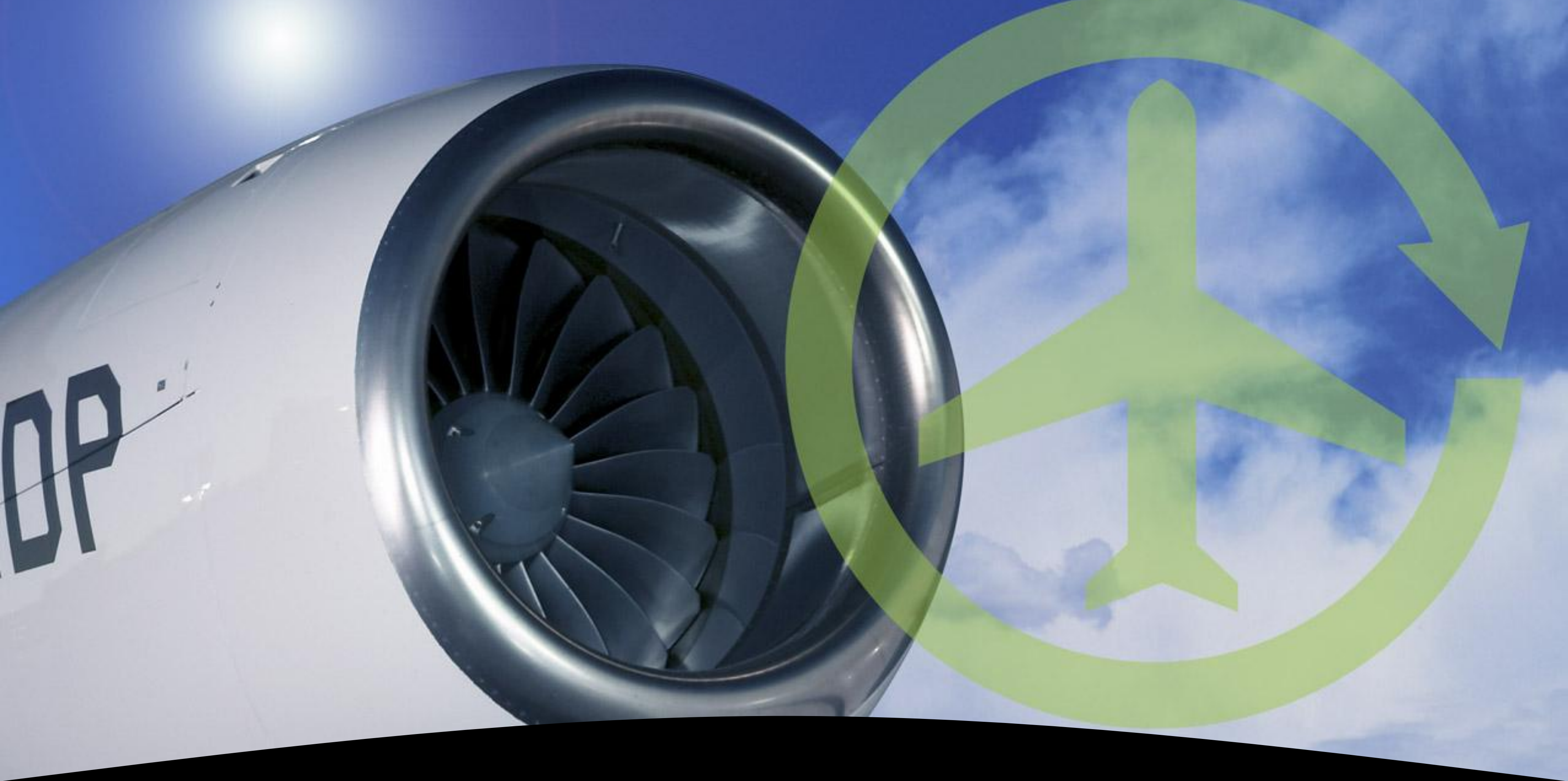


Small Engine / Low Emissions Combustor Design Considerations

Richard Hausen

November 6th, 2014

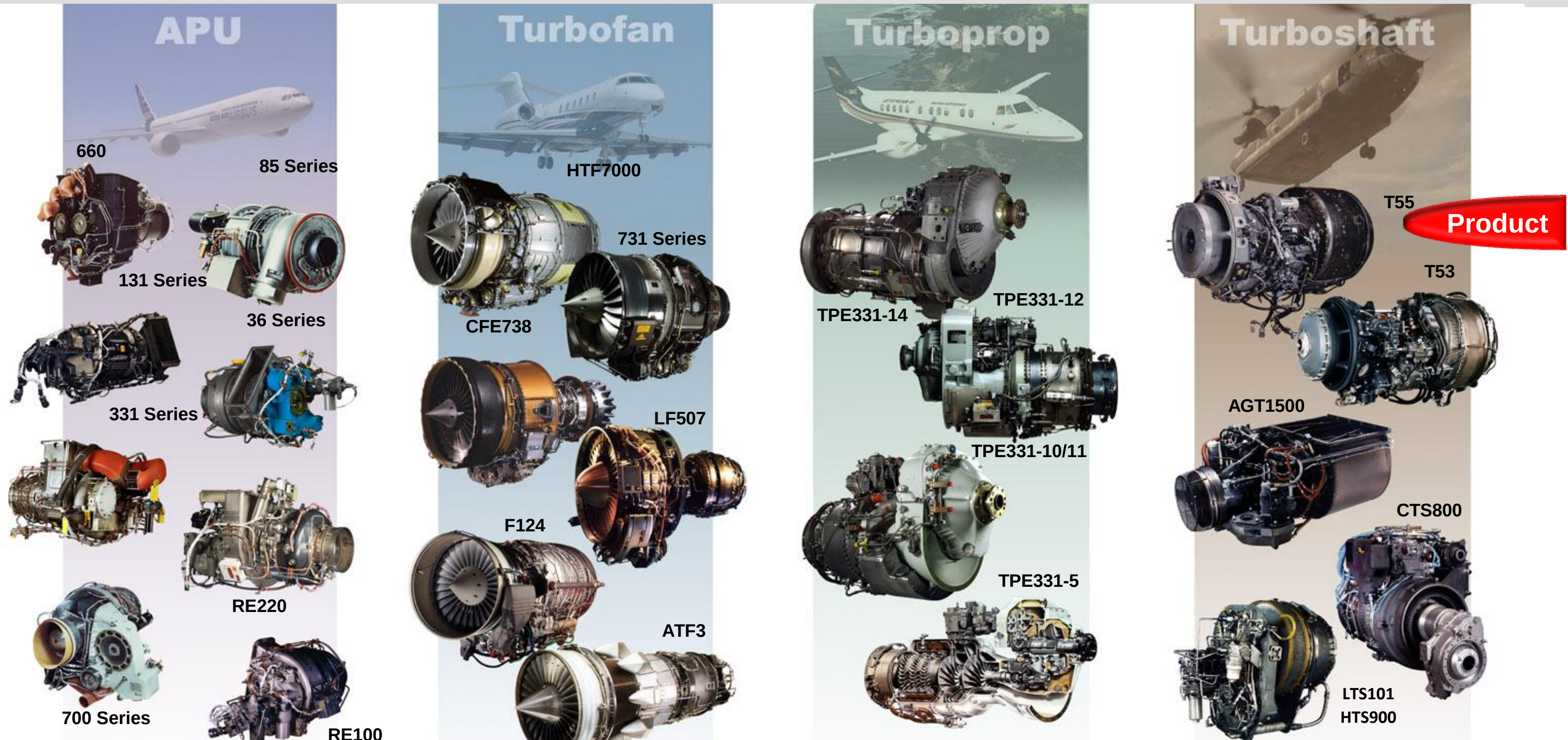
13th Annual Israeli Jet Engine Symposium (AIJES)

Honeywell

Agenda

- Honeywell aero gas turbine product lines
- Environmental regulations
- Small engine challenges for low emissions combustors
- Honeywell's design approach and development process
- Enablers for developing combustor technology
- Honeywell SABER-1 combustor technologies
- Analytical and Experimental Results
- Go-forward plans
- Summary

Honeywell Turbine Engine Products



APUs
100 to 1400 hp for commercial and military aircraft

Turbofan Engines
3,000 to 10,000 lb thrust for commercial and military aircraft

Turboprop Engines
575 to 1,600 shp for commercial and military aircraft

Turboshaft Engines
500 to 5,000 shp for tanks, commercial and military rotorcraft

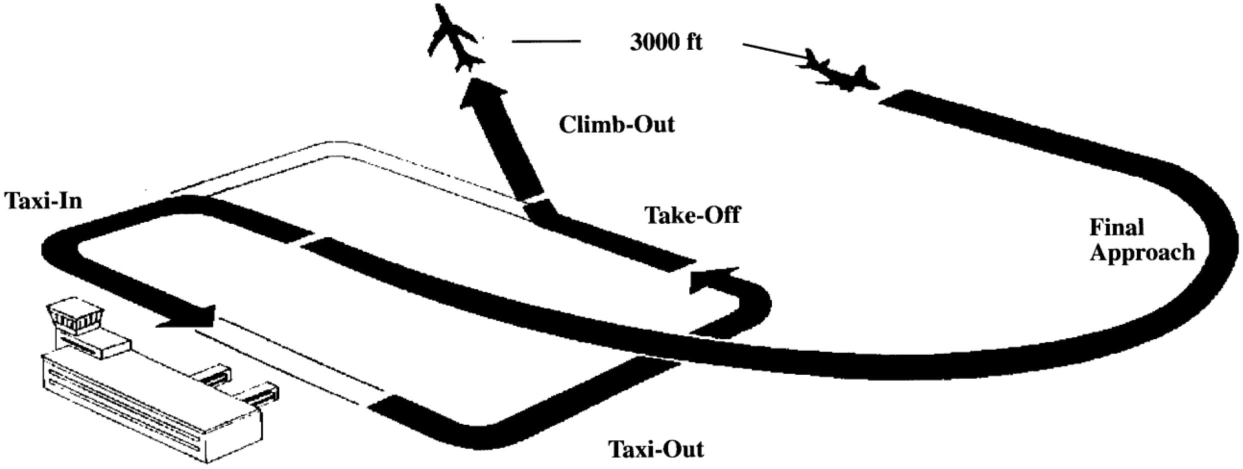
B08-147

More Than 135,000 Engines Delivered

Drivers for Low Emissions

- Situation:
  - Pollutants: NOx, CO, UHC and Smoke / nvPM
  - Local air quality and global climate change
- Regulations & Other Drivers:
  - ICAO regulation (LTO cycle)
  - Economic measures (Airport landing charges)
  - Market expectations

Regulations



More on Emissions Regulations

- ICAO*
  - Sets standards for aviation emissions
  - Works through CAEP** which meets every 3 years to update standards
  - CAEP has representation from government agencies & industry

Regulations

- ICAO regulations
  - DP/Foo for NOx, CO, UHC
  - Smoke – Filter stain
  - nvPM - Most likely will be decided during CAEP/10 in 2016

$$\frac{D_p}{F_\infty} = \frac{\sum_{LTO} t_m \times W_f \times EI}{F_\infty}$$

LTO Thrust & Time in Mode		
Mode	Time Minutes	% Rated Thrust
Take-off	0.7	100
Climb	2.2	85
Approach	4	30
Taxi/idle	26	7

* International Civil Aviation Organization
** Committee on Aviation Environmental Protection
EI – Emissions Index g /Kg (Pollutant/Fuel)
DP/Foo – Mass of pollutant during LTO cycle / Rated thrust of engine

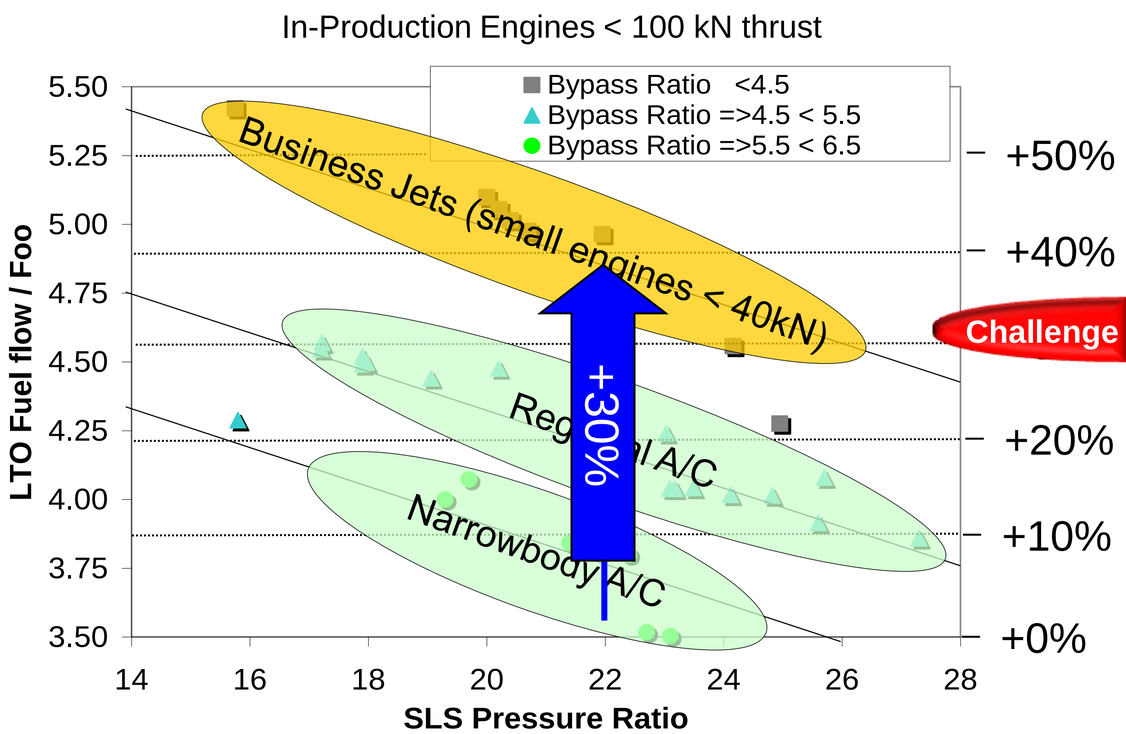
Engine Cycle Effects on LTO cycle

- Landing/Take-off (LTO) Emissions Cycle*:

$$\frac{D_p}{F_\infty} = \frac{\sum_{LTO} t_m \times W_f \times EI}{F_\infty}$$

- Cycle effect focuses only on performance parameters:

$$\frac{\tilde{W}_f}{F_\infty} = \frac{\sum_{LTO} t_m \times W_f}{F_\infty}$$



Engine Performance has significant impact on LTO emissions
Small Engines have 30% emissions challenge

*International Civil Aviation Organization Annex 16, Volume II, 3rd edition.

Performance Requirement Parameters for Low Emissions Combustors

Emissions

- NOx
- CO
- UHC
- Smoke

Operability

- Ignition & starting
- Stability (LBO margin)

Life

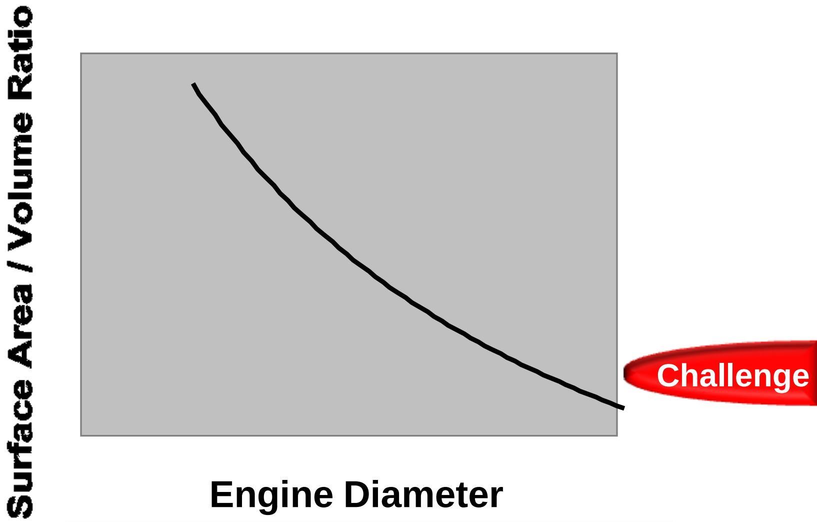
- Combustor life:
  - Temperatures
  - Temperature gradients
- Turbine life:
  - Pattern Factor
  - Radial Temp Profile
  - Pressure drop
  - No carbon
- No acoustics

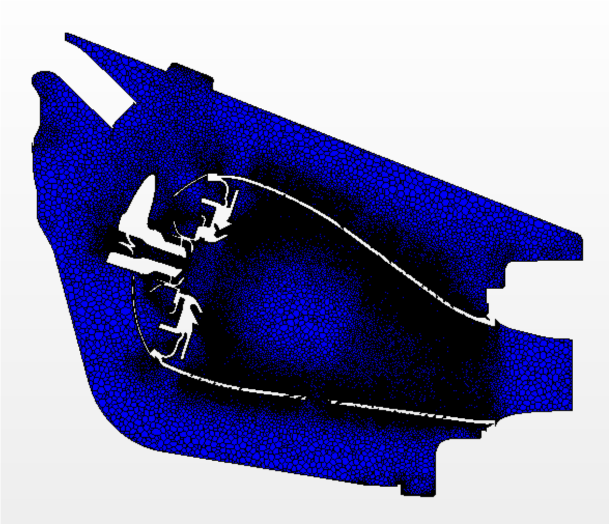
Challenge

The low emissions combustor must satisfy emissions regulations along with the other combustor design requirements

Requirements & Challenges in Advanced Combustor Development for Small Engines

- High surface area/volume ratio
  - Proportionally more cooling required
- Centrifugal compressor Effects
  - Packaging diffuser discharge with combustor to minimize pressure distribution effects
- Cyclic content
  - More than 1 cycle per hour induces more fatigue and interactions with other modes (creep, oxidation, spallation)

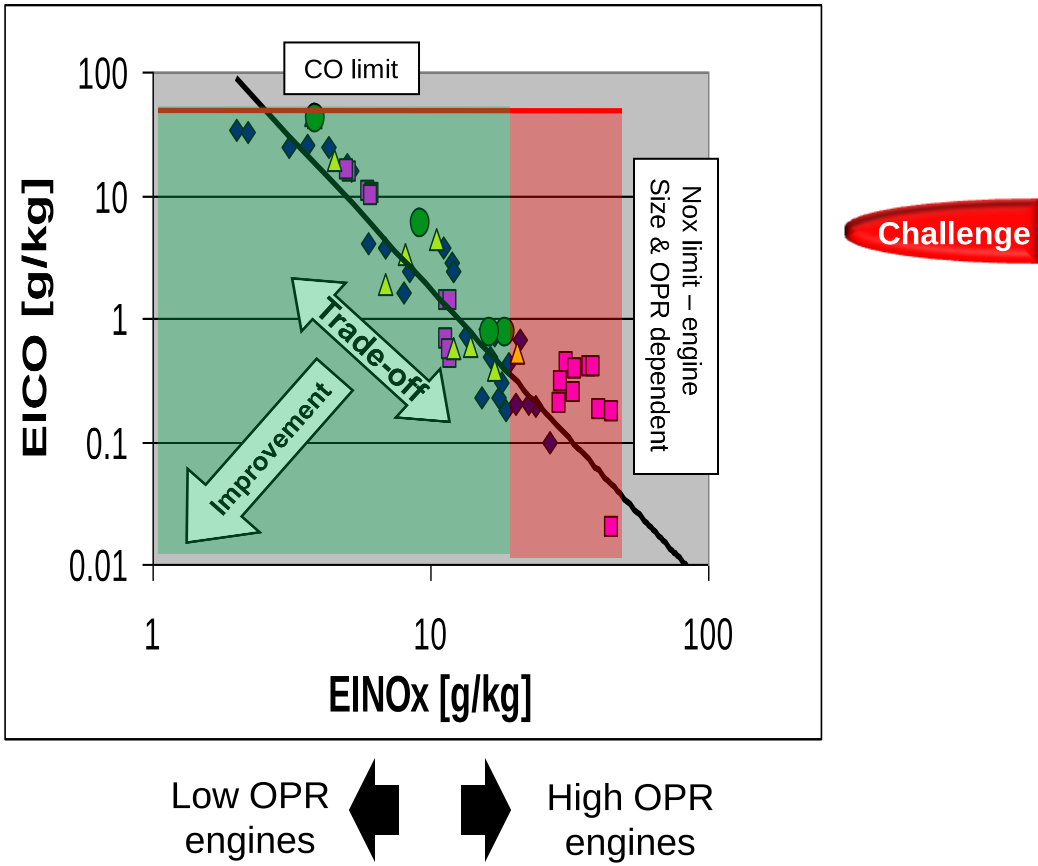




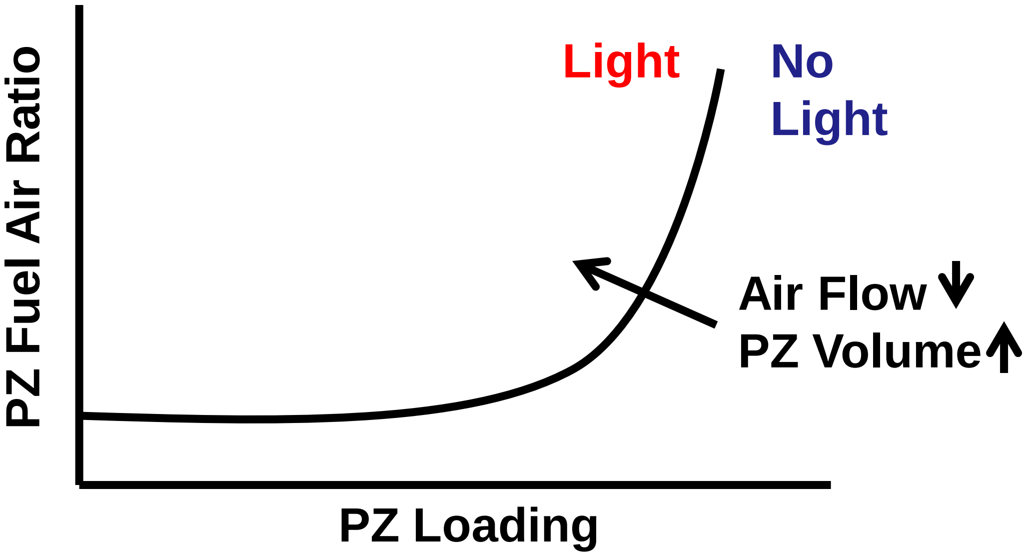
Challenge to Emissions Reduction

- Aero engines have wide range of firing temperatures at the emissions measurement points
- Both NOx and CO are criteria pollutants
  - Inversely correlated with flame temperature
- Implications:
  - Need to reduce coupling between combustor flame temperature from engine firing temperature (staging)
  - Combustor optimization dependent upon engine operating conditions

State-of-the-art combustor technology
at 7%, 30%,85%,100% rated thrust
Plotted from Engine Emissions Databank



Trade Challenges with Low NOx Combustor



$$\phi_{load} = \frac{Wa_{comb}}{(\delta_{3.0})^{1.75} \cdot VOL_C \cdot e^{\left(\frac{T_{3.0}+459.67}{540}\right)}}$$

<u>Trade Considerations</u>

- Reduced PZ aero loading improves <u>ignition & starting</u>
- Reduced PZ airflow reduces PZ aero loading but it may require reduced cooling which reduces <u>combustor life</u> & excessive <u>smoke</u> can result if PZ F/A is too rich

Challenge

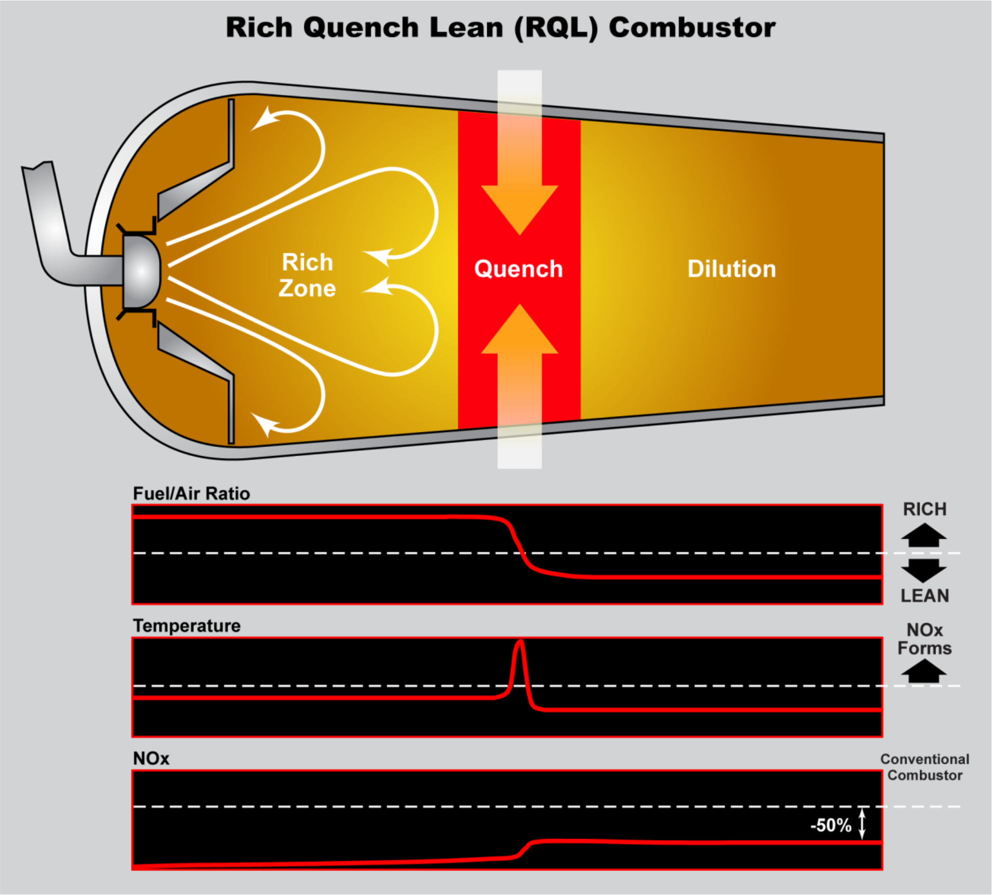
- Increased volume reduces PZ aero loading but also increases <u>NOx</u>

The low emissions primary zone design is realized through some often conflicting design choices

RQL Technology Focus Areas

1. Improved Mixing for primary zone fuel to air ratio uniformity

2. Lower cooling flux for higher primary zone fuel to air ratio & less CO generation at low power



Approach

3. Residence time optimization

4. Quench Zone mixing optimization

Technology Maturation Process

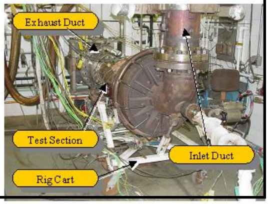
Technology Readiness Levels (NASA)

System Test & Operations	TRL 9
System/Subsystem Development	TRL 8, TRL 7
Technology Demonstration	TRL 6, TRL 5
Technology Development	TRL 4
Research to Prove Feasibility	TRL 3, TRL 2
Basic Technology Research	TRL 1

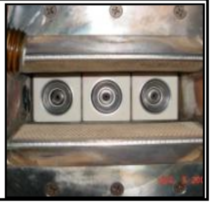
Flight Testing
Method:
B757 Flying Test Bed
Purpose:
Operability, Handling

Engine Testing
Method:
Ground Engine Testing
Purpose:
Durability, Emissions, Noise

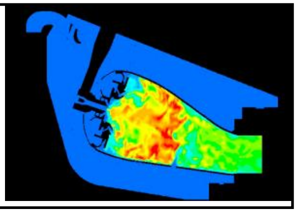
Annular Rig Test
Method:
Testing with Scaled Conditions
Purpose:
Test Assessment All Parameters



Sector Rig Test
Method:
Sub-element Testing
Purpose:
Test Evaluation of Concepts



Analysis
Method:
CFD w/ Large-Eddy-Simulation
Purpose:
Concept Screening & Evaluation



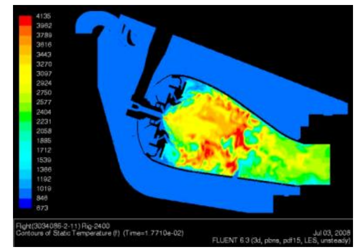
Process

Combustion Design and Analysis Enablers

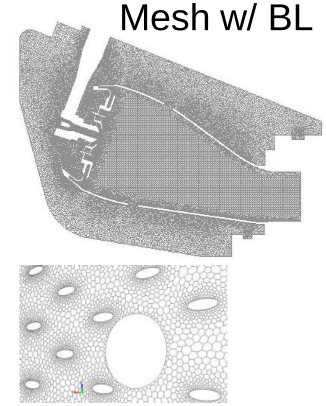
Combustor Analysis

- CFD Analysis focus:
  - High-fidelity mesh generation
  - Large Eddy Simulation
  - High-Fidelity Reduced Mechanisms for Jet-A
  - Soot Modeling & Radiation
  - Spray Modeling
  - Conjugate Heat Transfer
  - High Performance Computing
- Thermo-mechanical Analysis focus:
  - Combustor materials & coatings Properties & Lifing

LES Analysis



Conformal Mesh w/ BL



High Performance Compute Cluster

Enablers

Partnership with Academia

Arizona State University

Honeywell

Combustion Testing Enablers

Combustor Testing

Leverage Existing facilities:

- Sector & Annular Rig Testing
- Tech7000 Engine
- B757 Flight testing

Continue to Develop :

- Configured Specimen Testing
- Optical access to primary zone
- Fuel Spray Diagnostics

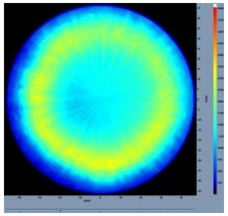
Sector & Annular RigTesting

Tech7000 Engine Ground/Flight

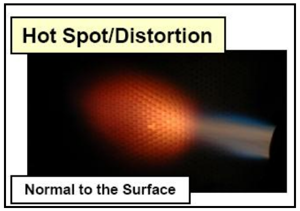
In-Situ Optical Diagnostics

Enablers

Fuel Spray Diagnostics



Configured Specimen Testing



Combustor Technology: Well Coordinated Combustor Development Shop and Production Shop

Production Facility

- High volume
- Low cost
- Full manufacturing capability
- Process knowledge transitioned to & from Development Shop

Process Knowledge

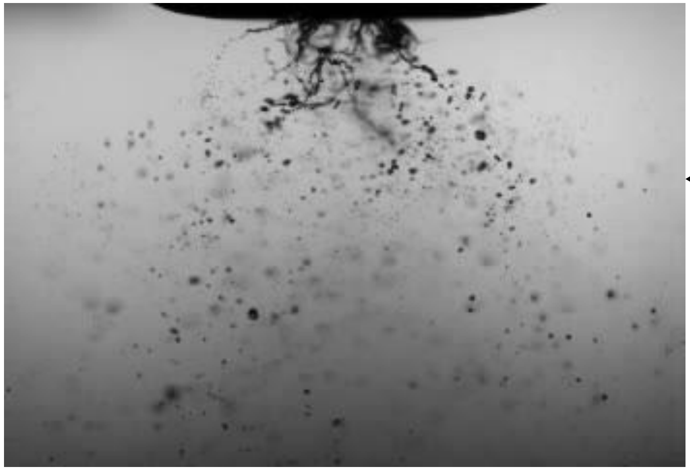
Combustor Development Shop

- Rapid hardware turnaround
- Full manufacturing & repair capability
- Production quality
- Process knowledge transitioned to & from Production Facility

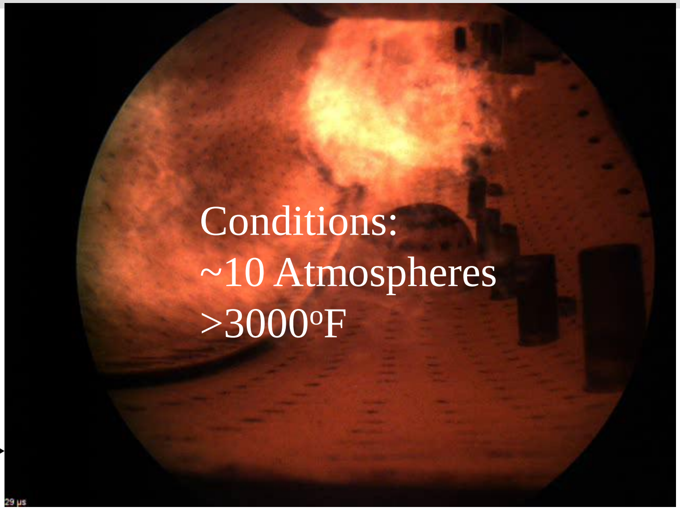
Combustor performance remains unchanged between facilities

Enablers

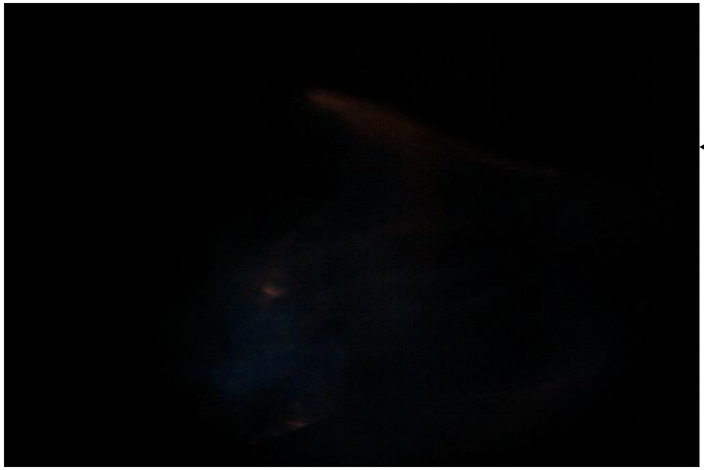
Optical Capability Provides Enhanced Understanding



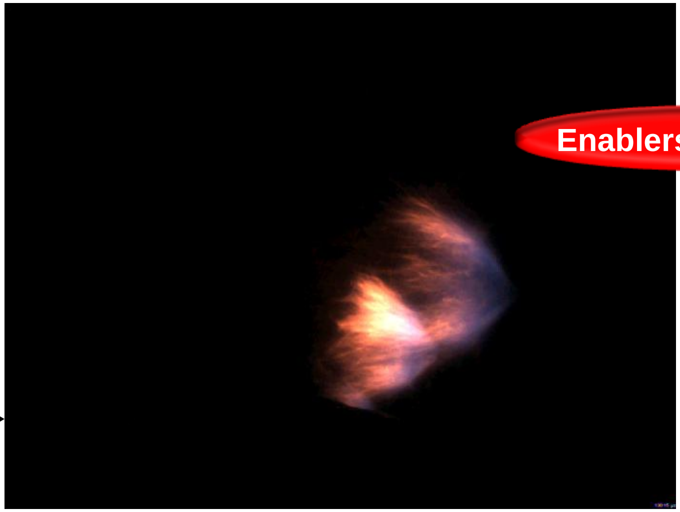
Atomizer spray @ 25,000 fps



Full power on full annular rig @ 20fps



Post ignition on full annular rig @ 20 fps



LBO on sector rig @ 20fps

Enablers

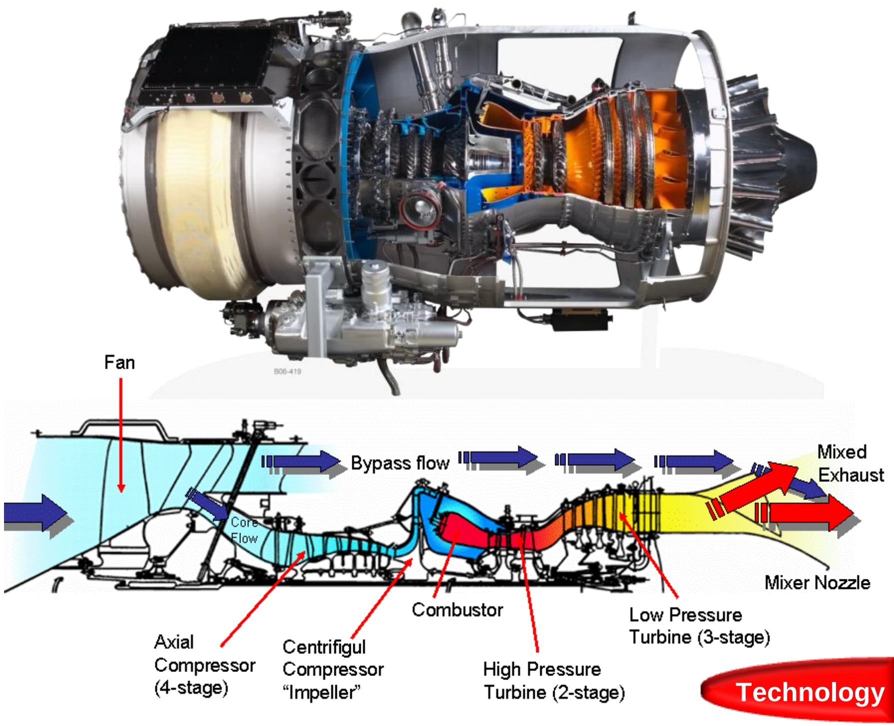
HTF7000 Turbofan Engine Family

Overall Description:

- 30.6 kN (6,900 lbs) SL takeoff thrust
- PR@Sea level = 22, BPR = 4.2
- Architecture: 2 spool, 2 fan, 4 axial + centrifugal compressor, 2-stage HP turbine, 3-stage LP turbine

Aircraft Applications:

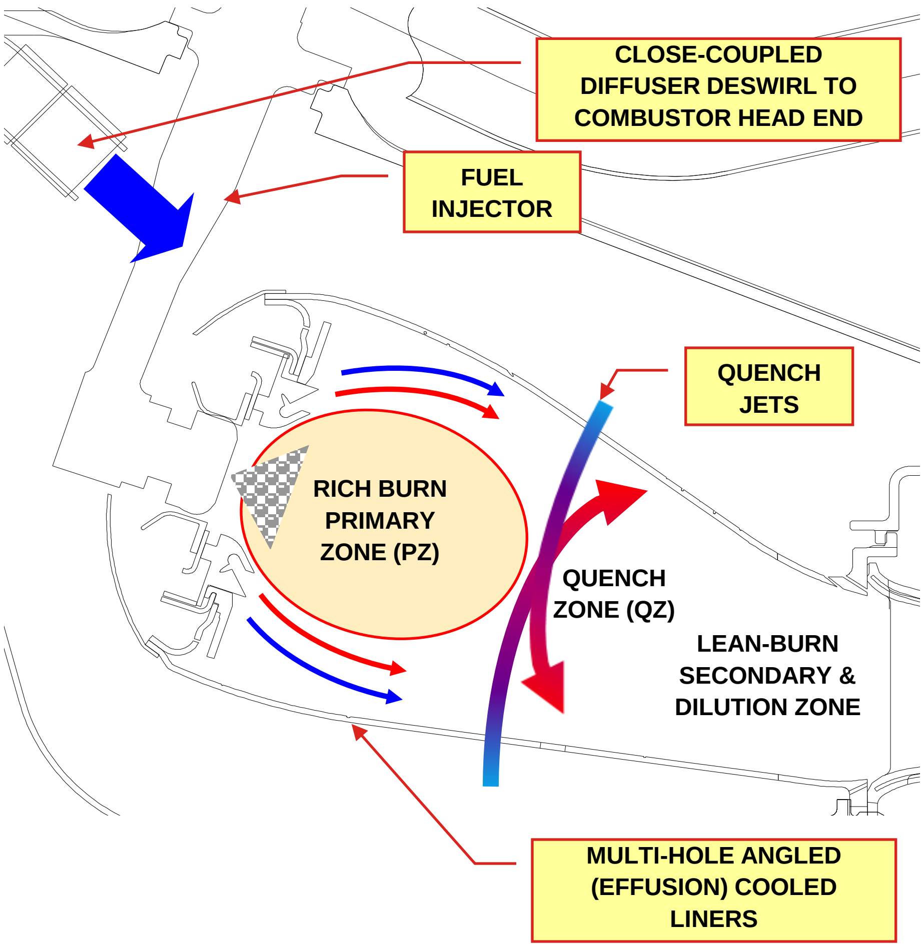
- HTF7000: Bombardier Challenger 300, Certified in 2002 with 600 engines w/ 2,000,000 hours; Recertified with SABER-1 combustor in 2010
- HTF7250G: Gulfstream G280, Certified in 2013
- HTF7500E: Embraer Legacy 450/500, Certified in 2014
- HTF7350: Bombardier Challenger 350 - 2014



HTF7000 Powerplant System

Low-Emissions Combustor Technology Initially Focused on HTF7000

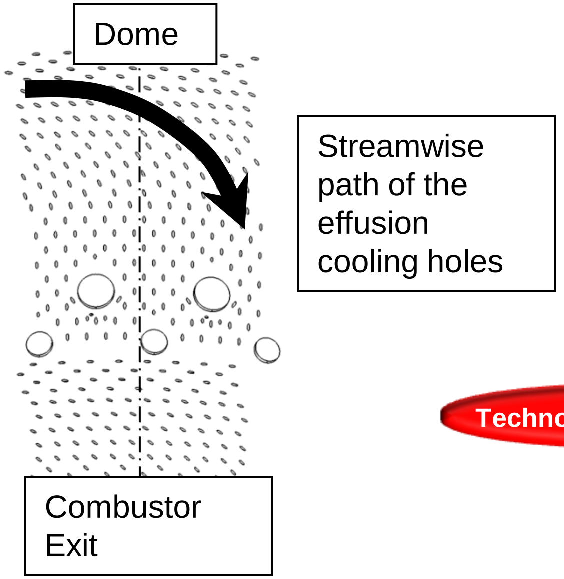
Design Features of SABER-1



SABER

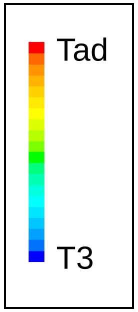
Single **A**nnular com**B**ustor for **E**missions **R**eduction

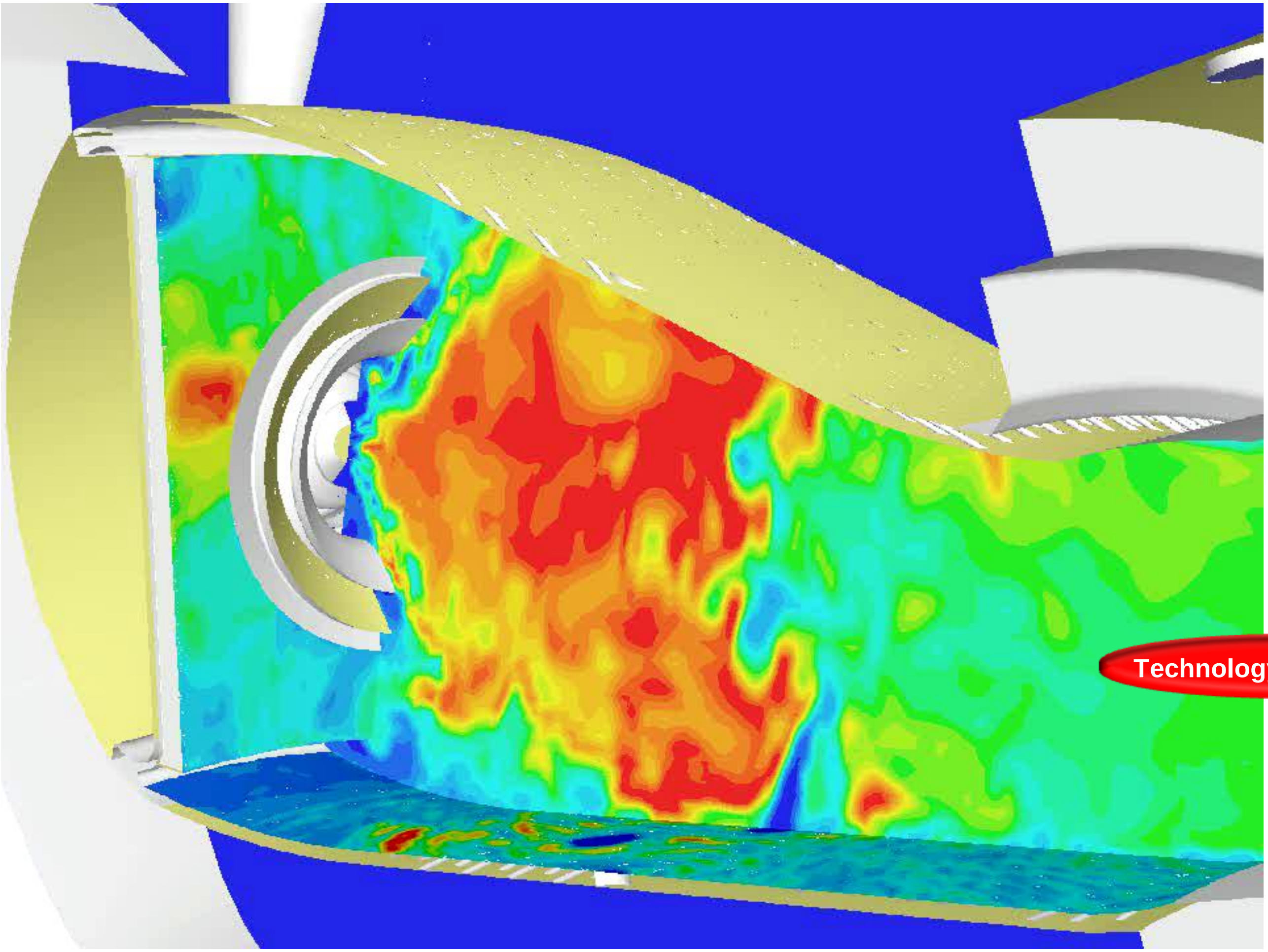
MULTI-HOLE ANGLED (EFFUSION) COOLED LINERS



Technology

Temperature Contours are Injector CL



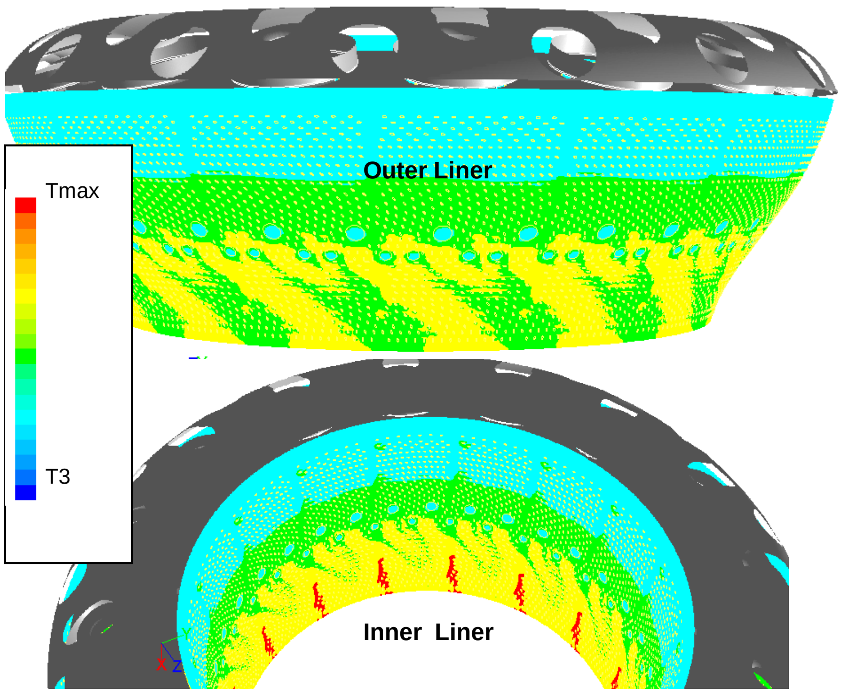


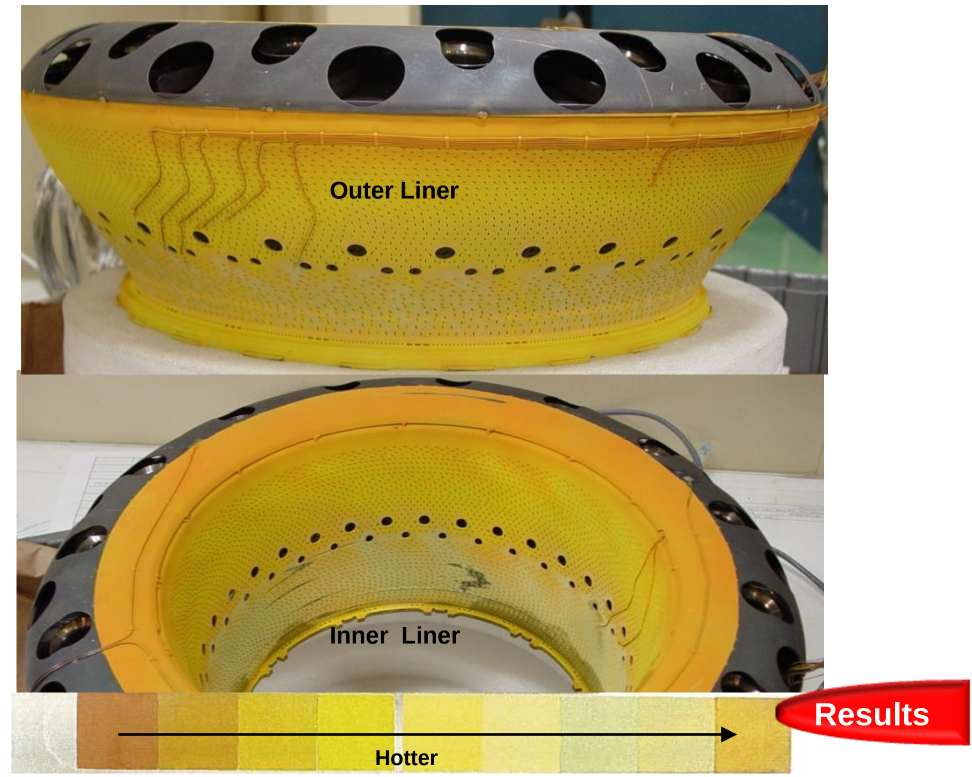
CFD Modeling approach:

- Geometry: High-fidelity Annulus + Combustor Model
- Turbulence: Large Eddy Simulation
- Chemistry: Laminar Flamelet with reduced jet-A mechanism
- Fuel Spray: Lagrangian tracking, from experimental data
- Soot: Customized formation, coagulation, oxidation model
- Radiation: Discrete-Ordinates

Technology

Comparison of predicted/measured wall temperatures



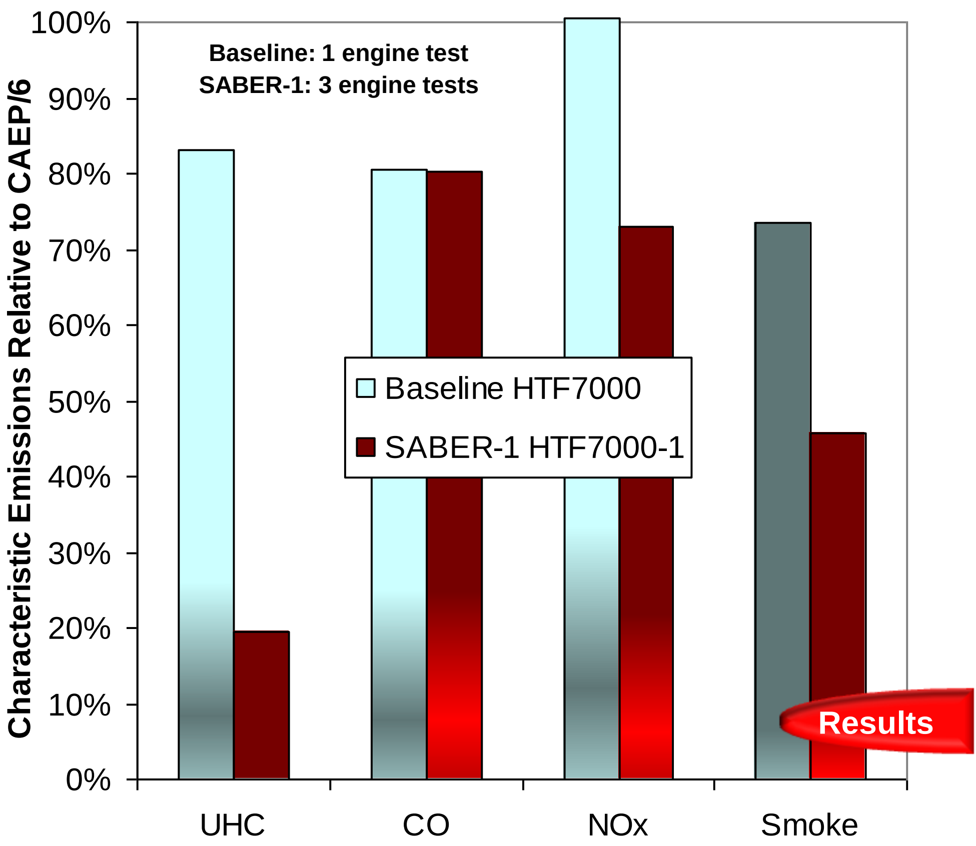


- Liner Temperatures predicted using hot-side convective/radiation boundaries*
- Quantitative predictions match well to measured results

* R. Dudebout, R. Bohman and R. R. Reynolds "Development of an Effusion Cooled Combustor for the TFE731-60 Turbofan Engine", ISABE 2007-1199, Sept 2007.

SABER-1 Validation & Certification

- Extensive development testing
  - 18 sector rig tests
  - 30 rig tests
  - 2 endurance tests
  - 2 emissions tests
  - 1 noise test
  - 3 flight tests
- Initial certification in 2010:
  - Compatibility, Operability, Durability and Emissions validated



Significant Emissions Reduction Achieved

Summary & Outlook

- ICAO LTO Emissions for Small Engines have sensitivity to scale effects
- Low emissions combustors require careful balance to satisfy operability and hot section life requirements in addition to emissions regulations
- Analytical design, test and fabrication tools enable successful delivery low emissions designs to market
- Honeywell has developed SABER Rich-Quench-Lean technology for initial application to the HTF7000 turbofan engine family
- Honeywell continues work to further reduce emissions on the SABER family of combustors

Summary