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

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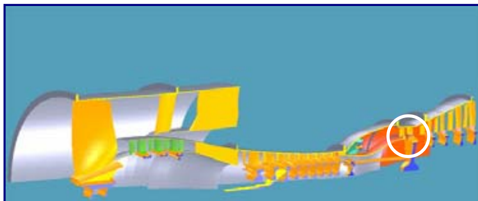
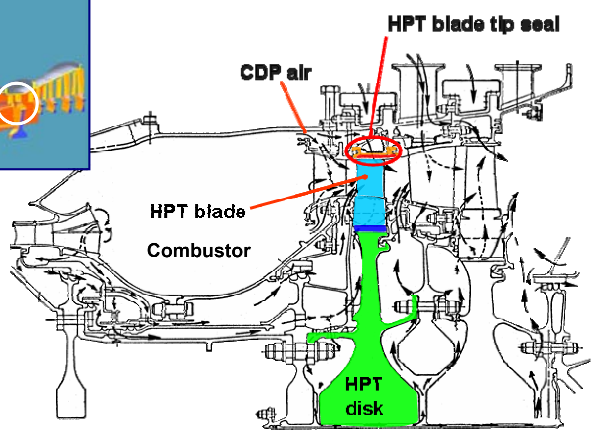
Propulsion 21

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

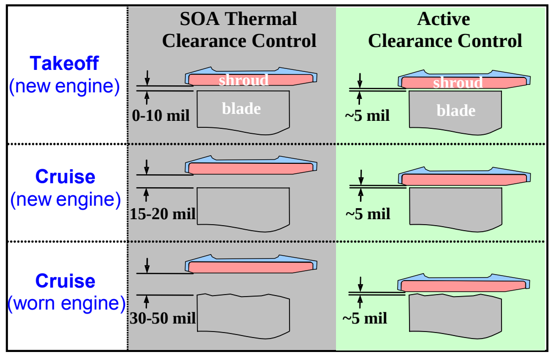




System studies have shown the benefits of reducing blade tip clearances in modern turbine engines. Minimizing blade tip clearances throughout the engine will contribute materially to meeting NASA’s Ultra-Efficient Engine Technology (UEET) turbine engine project goals. NASA GRC is examining two candidate 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?

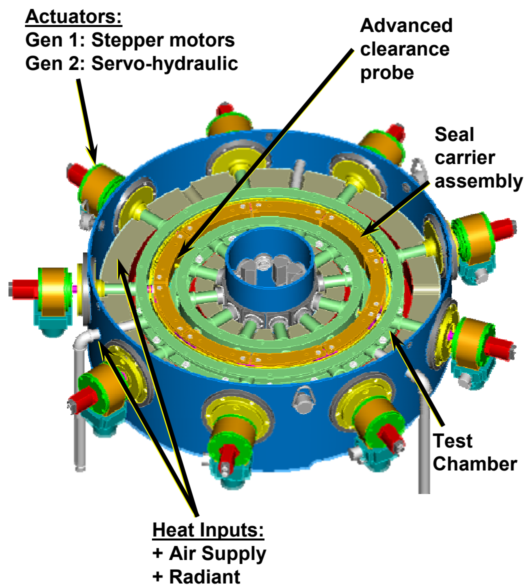
Well I am glad you asked: benefits of clearance control in the turbine section include lower specific fuel consumption (SFC), lower emissions (NOx, CO, CO2), retained exhaust gas temperature (EGT) margins, higher efficiencies, longer range (because of lower fuel-burn).

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:

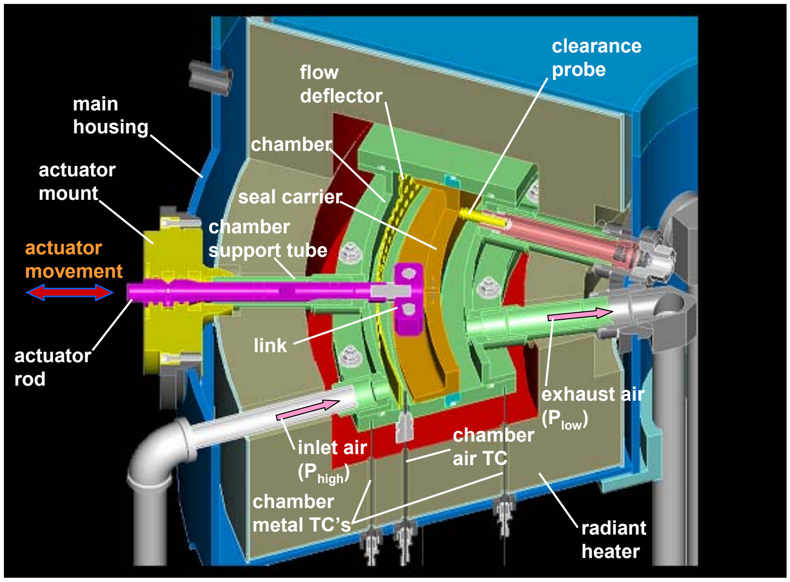
+ Individual component seal leakage rates and to compare them to an industry reference level at engine simulated pressures but at ambient temperature. High temperature tests are planned in the future.

+ Evaluate system leakage both statically and dynamically

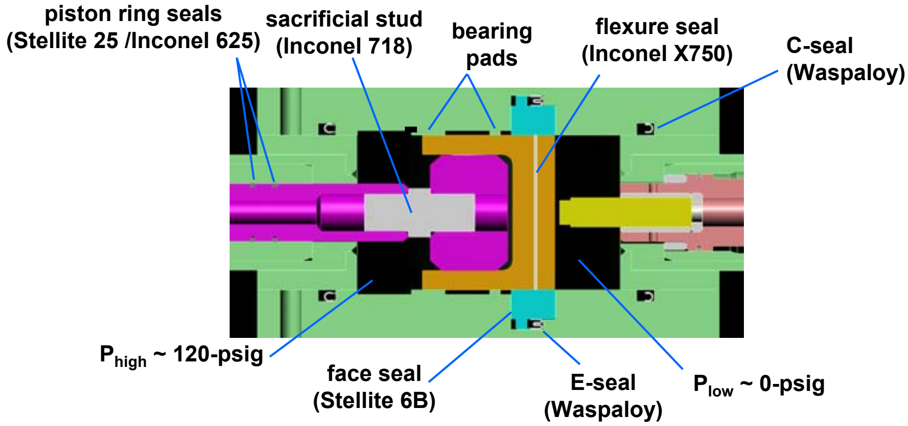
+ Evaluate candidate actuator’s ability to position the seal carriers in a repeatable fashion

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

ACC Test Rig Components



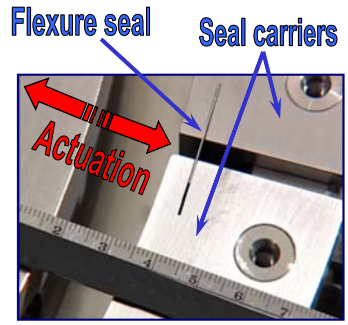
ACC Test Rig - Secondary Seals



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



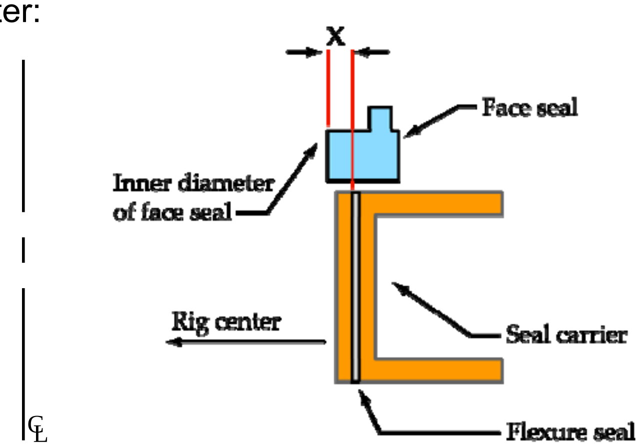
- Outward radial motion dilates the seal shroud.
- Inward radial motion contracts the shroud.

Study Objectives for Recent Testing

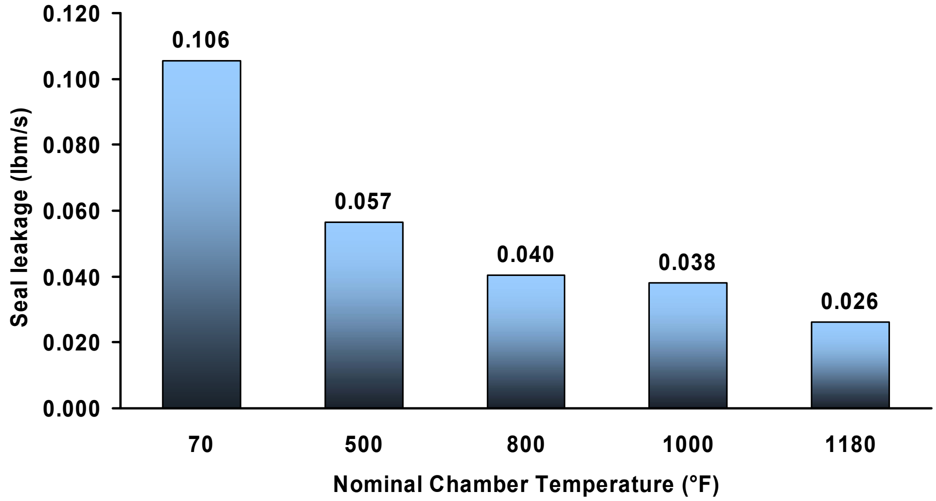
- Determine dependence of system leakage on:
  - Test pressure, temperature
  - Seal carrier position
  - Seal carrier direction of motion (inward vs. outward)
  - Actuation rate
- Quantify performance of the new servo-hydraulic actuators
  - Evaluate individual actuator accuracy and repeatability.
  - 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:

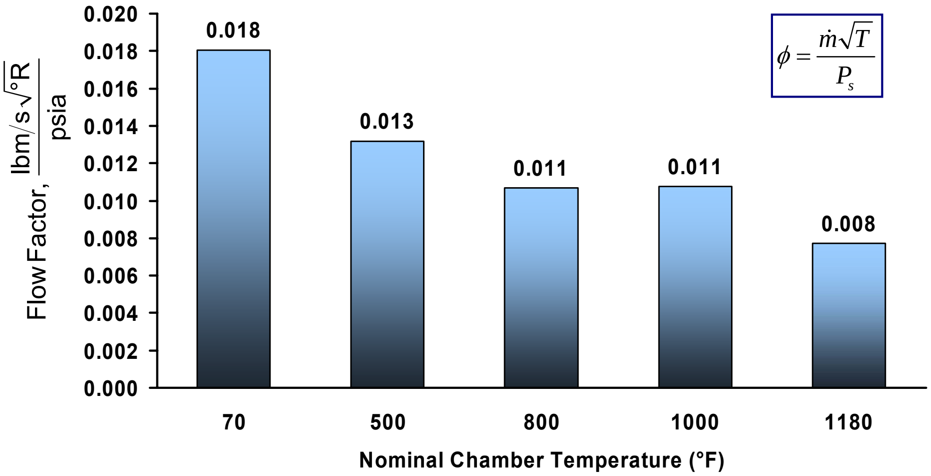


System Leakage vs. Temperature



Static leakage decreases with increasing temperature.

Flow Factor vs. Temperature

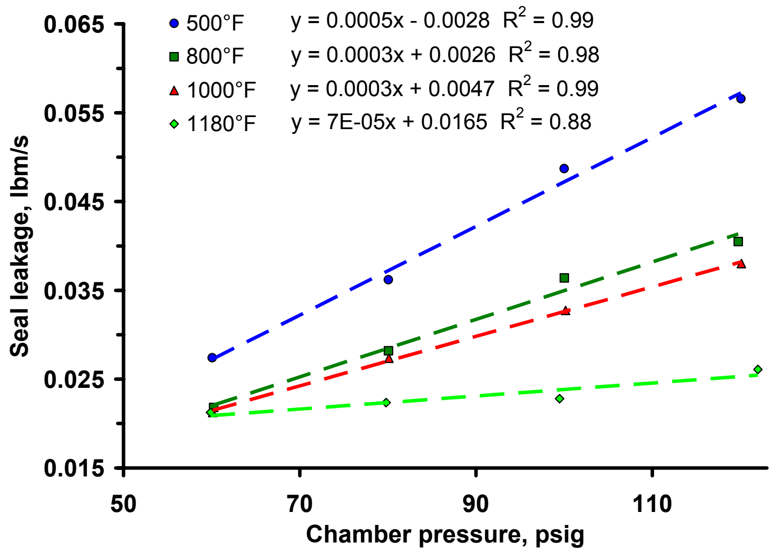


<u>Flow factor generally decreases with increasing temperature:</u>

Increased test temperature results in:

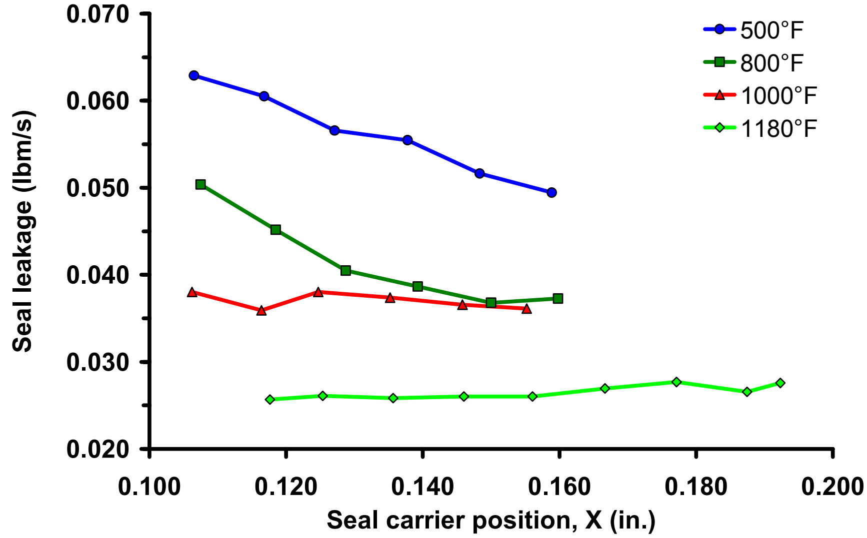
- Reduced secondary seal clearances
- Increased gas viscosity

Leakage Dependence on Pressure



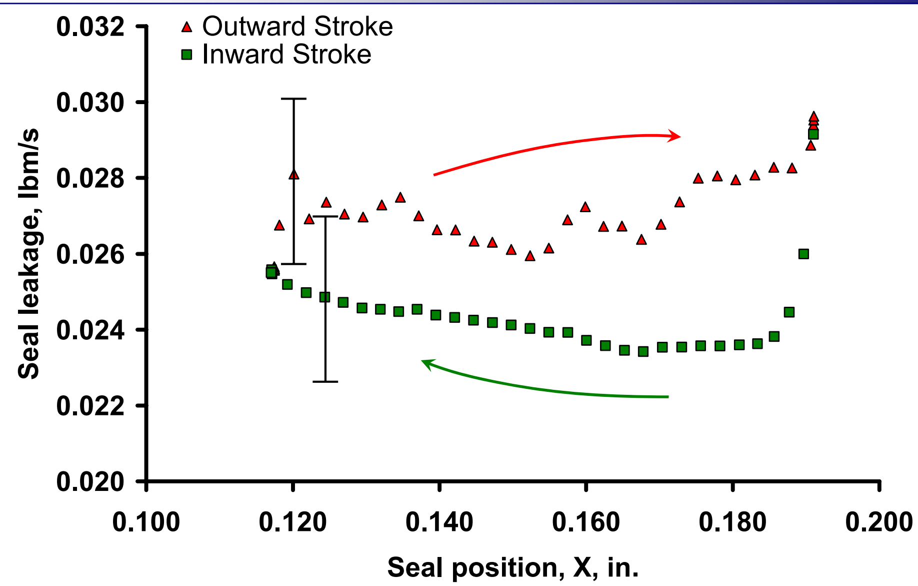
Static leakage: Linear dependence on pressure.

Leakage Dependence on Seal Carrier Position



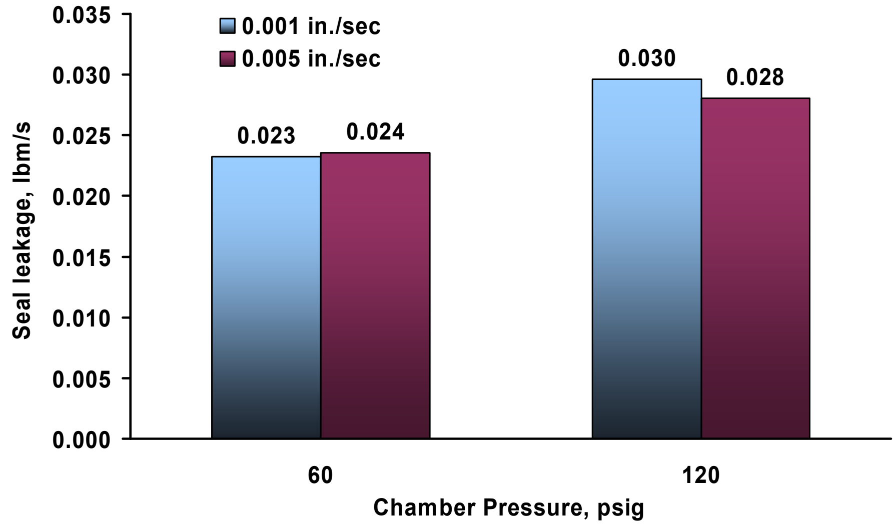
- **At 500 and 800°F, leakage slightly lower at outward positions (larger X).**
- **Virtually no leakage dependence on position at 1000 or 1180°F.**

Direction of Motion Effects at 1180°F

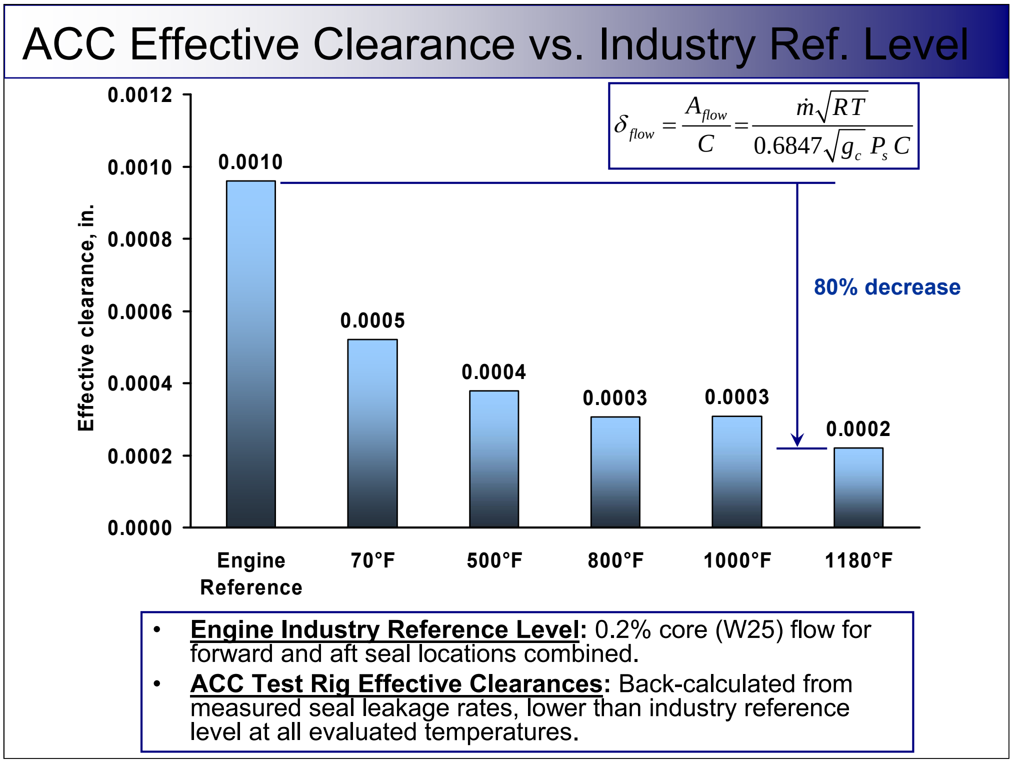


Overlap of leakage error in data sets indicates direction of motion has virtually no effect on leakage at 1180°F.

Effects of Actuation Speed on Leakage at 1180°F



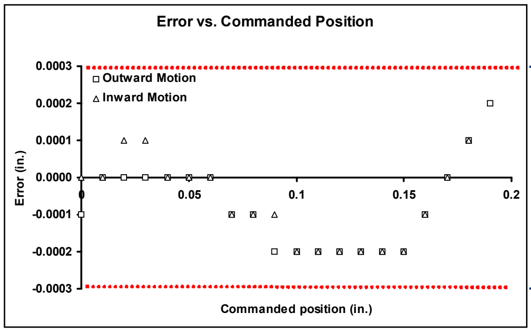
- 0.001 in./sec tests showed improved leakage resolution over 0.005 in./sec tests.
- Carrier actuation speed has virtually no effect on peak leakage.

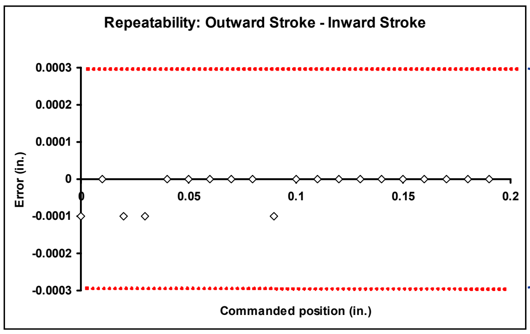


If one were to idealize the ACC system as an elastic structure (e.g. a rubber ring or band) that could move radially inward/outward, seals would only be required between the sides of the moving structure and the surrounding static structure. Engine designers have acknowledged that seals in these areas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

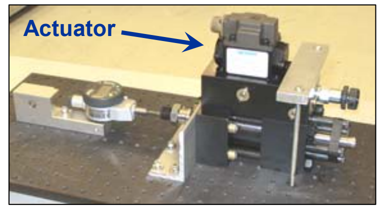
Back-calculating the equivalent unit flow area per unit circumference using the measured ACC system leakage rates and the equation for isentropic flow under choked flow conditions, we obtained a value of 0.0008 in^2/in. We see that the unit flow areas compare favorably. We recognize that further assessments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

Actuator Positional Accuracy and Repeatability Tests





Acceptable Range

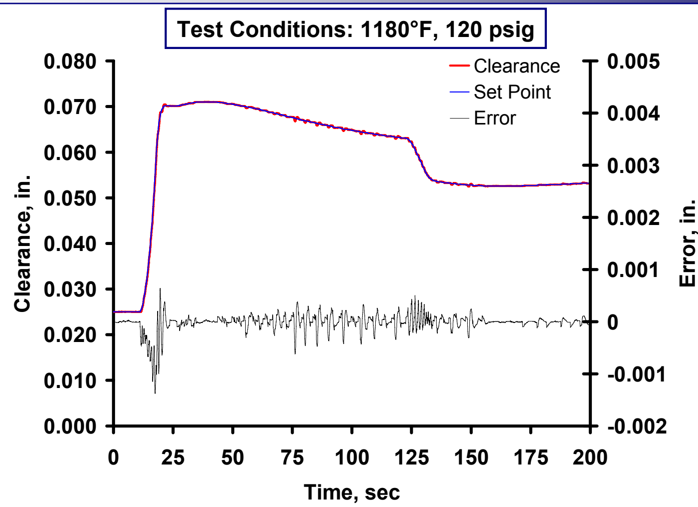


Actuator on Precision Test Fixture

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



- 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

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