

TEST RIG FOR EVALUATING ACTIVE TURBINE BLADE TIP  
CLEARANCE CONTROL CONCEPTS

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**Test Rig For Evaluating Active  
Turbine Blade Tip Clearance Control Concepts**

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## Overview

- **Objectives**
  - ACC System Concept
  - ACC Concept Evaluation Test Rig
- **ACC Concept System/Test Rig Design Overview**
  - Rig Specifications
  - Design Criteria
- **Test Rig and Support Systems**
  - Design of Main Components
  - Control Logic
  - Fabrication Status
- **Conclusions/Discussion**

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## Objectives

- **Design a mechanical ACC system for HPT tip seal clearance management**
  - Improve upon slow thermal response of “case cooling” methods used today.
  - Provide continuous ACC throughout entire flight profile.
- **Design a test rig to evaluate ACC system concepts.**
  - Evaluate actuator concept response and accuracy under appropriate thermal and pressure conditions in a non-rotating environment.
  - Evaluate clearance sensor response and accuracy in a non-rotating “hot” environment.
  - Measure secondary seal leakage due to segmented shroud design, shroud actuation, and case penetration.
- **Test Rig Capabilities:**
  - Chamber temperatures up to 1500 °F.
  - Seal carrier backside pressure up to 120 psi (simulate cooling air  $\Delta p$ ).
  - Sized for actual seal hardware (20” diameter turbine).
  - Simulate realistic tip seal clearance changes due to mechanical and thermal loading (electronically).
  - Positioning feedback sensing, rig construction, and actuation system designed to achieve positioning accuracy  $\leq 0.004$ -in.

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## Multiple Independent Actuator ACC System Design

- Provides best potential for high positional accuracy requirements (< 0.005-in).
- Fuel-draulic actuators utilize engine high pressure fuel to power system (> 3000-psi).
- Number of actuators/shroud segments is scalable to engine size (force and accuracy requirements).
- Overcomes thermal binding and positional accuracy issues identified with other mechanically linked concepts (e.g., unison ring).
- Independent actuators can provide both axisymmetric and asymmetric clearance adjustments depending on load condition (e.g., backbone bending, flight loads, non-uniform thermal loads).

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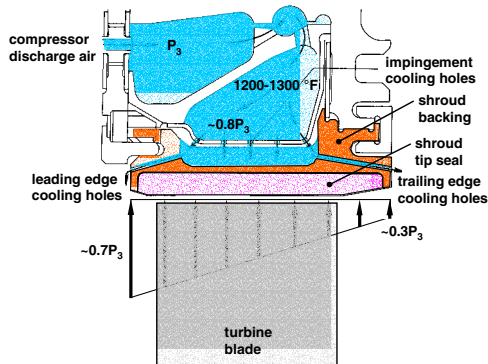


We have focused our efforts on designing mechanical ACC systems that articulate the seal shroud via mechanical linkages connected to actuators that reside outside the extreme environment of the HPT. We opted for this style of design due to a lack of high temperature/low profile actuators that are presently available.

We have also selected multiple hydraulic actuators for this first generation ACC system. Fuel-draulic actuators are already a well established technology.

## Test Rig/ ACC System Specifications

- **Temperature**
    - The backside of the HPT shroud (blade outer-air-seal) is generally cooled with compressor discharge air (P<sub>3</sub> air: **1200 to 1300-°F**)
  - **Pressure**
    - The cooling air is also used to purge the leading and trailing edges of the shroud segments, providing a positive backflow margin from the hot rotor inlet flow.
    - P<sub>3</sub> is highest during maximum thrust events such as takeoff and re-accel. For large commercial engines this translates to a maximum cooling air pressure differential of up to **150-psid** across the shroud.
  - **Actuation Range and Rate**
    - Maximum tip clearance changes due to axisymmetric and asymmetric loads on the rotor and stator components are on the order of 0.050-in.
    - FAA requires that engines have the ability to reach 95% rated takeoff power from flight idle (or from 15% rated takeoff power) in 5.0 seconds.
- **0.01-in/s**



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The design was concentrated on simulating the temperature and pressure conditions that exist on the backsides of the seal segments, without the need for a rotating turbine. This greatly simplified the rig design. We plan to assess the response of the ACC system to the effects of a turbine wheel (i.e., rapid clearance closures due to mechanical and thermal loads) by simulating closures electronically, as will be discussed in a later.

## Design Criteria

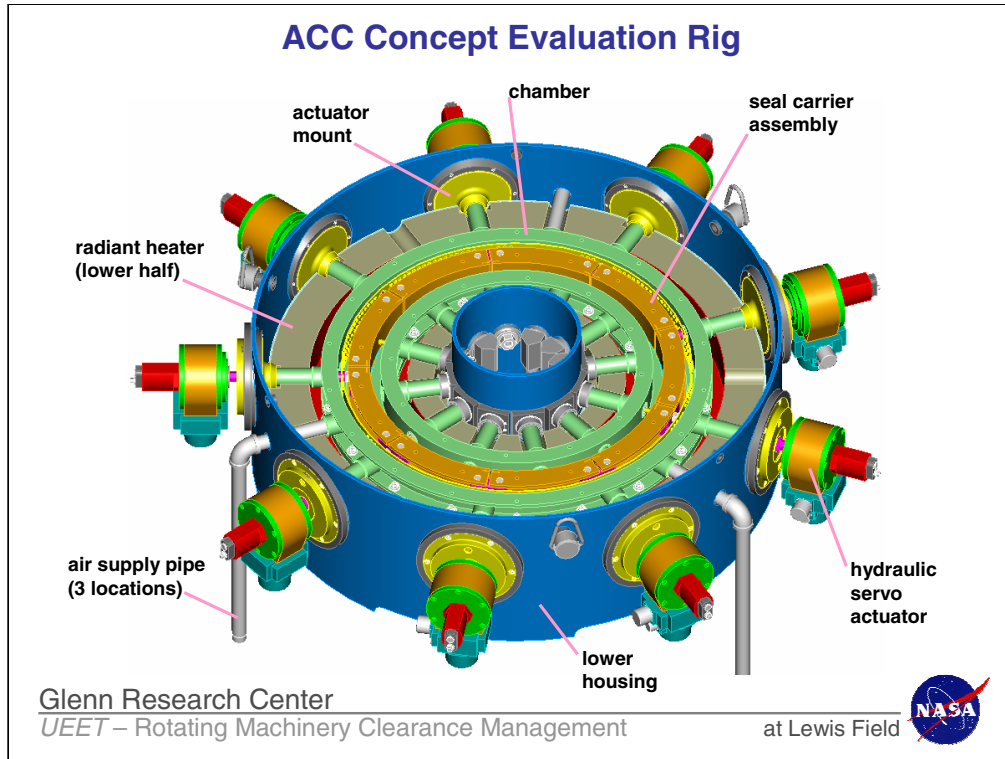
- The substantial diameter of the segmented shroud structure (~20-in), under moderate pressures (~120-psi), gives rise to significant loads, and hence stresses, to which the actuation system and components must react.
- These stresses coupled with high temperatures (1200 to 1300°F) can significantly reduce component cycle life due to creep.
- Managing these stresses with adequate materials and geometry to improve component cycle life was a driving factor in the rig component design.
- Larson-Miller parameter data for a variety of high temperature, super alloys was utilized to design components to achieve a desired minimum cycle life.
  - Inconel 718 utilized for most of the hot section components.
  - Components were designed for less than 0.5% creep strain, resulting in a 15-ksi limiting stress.
  - **15-ksi stress level corresponds to over 100,000 hours life at 1300°F and approximately 300 hours life at 1500°F.**

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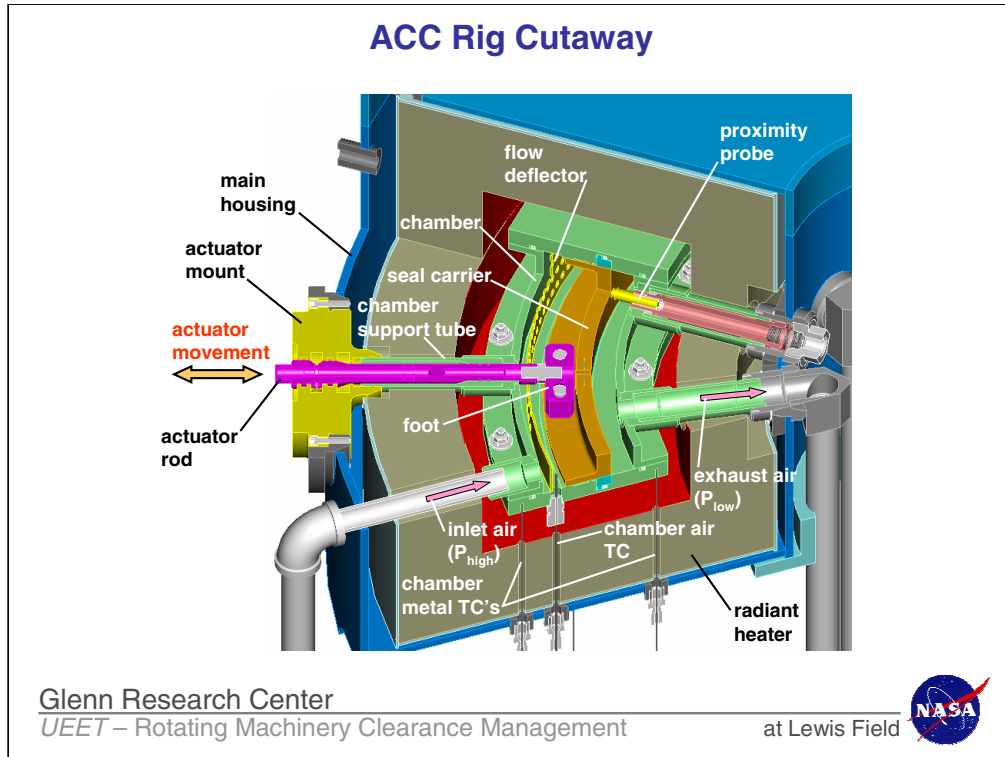


Here we see the Gen 1 ACC System Concept and Test rig.

The test rig comprises six main components: the housing, the radiant heater, the pressurized chamber, the seal carrier assembly, the actuator rod assemblies, and the hydraulic actuators.

At the heart of the rig is a segmented shroud structure (seal carrier) that would structurally support the tip seal shroud segments in the engine. Radial movement of the seal carriers controls the effective position/diameter of the seal shroud segments, thereby controlling blade tip clearance.

The rig housing consists of two concentric cylinders, which form an annular cavity. An annular radiant heater made of upper and lower halves surrounds the segmented seal carrier structure to simulate the HPT tip seal backside temperature environment. A pressurized chamber encloses the carrier segments inside the annular heater through which heated pressurized air is supplied to simulate the P3 cooling/purge air pressure on the seal backsides. Heated air enters the chamber via three pipes that are fed from a manifold at the air heater exhaust through radial inlet ports as shown.



The carrier segments are connected to independent hydraulic actuators through an actuator rod assembly. The foot of the actuator rod assembly positions the carrier segments in the radial direction, while allowing relative circumferential movement or dilation of the seal carrier segments through a pinned and slotted arrangement.

A series of radial tubes projecting outward from the chamber's inner and outer side walls serve as supports, air supply and exhaust ports, probe fixtures, and the actuator rod guides. The chamber functions to support and align the carrier segments and actuator rods, as well as to house instrumentation and to seal the pressurized air from the radiant heater which is not designed to carry any pressure loading.

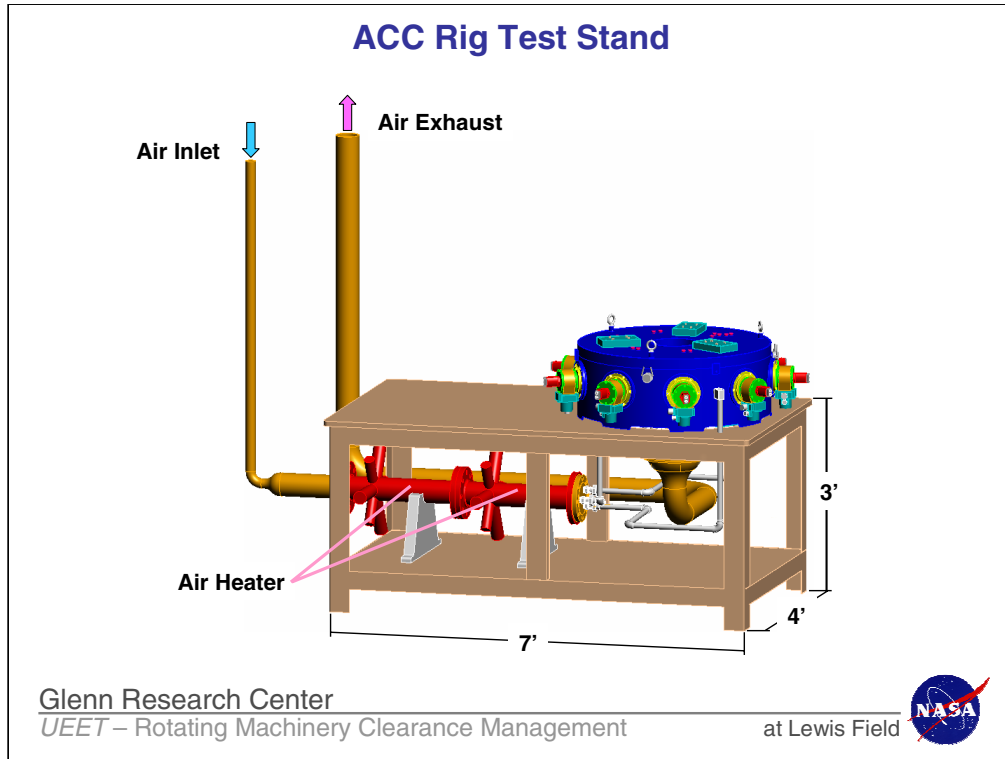
The inlet flow is baffled circumferentially around the outer chamber wall by a flow deflector to achieve uniform heating of the seal carrier assembly. The pressurized air is sealed along the sides of the seal carrier segments by contacting face seals that are energized via metal "E"-seals imbedded in the upper and lower chamber plates. The joints between adjoining carrier segments are sealed with thin metal flexures. Air that escapes over and between the carrier segments is vented out of the rig through a number of exhaust pipes that protrude radially along the inner chamber wall. The number and inner diameter of exhaust pipes were chosen to eliminate the possibility of backpressure at the exhaust ports.

High temperature proximity probes measure the radial displacement of the seal carriers at various circumferential locations. These measurements provide direct feedback control to the independent actuators and allow the desired radial position (clearance) to be set. The direct feedback control system allows for simulation of realistic transient tip clearance changes in lieu of a rotating turbine wheel. Superimposing a mission-clearance-profile over the actual clearance measurement input to the actuator controllers will allow researchers to assess the system's response to the most dramatic transient events such as mechanical and thermal loading of the rotor during takeoff and re-accel.

The proximity probes are held at a constant standoff to the chamber inner wall via a spring-loaded piston arrangement. The spring-loaded mounting keeps the proximity sensor at a relatively constant position to the chamber inner sidewall during the initial heating of the rig. This arrangement also allows for easy removal of the probes without dismantling the housing.

The chamber air temperatures will be measured at three circumferential locations on the high-pressure side of the carriers to show how well the pressurized air is mixed by the chamber baffle. The chamber flange metal temperatures will be measured via two surface thermocouples attached to the inner and outer flange on the lower cover plate.

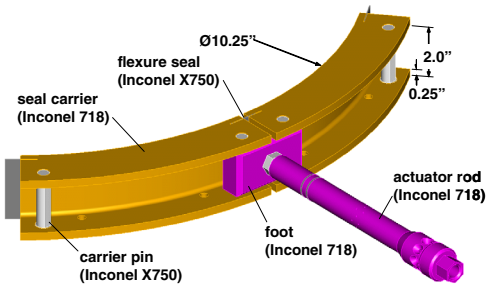




This slide shows the rig's air supply and exhaust plumbing layout as well as the test stand dimensions.

The air heater system comprises two 36-kW, inline, flanged heaters, manufactured by Osram Sylvania. It is designed to supply up to 75-scfm of air at 120-psi and 1500 °F.

## Carrier-Actuator Rod Assembly



- The slots are cut on a tangent to the radius on which the carrier pinholes are located.
- Prevents the carrier segment from cocking while it is displaced radially and circumferentially.
- The length of the slot allows a radial displacement of 0.2-in for each of the nine segments.

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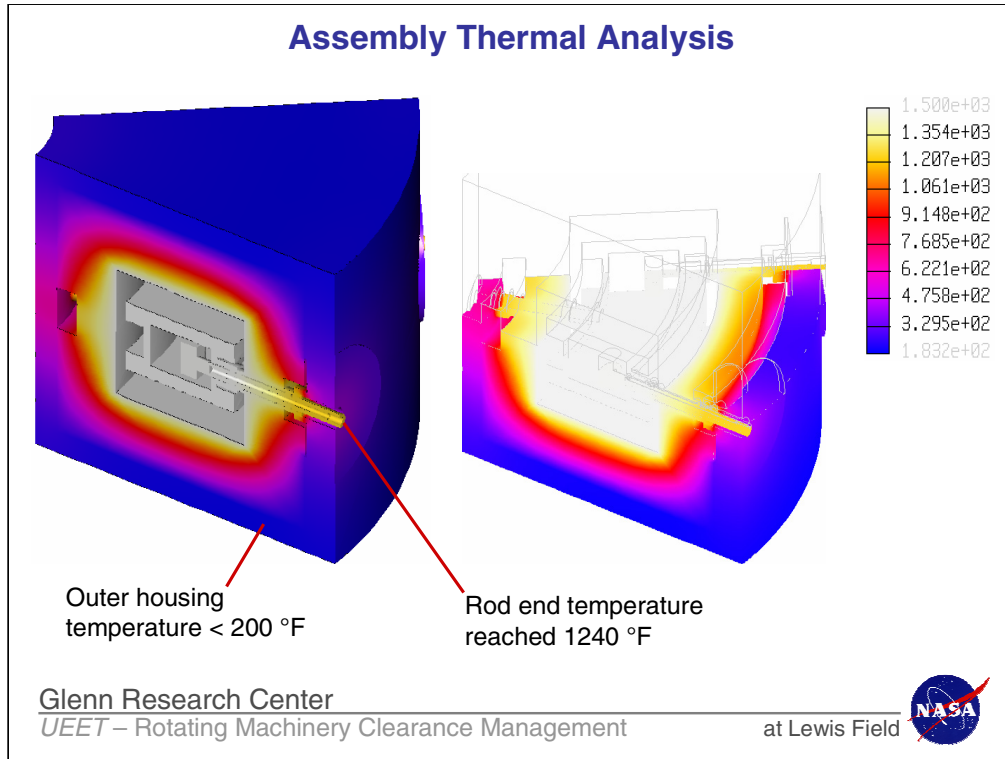
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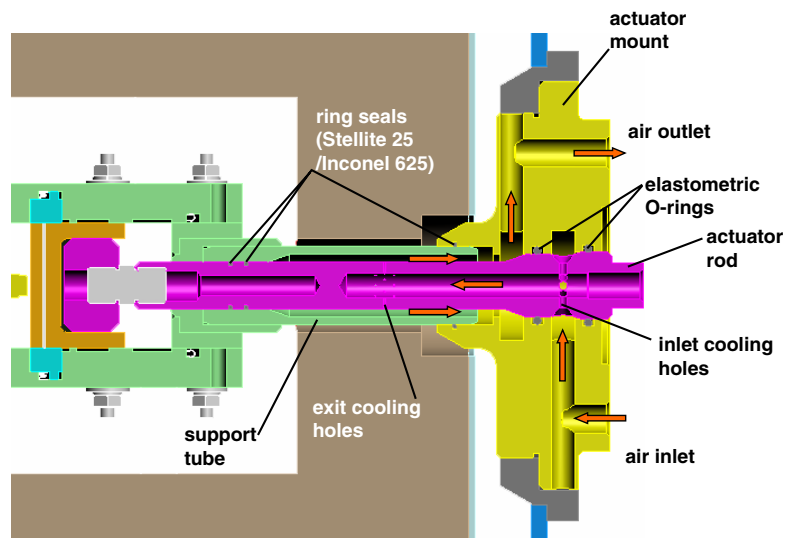
Because the carriers are constrained by a pinned connection at one end and a slotted connection at the other, the segments must shift circumferentially as they are displaced in the radial direction. The slots in the feet are cut on a tangent to the radius on which the carrier pinholes are located. This keeps the carrier segments from cocking while it is displaced in both the radial and circumferential directions. The circumferential length of the carrier segments as well as the length of the slot in the actuator rod foot allows a radial displacement of 0.2-in for each of the nine segments. The slots for the flexure seals have adequate clearance to prevent the segments from becoming arch-bound as the segments are moved radially inward.

The pins are made of Inconel X750. This material was selected to help minimize galling against adjacent Inconel 718 components. The pins have flats machined on the diameter that contacts the slots, providing a bearing surface and reducing the contact stress developed between the pin and foot



A steady-state thermal analysis estimated rod-end temperatures above 1240 °F with the radiant heater and chamber at 1500 °F. This rod-end temperature greatly exceeds the upper operating temperature (~250 °F) allowed by conventional hydraulic actuators. A cooling scheme for the rod end was then designed to allow the use of conventional actuators.

## Cooled Actuator Rod Design

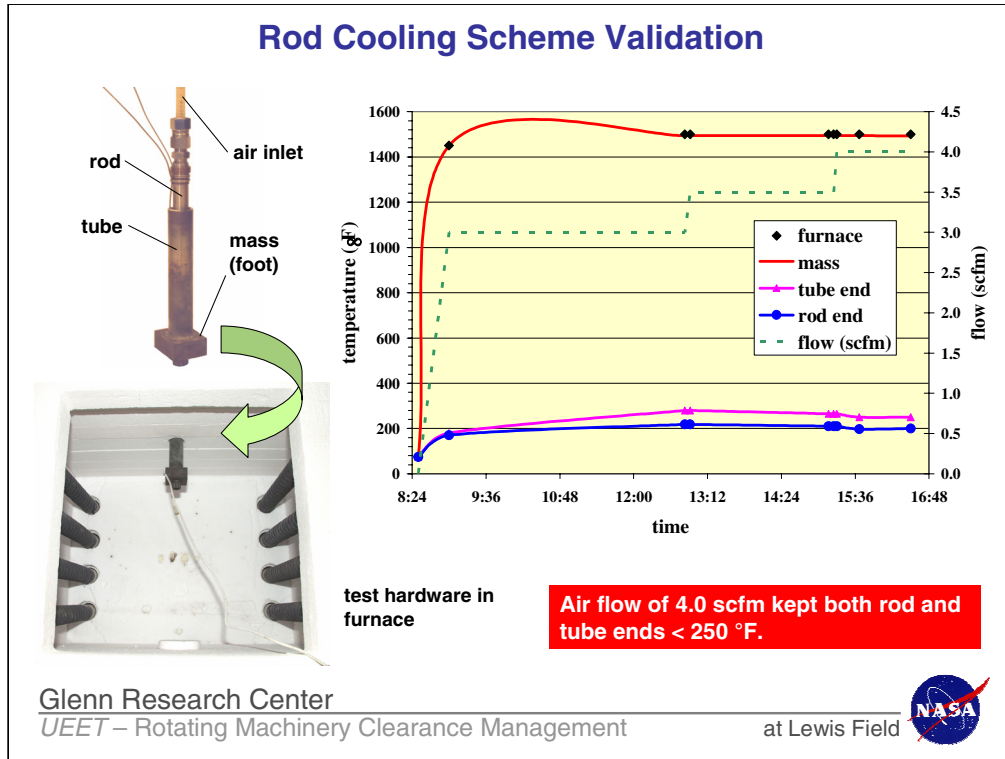


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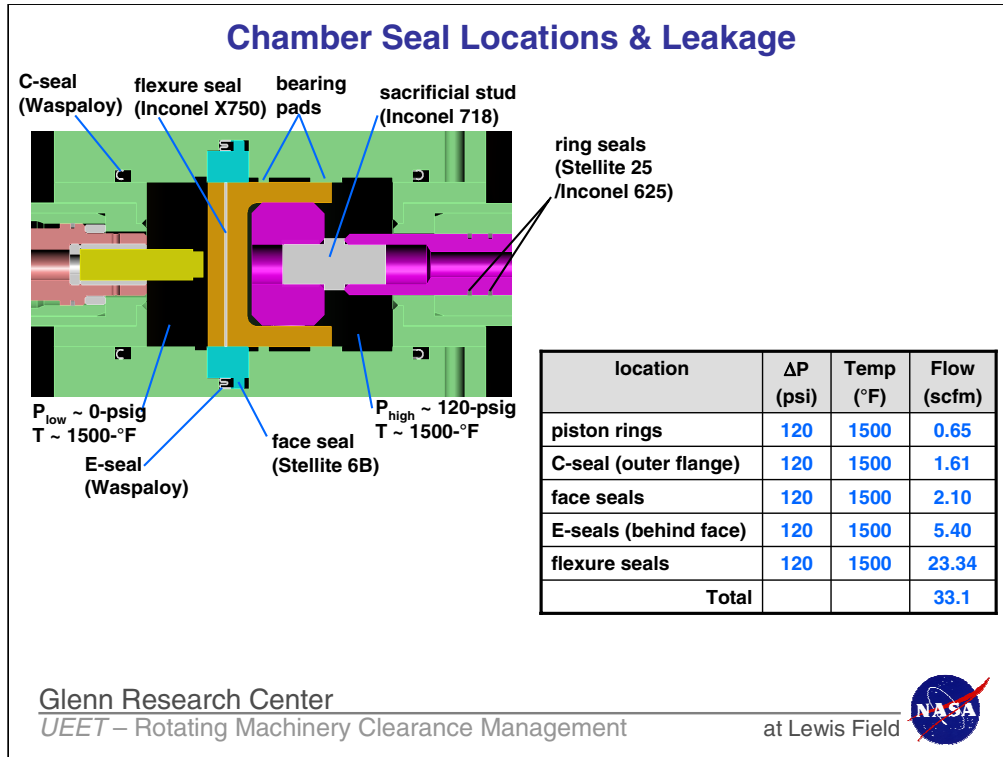
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The cooling scheme allows the actuator rod and support tube to function as a tube-in-tube heat exchanger using a small flow rate of ambient air to cool the assembly.

The cooling holes were made from three sets of six, 0.03-in diameter holes drilled around the circumference of the hollow rod. Ambient air, supplied at the rod end through features in the actuator mount, travels axially through the center of the rod, passes radially through the cooling holes, and exits between the support tube and outer diameter of the rod.



A mockup of the cooled actuator rod design was built to validate the design. A solid steel block (simulating the actuator foot) was bolted to one end of a stainless steel tube (simulating the rod). Another larger tube was welded to the block (simulating the support tube) in a concentric arrangement. An air supply line was attached to the end of the inner tube from which the assembly was supported and inserted into a box furnace. The insulation thickness of the furnace closely approximated that of the radiant heater designed for the rig. A plastic supply line was used minimize heat loss through the supply tube. Thermocouples were attached to measure the temperatures of the mass, the end of the inner rod, and the end of the outer tube. The furnace was heated to 1500 °F and after the mass temperature stabilized at 1500 °F, ambient air at approximately 70 °F was supplied to the assembly. Temperatures of the furnace, mass, tube end, and rod end are shown as a function of time on the left vertical axis. The cooling air volumetric flow is shown on the right vertical axis. The chart shows that for minimal air flow (3.0 to 4.0-scfm) both the tube and rod end temperatures were kept below 250 °F. Thus the cooling scheme design was successfully validated and implemented into the rig design to allow the use of conventional actuators.



The nature of this ACC concept with its segmented shroud design and case penetration requires multiple high temperature seals. The test rig will allow the development and evaluation of these seals that will eventually be required in an engine. Obviously the leakage created by the use of these secondary seals must be minimized to gain the benefits of the ACC system. For the test rig, the secondary seal leakage drove the design of the air heater.

Flexure seals are used to prevent the radial flow of pressurized air between the carrier segment joints. The 2.0-in wide by 0.9-in long flexures are made of 0.02-in Inconel X750 sheet stock. This material was chosen for its galling resistance to the carrier material. The carrier slits that contain the flexures are designed with a 0.01-in clearance.

The chamber contains four “C-seals”, two on the upper and lower outer diameter flanges and two on the upper and lower inner diameter flanges of the cover plates. The seals are made of Waspalloy and have a cross sectional thickness of 0.015-in. The seals were designed by Perkin-Elmer to seal against a 120-psi pressure at 1500 °F and they require a 150-lbf/in seating load per seal at assembly.

The upper and lower cover plates also house a metal face seal assembly. These seals act to block the pressurized air from flowing between the cover plates and carrier segments. The face seal, made of Stellite 6B, is a pressure balanced design and utilizes an “E-seal” as a preload and secondary seal device. Stellite 6B was selected for the face seal material due to its high temperature properties and anti-galling performance against Inconel 718. The E-seals, also designed by Perkin-Elmer Fluid Sciences and made of Waspalloy, provide a closing force to the face seal on the carrier segments and prevent air from leaking between the face seal and cover plate. Each E-seal provides about 10-lbf/in preload to its corresponding face seal. The face seal was designed with a generous cross section, due to its large diameter, to provide stiffness for operation as well as manufacturing.

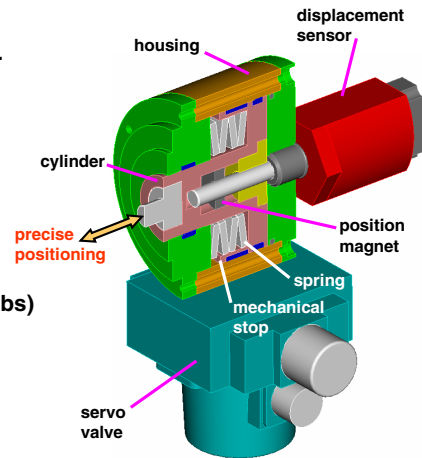
The actuator rod contains two pairs of expanding concentric ring seal sets on its bearing surface. Each pair is made of an outer Stellite 25 ring and an inner Inconel 625 ring. The seals were designed by Precision Rings, Inc. (Indianapolis, IN) for a 120-psi at 1500 °F.

## ACC Actuator Development

**Gen 1 Actuator:** Custom hydraulic-servo actuator

Capabilities	Min Req.	Actual
Stroke	0.1-in	0.2-in
Accuracy	0.001-in	0.0006-in
Load	1800 lbf	3000 lbf
Rate	0.01-in/s	0.04-in/s

- Compact, Lightweight
- Failsafe (retracts, fails open – avoids blade rubs)
- $P_{high}$ ,  $P_{low}$ , position measurement



**Gen 2 Actuator:** Currently evaluating advanced designs using piezo, SMA, magneto-strictive and other technologies.

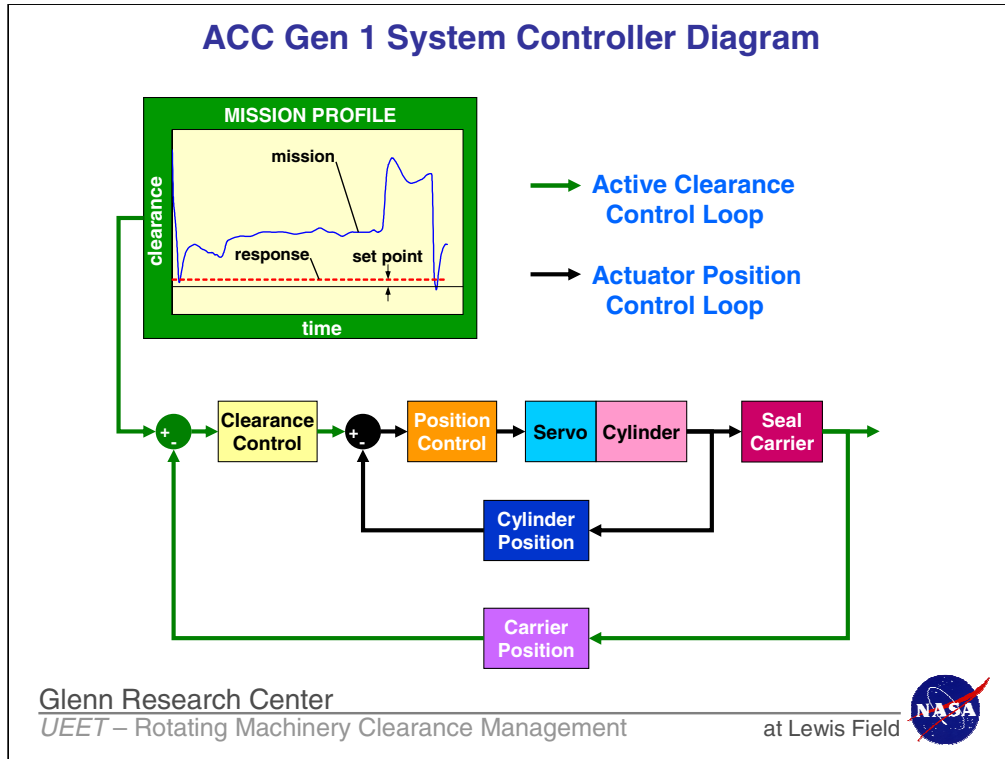
Can “Smart” actuators out perform “standard” technology ???

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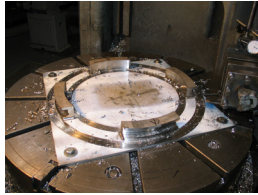


This slide shows a diagram of the control system strategy that will be employed to operate and evaluate this first generation ACC system as well as future systems. Each of the nine independent hydraulic actuators will have its own feedback control allowing the positioning of each cylinder or actuator. An outer loop will be monitoring the position of the carrier segments. The outer loop will determine the minimum clearance off of which the desired clearance will be measured. The control system will be used to evaluate the accuracy and response of the ACC system to both steady state and transient clearance profiles.

Our next speaker, Mr. Kevin Melcher of the Controls and Instrumentation Branch at NASA GRC, will provide a more in depth discussion on his development of this control system and his work on defining control system requirements and architecture for advanced ACC systems.



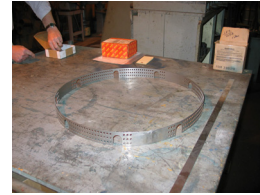
## Test Rig Fabrication Status



Carrier Segments



Radiant Heater Housing



Flow Deflector



Chamber



Main Housing



Main Housing Lid

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Here we can see some of the main components of the test rig as they are currently being fabricated. The components are about 75% complete. We expect assembly to occur at the end of the month, with rig check out occurring towards the end of December.

## Future Work

- **The ACC system performance will be evaluated under a series of HPT simulated temperature and pressure conditions.**
  - Actuator stroke, rate, accuracy, repeatability
  - System concentricity, 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 actuator design as well as other actuator concepts.**
  - SMA's, piezoelectric, magnetostrictive, other
- **Optimization of ACC system components for future flight hardware development.**
  - increased cycle life
  - reduced size and weight

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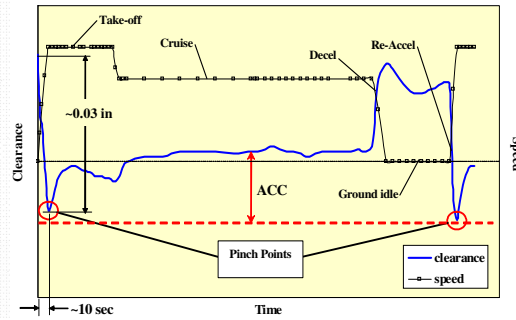
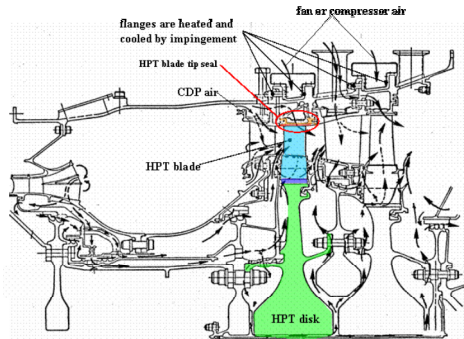
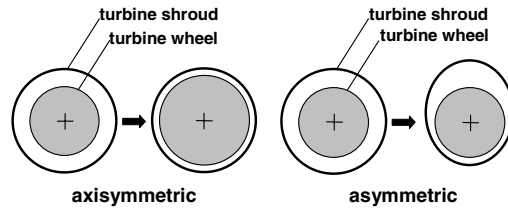
## APPENDIX

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## HPT Blade Tip Clearance Variation

- **Load Mechanisms**
  - Engine Loads (centrifugal, thermal, internal engine pressure, thrust)
  - Flight (inertial, aerodynamic, and gyroscopic)
- **Wear Mechanisms**
  - Rubs
  - Erosion



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## Motivation (Benefits of ACC for HPT)

- **Fuel Savings/ Reduced Emissions**
  - 0.010-in tip clearance is worth ~1% SFC
  - Less fuel burn, reduces emissions
- **Increased Cycle Life (Reduced Maintenance Costs)**
  - Deterioration of exhaust gas temperature (EGT) margin is the primary reason for aircraft engine removal from service.
  - 0.010-in tip clearance is worth ~10 °C EGT.
  - Allows turbine to run at lower temperatures, increasing cycle life of hot section components and engine TOW (~1000 cycles).
- **Increased Efficiency/Operability**
  - Increased payload and mission range capabilities
- **HPT Reaps the Most Benefit Due to ACC**
  - Improved tip clearances in the HPT resulted in Life Cycle Cost reductions 4x > LPT and 2x > HPC. (Kawecki, 1979)

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