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

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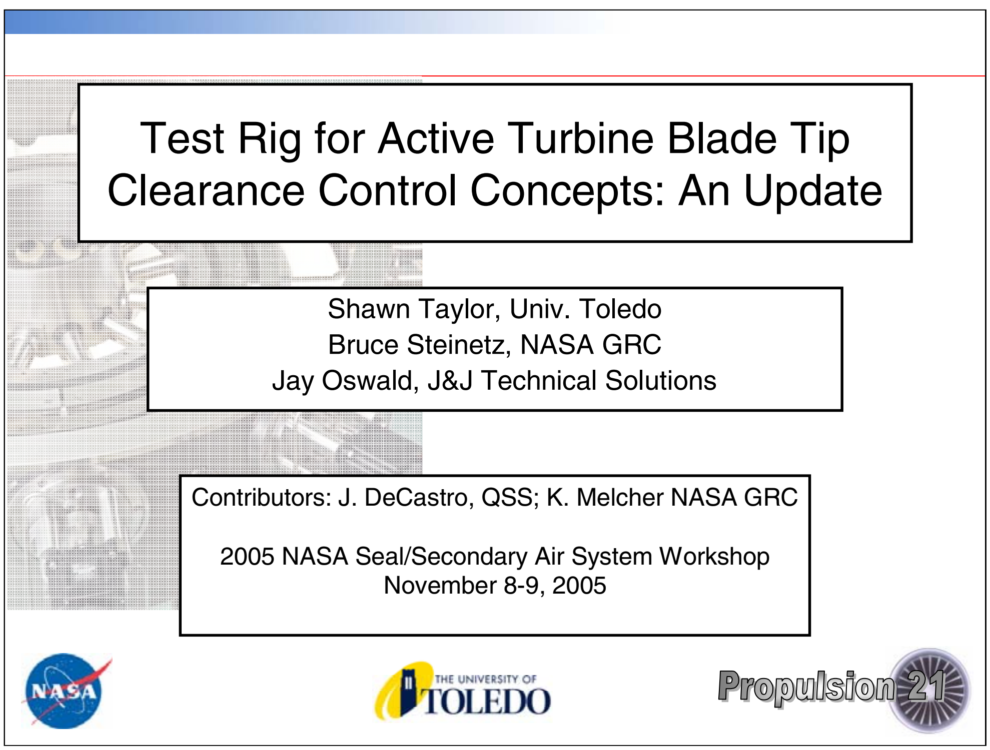
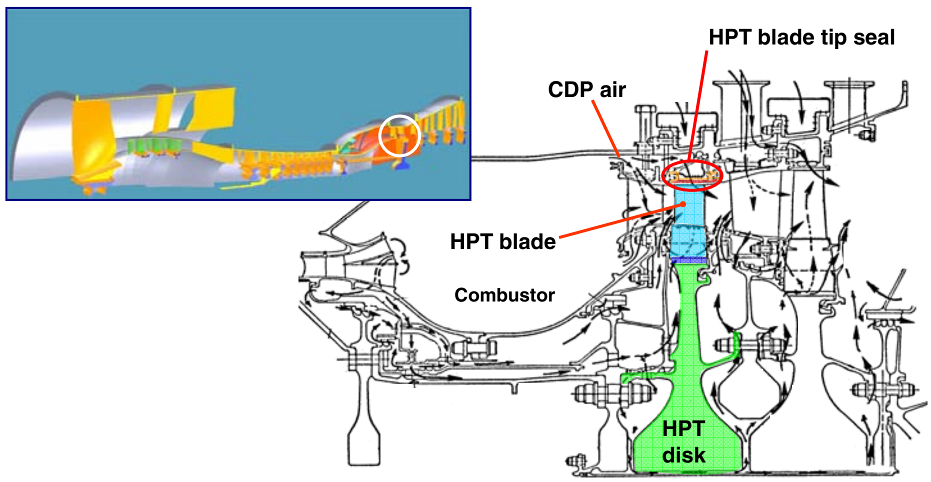


Active Clearance Control (ACC) Objective

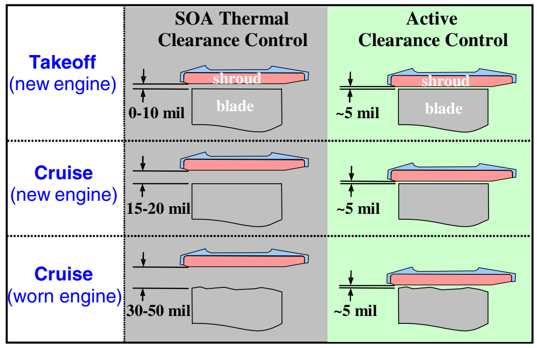
Develop and demonstrate a fast-acting active clearance control system to improve turbine engine performance, reduce emissions, and increase service life



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

Benefits of Blade Tip Clearance Control

- **Fuel Savings & Reduced Emissions**
  - 0.010” tip clearance is worth ~0.8-1% SFC
  - Reduced NOx, 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 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).

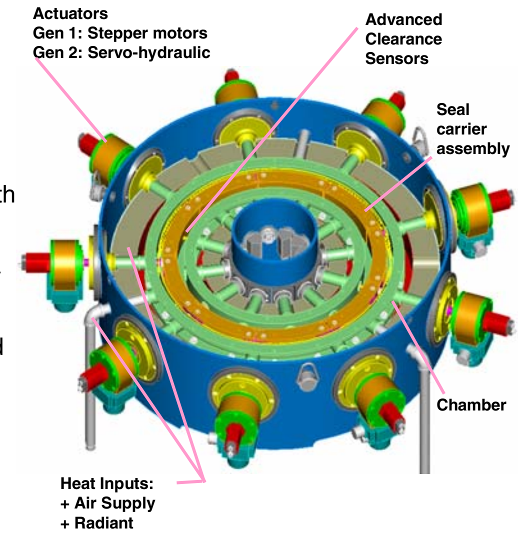
Blade tip clearance opening is a primary reason for turbine engines reaching their FAA certified exhaust gas temperature (EGT) limit and subsequent required refurbishment. As depicted in the chart on the right, when the EGT reaches the FAA certified limit, the engine must be removed and refurbished. 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 Goals

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

Active Clearance Control Test Rig



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

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

The goals of research effort are summarized here.

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

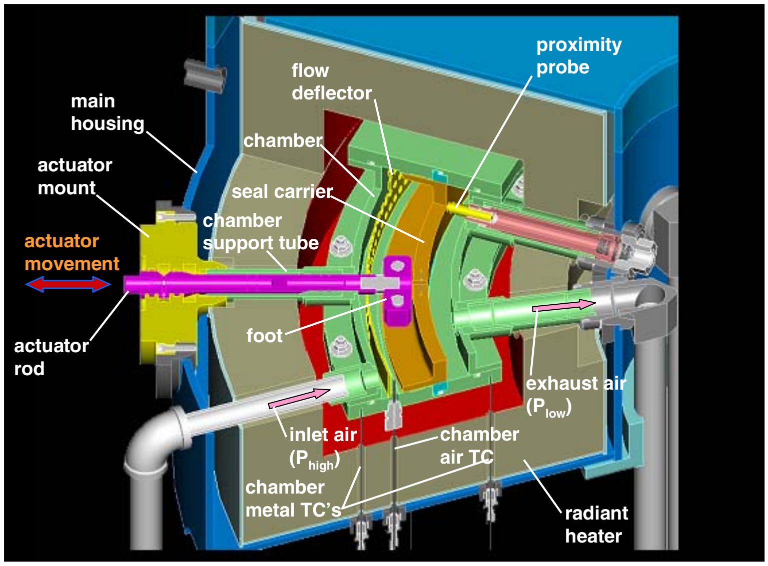
+ Individual component seal leakage rates and to compare them to an industry reference level at engine simulated pressures but at ambient temperature. High temperature tests are planned in the future.

+ Evaluate system leakage both statically and dynamically

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

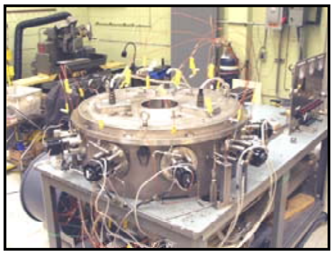
+ Evaluate clearance sensors as part of the closed loop feedback control.

ACC Test Rig Components



Recent Accomplishments

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



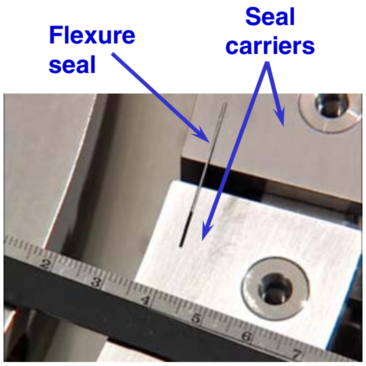
Fully Instrumented Rig Assembly

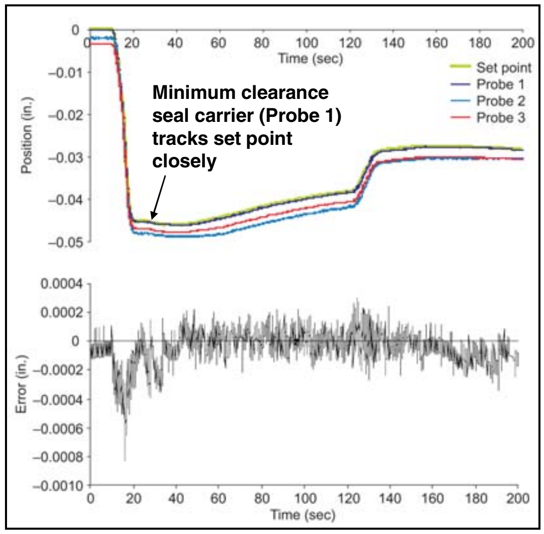
Completed Heater Controls

Simulated Engine Take-off Clearance Profile

Simulated engine take-off transient:

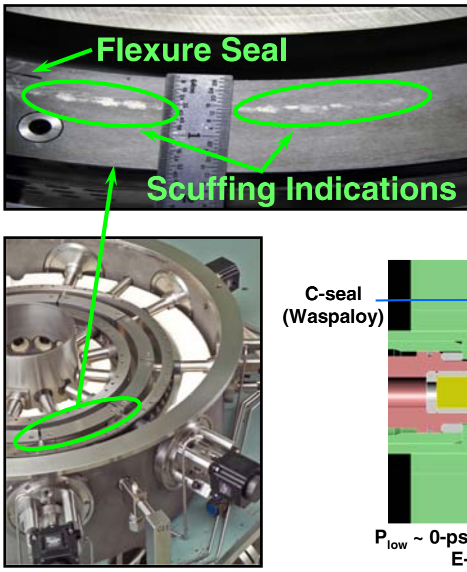
- Closed-loop position control using capacitance probes at 20 psig.
- Seal carrier tracked the set-point to within 0.001".

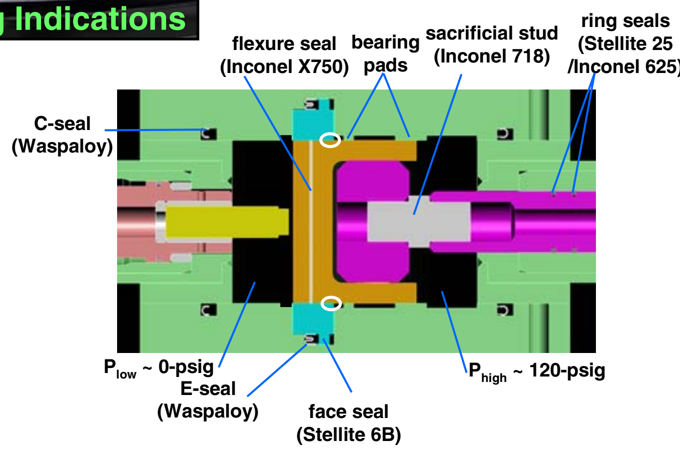




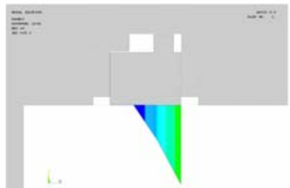
Seal Carrier Scuffing Indications

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

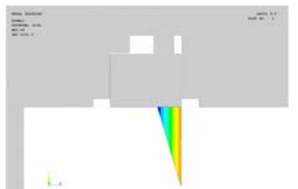




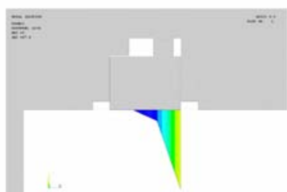
Face Seal Finite Element Analysis



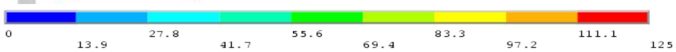
Static Carriers



Inward Carrier Motion



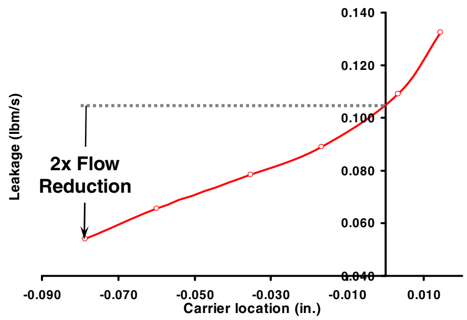
Outward Carrier Motion



FEA at 120 psig

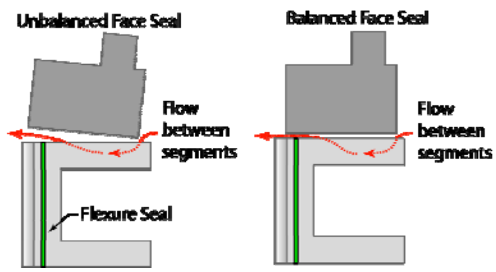
- Unbalanced face seal pressure profile causes outer edge loading when seal carriers are both static and in motion.
- Edge loading caused scuffing indications on seal carriers.

Repositioning Carrier Reduces Leakage

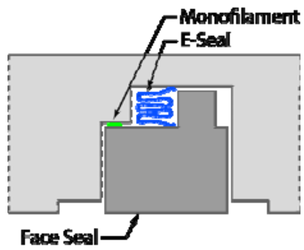


Seal	Leakage, % of total
Outer C-Seals	1
Air Inlet Rings	2
Actuator Rod Ring Seals	6
Face Seals	7
Flexure Seals	85
Total	100

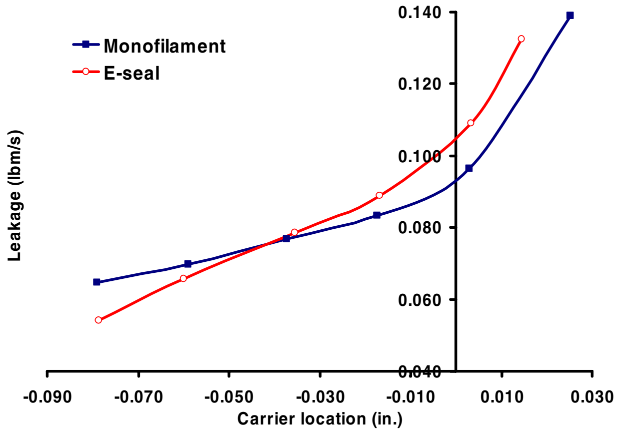
- Face seal unbalance:
  - Causes leakage dependence on seal carrier position.
  - Increases leakage over flexure seals due to edge loading.
  - Goal: achieve leakage independent of carrier position.



Monofilament Trial Seal



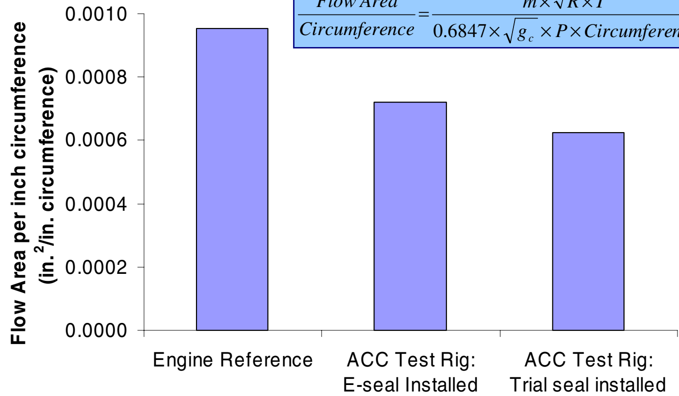
Monofilament Substituted for E-seal, Radially Inward



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

ACC Unit Leakage vs. Industry Ref. Level

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

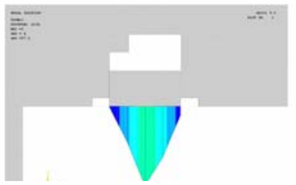


- Industry Reference Level: Determined for forward/aft side seals for an idealized elastic ring structure. Each seal having leakage rate of 0.1% core flow.
- ACC Test Rig: Effective unit leakage flow area back calculated from measured flow.

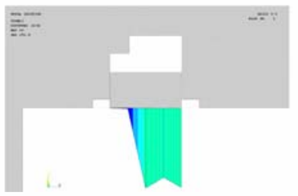
If one were to idealize the ACC system as an elastic structure (e.g. a rubber ring or band) that could move radially inward/outward, seals would only be required between the sides of the moving structure and the surrounding static structure. Engine designers have acknowledged that seals in these areas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

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

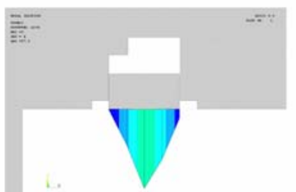
Face Seal Improvement with FEA



Static Carriers



Inward Carrier Motion

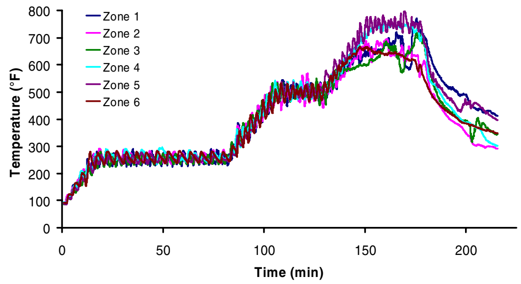


Outward Carrier Motion

FEA at 120 psig

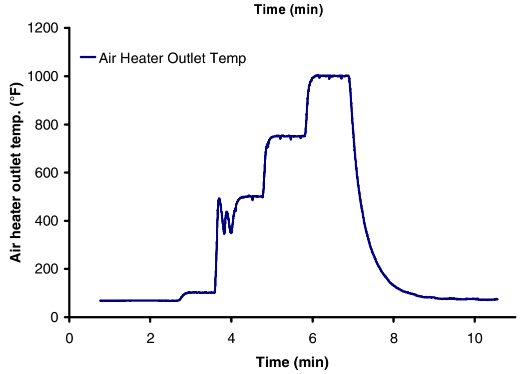
- Face seal pressure unbalance can be improved by decreasing the seal height.
- Balancing the face seal pressure profile mitigates seal edge loading.

Radiant and Air Heater Check-out



Radiant Heaters

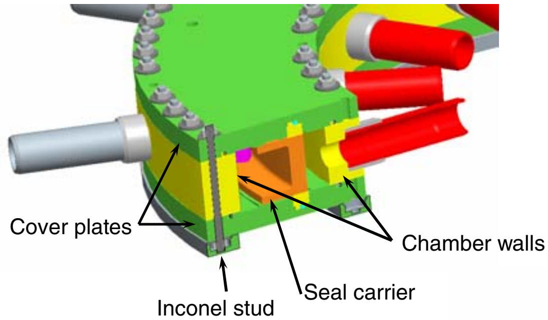
- Demonstrated simultaneous operation of all 6 zone heaters.



Air Heater

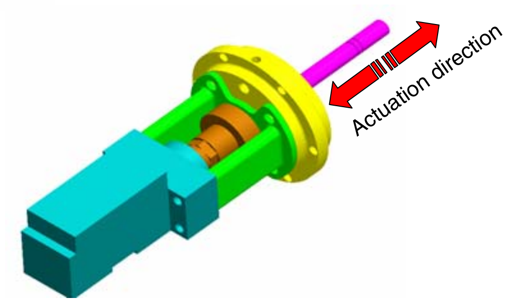
- Demonstrated ability to reach 1000°F with new air heater.

New Hardware Updates



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

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



Summary

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

Future Work

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

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