2006 NASA Seal/Secondary Air System Workshop
November 14-15, 2006

www.nasa.gov

Purposes

- Identify technical challenges to improving turbomachinery seal leakage and wear performance, reliability and cost effectiveness
- Develop a coordinated effort to resolve foundational issues for turbomachinery seal technologies
- Identify and foster opportunities for collaboration
- Advocate for funding

Membership

- Open to industry, academia, and government
- Ideally there would be representation from:
  - NASA
  - Other government agencies (DOD, DOE)
  - Engine companies –both aero and space
  - Seal companies
  - University researchers
- Questions:
  - U.S. only or open to foreign interests?
  - How many people does a working group need to be viable and functional?

Survey Response

- Number of responses: 6 as of 10/31/06

		Interest? Yes	Interest? No
– Industry:	5	5	
• No. Engine companies	2	2	
• No. Seal Companies			
• Other			
– Government:	1	1	
– Academia:			

Survey Response - Purpose

Ways to serve community	Yes	1st	2nd	3rd
Identify Technical Challenges to improving turbomachinery seal leakage and wear performance, reliability, and cost effectiveness	6	5	1	
Develop coordinated effort to resolve foundational issues for turbomachinery seal technologies	5		2	2
Identify & foster opportunities for collaboration	5		1	1
Serve as agent to coordinate technical investment in seal technology across government agencies with vested interest in turbomachinery	4	1		1
Serve as a catalyst for technical discussions	5		2	1
Advocate for funding	3			1

Survey Response – Meeting Frequency

Annually	1
Semi-annually	4
Quarterly	
Biennially	1
Never	
Other	

Survey Response – Areas of Experience & Expertise

- Submarine Design
- Machinery Operation & Maintenance
- High temperature/high pressure rotor-stator sealing
- Fluid-dynamics & heat transfer in rotating systems (jet engines – internal air; turbogenerators)
- Experimental methods in fluid dynamics & heat transfer
- Two-phase (air/oil) flow & heat transfer
- Air systems, seals, heat transfer, gas turbine design
- Development & application of labyrinth, brush, carbon, & rope seals
- Cryogenic and high temperature shaft seals – brush, finger, non-contacting film riding concepts

Survey Responses – Currently working on

- Seals for centrifugal compressors in O & G industry
- High pressure ratio seals in rotating cavities
- Labyrinth seals
- Brush seals
- Carbon face seals
- Advanced sealing, DOE High Hydrogen Turbine Program
- Large industrial gas turbines
- Low leakage, non-contacting finger seals
- Sealing in dusty lunar environment

Survey Responses – Types of seals you use, design, or sell

- Labyrinth - 5
- Brush - 4
- Carbon Face
- Cloth seals for many static applications
- Finger
- New concepts

Survey Responses – Your Biggest Technical Challenges related to turbomachinery seals

- Sealing pressure; dry gas seal failures
- Durability
- Low leakage, durable, long life, low cost, easily installed seals
- Reduced heat up while reducing leakage
- Wear of brush seals
- Achieving low leakage and long life seals at high temperature and high speed

Survey Response – technical challenges related to **<u>Analysis</u>**

- Acoustic stability
- Dynamic tracking
- Validation of physics-based models for performance and durability
- Predicting wear
- Fluid-structure interactions particularly for compliant, non-contacting designs

Survey Response – technical challenges related to **Materials**

- Creep resistance of high strength alloys
- Temperature limitations on carbons & metals rub tolerance
- Scaling of capabilities
- High temperature applications
- Lack of material property data
- High temperature materials
- Friction coefficient data

Survey Response – technical challenges related to **Geometry**

- Size of mechanical seal assemblies
- Scaling of seal assemblies
- Controlling leakage at circumferential splits in seal
- Scaling up from prototypes to actual hardware

Survey Response – technical challenges related to **Manufacturing**

- Cost -2
- Repairability
- Low cost, reliable techniques

Survey Response – technical challenges related to **Maintenance**

- Wear
- Cost
- Excessive wear of rub damage

Survey Response – technical challenges related to **Testing**

- Realistic subscale testing
- Rotordynamics testing
- Full-scale prototype testing
- Cost of engine testing
- Dynamic testing
- Off-design conditions i.e. demo of durability during system failure modes
- Lack of facility for testing large, near full-scale parts
- Resources for test articles

Survey Response – technical challenges related to **Incorporation into Engine System**

- Understanding closure between rotor and stator during start and shutdown transients
- Access to engine systems

Where do we go from here?

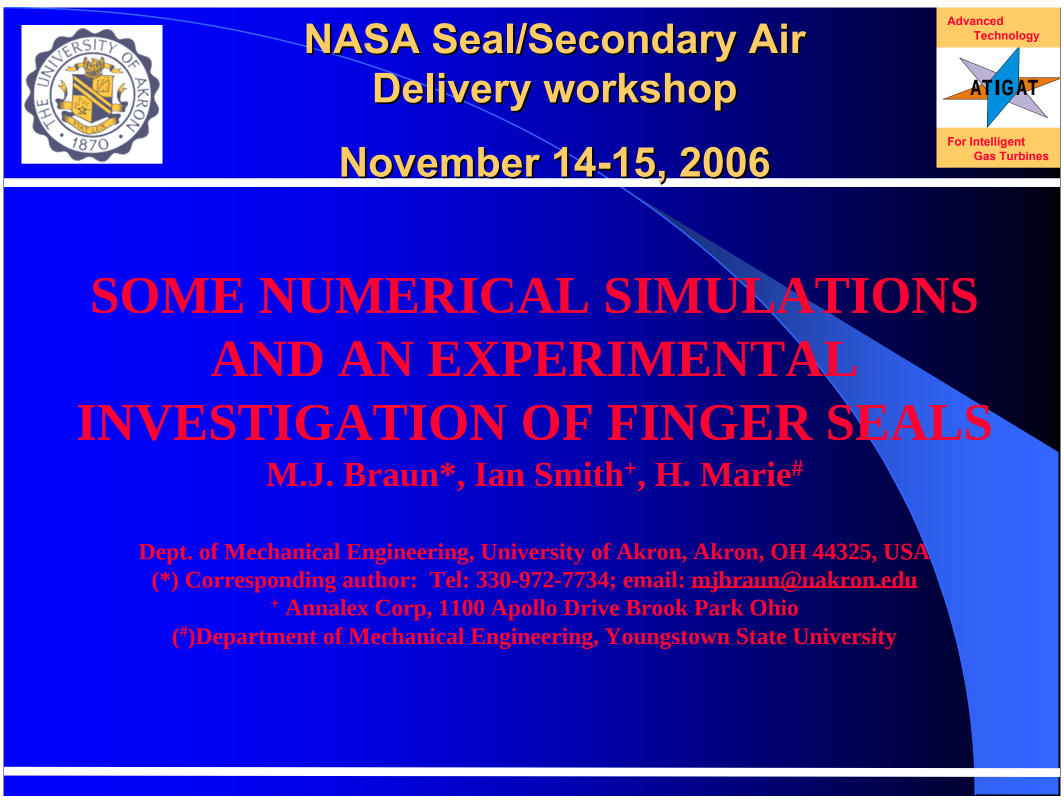
- Accept additional survey responses until November 30, 2006.
  - Blank copies can be found at the registration table
- Decide if sufficient interest exists to establish the working group.
- Respondents to survey will receive a summary of results via e-mail as well as notification of future plans.

SOME NUMERICAL SIMULATIONS AND AN EXPERIMENTAL INVESTIGATION OF FINGER SEALS

Minel J. Braun
University of Akron
Akron, Ohio

Ian Smith
Analex Corporation
Brook Park, Ohio

Hazel Marie
Youngstown State University
Youngstown, Ohio



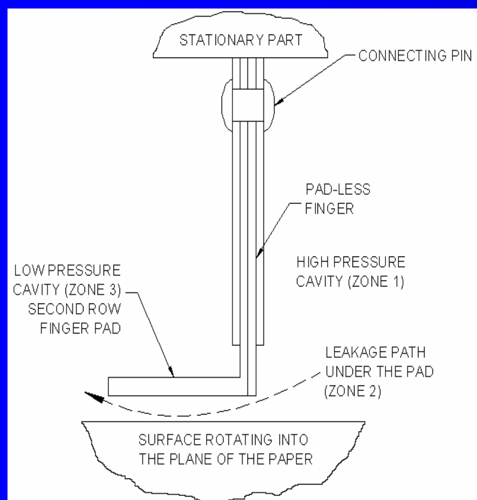
ACKNOWLEDGEMENT

Advanced Technology For Intelligent Gas Turbines (ATIGAT)

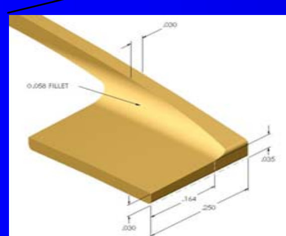
The authors want to express their gratitude to M. Proctor and B. Steinetz of NASA Glenn Research Center, Cleveland, Ohio for the financial support and technical consultations.

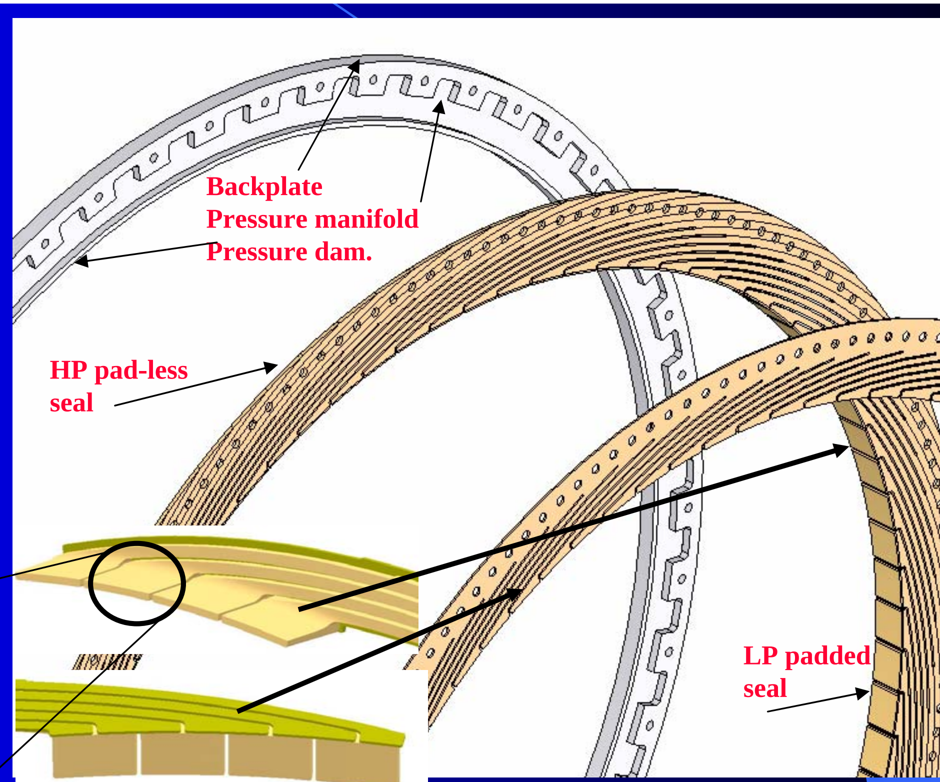
CONCEPT AND COMPONENTS

Advanced Technology For Intelligent Gas Turbines (ATIGAT)



General Configuration

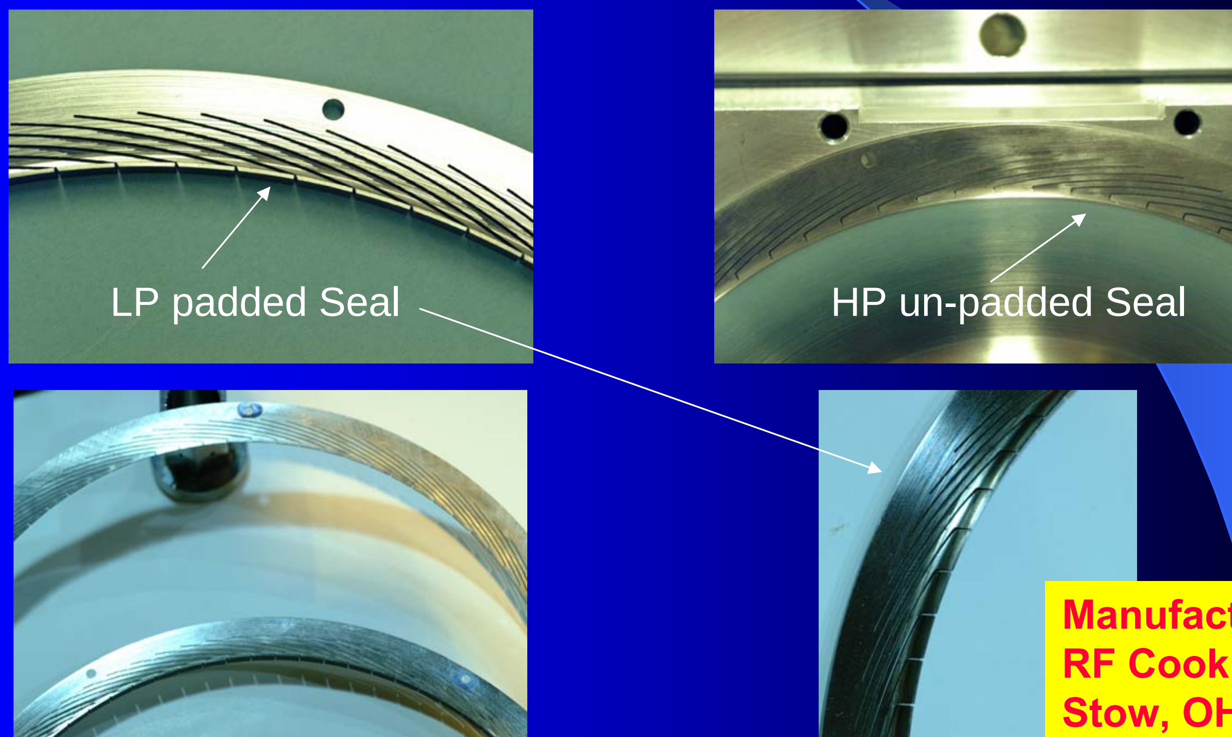




Full Wafer of Padded Fingers (8.5” ID, 9.666” OD, 81 Fingers) and details (b, c) of the Arrangement of the High and Low Pressure Fingers

ACTUAL HARDWARE

Advanced Technology For Intelligent Gas Turbines (ATIGAT)



Manufactured by:
RF Cook
Stow, OH 44224

Padded and Unpadded Sections of HP- and LP-seals

DESIGN PARAMETERS

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

Advanced Technology For Intelligent Gas Turbines

ATIGAT

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.

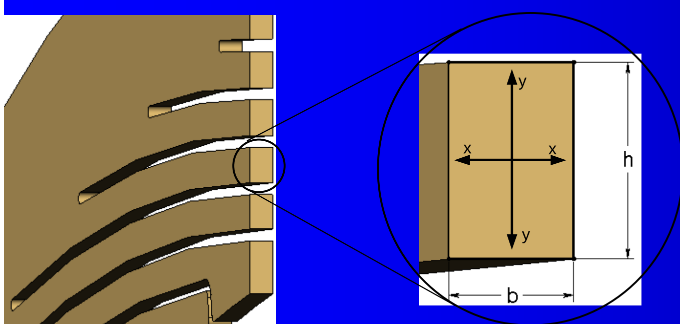
The compliant finger that moves radially outward with rotor growth and motion has to be able to ride the rotor back down as the rotor diameter recovers or the rotor moves "away".

Thus there is an optimum stiffness for the finger;

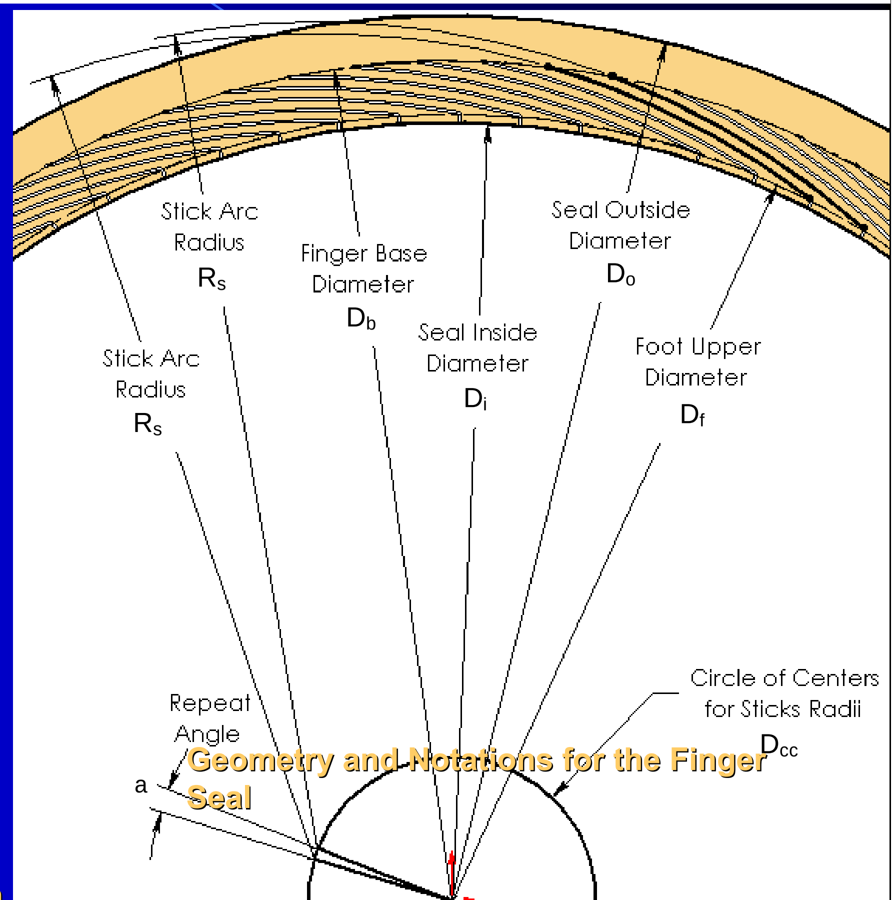
DESIGN PARAMETERS (cont'd)

(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

DESIGN PARAMETERS (cont'd)

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

Variations in Finger Pad Design

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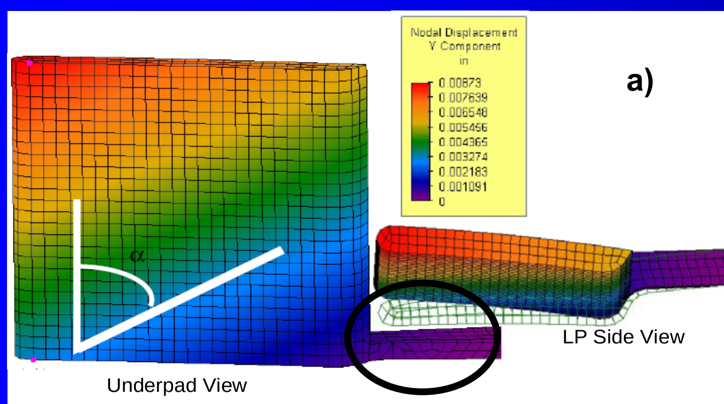
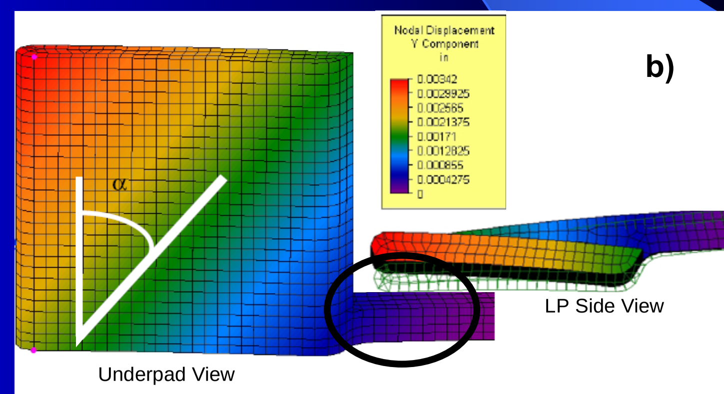
The finger seal obtains its hydrodynamic lifting capabilities from the pattern of the padded fingers underside, which "rides" the surface of the shaft. The objective in the design of the pad was to determine an optimal configuration that would enable the pad portion to lift from the rotating rotor and 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

DESIGN PARAMETERS (cont'd)

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

Variations in Finger Pad Design

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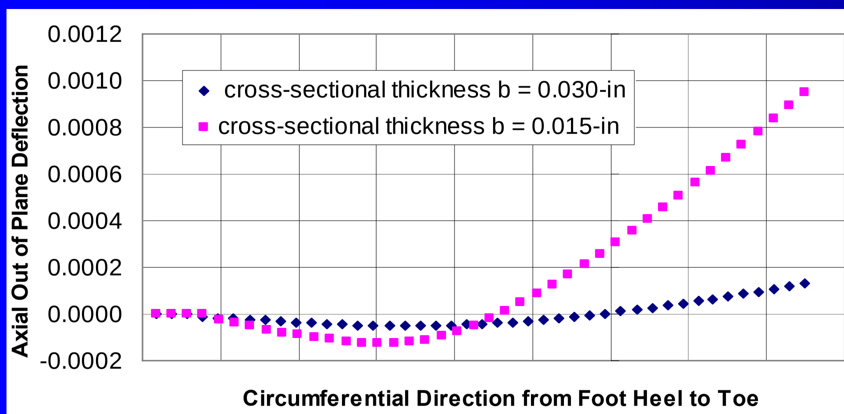
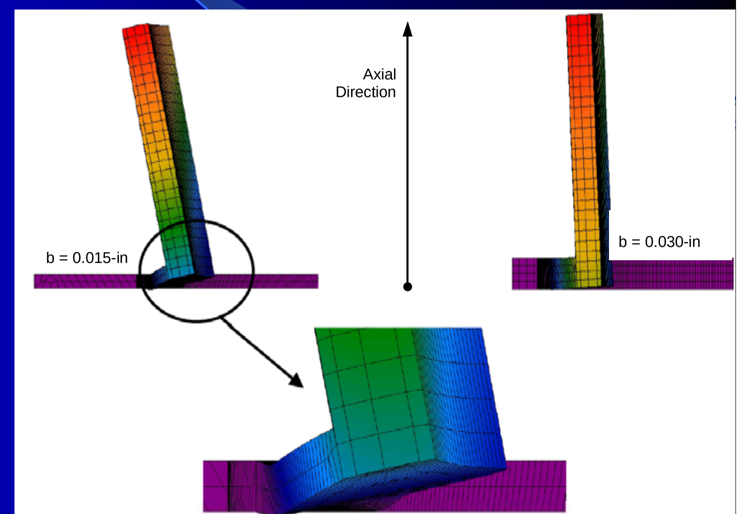


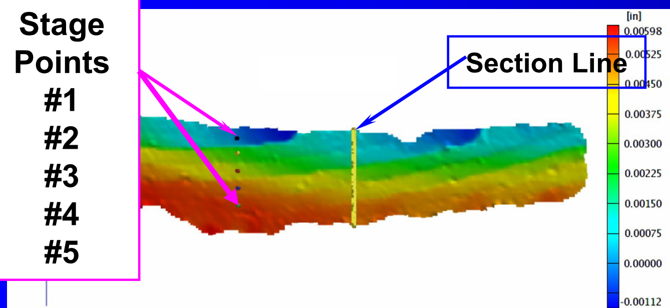
Shape of the underpad surface Axial Out-of-Plane Twisting for Stick Thickness of b=0.015-in and b=0.030-in

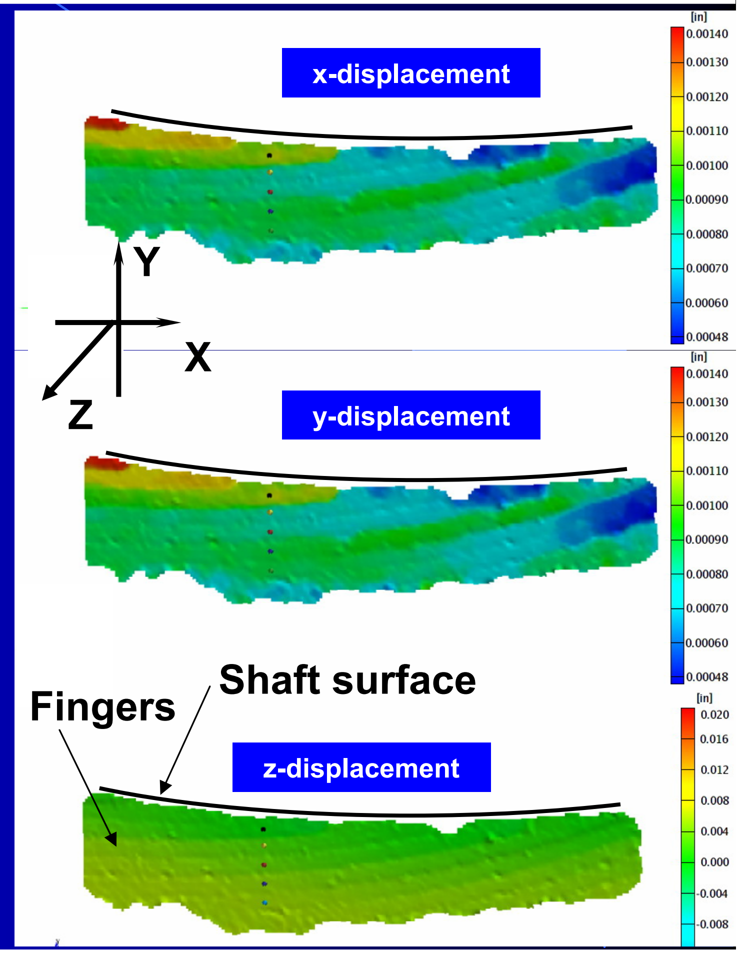


Another view of pad and stick deformation

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.

CONCLUDING REMARKS (1)

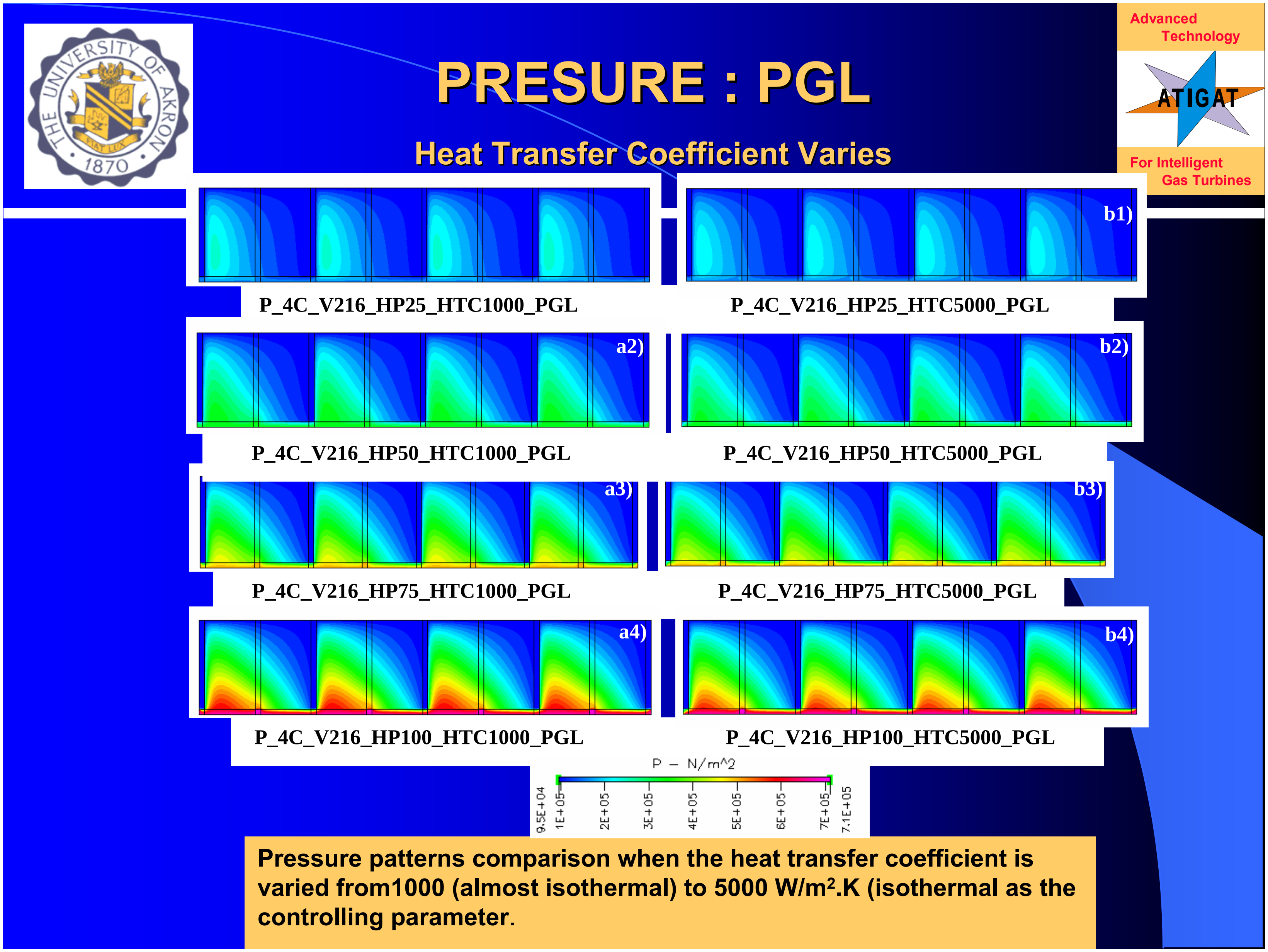
Finger Behavior with Rotating Shaft and Axial Pressure Differential

- 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

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.



PRESURE : PGL
Heat Transfer Coefficient Varies
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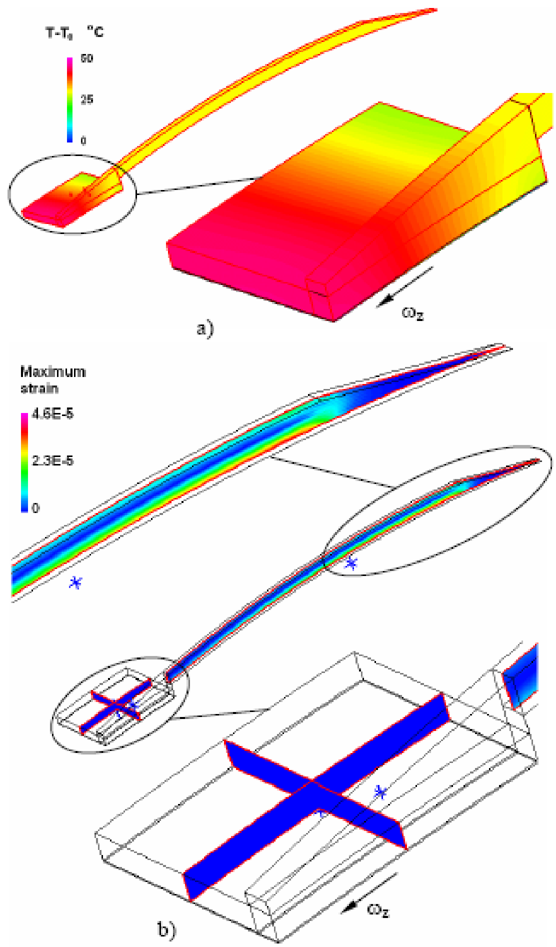
THE UNIVERSITY OF AKRON 1870
b1)
P_4C_V216_HP25_HTC1000_PGL
P_4C_V216_HP25_HTC5000_PGL
a2)
b2)
P_4C_V216_HP50_HTC1000_PGL
P_4C_V216_HP50_HTC5000_PGL
a3)
b3)
P_4C_V216_HP75_HTC1000_PGL
P_4C_V216_HP75_HTC5000_PGL
a4)
b4)
P_4C_V216_HP100_HTC1000_PGL
P_4C_V216_HP100_HTC5000_PGL
P – N/m^2
9.5E+04
1E+05
2E+05
3E+05
4E+05
5E+05
6E+05
7E+05
7.1E+05
Pressure patterns comparison when the heat transfer coefficient is varied from1000 (almost isothermal) to 5000 W/m².K (isothermal as the controlling parameter.



(a) Temperature and (b) strain in the pad and leg. Adiabatic conditions, 20,000rpm

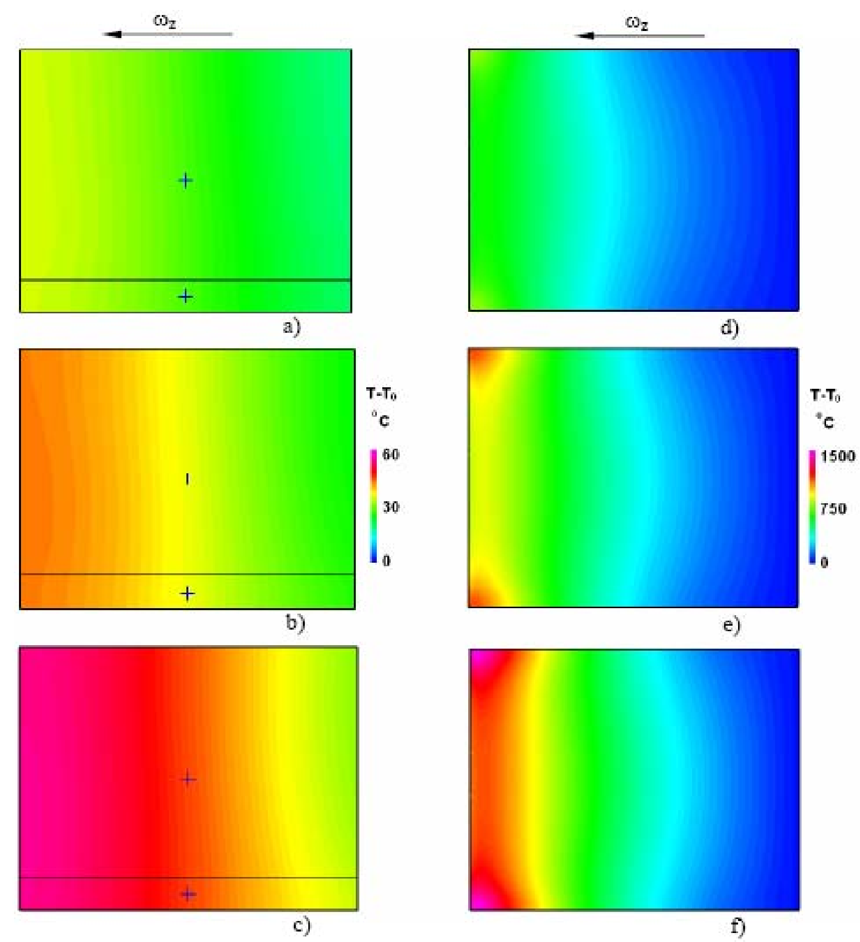


Figure 8. Temperature on the bottom of the pad for moving fingers (a, b, c) and rigid fingers (d, e, f). Shaft rotates at 20,000 rpm (a, d), 30000 rpm (b, e) and 40000 rpm (c, f) respectively. Temperature boundary conditions are shown in Figure 3c.

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EXPERIMENTAL WORK

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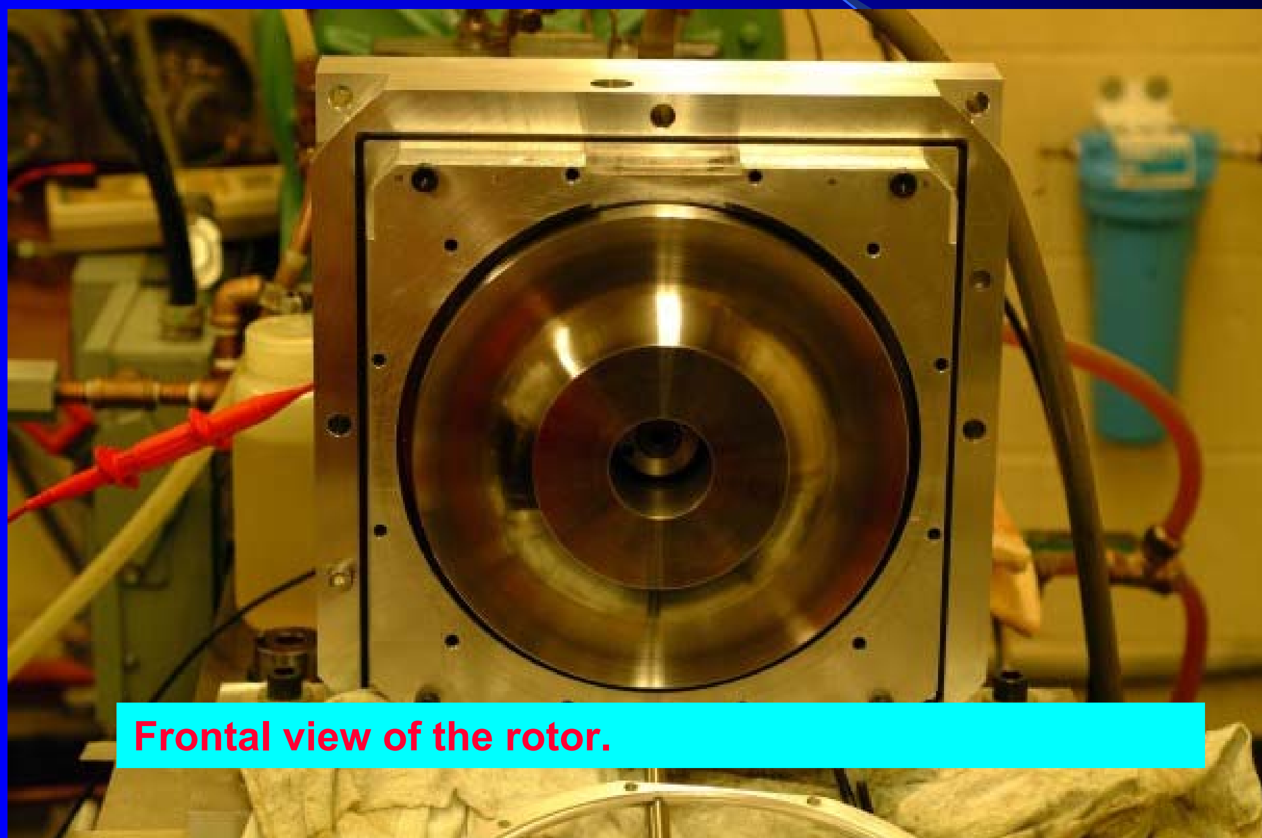
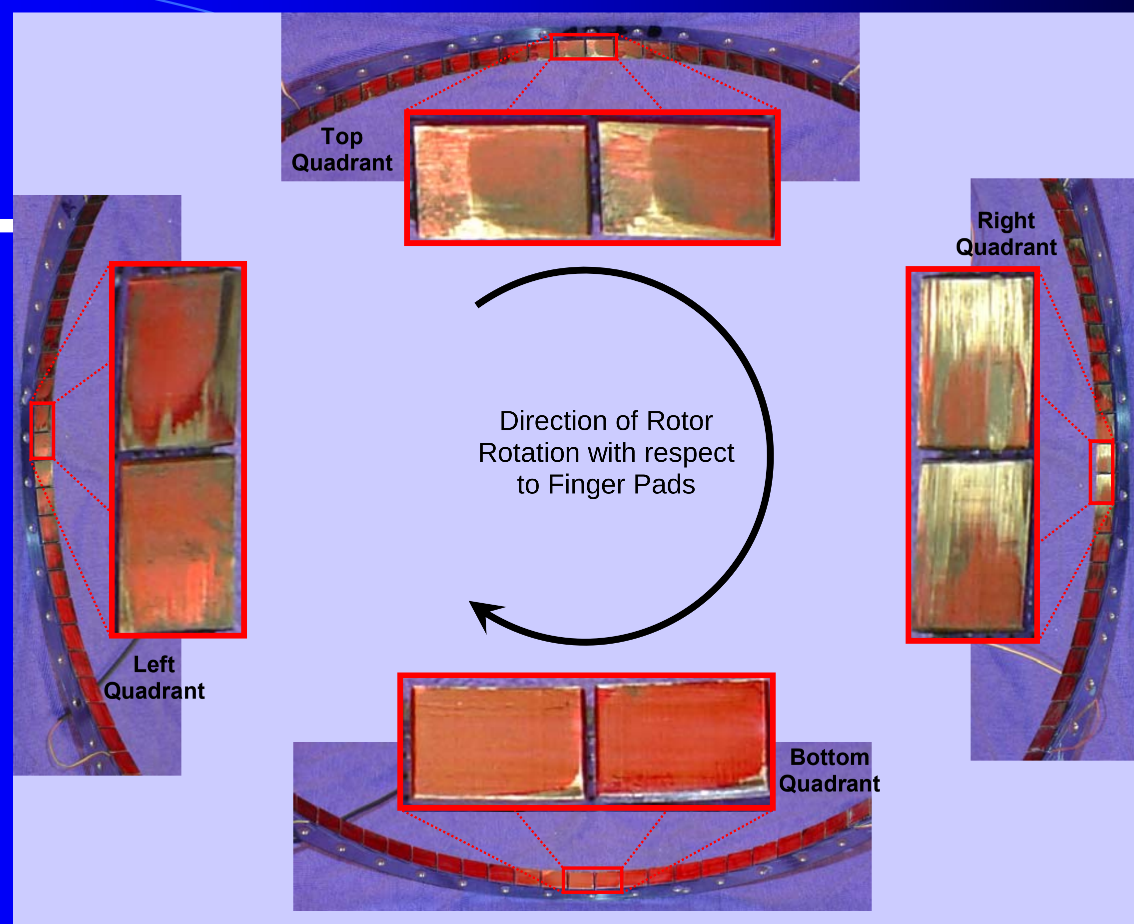
ROTOR: FRONTAL VIEW



Frontal view of the rotor.



Circumferential Wedge Pad Laminate: 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

Experiment Objectives

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- Obtain performance data on various finger seal designs and configurations
- Gain a better understanding of finger seal functionality, in order to foster future compliant seal concepts

Seal Assembly

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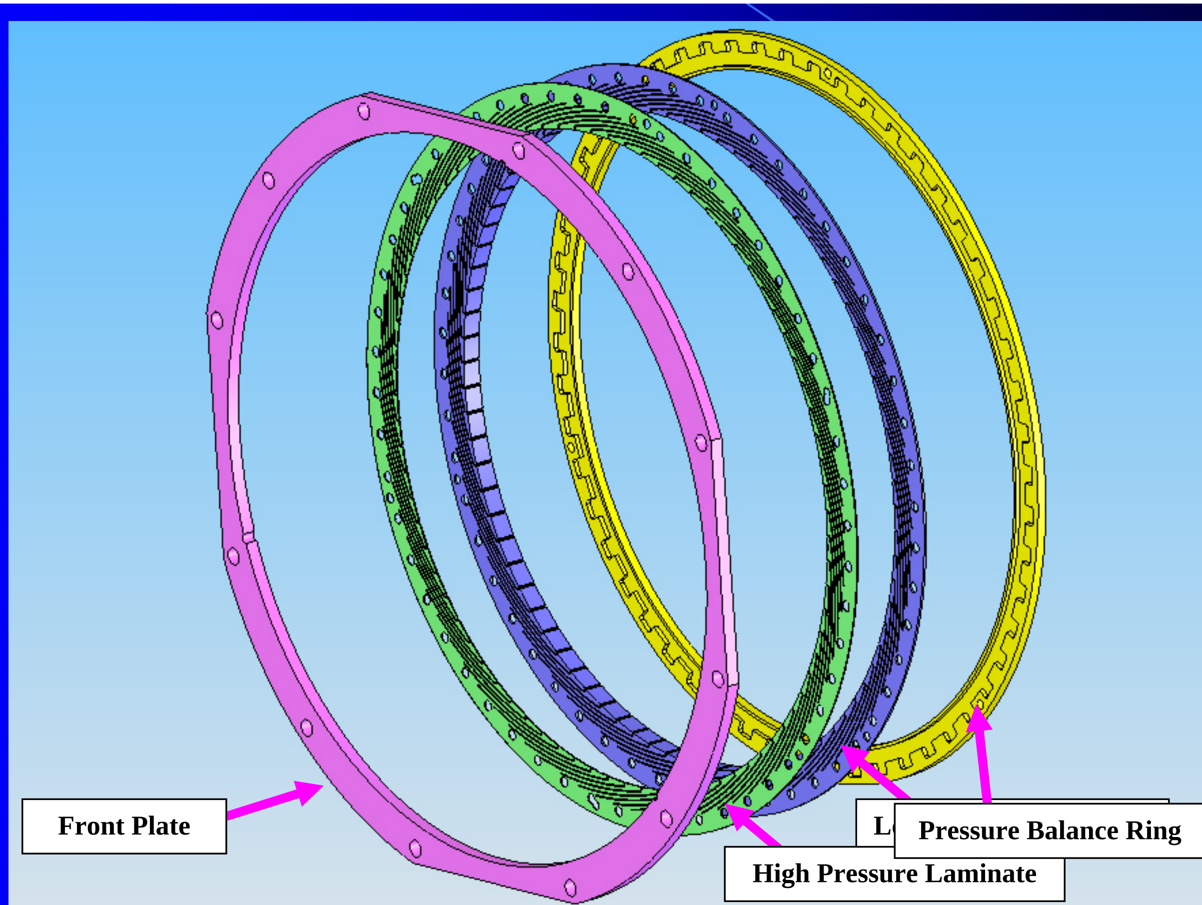
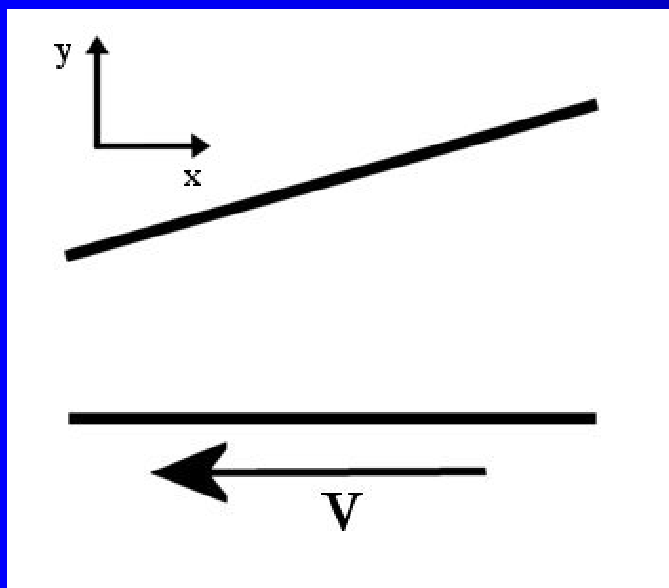
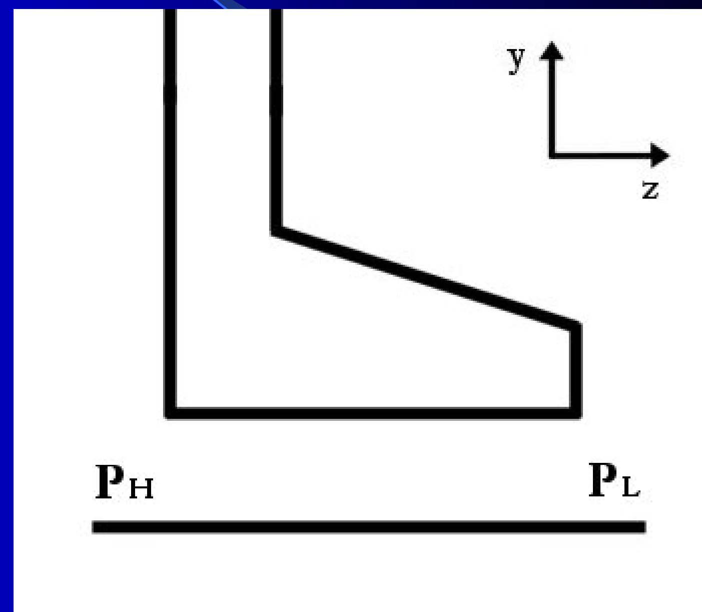


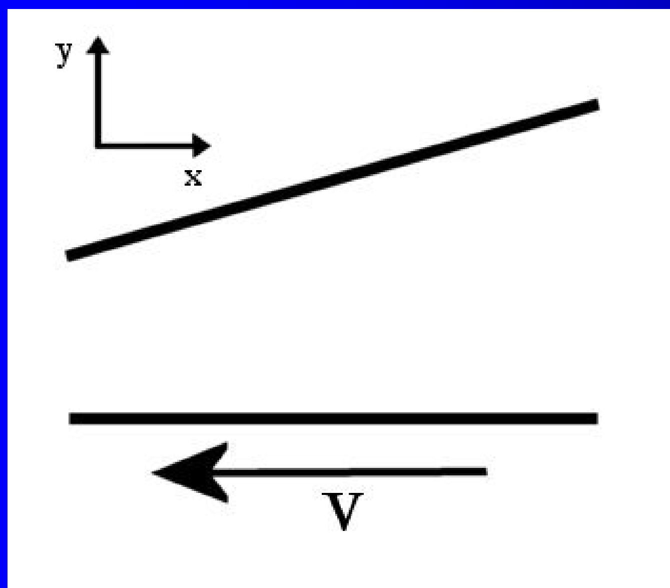
Single Wedge Pad Geometry

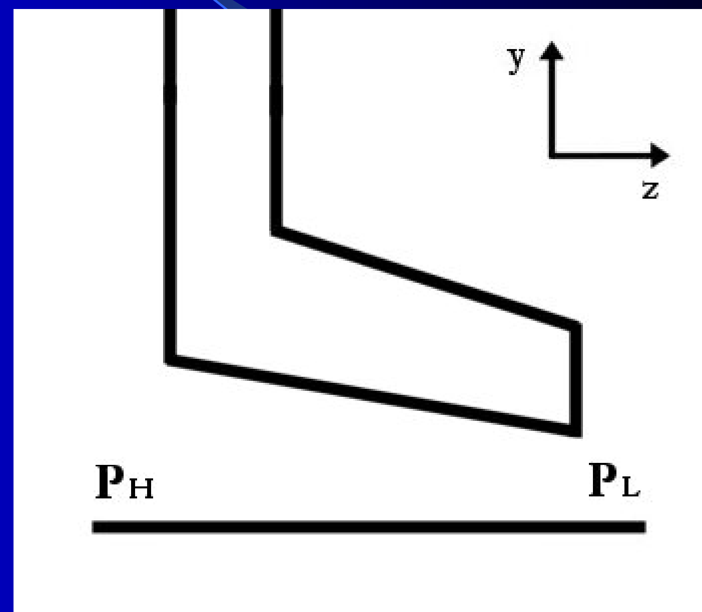




- Converging circumferential wedge accelerates air entrained by rotor surface, generating a lifting force under each pad

Double Wedge Pad Geometry





- Converging axial wedge generates additional lift from escaping air

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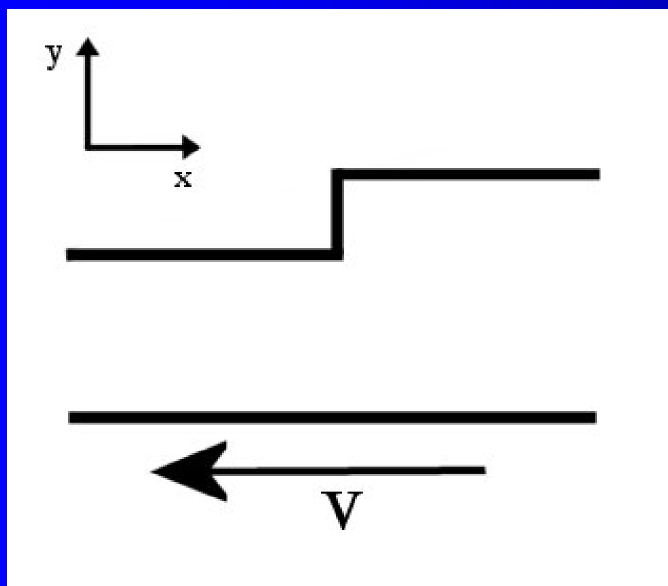
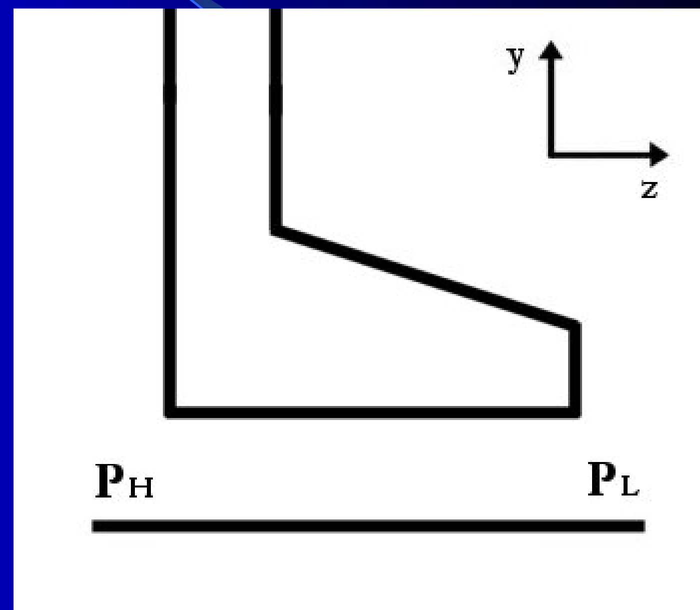
Step Pad Geometry

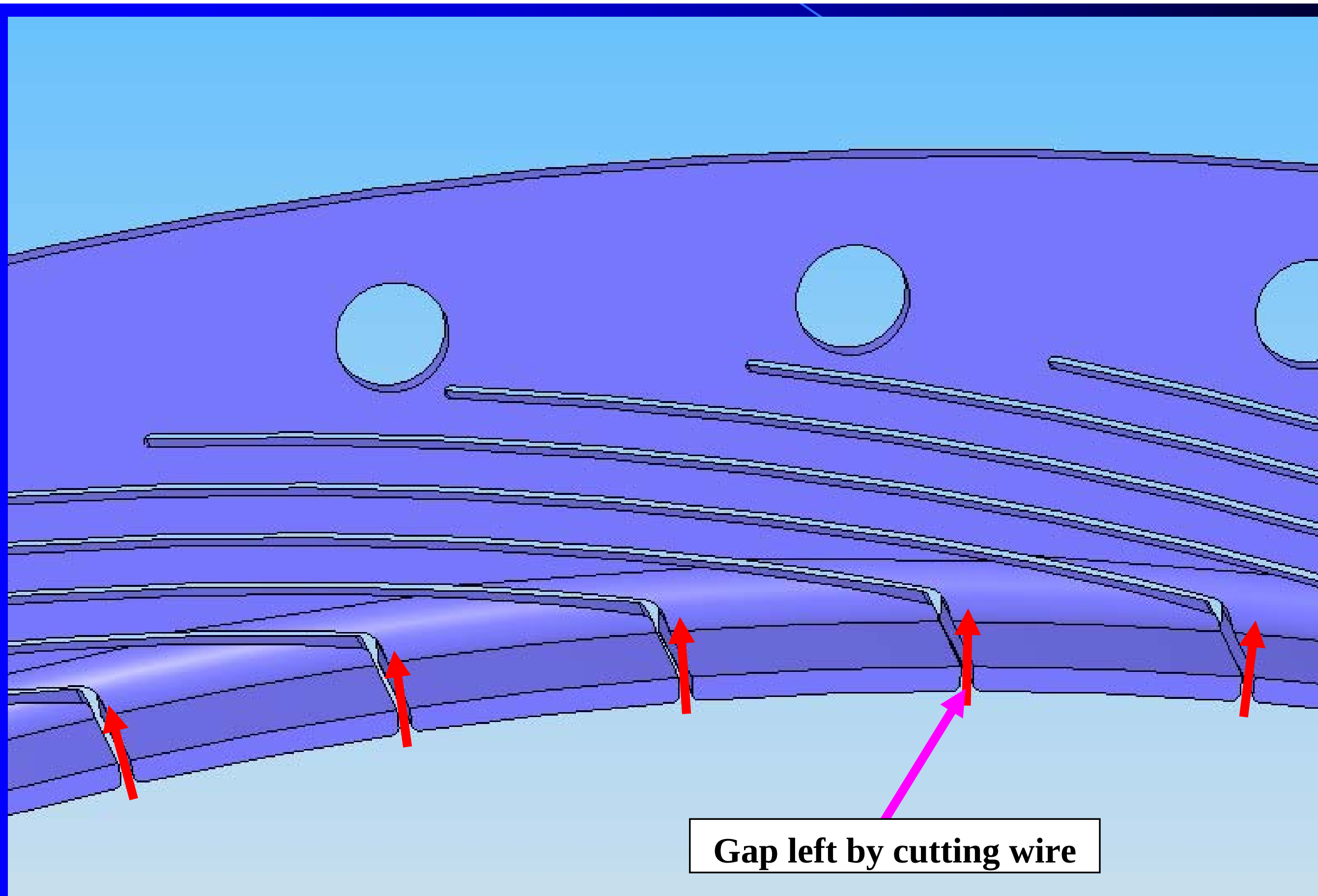




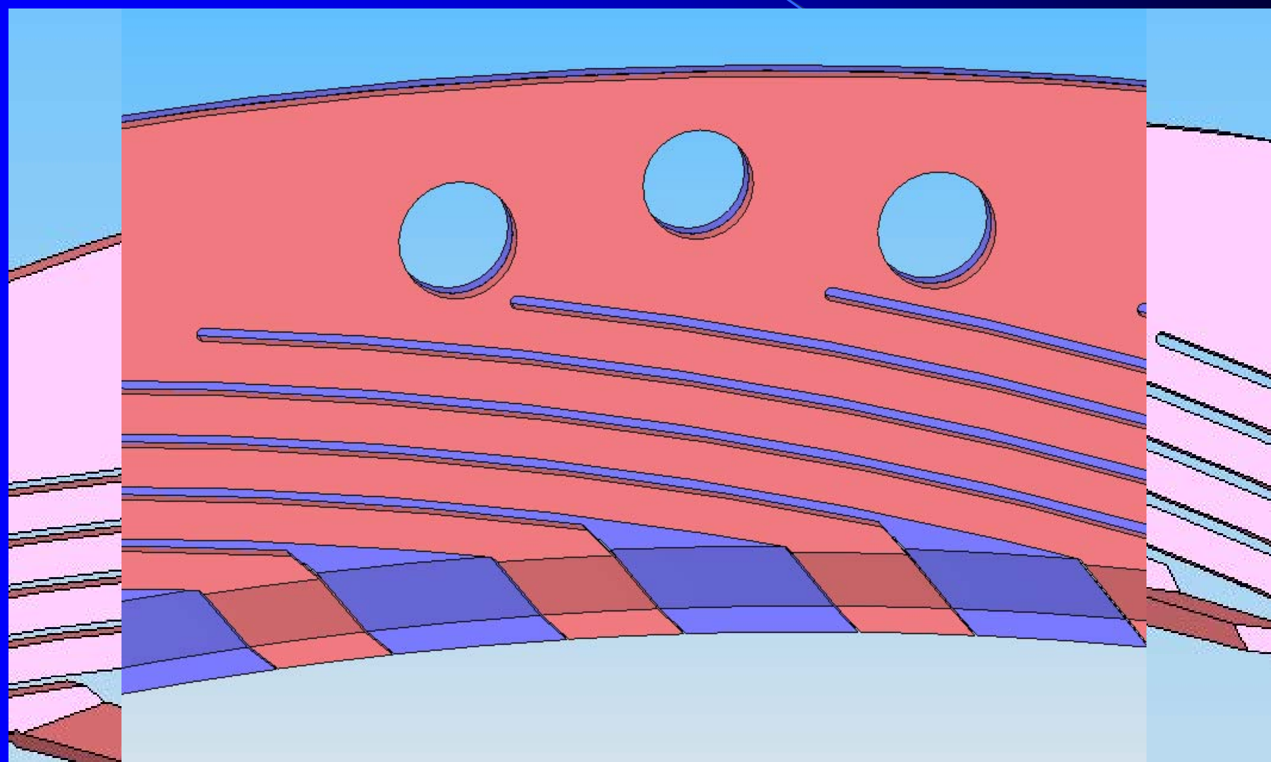
Design Goals of the Double Pad

- Provide lifting ability to both the high and low pressure laminates
- Reduce leakage paths between adjacent finger pads

Design Goals of the Double Pad



Design Goals of the Double Pad



- Interlocking pads cut down leakage and create a continuous lifting surface

Front Plate Designs

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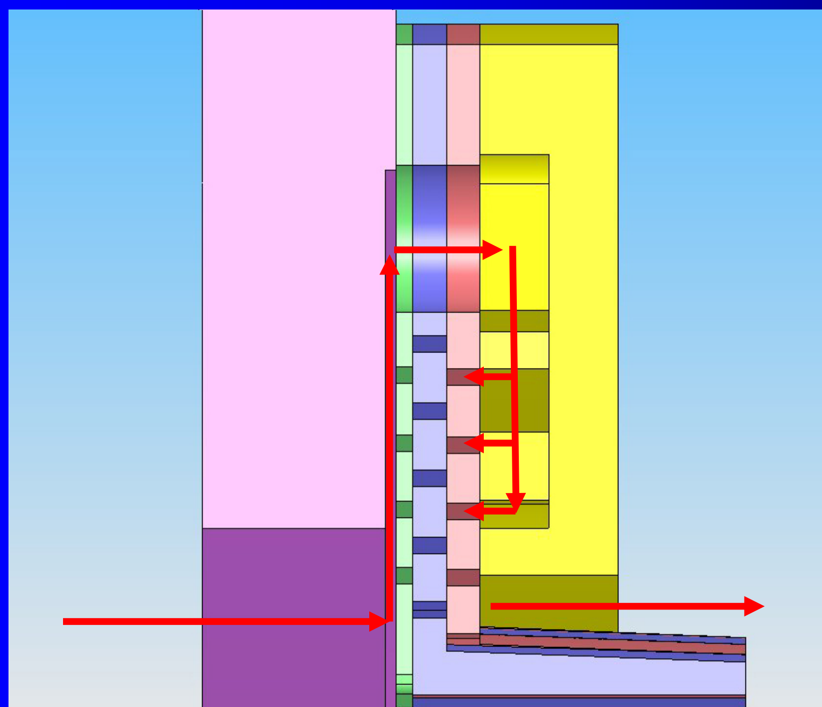

- Original front plate allows upstream air to pass directly through to the pressure balance ring
- Decreasing front plate inner diameter restricts flow through the pressure balance ring

Procedure for Dynamic Testing

- Establish pressure differential of 10 psi
- Accelerate rotor to 5,000 RPM
- Allow pad temperatures to stabilize
- Repeat for 7,500, 10,000, 12,500, and 15,000 RPM
- Bring rotor to a stop
- Detach and examine seal for wear marks in ink

Effect of Rotor Speed on Flow

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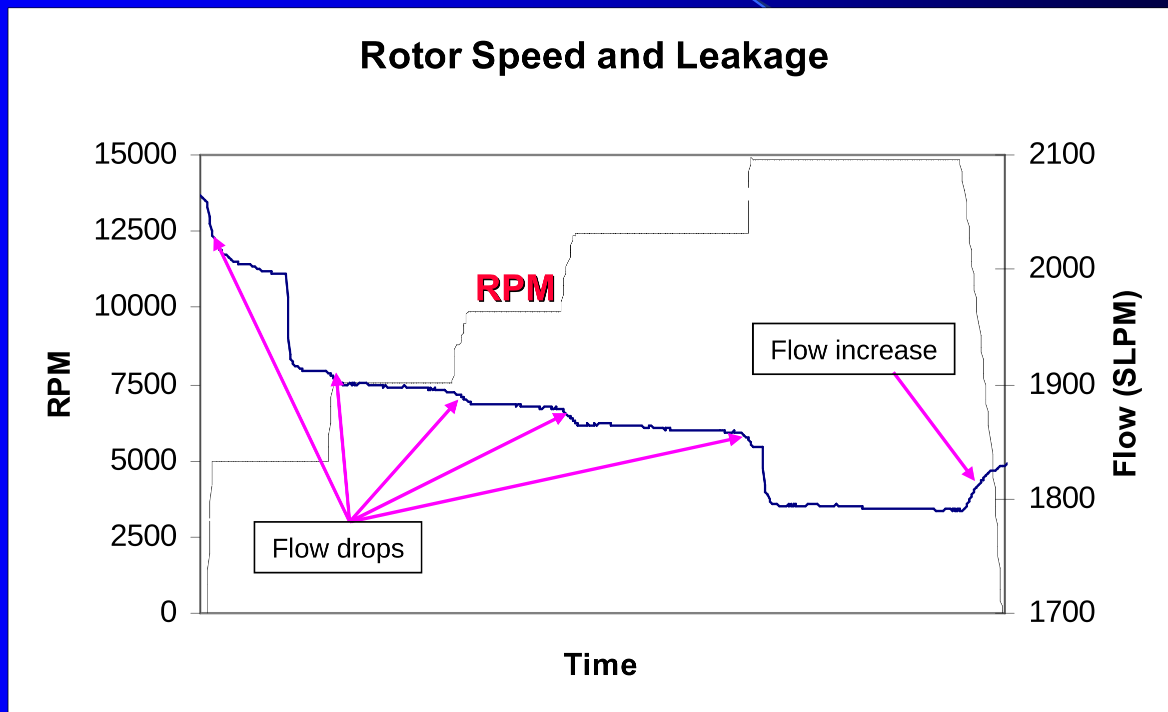
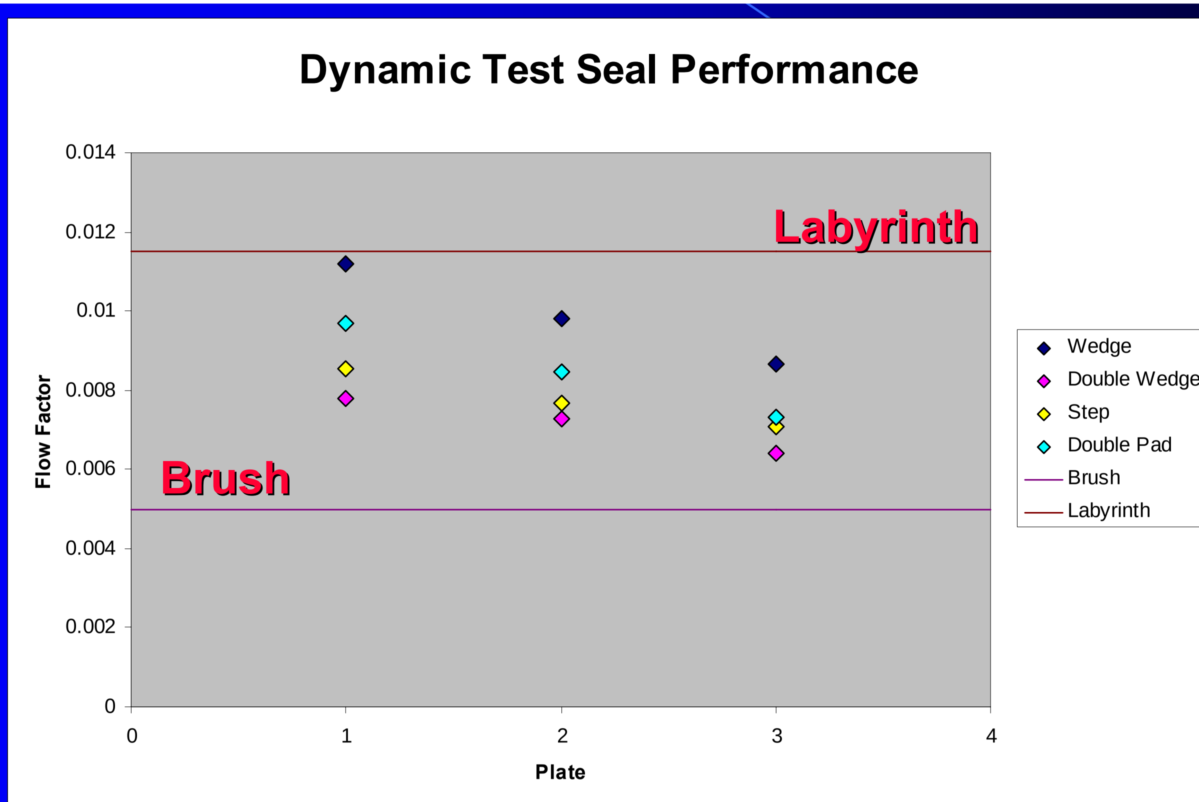


- Moving rotor surface creates a resistance to flow
- This can be seen when leakage drops at each increase in speed, and increases when the rotor is brought to a stop

Effectiveness of All Seal/Plate Combinations



Operating Conditions – 10 psi, 70° F, 15,000 RPM

Thermocouple Locations for Monitoring Pad Touchdowns

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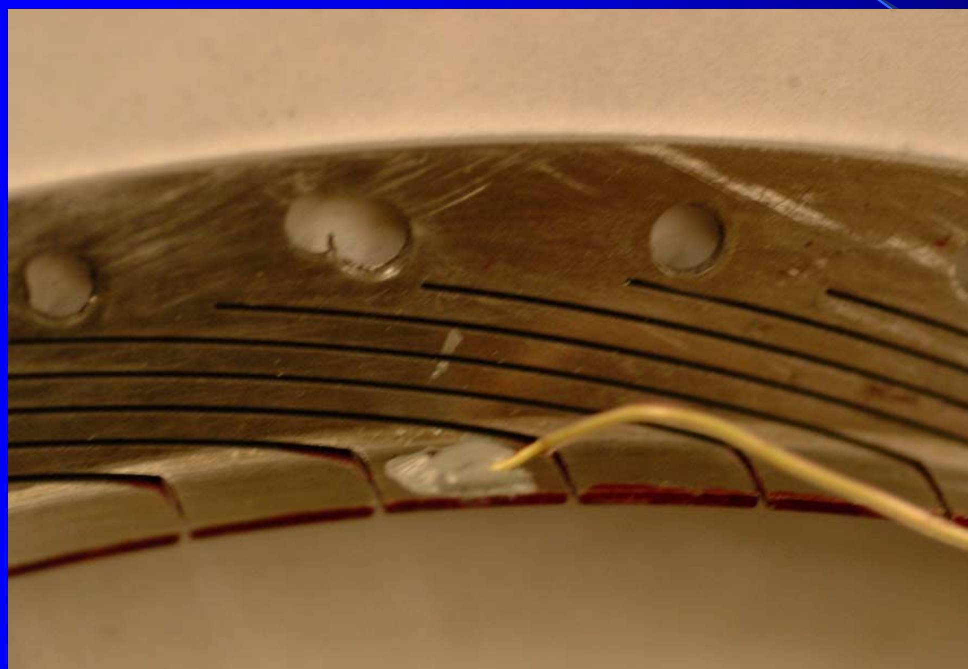
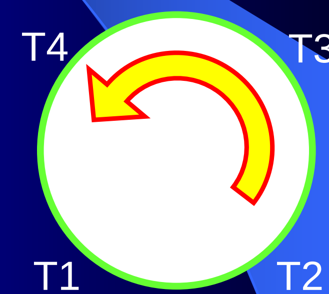
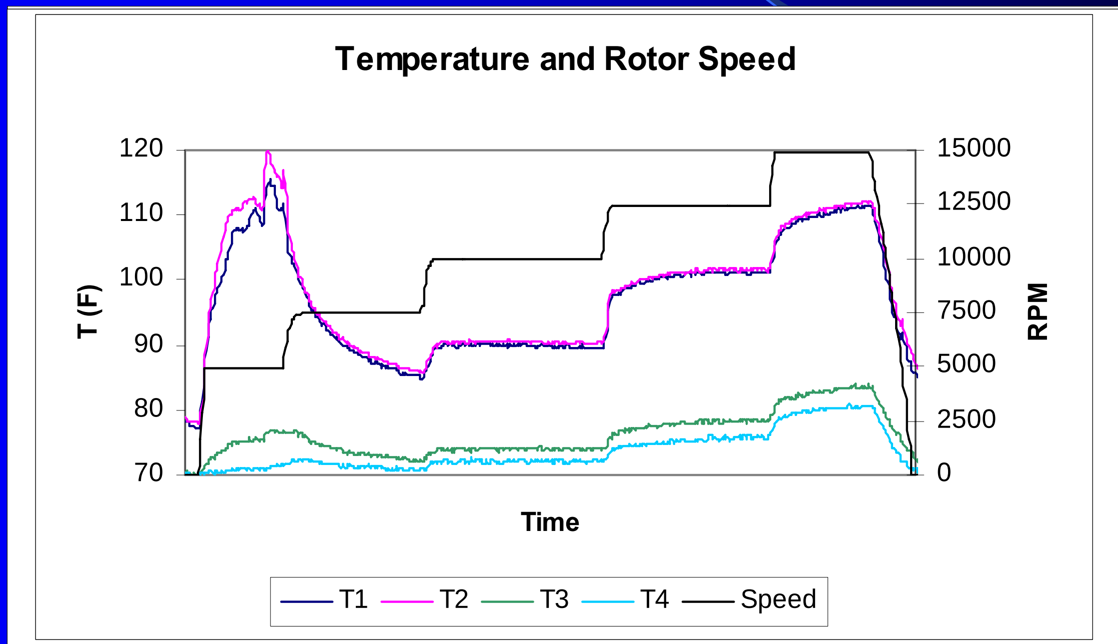


The Locations View from Front of Test Section



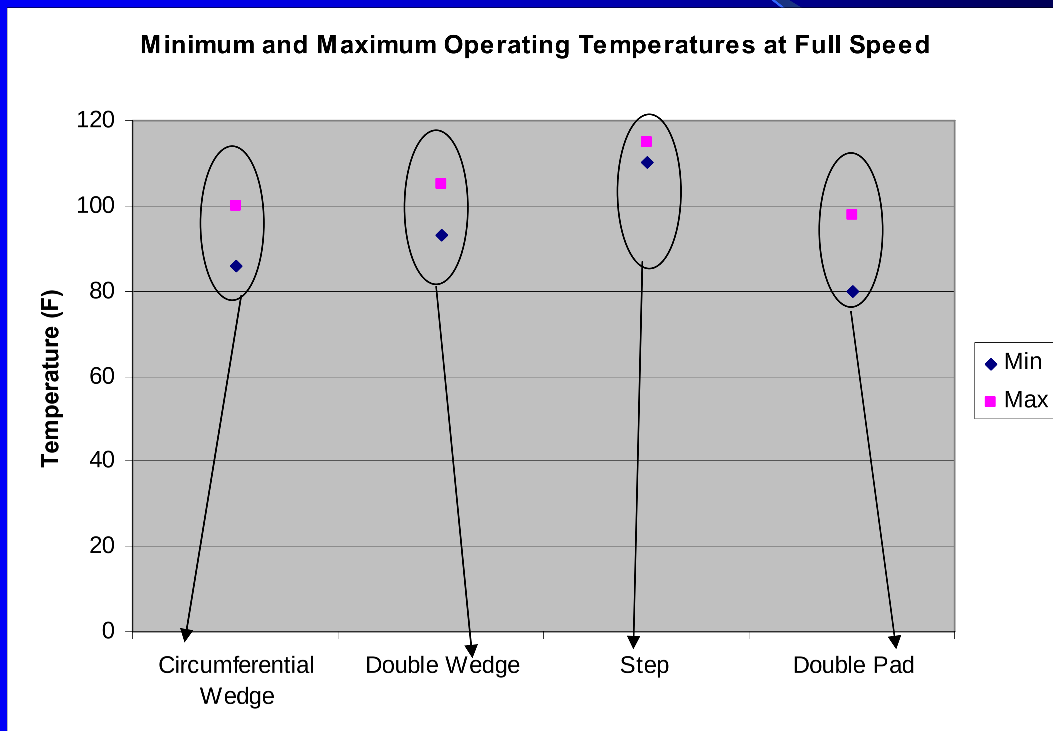
- Thermocouples are bonded by epoxy to the tops of finger pads in 4 locations

Typical Temperature Behavior



- Temperature closely follows speed profile
- Finger pad rubbing can be clearly seen

Dynamic Test Temperature Variation



Operating Conditions – 10 psi, 70° F, 15,000 RPM

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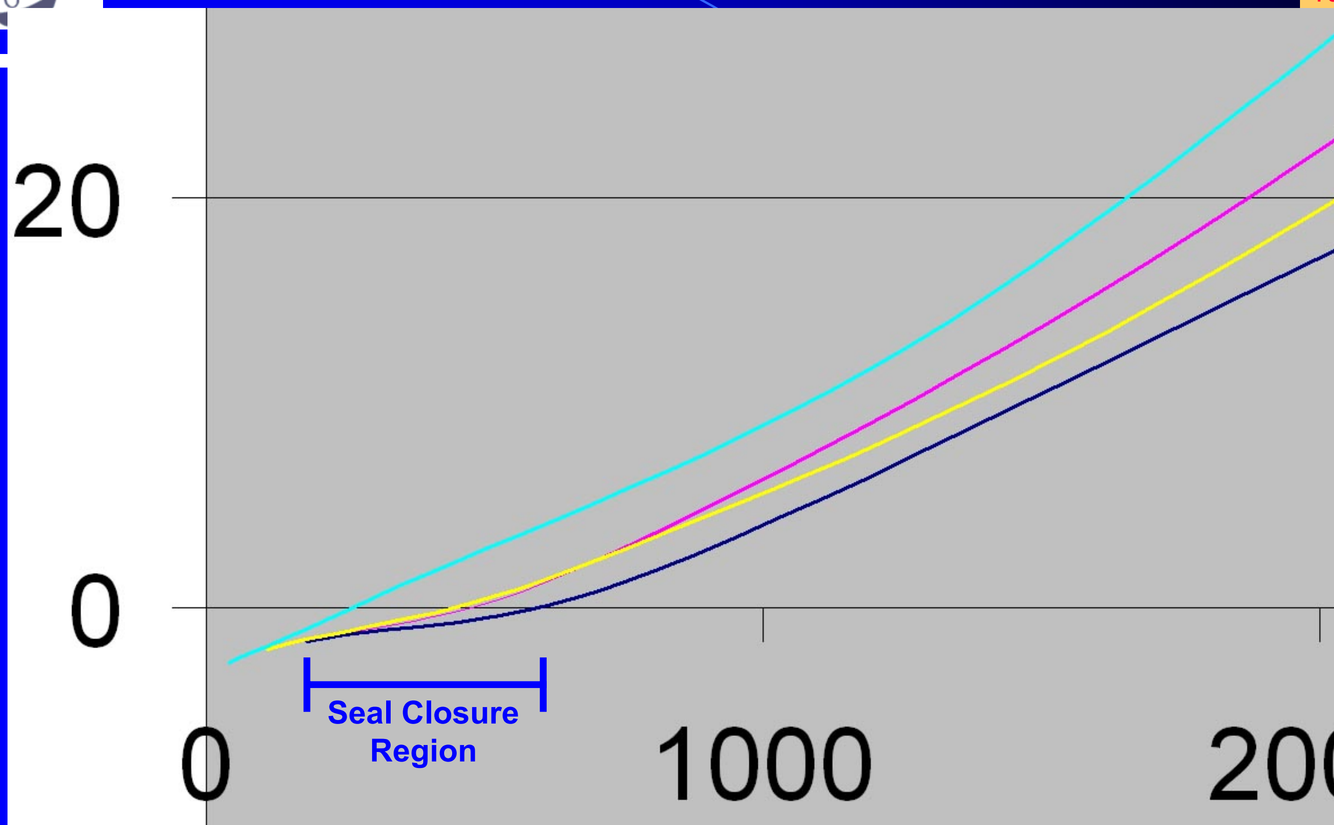
Static Test Procedure

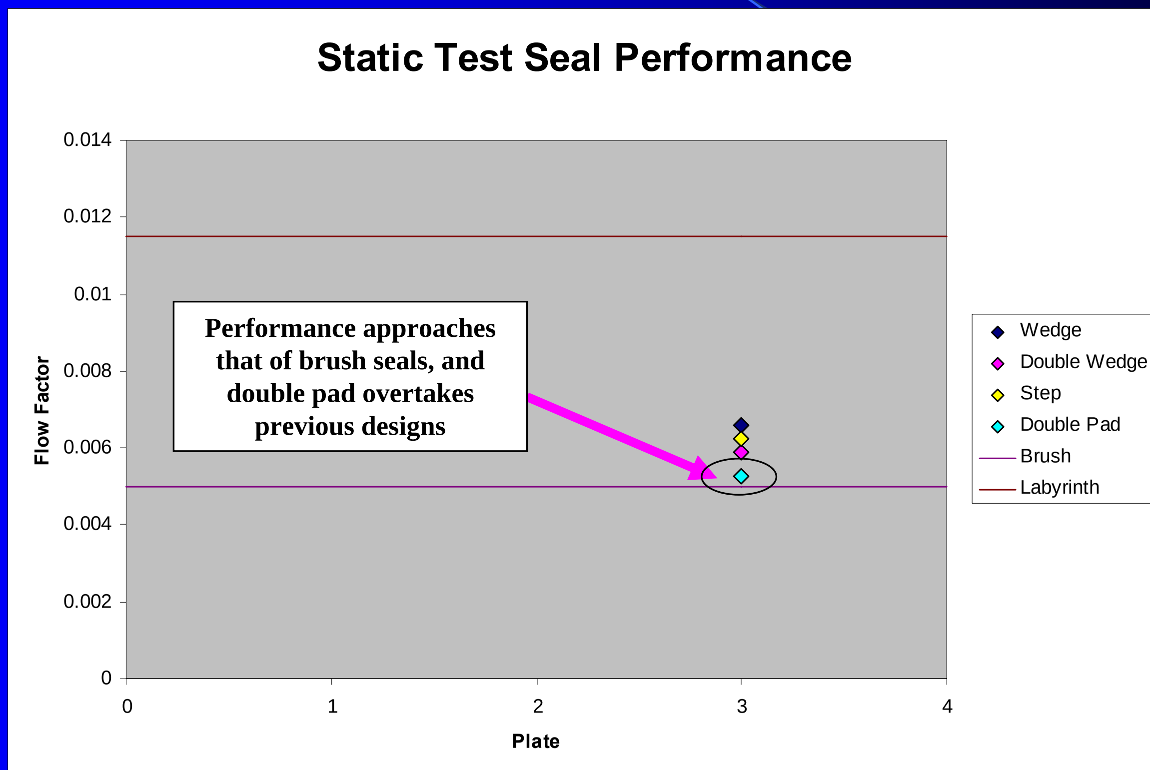
- Each seal type is assembled with front plate 3
- Flow into the test section is brought from full close to full open over a short amount of time
- The established test section pressure is plotted versus flow

Maximum Static Test Pressure

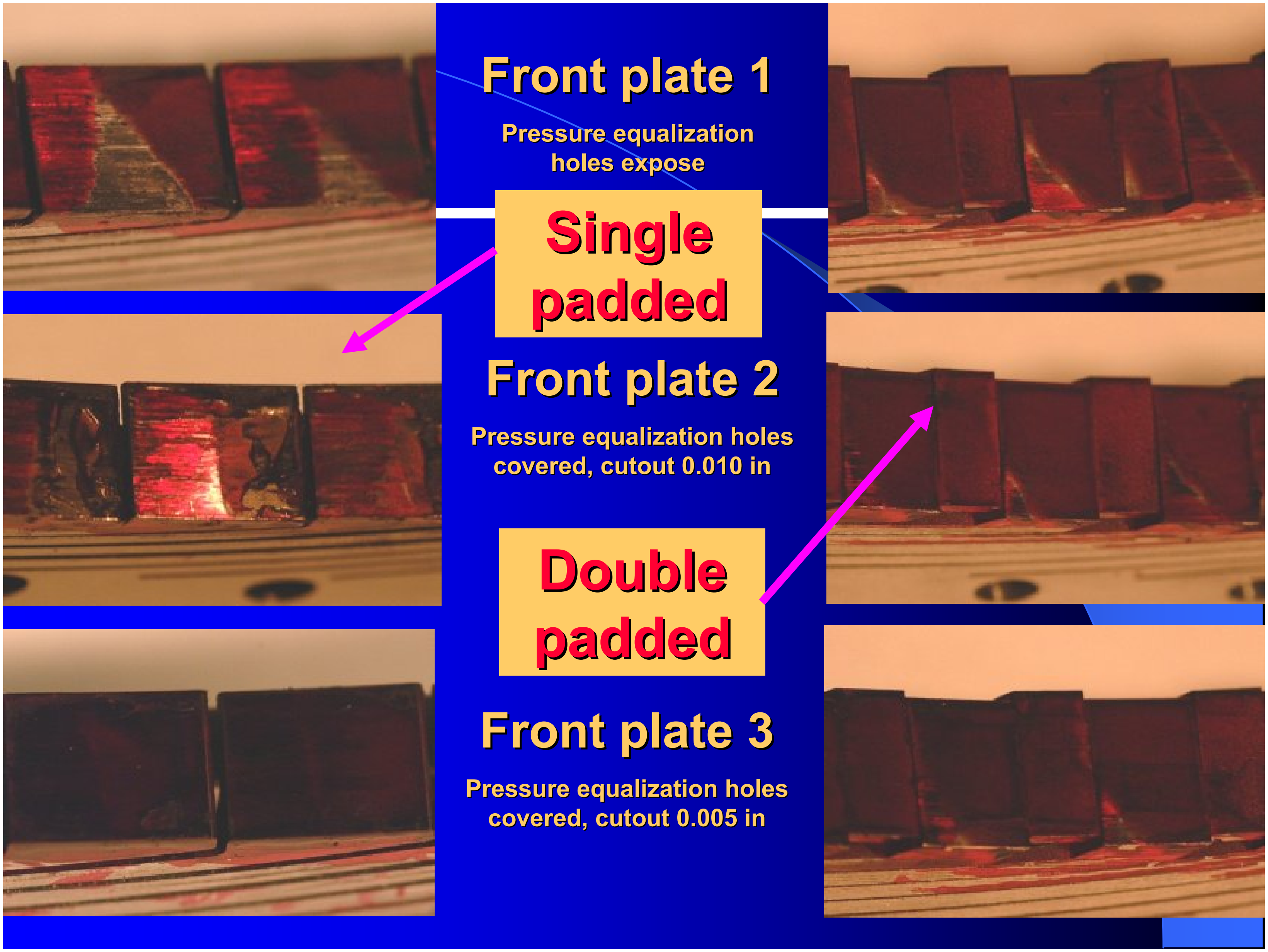


Operating Conditions – 3rd Front Plate, 70° F, 0 RPM

Seal Effectiveness at 60 psi



Operating Conditions – 3rd Front Plate, 60 psi, 70° F, 0 RPM


Front plate 1
Pressure equalization holes expose
Single padded
Front plate 2
Pressure equalization holes covered, cutout 0.010 in
Double padded
Front plate 3
Pressure equalization holes covered, cutout 0.005 in

Conclusions

- All seal types have been shown to lift effectively, and experience only minor wear during startup
- The double pad design outperforms previous seals, providing lower operating temperatures, and less leakage at higher pressures
- Future experimentation at higher pressures, temperatures, and operating speeds will show the full potential of finger sealing technology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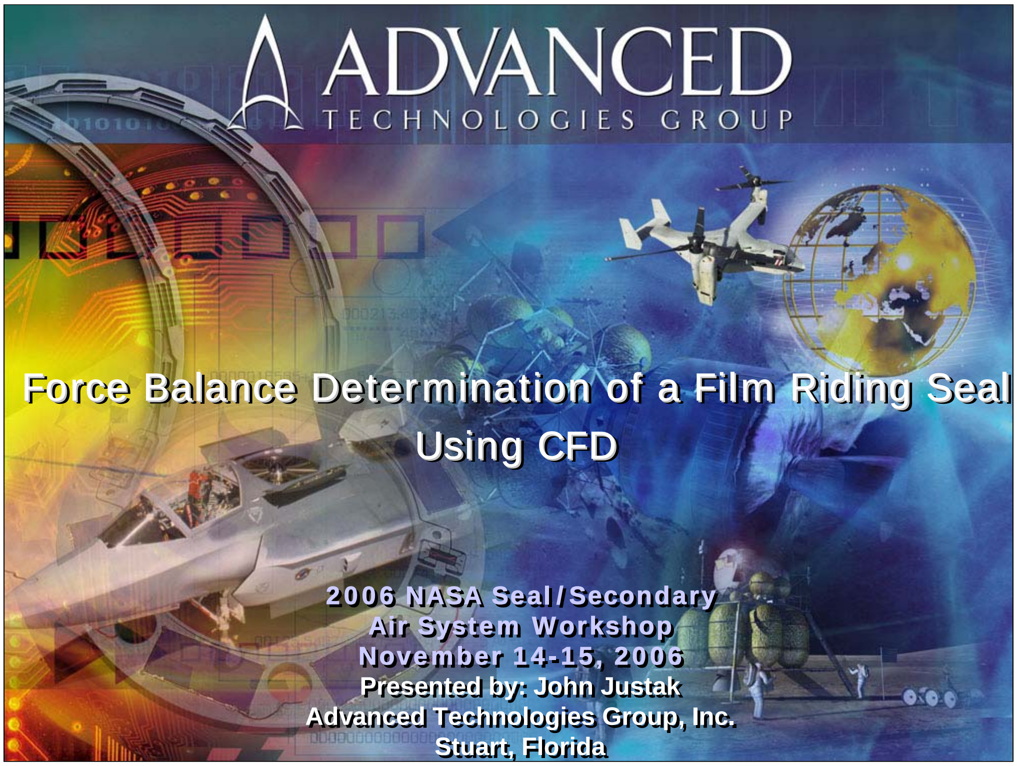
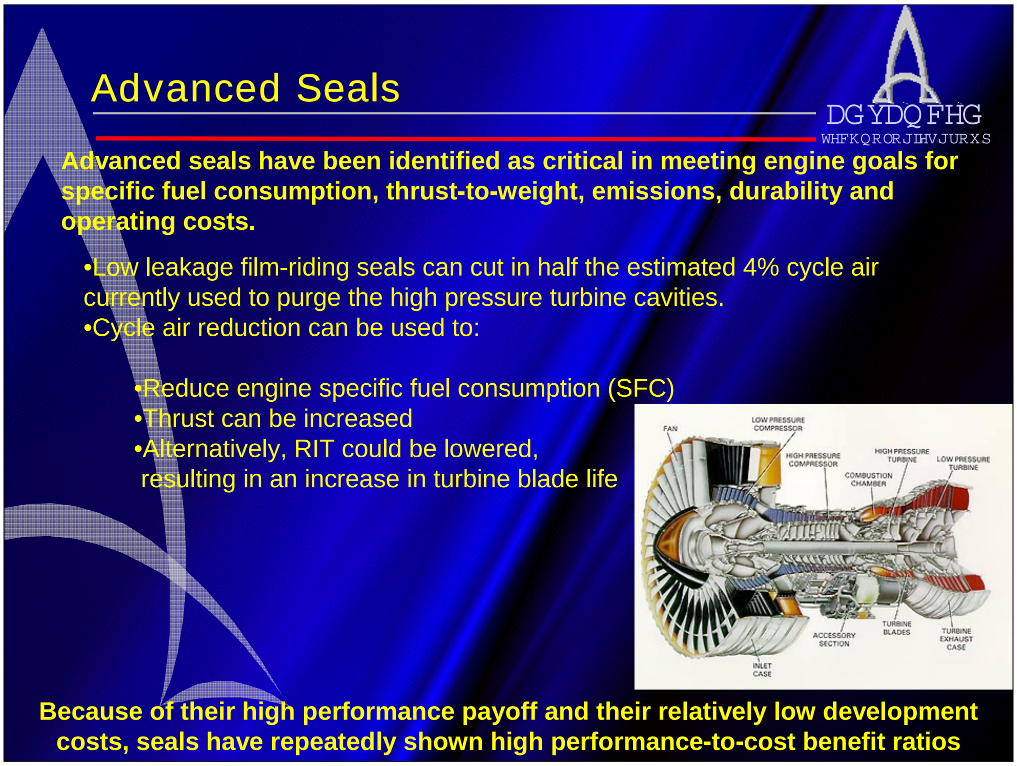
That is all folks

FORCE BALANCE DETERMINATION OF A FILM RIDING SEAL USING CFD

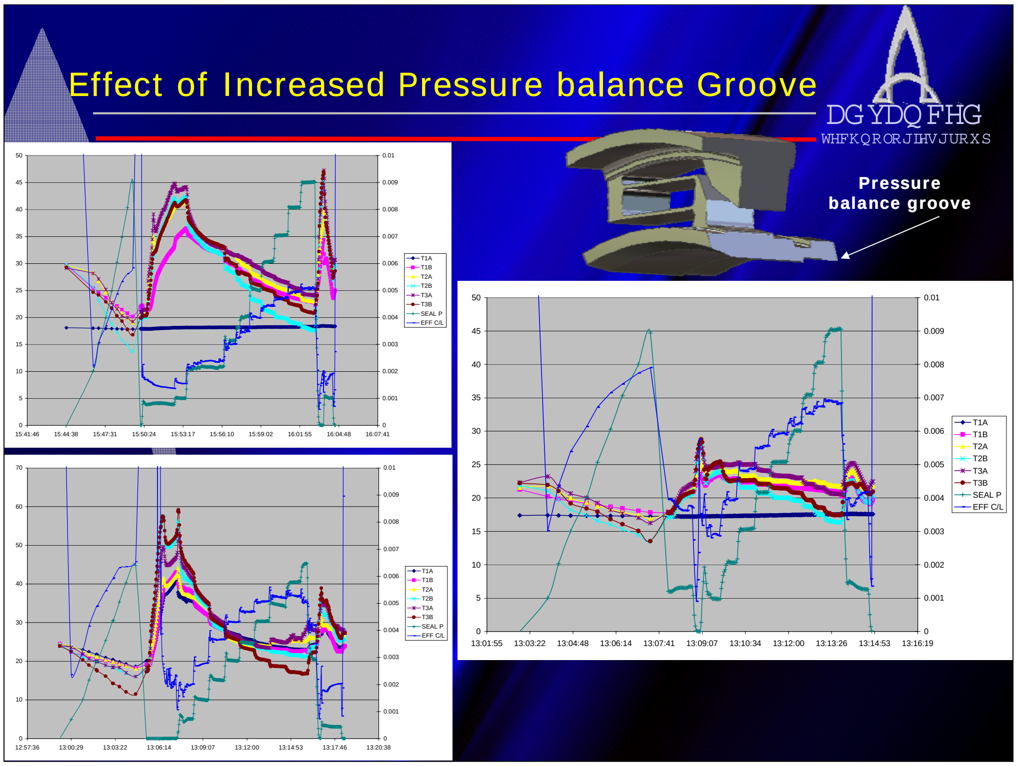
John Justak
Advanced Technologies Group, Inc.
Stuart, Florida



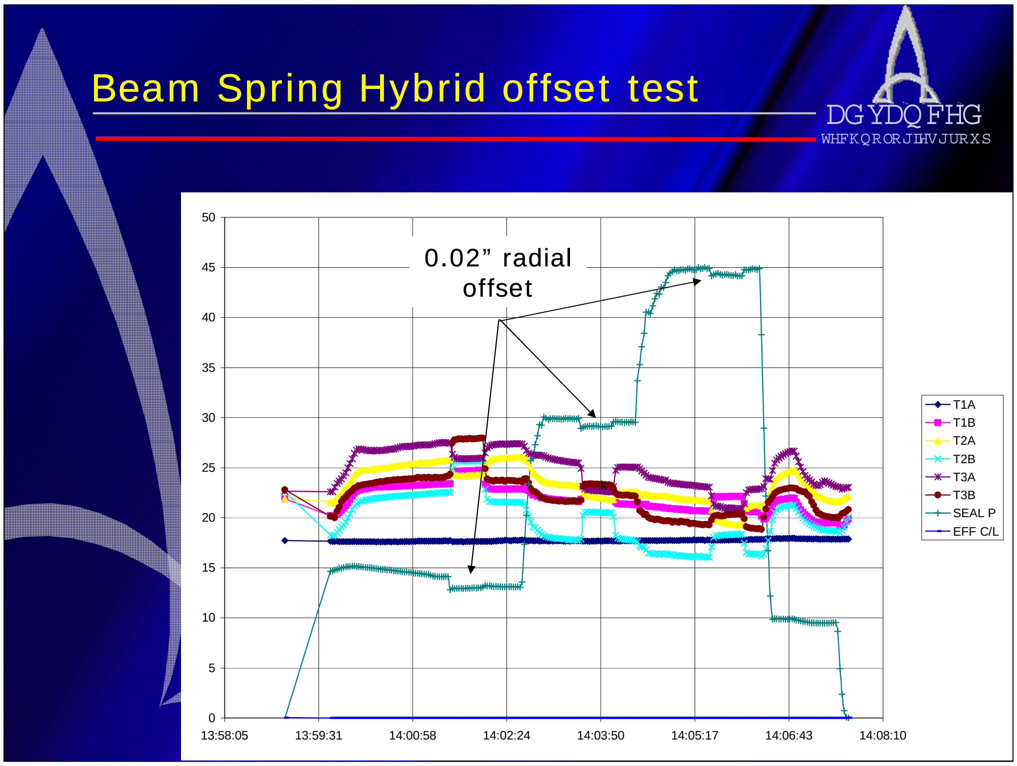


The benefits of Advanced seals can be utilized in every compartment on the engine. IN addition, industrial gas turbines and steam turbines will benefit as well as cryogenic turbomachinery. Advanced Gas turbine seals continue to be one of the key components in the development of future engines.

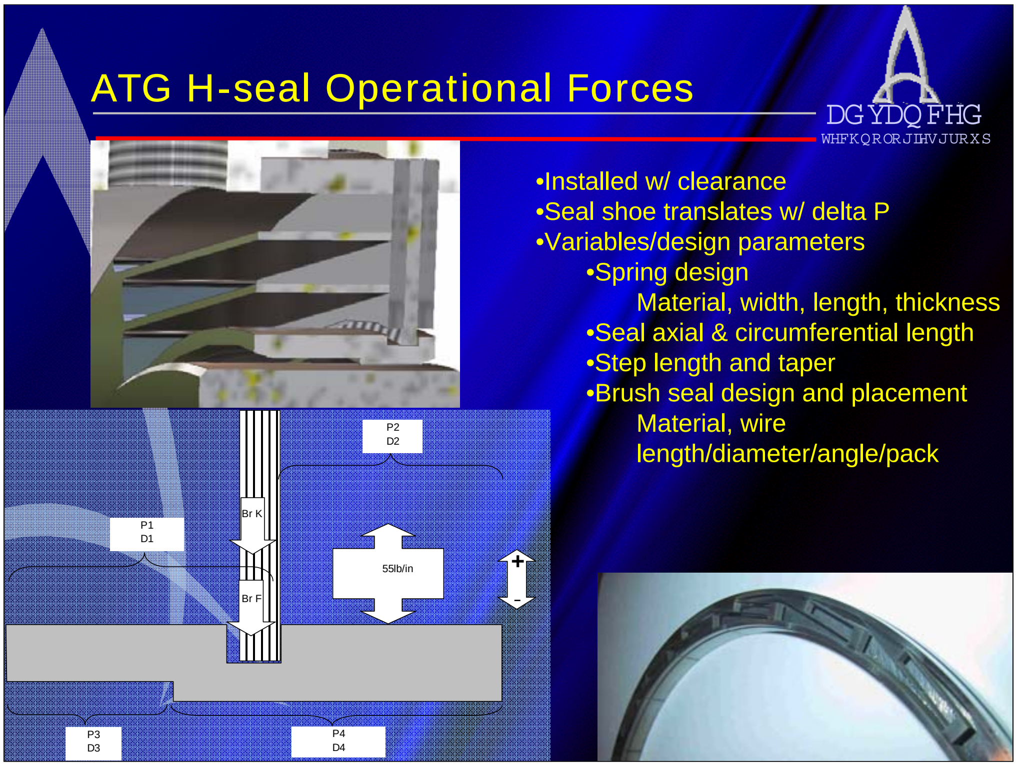
The ATG H-seal utilizes hydrostatic pressures to provide a compliant seal surface. The seal surface is supported by a spring housing that is "soft" radially and stiff axially. The seal utilizes a brush seal as a secondary seal which also provides damping for the hydrostatic bearing surface. The seal components can be modified to handle large radial and axial excursions as well as high temperature and pressure.



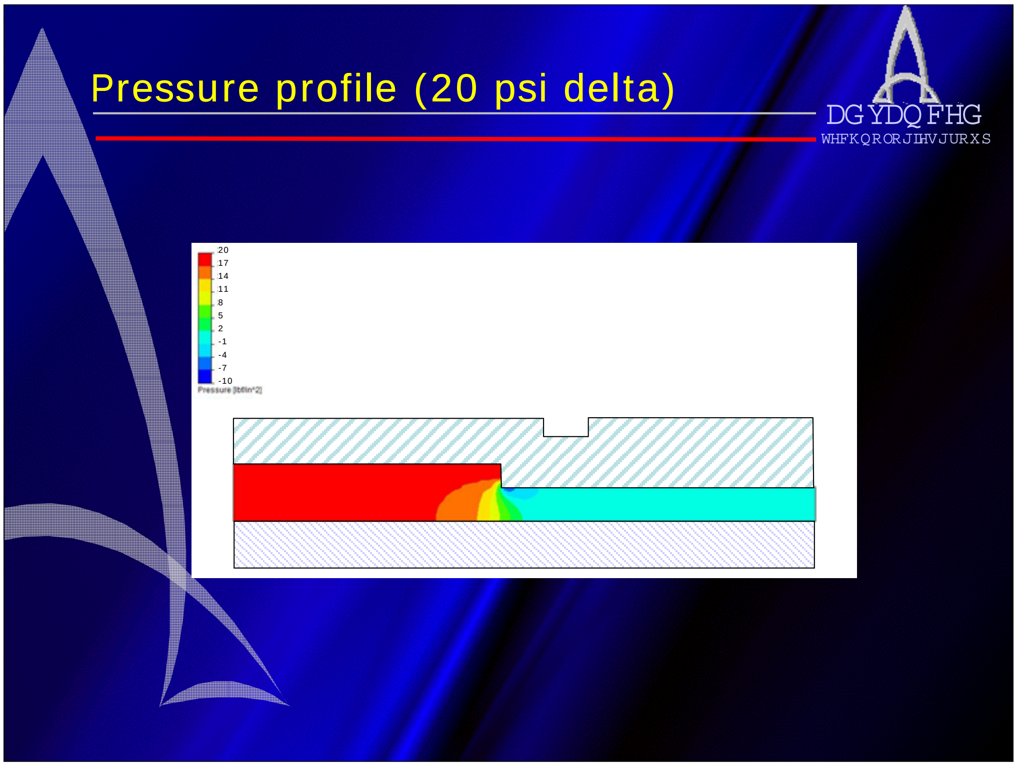
Earlier testing with the seal (installed as a hydrodynamic film riding seal) indicated that pressure balancing of the surfaces was required. During rig testing the pressure groove which shown in the upper right image, was increased in axial length. The predicted and experimental results are shown the three excel plots. Starting in the lower left corner and working clockwise, as the groove length is increased so does the effective clearance. This indicates that we can set the clearance between the seal shoe and rotor.



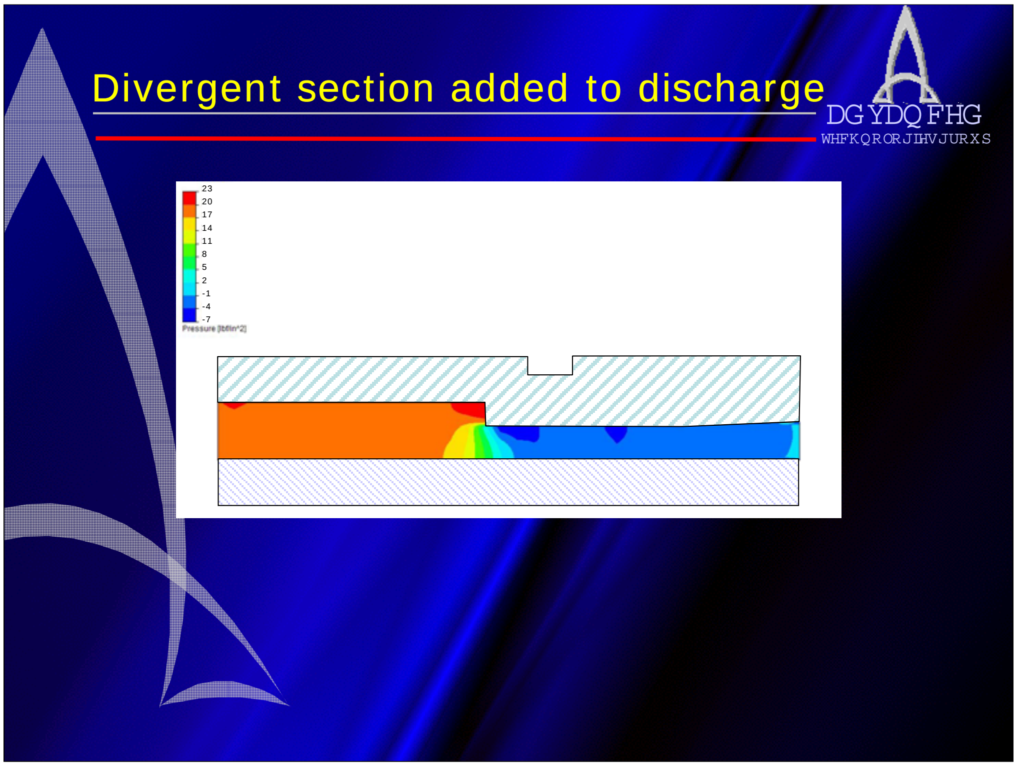
It was during offset tests (0.02” radial offset during 15,000rpm rotation) that we realized the hydrostatic forces at work. During this test the seal was moved 0.02” inches radially into the 15000rpm rotor at three seal pressures of 15, 30 and 45 psi. The ATG H-seal shoes little effect from the offset. There does not appear to be any rotor contact despite an effective clearance of 0.005”. All temperatures and pressures remain relatively constant during the offset and there appears to be no hysterisis.



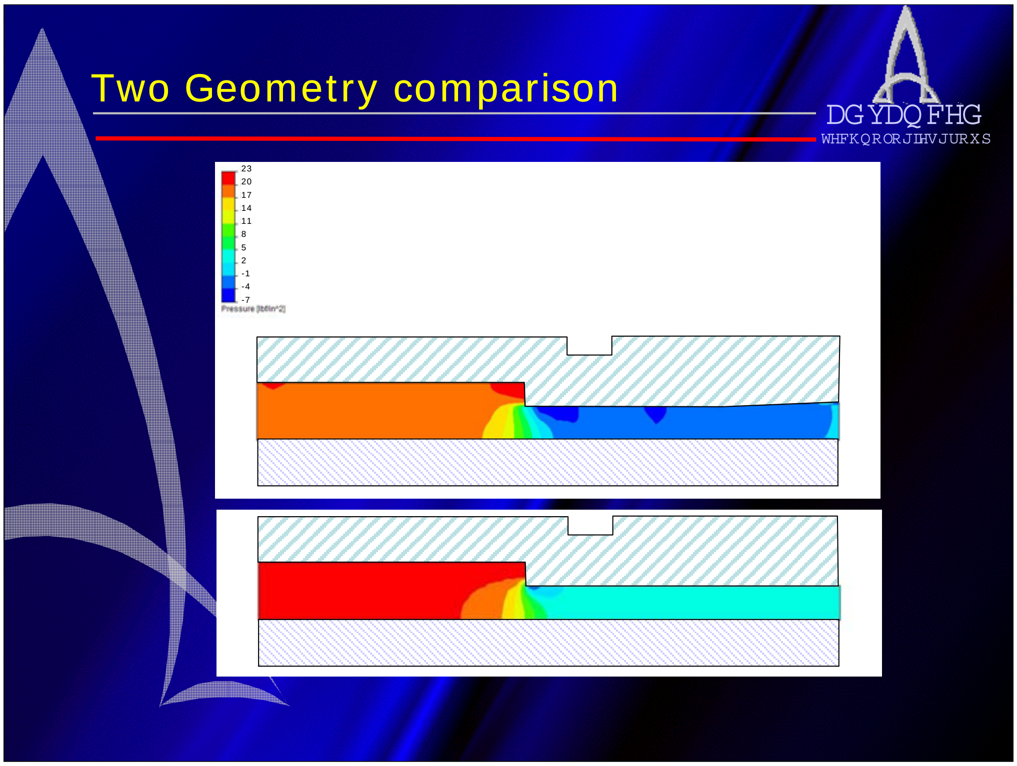
A free body diagram was developed to aid in the design and development of the H-seal. Static force can be applied. However, the seal is dynamic. As the seal moves toward or away from the rotor the pressures between them change.



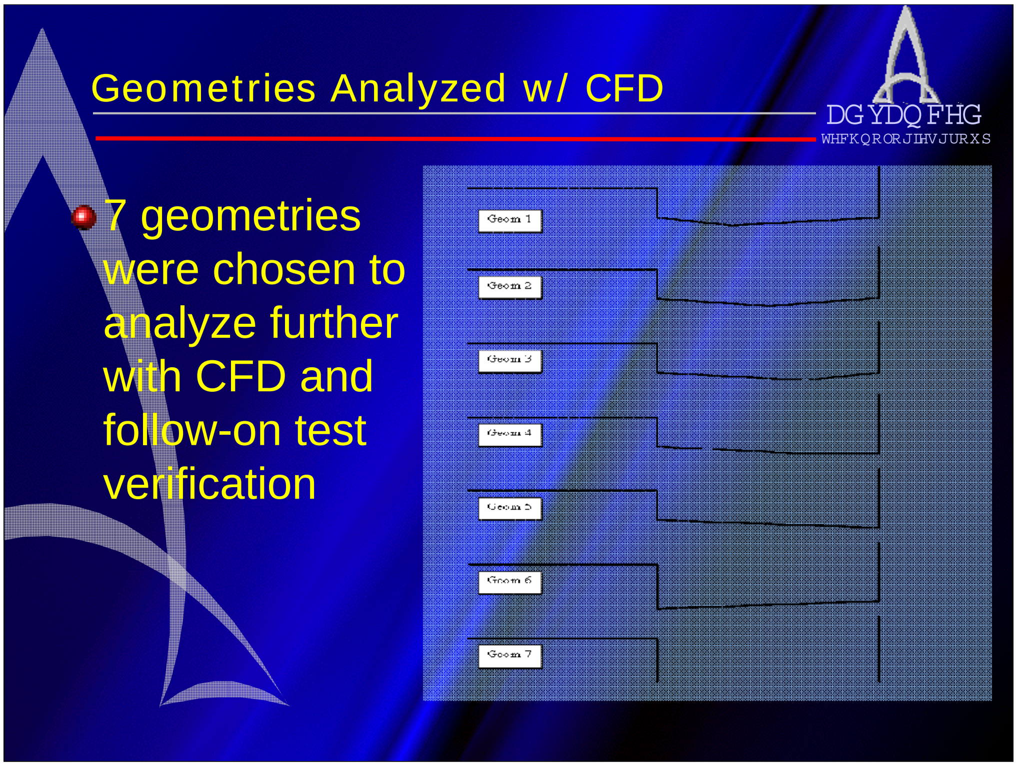
This seal has the narrow portion between the seal and rotor completely concentric. A small area at the entrance corner indicates a pressures below static discharge pressures. It is this low pressure that causes the seal to contract towards the rotor.



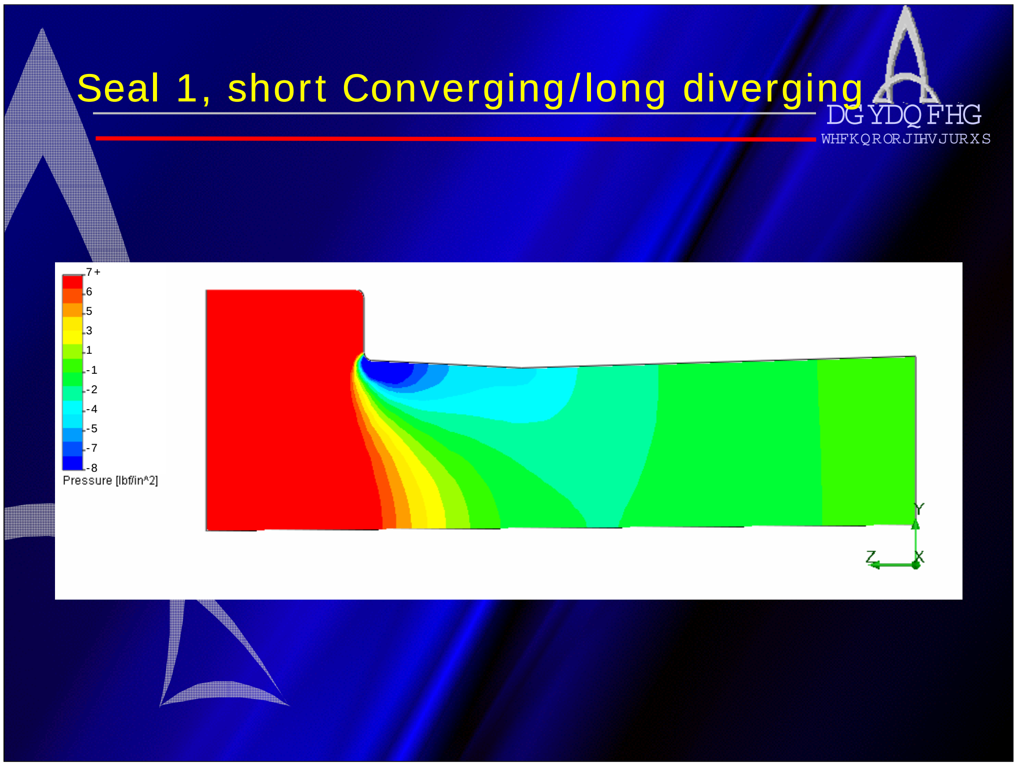
If a small divergent section is applied to the low pressure side of the seal seal pressures are reduces even further.



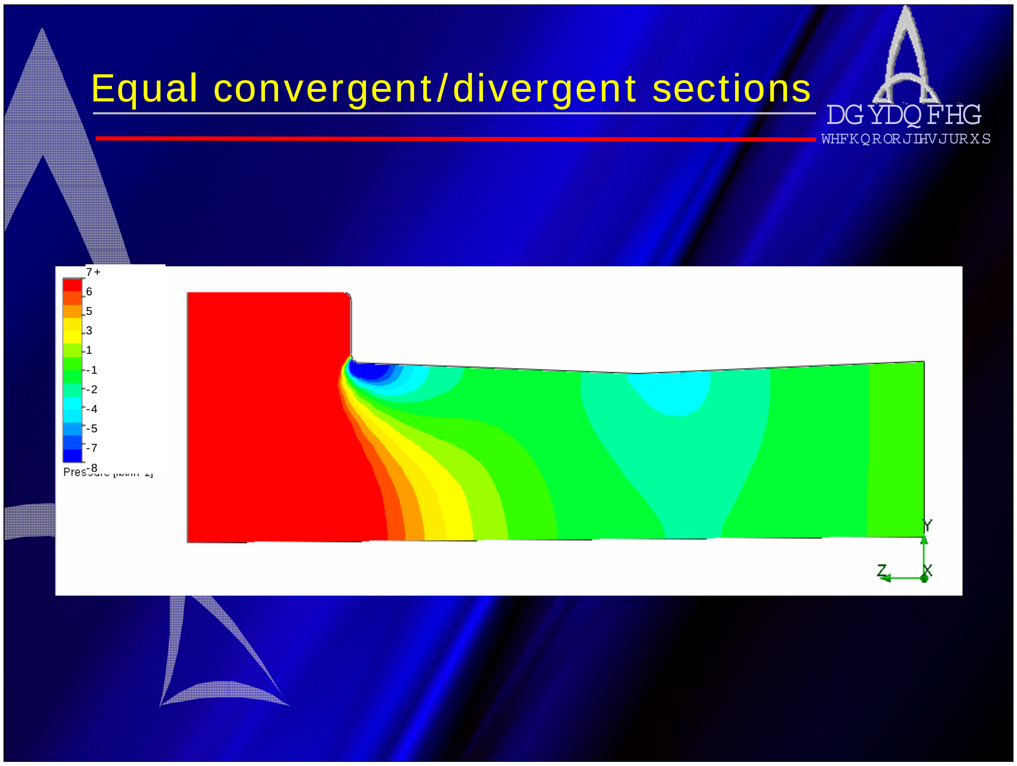
A graphic side by side comparison clearly shows what effect the small divergent section has on the static seal pressures.

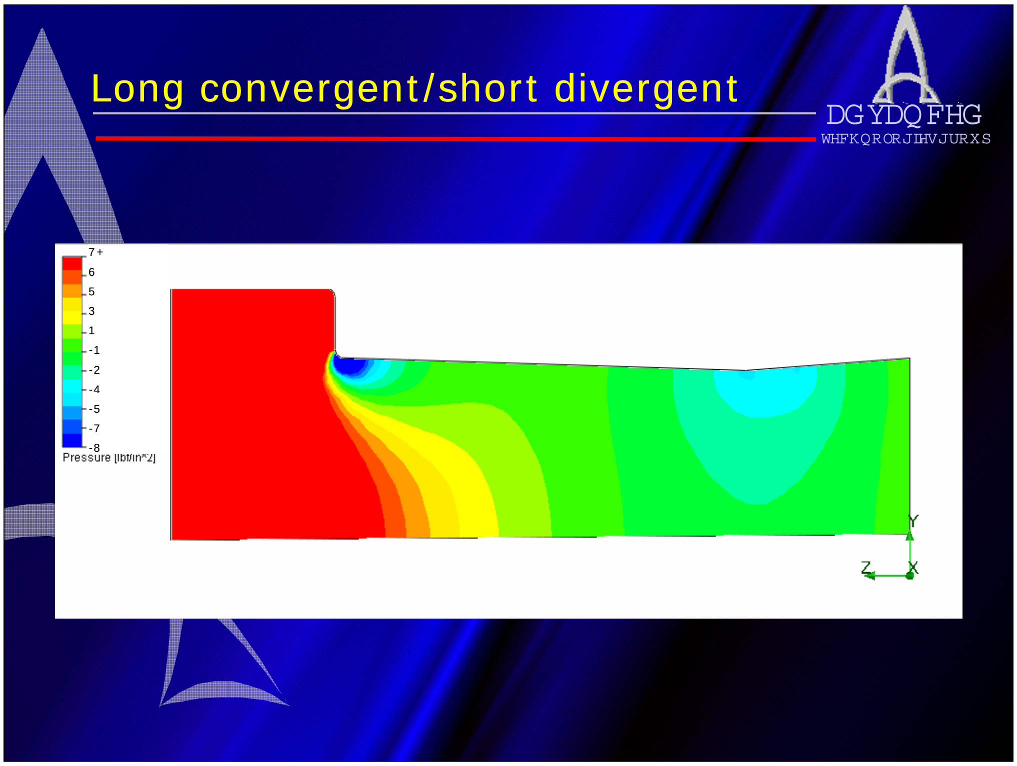


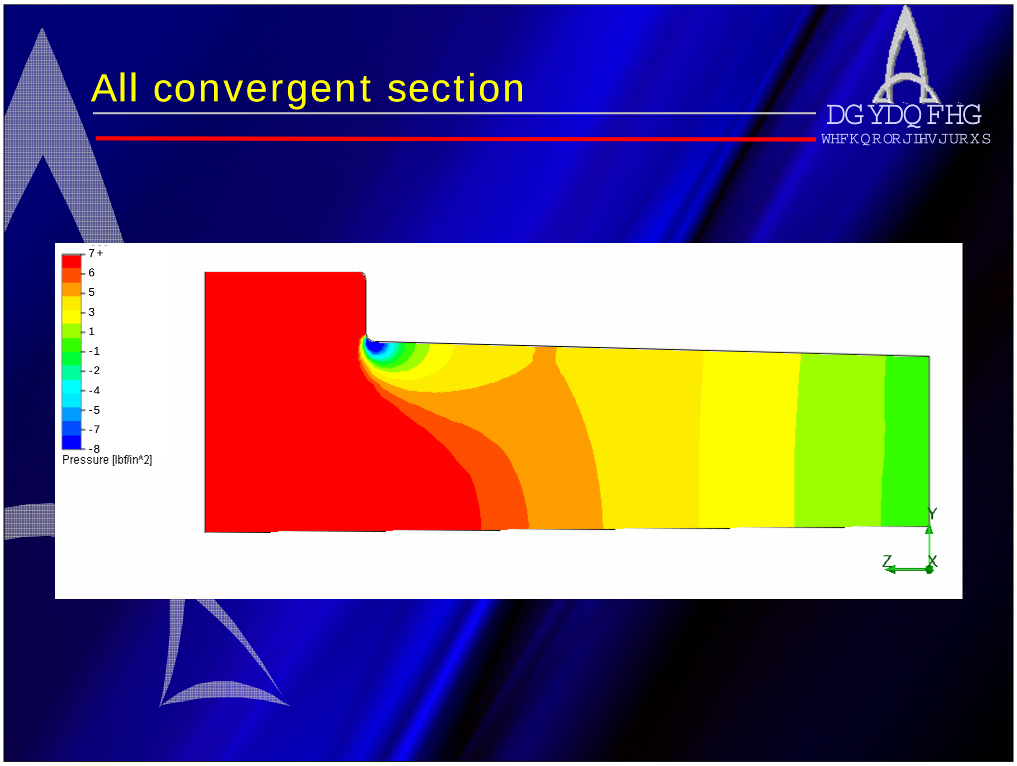
7 basic geometries were modeled to determine their effects on fluid static pressures.



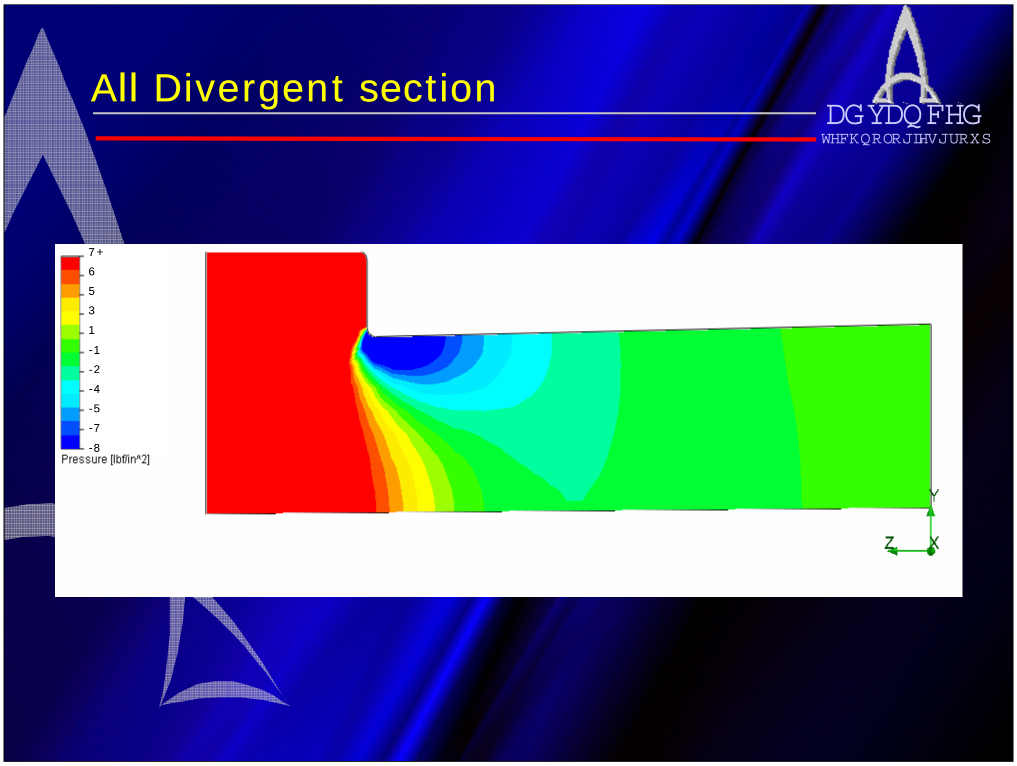
Seal 1, short Converging/long diverging
7+
6
5
3
1
-1
-2
-4
-5
-7
-8
Pressure [lbf/in^2]
Y
Z
X

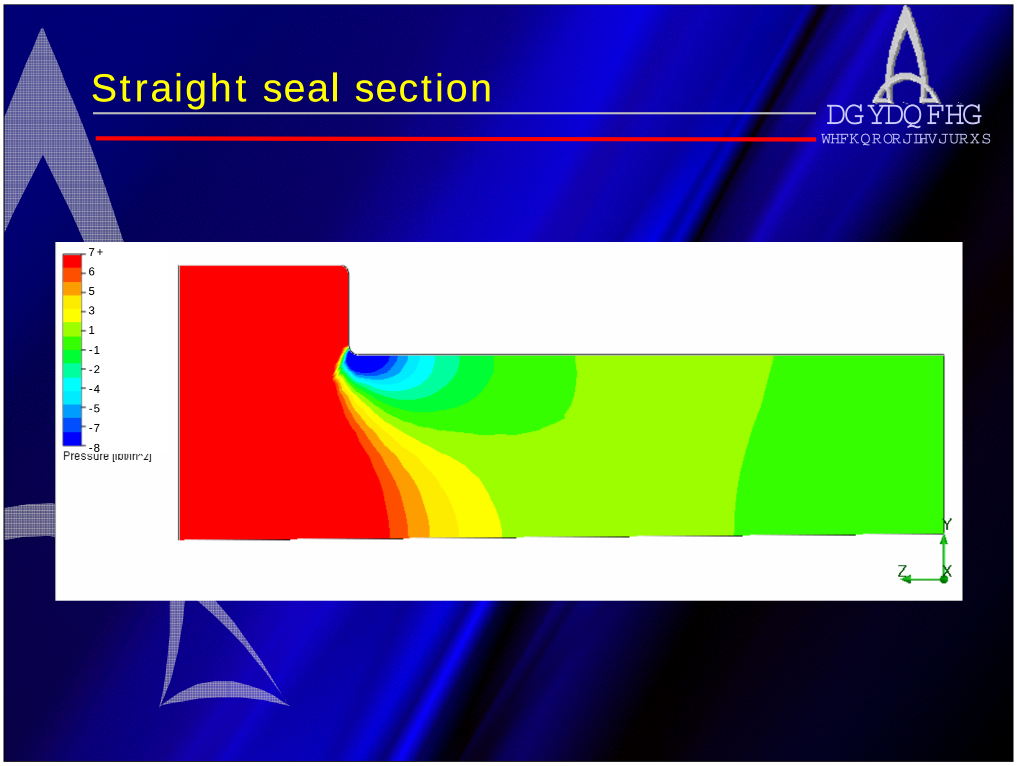

Equal convergent/divergent sections
7+
6
5
3
1
-1
-2
-4
-5
-7
-8
Y
Z
X

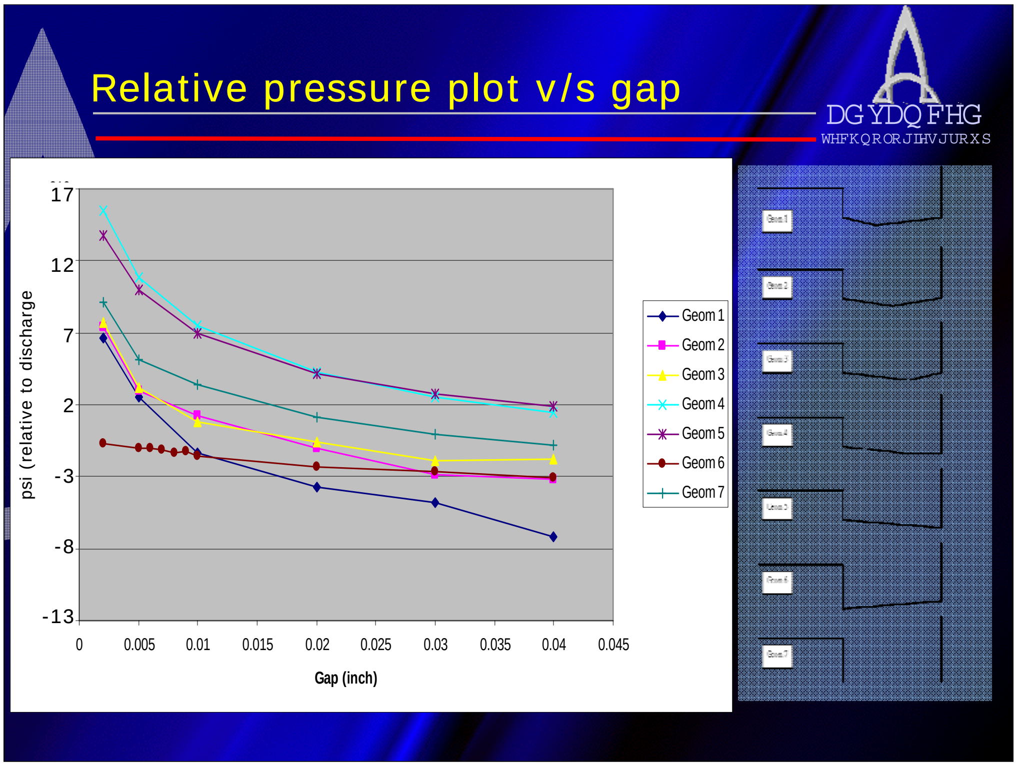

Long convergent/short divergent
7+
6
5
3
1
-1
-2
-4
-5
-7
-8
Pressure [lbf/in^2]
Y
Z
X



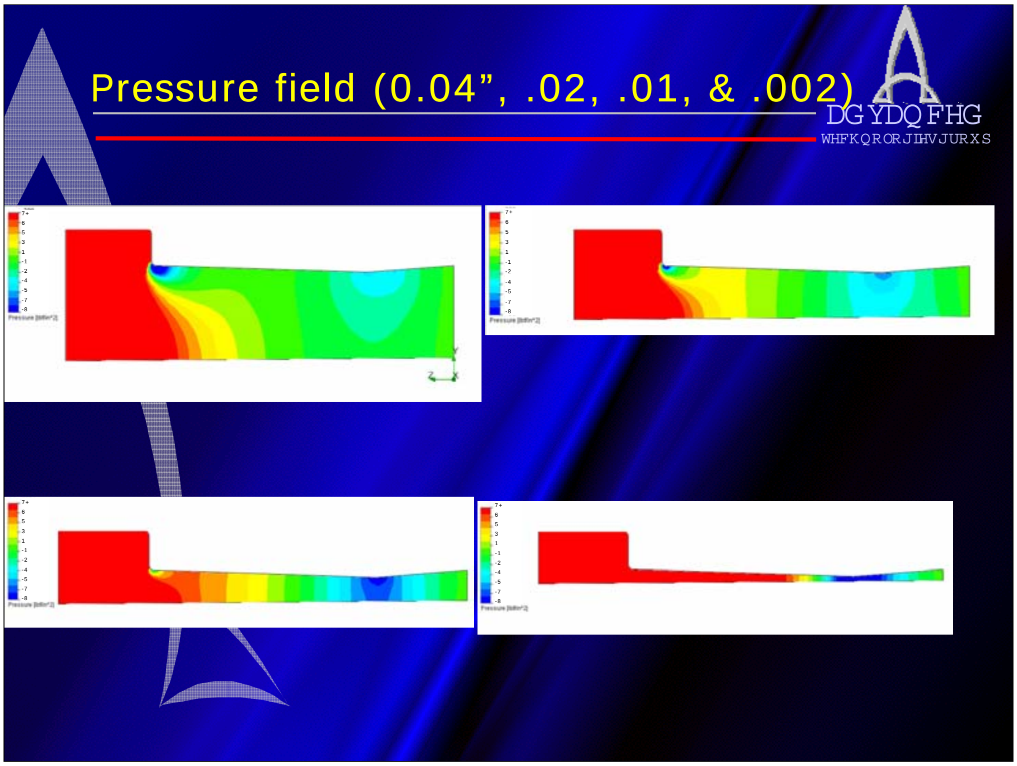
All convergent section
7+
6
5
3
1
-1
-2
-4
-5
-7
-8
Pressure [lbf/in^2]
Y
Z
X


All Divergent section
7+
6
5
3
1
-1
-2
-4
-5
-7
-8
Pressure [lbf/in^2]
Y
Z
X

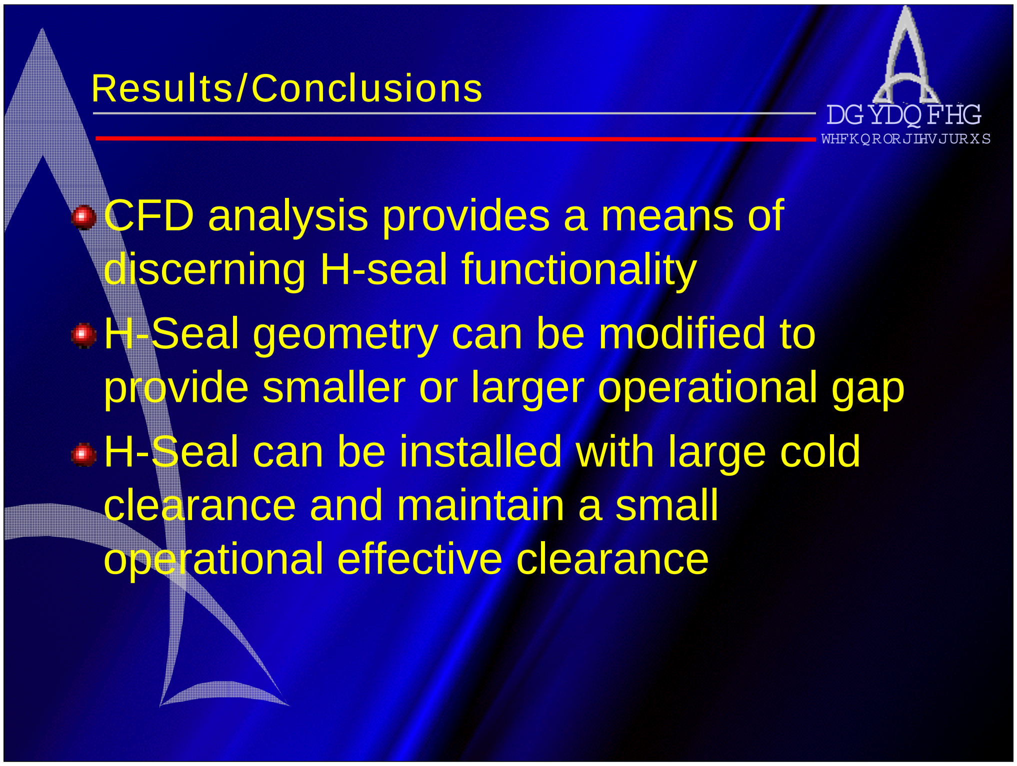

Straight seal section
7+
6
5
3
1
-1
-2
-4
-5
-7
-8
Pressure
Y
Z
X



The CFD static pressure results were then plotted over the seal surfaces to determine the overall force differences. Typically with all of the geometries as the seal gap closes, the pressure increases. Thus, the seal closes to a certain point and then the force balance is reached at different gaps based on the seal geometry. However, geometry 6 had static pressures which continued to always be negative, or lower than the discharge pressure. This could lead to seal contact and failure.



For geometry 3, the CFD plots for 4 different gap sizes.


Results/Conclusions
CFD analysis provides a means of discerning H-seal functionality
H-Seal geometry can be modified to provide smaller or larger operational gap
H-Seal can be installed with large cold clearance and maintain a small operational effective clearance

CURRENT STATE OF DEVELOPMENT

- The technology is currently being applied to several engine applications
  - Design and test Higher delta P designs
  - Design and test High surface speed designs
  - Design and test seals over segmented rotor
- Extensive CFD analysis has been completed, more is being performed

ROBUSTNESS OF MODELING OF OUT-OF-SERVICE GAS MECHANICAL FACE SEAL

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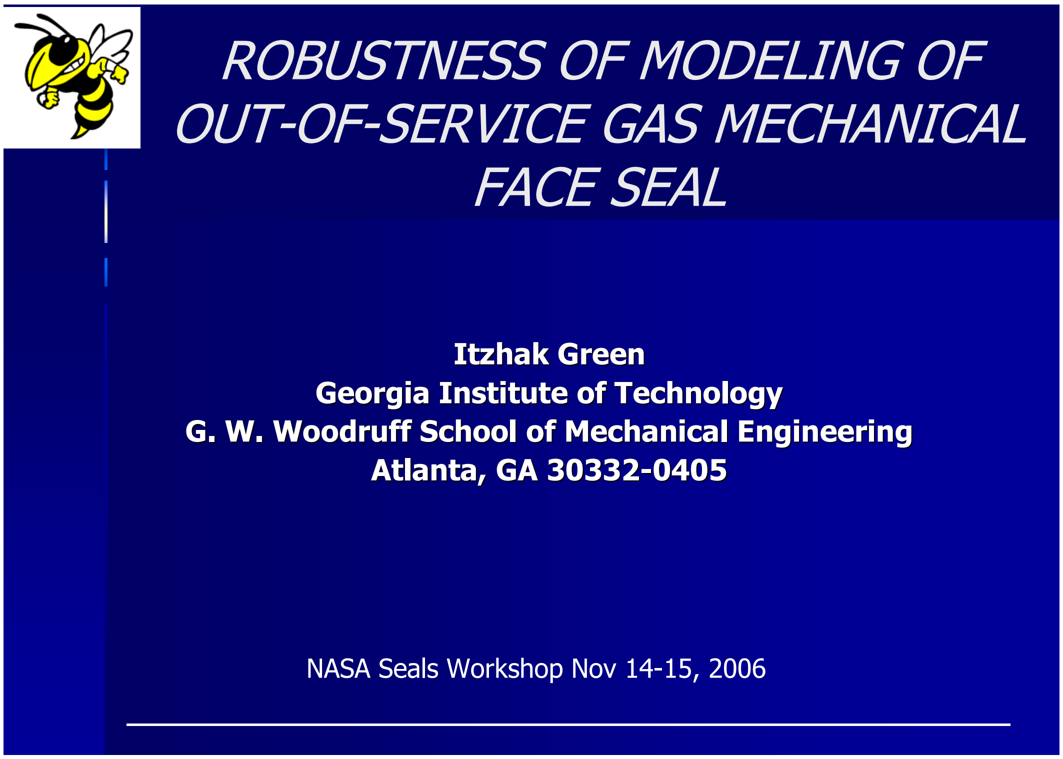
Atlanta, Georgia



Gas lubricated mechanical face seal are ubiquitous in many high performance applications such as compressors and gas turbines. The literature contains various analyses of seals having orderly face patterns (radial taper, waves, spiral grooves, etc.). These are useful for design purposes and for performance predictions. However, seals returning from service (or from testing) inevitably contain wear tracks and warped faces that depart from the aforementioned orderly patterns. Questions then arise as to the heat generated at the interface, leakage rates, axial displacement and tilts, minimum film thickness, contact forces, etc. This work describes an analysis of seals that may inherit any (i.e., random) face pattern. A comprehensive computer code is developed, based upon the Newton-Raphson method, which solves for the equilibrium of the axial force and tilting moments that are generated by asperity contact and fluid film effects. A contact mechanics model is incorporated along with a finite volume method that solves the compressible Reynolds equation. Results are presented for a production seal that has sustained a testing cycle.

Modeling Challenges

Q. Are models useful, and useful for what?
A. Typically used for design, predicting trends, etc.

Q. How "Complete" or "Robust" are they?
A. Limited by assumptions (how valid are they?), and capabilities (math models & complexity, numerical implementation, and CPU time)

Q. Can models be used for postmortem analysis?
- Faces maybe flat upon installation – highly unlikely that they remain as such.
- Cracked faces/shafts (they happen, but are these modeled?).
- Worn faces ("wear models" are empirical; first-law & robust "wear models" are yet to be developed).

Q. How robust are existing models?
(I) First Generation (classify, "contacting," "non-contacting," etc.)
(II) Next Generation (no classification needed, including multi-effects)

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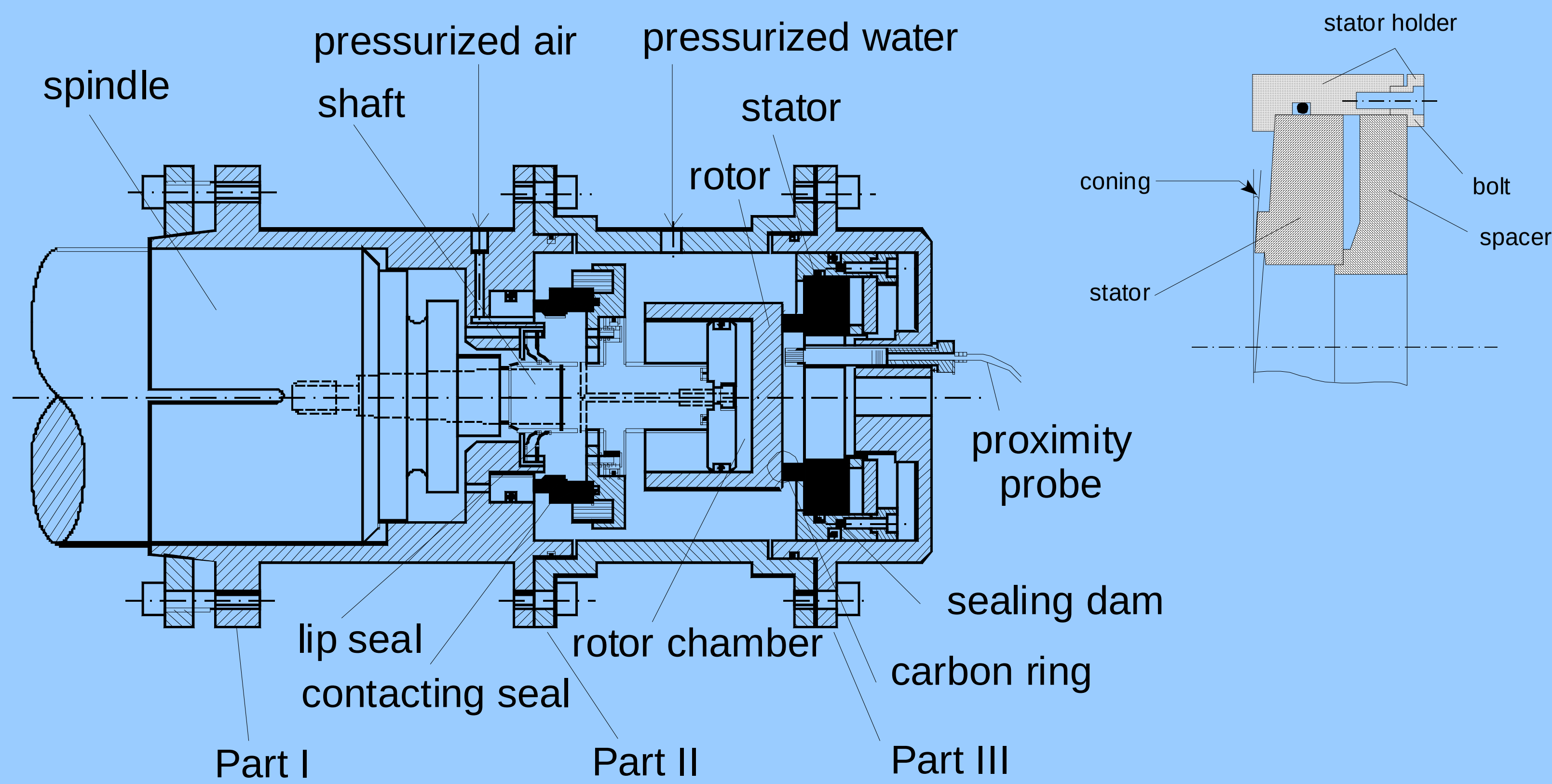
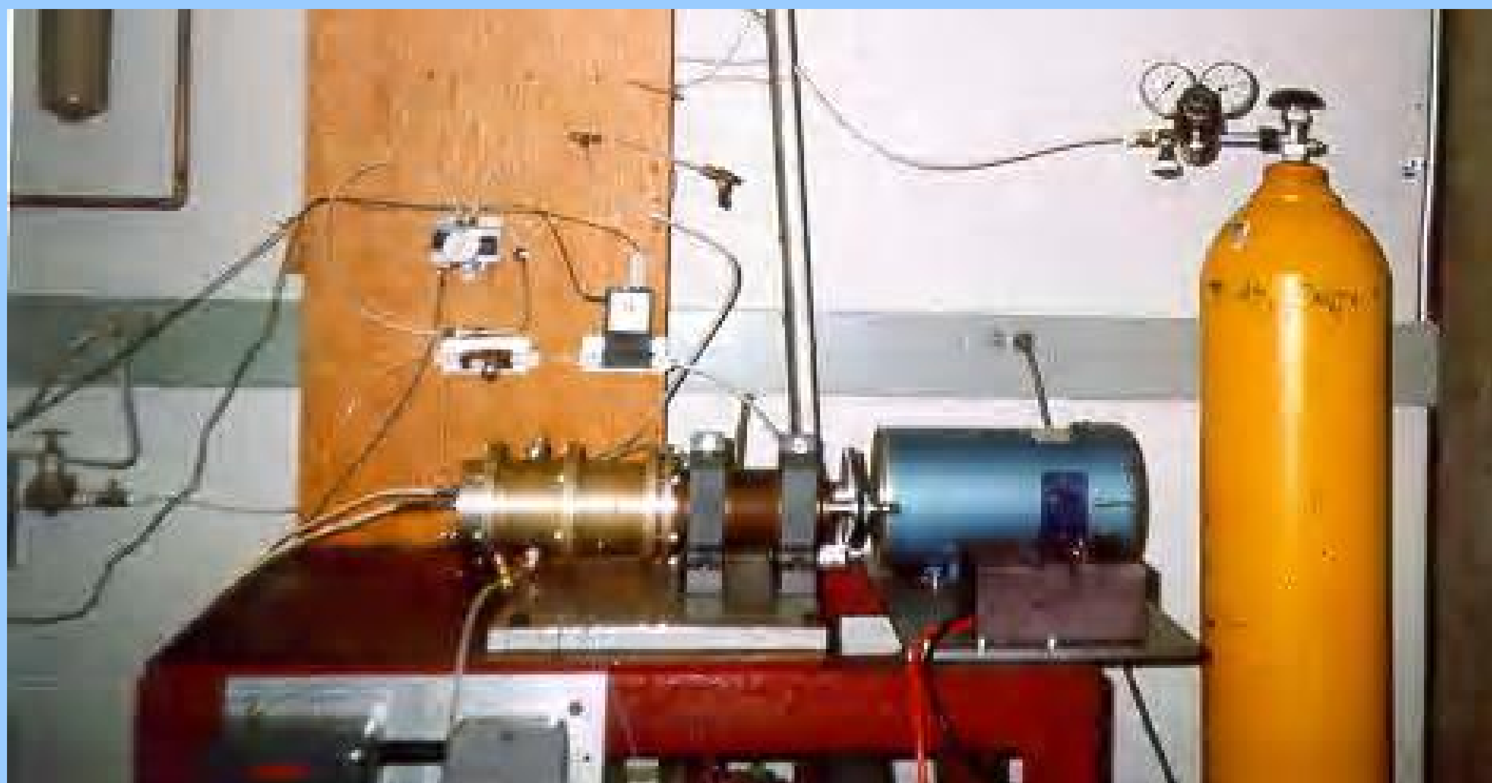
Flexibly Mounted Rotor Face Seal Test Rig



FMR Mechanical Face Seal Test Rig (Photograph)



Prong I: Real-Time Diagnostics

Three indicators:

- Time domain – probe signals
- Frequency domain -- Power spectral density functions (FFT)
- Angular orbit plots – seal absolute and/or relative misalignment, γ_x vs. γ_y.

*All calculations are performed and plotted in **real-time** (using a PC with a dSpace DAQ board).*

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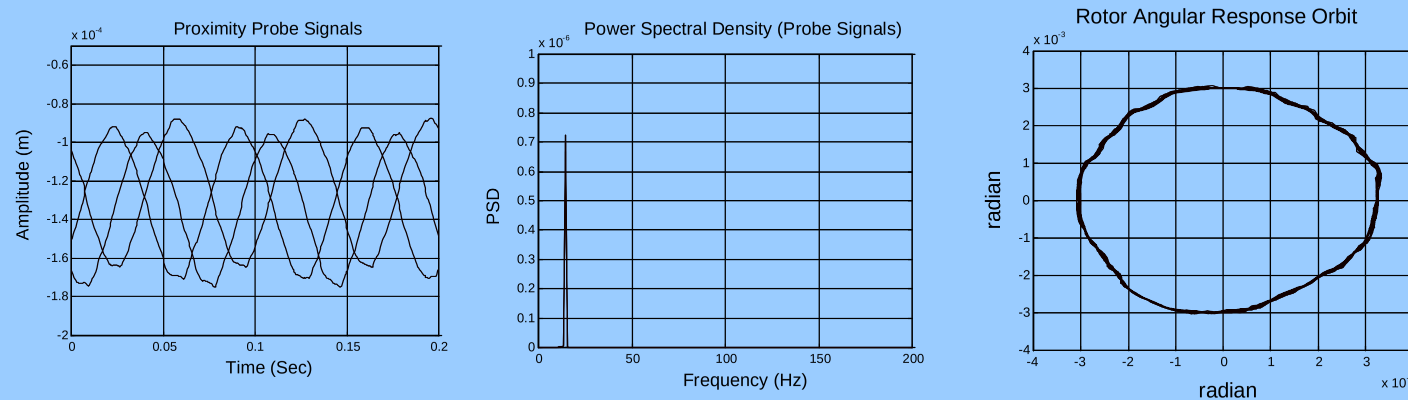
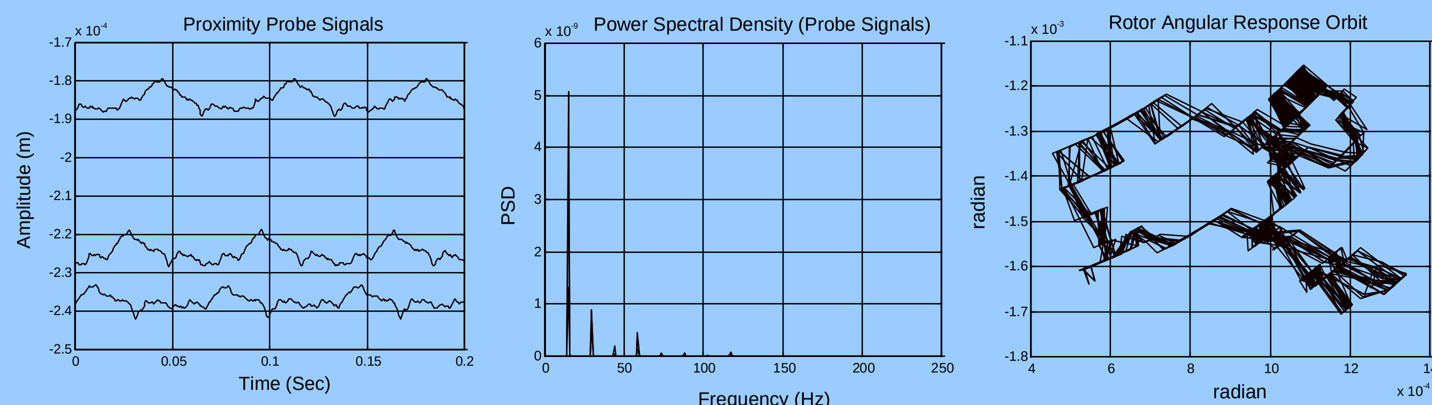
Noncontacting Operation (in Real-Time)



Intermittent Contacting Operation (in Real-Time)



Prong II: Seal Control – Contact Reduction/Elimination

- Clearance control of a mechanical face seal is achieved using cascade dual PI controllers with anti-windup acting on the variance of probe signals.
- System identification: experimentally (phenomenologically) determined seal model - theoretical model is not required.
- Using eddy current proximity probes to directly measure seal clearance and tilts as opposed to indirect methods (such as using thermocouples that measure face temperature).
- The controlled seal can follow seal clearance set-point changes with minimum control effort, while not being affected by disturbances in shaft speed and/or sealed water pressure.

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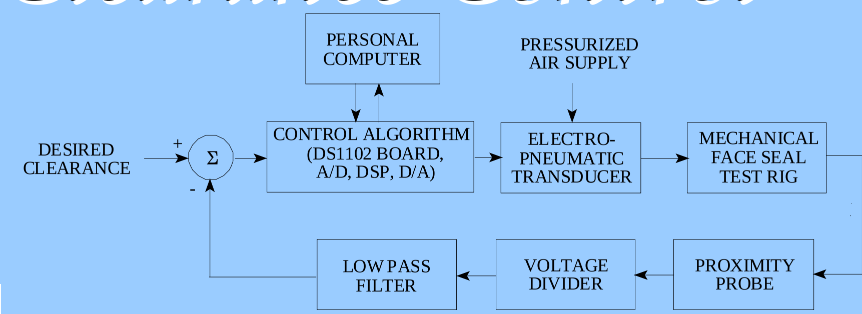
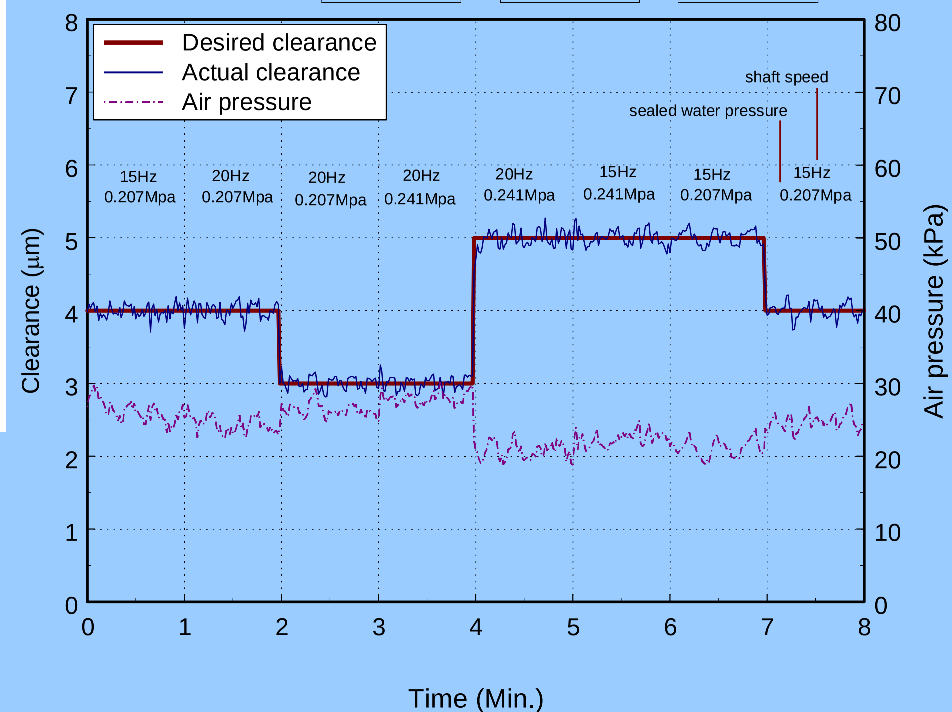
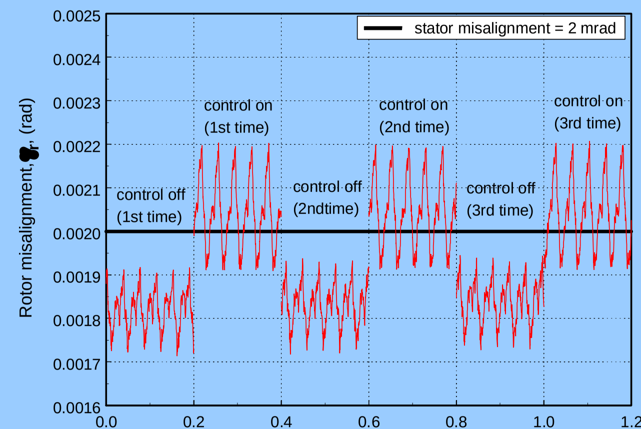
Set Point Clearance Control

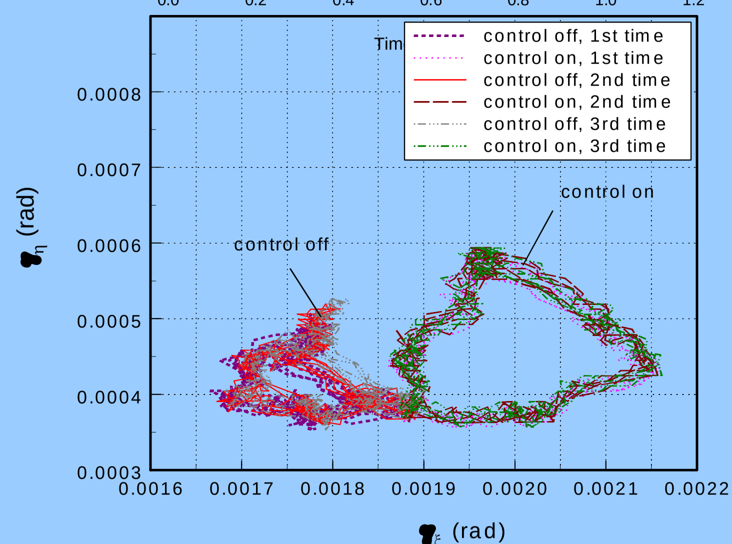


Time Min	Clearance µm	Rotation Speed Hz	Sealed water Pressure KPa
0	4(*)	15(*)	207(*)
1		20(+5)	
2	3(-1)		
3			241(+37)
4	5(+2)		
5		15(-5)	
6			207(-37)
7	4(-1)		



Uncontrolled/Controlled Seal

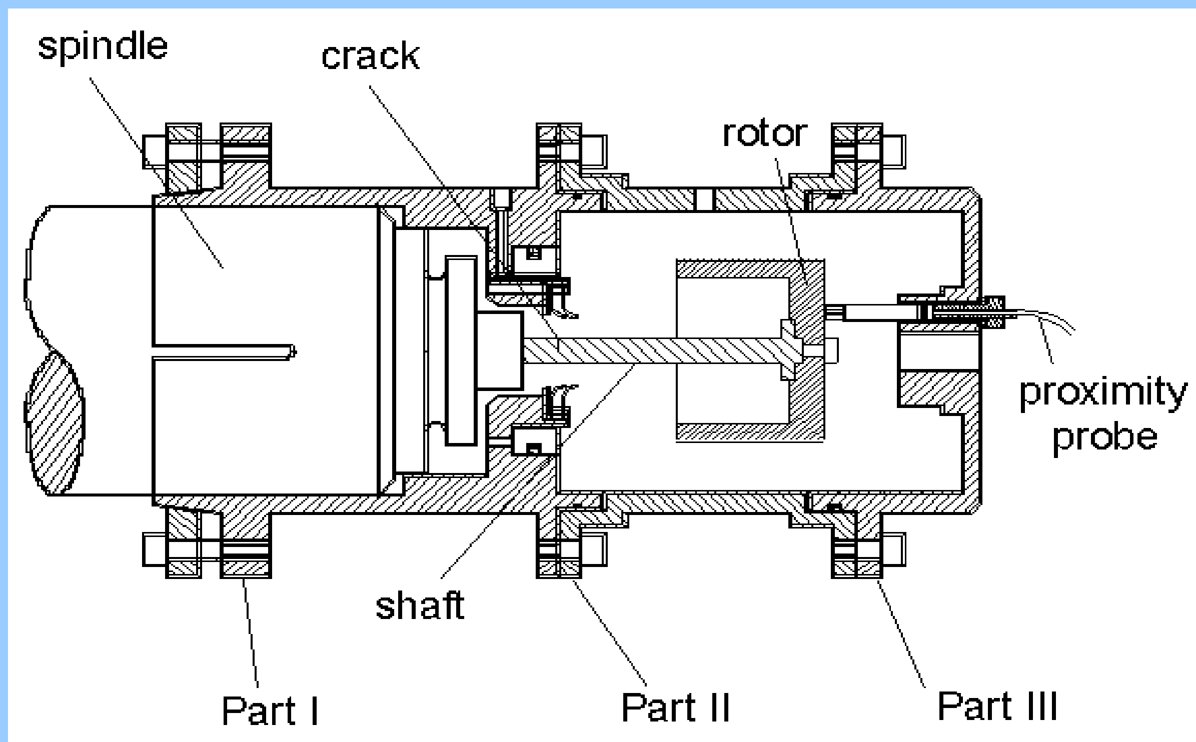




Controlled Seal:

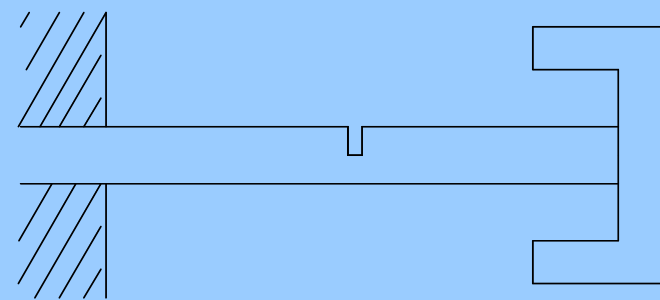
- Rotor better tracks stator misalignment
- Virtual elimination of higher harmonic oscillations
- Closer to circular orbits, i.e., noncontacting operation

Prong III: Crack Detection in Seal/Rotor Driving Shaft (Seal Absent)

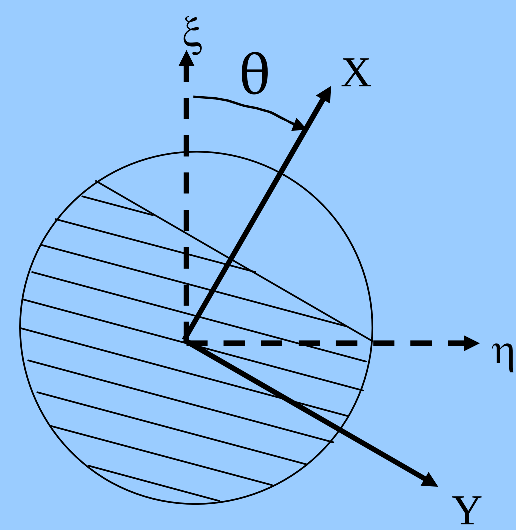


Modeling

- ◆Cracked Rotors
  - Crack Modeling
  - Crack Indicators
  - Methods of Detection

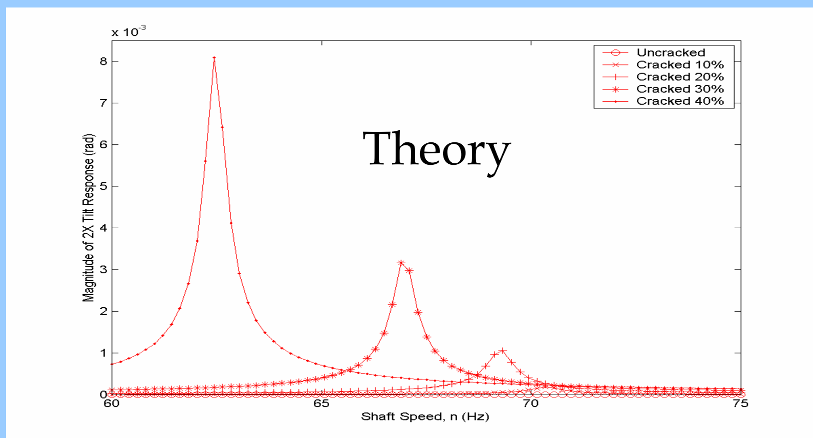


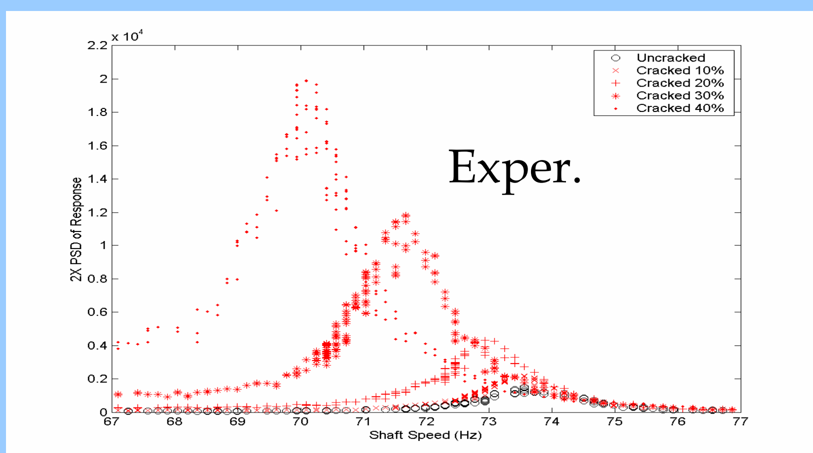
- ◆Analytical Work - Part I (Green and Casey, 2005)



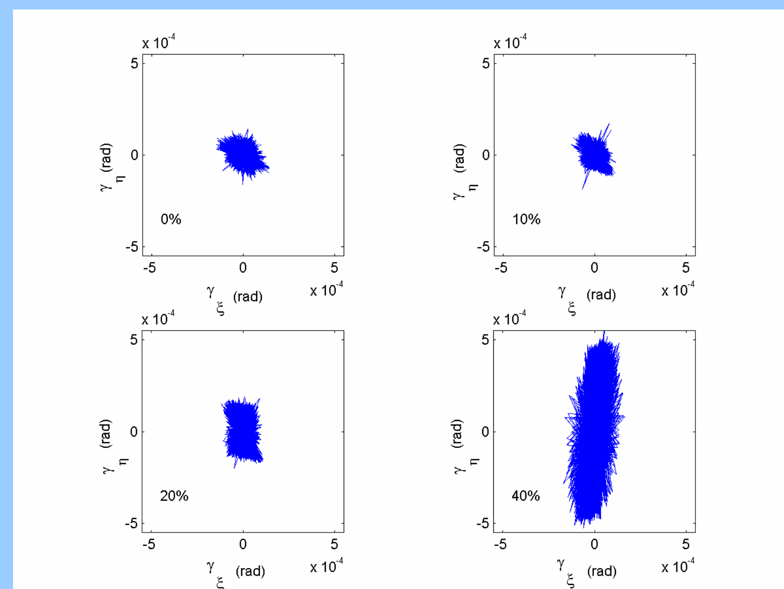
- ◆Experimental Work- Part II

Supercritical 2X Component





Experimental Orbits at various crack depths



Robust Modeling Objectives

Robust modeling should address these issues:

- Dynamics (high speeds, large masses -> inertia effects)
  - -- stability, transients response, steady-state: misalignments, secondary seals and anti-rotation pins (Green (1985, 2006))
  - -- coupled rotordynamics? (systems approach)
- Asperity Contact
  - -- mechanical ("dry") friction in sliding
  - -- mechanical load support and deformation (EP)
- Mechanical Deformations (Pressure)
- Thermal Deformations (viscous and dry friction, TEI)
- Wear
- Face patterns (lift-off seals, typically for compressible seals)

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Objectives (cont.)

To develop a (numerical) procedure where the solution includes multi-coupled phenomena (e.g., the Reynolds and energy Eqs., the EOM, contact mechanics, wear models).

The solution must be simultaneous in all the degrees of freedom.

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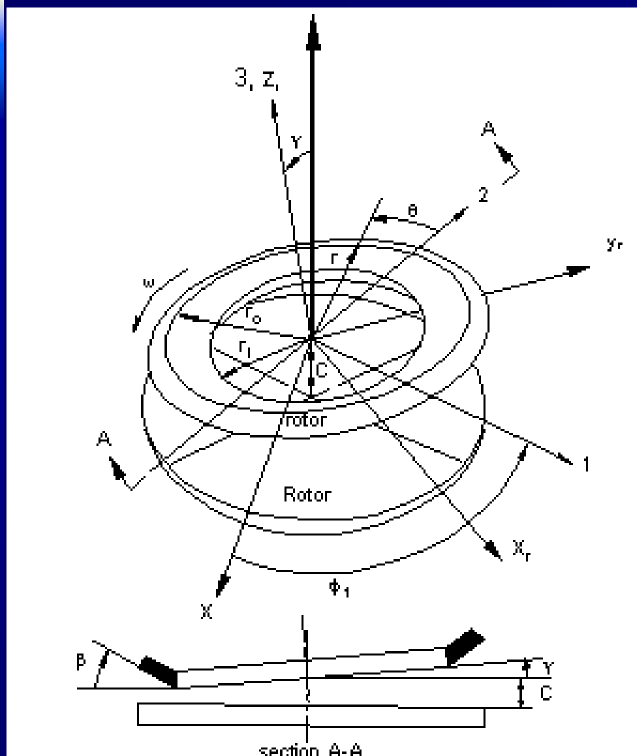
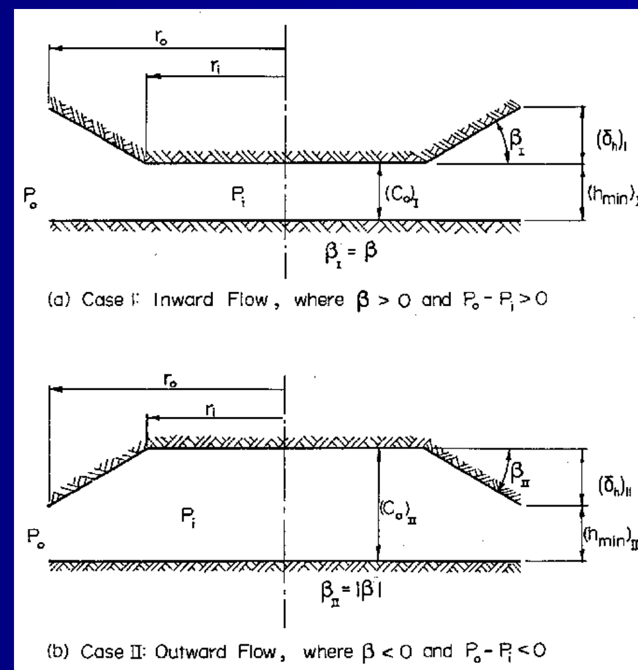
Flat/coned face



- Inward/Outward Flow



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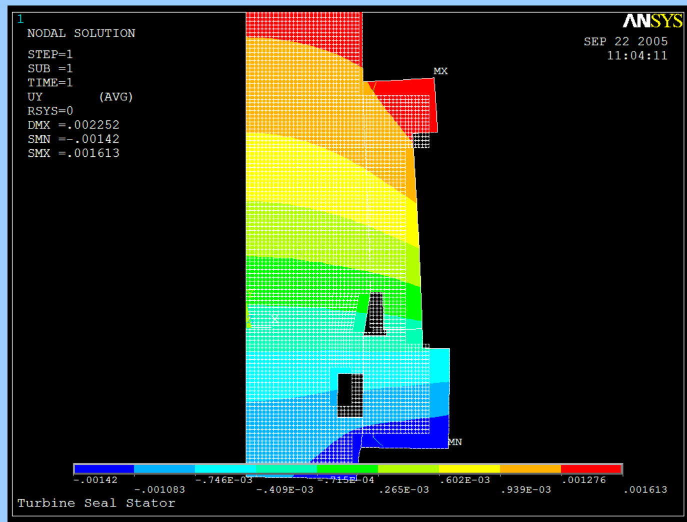
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RSYS=0
DMX =.002252
SMN =-.00142
SMX =.001613
ANSYS
SEP 22 2005
11:04:11
MX
MN
-.00142
-.001083
-.746E-03
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-.715E-04
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.602E-03
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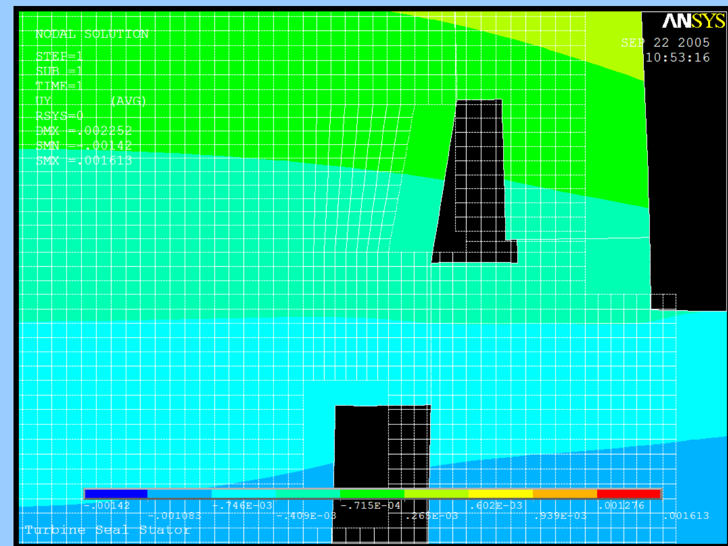
.001276
.001613
Turbine Seal Stator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SMX =.001613
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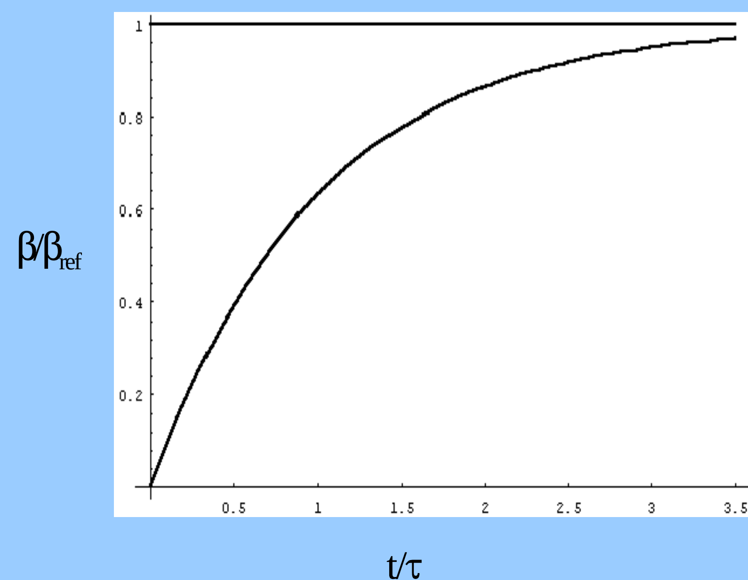
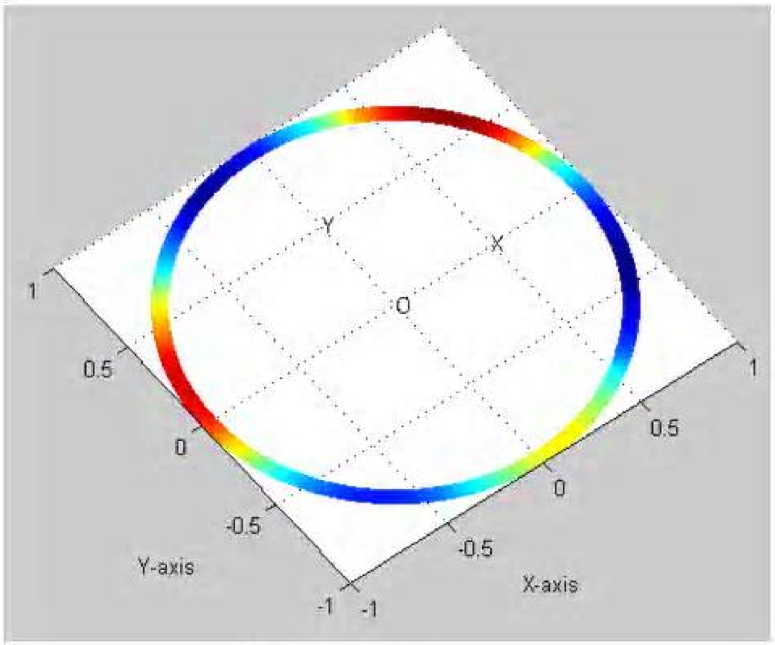
10:53:16
Turbine Seal Stator

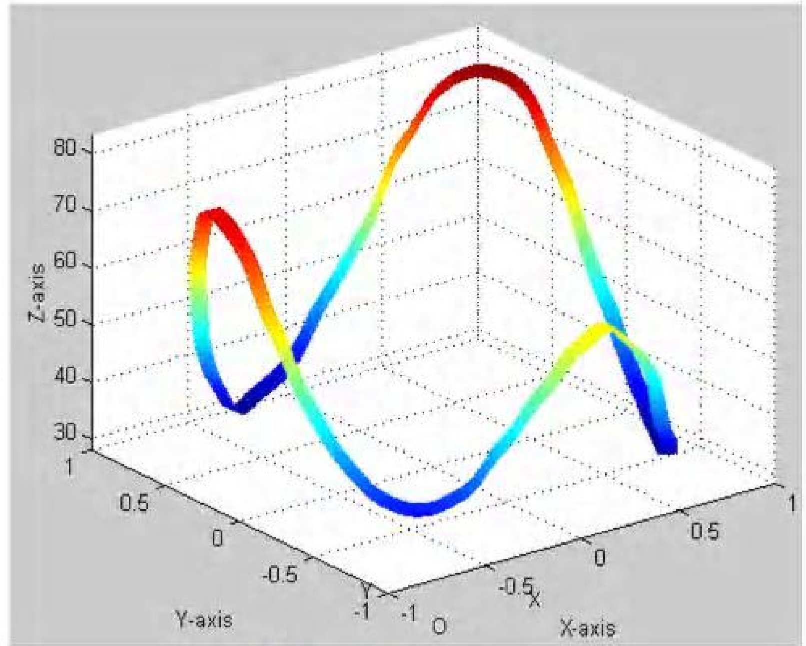

β/βref
t/τ
0.2
0.4
0.6
0.8
1
0.5
1
1.5
2
2.5
3
3.5

Out-of-Service faces*

- wear?
- thermal/mechanical warping?



Top view



Oblique view

* Green and Artiles (2006), manuscript in preparation

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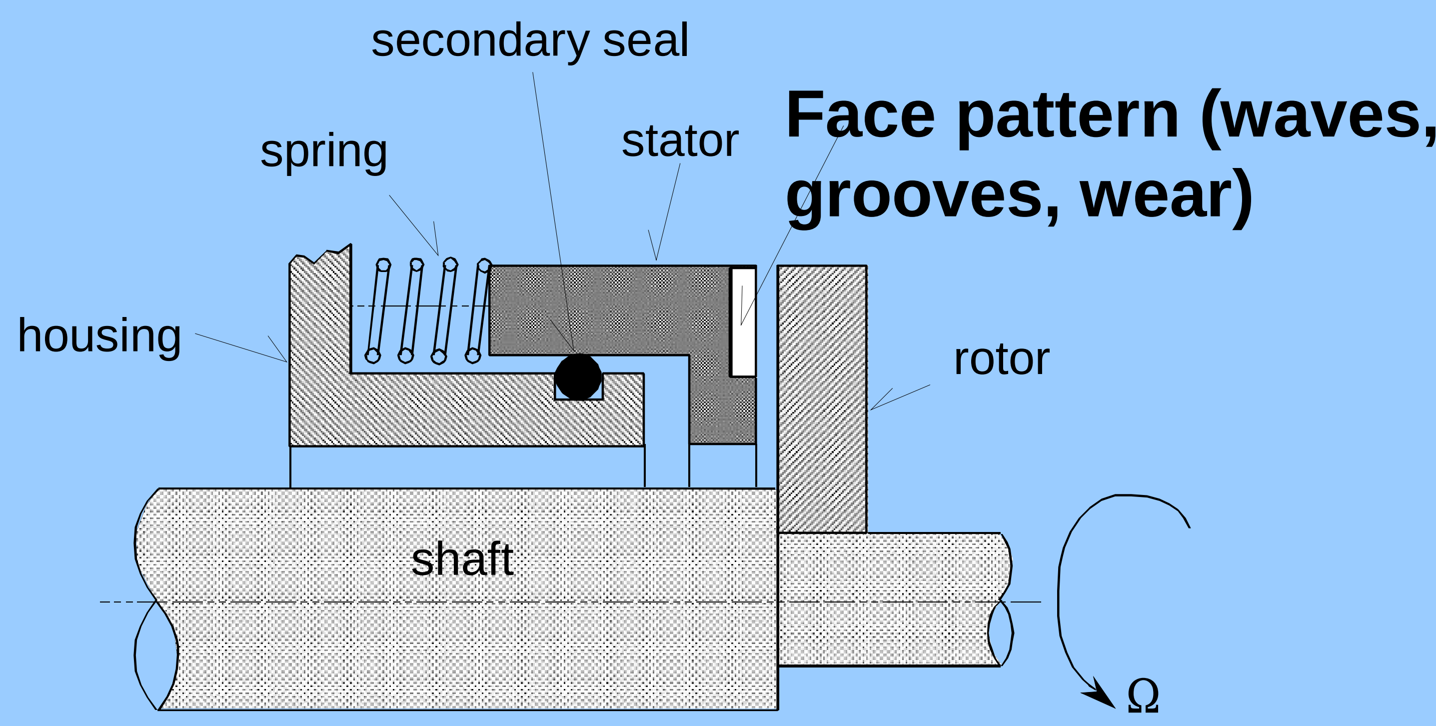


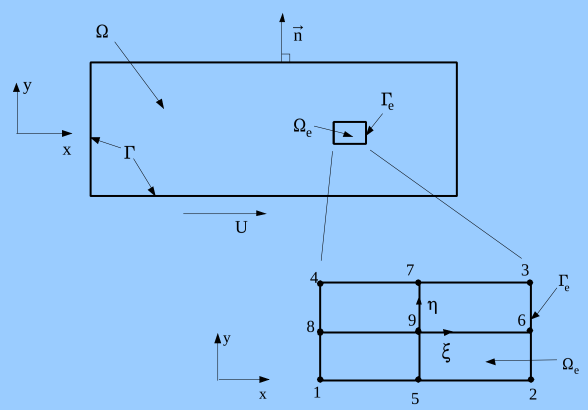
Schematic of Noncontacting Mechanical Face Seal
with Flexibly Mounted Stator

Finite Element Discretization (FEM)

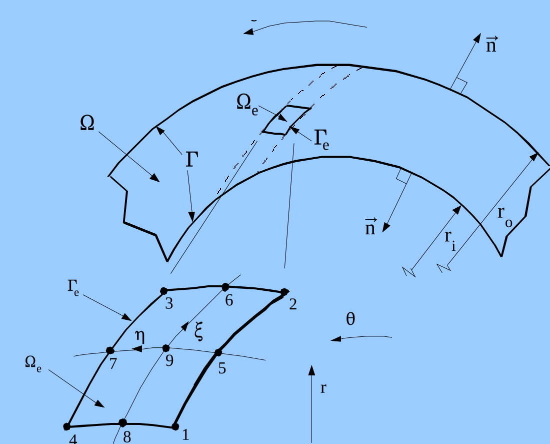
Multiplying RE by a weight factor $\mathbf{W}^T$ and integration by parts gives the weak form:

$$\int_{\Omega} \left\{ -\vec{\nabla} \boldsymbol{W}^{T} \cdot \left[\Phi\, p h^{3} \vec{\nabla} p - 6\mu\, \vec{u}\, p h \right] - \boldsymbol{W}^{T} 12\mu \frac{\partial (ph)}{\partial t} \right\} d\Omega = 0$$

Discretize domain into small finite elements:



Cartesian coordinate discretization



Polar coordinate discretization

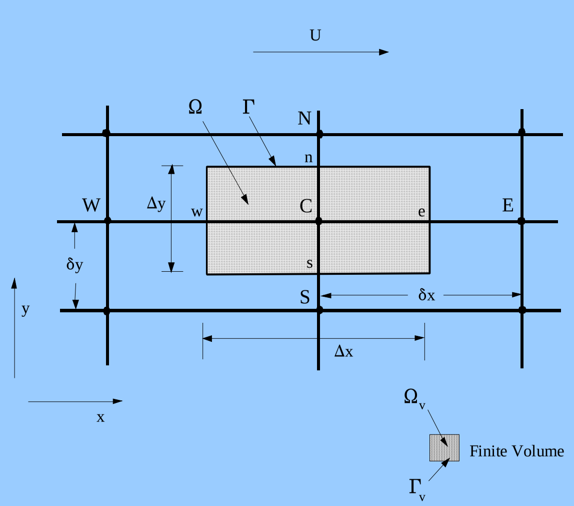
$$p(\xi,\eta) = \sum_{i=1}^{9} \boldsymbol{N_i}(\xi,\eta)\, p_i \qquad \frac{\partial p(\xi,\eta)}{\partial \xi} = \sum_{i=1}^{9} \boldsymbol{N_{i,\xi}}(\xi,\eta)\, p_i \qquad \frac{\partial p(\xi,\eta)}{\partial \eta} = \sum_{i=1}^{9} \boldsymbol{N_{i,\eta}}(\xi,\eta)\, p_i$$

Finite Volume Discretization (FVM)

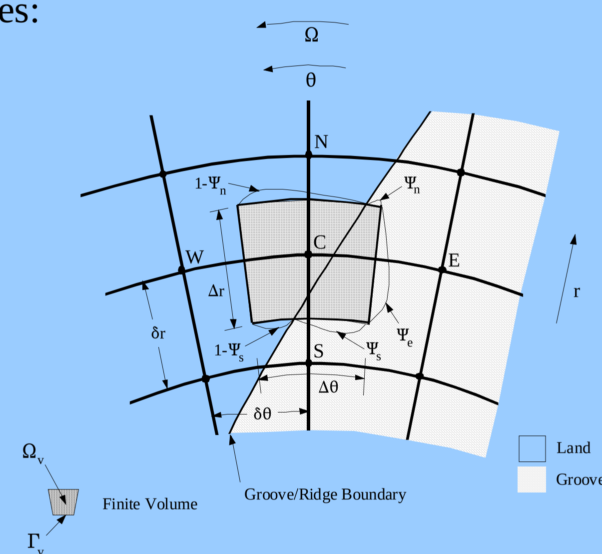
Apply Green's theorem to RE - represents mass conservation over the domain

$$\int_{\Gamma} \left[\Phi p h^{3} \vec{\nabla} p - 6 \mu \vec{u} p h \right] \cdot \vec{n} \, d\Gamma = \int_{\Omega} \left\{ 12 \mu p \frac{\partial h}{\partial t} + 12 \mu h \frac{\partial p}{\partial t} \right\} d\Omega$$

Discretize the domain into small finite volumes:

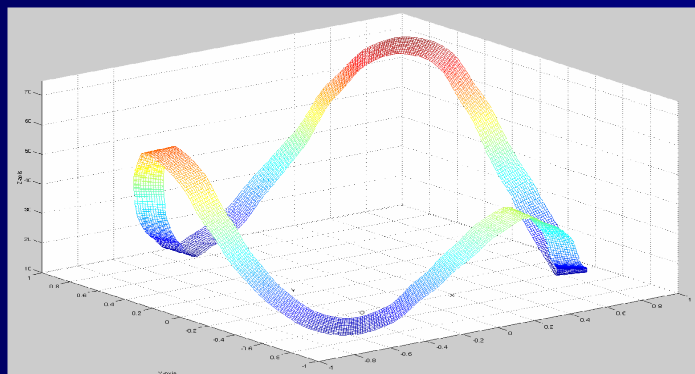


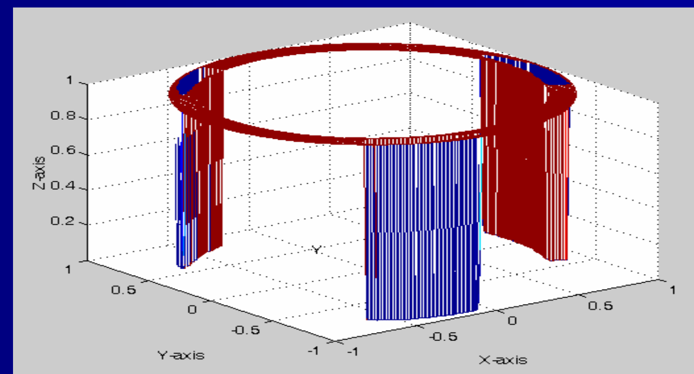
Cartesian coordinate finite volume discretization

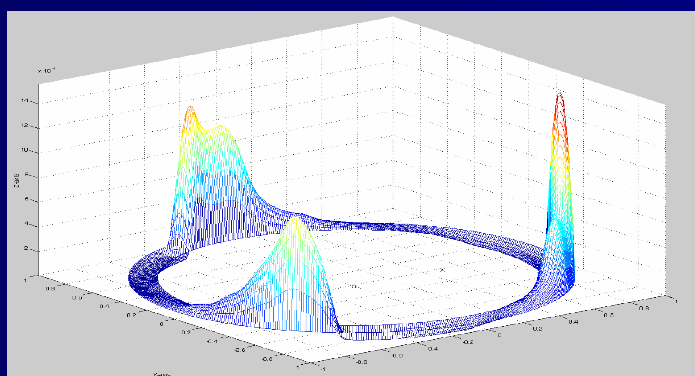


Polar coordinate finite volume discretization

Incompressible Flow







Issues:

- Flow factors (Patir & Chang)

- Cavitation (Elrod, JFO)

- Starvation (?) (can be an issue in low pressure seals)

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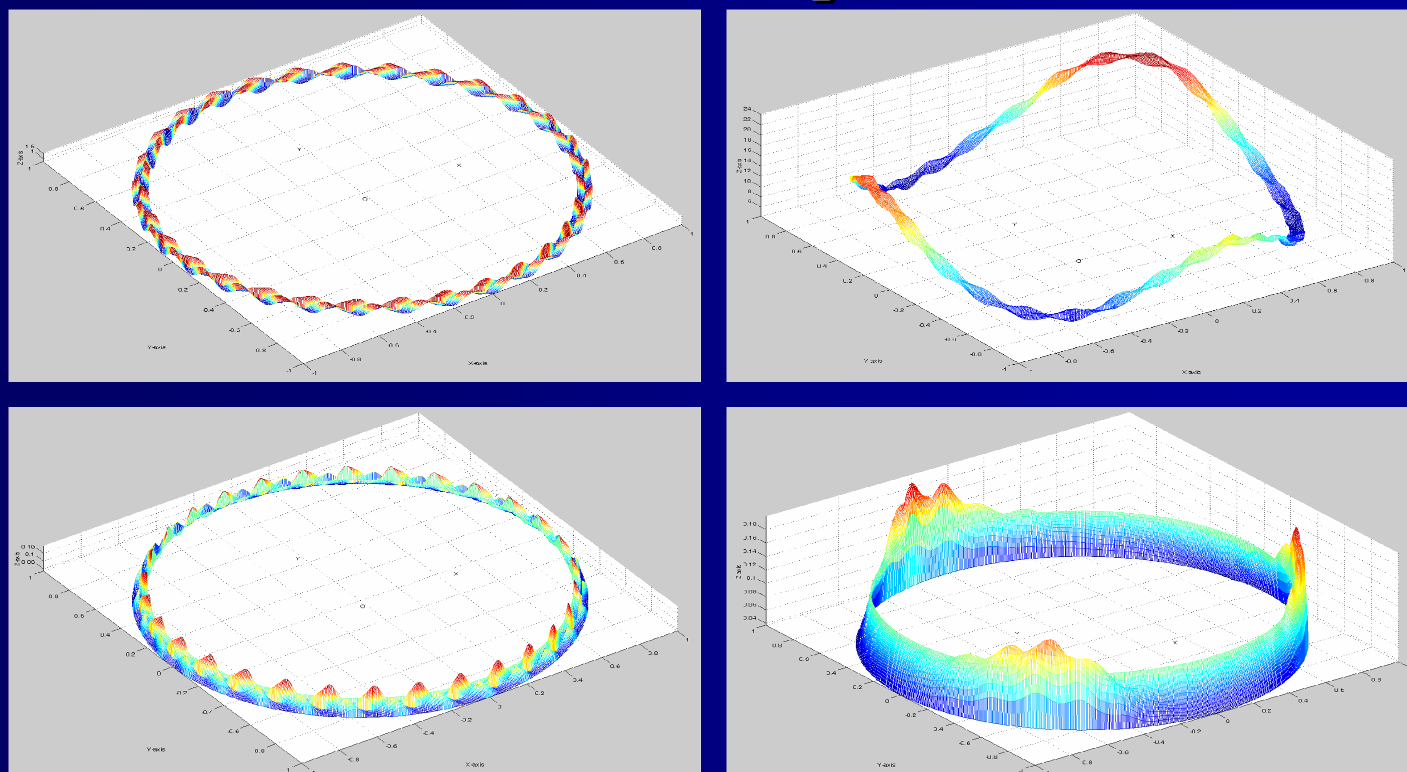
Compressible Flow – Herringbone wavy seal (w/o and w/ face def.)



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EP Contact Load Support (Jackson & Green, 2005)

$$0 \le \omega^* \le \omega_t^* = 1.9$$

$$P_F^* = \left(\omega^*\right)^{3/2}$$

$$\omega_t^* \le \omega^*$$

$$P_F^* = \left[\exp\left(-\frac{1}{4}\left(\omega^*\right)^{\frac{5}{12}}\right)\right]\left(\omega^*\right)^{3/2} + \frac{4H_G}{CS_y}\left[1-\exp\left(-\frac{1}{25}\left(\omega^*\right)^{\frac{5}{9}}\right)\right]\omega^*$$

- Statistically this formulation differs from the FEM data for all five materials by an average error of 0.94% and a maximum of 3.5%.
- Found to be valid not only for steels, but also for cupper, aluminum, and other metallic materials (Quicksall, Jackson and Green, 2004).

Rough Surfaces -- Statistical Model

$$\phi = (2\pi)^{-1/2}\left(\frac{\sigma}{\sigma_s}\right)\exp\left[-0.5\left(\frac{z}{\sigma_s}\right)^2\right]$$

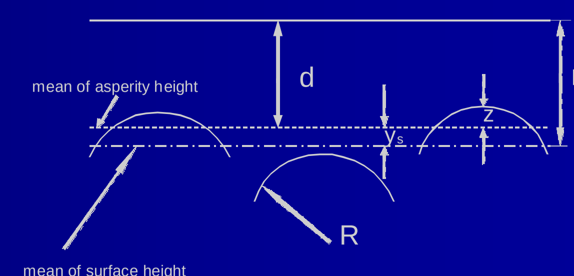
$$A(d) = \eta A_n \int_d^\infty \overline{A}(z-d)\phi(z)dz$$

$$P(d) = \eta A_n \int_d^\infty \overline{P}(z-d)\phi(z)dz$$

Plasticity Index

$$\psi = \sqrt{\frac{\sigma_s}{\omega_c}}$$

- Greenwood and Williamson (1966) formulated the statistical model using Hertz contact.
- The integrals are evaluated using Gauss-Legendre quadrature.
- **Jackson & Green (2005)**



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Subsystem Coupling

Kinetic equations (including time-dependent thermal effects):

$$\frac{\partial}{\partial t}\begin{Bmatrix} \dot{Z} \\ Z \\ \dot{\gamma}_s \\ \gamma_s \\ \dot{\psi} \\ \psi \\ \beta \end{Bmatrix} = \begin{Bmatrix} \left(F_{sZ} + F_{fZ} - F_{cls}\right)/m \\ \dot{Z} \\ \left(M_{sx} + M_{fx}\right)/I + \dot{\psi}^2\gamma_s \\ \dot{\gamma}_s \\ \left[\left(M_{sy} + M_{fy}\right)/I - 2\dot{\psi}\dot{\gamma}_s\right]/\gamma_s \\ \dot{\psi} \\ \left\{\beta_{ref}\left[\left(h_{ref}/h\right)\left(\dot{\psi}_r/\omega_{ref}\right)^2\right] - \beta\right\}/\tau \end{Bmatrix}$$

+

Lubrication equations:

$$\left[S\right]\left\{\dot{p}\right\} = \left\{R\right\}$$

or

$$\{\dot{p}\} = \{R\}$$

=

Coupled set of first-order ODEs:

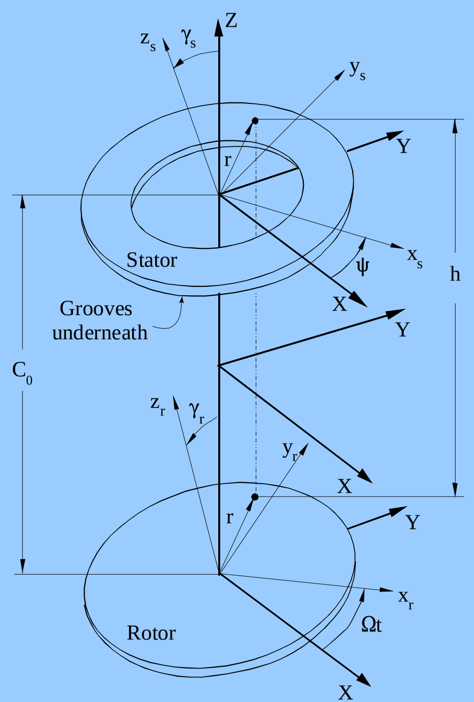
$$FEM: \quad [A(t,\varphi)]\{\dot{\varphi}\} = \{R(t,\varphi)\}$$

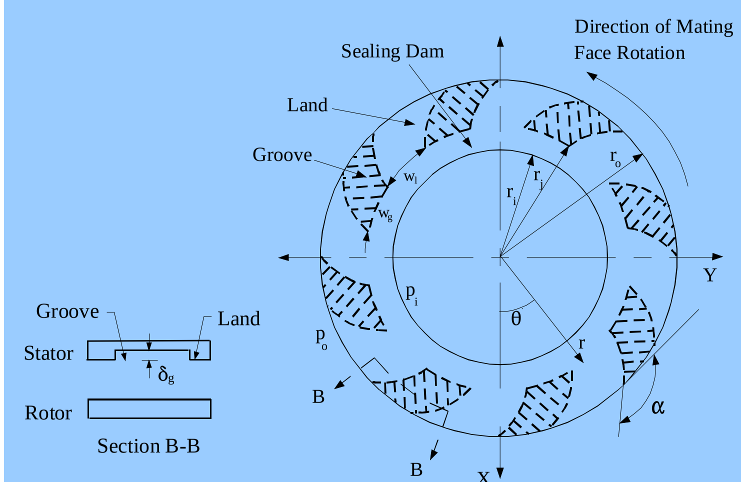
$$FVM: \quad \{\dot{\varphi}\} = \{R(t,\varphi)\}$$

1) Systematic coupling of kinetic and lubrication equations

2) Simultaneous solution using numerical ODE solver

Spiral Groove – Load Support in Compressible Flow





Tilts are small, so treated as vector tilts:

$$\vec{\gamma}_s = \gamma_X \vec{e}_X + \gamma_Y \vec{e}_Y$$

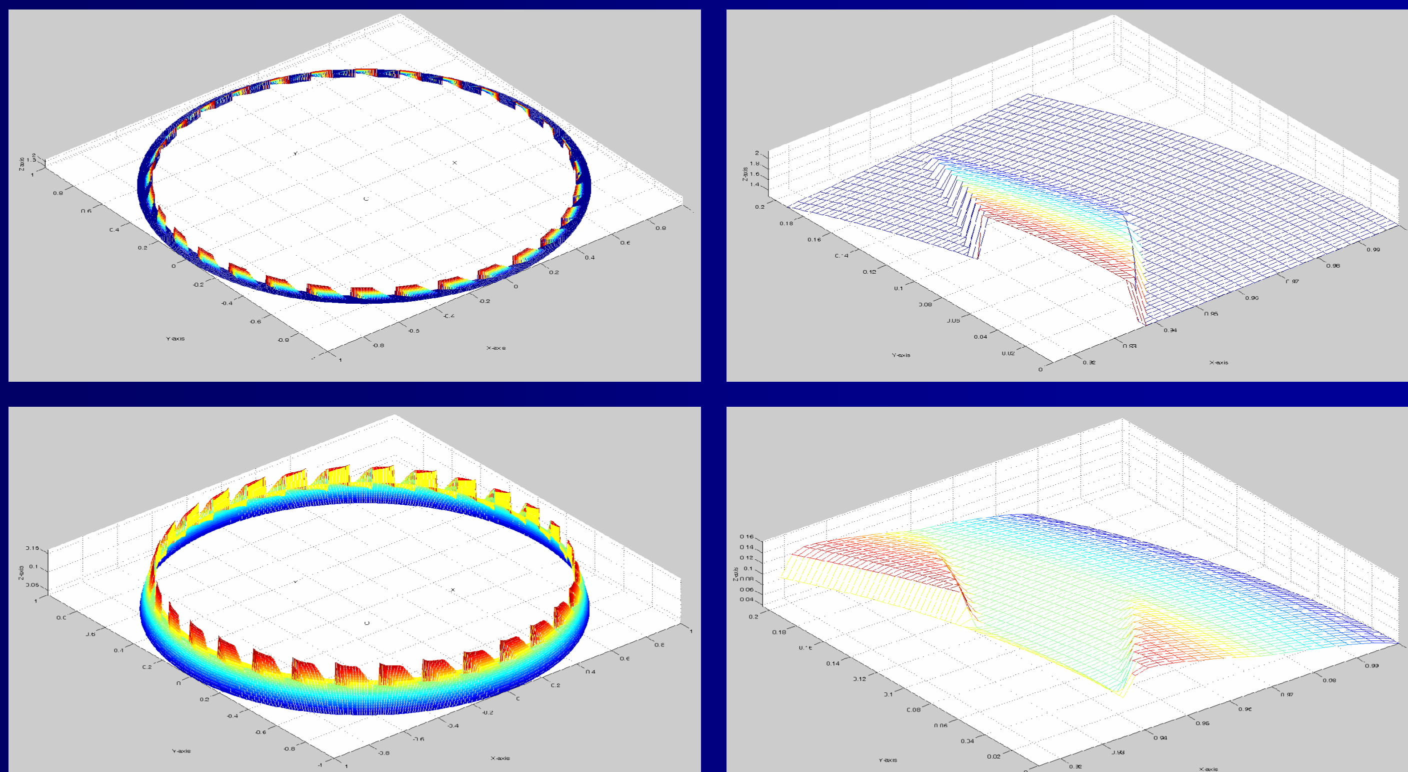
3 degrees of freedom:

$$\begin{bmatrix} k_{f,Z} & k_{f,\gamma_X} & k_{f,\gamma_Y} \\ k_{m_X,Z} & k_{m_X,\gamma_X} & k_{m_X,\gamma_Y} \\ k_{m_Y,Z} & k_{m_Y,\gamma_X} & k_{m_Y,\gamma_Y} \end{bmatrix}$$

According to linearized gas film properties,
the axial mode is decoupled from the tilt modes:

$$\begin{bmatrix} k_{f,Z} & 0 & 0 \\ 0 & k_{m_X,\gamma_X} & k_{m_X,\gamma_Y} \\ 0 & k_{m_Y,\gamma_X} & k_{m_Y,\gamma_Y} \end{bmatrix}$$

Spiral Groove (example)



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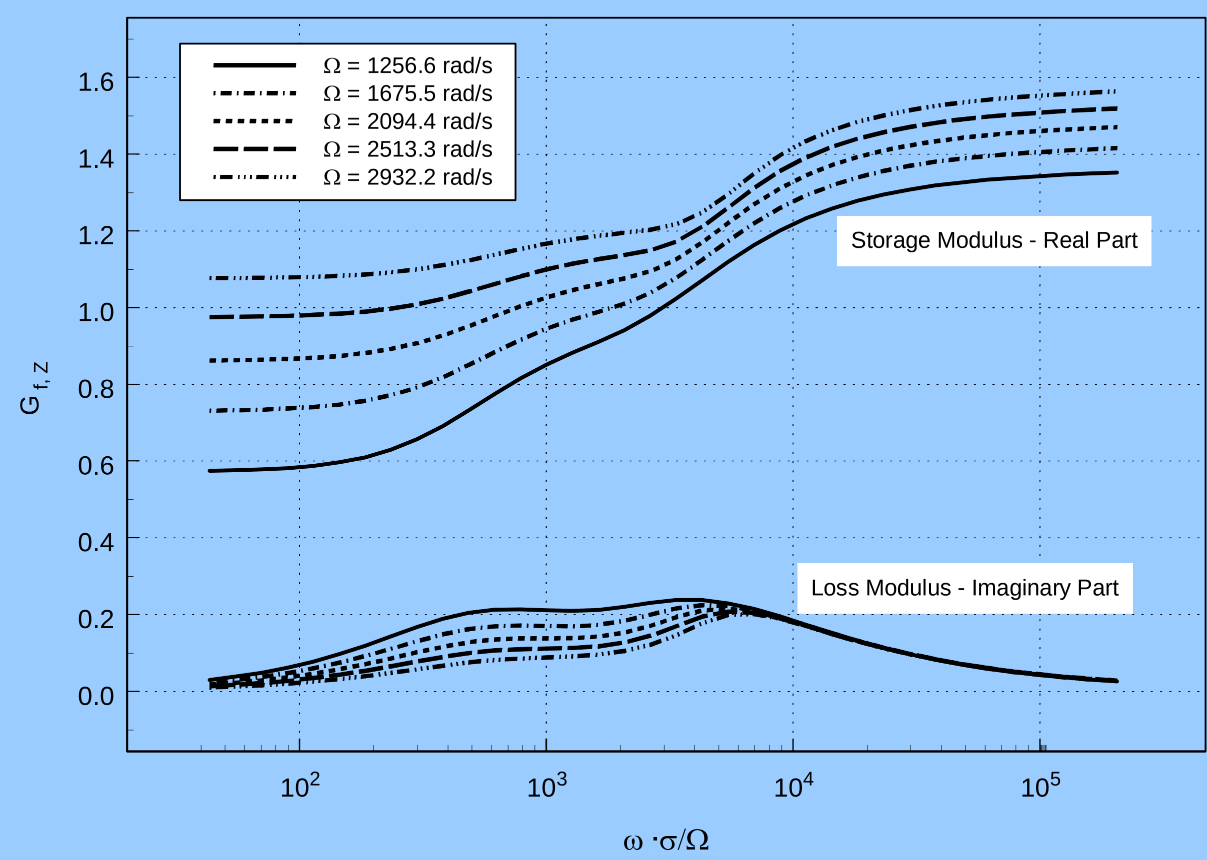
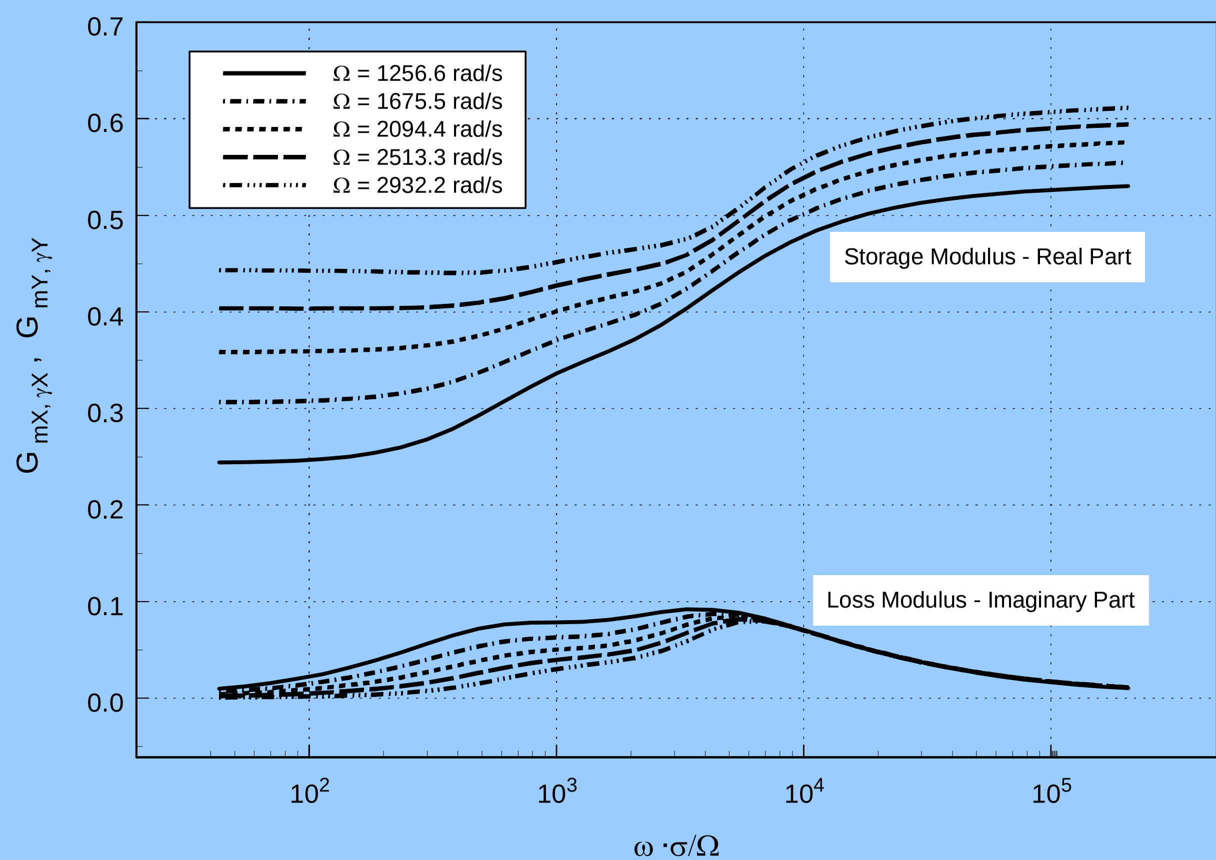
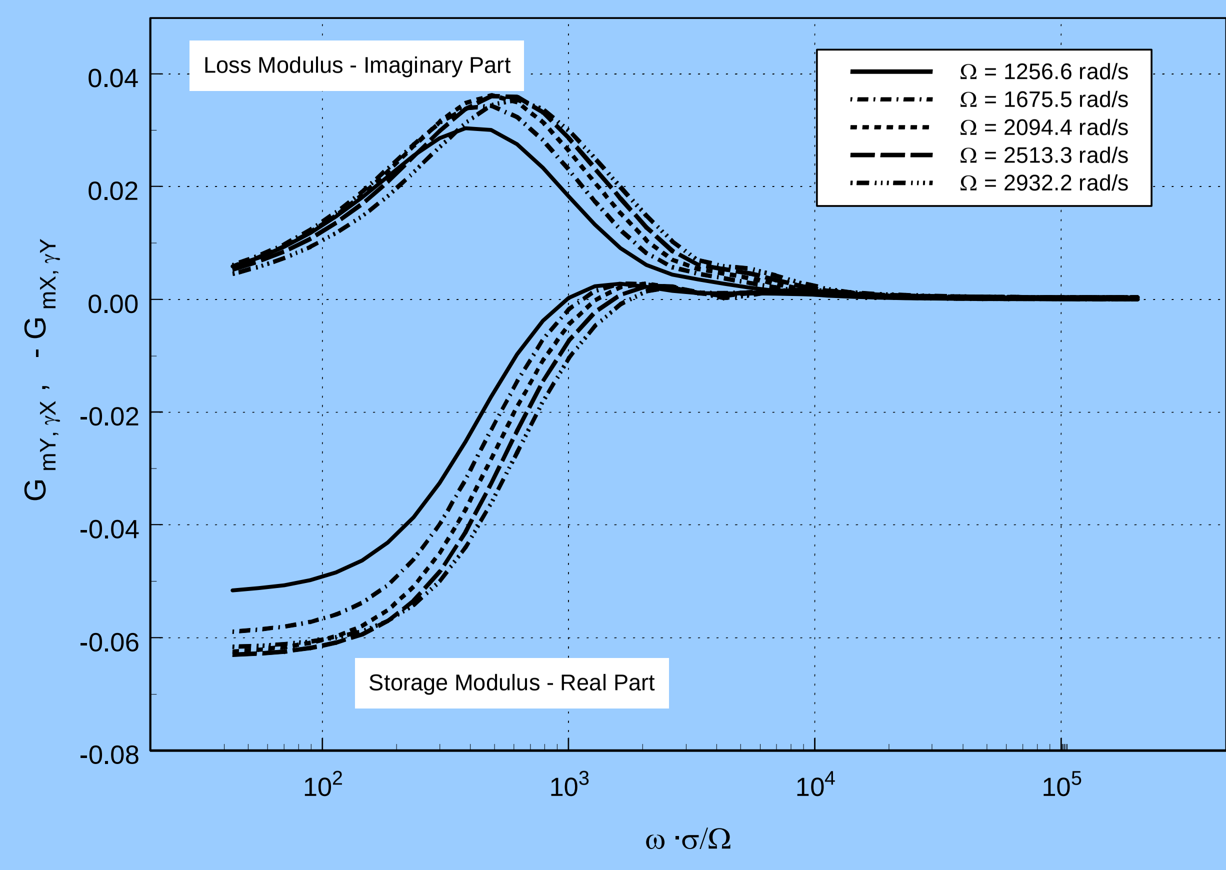
Axial Force Frequency Responses for Mechanical Face Seal



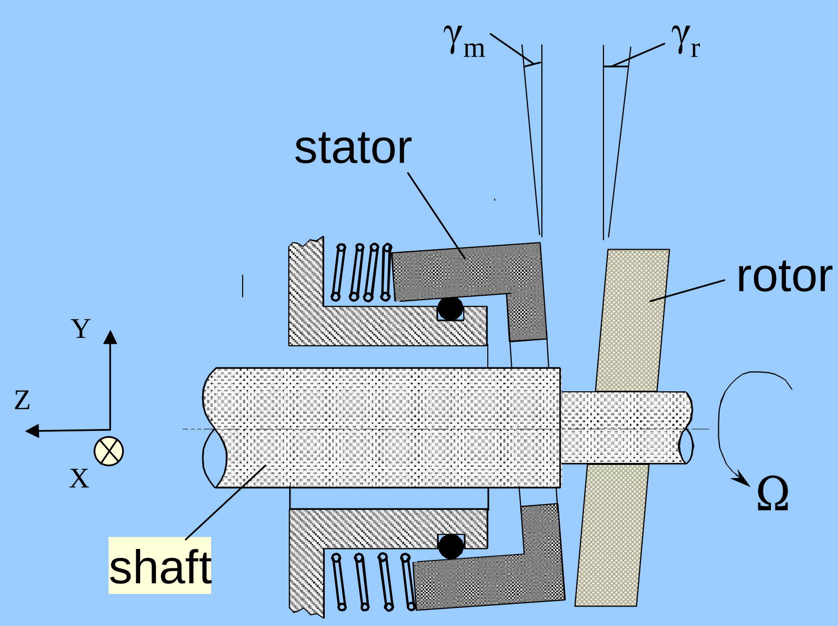
Direct Moment Frequency Responses for Mechanical Face Seal



Cross-Coupled Moment Frequency Responses for Mechanical Face Seal



Rotor runout and static stator misalignment



Static stator misalignment provides constant moment about *X* axis

$$M_{Xi} = \gamma_m \cdot k_{s\gamma}$$

Equations of motion with pseudo springs representing the gas film stiffness (Axial mode decoupled from the tilt modes:

$$m^* \ddot{Z} = - k_{f,Z,g} Z - k_{sZ} Z - d_{sZ} \dot{Z}$$

$$I_t^* \ddot{\gamma}_X = - k_{m_X,\gamma_X,g} \left[\gamma_X - \gamma_r \cos(\Omega t) \right] - k_{s\gamma} \gamma_X - d_{s\gamma} \dot{\gamma}_X - k_{m_X,\gamma_Y,g} \left[\gamma_Y - \gamma_r \sin(\Omega t) \right] + M_{Xi}$$

$$I_t^* \ddot{\gamma}_Y = - k_{m_Y,\gamma_X,g} \left[\gamma_X - \gamma_r \cos(\Omega t) \right] - k_{m_Y,\gamma_Y,g} \left[\gamma_Y - \gamma_r \sin(\Omega t) \right] - k_{s\gamma} \gamma_Y - d_{s\gamma} \dot{\gamma}_Y$$

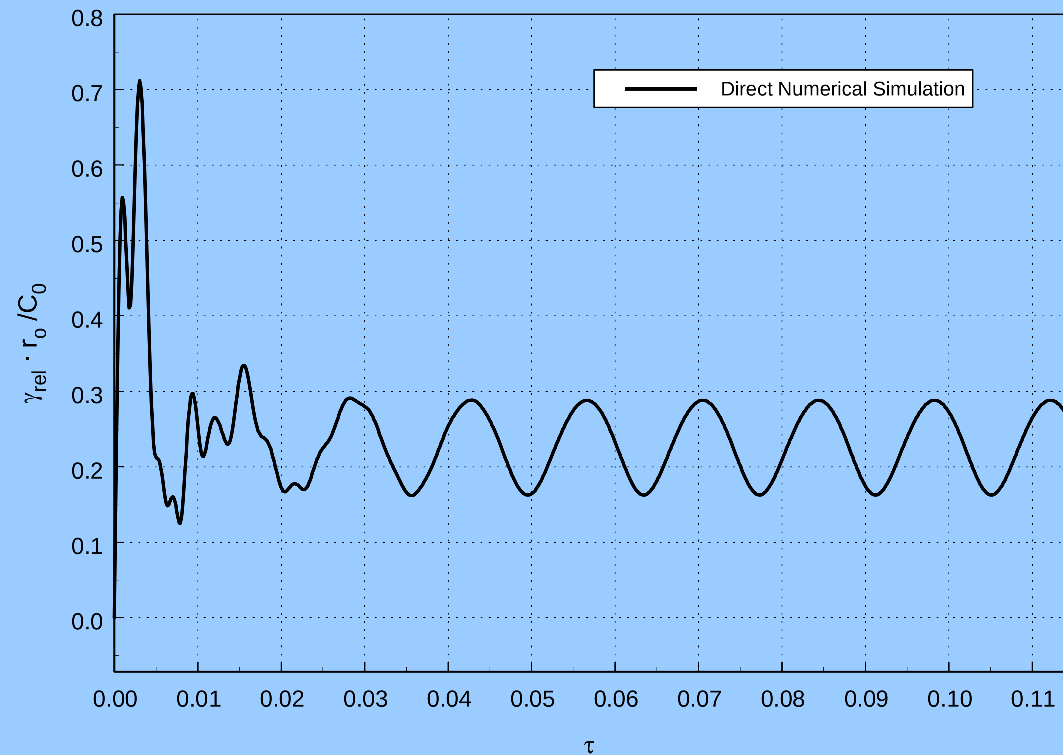
Comparison of Solutions for Transmissibility

Correspondence Principle:

$$\left|\frac{\gamma_{rel}}{\gamma_r}\right|_{max} = 0.135$$

Direct Numerical Simulation:

$$\left|\frac{\gamma_{rel}}{\gamma_r}\right|_{max} = 0.144$$



r_o=6.0 mm	r_j=5.16 mm	r_i=4.80 mm
C_0=6.0 μm	Ω=2094.4 rad/s	μ=1.8 (10)$^{-5}$ N·s/m^2
P_i=1.0 (10)^5 Pa	P_o=2.0 (10)^5 Pa	m^*=1.0 kg
I_t^*=1.8 (10)$^{-3}$ kg·m^2	N_g=12	α=160 deg
β=0.5	δ=12 (10)$^{-6}$ m	k_{sZ}=5.0 (10)^5 N/m
d_{sZ}=300.0 N·s/m	$k_{s\gamma}$ =900.0 N·m/rad	$d_{s\gamma}$=0.54 N·m·s/rad
γ_r= 0.2 mrad	γ_m= 0.5 mrad	

Transient operation conditions

$$f = 0 \qquad t < 0,\ t > t_3$$

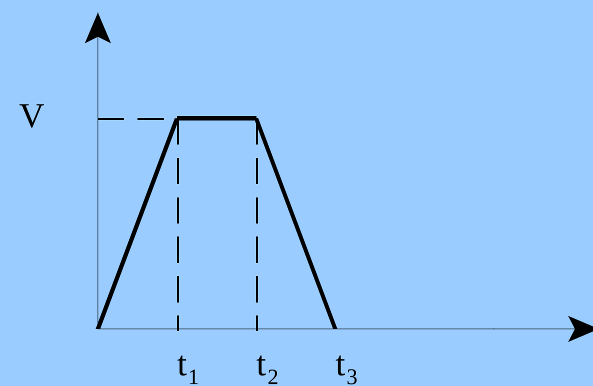
$$f = V\tfrac{t}{t_1} \qquad 0 \le t \le t_1$$

$$f = V \qquad t_1 \le t \le t_2$$

$$f = V\left(1 - \frac{t - t_2}{t_3 - t_2}\right) \qquad t_2 \le t \le t_3$$

where V is a desired steady-state value

$$\{V\} == \{\dot{\psi}_r = \omega,\ p_i,\ or\ \ p_o\}$$



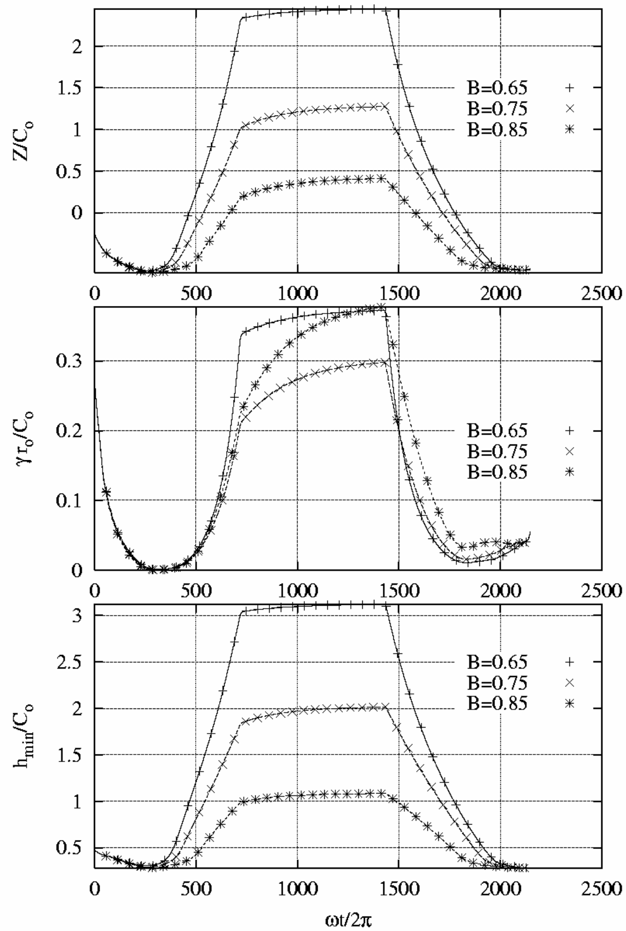


Fig. 4a: Balance ratio effects upon transient response (τ = 2 s)

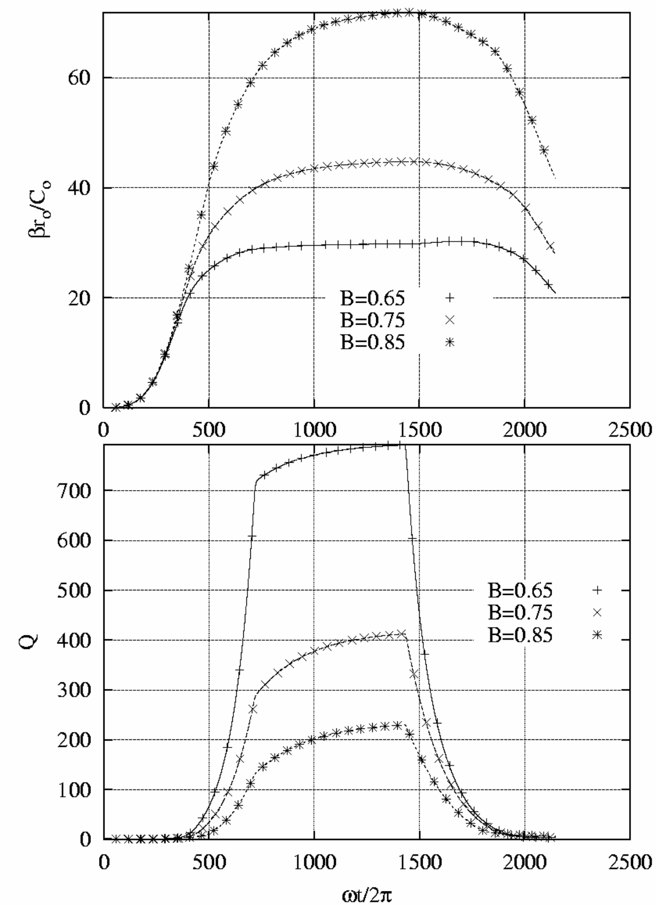


Fig. 4b: Balance ratio effects upon coning and flow (τ=2 s)

NASA Seals Workshop
November 14-15, 2006

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Mechanical Seal Codes

	INCOMP	COMP	SEPARATE	MIXED3D	TAU	TAU-G	Comments
Transient Dynamic Analysis	yes	yes	no (1a)	no	yes	yes	(1a) can predict analytically separation speed, (1n) separation speed is obtained from numerical simulation
Degrees of Freedom	3 (non-axisymmetric)	3 (non-axisymmetric)	2 (axisymmetric)	3 (non-axisymmetric)	3 (non-axisymmetric)	3 (non-axisymmetric)	
Incompressible	yes	no	yes	no	yes	no	
Compressible	no	yes	yes	yes	no	yes	
Noncontacting	yes	yes	yes(2)	yes(2)	yes(2)	yes(2)	(2) seamless transition from contacting to noncontacting modes of operation; thus, classification of conttact/noncontact is no longer needed.
Contacting	no	no	yes(2)	yes(2)	yes(2)	yes(2)	
Coning	yes(3)	yes(3)	yes(3)	yes(4)	yes(3)	yes(4)	(3) linear coning; (4) cubic coning
Wavy	no	no	no	yes(5)	no	yes(5)	(5) periodic; or arbitrary (read from file)
Spiral grooves	no	no	no	yes(6)	no	yes(6)	(6) Includes a sector solution (as an option)
Thermal Face Deformation	no	no	no	no	yes(7)	yes(7)	(7) using time-dependent ad hoc differential equation (allows complete transient analysis)
Separation Speed	no	no	yes(1a)	no	yes(1n)	yes(1n)	
Wear Model	no	no	no	no	yes(8)	yes	(8) Under development

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A RAPID SURVEY OF THE COMPATIBILITY OF SELECTED SEAL MATERIALS WITH CONVENTIONAL AND SEMI-SYNTHETIC JP–8

John L. Graham and Richard C. Striebich
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Dayton, Ohio

Donald K. Minus and William E. Harrison III
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Wright-Patterson Air Force Base
Dayton, Ohio

A Rapid Survey of the Compatibility of Selected Seal Materials with Conventional and Semi-Synthetic JP-8

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Opening remarks.

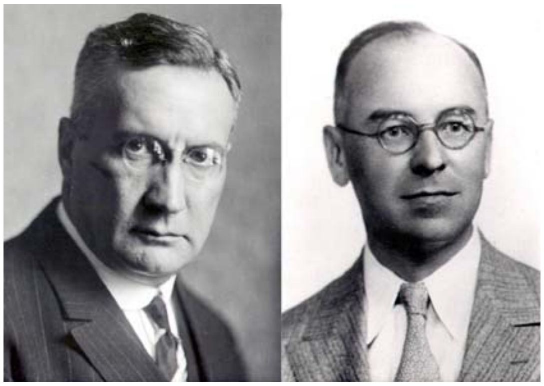
Since the synthesis of a liquid hydrocarbon fuel from coal by Franz Fischer and Hans Tropsch in 1923, there has been cyclic interest in developing this fuel for military and commercial applications. In recent years the U.S. Department of Defense has taken interest in producing a unified battlespace fuel using the Fischer Tropsch (FT) process for a variety of reasons including cost, quality, and logistics. In the past year there has been a particular emphasis on moving quickly to demonstrate that an FT fuel can be used in the form of a blend with conventional petroleum-derived jet fuel. The initial objective is to employ this semi-synthetic fuel with blend ratios as high as 50 percent FT with longer range goals to use even high blend ratios and ultimately a fully synthetic jet fuel. A significant concern associated with the use of a semi-synthetic jet fuel with high FT blend ratios is the effect these low aromatic fuels will have on fuel-wetted polymeric materials, most notably seals and sealants. These materials typically swell and soften to some degree when exposed to jet fuel and the aromatic content of these fuels contribute to this effect. Semi-synthetic jet fuels with very low aromatic contents may cause seals and sealants to shrink and harden leading to acute or chronic failure. Unfortunately, most of the material qualification tests are more concerned with excessive swelling than shrinkage and there is little guidance offered as to an acceptable level of shrinkage or other changes in physical properties related to low aromatic content. Given the pressing need for guidance data, a program was developed to rapidly survey the volume swell of selected fuel-wetted materials in a range of conventional and semi-synthetic jet fuels and through a statistical analysis to make a determination as to whether there was a basis to be concerned about using fuels with FT blend ratios as high as 50 percent. Concurrent with this analysis data was obtained as to the composition of the fuel absorbed in fuel-wetted materials through the use of GC-MS analysis of swollen samples as well as other supporting data. In this presentation the authors will present a summary of the results of the volume swell and fuel absorbed by selected O-rings and sealants as well as a description of the measurement protocols developed for this program.

Fischer-Tropsch Fuel

Developed by Franz Fischer and Hans Tropsch in 1923.

Hydrocarbon feedstocks are converted to carbon monoxide and hydrogen via high-temperature partial oxidation (Mond, 1879).

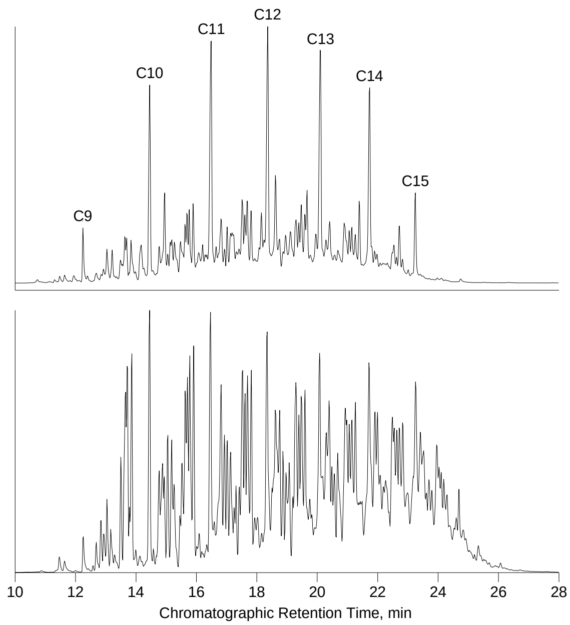
This mixture (called syngas) is then recombined over a catalyst to form a complex mixture of paraffins and iso-paraffins.



Franz Fischer Hans Tropsch

When we talk about synthetic fuels we're almost always talking about the Fischer-Tropsch process.

Fischer-Tropsch Fuel



JP-Fuel

75- 90% Alkanes
- Paraffins
- iso-Paraffins
- Cyclo-Paraffins

10-25% Aromatics
1-3% di-Aromatics (naphthalenes)
<1% Other
<1% Heteroatomic Species (sulfur)

Synthetic JP-Fuel (FT)

100% Alkanes
- Paraffins
- iso-Paraffins

Sulfur Species: Lubricity

Aromatics: Elastomer Compatibility

In contrast FT fuel is composed entirely of paraffins and iso-paraffins....

Potential Strategies for Formulating FT Fuels

1) **Blend FT fuels with appropriate aromatics**
   + Conceptually offers a relatively simple solution
   - 10-20% Aromatics will be required
   - Aromatics contribute undesirable characteristics
   - Which aromatics? Not all aromatics contribute equally to swell

2) **Blend FT fuels with something other than aromatics**
   + Eliminates the problems associated with aromatics
   + Could hopefully be added in very small amounts
   + Offers opportunities for multi-functional additives
   - No swelling promoters are currently available for fuel

3) **Blend FT fuels with JP-8 (Semi-synthetic JP-8)**
   + Potentially offers the simplest solution
   + Presents the fewest unknowns to OEMs
   + Operational experience with Sasol in South Africa
   - JP-8s are typically 75-90% paraffins (10-25% ‘active’ species)
   - By definition JP-8 behavior will be shifted towards FT
   - The range of acceptable blending ratios is uncertain

Common to all of these approaches is the issue of defining of an acceptable end-point

Potential strategies for making FT fuel compatible with conventional petroleum distillate fuels.

How do we define and acceptable end-point?

Qualification Tests for Material Physical Properties

Qualification tests for materials were written to qualify materials, not fuels.

Qualification tests were presumably written to qualify materials for service in petroleum distillate fuels such as JP-4 and JP-5.

Qualification tests often list maximum and/or minimum values following exposure in Type I and Type III reference fluids;

Type I	100% iso-Octane
Type III	30%v/v Toluene in iso-Octane

The maximum and minimum values specified in these tests does not necessarily mean that these are allowable in-service ranges, but rather these are initial values about which they are anticipated to vary by some nominal amount once in service.

For example, a common specification for O-rings is that they swell from 1-25% when aged in Type I and III fluids.

The existing material qualification tests do not provide adequate guidance to determine the compatibility of alternative fuels.

Specification tests for materials were written to qualify materials, not fuels.

Initial Flight Test Program: 25-50% FT/JP-8 Blend

Spring 2006
Plans were put in motion to perform a a flight test with a semi-synthetic blend consisting of 25-50%v FT fuel in JP-8

Summer 2006
Ground tests at Tinker AFB

Fall 2006
Single-engine flight test (B-52) at Edwards AFB

Winter 2006
8-engine flight test (B-52) at Edwards AFB

Spring 2006
From a material compatibility perspective is safe to fly a 25-50%v FT fuel in JP-8?

Outline of an accelerated test plan in support of flight tests with semi-synthetic JP-8.

A Statistical Approach to Fuel Compatibility

The basis for a statistical approach to fuel compatibility is the fact that all materials presently in use have passed their respective qualification tests.

Through the course of normal use they are exposed to a range of JP-8s with a commensurate range of compositions, including aromatic content, and range of fuel/material interactions (e.g. volume swell).

If the behavior of an alternative fuel falls within the bounds of 'normal' JP-8 behavior, the fuel should be compatible with JP-8.

This approach does not necessarily demonstrate *absolute performance limits*, but rather provides guidance as to the degree of compatibility between JP-8 and an alternative fuel.

The basis for a statistical approach.

Experimental Program - Overall Approach

Obtain representative physical property data (volume swell) in a range of JP-8s to develop a statistical description of how a particular material behaves in 'normal' JP-8 (≥10% aromatics).

Obtain the same data in a semi-synthetic (FT/JP-8) fuel blend and compare these two populations to obtain a measure of the overlap between them.

Overall approach to employing a statistical model.

Experimental Program - Methods

Estimate the semi-volatile content of the original dry material
+ Thermogravimetric Analysis (TGA)
+ Provides an estimate of the propensity to shrink in fuel
+ Reconcile volume swell and fuel absorption data

Measure the amount and composition of the fuel absorbed
+ Direct Thermal Desorption GC-MS
+ Fuel/polymer partition coefficients
+ Estimate the relative contributions of aromatics and alkanes

Measure the volume swell
+ Optical Dilatometry
+ Relatively simple *in situ* method based on digital imaging
+ Provides temporal information

All of these methods use small samples (1-5 mg samples in 1-10 mL of fuel) and are suitable for high-throughput testing.

Experimental methods.

Test Matrix

10 Neat Fuels (9 JP-8s and 1 FT fuel)
30 Blends (25%, 37.5%, 50%, and 75%v/v FT)

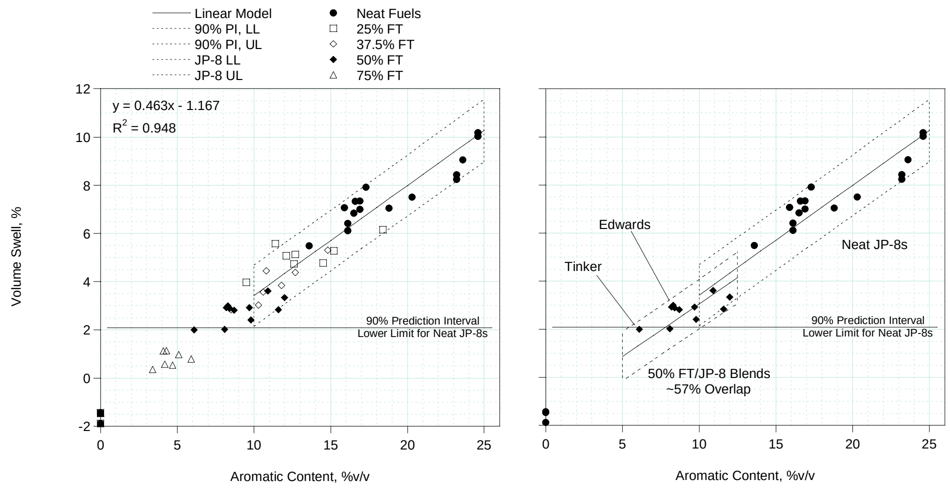
29 Non-metallic Materials

6 Sealants	2 Bladders
4 O-rings	2 Hoses
4 Films	2 Composites
3 Coatings	1 Foam
3 Adhesives	3 Miscellaneous

O-rings	**Sealants**
Nitrile Rubber	Polythioether/Polyurethane
Fluorosilicone	Fluorosilicone
Fluorocarbon (2)	Polysulfide (3)
	Polythioether

Test Matrix

O-rings: N0602-001 Nitrile Rubber



		Semi-	Fuel Absorbed		Partitioning			Swelling		Overlap
O-ring	Material	Volatiles	0% Aro.	25% Aro.	Alkanes	Aromatics	Ratio	Coefficient	R2	90% PI
N0602	Nitrile	**10.1%m**	**8.7%v**	27.9%v	0.120	0.412	**3.4**	0.451	**0.948**	**57%**

Results summary.

Semi-volatile content (TGA) reflects the propensity of a material to shrink.

Comparing the fuel absorbed with the semi-volatiles lost is an indicator of the balance between material to the fuel and gained from the fuel.

Partitioning reflects the sensitivity to the aromatic content.

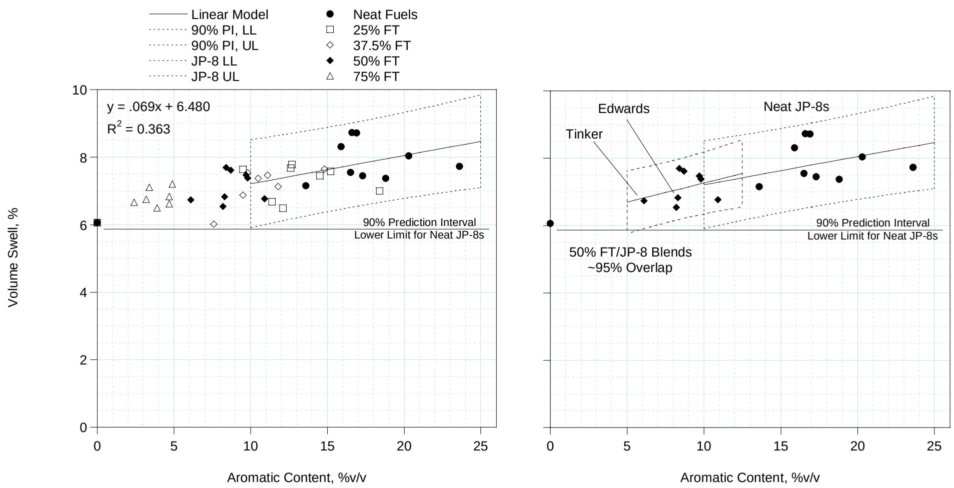
The swelling coefficient reflects the overall result of the polymer:fuel interaction.

The coefficient of determination (R2) reflects the strength of the correlation between the volume swell and aromatic content of all JP-8s.

The overlap between the 90% prediction intervals for the 50% fuel blends and the parent fuels is an approximate measure of the degree of compatibility between the test material and ‘normal’ JP-8s.

Note that in many cases the distribution narrows as the concentration of aromatics approaches zero.

O-rings: L1120-001 Fluorosilicone



		Semi-	Fuel Absorbed		Partitioning			Swelling		Overlap
O-ring	Material	Volatiles	0% Aro.	25% Aro.	Alkanes	Aromatics	Ratio	Coefficient	R2	90% PI
L1120	Fluorosilicone	**0.0%m**	**5.0%v**	**7.9%v**	0.057	0.105	**1.8**	0.069	**0.363**	**95%**

Results summary.

Semi-volatile content (TGA) reflects the propensity of a material to shrink.

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Partitioning reflects the sensitivity to the aromatic content.

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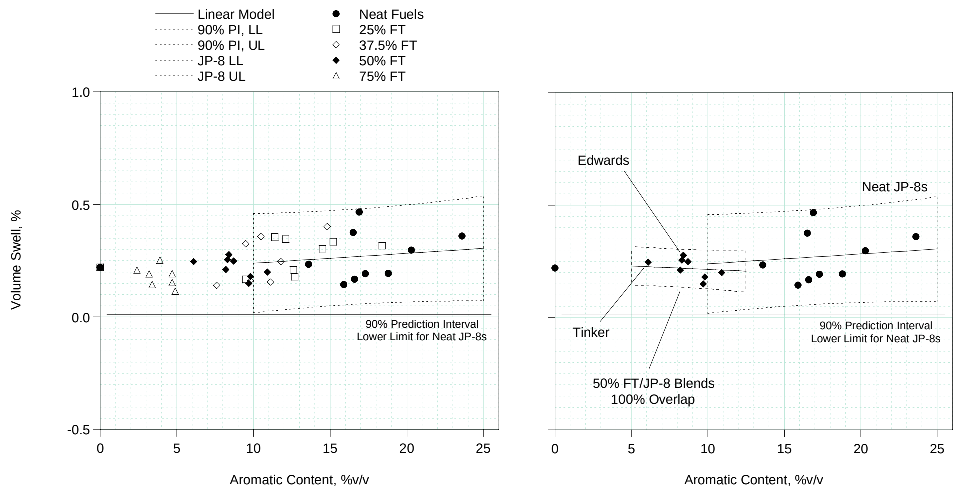
The overlap between the 90% prediction intervals for the 50% fuel blends and the parent fuels is an approximate measure of the degree of compatibility between the test material and 'normal' JP-8s.

O-rings: V0747 & V0835 Fluorocarbon



		Semi-	Fuel Absorbed		Partitioning			Swelling		Overlap
O-ring	Material	Volatiles	0% Aro.	25% Aro.	Alkanes	Aromatics	Ratio	Coefficient	R2	90% PI
V0747	Fluorocarbon	0.3%m	1.0%v	1.7%v	0.006	0.052	8.1	0.007	0.143	100%
V0835	Fluorocarbon	0.6%m	1.6%v	2.4%v	0.010	0.058	5.8	0.002	0.001	100%

Results summary.

Semi-volatile content (TGA) reflects the propensity of a material to shrink.

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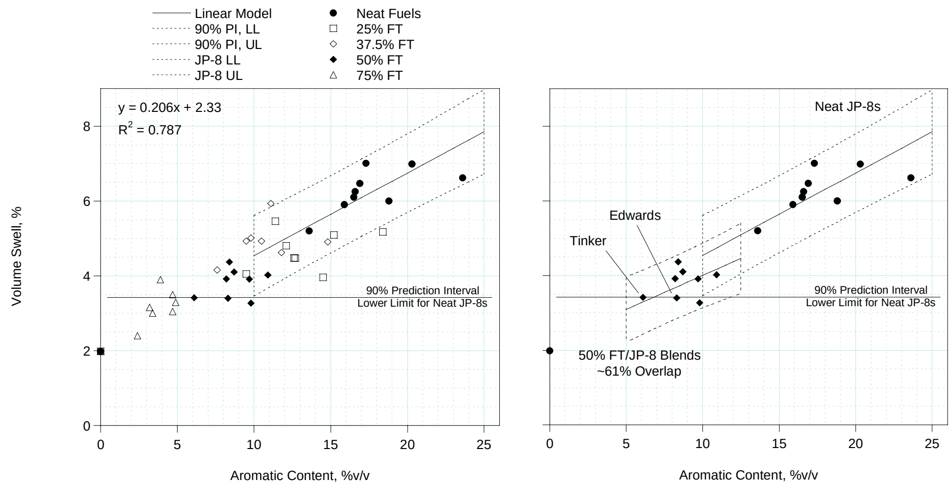
The overlap between the 90% prediction intervals for the 50% fuel blends and the parent fuels is an approximate measure of the degree of compatibility between the test material and ‘normal’ JP-8s.

Sealants: PR-2911 Polythioether/Polyurethane



		Semi-	Fuel Absorbed		Partitioning			Swelling		Overlap
Sealant	Material	Volatiles	0% Aro.	25% Aro.	Alkanes	Aromatics	Ratio	Coefficient	R2	90% PI
PR-2911	Polythioether/Polyurethane	0.0%m	5.5%v	13.4%v	0.059	0.231	3.9	0.206	0.787	61%

Results summary.

Semi-volatile content (TGA) reflects the propensity of a material to shrink.

Comparing the fuel absorbed with the semi-volatiles lost is an indicator of the balance between material to the fuel and gained from the fuel.

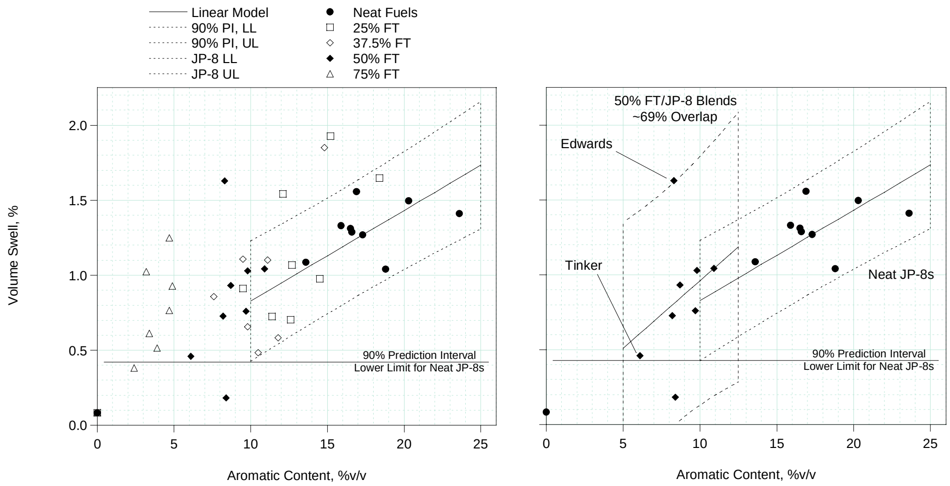
Partitioning reflects the sensitivity to the aromatic content.

The swelling coefficient reflects the overall result of the polymer:fuel interaction.

The coefficient of determination (R2) reflects the strength of the correlation between the volume swell and aromatic content of all JP-8s.

The overlap between the 90% prediction intervals for the 50% fuel blends and the parent fuels is an approximate measure of the degree of compatibility between the test material and ‘normal’ JP-8s.

Sealants: Q4-2817 Fluorosilicone



		Semi-	Fuel Absorbed		Partitioning			Swelling		Overlap
Sealant	Material	Volatiles	0% Aro.	25% Aro.	Alkanes	Aromatics	Ratio	Coefficient	R2	90% PI
Q4-2817	Fluorosilicone	4.3%m	2.9%v	3.0%v	0.026	0.080	3.1	0.052	0.419	69%

Results summary.

Semi-volatile content (TGA) reflects the propensity of a material to shrink.

Comparing the fuel absorbed with the semi-volatiles lost is an indicator of the balance between material to the fuel and gained from the fuel.

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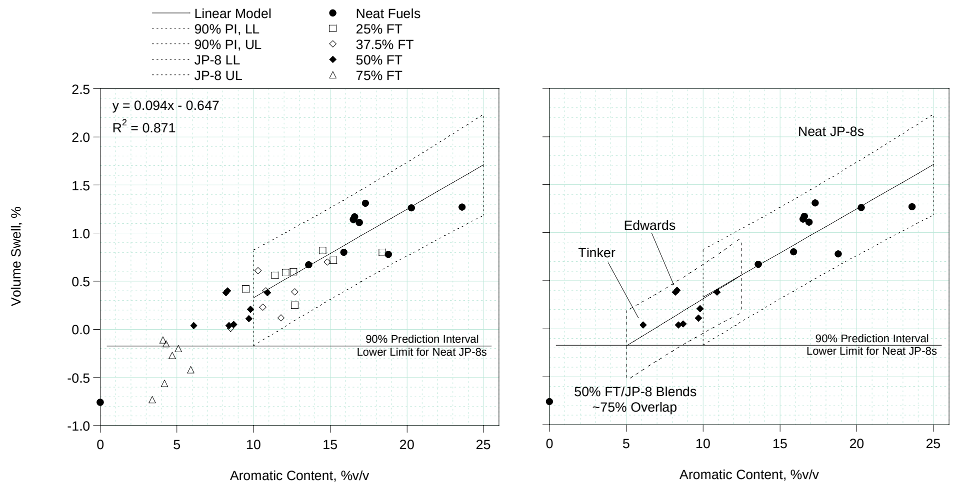
Sealants: PR-1776 MnO_2 Cured Polysulfide



		Semi-	Fuel Absorbed		Partitioning			Swelling		Overlap
Sealant	Material	Volatiles	0% Aro.	25% Aro.	Alkanes	Aromatics	Ratio	Coefficient	R2	90% PI
PR-1776	MnO2 cured Polysulfide	3.9%m	3.4%v	8.7%v	0.035	0.142	4.0	0.094	0.871	75%

Results summary.

Semi-volatile content (TGA) reflects the propensity of a material to shrink.

Comparing the fuel absorbed with the semi-volatiles lost is an indicator of the balance between material to the fuel and gained from the fuel.

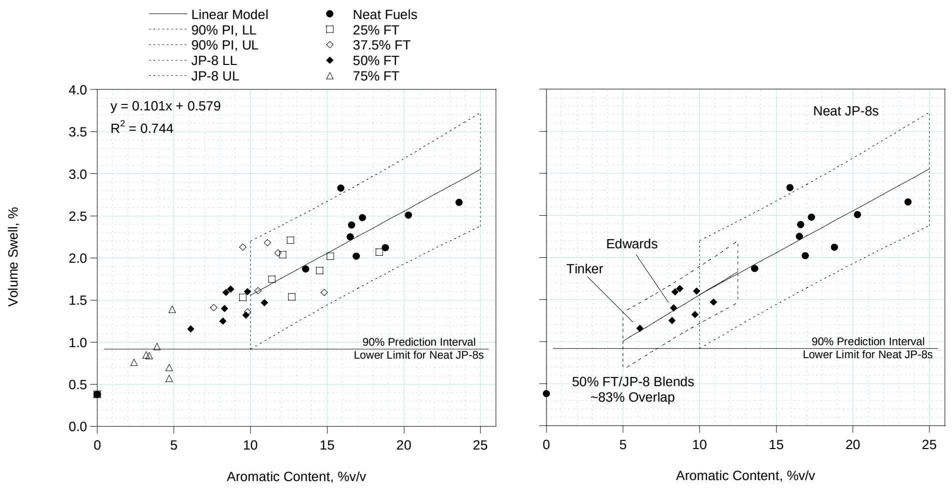
Partitioning reflects the sensitivity to the aromatic content.

The swelling coefficient reflects the overall result of the polymer:fuel interaction.

The coefficient of determination (R2) reflects the strength of the correlation between the volume swell and aromatic content of all JP-8s.

The overlap between the 90% prediction intervals for the 50% fuel blends and the parent fuels is an approximate measure of the degree of compatibility between the test material and ‘normal’ JP-8s.

Sealants: PR-1422 Cr_2O_7 Cured Polysulfide



		Semi-	Fuel Absorbed		Partitioning			Swelling		Overlap
Sealant	Material	Volatiles	0% Aro.	25% Aro.	Alkanes	Aromatics	Ratio	Coefficient	R2	90% PI
PR-1422	Cr2O7 cured Polysulfide	1.9%m	2.8%v	9.9%v	0.033	0.164	4.9	0.101	0.744	83%

Results summary.

Semi-volatile content (TGA) reflects the propensity of a material to shrink.

Comparing the fuel absorbed with the semi-volatiles lost is an indicator of the balance between material to the fuel and gained from the fuel.

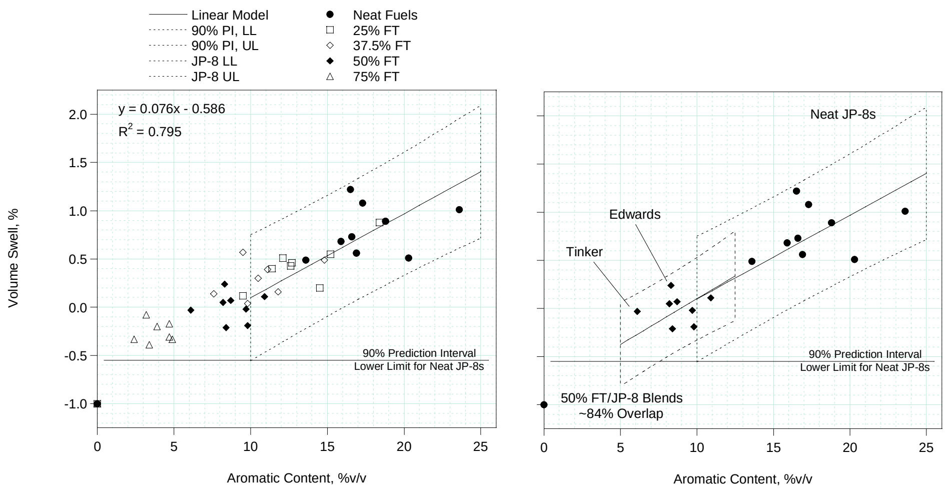
Partitioning reflects the sensitivity to the aromatic content.

The swelling coefficient reflects the overall result of the polymer:fuel interaction.

The coefficient of determination (R2) reflects the strength of the correlation between the volume swell and aromatic content of all JP-8s.

The overlap between the 90% prediction intervals for the 50% fuel blends and the parent fuels is an approximate measure of the degree of compatibility between the test material and ‘normal’ JP-8s.

Sealants: PR-1440 MnO_2 Cured Polysulfide



		Semi-	Fuel Absorbed		Partitioning			Swelling		Overlap
Sealant	Material	Volatiles	0% Aro.	25% Aro.	Alkanes	Aromatics	Ratio	Coefficient	R2	90% PI
PR-1440	MnO2 cured Polysulfide	3.0%m	2.9%v	7.1%v	0.021	0.137	6.5	0.076	0.795	84%

Results summary.

Semi-volatile content (TGA) reflects the propensity of a material to shrink.

Comparing the fuel absorbed with the semi-volatiles lost is an indicator of the balance between material to the fuel and gained from the fuel.

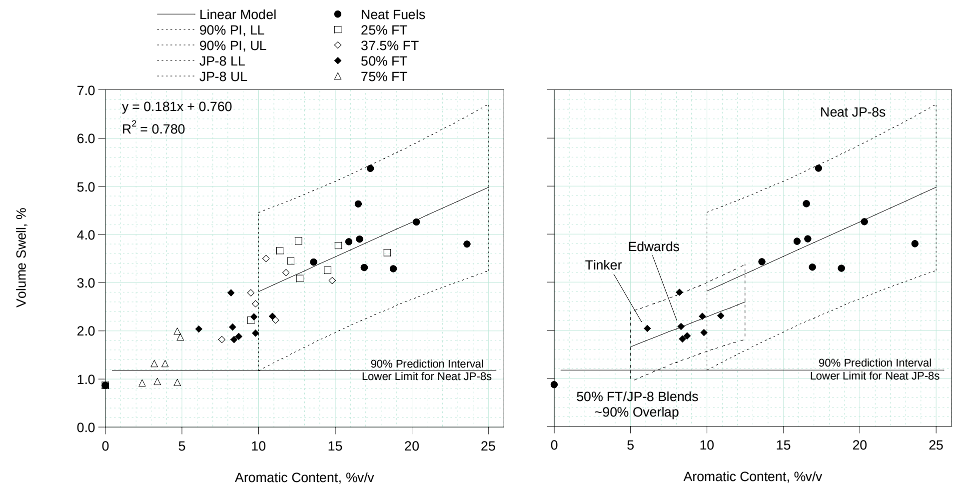
Partitioning reflects the sensitivity to the aromatic content.

The swelling coefficient reflects the overall result of the polymer:fuel interaction.

The coefficient of determination (R2) reflects the strength of the correlation between the volume swell and aromatic content of all JP-8s.

The overlap between the 90% prediction intervals for the 50% fuel blends and the parent fuels is an approximate measure of the degree of compatibility between the test material and ‘normal’ JP-8s.

Sealants: PR-1828 Epoxy Cured Polythioether



		Semi-	Fuel Absorbed		Partitioning			Swelling		Overlap
Sealant	Material	Volatiles	0% Aro.	25% Aro.	Alkanes	Aromatics	Ratio	Coefficient	R2	90% PI
PR-1828	Epoxy cured Polythioether	2.3%	2.0%	9.5%	0.025	0.172	7.0	0.181	0.780	90%

Results summary.

Semi-volatile content (TGA) reflects the propensity of a material to shrink.

Comparing the fuel absorbed with the semi-volatiles lost is an indicator of the balance between material to the fuel and gained from the fuel.

Partitioning reflects the sensitivity to the aromatic content.

The swelling coefficient reflects the overall result of the polymer:fuel interaction.

The coefficient of determination (R2) reflects the strength of the correlation between the volume swell and aromatic content of all JP-8s.

The overlap between the 90% prediction intervals for the 50% fuel blends and the parent fuels is an approximate measure of the degree of compatibility between the test material and ‘normal’ JP-8s.

Summary

O-rings

		Semi-	Fuel Absorbed		Partitioning			Swelling		Overlap
O-ring	Material	Volatiles	0% Aro.	25% Aro.	Alkanes	Aromatics	Ratio	Coefficient	R2	90% PI
N0602	Nitrile	10.1%m	8.7%v	27.9%v	0.120	0.412	3.4	0.451	0.948	**57%**
L1120	Fluorosilicone	0.0%m	5.0%v	7.9%v	0.057	0.105	1.8	0.069	0.363	**95%**
V0747	Fluorocarbon	0.3%m	1.0%v	1.7%v	0.006	0.052	8.1	0.007	0.143	**100%**
V0835	Fluorocarbon	0.6%m	1.6%v	2.4%v	0.010	0.058	5.8	0.002	0.001	**100%**

Sealants

		Semi-	Fuel Absorbed		Partitioning			Swelling		Overlap
Sealant	Material	Volatiles	0% Aro.	25% Aro.	Alkanes	Aromatics	Ratio	Coefficient	R2	90% PI
PR-2911	Polythioether/Polyurethane	0.0%m	5.5%v	13.4%v	0.059	0.231	3.9	0.206	0.787	**61%**
Q4-2817	Fluorosilicone	4.3%m	2.9%v	3.0%v	0.026	0.080	3.1	0.052	0.419	**69%**
PR-1776	MnO2 cured Polysulfide	3.9%m	3.4%v	8.7%v	0.035	0.142	4.0	0.094	0.871	**75%**
PR-1422	Cr2O7 cured Polysulfide	1.9%m	2.8%v	9.9%v	0.033	0.164	4.9	0.101	0.744	**83%**
PR-1440	MnO2 cured Polysulfide	3.0%m	2.9%v	7.1%v	0.021	0.137	6.5	0.076	0.795	**84%**
PR-1828	Epoxy cured Polythioether	2.3%m	2.0%v	9.5%v	0.025	0.172	7.0	0.181	0.780	**90%**

Results summary.

Conclusions

We have developed a statistical approach to estimate the material compatibility of synthetic and semi-synthetic fuels with JP-8.

The method is based on comparing a characteristic response (volume swell) of a material in a reference population of ‘normal’ JP-8s and in the test fuel.

To-date we have completed the analysis of selected O-rings, sealants, fuel barrier materials, adhesives and composites.

To-date, none of these materials have indicated there will be an acute problem operating with 50% FT fuel blends.

The materials that are of greatest concern are the nitrile and nitrile-like materials, especially those with high plasticizer contents.

Some caution needs to be exercised in interpreting the results for materials that rely on physical properties that may not be reflected in the volume swell, most notably interfacial adhesion (adhesives, composites, sealants).

Conclusions.

Future Work

Complete the present test program including obtaining data on the remaining samples.

Extend the program to include other fundamental physical properties such as compressive modulus and adhesion.

The database of JP-8s should be expanded to establish a more complete statistical description of the population of JP-8s.

Suitable methods and reference materials should be developed to circumvent the problem of variations in test materials. This may be accomplished through the use of parallel analysis of samples in selected reference fluids.

Apply this approach to the development of a fully synthetic JP-8. For example, a JP-8 with selected additives and/or a non-petroleum source of aromatics.

Future work.

Acknowledgements

We would like to gratefully acknowledge the United States Air Force, AFRL/PRTG and the United States Department of Energy for supporting this work.

I'd also like to acknowledge the tireless work of Doug Wolf and his co-workers in the UDRI Micro Analytical Laboratory for their work on the optical dilatometry.

And finally, I'd like to acknowledge my students; Chad Huelsman, Valerie Sutton, and George Fels for their hard work.

Acknowledgements.

Questions?

OVERVIEW OF LIDS DOCKING AND BERTHING SYSTEM SEALS

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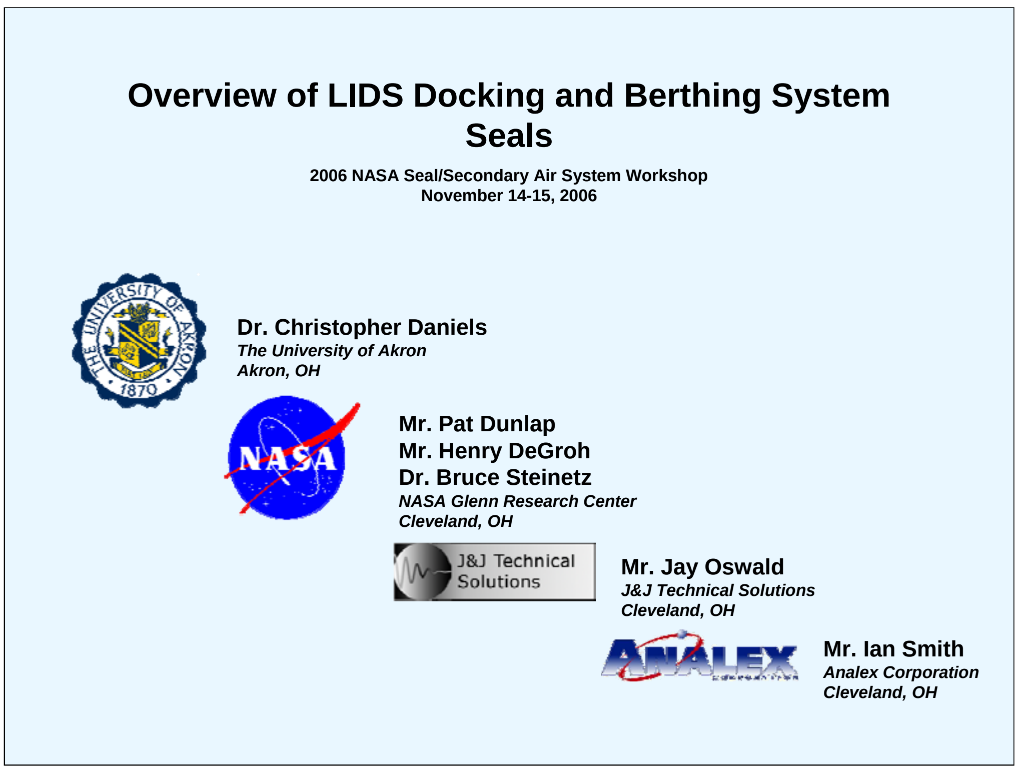
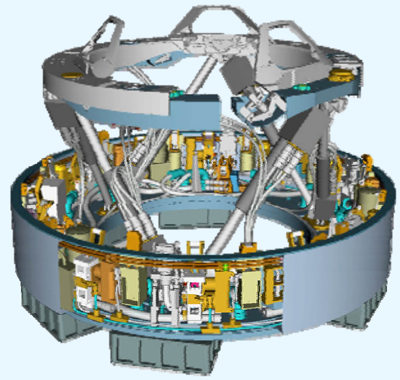


Description of the Application: Low Impact Docking System (LIDS)

- Low Impact Docking System (a.k.a. Advanced Docking Berthing System (ADBS))
- Next-generation space vehicle mating system
- Establishes a standard interface for mating spacecrafts that is:
  - compact
  - smart
  - lightweight
  - low impact
  - reduces the risks associated with mating spacecraft.
- Simplifies spacecraft docking operations by eliminating high-impact loads
- Supports autonomous docking and berthing operations
- Supports a wide range of spacecraft and mating operations.
  - Crew Exploration Vehicle
  - International Space Station



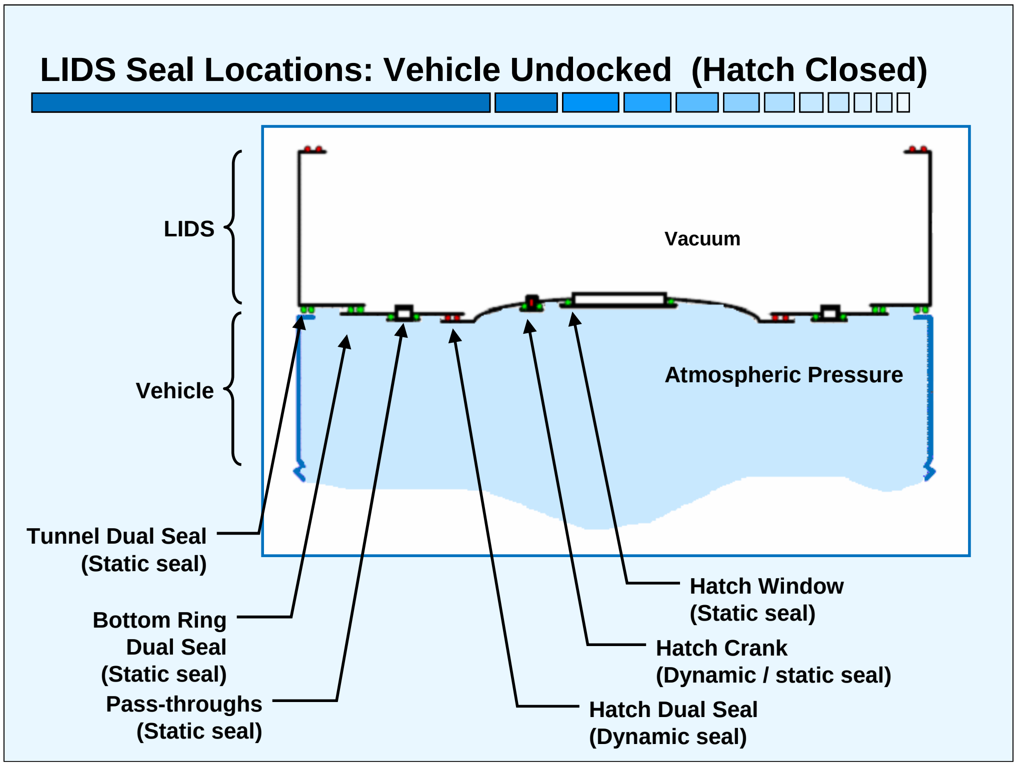
Graphic of the Low Impact Docking System.

+ The Advanced Docking Berthing System shown on the right is under development at Johnson Space Center. The future for the system is to become the agency's standard mating system going forward through the Constellation Program.

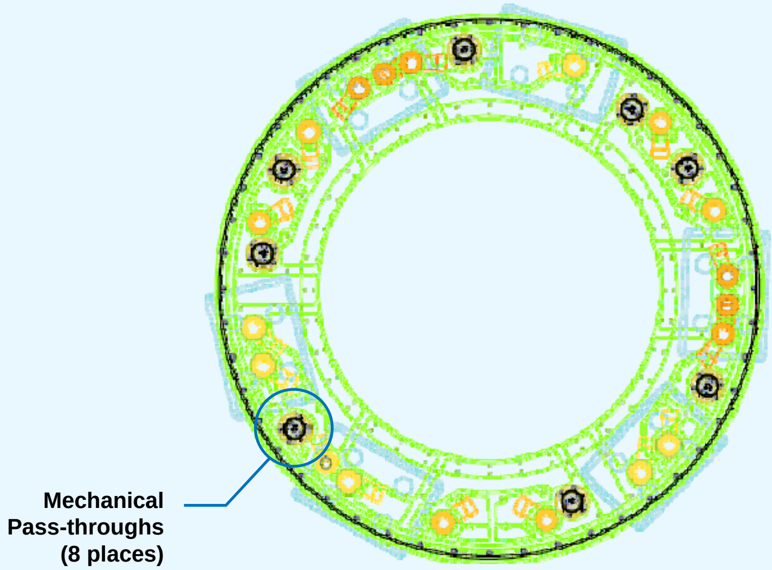
+ The system offers several advantages over the current Russian built system. Most importantly, it reduces the risks associated with mating.

+ It does this by mating with very low impact, and by offering system redundancy.

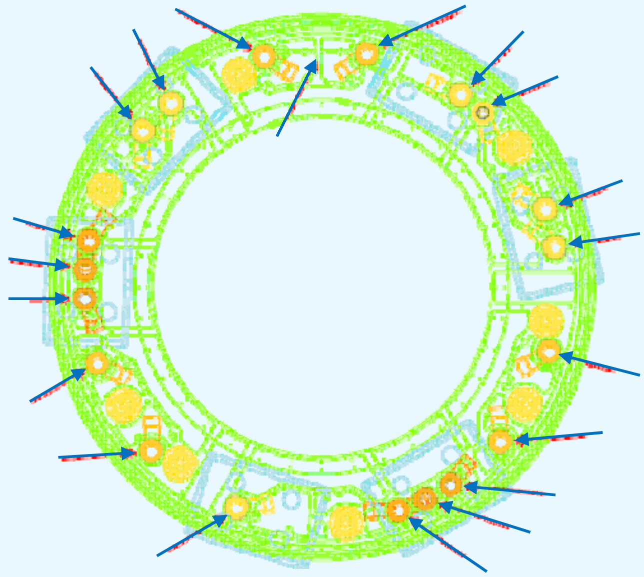
+ The system is redundant on every level because it is androgynous. Each joint is a mate between two identical systems.


LIDS Seal Locations: Vehicle Undocked (Hatch Closed)
LIDS
Vehicle
Vacuum
Atmospheric Pressure
Tunnel Dual Seal
(Static seal)
Bottom Ring
Dual Seal
(Static seal)
Pass-throughs
(Static seal)
Hatch Window
(Static seal)
Hatch Crank
(Dynamic / static seal)
Hatch Dual Seal
(Dynamic seal)

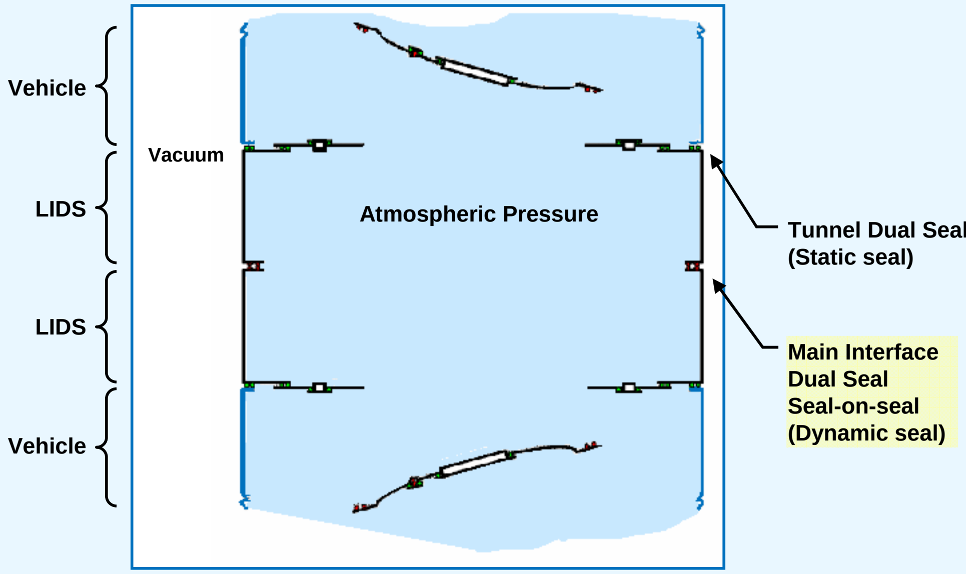
LIDS Seal Locations: Mechanical Pass Thru



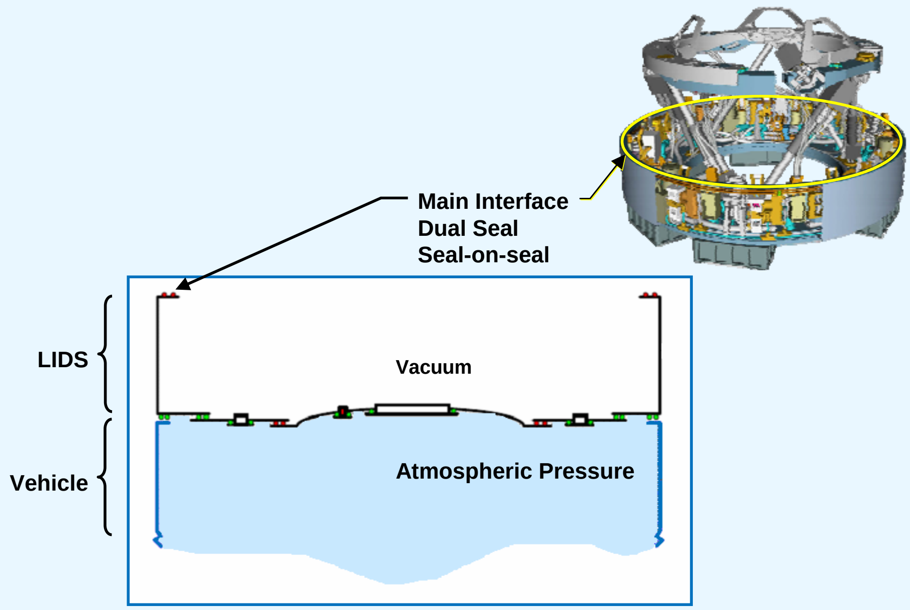
LIDS Seal Locations: Electrical and Pyro Connectors



LIDS Seal Locations: Vehicle Docked (Hatches Open)



LIDS Seal Locations: Main Interface Seal



Main Interface Seal
Challenges and Specifications

Vehicle to vehicle mating requires androgynous (gender neutral) interface

- Androgynous interface requires seal-on-seal configuration
- Seal must accommodate vehicle misalignments and manufacturing tolerances

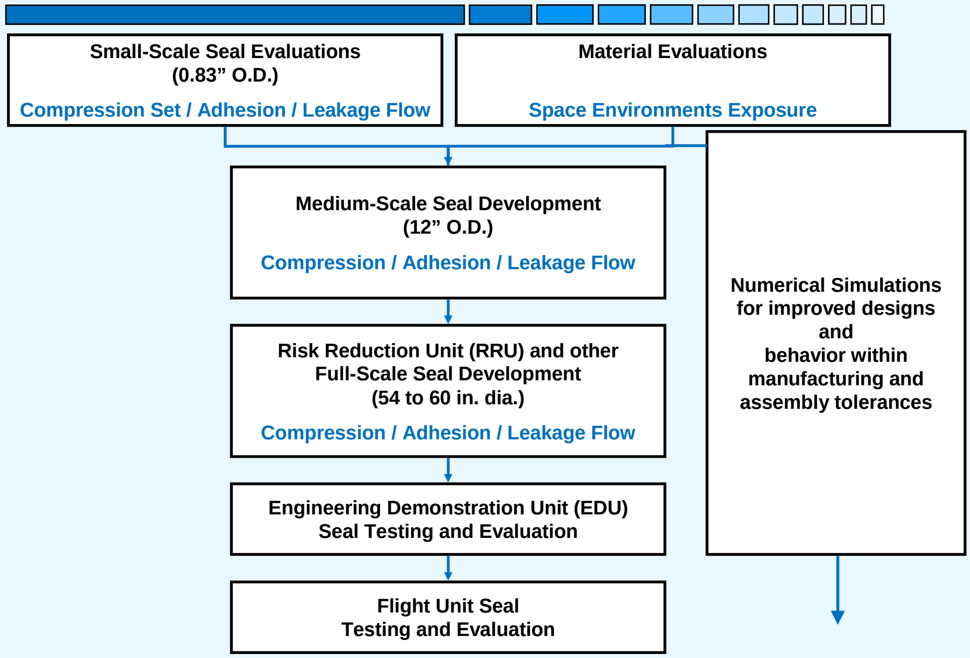
Seal materials must withstand:

- Atomic oxygen in low Earth orbit
- Particle and ultraviolet radiation
- High number of mating cycles
- Micrometeoroid and orbital debris (MMOD)
- Long duration under vacuum
- Thermal gradients and transients
- Thermal environment: -100 to 100°C
- Operating temperature: -50 to 50°C
- Long periods under mating conditions

Seal specifications:

- Compression force < 100 lbf / linear inch / seal
- Adhesion force ~ 0 lbf
- Confined width and height requirements
- Leakage < 0.02 lbm_{AIR} / day under all conditions

Approach

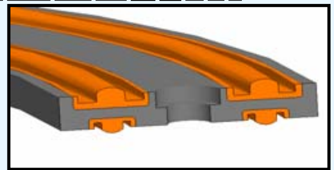

Small-Scale Seal Evaluations
(0.83" O.D.)
Compression Set / Adhesion / Leakage Flow
Material Evaluations
Space Environments Exposure
Medium-Scale Seal Development
(12" O.D.)
Compression / Adhesion / Leakage Flow
Risk Reduction Unit (RRU) and other Full-Scale Seal Development
(54 to 60 in. dia.)
Compression / Adhesion / Leakage Flow
Engineering Demonstration Unit (EDU) Seal Testing and Evaluation
Flight Unit Seal Testing and Evaluation
Numerical Simulations for improved designs and behavior within manufacturing and assembly tolerances

Seal Concepts Under Development/Evaluation

Elastomeric Seals

Gask-o-seal:

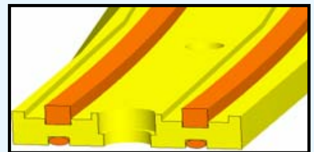
- Able to form near-hermetic seal
- Able to perform under gapping / misalignment conditions
- Currently flying as static berthing seal on Space Station: Common Berthing Module
- Concerns:
  - Long term space exposure
  - Seal-to-seal adhesion
  - Examining remedies.



Gask-o-seal

Gasket Seal:

- Near Term Risk Reduction Unit (RRU) trial seal
- Using to check-out JSC and GRC test hardware

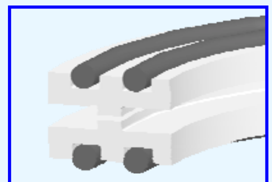


Gasket Seal

Metallic Seals

Metal Face Seal:

- Immune to UV, AO, IR effects
- No known adhesion issue
- Concerns:
  - Very low leakage
  - Large diameter, precision flat surfaces



Metallic Face Seal

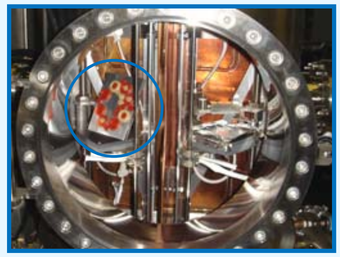
Elastomer Material Evaluations

Evaluation of relevant seal properties

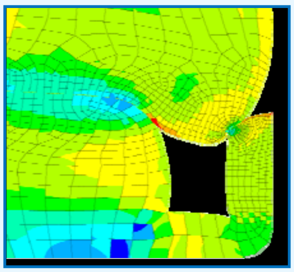
- Compression set
- Elastomer-to-elastomer adhesion
- Leakage rates

Space Environments Exposures

- Understanding / quantifying the effects of
  - Atomic oxygen
  - Ultraviolet and particle radiation
  - Micrometeroid / orbital debris impacts



Photograph of elastomer specimens in the UV exposure chamber



Numerical simulation of two misaligned Gask-o-seals in contact

Numerical predictions

- Mechanical properties of elastomers measured at various temperatures
- Compression load and deformation predicted

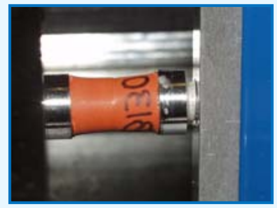
Details provided in the next two presentations

- Space Environments Effects on Candidate LIDS Seal Materials
- FEA Modeling of Elastomeric Seals for LIDS

Evaluation of Relevant Seal Properties

Compression Set

- Determines the ability of elastomeric compounds to retain elastic properties after prolonged compression per ASTM Standards



Photograph of an adhesion test in progress

Adhesion

- Quantifies adhesion between two elastomeric samples

Leakage Flow

- Measure leakage rate of air under vacuum conditions before and after space environments exposures to quantify degradation from AO, UV, ionizing radiation, and MMOD

Medium Scale Flow/Compression Fixture

- Measures leakage rate of candidate seal geometries and materials in nominal and off-nominal configurations
- Quantifies compression and adhesion forces required to mate and demate candidate seal geometries and materials

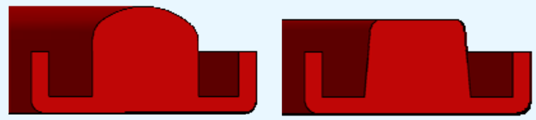
Medium-Scale (12”) Gask-O-Seal Compression Tests

Objectives:

- Determine maximum compressive load
- Characterize decay in maximum compressive load on seal
- Measure maximum adhesion on seal as a function of hold time and number of cycles
- Measure compression set

Procedures:

- Compression set test #1
  - Load and hold for 70 hours (using LIDS docking profile)
  - Unload
  - Wait 30 minutes
- Cyclic loading (Cycles 2-21):
  - Load and hold for 30 minutes
  - Unload
  - Wait 30 minutes
- Compression set test #2
  - Load and hold for 70 hours
  - Unload
  - Wait 30 minutes
- Load for 30 minutes (Cycle 22)



Cross-sections of the elastomer seal concepts with elliptical top (left) and flat top (right) sealing surfaces.

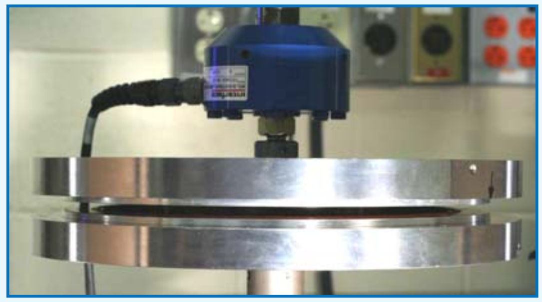


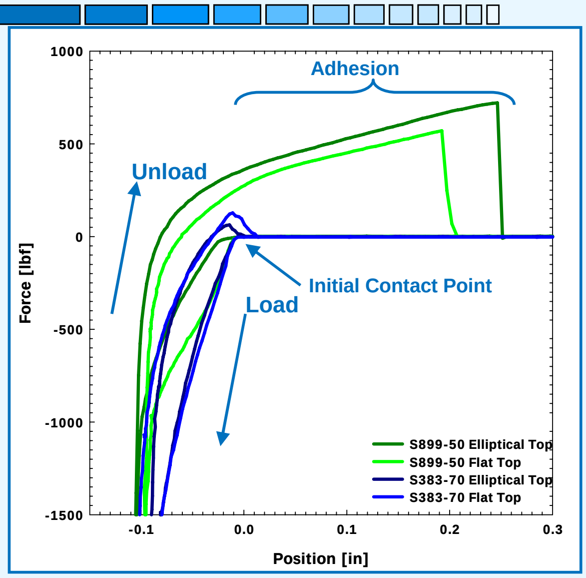
Photo of the compression testing of 12” Gask-o-seals in an axially aligned seal-on-seal configuration.

Medium-Scale Compression Video

Medium-Scale Compression Results

Test specimens:
- Parker Hannifin Gask-o-seal
  - Common Berthing Mechanism (CBM) design
- Two compounds
  - S0383-70
  - S0899-50
- Two configurations
  - Elliptical top
  - Flat top

Results
- Both compounds showed adhesion before release
- During separation, the S0899-50 elastomer stretched 0.25 / 0.20 inch (elliptical / flat top) beyond the initial contact point
- Compression set results were masked by the high levels of adhesion of the S0899-50 compound

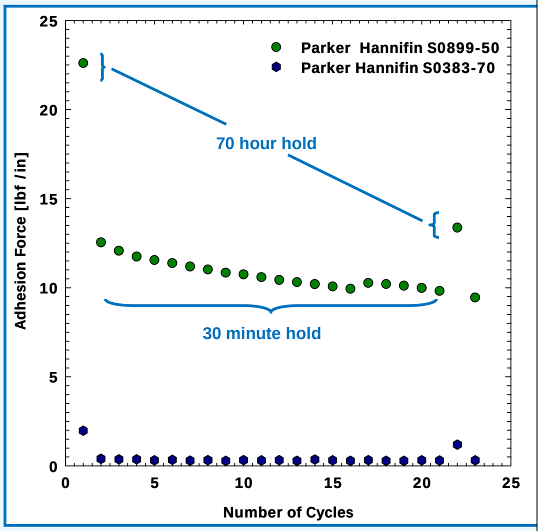


S1853-50 and S0899-50 are identical elastomer compounds with different designations from different divisions within Parker Hannifin. S0899-50 is used throughout this (and other) presentations for uniformity.

Adhesion Forces of Elliptical Top Gask-o-seals

Results

- Adhesion increases with contact duration (70 hrs versus 30 min)
- Adhesion generally decreases with number of mate cycles
- No trends were observed in the adhesion with sealing surface configuration (not shown)
- Adhesion levels of the S0383-70 elastomer seals were stable and lower than those for S0899-50



Medium-Scale Seals

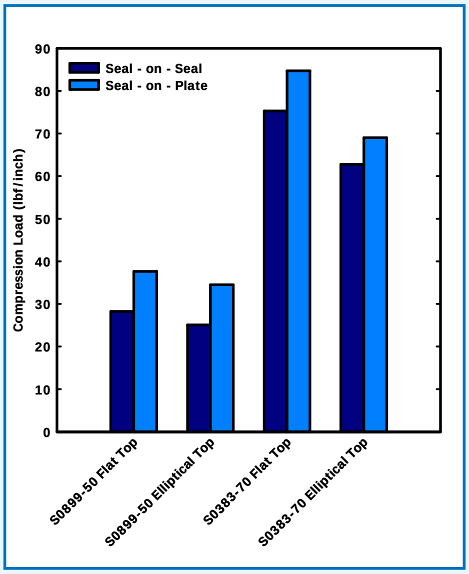
Compression forces required for 58” dual-bead seal-on-seal is predicted to be:

~5100 lbf (S0899-50 / Elliptical top)

~4600 lbf (S0899-50 / Flat top)

~13700 lbf (S0383-70 / Elliptical top)

~11400 lbf (S0383-70 / Flat top)



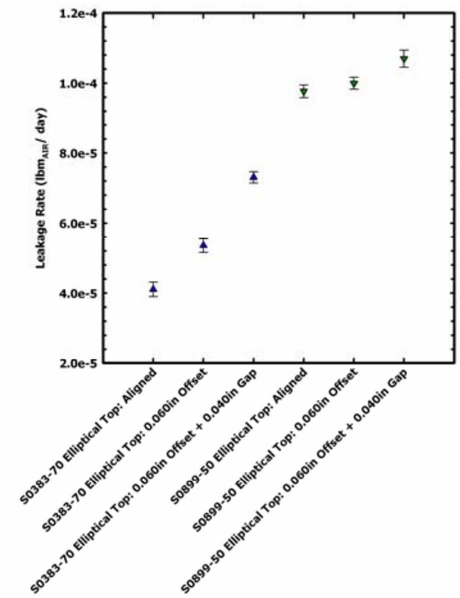
Medium-Scale Leakage Results: Effect of Configuration

Test Specimens and Setup

- Parker Hannifin Gask-o-seals
  - CBM design
  - Elliptical top
- Two elastomer compounds
  - S0383-70
  - S0899-50
- Three configurations
  - Aligned seal-on-seal
  - Axial misalignment (0.060 inch)
  - Axial misalignment (0.060 inch) + Angular misalignment (0.040 inch)

Results

- The leakage of seals was greatest with both axial and angular misalignments
- When the seals were aligned, the leakage was the lowest
- S0899-50 seals leaked greater than S0383-70



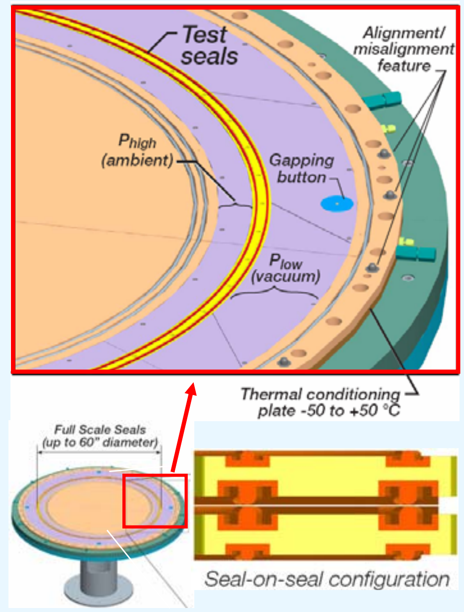
Full Scale LIDS Seal Test Rig Development

Goal: Evaluate full-scale seal leakage rates under anticipated thermal, vacuum, and engagement conditions

Features:

- Static seal-on-seal or seal-on-plate configurations
- Seal diameters:
  - Risk reduction unit............................54”
  - Engineering demonstration unit........58”
  - Flight unit..TBD
- Simulated environmental conditions
  - Thermal -50°C to +50°C (shade or sun)
- Pressure (ΔP)
  - Operational: Ambient pressure to vacuum
  - Pre-flight checkout: 15 psig to ambient
- Engagement conditions
  - Vehicle alignment/misalignment (±0.060”)
  - Gapping: Non-uniform clamping engagement (0.040”)

Future: An actuation system to bring seals together simulating docking



Materials International Space Station Experiment (MISSE 6A and 6B)

Goals and Objectives

- To expose three candidate elastomers to space environments in low-Earth orbit to evaluate their applicability as material for primary mating interface seal for LIDS
- Combined and simultaneous exposure to atomic oxygen, ultraviolet and ionizing radiation, MMOD, and temperature transients in a hard vacuum cannot be replicated in terrestrial laboratories.

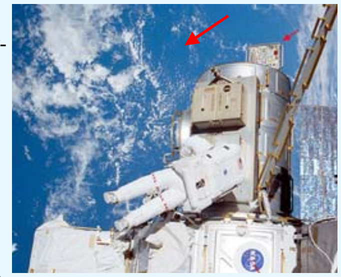


Photo of previous MISSE PEC taken during STS110

Anticipated data

- Leakage rates of three candidate elastomers o-rings after
  - exposure to combined space environments (to be compared with as-received samples).
  - exposure to UV, ionizing radiation, and thermal cycling only under hard vacuum conditions.
- Leakage rate of S0383-70 elastomer o-ring after exposure to thermal cycling only under hard vacuum conditions.
- Leakage rate of S0383-70 with additional post-cure after exposure to combined space environments.
- Leakage rate of S383-70 with a UV/AO protective coating after exposure to combined space environments.
- Adhesion level of pairs of S0383, S0899, and XELA-SA-401 elastomer o-rings after exposure to thermal cycling under hard vacuum conditions (simulating docking conditions).

Diagram showing the MISSE 6A and 6B o-ring AO/UV exposure assembly

Schedule

Material Evaluations

- Atomic Oxygen, Ultraviolet and Particle Radiation, Micrometeoroid / Orbital Debris Impact
- Ongoing

Small-scale Seal Evaluations

- Elastomeric-seal concepts, metallic-seal concepts
- Ongoing

Medium-scale Seal Evaluations

- Seals showing promise after small-scale evaluation
- Through 2008

Full-scale Seal Evaluations (Static System)

- Rig fabrication out for bid
- Anticipate testing in Spring / Summer 2007

Full-scale Seal Evaluations (Actuated System)

- Actuation system out for bid
- Anticipate testing in Summer / Fall 2007

MISSE 6A and 6B

- Launch planned for Fall 2007

1st LIDS Flight

- Launch planned for 2012

Appendix

NASA GRC In-house Team

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Mr. Patrick Dunlap
Mr. Arthur Erker
Mr. Jay Oswald
Mr. Malcolm Robbie
Mr. Ian Smith
Dr. Bruce M. Steinetz
Mr. Michael Tong
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SPACE ENVIRONMENT'S EFFECTS ON SEAL MATERIALS

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A Low Impact Docking System (LIDS) is being developed by the NASA Johnson Space Center to support future missions of the Crew Exploration Vehicle (CEV). The LIDS is androgynous, such that each system half is identical, thus any two vehicles or modules with LIDS can be coupled. Since each system half is a replica, the main interface seals must seal against each other instead of a conventional flat metal surface. These sealing surfaces are also expected to be exposed to the space environment when vehicles are not docked. The NASA Glenn Research Center (NASA GRC) is supporting this project by developing the main interface seals for the LIDS and determining the durability of candidate seal materials in the space environment. In space, the seals will be exposed to temperatures of between 50 to –50 °C, vacuum, atomic oxygen, particle and ultraviolet radiation, and micrometeoroid and orbital debris (MMOD). NASA GRC is presently engaged in determining the effects of these environments on our candidate elastomers. Since silicone rubber is the only class of seal elastomer that functions across the expected temperature range, NASA GRC is focusing on three silicone elastomers: two provided by Parker Hannifin (S0-899-50 and S0-383-70) and one from Esterline Kirkhill (ELA-SA-401). Our results from compression set, elastomer to elastomer adhesion, and seal leakage tests before and after various simulated space exposures will be presented.

Outline

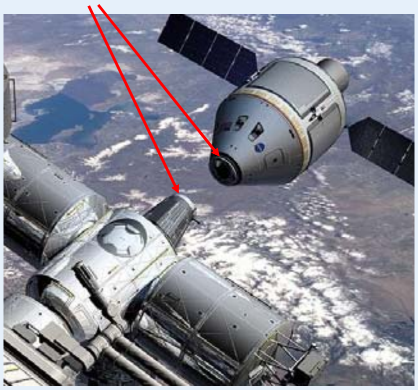
- **Introduction**
  - Low Impact Docking System (LIDS).
  - LIDS main interface seal, challenges and candidate elastomers.
  - The expected mission space environment.
- **Simulating the space environments (Atomic Oxygen, Ultraviolet & Ionizing Radiation, MicroMeteoroid Orbital Debris)**
- **MicroMeteoroid Orbital Debris (MMOD) results**
- **Leak rate testing and results**
- **Adhesion testing and results**
- **Compression set testing and results**
- **Conclusions**
- **Future Work**

NASA Glenn Research Center
Seal Team

Introduction

Low Impact Docking System (LIDS)

LIDS main interface seal



- Very low leakage requirements:
  - CEV < 0.02 lbm/day
  - Apollo ~ 4.5 lbm/day
- Seals must survive long-term exposure to space.
- -50 °C to 50 °C operating range.
- Candidate silicone seal materials: Parker Hannifin S0899-50 and S0383-70, and Esterline Kirkhill XELS-SA-401.

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Seal Team

Drawing of the planned CEV docking with Space Station; LIDS enables the coupling of the two together; the elastomer of the LIDS primary seal stops air from leaking out after docking.

The expected mission space environment

- **Mission Duration**
  - Short term design limited to International Space Station and initial Lunar missions.
  - 12 year mission maximum.
- **Vacuum:**
  - Total mass loss (TML) < 1 %.
  - Collected volatile condensable materials (CVCM) < 0.1 %.
- **Atomic Oxygen**
  - 1 year exposure = 5 x 10^{21} atoms/cm^2 fluence, exposures planned up to 6 x 10^{22} atoms/cm^2 = 12 years exposure.
- **Ultraviolet Radiation**
  - Simultaneous Near Ultraviolet (NUV, 220-400 nm) and Vacuum Ultraviolet (VUV 115-200 nm) exposures to ~800 ESH completed.
- **Ionizing Radiation**
  - Maximum mission dose ~ 0.6 Mrad (Si), electron particle radiation used.
- **Micro Meteoroid and Orbital Debris (MMOD)**
  - Working with JPL/CalTech to better define largest particle expected ~0.5 mm, and smaller high frequency particle threats.

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While in space, the LIDS seal will be exposed to vacuum, atomic oxygen, radiations, and solid high velocity projectiles of various forms (MMOD). The amounts of these exposures are highly dependent on the flight path of the particular mission. A worst case exposure would be 15 years, but a trip to ISS, or even to the Moon would be much less. We are using the “Constellation Program Design Specification for Natural Environment” CXP-00102, as our primary source for mission exposures. The effects of vacuum are examined throughout testing, since AO and UV exposures are done with vacuum imposed. UV testing takes the longest; testing out to 1000 hours of equivalent sun hours (ESH) are underway, with accommodations to test longer if needed. MMOD testing employs significant mission flight path analysis and specialized testing. Arrangements for this are underway with facilities at NASA Johnson/CalTech and NASA Johnson/White Sands being employed.

Long-Term Atomic Oxygen (AO) Exposure Facility

Long-term exposure facility:

- Facility used to expose seal materials to oxygen for long periods of time.
- Exposure is isotropic, bathing the specimens in AO, exposing all surfaces.

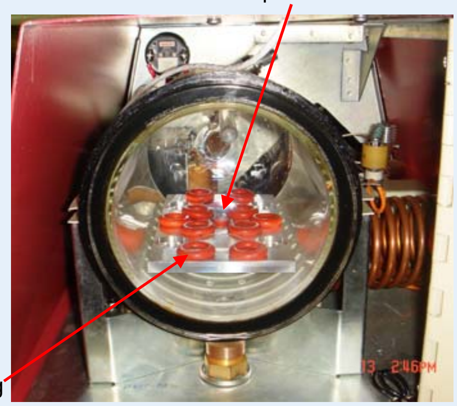

Photo of seal test specimens in the reaction chamber in the SPI Plasma Prep II

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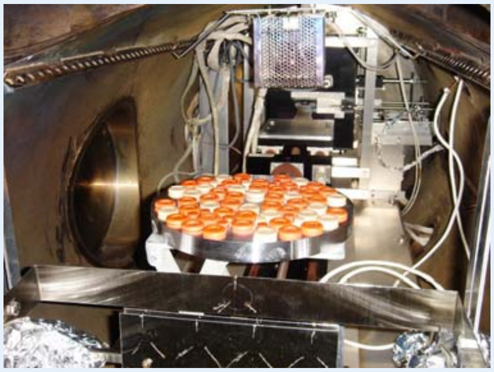
Two SPI Supplies Plasma Prep II facilities operated on air were used to provide the isotropic atomic oxygen arrival. The facilities use radio frequency (RF) (13.56 MHz) to create a discharge between two electrodes which surround a glass reaction chamber. A thermal plasma is produced which is at an energy of about 0.1 eV. Typical vacuum chamber pressure during operation was 16-27 Pa (120-200 mTorr). Temperature measured in past experiments was 65ºC. The two facilities were operated in parallel. One contained an aluminum machined sample tray containing the Parker-Hannifin S0383-70 seal samples and the other contained a similar tray with the Parker-Hannifin S0899-50 seal samples. Each tray had its own polyimide Kapton fluence witness and a sapphire window (2.54 cm diameter) for a contamination witness. Fluences resulting from exposures of S0-899-50 were estimated from Kapton witness coupons exposed alone in a rate test prior to the exposure; this was done because during exposure of S0-899-50 material, contamination of the Kapton witness resulted in erroneous erosion yields.

Shorter term Atomic Oxygen Exposures

- Facility used to expose materials to atomic oxygen for shorter periods.
- Directed beam only exposes top surfaces of specimens to AO.
- Five Kapton fluence witnesses are used with an erosion yield of $3x10^{-24}$ cm^3/atom.



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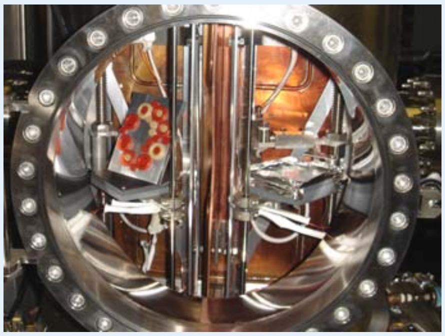
The atomic oxygen directed beam facility uses an Electron Cyclotron Resonance Plasma Source from Applied Science and Technology Inc. (ASTeX) operated on pure oxygen to generate a directed thermal energy beam of atomic oxygen with less than 1% ions at energies of typically 15-18 eV. The source operates at microwave energy (2.45GHz, 1000 W) and uses two large electromagnets for both dissociation of oxygen through electron collision and for beam focusing. The vacuum chamber used for exposure is 71 cm in diameter by 1.71 m long. Pumping is provided by a diffusion pump, mechanical pump and roots type blower that operate on Fomblin (perfluorinated polyether) oil. The base pressure of the vacuum chamber is typically 2e-6 torr to 5e-5 torr, but during operation can range from 2e-4 to 8e-4 torr depending on the oxygen gas flow rate. In addition to producing atomic oxygen, the source also produces VUV radiation at 130 nm at an intensity of approximately 150 suns. Seal samples were installed into recessed grooves cut into a circular plate that was mounted in the facility for exposure. Five polyimide Kapton fluence witness samples were also included on the plate to provide information on the atomic oxygen dose as well as the spatial distribution.

Ultraviolet Radiation Exposures

- VUV Deuterium Lamp (115-200 nm).
- NUV Hg-Xe Arc Lamp (220-400 nm).
- Cryopump vacuum chamber (5 x 10^{-6} torr).
- Seal samples exposed to after AO exposure.



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The Vacuum Ultraviolet (VUV)/Near Ultraviolet (NUV) exposure facility uses a cryogenic vacuum pumping system and VUV and NUV light beams simultaneously. The light source for VUV exposure was a 30-watt deuterium lamp with a magnesium fluoride end-window (Hamamatsu model L7293) which provided a lower cut-off wavelength of 115 nm. Calibration was conducted in vacuum using a cesium iodide (CsI) phototube sensitive in the 115-200 nm wavelength band. The light source for NUV exposure was a 500-watt mercury (xenon) arc source (Oriel Model 66142) which provided NUV of wavelengths in the 220-400 nm range. This NUV source was calibrated before and after each exposure using a pyroelectric detector system (Oriel Model 70362) and a 260 nm narrow bandpass filter. The ratio of lamp intensity compared to the sun's air mass zero intensity in the same wavelength range is referred to as "equivalent suns". Equivalent space exposure, referred to as "equivalent sun hours," is obtained by multiplying the number of test hours by "equivalent suns" for the NUV and the VUV wavelength ranges, 220-400 nm and 115-200 nm, respectively. The NUV and VUV exposures are not uniform over the plate thus exposures are mapped across the plate and the exposure of each specimen tracked. A bright spot located near the center of the plate is avoided. For each test, prior to exposure, all samples were installed in the facility and the chamber was brought to high vacuum for approximately 24 hours to achieve an operating pressure of approximately 5x10-6 torr prior to commencing NUV/VUV exposure.

Ionizing Radiation Exposures

- E-Beam Services in Lebanon Ohio, 150 kW DC Electron Beam Accelerator.
- 4.5 MeV electrons.
- Does of 0.45, 0.9, and 1.3 Mrad (Si).
- 92 Parker specimens exposed, 6 Kirkhill specimens.
- Specimens exposed through entire thickness.

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Particle radiation exposures where done at E-Beam Services in Lebanon Ohio using a 150 kW DC Electron Beam Accelerator which produced 4.5 MeV electrons and a dose of 0.5 Mrad (water) per pass. Both of the Parker elastomers were exposed to 0.5, 1.0 and 1.5 Mrad (water) exposures. No Kirkhill o-rings were available at the time exposures were done. The radiation provided by E-Beam Services is electrons and exposures are reported in units of Mrad (water). We expect this source to give an indication of damage from particle sources in space, even though most solar energetic particles are protons, because damage is primarily determined by energy absorbed and by penetration of the radiation. Sufficiently high fluences were used so that equivalent energy was absorbed and thus hopefully damage equivalent to proton particles. Indications are that below surface doses were slightly higher than noted surface doses due to secondary bremsstrahlung radiations. The approximate conversion of rad dose in Si to rad dose in water in this case, based on stopping powers only, is ~0.9 rad(Si)/rad(water). Thus our three dose levels were 0.45, 0.9, and 1.3 Mrad (Si). Specimens were secured on an aluminum plate and the plates placed in nitrogen filled bags and sealed prior to exposures. Temperature maximum during electron radiation exposures was about 41 oC.

MMOD Test Facilities

- NASA White Sands Test Facility and NASA Johnson Space Center
  - Karen Rodriguez POC
- California Institute of Technology Pasadena, CA and JPL
  - Ares Rosakis POC at Caltech.
  - Virendra Sarohia JPL-Caltech liaison.

	Caltech	White Sands
Max Velocity	10.5 km/s	7.5 km/s
Particle Size	~0.1 to 2.0 mm	~0.05 to 3.6 mm
Success Rate	~99%	80 to 65 %
Number of Particles per shot	1 to 6	1
Analysis Support	Extensive	Good

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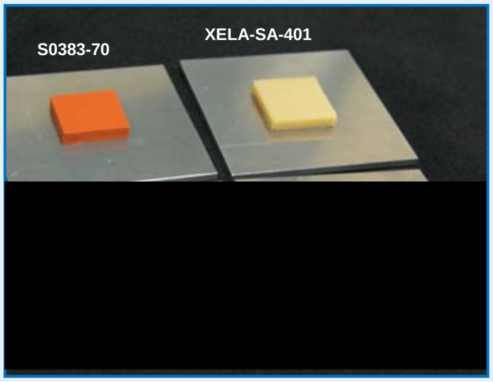
MMOD Test Specimens (Phase I)

Six test specimens:

- Parker S0383-70
- Kirkhill XELA-SA-401
- Ceramic SiC 0.125 inch thick.
- SS plate (0.125 inch thick).

Impacted with 0.5 mm stainless steel particle at 7.5 km/sec.

Elastomer samples were glued onto 3"x3"x1/8" thick Al 7075 plates.



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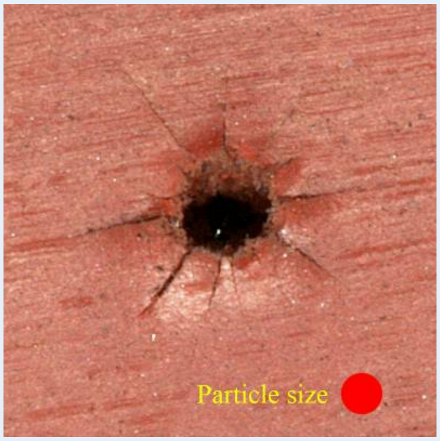
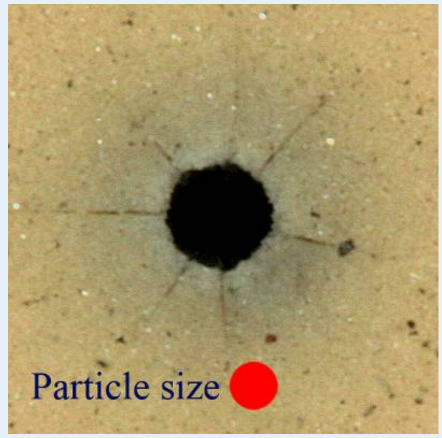
MMOD Test Results

Projectile: Stainless Steel, sphere 0.5 mm dia., 7.5 km/s



Parker S0383-70



Kirkhill XELA-SA-401

• 0.5 mm projectile damages a 5 mm diameter area, 5 mm deep.

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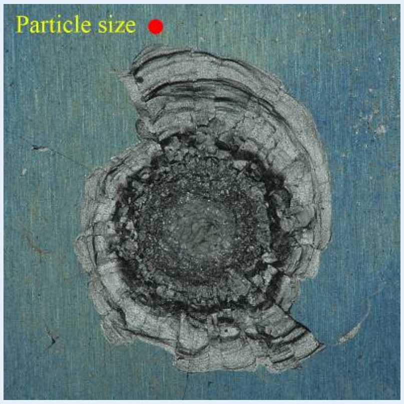
The photographs show the impact craters caused by the 0.5 mm, 7.5 km/s, stainless steel projectile, simulating an MMOD strike. The Parker material had raised edges around the impact crater. The ELA specimen was analyzed via a Computed Tomography (CT) scan to measure the internal damage. The CT scan revealed that the particle left an impact crater of depth 0.165 inches into the 0.200 inch thick target, although it was also evident that particle fragments had penetrated deeper without removing material.

MMOD Test Results

Projectile: Stainless Steel, sphere 0.5 mm dia., 7.5 km/s



SiC

Stainless Steel

- Huge area of the SiC plate damaged (10 mm +)
- Highly raised edges in the Stainless Steel, 3 mm diameter.

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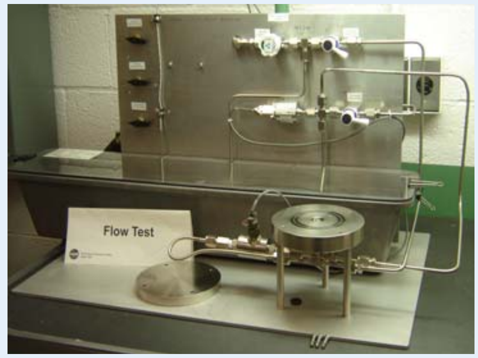
This photographs show the damage caused by the 0.5 mm steel projectile. Deep, long cracks radiated from the crater in the SiC plate. The edges of the crater in the stainless steel were highly raised.

Small Scale Flow Test Fixture

- Quantifies leakage flow past 2-309 size o-ring seal specimens.
- Test conditions
  - 25% O-ring compression.
  - Seal against flat plate.
  - P_{HIGH} = 14.7 psia.
  - P_{LOW} = 0.0 psia.
- Specimen are connected to a leak decay system to accurately quantify losses.
- Data processing then scales up the leak to estimate the primary LIDS seal leakage.



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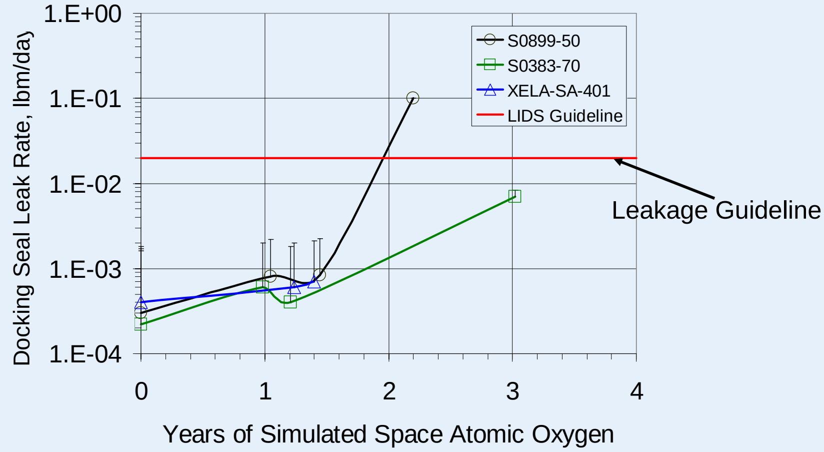
Leak Flow Test Results



• S0899-50 exceeds allowable leak rate after 2 yr AO.

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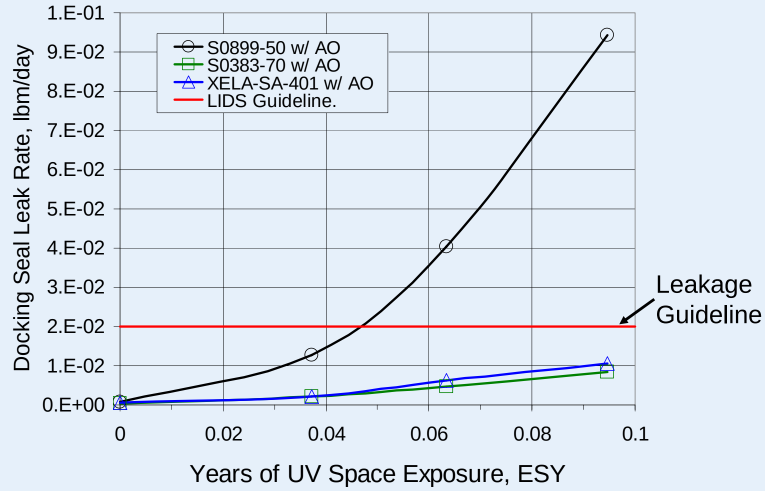
Shown in this plot is the leak rate measured from our 2-309 o-rings scaled up to estimate the leakage from the full ~54 inch (137 cm) diameter LIDS seal. This leak rate is for a single seal. Present designs use a double seal, thus these leak rates are worst case scenarios after a full failure of one of the seals. As received leakage is shown by values at zero years of AO exposure. The red line indicates the maximum leak rate presently sought for the LIDS seal; after 2 years of exposure the Parker S0-899-50 material fails by exceeding this maximum. Atomic oxygen reacts with Si in these silicone based elastomers, forming glassy SiO_2 phases on exposed surfaces. Exposed surfaces become glossy, harder, and less sticky (for example, dust does not collect on them as much).

Leak Rate Results after AO + UV exposures



- S0899-50 fails after 1.2 yr AO + 400 ESH.
- S0383-70 and XELA-SA-401 ok up to 1.2 yr AO + 1700 ESH.

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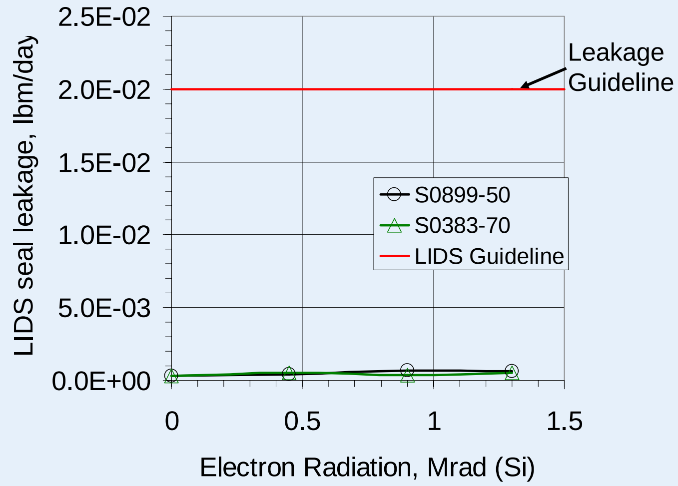
Shown in this plot is the leak rate measured from our 2-309 o-rings scaled up to estimate the leakage from the full ~54 inch (137 cm) diameter LIDS seal. This leak rate is for a single seal. Present designs use a double seal, thus these leak rates are worst case scenarios after a full failure of one of the seals. All specimens in this group were exposed to a fluence of 5.77 x 10^{21} atoms/cm^2 atomic oxygen (AO) prior to exposure to the various levels of ultraviolet (UV) radiation. The red line indicates the maximum leak rate presently sought for the LIDS seal; after the simulated space exposure of about 1.2 years AO and 0.05 ESY (equivalent Sun year) of UV radiation, the Parker S0-899-50 material fails by exceeding the maximum allowable leak rate of 0.02 lbm/day. The estimated error in the measured leakage was +/- 0.0014 lbm/day at leak rates below 0.02 lbm/day; at higher leak rates uncertainties were about +/- 10%.

Flow Test Results after Ionizing Radiation Exposure



- Leak rate of candidate elastomers was not affected by ionizing radiation.

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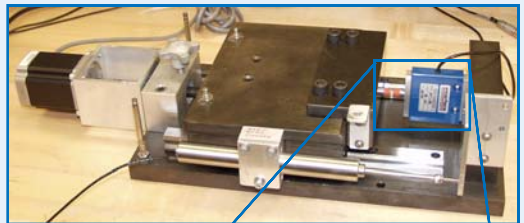
The plot shows the abilities of the Parker elastomers to seal are not significantly effected by expected mission doses of particle radiation. Leak measurement uncertainty was +/- 1.4 x 10^{-3} lbm/day.

Particle radiation exposures where done at E-Beam Services in Lebanon Ohio using a 150 kW DC Electron Beam Accelerator which produced 4.5 MeV electrons and a dose of 0.5 Mrad (water) per pass. Both of the Parker elastomers were exposed to 0.5, 1.0 and 1.5 Mrad (water) exposures. No Kirkhill o-rings were available at the time exposures were done. Sufficiently high fluences were used so that equivalent energy was absorbed and thus hopefully damage equivalent to proton particles. Indications are that below surface doses were slightly higher than noted surface doses due to secondary bremsstrahlung radiations. The approximate conversion of rad dose in Si to rad dose in water in this case, based on stopping powers only, is ~0.9 rad(Si)/rad(water). Thus our three dose levels were 0.45, 0.9, and 1.3 Mrad (Si). Specimens were secured on an aluminum plate and the plates placed in nitrogen filled bags and sealed prior to exposures.

Adhesion Test Fixture

- Quantifies adhesion between specimens after 25% compression for 1, 2, 4, 8, 16, and 24 hours.
- Specimens: elastomer cylinders
  - 0.953 cm (0.375 in.) OD.
  - 0.533 cm (0.210 in.) thick.



Photograph of an adhesion test in progress showing the deformation before separation (left).

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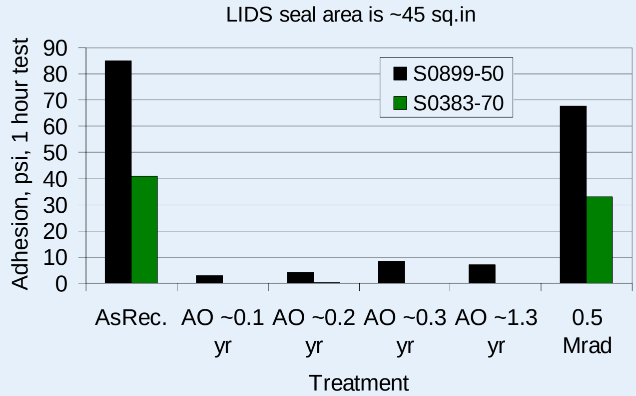
Adhesion Test Results after AO and Ionizing Radiation



- Adhesion of XELA-SA-401 is negligible.
- Adhesion of S0383-70 is negligible after 0.1 yr AO.
- Adhesion of S0899-50 is greatly reduced after 0.1 yr AO.

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Adhesion test results for Parker-Hannifin S0-8990-50 and S0-383-70 in the as received condition and after exposure to electron radiation and various amounts of atomic oxygen. As received adhesion was negligible for the Kirkhill elastomer ELS-SA-401. Adhesion for S0-383-70 after AO was also essentially zero. The surface area of the LIDS seal is approximately 45 in.^{2}, thus if adhesion between the seals was 10 psi, it would require a force of about 450 lb to get them apart. The variability or scatter among like test was about +/- 20%.

Compression Set Test Fixture

• Quantifies permanent deformation after specimen has been compressed for extended periods of time, 70 hr.

• Testing per ASTM Standards D395 (Test Method B) and D1414.

• Specimen are 2-309 size o-rings 2.11 cm (0.832 in) OD, 0.533 cm (0.210 in.) cord diameter.

• Test conditions 25% Compression, 70 hr. at room temperature, unlubricated.

• Result is the median of three samples.

Compression set test fixture

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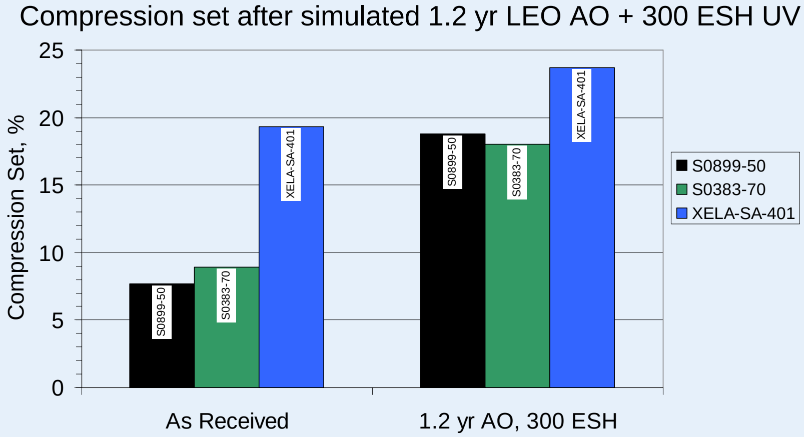
Photograph of the stainless steel plates used to test the compression set of LIDS candidate elastomers. The plates have a diameter of 35.6 cm.

Compression Set Test Results



• Compression set largely unaffected by AO or ionizing radiation alone.

• Compression set significantly increased due to UV exposure.

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Compression set measurements are somewhat artistic. Some of the data was also gathered by different people which did not contribute positively to measurement consistency. In general, scatter and uncertainties in compression set measurements resulted in an estimated accuracy of between +/-10 to +/-30% depending on the particular group and the number of measurements made to date (to be clear, for example, a compression set of 10. +/-2. % was typical). This plot shows the compression set of the candidate materials in the as received conditions, and after a combined exposure of about 1.2 years atomic oxygen (5.77 x10^{21} atoms/cm^2) plus about 300 equivalent sun hours of ultraviolet radiation in the NUV and VUV wavelength range (~100nm to 400 nm). This exposure increased compression set for all three of our candidate seal materials.

Conclusions

- Environmental exposures are highly dependent on mission/flight path.

Vacuum:

- All three elastomers meet mass loss and condensation requirements.

Atomic Oxygen:

- Parker's S0899-50 exceeded the maximum allowable leak rate after 2 yrs. of AO exposure; data indicates S0383-70 will similarly fail after 4 yrs. AO (fluence = 2x 10^{22} atoms/cm^2).
- Adhesion for XELA-SA-401 was negligible; Adhesion for S0383-70 was negligible after small amounts of AO; Adhesion of S0899-50 was deceased to about 5 psi after 0.1 yr AO.
- AO by itself did not influence compression set in these elastomers.

Ultraviolet Radiation (110 to 400 nm)

- Ultraviolet exposure caused increases in leakage. S0899-50 failed after about 400 ESH of UV + 1.2 yr AO exposure. If current trends continue, S0383-70 and XELA-SA-401 will exceed the maximum leak rate of 0.02 lbm/day after about 1800 ESH + 1.2 yr AO.

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Conclusions

UV (continued)

- AO with UV caused the compression set of XELA-SA-401 to increase by about 20%, and a doubling of compression set for the Parker materials.

Ionizing Radiation

- The elastomers are not significantly effected by the expected levels of Ionizing Radiation.

MicroMeteoroid Orbital Debris (MMOD)

- A projectile of 0.5 mm diameter damaged areas about 10 times that diameter, boring deep (5 mm) into the specimens.

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Future Work

- Finishing planned AO, UV, and particle radiation exposures.
- Perform extended UV exposures.
- Commence detailed MMOD studies, low frequency larger particles and high frequency smaller particles with leakage testing.

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FINITE ELEMENT ANALYSIS OF ELASTOMERIC SEALS FOR LIDS

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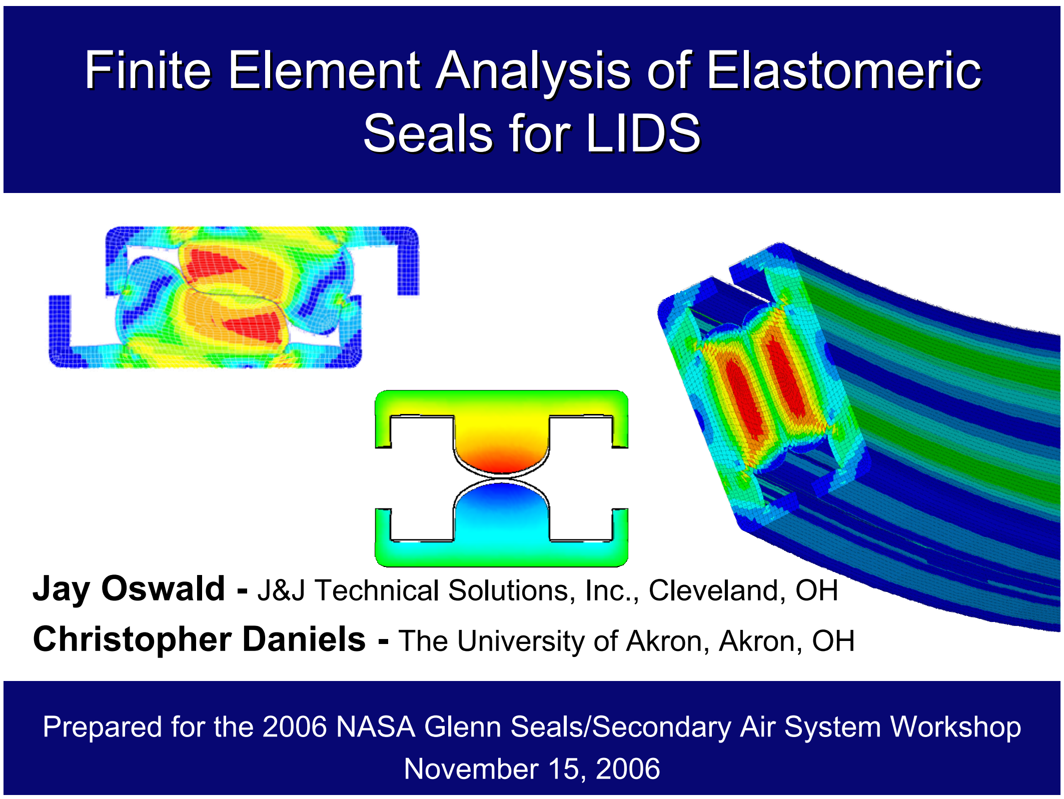


Objectives & Motivation

Objective

- Create a means of evaluating seals w/o prototypes

Motivation

- Cost
  - Prototype 54” seal ~$100k per seal pair
  - FEA license + high end workstation ~ $30k per year
- Development time
  - 6 months lead time for a new seal design
  - Many designs per day (solution time <1 minute)
- Understanding
  - Difficult to experimentally measure strains, contact pressure profile, stresses, displacements

Part I

Hyperelastic Material Modeling

Special Properties of Hyperelastic Materials

- Fully or nearly Incompressible
  - Bulk modulus typically 100-1000x shear modulus
  - Poisson’s ratio approaches 0.5
  - Problems in displacement-based FEA formulation
    - Requires B-bar or mixed u-P formulation
- Huge elastic range of deformation
  - Strains > 80% are (mostly) recoverable
    - Analysis should account for nonlinear geometry and material properties

Hyperelasticity vs. Linear Elasticity

Linear elasticity:

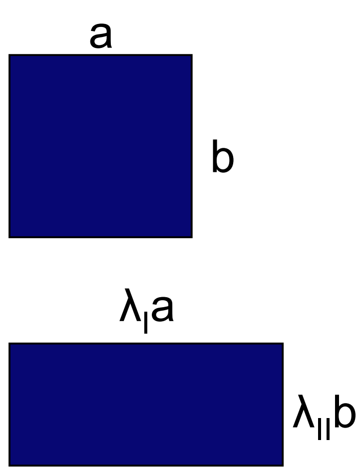
W = cε:ε

(which is like: $E = \frac{1}{2} k\Delta x^2$)

Hyperelasticity:

W = f(I$_1$,I$_2$,I$_3$)

or **W = f(λ$_I$, λ$_{II}$, λ$_{III}$)**



$$\sigma_{ij} = \frac{\partial W}{\partial \varepsilon_{ij}}$$

Definition of second Piola-Kirchoff stress from strain energy density and Green-Lagrange strain

$$I_1 = \lambda_I^{\,2} + \lambda_{II}^{\,2} + \lambda_{III}^{\,2}$$

$$I_2 = \lambda_I^{\,2}\lambda_{II}^{\,2} + \lambda_{II}^{\,2}\lambda_{III}^{\,2} + \lambda_{III}^{\,2}\lambda_{II}^{\,2}$$

$$I_3 = \lambda_I^{\,2}\lambda_{II}^{\,2}\lambda_{III}^{\,2} = 1 + \left(\frac{\Delta V}{V}\right)^2 = J^2$$

$\lambda_I, \lambda_{II}, \lambda_{III}$: principal stretch ratios

I_1, I_2, I_3 : strain invariants

J : Jacobian (volume ratio)

Some forms of the work function

Polynomial models: (Mooney-Rivlin, Neo-Hookean)

$$W = \sum_{i+j=1}^{N} C_{ij} \left(\bar{I}_1 - 3\right)^i \left(\bar{I}_2 - 3\right)^j + \sum_{k=1}^{N} \frac{1}{d_k} \left(J - 1\right)^{2k}$$

Yeoh model: j=0, neglects second strain invariant

- For plane strain Yeoh is equivalent to general polynomial form because $I_1 = I_2$

Comparison of lowest order terms for a 50 durometer material

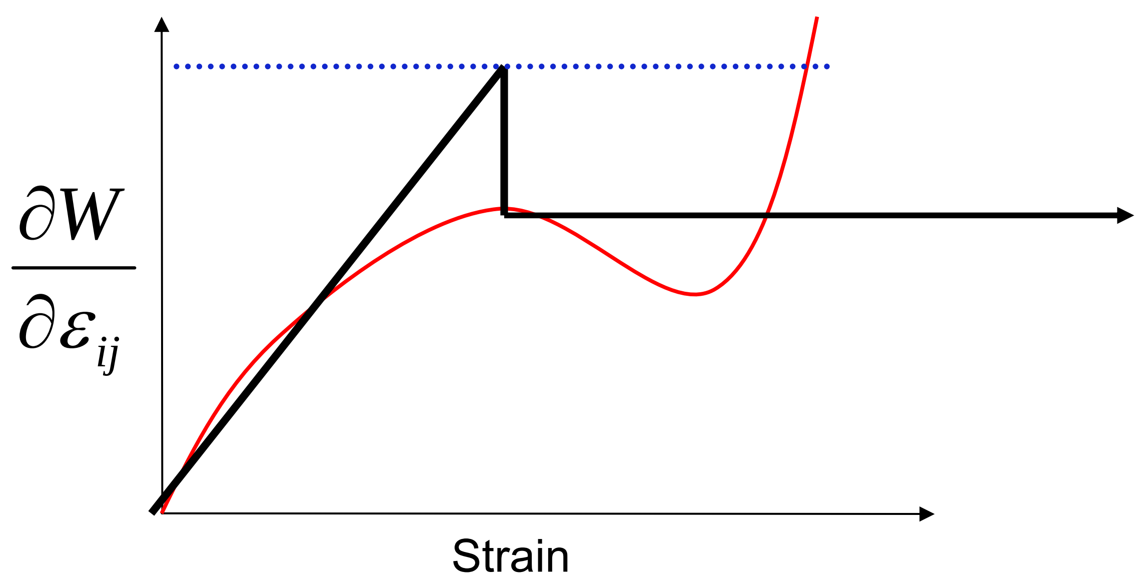
$1/d_1 \approx 200{,}000$ $\quad$ $c_{1,0} \approx 40$

Constraints on the work function

Zero strain must have zero energy (W(0) = 0)

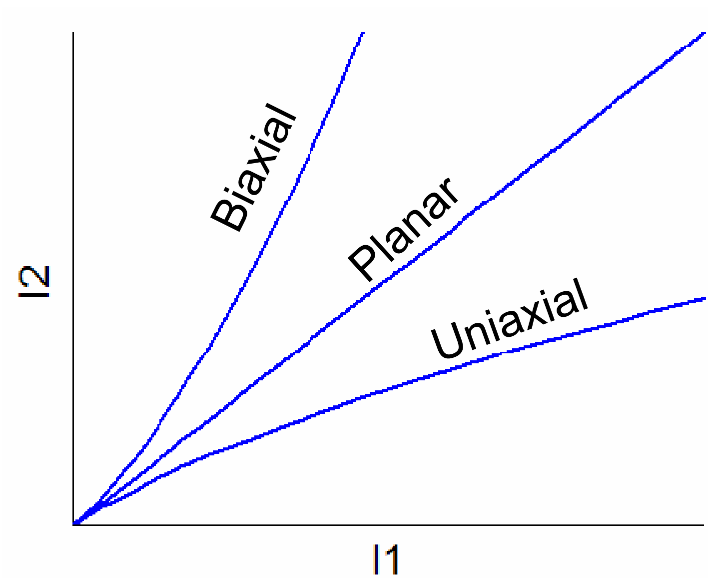
Zero strain must have zero stress (W'(0) = 0)

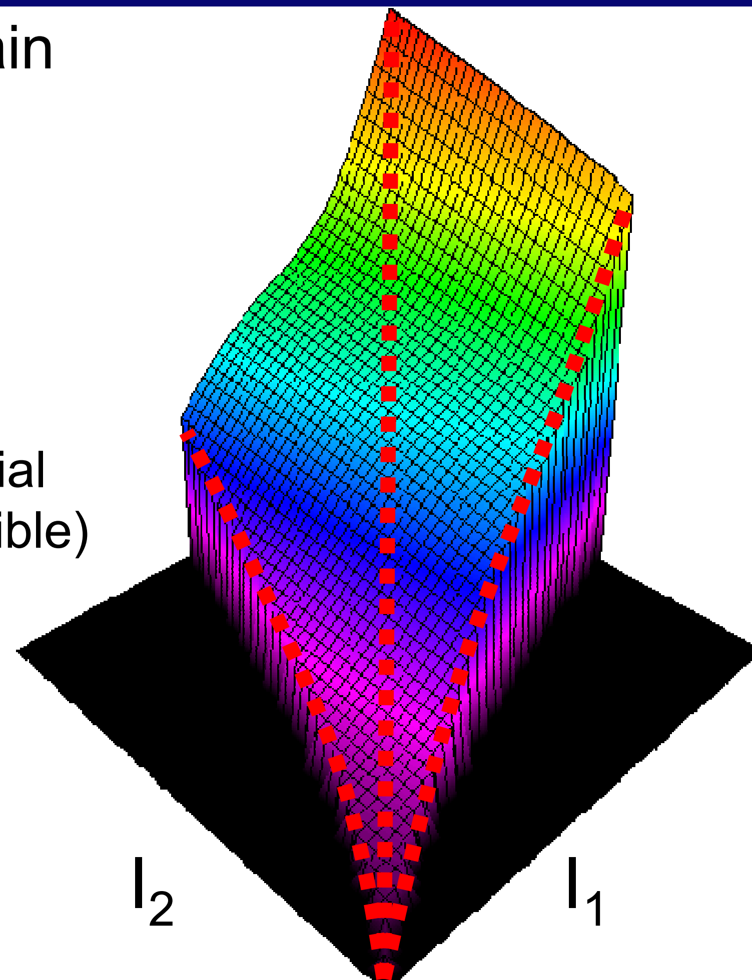
Second derivative must be positive (W''(ε) > 0 for all ε)



Determining W

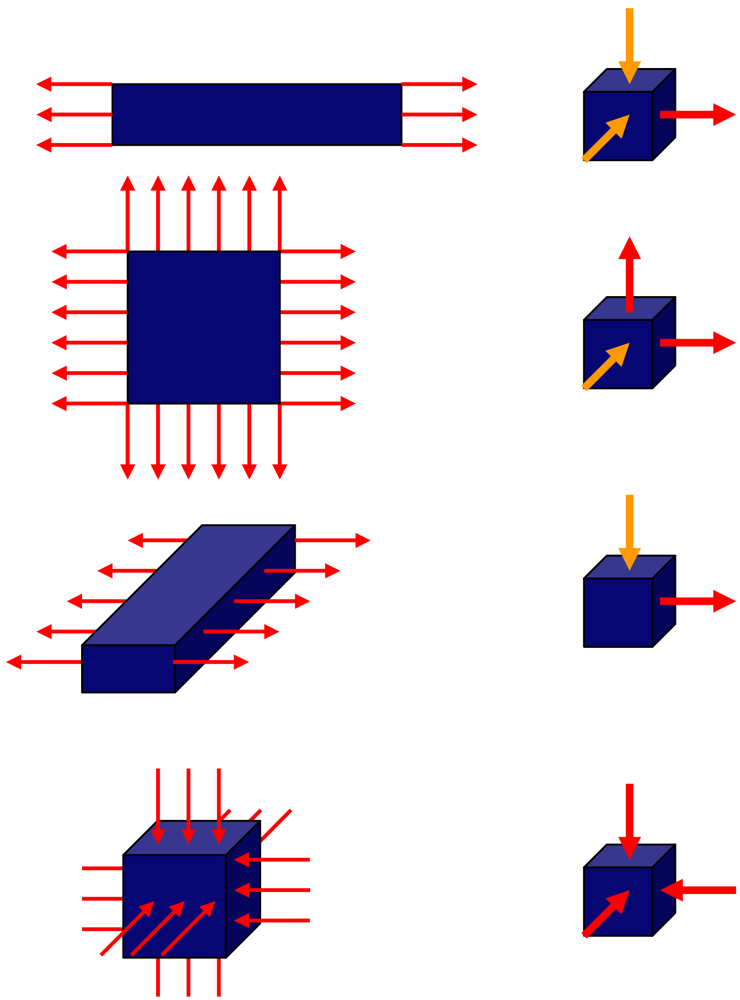
- Fit W to experimental stress-strain states
  - Three basic strain modes
    - Uniaxial tension
    - Biaxial tension
    - Planar tension
  - All deformation falls between uniaxial and biaxial – (I3 = 1 → incompressible)





Energy density function of a hyperelastic material

Basic strain states of a nearly incompressible material



	Load	Strain	Stretch Ratios
Uniaxial			$\lambda_I = \frac{1}{\lambda_{II}^2} = \frac{1}{\lambda_{III}^2}$
Biaxial			$\lambda_I = \lambda_{II} = \frac{1}{\sqrt{\lambda_{III}}}$
Planar			$\lambda_I = \frac{1}{\lambda_{II}}, \lambda_{III} = 1$
Volumetric			$\lambda_I = \lambda_{II} = \lambda_{III} < 1$

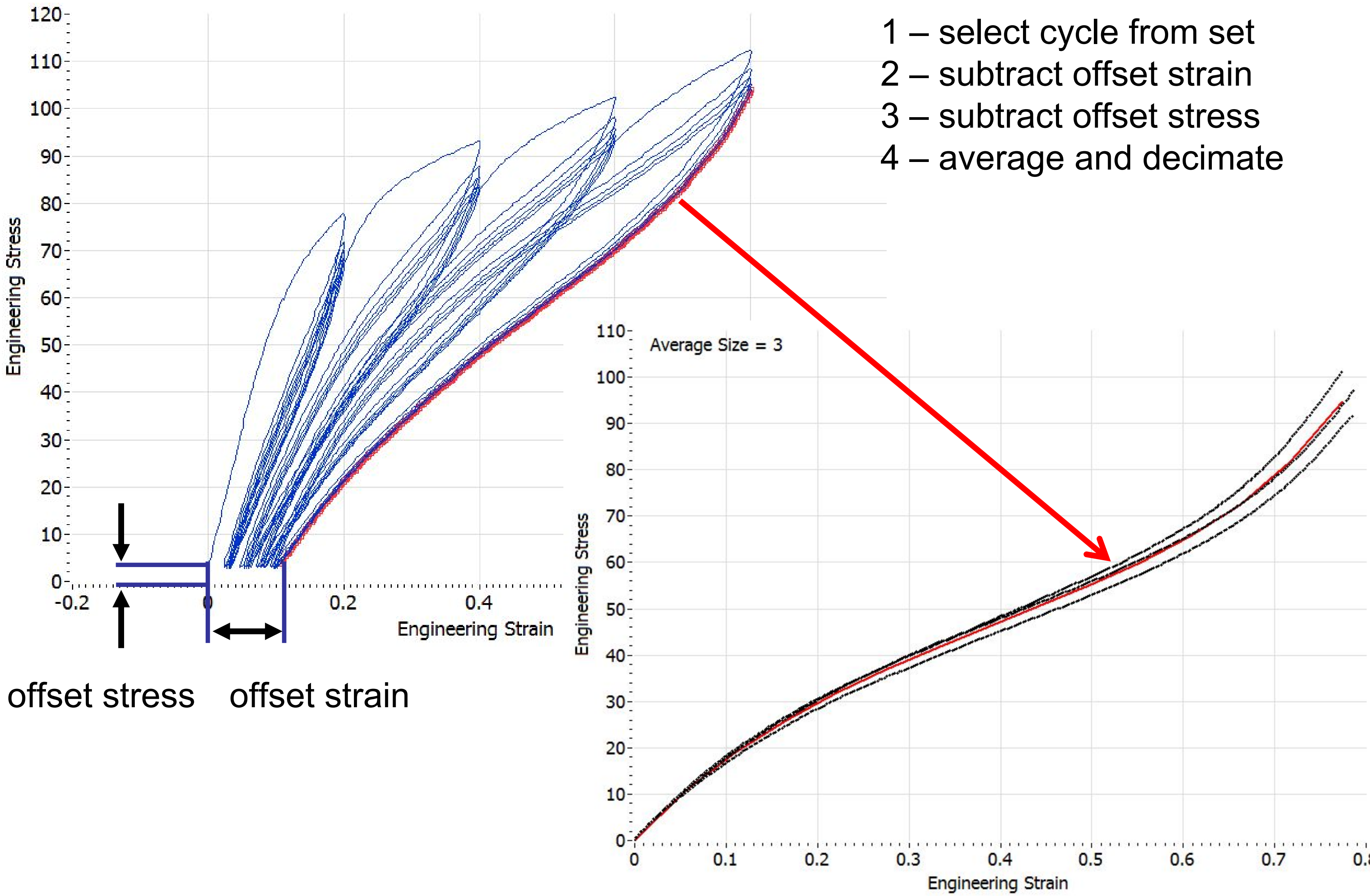
Material Tests Performed

- Materials: XELA-SA-401, S0899-50, S0383-70
  - 40, 50, 70 durometer hardness
- Test parameters
  - Various temperatures
    - -50, 23, 50, &125 ºC
  - 3 specimens per test
  - Uniaxial, planar, biaxial tension & volumetric
    - 20,40,60,80 % strain increments
- Other properties:
  - Coefficient of friction (elastomer on elastomer), thermal conductivity, heat capacity, density, emissivity, absorptivity

This data will be published soon in a NASA technical publication

Data Processing

1 – select cycle from set
2 – subtract offset strain
3 – subtract offset stress
4 – average and decimate

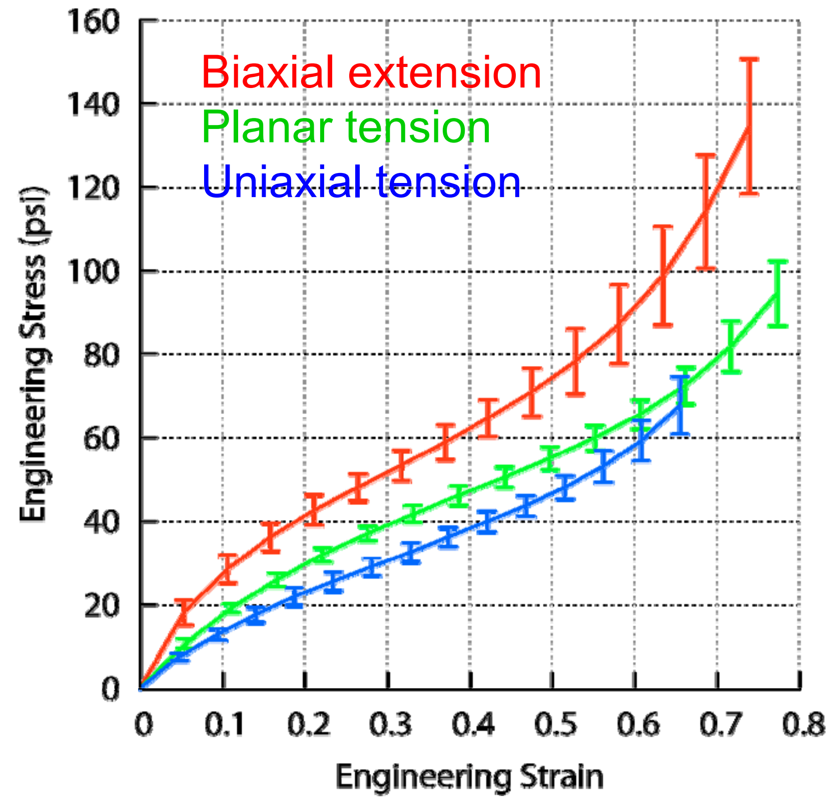


Processed Material Data

Uncertainty based off student's t distribution from multiple specimens

Results can be curve fitted to determine material property constants

This can be done as a function of temperature



Processed data from 40 durometer elastomer (-50 ºC)

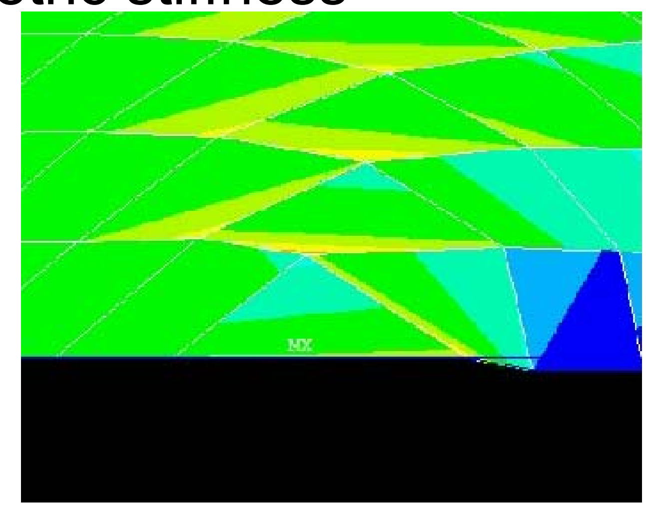
The strain energy density is the area under the curve for each deformation

Part II

Finite Element Analysis of Seals

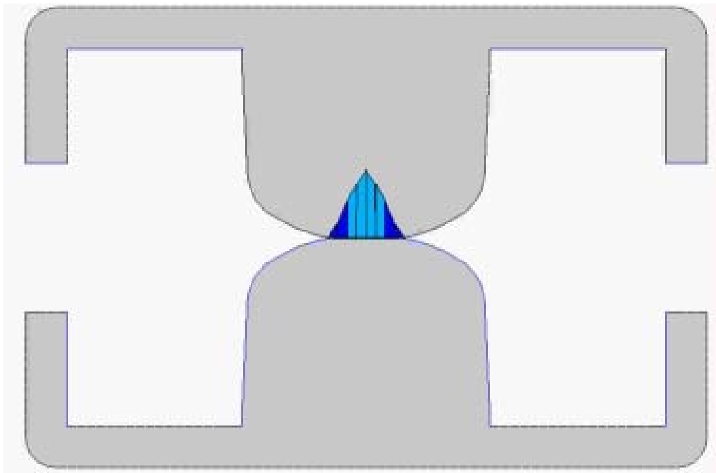
Hints for Elastomeric FEA

1) Stay away from triangular elements
   - Elements with 2 displacement BC will have only 1 degree of freedom due to incompressibility
2) Low order elements converge easiest 4-node brick works well
3) Sliding contact may require non-symmetric stiffness matrices for large friction coefficients
4) Watch corners for element distortion
5) u-P element formulation is most stable
6) Check for stability of material models

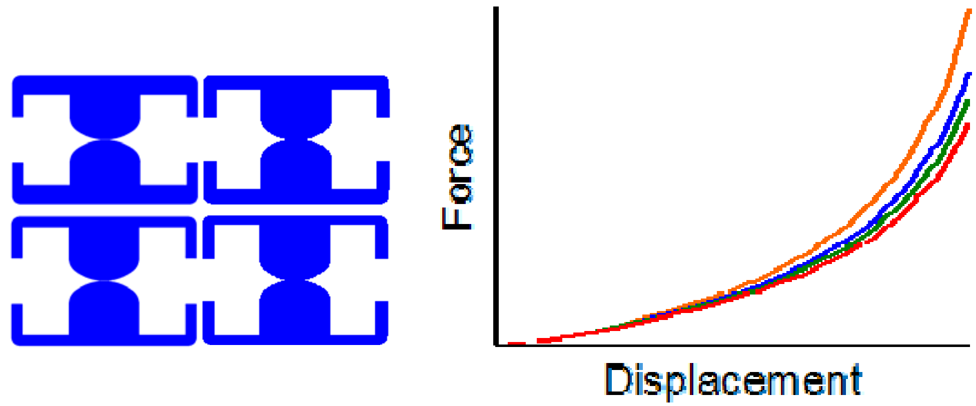


Severe element edge distortion
Analyses did not converge

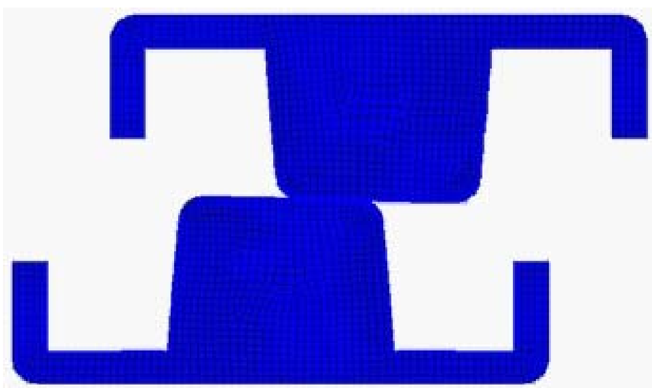
Types of FEA models of LIDS seals



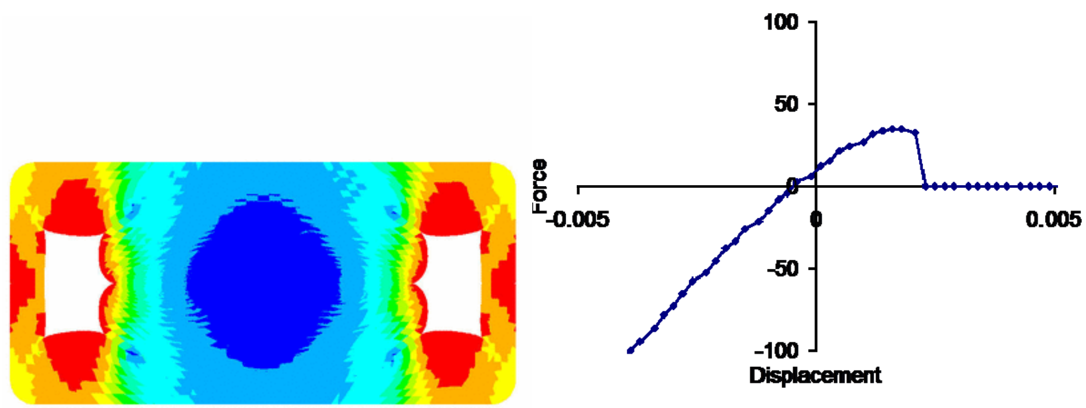
Aligned seal – contact pressure



Tolerance studies



Misaligned seal
Principal strains

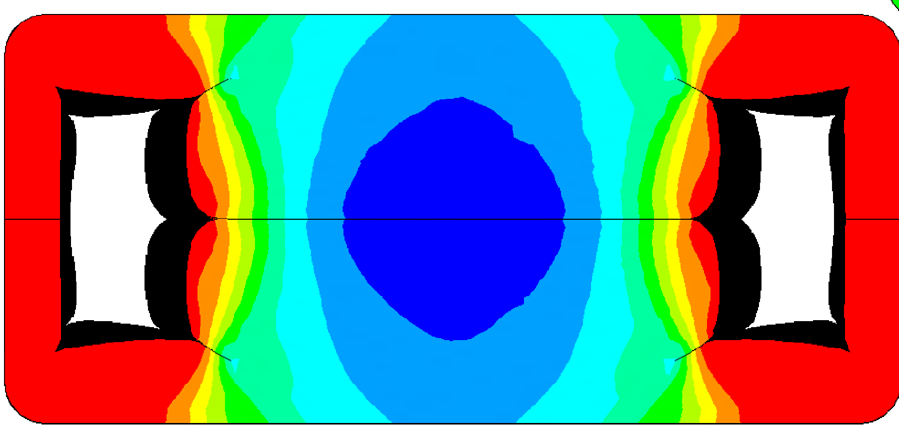


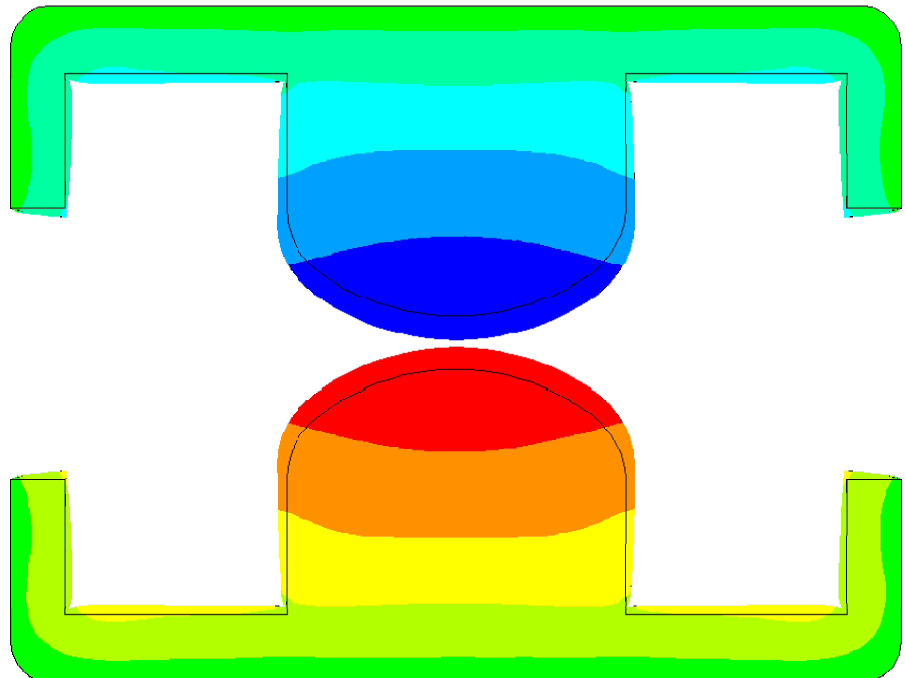
Gaskoseal adhesion analysis with cohesive elements at contact

Seal Thermal Analyses

- CTE of elastomers is very high
  - 350×10^{-6} °C^{-1}
  - Al: 24×10^{-6} °C^{-1}

Comparison of compression at 25ºC (front) and 125ºC (back). Contours are axial stress.





Y displacement of seals with 100ºC rise in temperature, black outline indicates original geometry

Summary

- Need 4 experimental strain states to
  - choose energy density function
  - fit material constants
  - determine compressibility of material
- Hyperelastic material present new challenges
- FEA analyses for LIDS
  - Force vs. displacement and pressure contours
    - Aligned & misaligned cases
  - Thermal expansion
  - Tolerance studies
  - Adhesion analysis

Further reading/information

- ANSYS gives excellent background for element technology/hyperelasticity
  - Nonlinear element technology
    - http://www.ansys.com//assets/tech-papers/nonlinear-element-tech.pdf
  - Hyperelasticity
    - http://www.tsne.co.kr/board/download.asp?strFileName=conflong_hyperel.pdf&dr=ansys
- Future publications of material properties, analysis, etc. will be posted on http://www.grc.nasa.gov/WWW/structuralseal

APOLLO SEALS: A BASIS FOR THE CREW EXPLORATION VEHICLE SEALS

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

Christopher C. Daniels
University of Akron
Akron, Ohio

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Apollo Seals: A Basis for the Crew Exploration Vehicle Seals

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2006 NASA Seal/Secondary Air System Workshop
November 14-15, 2006

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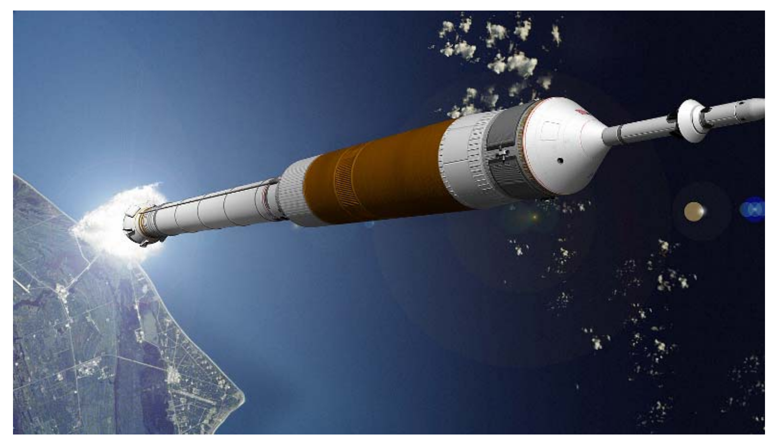
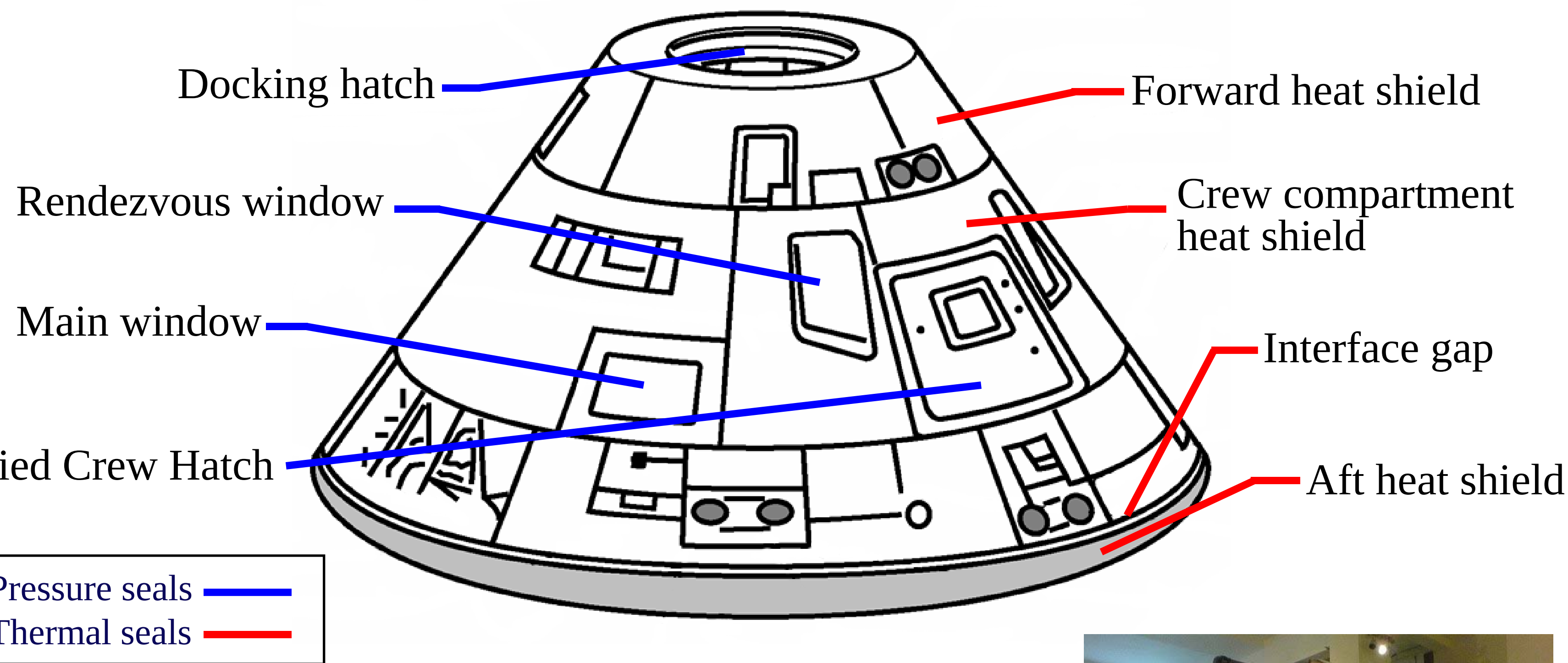
Crew Exploration Vehicle

- NASA's Vision for Space Exploration
  – Replace the Space Shuttle for missions to ISS
  – Return to the Moon
  – Allow manned exploration of Mars
- Apollo-like configuration
  – Blunt-body heat shield
  – Conical backshell
- CEV requires seal development
  – Prevent ingestion of reentry gases
  – Prevent loss of habitable atmosphere
- **<u>NASA GRC approach:</u> Study Apollo as a starting point for CEV seals**



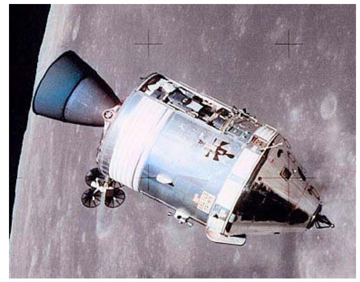
Apollo Command Module



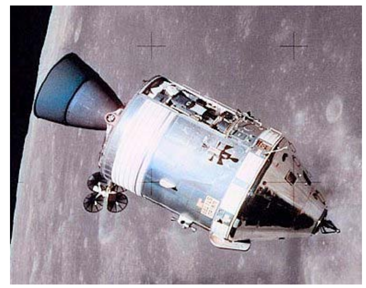
- Designed for manned lunar landing
  - 9 missions to lunar orbit
  - 6 missions to LEO
- Authors investigated Apollo/Skylab 3 on display in GRC Visitor Center

Apollo 10

Apollo vs. CEV: Capsule

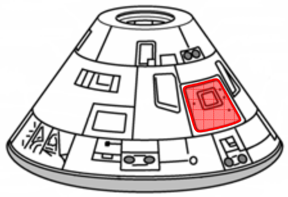
	Apollo 	**CEV** 
Astronauts	3	3 to 6 LEO 4 Lunar 6 Mars
Maximum Diameter	3.9 m (154 in)	5.0 m (200 in)
Number of missions	1	1*
Landing	Ocean	Land

Apollo vs. CEV: Mission Profile

		Apollo 	CEV 
	**Missions to LEO/ISS**		
	Mission duration	83 days	6 months
	Return velocity	Mach 25	Mach 25
	**Missions to Moon**		
	Mission duration	13 days	14 days (6 months w/ habitat)
	Return velocity	Mach 36	Mach 36
	**Missions to Mars**		
	Mission duration	NA	2.5 years
	Return velocity	NA	Mach 45

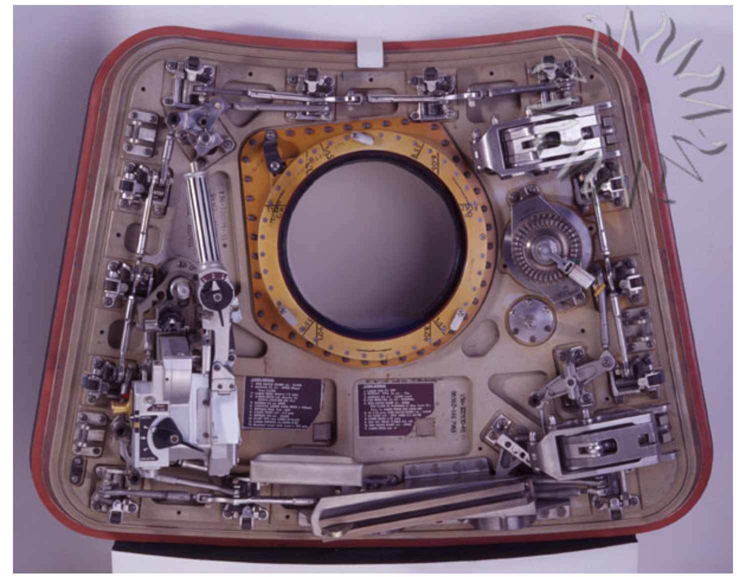
Apollo Pressure Seals

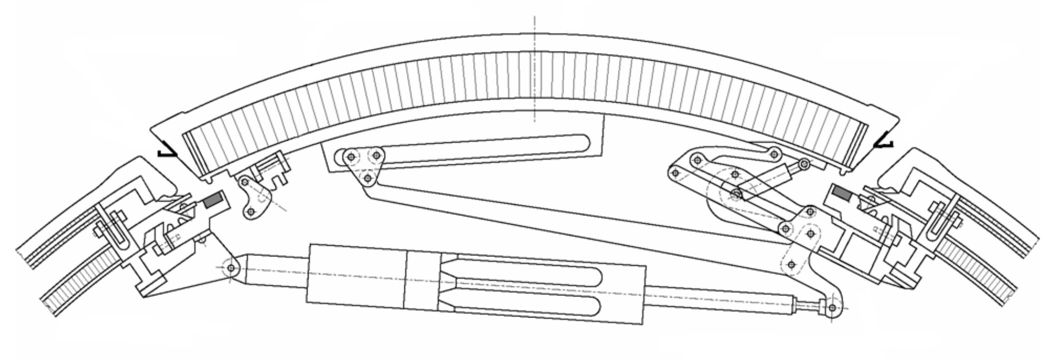
- Prevent loss of habitable atmosphere
  - Lunar missions
    - 5 psia
    - 100% O_2
  - Skylab missions
    - 5 psia
    - 70% O_2, 30% N_2
- Seal locations:
  - Bolted and riveted aluminum panels
  - Unified Crew Hatch
  - Docking system seals
  - Windows



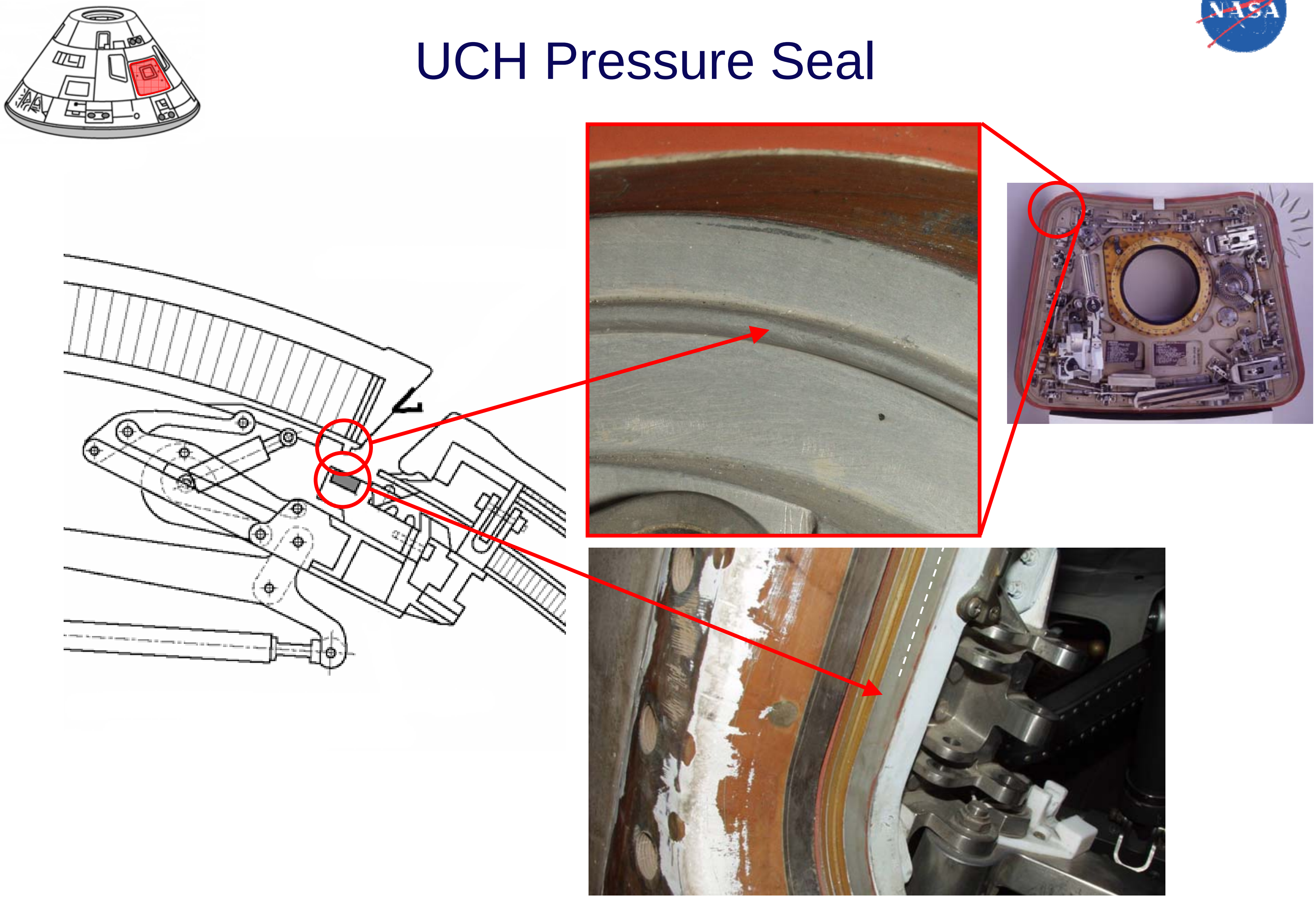
Unified Crew Hatch (UCH)

- In response to Apollo 1 fire, combined pressure hatch and heatshield hatch into single hatch (UCH)
- Allowed 30 sec. egress
  - Latches released in 3 sec.
  - Astronauts escape in 30 sec.
- UCH incorporated two seals
  - Pressure seal
    - Metal knife edge
    - Embedded into gasket
  - Thermal lip seal
    - Heat-molded silicone
    - More effective under pressure



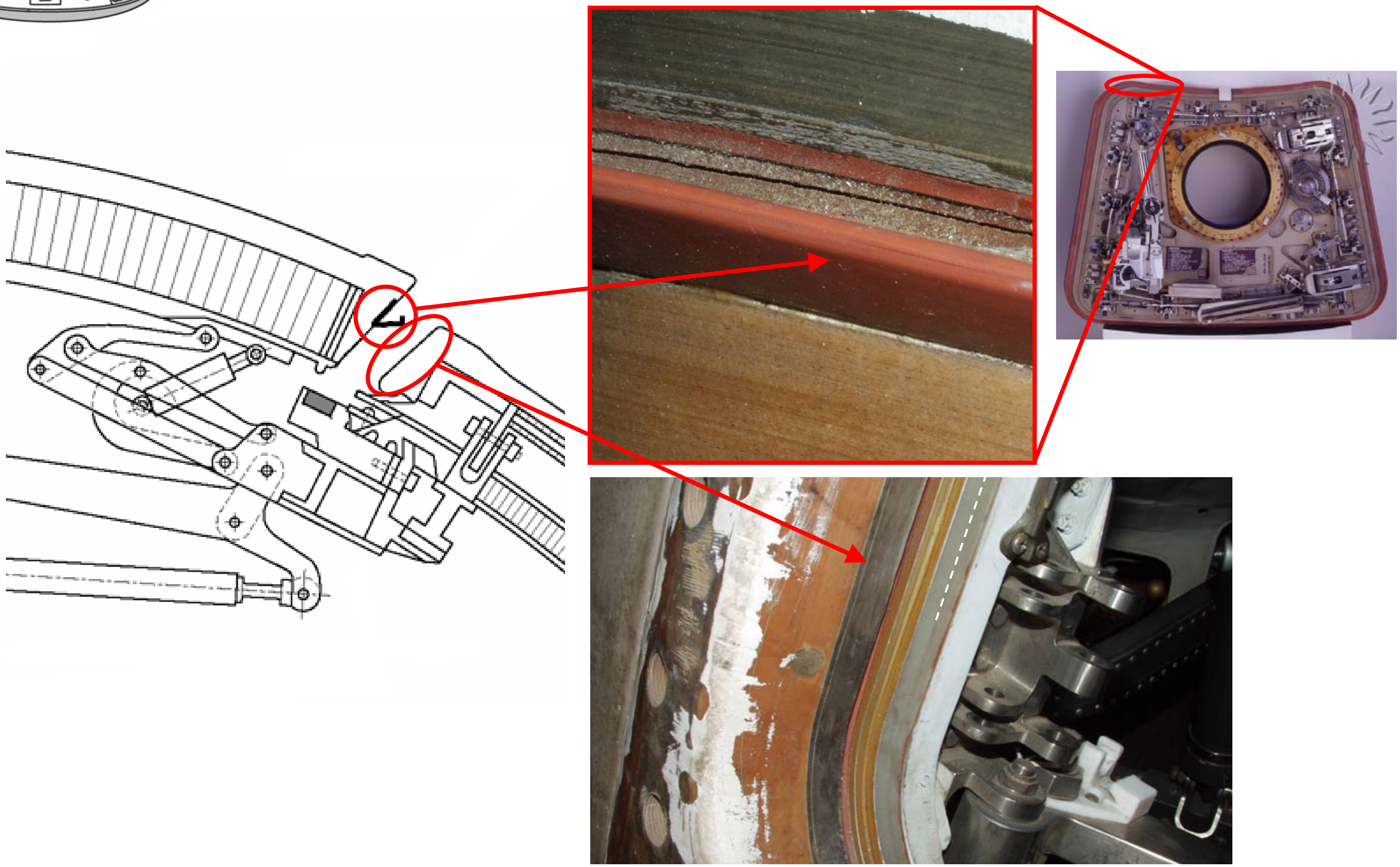


UCH Pressure Seal



National Aeronautics and Space Administration

UCH Thermal Seal



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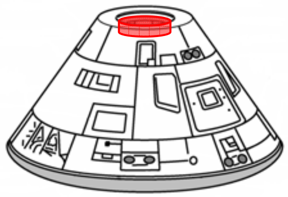
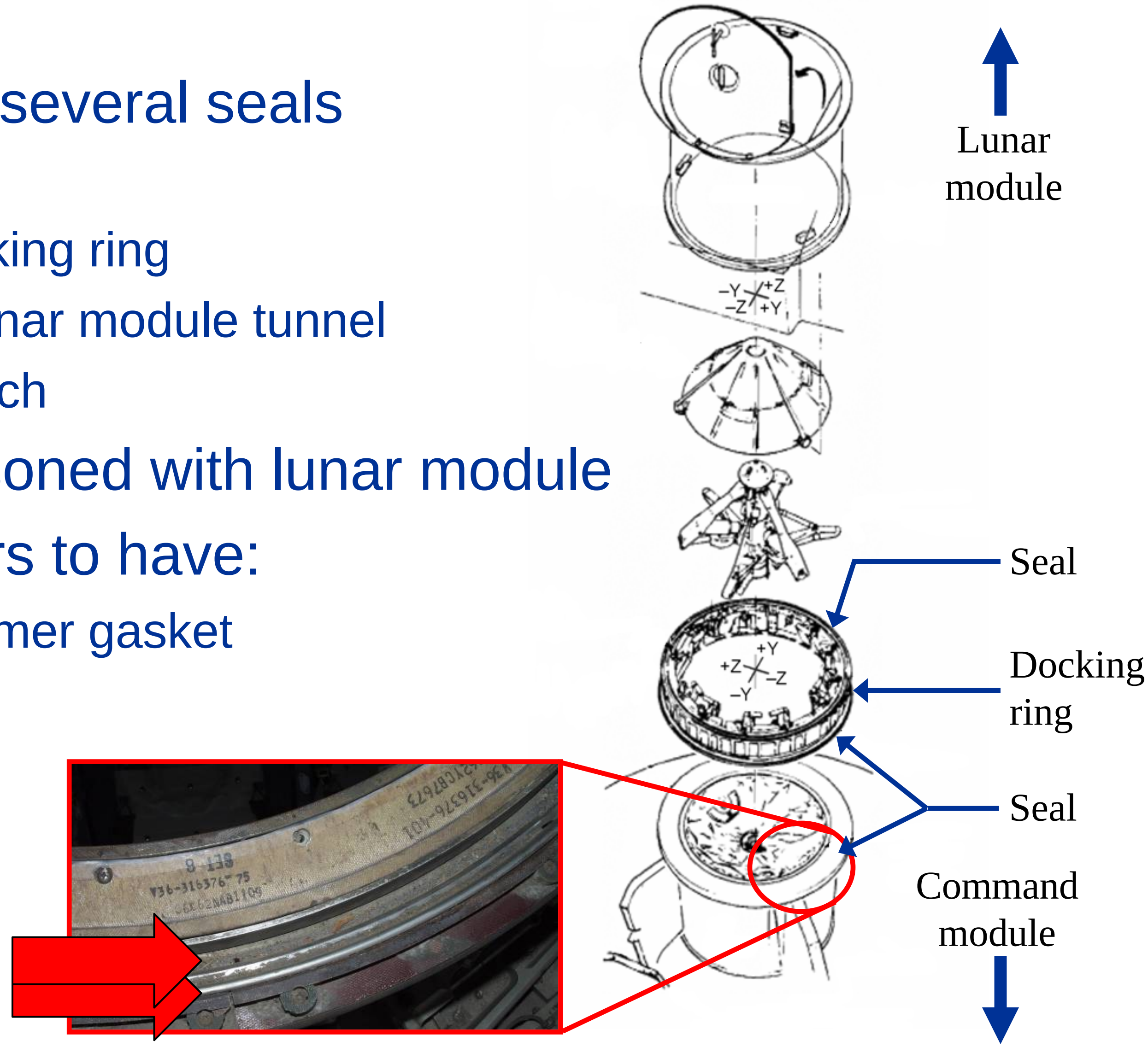


Docking System Seals

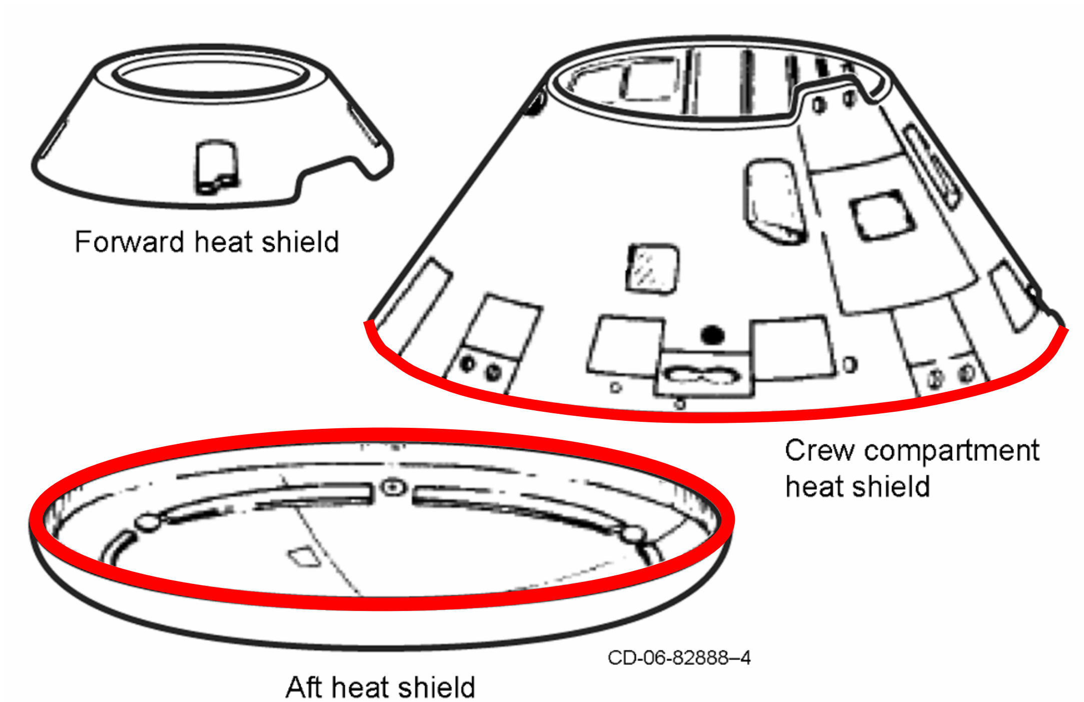
- Docking required several seals
  - CM tunnel hatch
  - CM tunnel to docking ring
  - Docking ring to lunar module tunnel
  - Lunar module hatch
- Docking ring jettisoned with lunar module
- CM tunnel appears to have:
  - Groove for elastomer gasket
  - Metal knife edge



High Temperature Thermal Seals

- Prevent ingestion of hot reentry gases
- Seal locations:
  - Aft heat shield
    - Tension tie bolts
    - Reaction Control System (RCS) oxidizer/fuel dump plugs
  - Crew compartment heat shield
    - Access panels
    - RCS motors
  - Forward heat shield interface gap
  - **Aft heat shield-to-crew compartment heat shield interface gap**
    - Thermal environment
    - Seal design

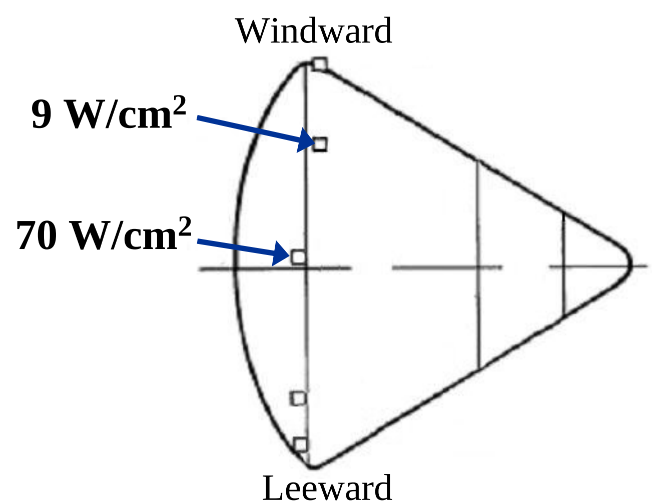
Aft Heat Shield-to-Crew Compartment Heat Shield Interface Gap

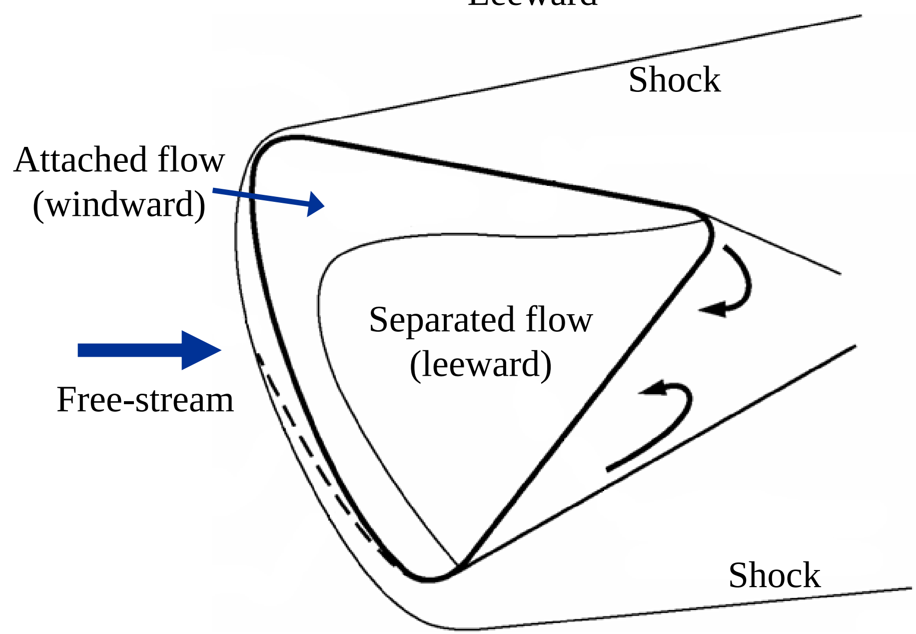


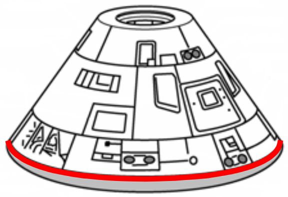
- Seals must resist reentry environment:
  - Silicone gaskets
  - Labyrinth tooth

Interface Gap Thermal Environment

- Thermal environment near gap difficult to predict
  - Very high axial heat flux gradient
  - Circumferential heat flux gradient
- Three-dimensional flowfield
  - Flow partially aligned with gap
  - Pressure gradient around capsule circumference
  - Flow separation near gap

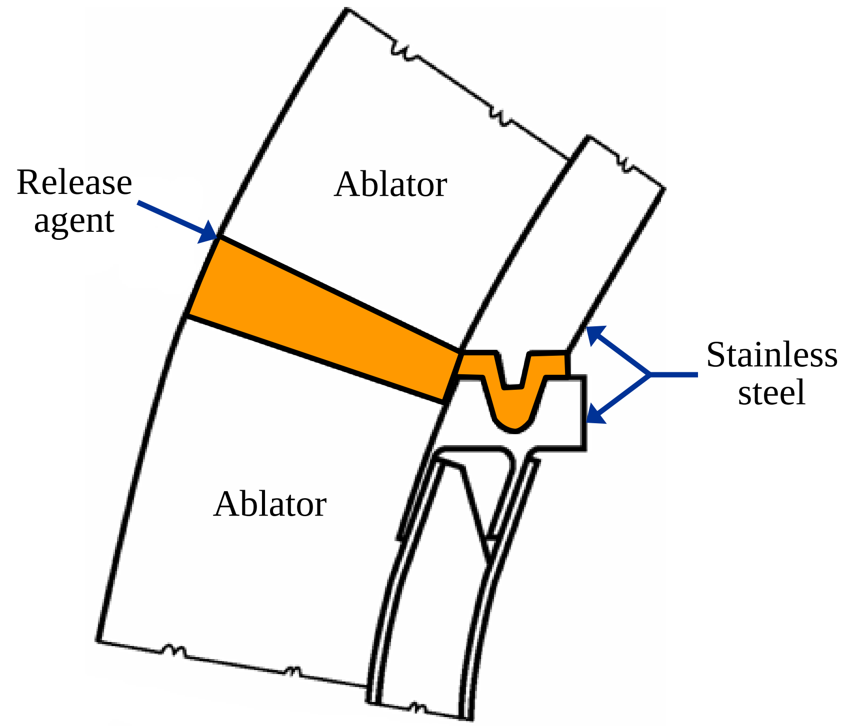






Heat Shield Interface Gap
Silicone Gaskets

- RTV silicone used to fill gap
  - High temperature capability
  - Ablative
- Release agent applied to upper gasket surface
  - Assembly of seal
  - Post-mission inspection
- Gasket formed in two parts:
  - Inner gasket between stainless steel structure
  - Outer gasket between ablator



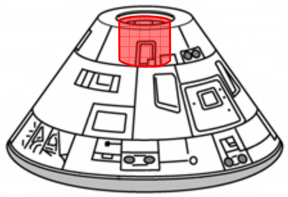
Conclusions

- Apollo seals used as a basis for understanding and designing seals for CEV
  - Pressure seals
    - Knife edge embedded into elastomer gasket
    - Heat-molded silicone seals
  - Thermal seals
    - High temperature silicone seals
- Aft heat shield-to-crew compartment heat shield interface gap
  - Environment difficult to predict
  - Flight experience shows silicone was successful
- CEV seal design
  - Apollo seals may be used as a basis
  - 40 years of advancement may allow new seal designs

Appendix

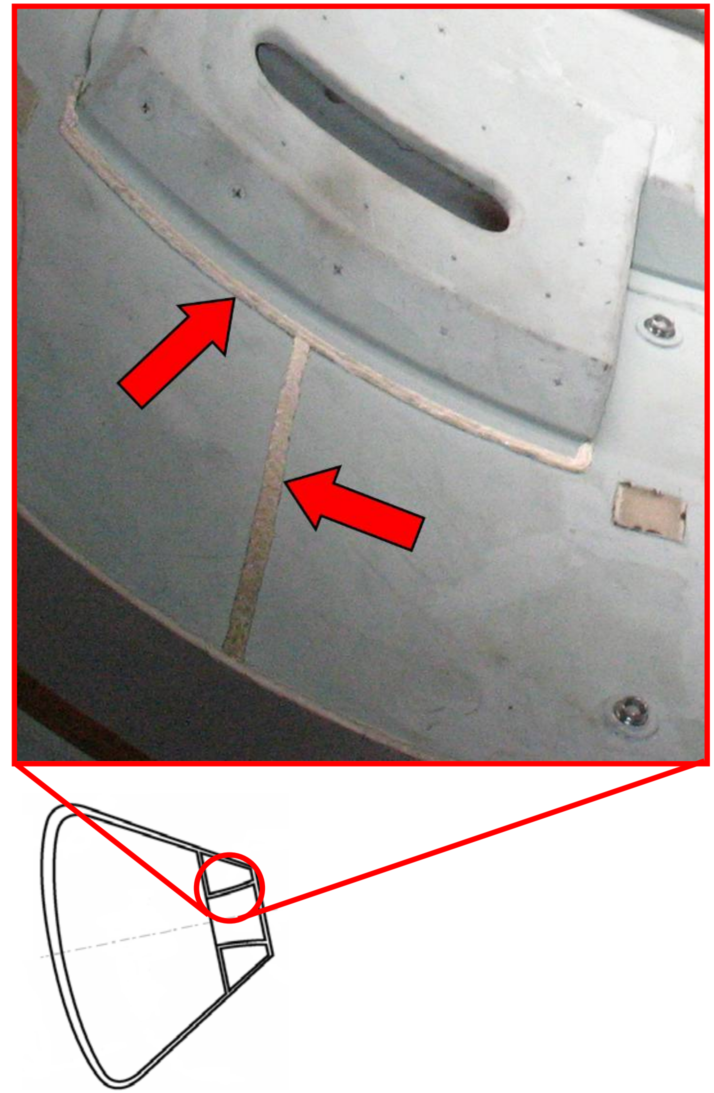
Overview

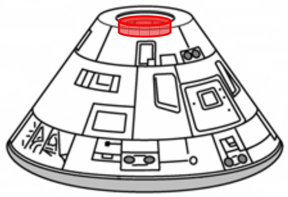
- **Crew Exploration Vehicle compared to Apollo**
  - Overview of the CEV
  - Overview of Apollo command module
  - Differences between Apollo and CEV
- **Overview of Apollo vehicle and seals**
  - Apollo Pressure Seals
    - Crew cabin atmosphere
    - Seals for crew cabin penetrations
  - Apollo Thermal Protection System (TPS) Seals
    - Apollo reentry environment
    - Heat shield penetrations
    - Inter-heat shield gaps



Bolted/Riveted Aluminum Panels

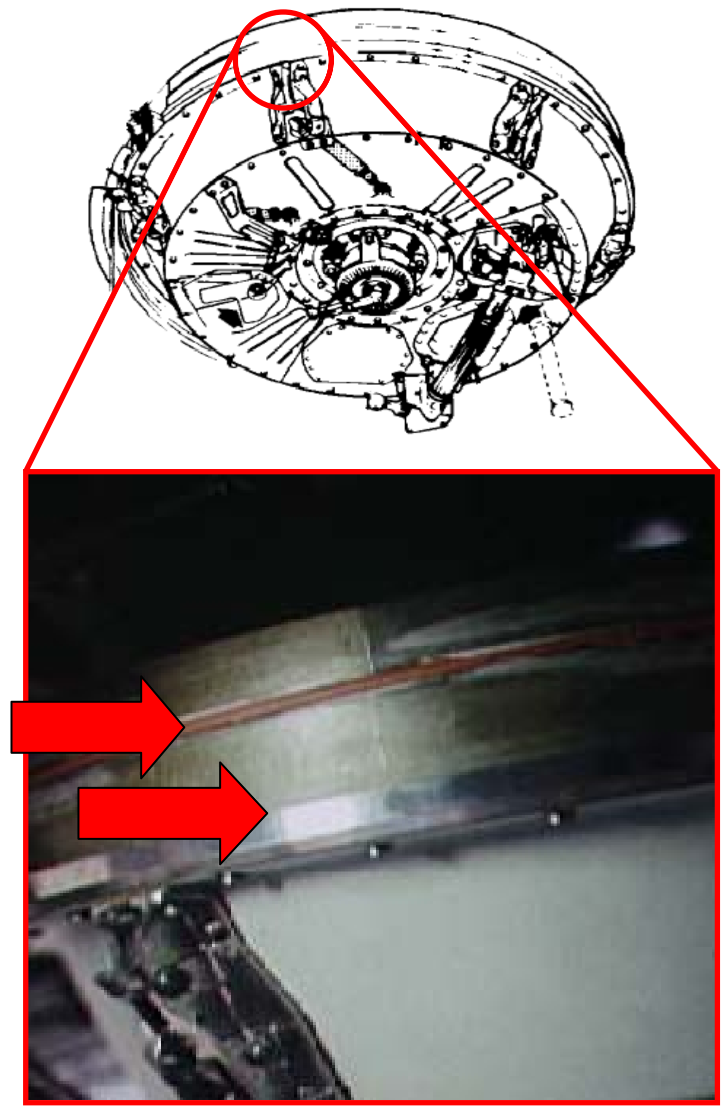
- Panel joints sealed with RTV
  - White RTV used in forward tunnel
  - Acceptable leakage for short mission durations
  - Major source of atmospheric loss
- Recommendations for long-duration spacecraft
  - Incorporate welded panels
    - Reduce leakage
    - Eliminate seal degradation
  - Easily replaceable seals

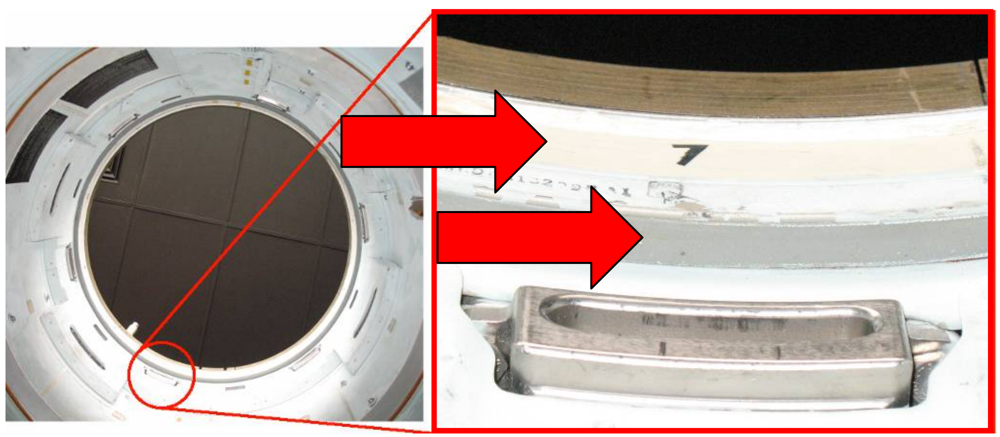


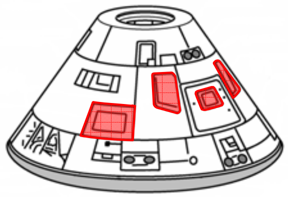


Forward Tunnel Hatch Seals

- Pressure seal
  - Metal knife edge on hatch
  - Elastomer gasket inside tunnel
  - Cabin pressure compressed knife edge into gasket
- Thermal seal
  - High-temperature silicone O-ring
  - Low thermal loads

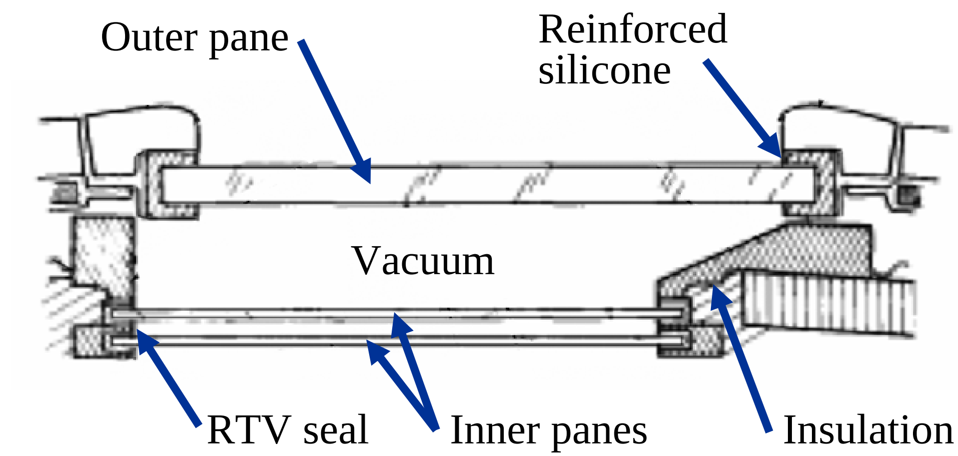


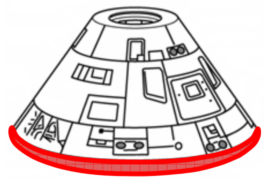




Command Module Windows

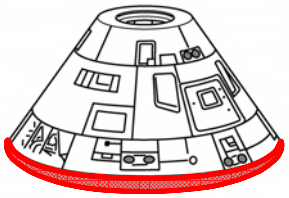
- Two inner pressure panes
  - Aluminosilicate material
  - Inner gap filled with nitrogen
  - Sealed with RTV
- Insulating layer
  - Multilayer fiberglass insulator
  - RTV coating
  - Bonded to capsule with RTV
- Outer thermal protection pane
  - Fused amorphous silica
  - Sealed with glass cloth-reinforced heat-cured silicone
  - Bonded with RTV



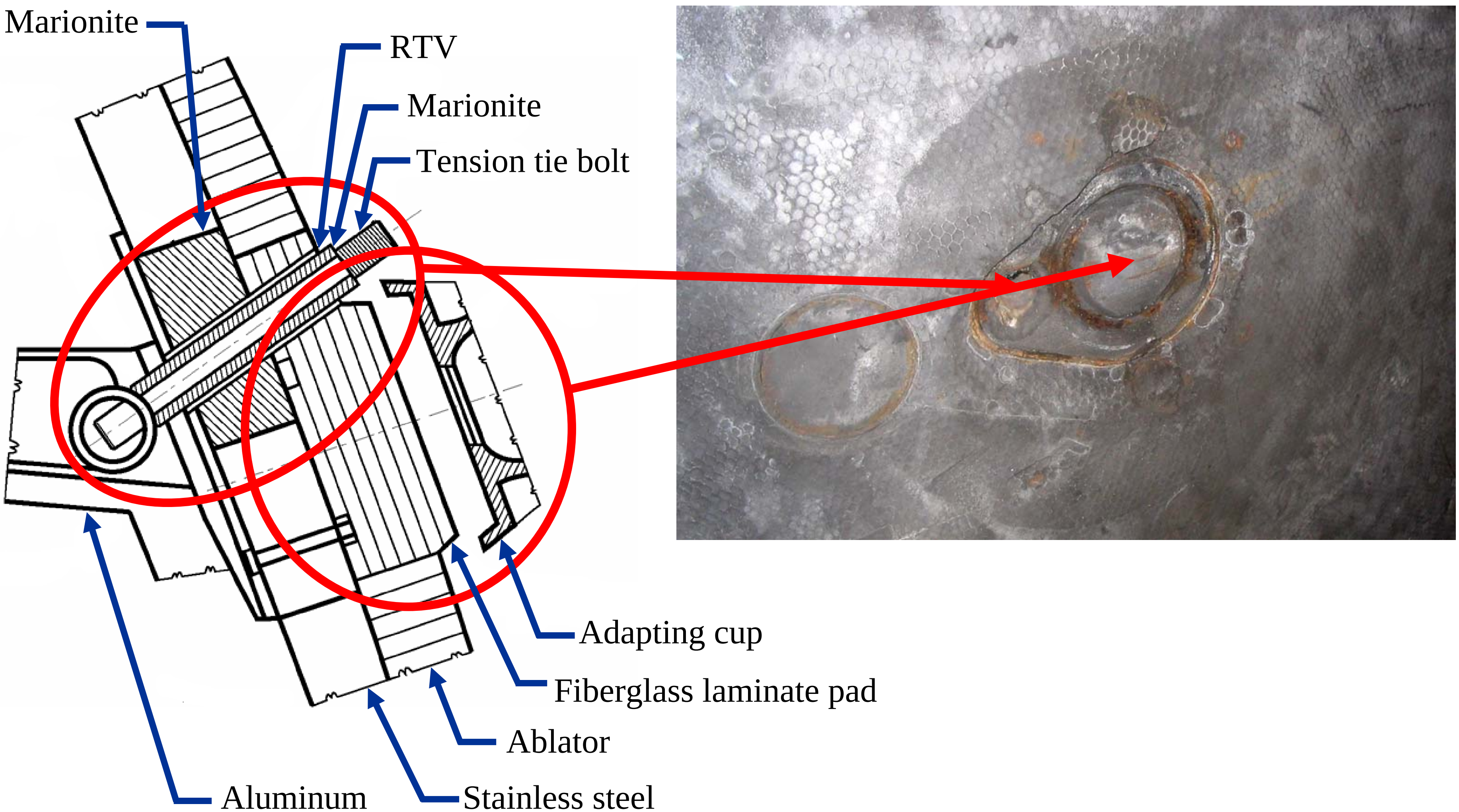


Compression/Shear Pads

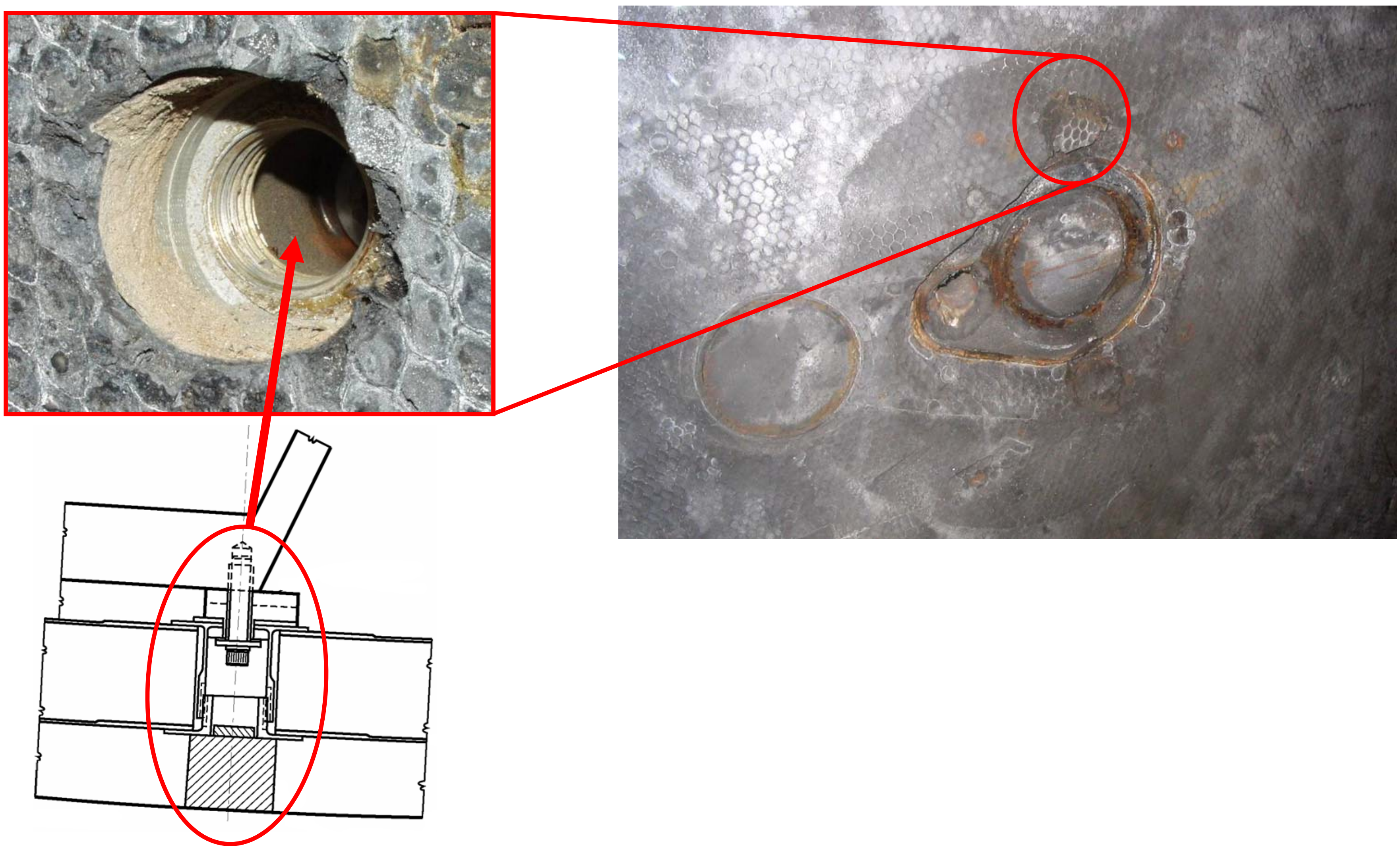
Scott Sullivan, "Virtual Apollo", pp. 21.



Compression/Shear Pads and Tension Tie Bolts



Ablator Plugs and Heat Shield Fasteners



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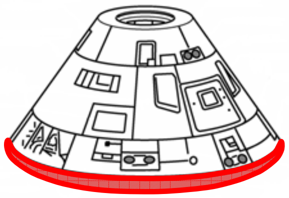
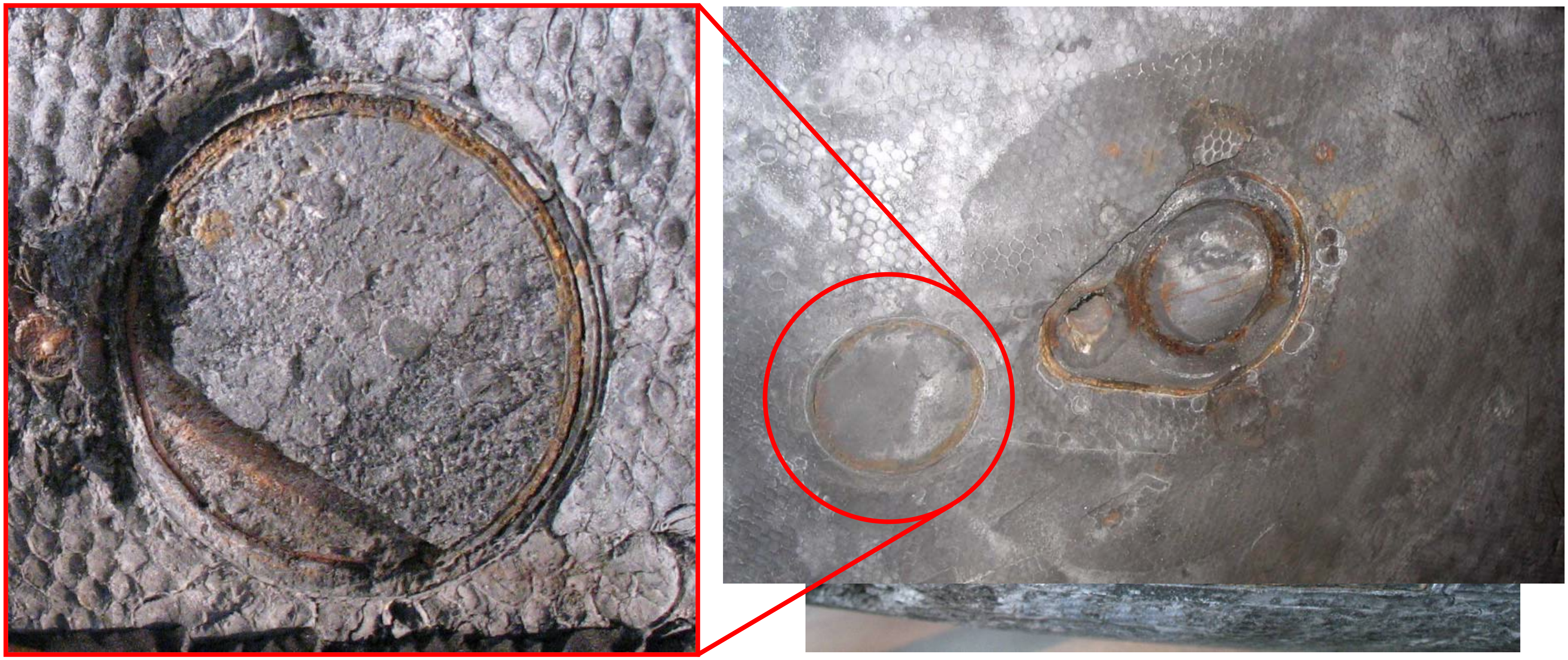


RCS Fuel/Oxidizer Dump Plugs



Oxidizer Dump Plug

Fuel Dump Plug

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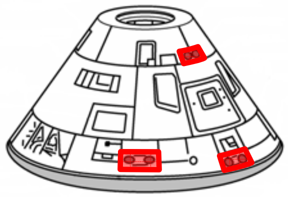
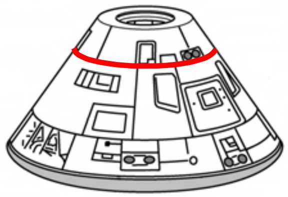
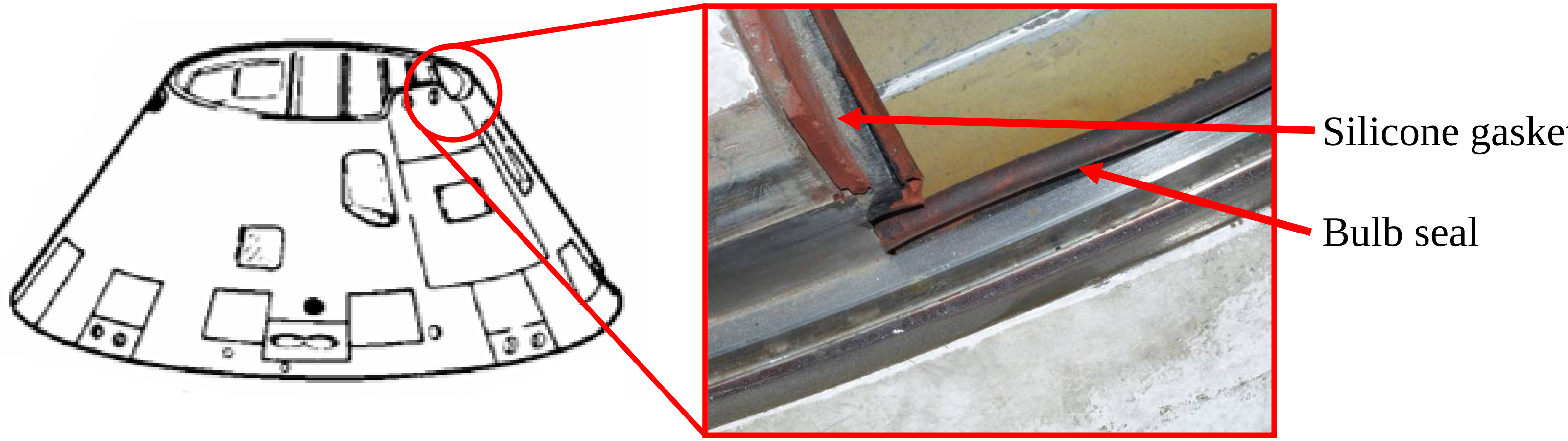


Access Panels and RCS Motors

- RTV used to seal gaps in:
  - Reaction Control System (RCS) motors
  - Access panels
- Visual inspection of seals
  - Little evidence of ablation
  - Low heat flux
  - Post-mission razor cuts

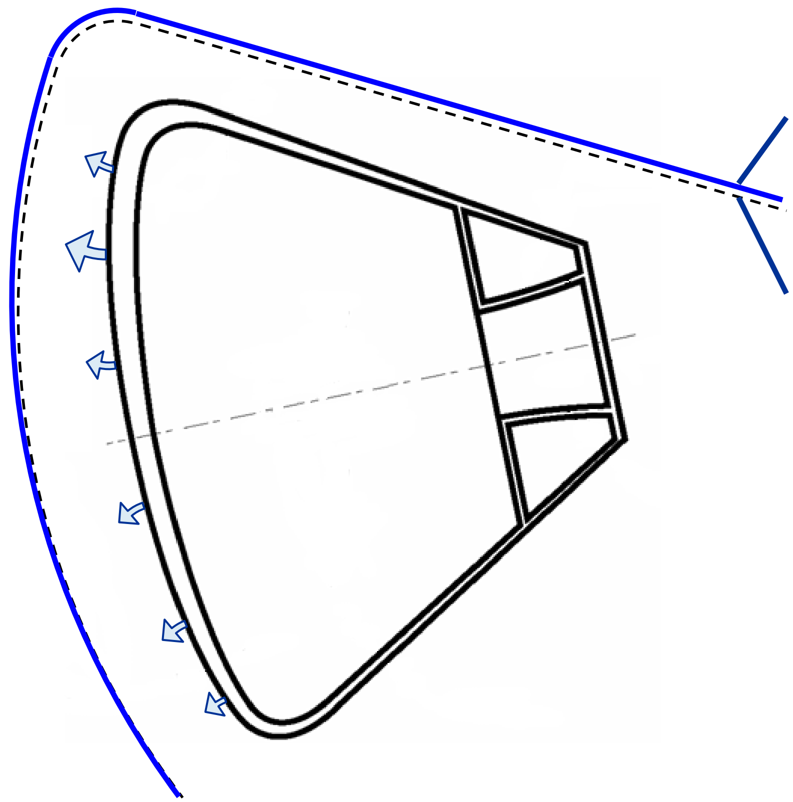


Crew Compartment Heat Shield-to-Forward Heat Shield Interface Gap



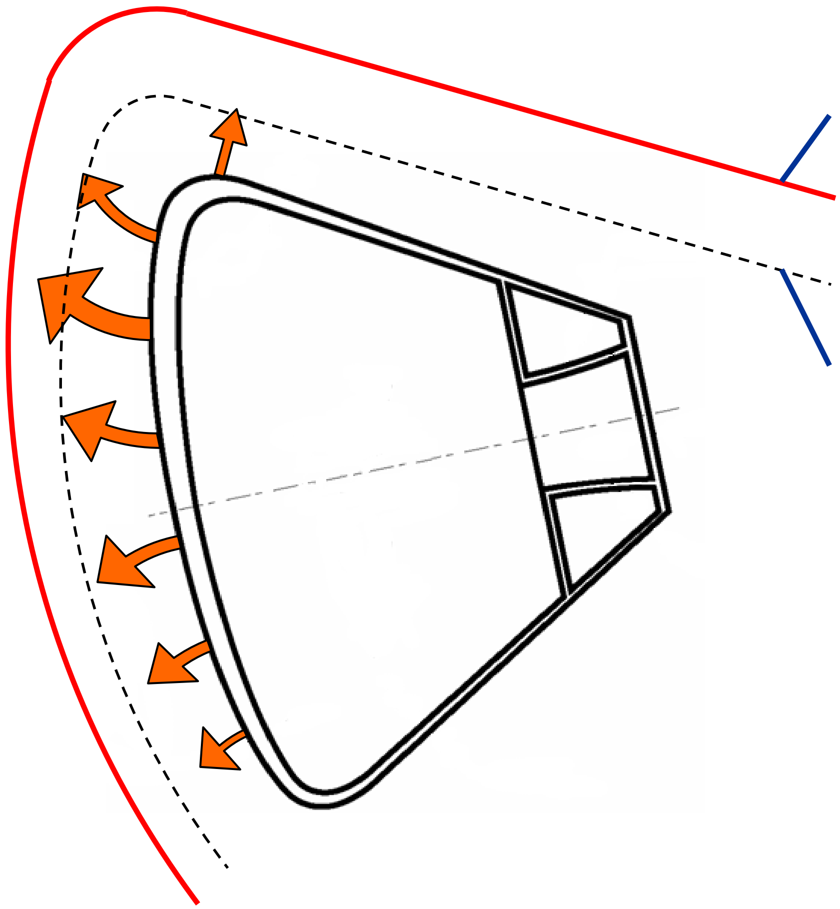
- Low heat flux at gap
- Forward heat shield jettisoned
  - Seal could not adhere heat shields together
  - Forward heat shield not recovered
- Gap sealed with heat-cured silicone bulb seal
- RCS motor perimeter sealed with silicone gasket

Reentry from LEO



- Flight pressure measurements agreed with flight models
- Ablation minimally altered boundary layer
- Heat transfer to vehicle affected by local ablation

Superorbital Reentry



- Pressure measurements lower than flight models
- High ablation rate altered boundary layer
- Pressure and heat flux on conical heat shield reduced

DEVELOPMENT AND EVALUATION OF HIGH TEMPERATURE GASKETS FOR HYPERSONIC AND REENTRY APPLICATIONS

Mrityunjay Singh
Ohio Aerospace Institute
Brook Park, Ohio

Tarah Shpargel
ASRC Aerospace
Cleveland, Ohio

National Aeronautics and Space Administration

Development and Evaluation of High Temperature Gaskets for Hypersonic and Reentry Applications

Mrityunjay Singh
Ohio Aerospace Institute
NASA Glenn Research Center
Cleveland, OH 44135

Tarah Shpargel
ASRC Aerospace
NASA Glenn Research Center
Cleveland, OH 44135

www.nasa.gov

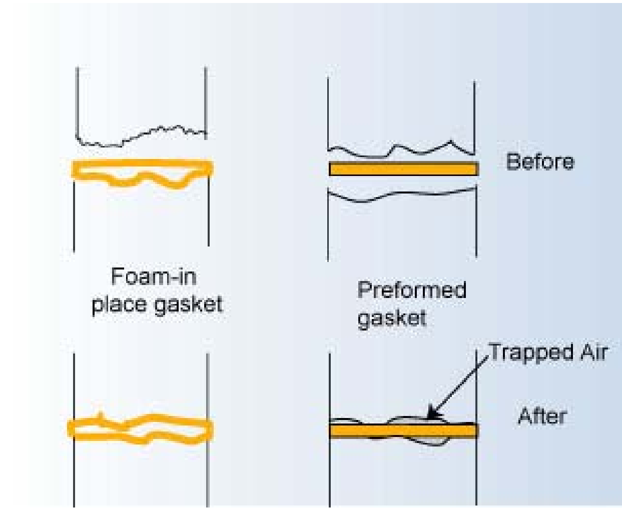
Outline

- **Background and Introduction**
    - *Need and Requirements*
    - *Sealants and Gasket Development and Testing in Space Shuttle RTF*
- **Experimental Procedures**
    - *Fabrication of Gaskets*
    - *Substrate Material*
    - *Testing Conditions*
- **Results and Discussion**
    - *Thermal Analysis*
    - *Load Bearing Characteristics and Thermal Stability (under loads)*
    - *Post Test Microstructural Characterization*
- **Summary and Conclusions**
- **Future Work**

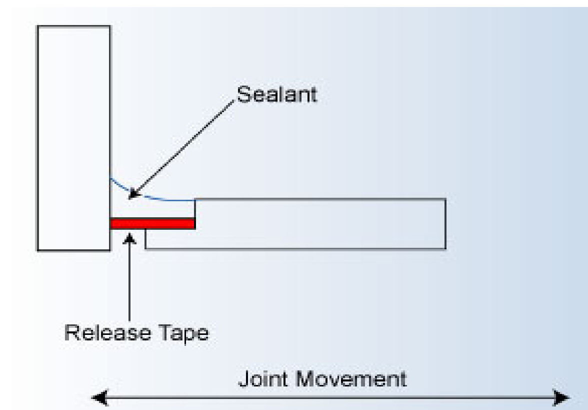
Typical Performance Requirements for Gaskets

General Requirements:

- Good dimensional tolerance
- Zero leakage through/over the gaskets
- Heat and thermochemical resistance
- Affordable and environmentally safe
- Ease of alignment/assembly
- Reusability and serviceability



- **Form-in-place gaskets:**
  - *Anaerobics (acrylate monomer, resins)*
  - *Silicones (RTVs)*
  - *Others (Polyurethanes, hot melts, Rubber modified polyesters, etc.)*
- **Preformed gaskets:**
  - Metallics, rubber, cork, flurocarbon, composites
  - Elastomers



RTV based Gaskets can be applied in both configurations

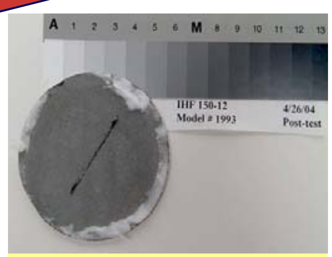
From Adhesives and Sealants (2005)

Glenn Refractory Adhesive for Bonding and Exterior Repair *(GRABER)*

Arc Jet Testing
Front View

Arc Jet Testing
Side View

Post Test- Front Side



Post Test- Back Side

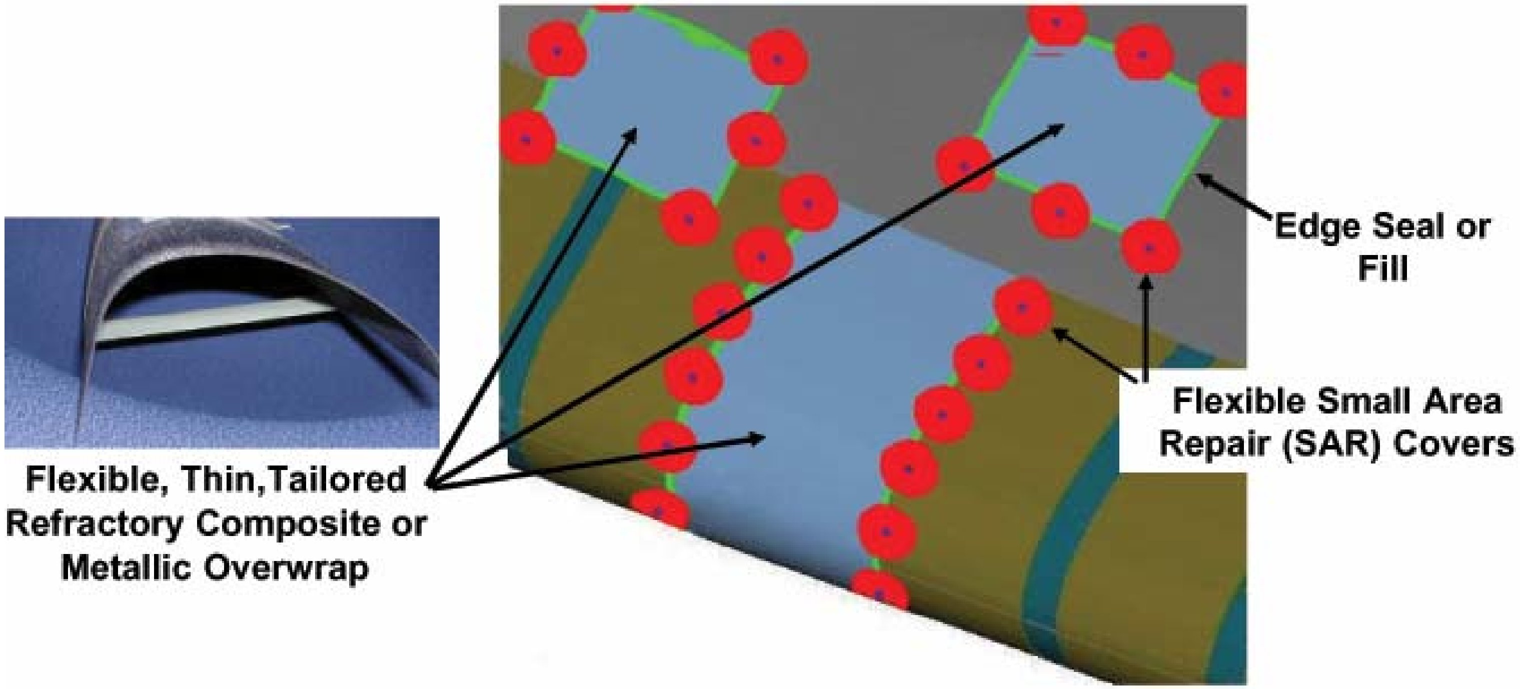
Multiuse Capability/Versatility of GRABER

- Repair of cracks, gouges, small holes, and missing surface coatings
- Edge sealant/adhesive for Plug concept
- Gap filler for T-seals and other areas
- Sealing the edges, gaps, attachment areas for flexible ceramic/metallic wrap concepts for large area damage repair
- Prepregs made with various ceramic fabrics are useful for various high temperature applications in aerospace and ground based systems.

- **Analogue RCC Plug Sealed with GRABER 5A Crack Sealant**
- **Survived the ArcJet Testing at JSC**

- **2005 R&D 100 Award**
- **Northern Ohio Live Magazine- Awards of Achievement, S&T Category- Runner Up**

Large Area RCC Leading Edge and Tile Repair



Drill/Tap Tools

Fasteners

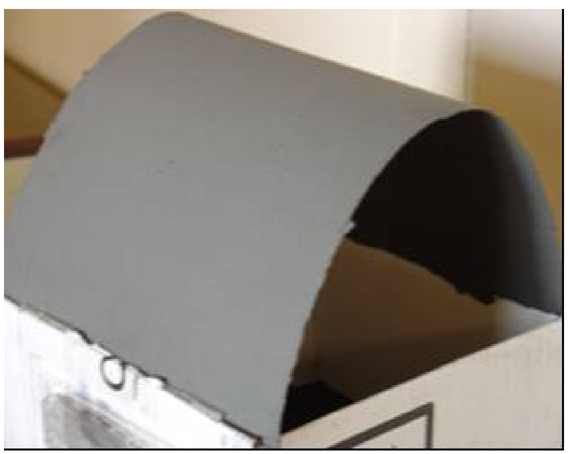
Gaskets

SAR Patch

Integrated System for Leading Edge and Tile Repair (InSTALER)

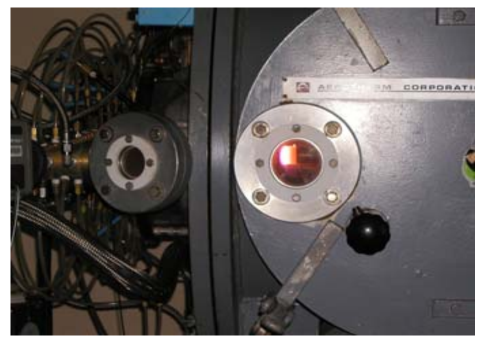
Flexible Ceramic Overwrap

DEVELOPMENT

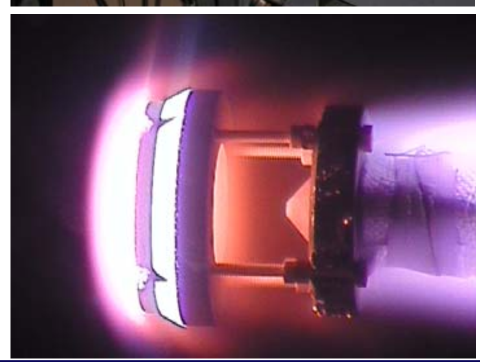


TESTING

QARE Rig Testing (GRC)



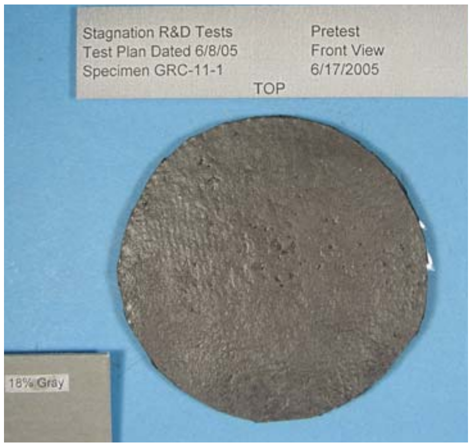
HYMETS (LaRC)



ArcJet Testing at JSC, ARC, and LCAT

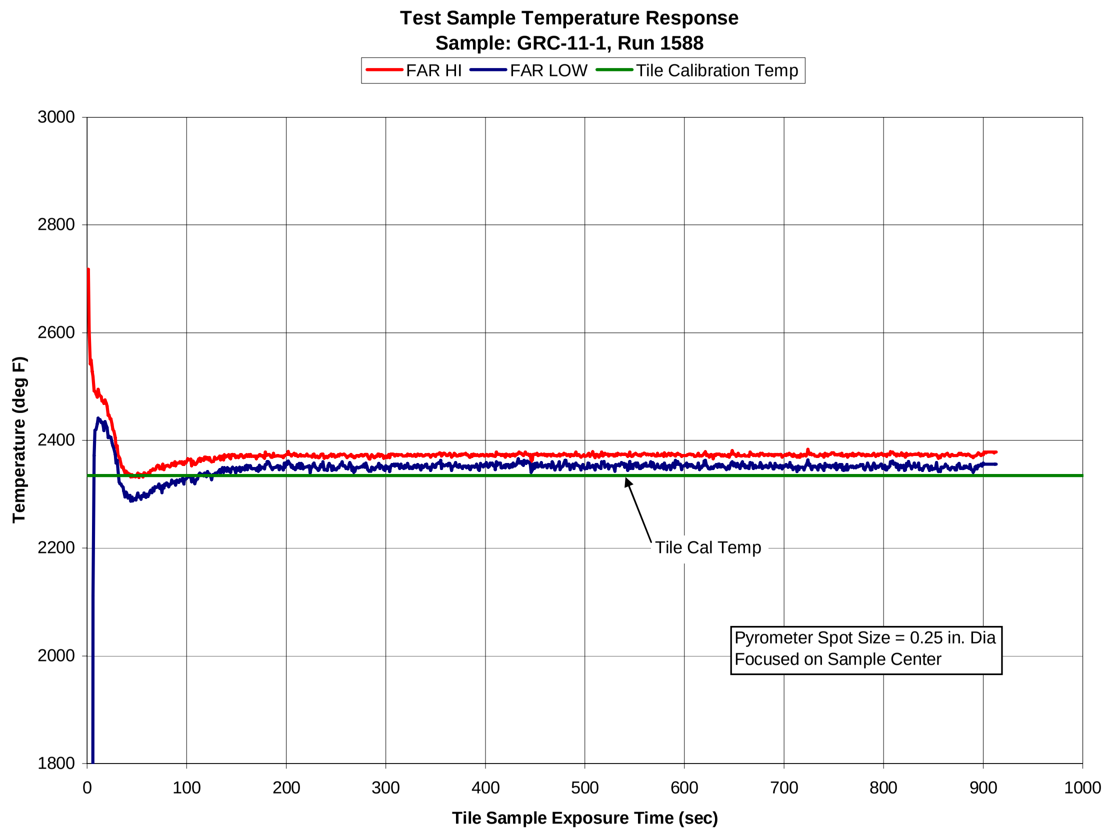
Integrated System for Leading Edge and Tile Repair (InSTALER)

Flexible Ceramic Overwrap



Pre-Test

Post Test

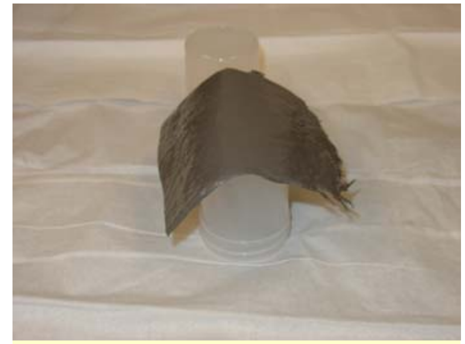


Excellent Plasma Performance in ArcJet Tests

Flexible Gaskets for Reentry Applications

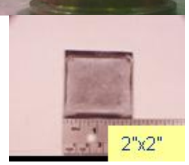
GRC 11 Gaskets made from RTV foam

GRC 16 Gaskets made from Ablative polymer

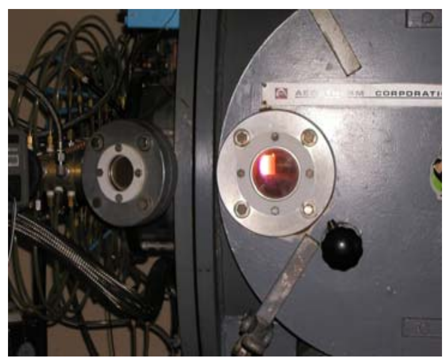


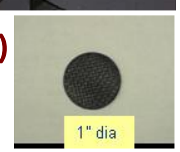
GRC 17 Gaskets made from silicone based RTV polymer

These gaskets have shown excellent plasma performance in various facilities under re-entry and hypersonic conditions.

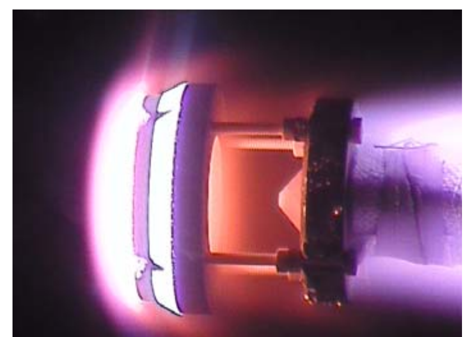


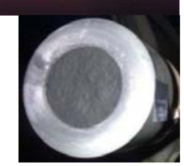
QARE Testing at GRC





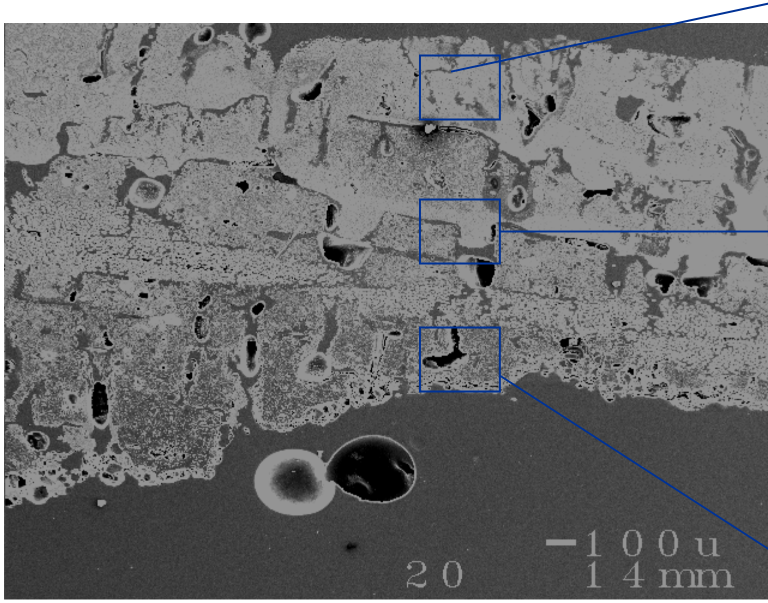
HYMETS (LaRC)



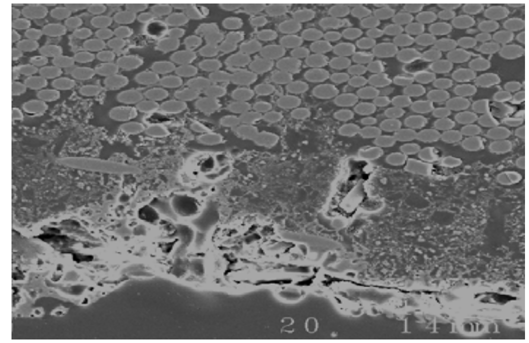


ArcJet Testing at ARC and LCAT

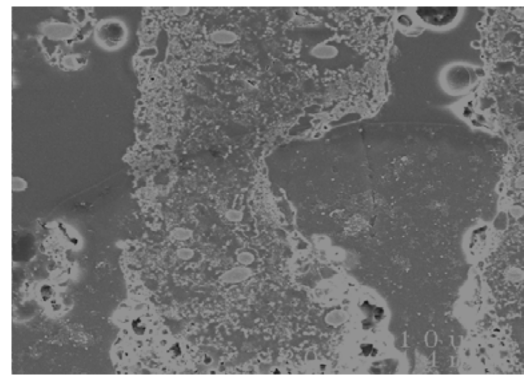
Microstructural Analysis of HYMETS Tested Gasket Samples



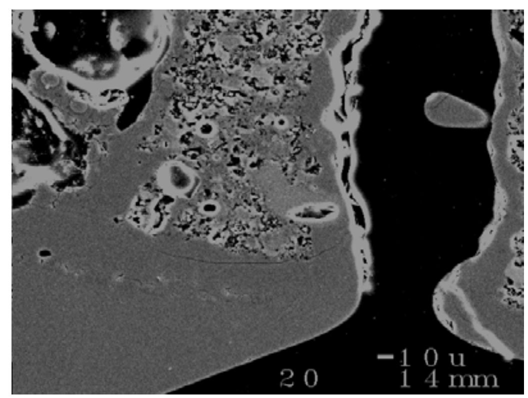
Back



Middle

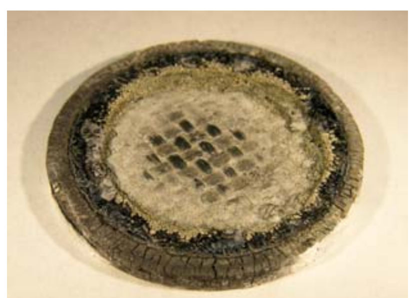


Front



HYMETS Sample #1

(RCC test profile, 9 minutes)



Development and Fabrication of Gasket Materials

- Two part RTV system provides control of amount of pores (final gasket density) by controlling the amount of gas generating component as well as fillers.
- GEN-1 flexible gaskets were made from RTV and a number of fillers (glasses with varying melting temperatures and refractory ceramics) along with chopped Tyranno-SA SiC fibers.
- Thin sheets of three thickness were prepared and used for rapid furnace heating, compressibility testing, and thermal properties characterization.

Nomenclature and Specimen Identification

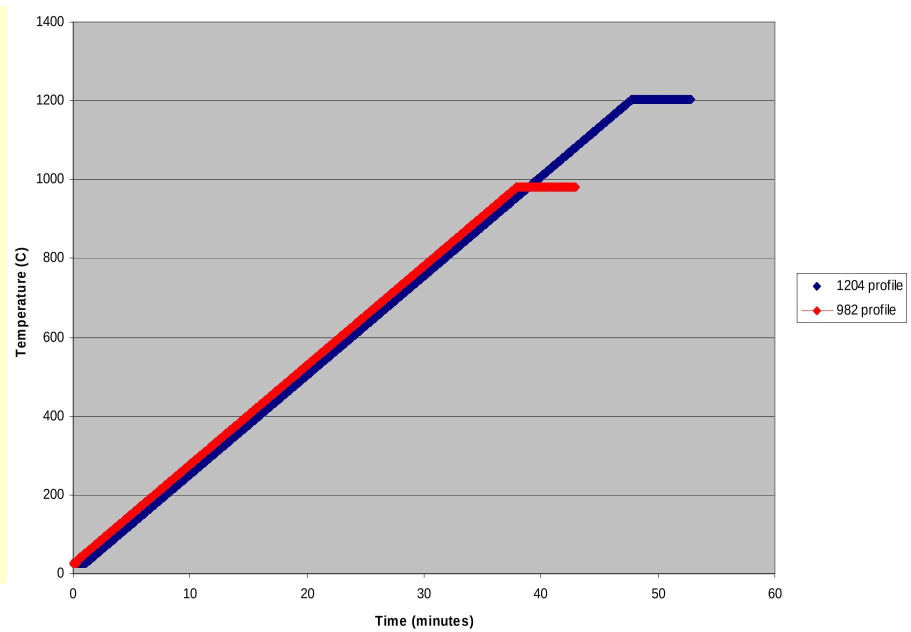
- Baseline RTV
- GRC 2 (RTV, Chopped Fibers, LT Fritz, and a Refractory Powder)
- GRC 9 (RTV, Chopped Fibers, HT Fritz, and a Refractory Powder)
- GRC 13 (RTV, some chopped fibers, LT Fritz, and two Refractory Powders)

Composite Substrates and Testing Conditions

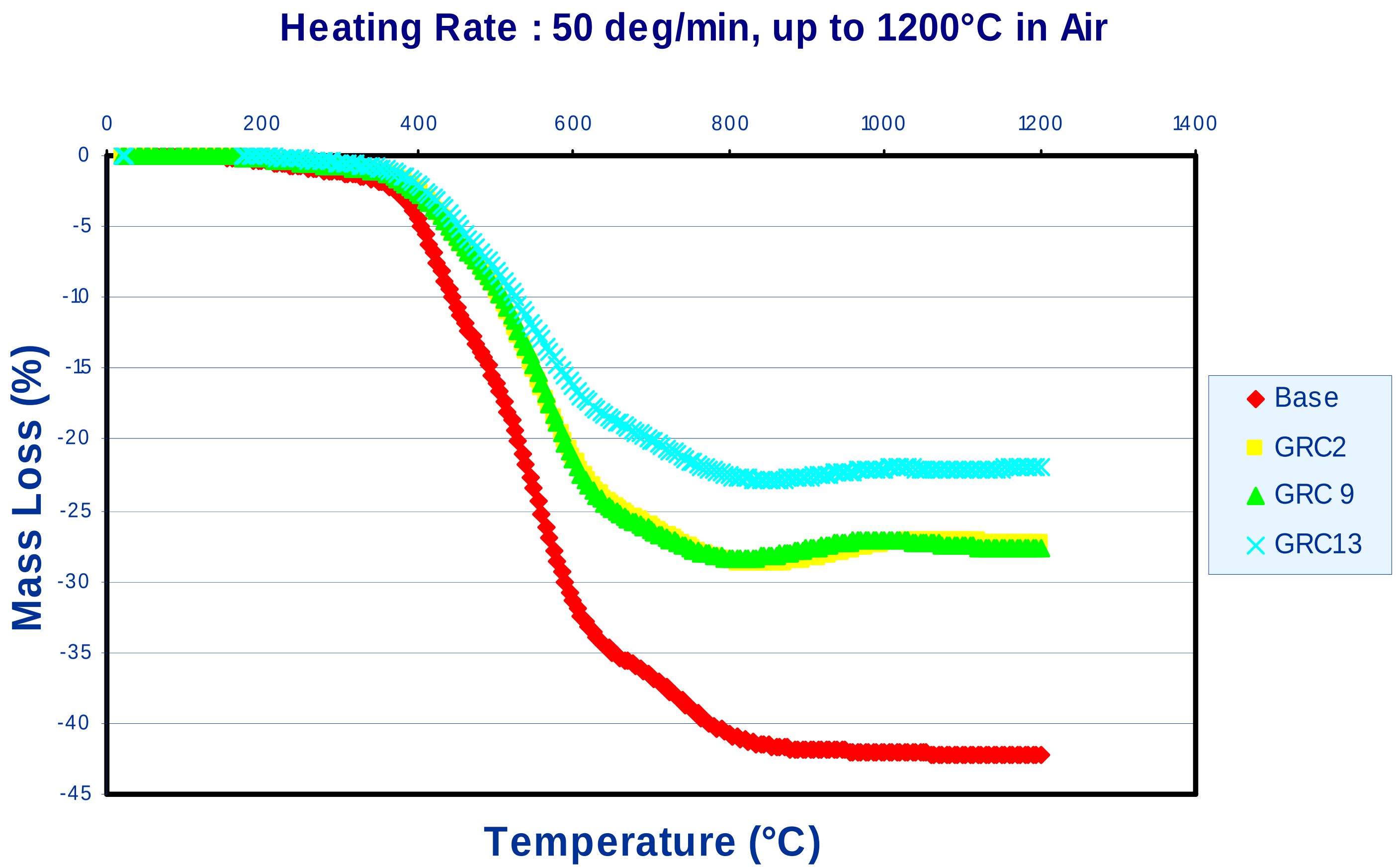
- **ACC-4 (T-300 Carbon Fibers and SiC coating) from C-CAT Composites was used as substrate material during compressibility and thermal stability tests.**
- **GRABER was used to seal the edges of 1”x1” ACC-4 specimens to prevent edge oxidation.**

Test Conditions:

- **Temperatures: *982°C (1800 F)* and 1204°C (2200 F)**
- **Pressure/ Load on Gaskets: *60 psi* and 100 psi**
- **Five minute hold**
- **Test was carried out in a Instron load frame with a high temperature furnace, in air**



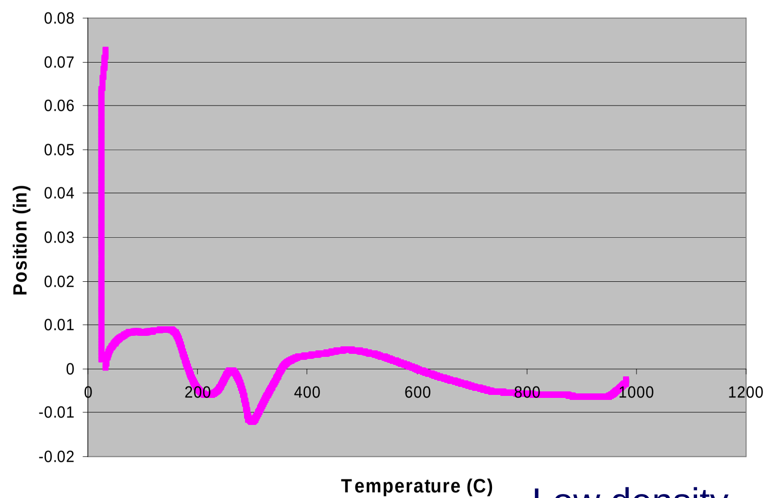
Thermogravimetric Analysis of Gasket Materials



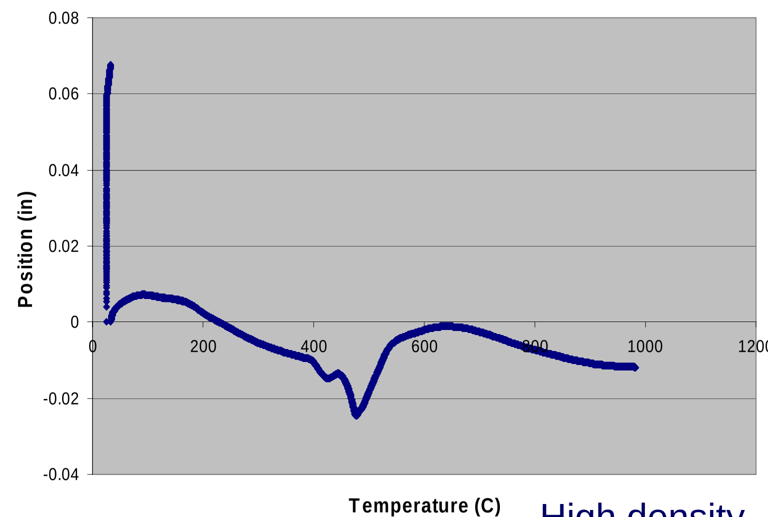
Compression Testing of Base Gasket Material at 60 psi and 982°C (5 min hold)

- Base gasket material fell apart after testing. There are no optical or SEM images available.
- Without composition modifications, it will not meet gasket performance requirements.
- Modified compositions GRC-2, GRC-9, and GRC-13 were used for further testing.

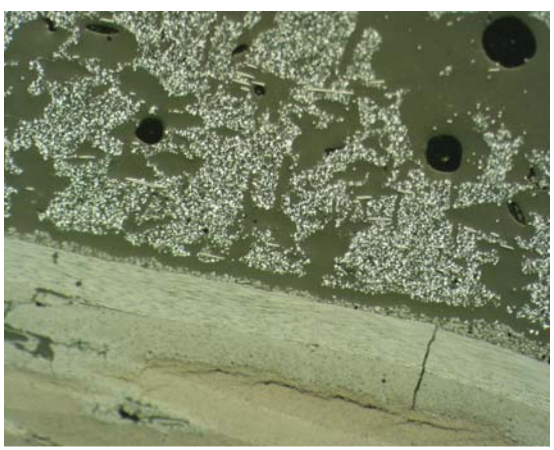
Compression Testing of GRC-2 Gasket Material at 60 psi and 982°C (5 min hold)



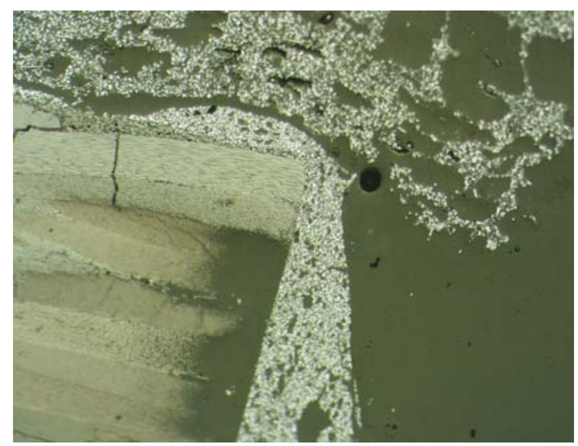
Low density (1.1 gm/cc)



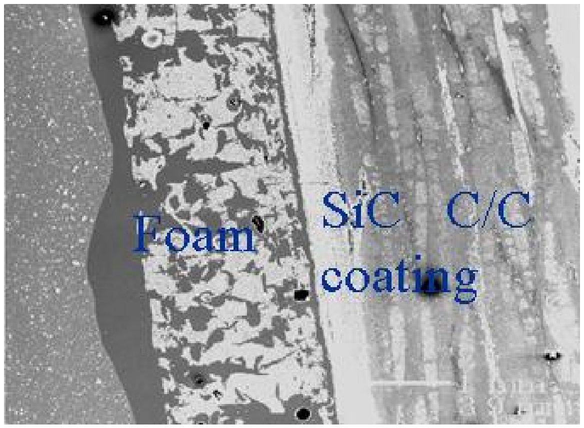
High density (1.26 gm/cc)



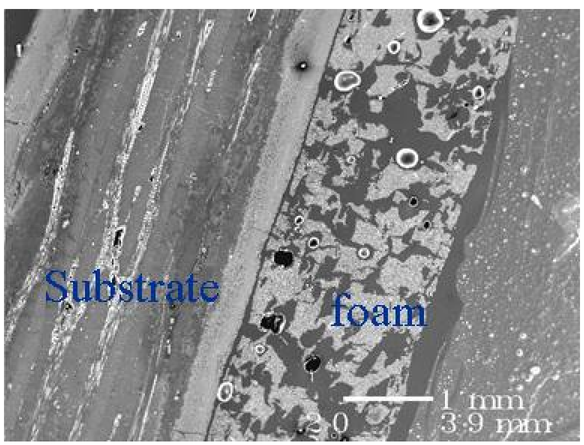
Optical images of GRC 2 at 50 X. The picture (right) shows the interaction of GRABER and the SiC coating. To the left is an image of the gasket material after heating.



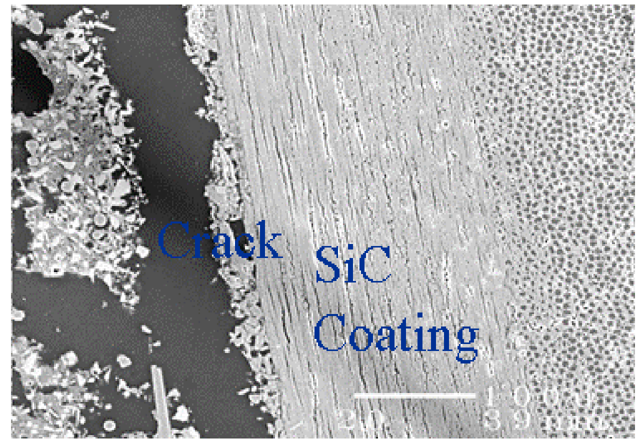
Micrographs of GRC-2 Gasket Material at 60 psi and 982°C (5 min hold)



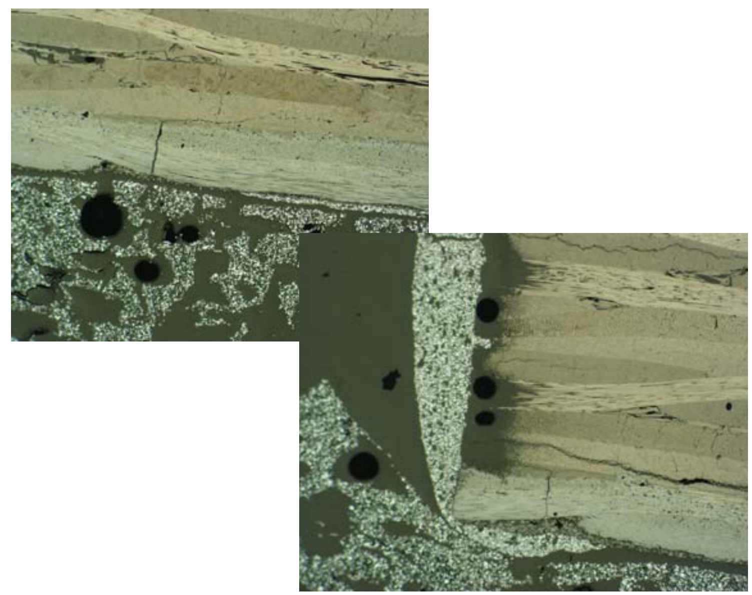
T_i: 4 mm; T_f: 2.2 mm



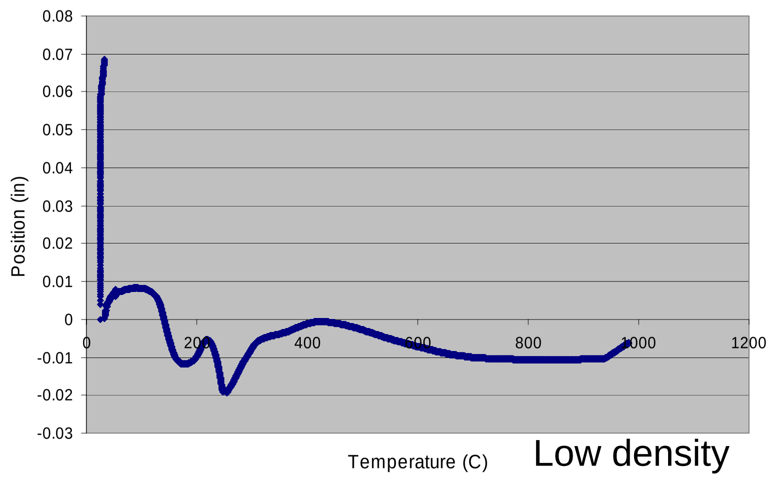
Lower Density



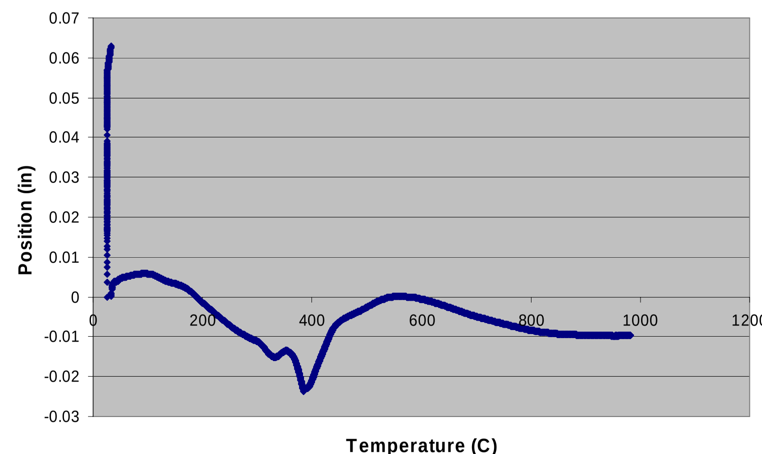
Higher Density



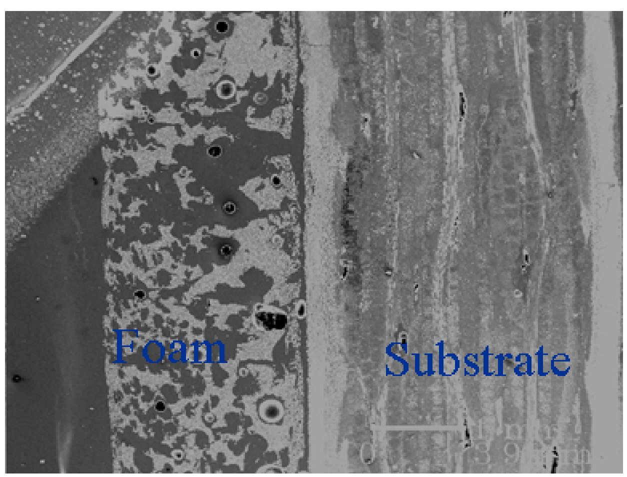
GRC 9 Gasket Material at 60 psi at 982°C (5 min. cycle)

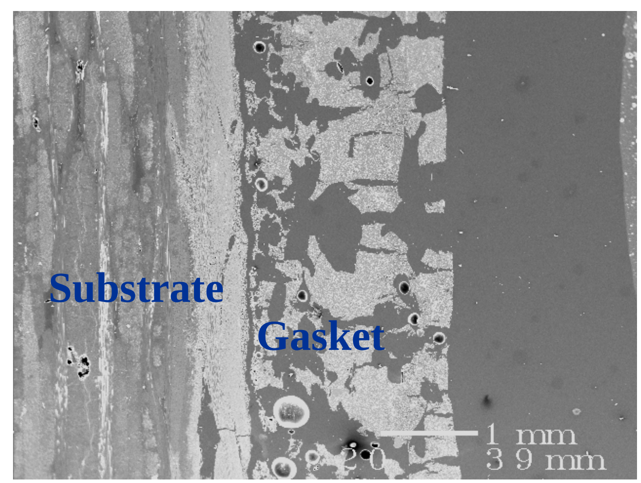


Low density (1.15 gm/cc)

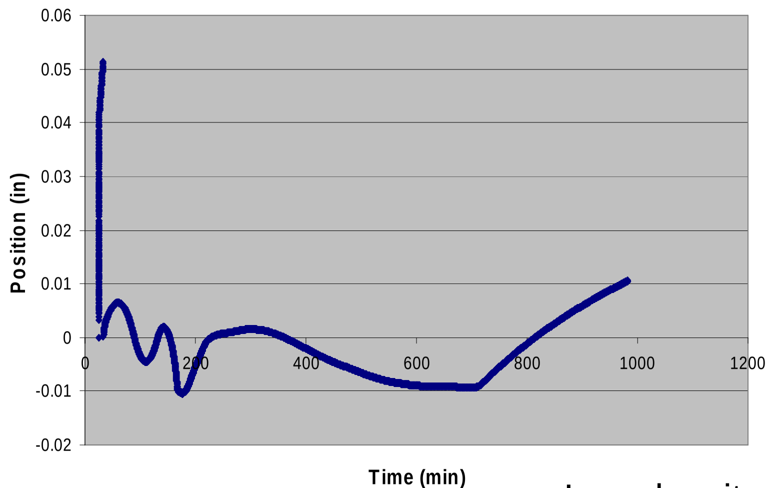


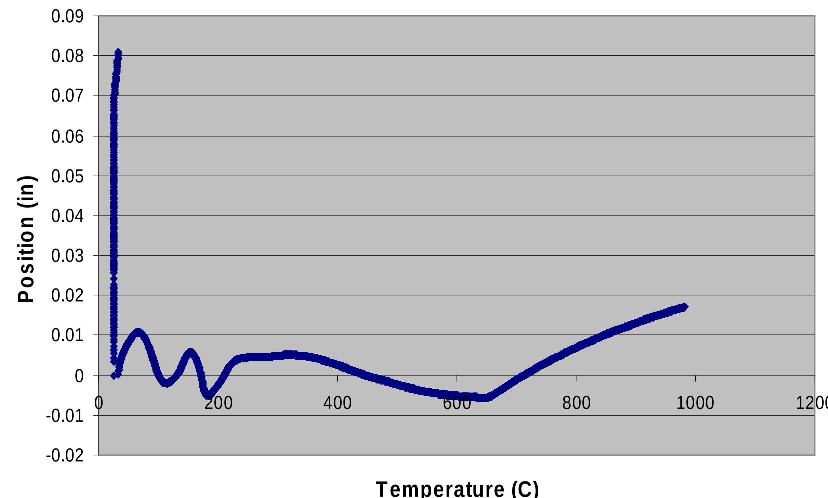
High density (1.32 gm/cc)





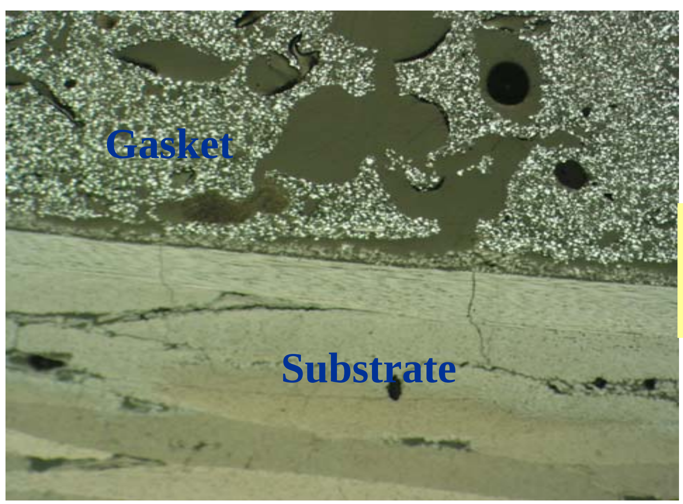
GRC 13 Gasket Material at 60 psi and 982°C (5 min. hold)



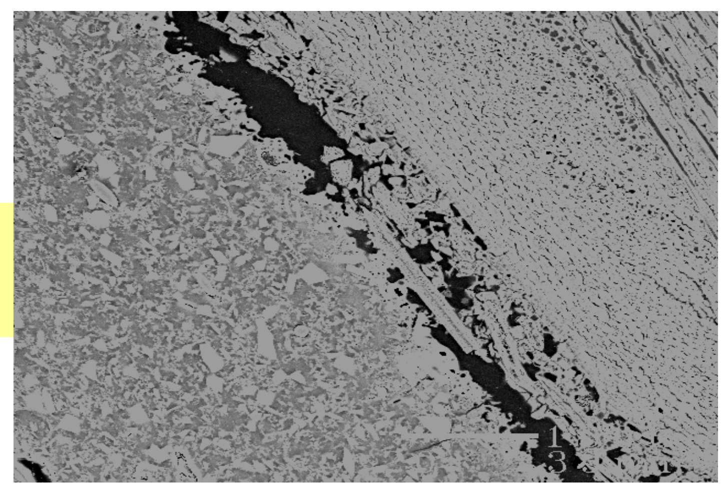


Low density (1.06 gm/cc)

High density (1.18 gm/cc)



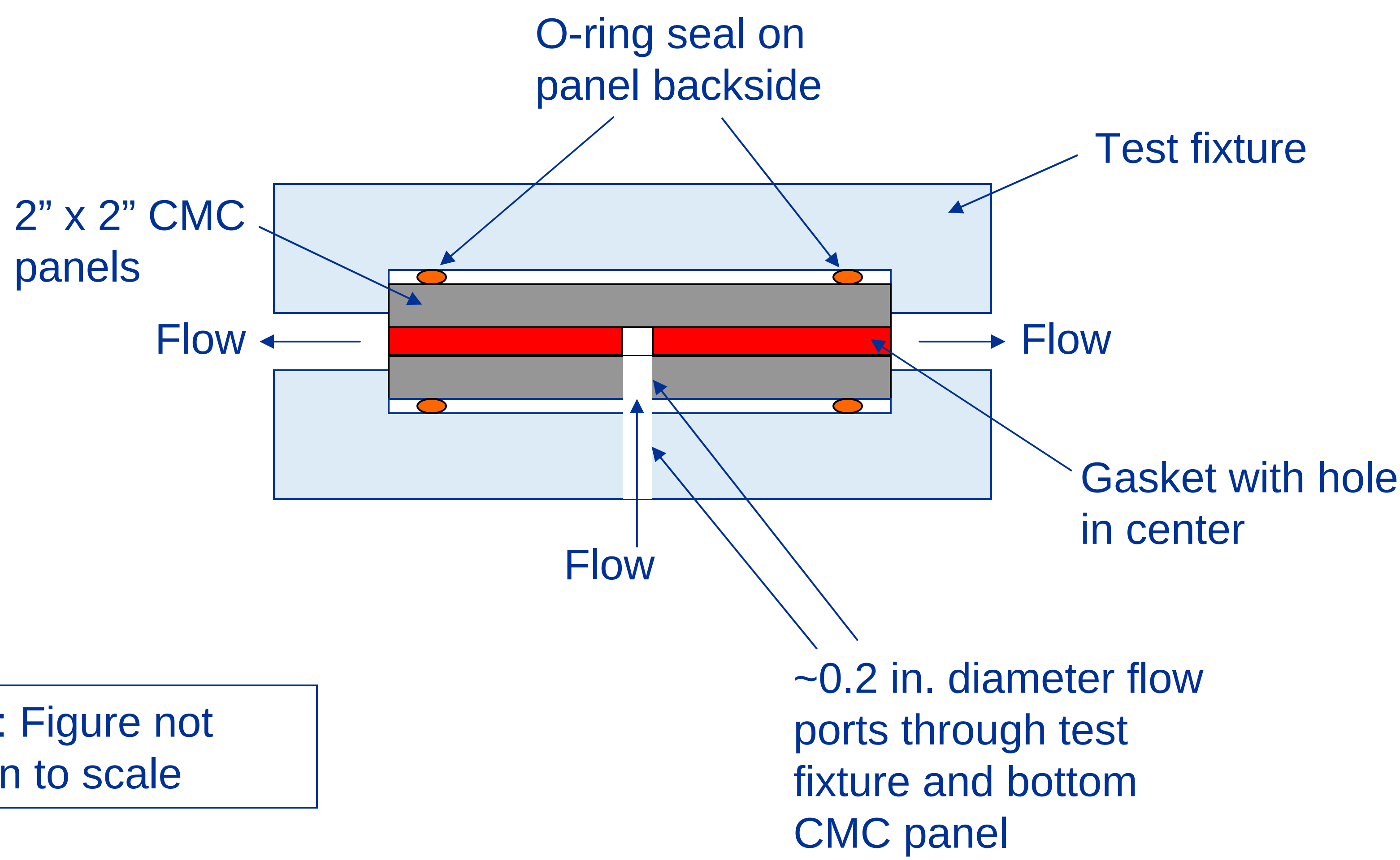
Microstructural Details of Gaskets



Summary and Conclusions

- A wide variety of flexible gasket compositions were developed and tested at high temperatures. The gasket material system has high temperature capability.
- GRABER sealants were very effective in sealing machined ACC-4 composite surfaces.
- The gasket composition do not bond strongly with the ACC-4 substrate materials.
- The density of gasket materials can be tailored to show appropriate compressibility.

Schematic for Potential Test Setup of GRC Gasket Materials



Note: Figure not drawn to scale

Pat Dunlap, NASA GRC

Acknowledgements

- Ron Phillips, ASRC Aerospace for Mechanical Testing
- Dr. Bruce Steinetz and Pat Dunlap, Seals Team
- Shuttle RTF Team Members from LaRC, ARC, and Boeing LCAT and Shuttle Program for support

HIGH TEMPERATURE METALLIC SEAL/ENERGIZER DEVELOPMENT FOR AEROPROPULSION AND GAS TURBINE APPLICATIONS

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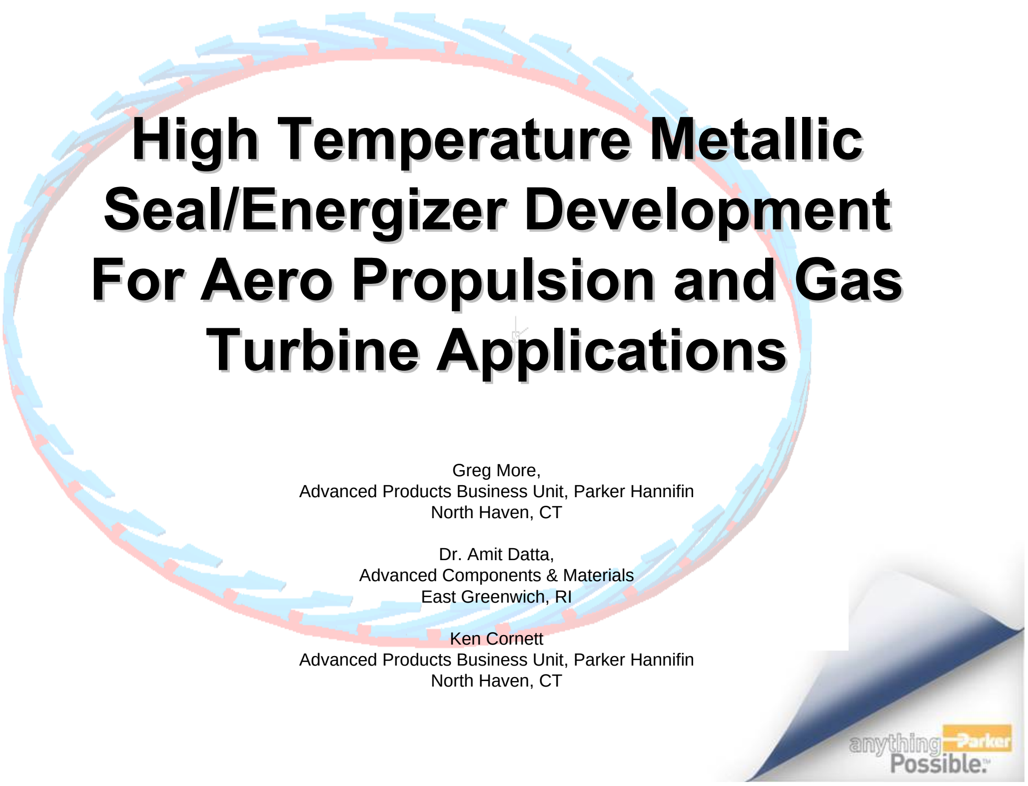
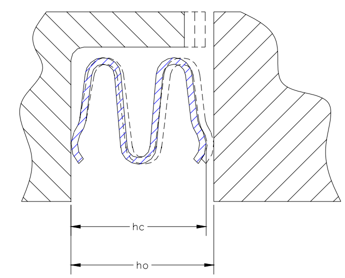
Advanced Components & Materials
East Greenwich, Rhode Island

Ken Cornett
Parker Hannifin
North Haven, Connecticut



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 static 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

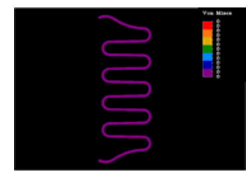


Seal gap is created resulting from stress relaxation at elevated temperatures. The original seal height ho is reduced to hc creating a gap when the flange moves away from the compressed condition.

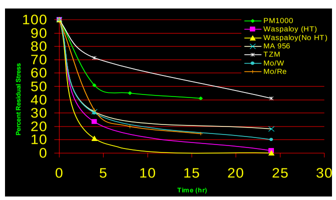
Program Review

High temperature seal development program review

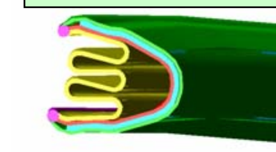
Phase I : Improved traditional sheet metal seal design and analysis

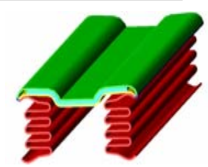


Phase II : Higher temperature sheet metal materials and improved thermal processing

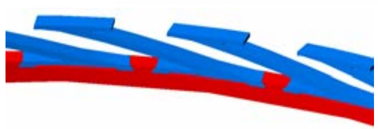


Phase III :Thermally insulated seals

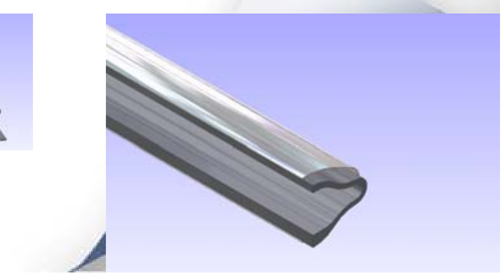




Phase IV : High temperature single crystal material spring element

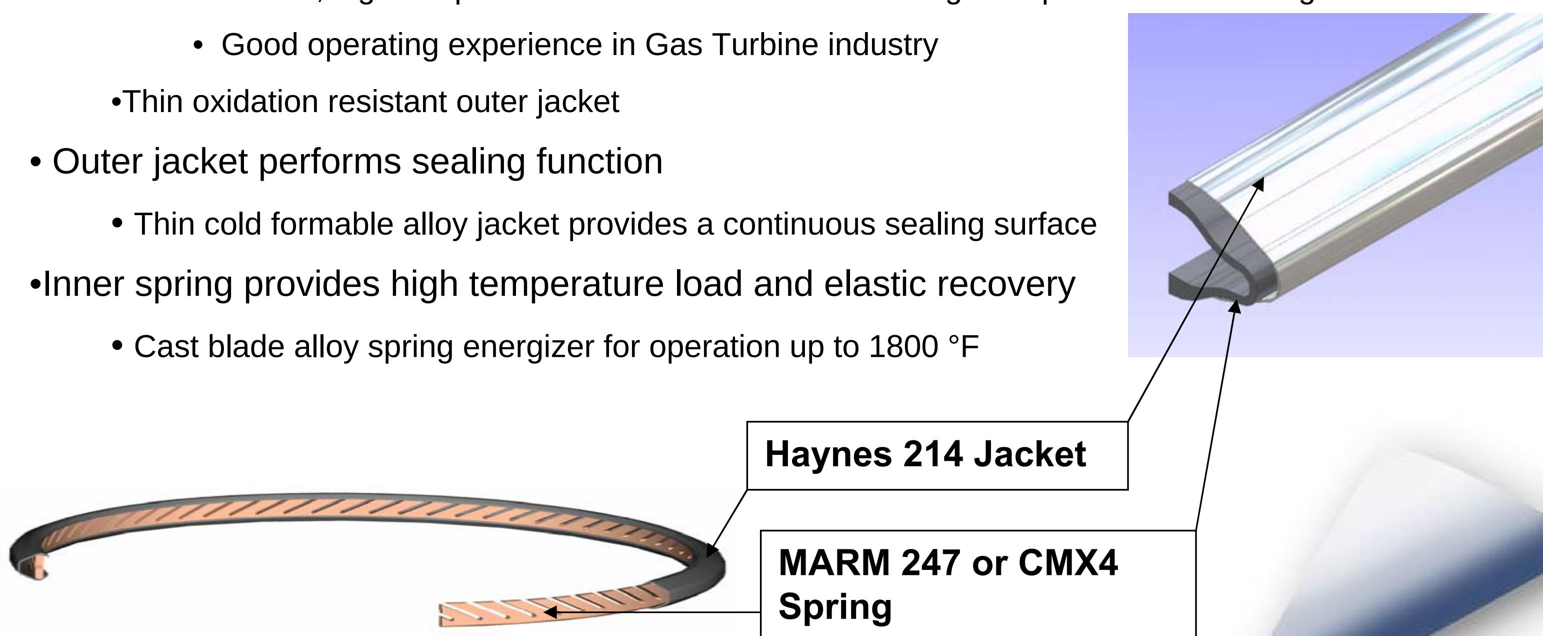


Phase V : High temperature single crystal material DFM and design optimization



Innovative Seal with Blade Alloy Spring

- In order to achieve next temperature range a different, non-traditional sealing, methodology is utilized
  - Separate seal loading and pressure barrier functions
  - A well known, high temperature cast material is used as high temperature seal energizer
    - Good operating experience in Gas Turbine industry
  - Thin oxidation resistant outer jacket
- 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



Innovative Seal with Blade Alloy Spring

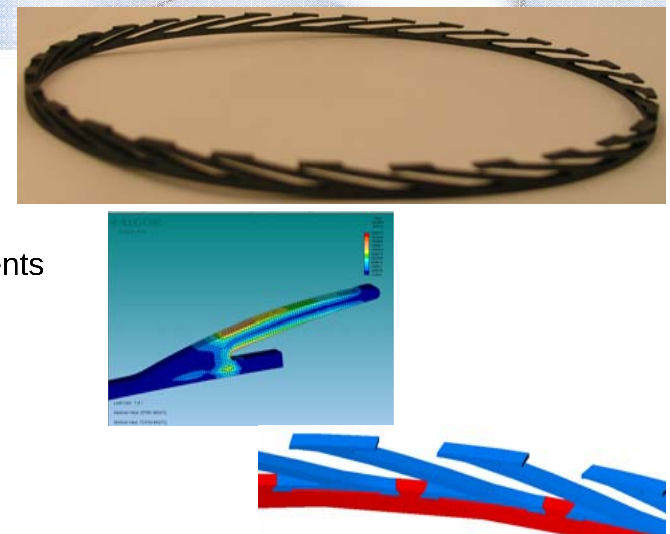
Cast Blade alloys have extremely high strength

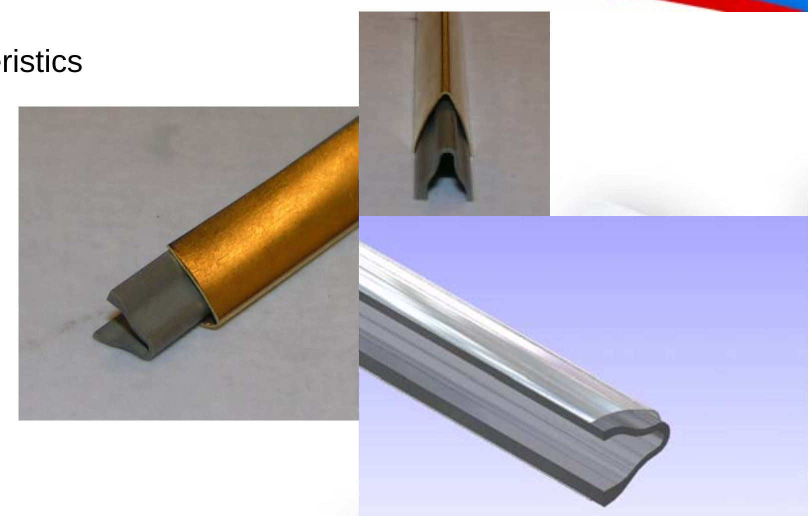
Alloy	Temperature,° F	Yield Strength,ksi	Elongation,%
MARM 247, poly crystal	1400	130	12
CMX4, Single crystal	1600	114	18
INCO 718,poly crystal	1472	100	10
Waspaloy,poly crystal	1600	75	35

- 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 Evolution

- 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
- Prototype III
  - Build from successes of PI and PII
  - Thorough FEA optimization
  - DOE optimized DFM program
    - Standard length U-Spring
    - U-Spring lengths to be joined into a hoop



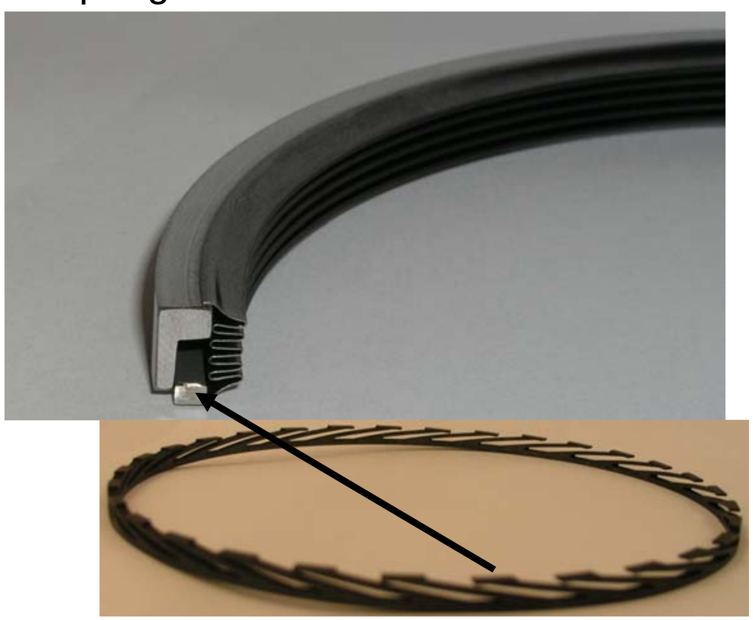


Comparative Relaxation and Leakage Testing

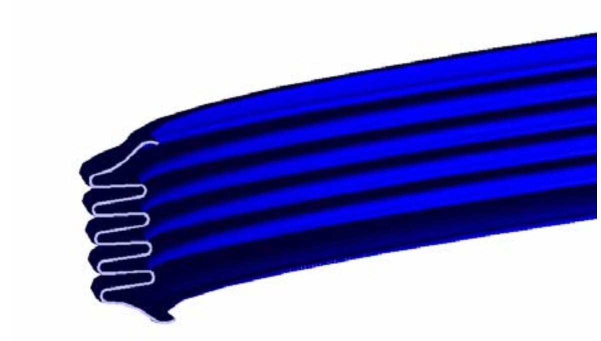
Cross Sectional comparison of high temperature sealing designs

High temperature modular seal

- Standard E-Seal with blade alloy spring



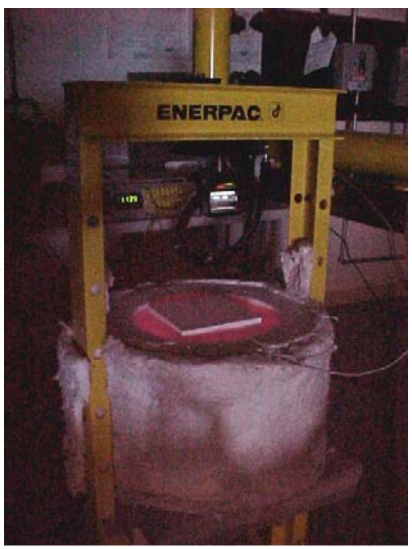
Traditional E-Seal produced from high temperature Waspaloy alloy



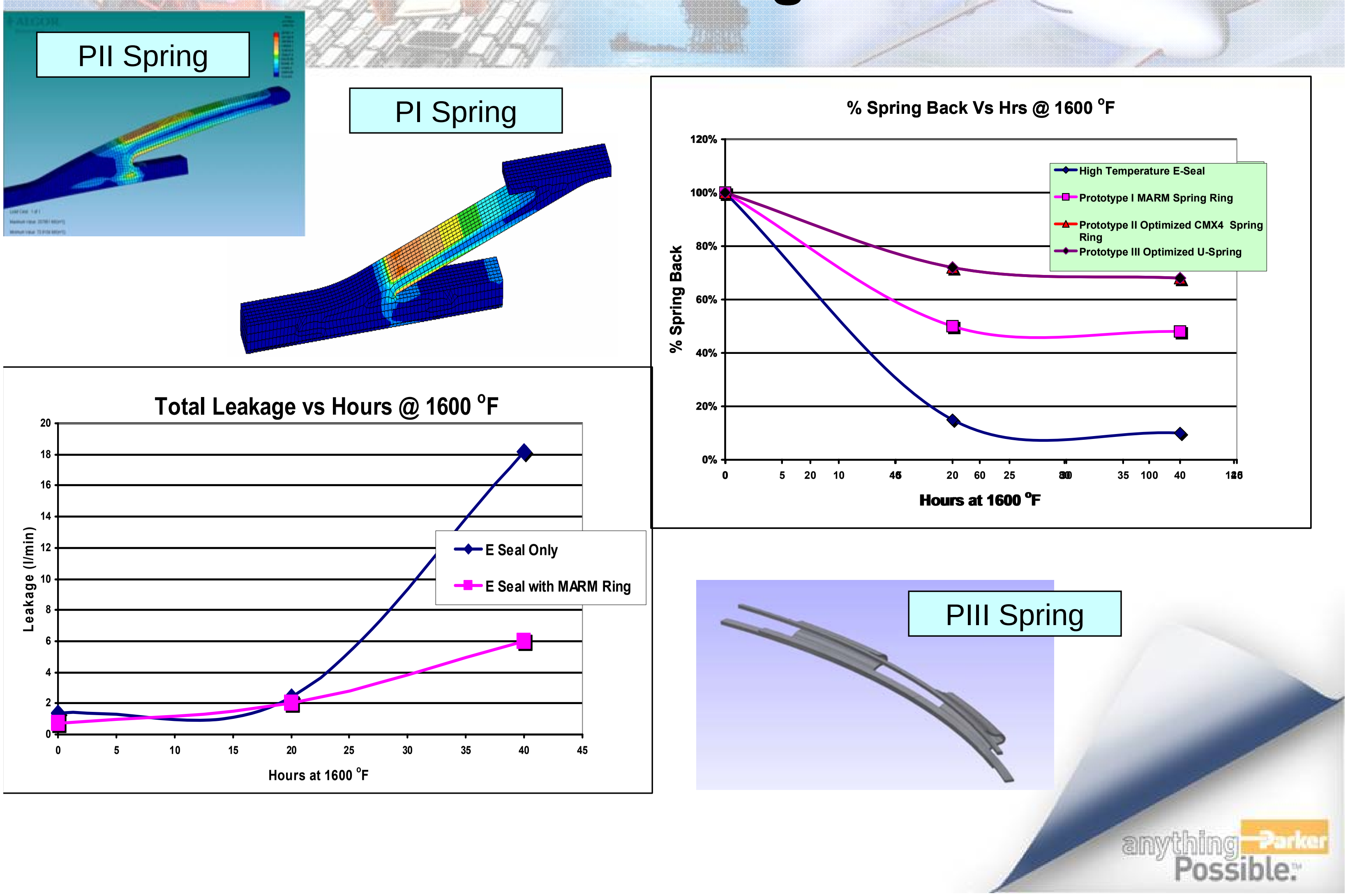
Stress Relaxation And Leakage Rate Testing

Performance testing experimental procedure:

- Stress relaxation
  1. Seals were compressed 15% between flanges and heated to 1600 °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 V : Testing Results



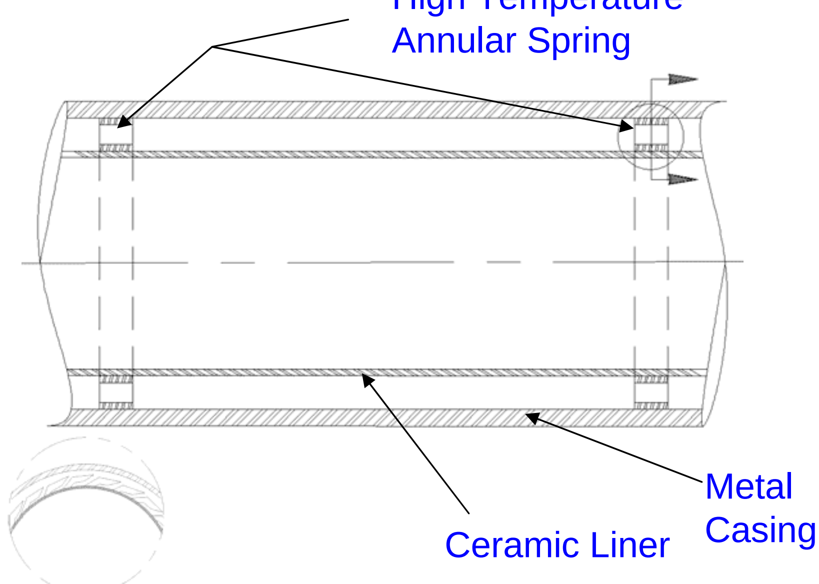
Spring Seal Manufacturing

- Optimization for manufacturability has been the primary program goal for 2006
  - Convert the fundamental concept into a commercially viable design with similar performance characteristics to Prototype II
- Through FEA analysis and design DOE an improved design configuration was developed
- Modular manufacturing approach
- Standard U-Spring configuration has been developed, produced, and tested
- U-Spring nests nicely within thin sheet metal jacket
  - Jacket serves as primary pressure barrier
  - Standard formed sheet metal jacket
- Standard U-Spring configuration allows for cost effective linear seals and hoop seals
  - By joining multiple U-Springs, any diameter seal can be cost effectively produced
  - Cast as a single crystal material
  - Design will use as cast near net shape to keep manufacturing costs low
- Patent pending manufacturing and processing approach

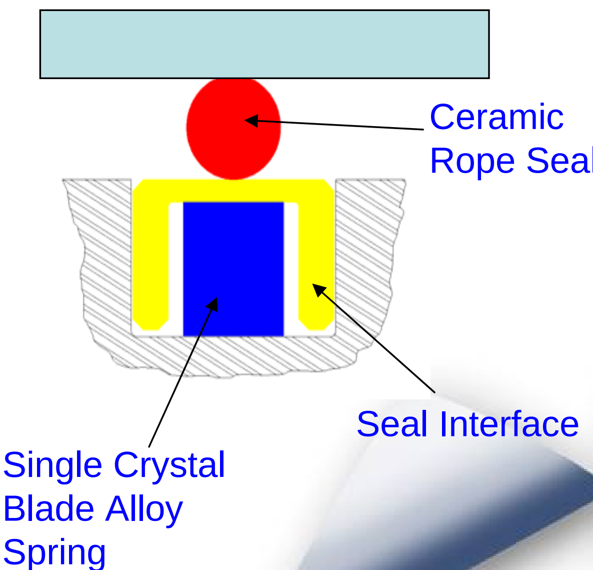
Other Applications for High Temperature Spring Design

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

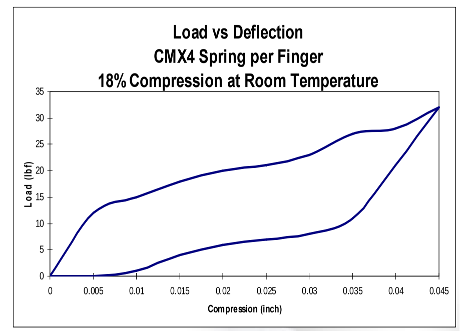


Conclusions

- The Ultra High Temperature seal program has successfully progressed and developed a high temperature static seal solution

- The third prototype has successfully combined the first and second prototypes high performance capabilities in a commercially viable solution

- Prototype II and Prototype III are viable solutions
  - Prototype II offers flexible load tune ability and seating load adjustment
  - Prototype III offers commercial viability for continuous hoop seals



- Moving forward
  - Better understanding of 100 hr data
  - Invest in production tooling
  - Develop final manufacturing process
  - Develop a production product technical performance data sheet

- 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
  - Better characterization of longer test periods
  - Other designs for operation at higher continuous operating temperatures are currently under development

anything Parker Possible.™

Questions ?

SURVEY OF DUST ISSUES FOR LUNAR SEALS AND THE RESOLVE PROJECT

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National Aeronautics and Space Administration

Survey of Dust Issues for Lunar Seals and the RESOLVE Project

By
Margaret P. Proctor and Paula J. Dempsey

Seals Team of the Mechanical Components Branch
Structures and Materials Division
NASA Glenn Research Center
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November 14-15, 2006

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Challenges of Future Lunar Exploration

"Dust represents the single largest technical challenge to prolonged human presence on the Moon."

Harrison Schmidtt, Apollo 17 Astronaut March 2005

- The extent and duration of planned lunar surface activities is much higher than prior Apollo experiences.
- Systems and components will be exposed to environmental factors for periods of time orders of magnitude longer than those previously addressed.

Dust mitigation strategies:

1. Design systems tolerant of dust properties
2. Develop techniques to clean or remove dust from surfaces
3. Active abatement methods to minimize or eliminate deposition and/or adhesion of dust

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Apollo Lunar Sample Return Containers a.k.a. "Rock Boxes"

- Used to return lunar regolith samples to earth
- Triple seals designed to provide a vacuum seal of 10^{-6} torr
- Aluminum box (7075 AA) with Knife edge seal in soft indium alloy (90% indium, 10% silver), 150 cm long

•Teflon spacer prevents contact prior to use.

•Single use and pressure required to maintain sealing.

•Double O-rings (L608-6 fluorosilicone) for add'l sealing.

Of the 12 Rock Boxes, 4 had substantial leaks due to bag material or dust on sealing surface[1]

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The Apollo Lunar Sample Return Container (ALSRC) maintained a lunar-like vacuum around the samples until they were opened in the Lunar Receiving Laboratory. In practice, substantial leakage was detected in 4 of the **12** ALSRC's returned from the moon due to pieces of equipment or dust interfering with the seals.

[1] Stansbery, E.K., Kaplan, D.I., Allton, J.H. and Allen, C.C.(1997) Planetary Protection Issues for a Mars Sample Return Mission. Report to the NASA Planetary Protection Officer. October 1997

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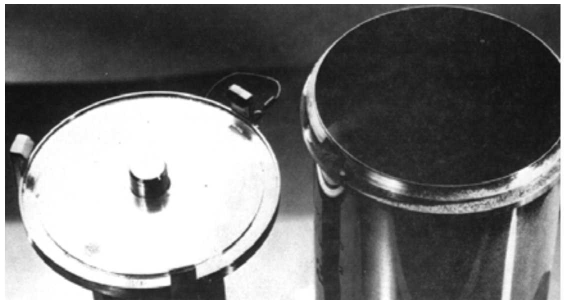
Apollo
Special Environmental Sample Containers



- 340L S.S. with knife edge seal into indium alloy
- 18 cm long
- At end of Apollo missions, no reports of leakage

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Apollo Space Suits

Space Suits

- Designed to operating pressure, temperature and maximum leak rate:

operating pressure:	3.75psig	(25.8 KPa),
temperature:	$\pm$ 250 ^{o}F	($\pm$ 394 ^{o}K),
maximum leak rate:	0.0315 lb/hr	(180 scc/min)

- Leakage increased with use.

Apollo Helmet Attaching Neck Ring

- Manufactured by Air-lock Inc.
- Aluminum alloy 7070-T6 treated with an anodized coating.
- Helmet disconnects have interior stainless steel bearings
- Seals in the Extravehicular Mobility Suits (EMS) were used to attach the space helmets to the spacesuit by a pressure-sealing neck ring.
- Between Extra-Vehicular Activities (EVAs) the helmet disconnect seals were cleaned and re-lubricated with Krytox oil and grease to reduce leakage.

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1. Carson, M.A., Rouen, M.N., Lutz, C.C. and McBarron, J.W.(1975) Biomedical Results of Apollo. Chapter 6 Extravehicular Mobility Unit. NASA SP-368
2. Young, L.A. and Young, A.J. The Preservation, Storage, and Display of Spacesuits. Smithsonian National Air and Space Museum Collection Care, Reprot Number 5, December 2001.
3. Apollo Operations Handbook (1971) Extravehicular Mobility Unit. Volume I. System Description. CSD-A-789-(1). Revision V, March 1971.
4. Gaier, J.R. (2005) The Effects Of Lunar Dust On Eva Systems During The Apollo Missions. NASA TM 2005-213610, March 2005.

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Apollo Helmet Attaching Neck Ring

- Attached to suit by a self-latching self-sealing quick disconnect coupling

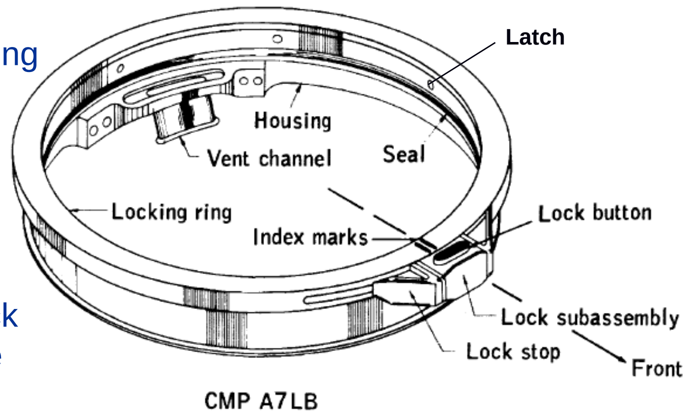
It has….

•Neck ring housing

•8 latch assemblies

•A rotating lock ring

•Push button lock assembly on the locking ring.



Command Module Pilot (CMP) Helmet

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Apollo Space Suits

Glove Disconnect Assembly

- Manufactured by Air-lock Inc.
- Aluminum alloy 2024-T4.
- Have interior stainless steel bearings.
- Pressure-sealing disconnects attached gloves to spacesuit
- arms
- Wrist bearings and rotational hardware connectors had fabric coverings to keep out the dust.
- Between EVAs glove disconnect seals were cleaned and re-lubricated with Krytox oil and grease to reduce leakage.
- Air-lock has a patent (4596054) on the synthetic resin lip seal used in the bearing assembly of the space suit at the rotary motion locations, such as at the glove connection.
- The suit side has a manually actuated lock/unlock mechanism.
- The glove has a sealed bearing that permits 360^{o} glove rotation.

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1. Young, L.A. and Young, A.J. The Preservation, Storage, and Display of Spacesuits. Smithsonian National Air and Space Museum Collection Care, Reprot Number 5, December 2001.
2. Apollo Operations Handbook (1971) Extravehicular Mobility Unit. Volume I. System Description. CSD-A-789-(1). Revision V, March 1971.
3. Gaier, J.R. (2005) The Effects Of Lunar Dust On Eva Systems During The Apollo Missions. NASA TM 2005-213610, March 2005.

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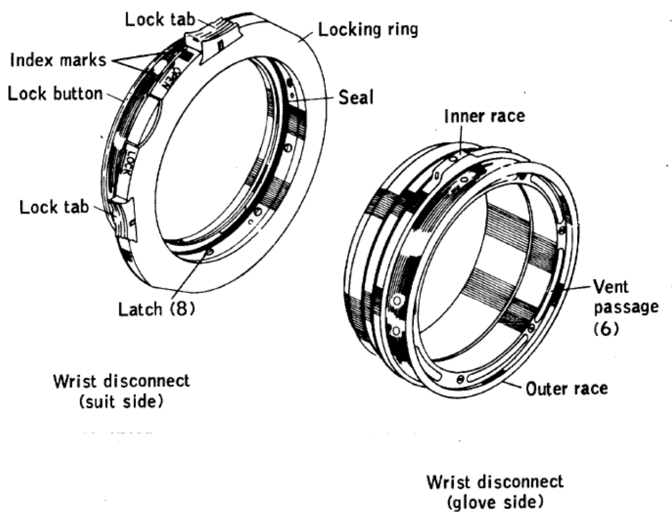
Apollo Space Suits-Glove Disconnect Assembly



Reference: Apollo Operations Handbook (1971) Extravehicular Mobility Unit. Volume I. CSD-A-789-(1)

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Lunar Soil Characteristics

Characteristic	Description
Size	90% < 1000 µm, 70% < 100 µm
Shape	Angular/subangular sharp
Bulk Density (0-30 cm)	1.58 ± g/cm^3
Hardness	5-7 (Mohs scale)
Porosity (0-15 cm)	52% ± 2%
Cohesion (0-15 cm)	0.52 KPa (.0053 kg/cm^2; .0754 psi)
Toxicity	Primarily non-toxic
Corrosiveness	Not active in vacuum
Electrostatic	Highly charged
Magnetic	<20 µm high ferromagnetic susceptibility
Thermal Conductivity	1.72-2.95 x 10^{-4} W/cm ^{o}K (Apollo 17)
Compressibility (loose)	0.3 (compression index)

Reference: Fuhs, S., Harris, J.(1992) Dust Protection for Environmental Control and Life Support Systems in the Lunar Environment. Proceedings of the Lunar Materials Technology Symposium.

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Size 1000 µm=1 mm=.04”

Bulk density - property of particulate materials. mass particles divided by the volume they occupy. The volume includes the space between particles as well as the space inside the pores of individual particles.

Hardness - resistance to permanent deformation (Diamond=10, Quartz=7, Gypsum=2)

Porosity of a porous medium (such as rock or sediment) describes how densely the material is packed. It is the proportion of the non-solid volume to the total volume of material. 15 cm depth measurement?

Cohesion-particles stick together

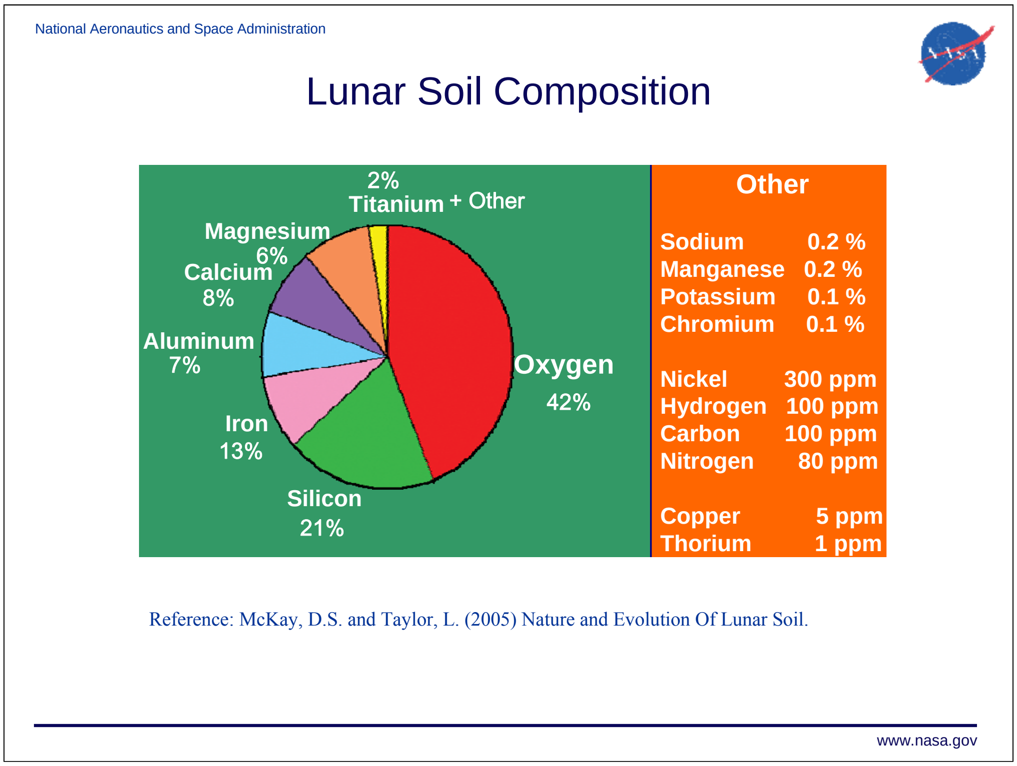
Electrostatic- forces exerted by a static (i.e. unchanging) electric field upon charged objects

Magnetic- Susceptibility of Soil Particles Increases as Grain Size Decreases; Effects of Vapor-Deposited Nanophase Feo are a Direct Function of Surface Area and Most Pronounced in the Finest Grain Sizes; Virtually All <10 µm Particles are Easily Attracted by a Simple Hand-held Magnet

Thermal Conductivity- ability to conduct heat. Apollo 17 heat flow probes 2.36 m

Copper is 385 W/m-K, 3.85 W/cm-K

Compressibility is a geological term used to quantify the ability of a soil to reduce in volume with applied pressure



Composition from Apollo mission samples at specific sites

Other

Titanium 2%????

Sodium	0.2 %
Manganese	0.2 %
Potassium	0.1 %
Chromium	0.1 %
Nickel	300 ppm
Hydrogen	100 ppm
Carbon	100 ppm
Nitrogen	80 ppm
Copper	5 ppm
Thorium	1 ppm

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Lunar Environment

Equatorial radius	1738.1 km
Surface area	37.8 x 10^6 km^2
Mass	7.35 x $10E^{22}$ kg
Density	3.34 g/cm^3
Surface gravity	1.63 m/sec^2
Orbital Period around earth	27.32 Earth days
Atmospheric Pressure	3 x 10^{-13} KPa (2 x 10^{-12} torr)
Measured Surface Temps. (Apollo)	Min -181 C (92 K) Max 111 C (384 K)
Atmosphere (%)	Helium (25);Neon (25);Hydrogen(23);Argon(20); Trace: Methane; Ammonia; Carbon Dioxide
Lunar Radiation Sources	Galactic cosmic rays (GCR) Solar particle events (SPE) wind, cosmic rays

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Summary of radiation found on page 48 of:

Heiken, G.H., Vaniman, D.T. And French, B.M., “LUNAR SOURCEBOOK, A User’s Guide to the Moon,” Cambridge University Press 1991.

Estimated lunar surface temperature of 40K from Lunar Study Group in 1972 based on Earth-based observations and need to be updated with actual measurements on the Lunar surface.

Dalton, C. and Hoffman, E. (1972) "Conceptual Design of a Lunar Colony" NASA Grant Rpt. NGT 44-005-114, NASA, Washington, D.C.

Shakleton Crater

Due to this almost constant illumination, the crater rim is considered a preferable location for a future lunar outpost.[9] The light could be converted into electricity using solar panels. The temperature at the location is also more favorable than on most of the surface, and does not experience the extremes along the lunar equator where it rises to 100 °C when the Sun is overhead, to as low as −150 °C during the lunar night. The continuous shadows in the south polar craters cause the floors of these formations to maintain a temperature that never exceeds about −173 °C, or 100 **K**.

http://www.answers.com/topic/shackleton

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The RESOLVE project

- **Purpose:**
  - find water or ice in lunar soil
  - demonstrate the ability to produce water and hence oxygen and hydrogen for life support and propellants from lunar regolith.
- **How will this be done?**
  - Core samples of lunar regolith heated in a Volatiles Characterization Oven to 150 ºC to look for water vapor or other volatiles.
  - Hydrogen reduction process reacts hydrogen to the oxides in the lunar regolith to form water, which can then be split into H_2 & O_2 using electrolysis. Process requires heating to ~900 ºC.

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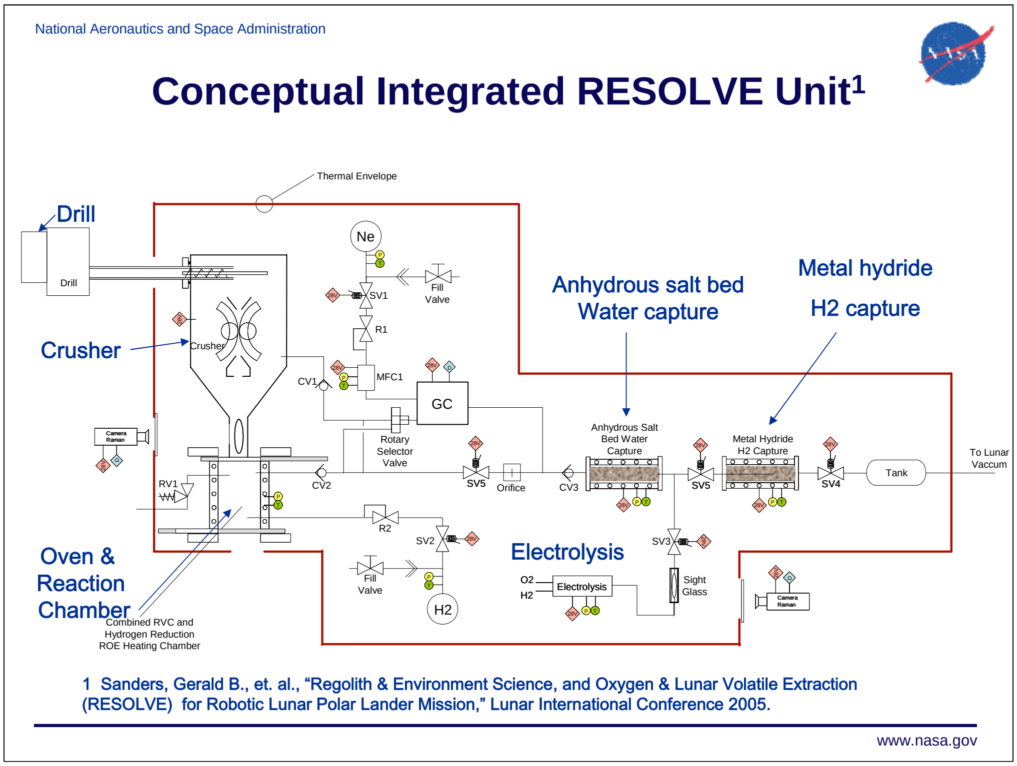

[1] Sanders, Gerald B., et. al., "Regolith & Environment Science, and Oxygen & Lunar Volatile Extraction (RESOLVE) for Robotic Lunar Polar Lander Mission**,"** Lunar Interanational Conference 2005.

Lunar regolith is loaded into the crusher, goes to heating chamber for volatiles characterization, and hydrogen reduction process. Off-gases from the oven pass through anhydrous salt bed for water capture. Water then goes through electrolysis to produce oxygen and hydrogen. For hydrogen reduction process, hydrogen is supplied to the reaction chamber (oven). Again the off-gases pass through the anhydrous salt bed for water capture. Remaining gases pass through a metal hydride bed for hydrogen capture.

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Seal Requirements for Volatiles Characterization Oven (VCO)

- Capable of -233 to 150 ºC
- Effective for 0-75 psi differentials (may be revised to 150 psid)
- Low or no out-gassing in a vacuum (lunar 10^{-14} atm or 7.6×10^{-12} torr)
- Leakage rate less than 0.5 cm^3/min during 20 minutes processing time at 5 atm differential assuming H_2
- Compatible with hydrogen, oxygen, water, water vapor, other volatiles
- Tolerant of vibrations up to 10g at 80-100 Hz
- Reusable up to 40 open/close cycles
  - Resistant to lunar radiation environment
  - Resistant to damage from lunar dust
  - Material repels lunar dust or has means to remove dust from seal*
  - Material flows around lunar dust trapped at seal interface*
- Light weight → Small load to achieve a seal
- Inexpensive
- High reliability → Low number of components
- Geometrically compatible with interface requirements

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Challenges of Sealing Hydrogen Reduction Reaction Chamber

- Same requirements as the volatiles characterization oven except:
  - 900 ºC
  - 3 batches processed at 900 ºC
- Initial bench testing allows the volatiles characterization oven to be separate from the hydrogen reduction chamber.
- Want the same chamber for both processes to reduce weight .

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Some Options for Sealing VCO

- O-Rings
  - Metal
  - Viton A -
  - Teflon – cold flows around single layer of dust particle
- Tungsten Carbide Knife edge on Tungsten Carbide
  - Knife is very hard and very sharp for cutting any particles between it and the hard flat sealing surface
- Knife edge into Indium or other soft metal that could be re-melted after each use to restore the “gasket” material.

Key: Protect sealing surface from dust !

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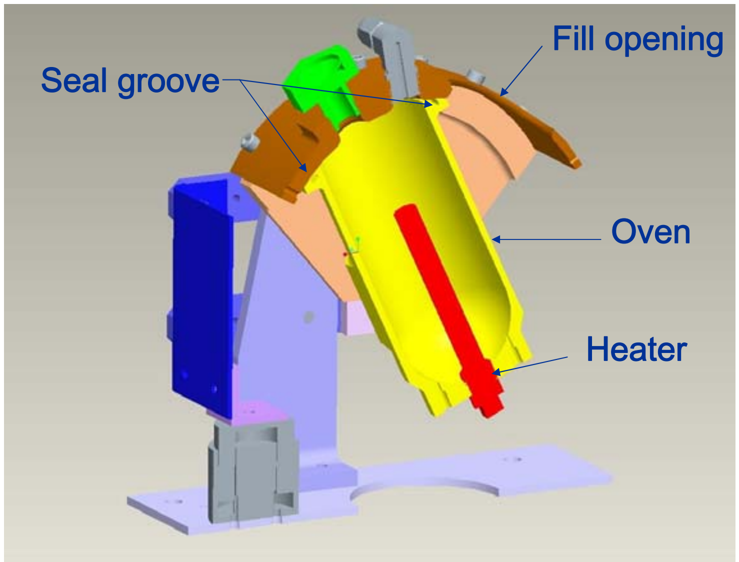
A Volatiles Characterization Oven Concept



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This is a cross sectioned view of a concept design being considered for the Volatiles Characterization Oven. The yellow oven rotates relative to the brown lid to the fill opening for loading regolith into the oven. Heating of the regolith occurs in the position shown in this chart. To dump the regolith the yellow oven and brown lid rotate ~180 degrees to the right and the yellow container rotates to align with the fill opening. Some type of o-ring would ride in the seal groove. The o-ring would be subject to sliding motion. The lid would shield the o-ring during the fill operation. However, it may still be necessary to provide a means to provide a wiper to clear any dust that may fall onto the o-ring as it slides past the fill opening.

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Summary

- Lunar dust poses a challenge to long term missions on the moon.
- Assessment of material capabilities in the lunar environment is needed.
- Protecting and/or cleaning sealing surfaces of lunar dust must be addressed for re-usable seals.
- The RESOLVE project poses a challenging seal problem.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The 2006 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 NASA's new fundamental aeronautics technology 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. Turbine engine studies have shown that reducing seal leakages as well as 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 seal technologies employed by the Apollo command module that serve as an excellent basis for seals for NASA's new Crew Exploration Vehicle (CEV).

15. SUBJECT TERMS
Seals; Turbine; Clearance control; Materials; Analyses; Experimental; Design; Docking mechanism; Space vehicles; Leakage; Hypersonic

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