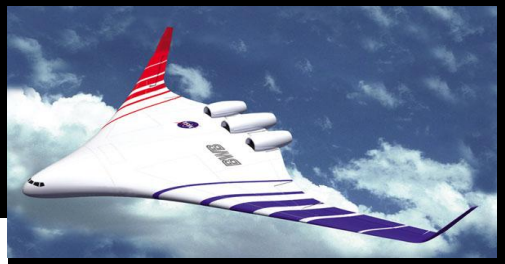
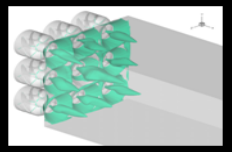
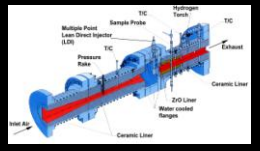
NASA Low NOx Fuel Flexible Combustor Technical Challenges
NASA Green Aviation Summit

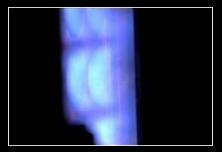
Chi-Ming Lee
Chief of Combustion Branch
NASA Glenn Research Center



September 8-9, 2010
NASA AMES







ERA/SFW System Level Metrics

…. technology for improving noise, emissions, & performance

CORNERS OF THE TRADE SPACE	N+1 (2015)*** Generation Conventional Configurations relative to 1998 reference	N+2 (2020)*** Generation Unconventional Configurations relative to 1998 reference	N+3 (2025)*** Generation Advanced Aircraft Concepts relative to user-defined reference
Noise (cum below Stage 4)	-32 dB	-42 dB	-71dB
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-40%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts

***Technology Readiness Level for key technologies = 4-6

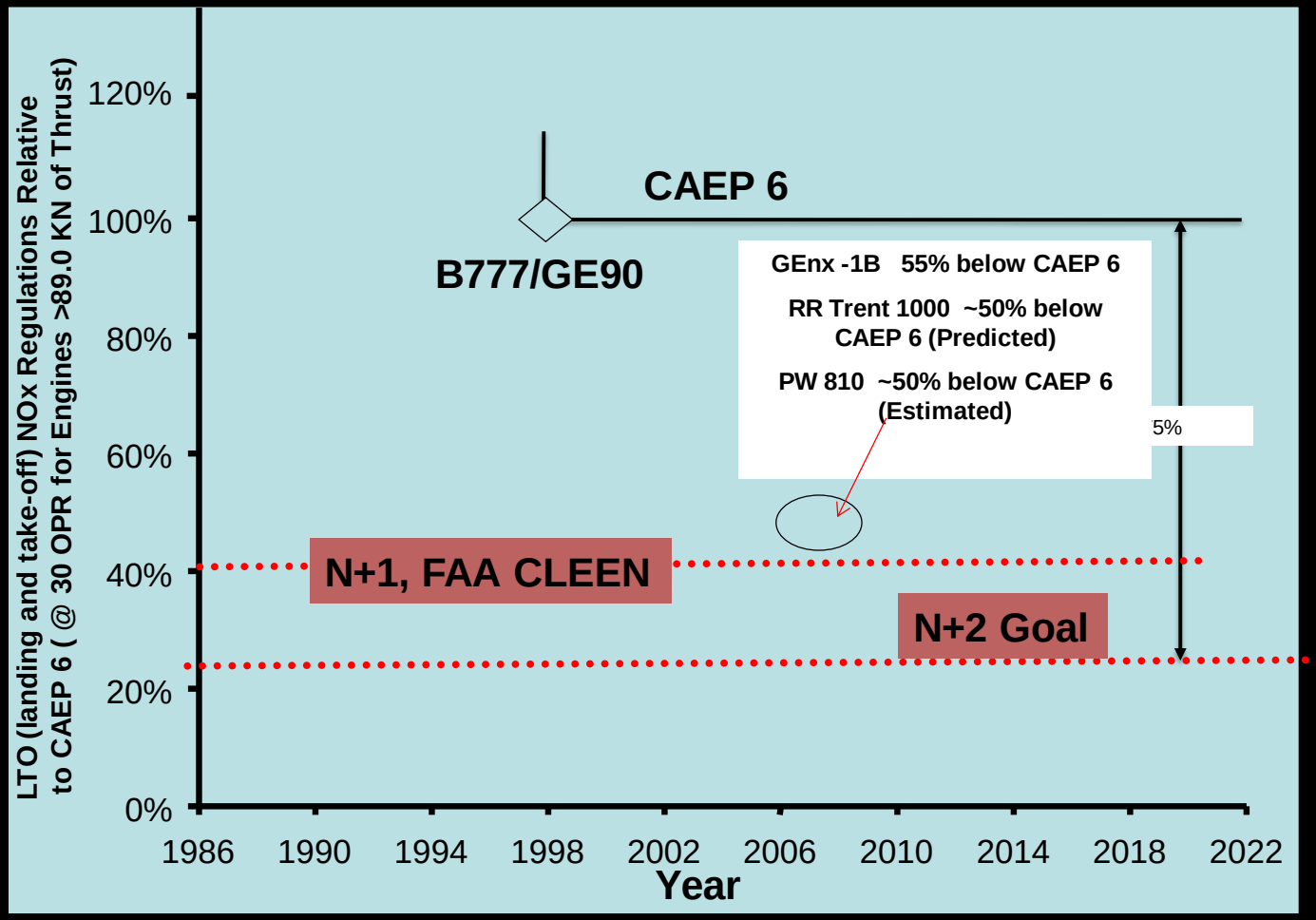
** Additional gains may be possible through operational improvements

* Concepts that enable optimal use of runways at multiple airports within the metropolitan area

Approach

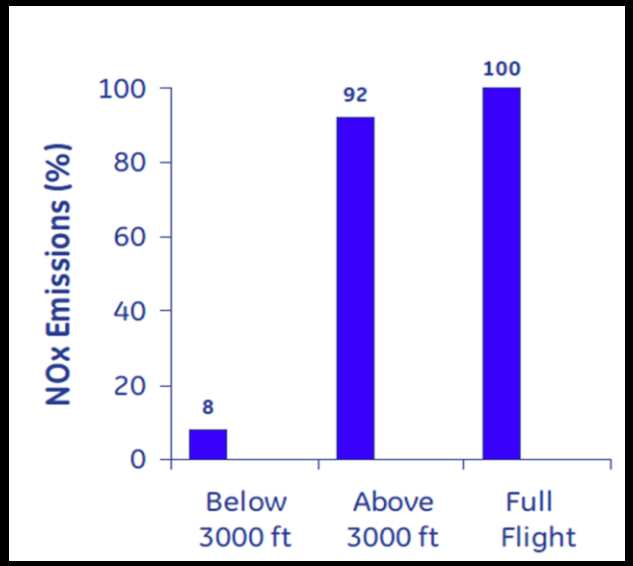
- *Enable Major Changes in Engine Cycle/Airframe Configurations*
- *Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools & Processes*
- *Develop/Test/ Analyze Advanced Multi-Discipline Based Concepts & Technologies*

CAEP6 ICAO NOx Regulations for Engines



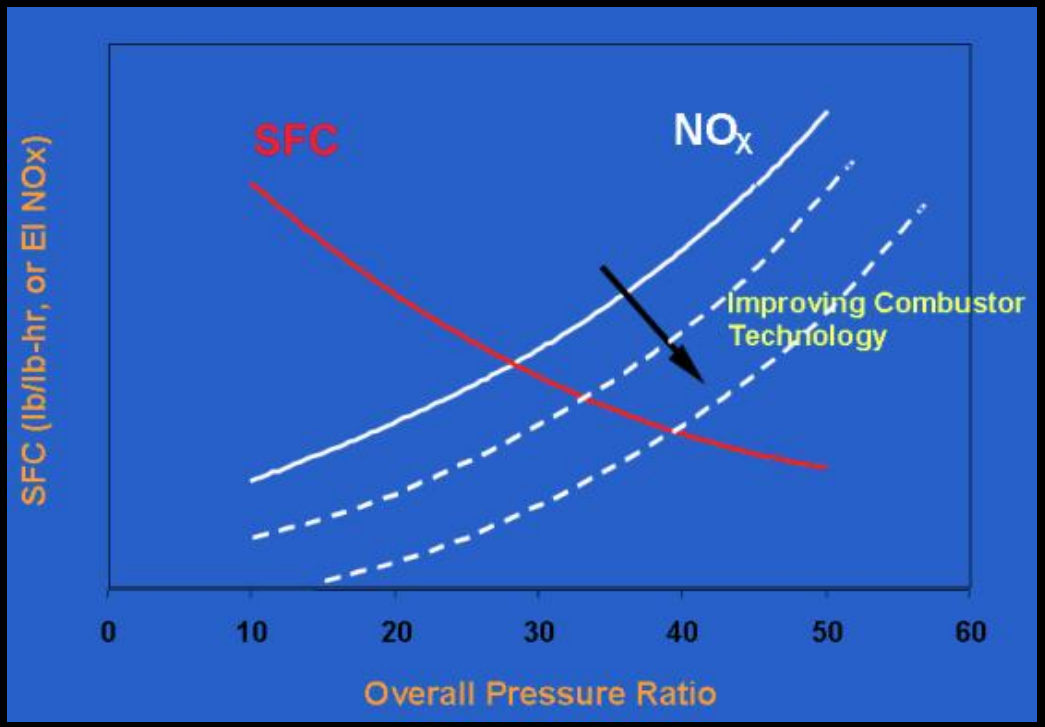
Motivation for NOx Technology Investment

- Environmental impact
  - **Ground level LTO NOx affects local air quality (NO2, ozone and secondary PM)**
  - **NOx above 3000 ft accounts for 92% of total mission**
  - **Cruise NOx affects climate and "global" air quality**
- Stringency increase for LTO and enroute NOx policies expected
- Balances SFC improvements (OPR ↑) and traffic growth

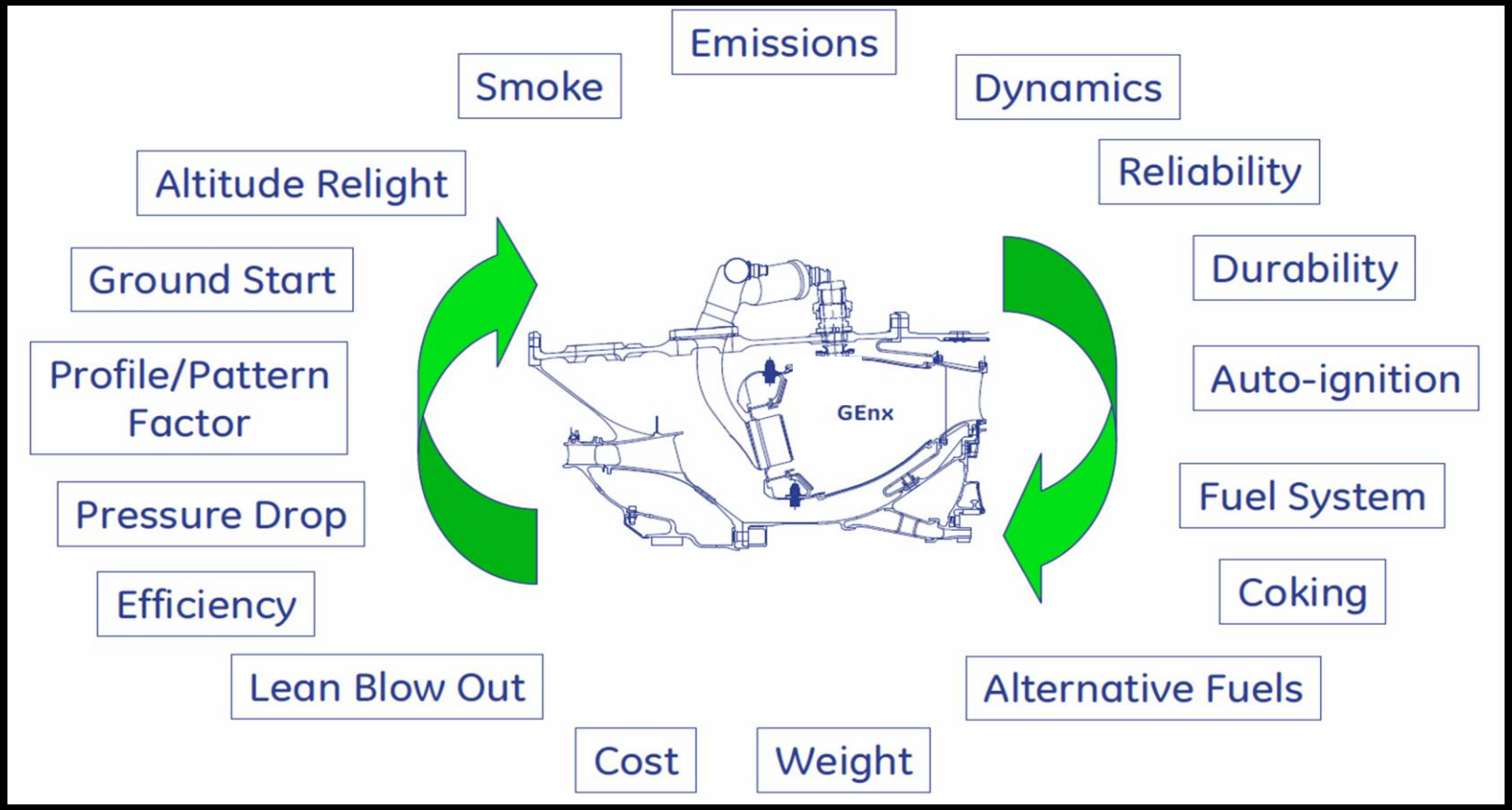


CAEP/8 NOx Stringency Sample Problem – Round 2 Process, Assumptions And Results, Working Paper CAEP8-MODTF3-WP11, Modelling And Database Task Force (MODTF), Oct. 2007

NOx emissions vs. the Overall Pressure Ratio and SFC

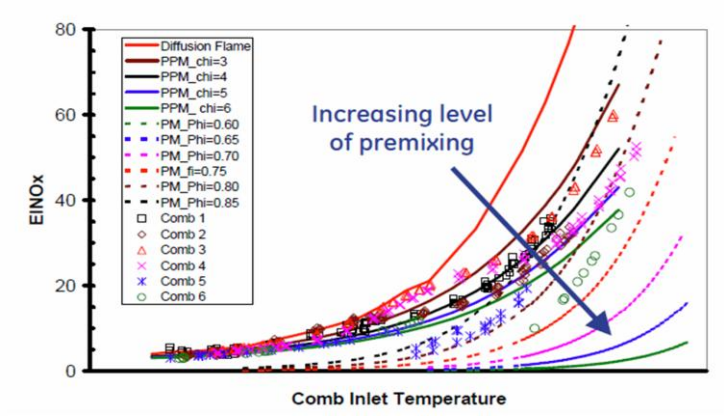


Balanced Combustor Design



ERA Technology Focus

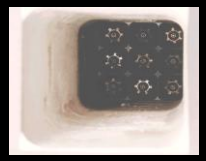
- Significant further NOx reduction
- Leaner combustion through reduced cooling
- Improved fuel-air mixer designs
- Active control strategies
- Advanced CMC liners



Emissions Reduction - Technology to Product Transition

NASA Program → **Industry Product Integration**

Market conditions and available technology improvements determine opportunity to launch new product engine



Complexity

"Off-Ramp" for Technology

Industry:

- Scaling to product engine size
- Production engine design
- Durability testing
- Transient testing (altitude/flying test-bed)
- Inclement weather testing
- Manufacturing processes and tooling
- Certification
- Product support

NASA Project will develop and demonstrate low emissions to a technology readiness level (TRL) 6

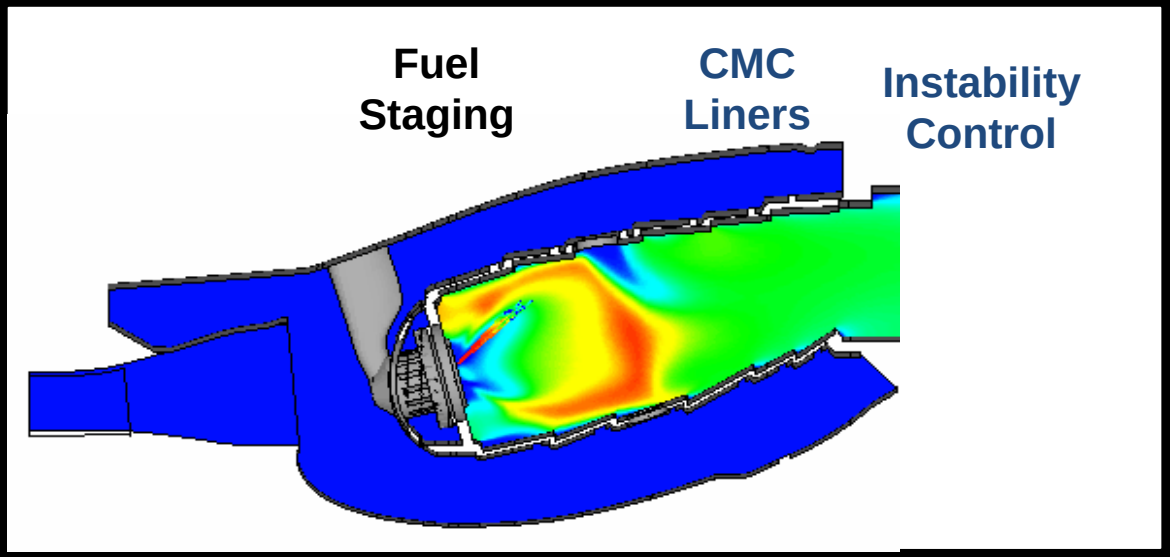
Flametube Combustor	Sector Combustor	Full Annular Combustor	Engine Integration	Certification and Entry Into service
TRL- 3	TRL- 4	TRL- 5	TRL- 6	TRL-9

NASA and Industry Partnership for Low-Emission Combustor Technology Development Followed by Possible Industry Certification and Product Implementation

Fuel Flexible/Low Emissions

Combustor Technical Challenges

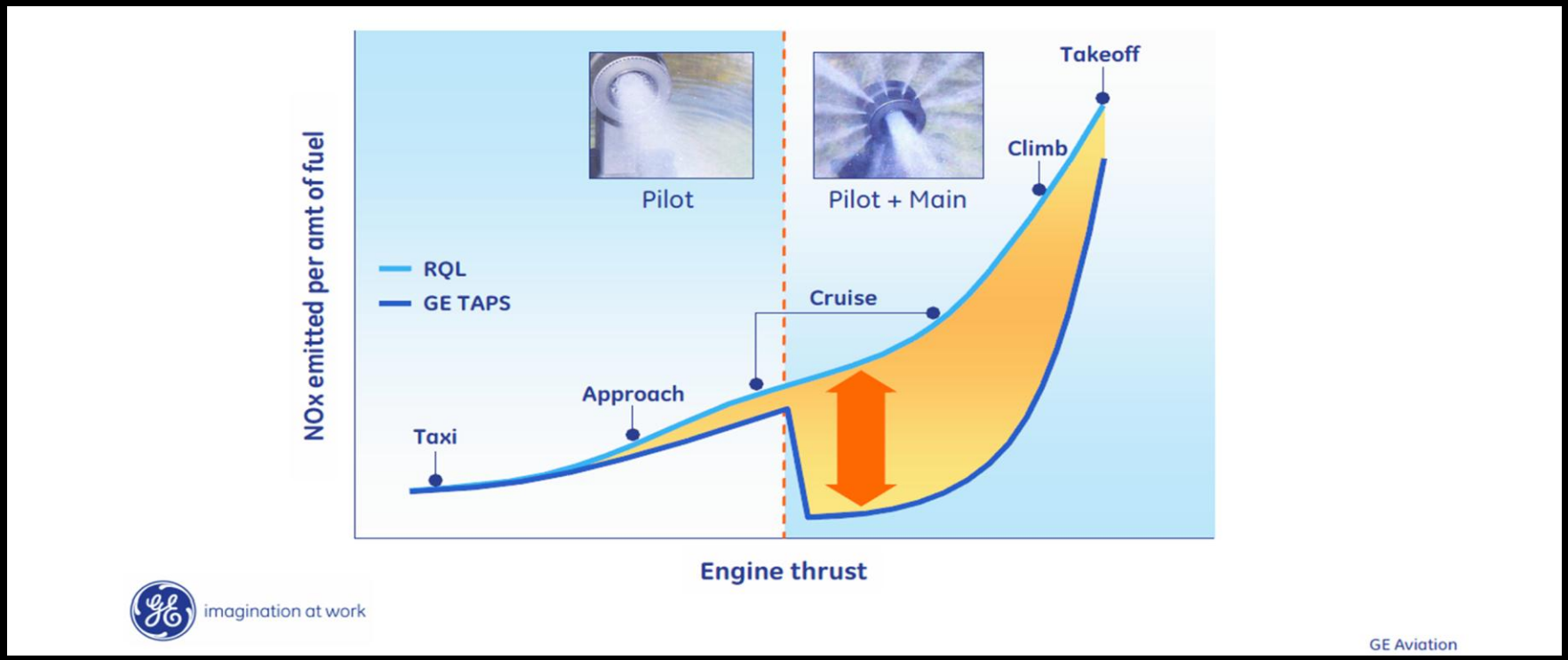
- Injector/Mixer Design
- Active Combustion Control
- High Temperature Combustion Liner



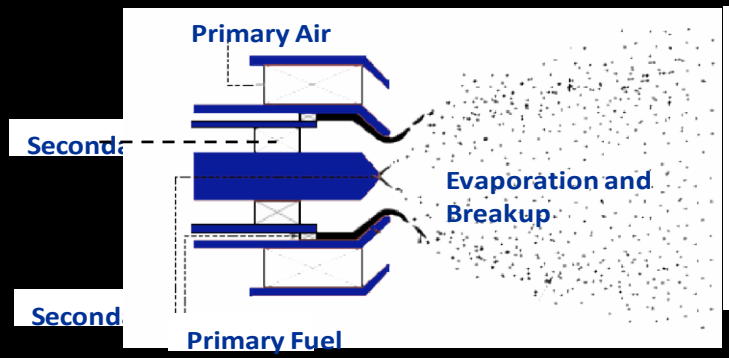
Injector/Mixer Design Challenge

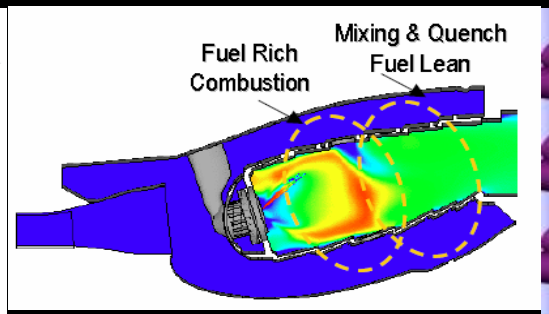
TAPS Fuel Staging Enables Low Nox at Cruise

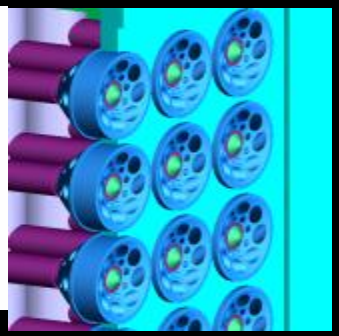
NOx flight cycle comparison (GE TAPS vs. traditional RQL combustor)

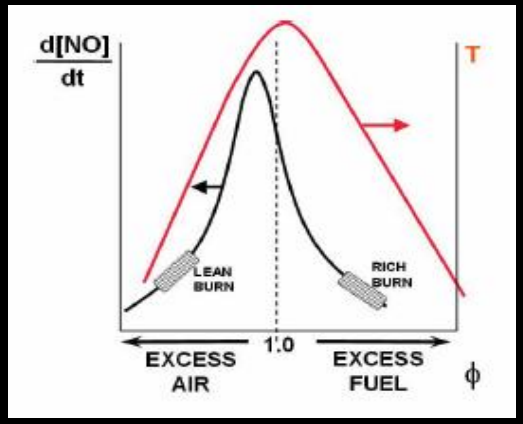


75% Nox Reduction Injector Development









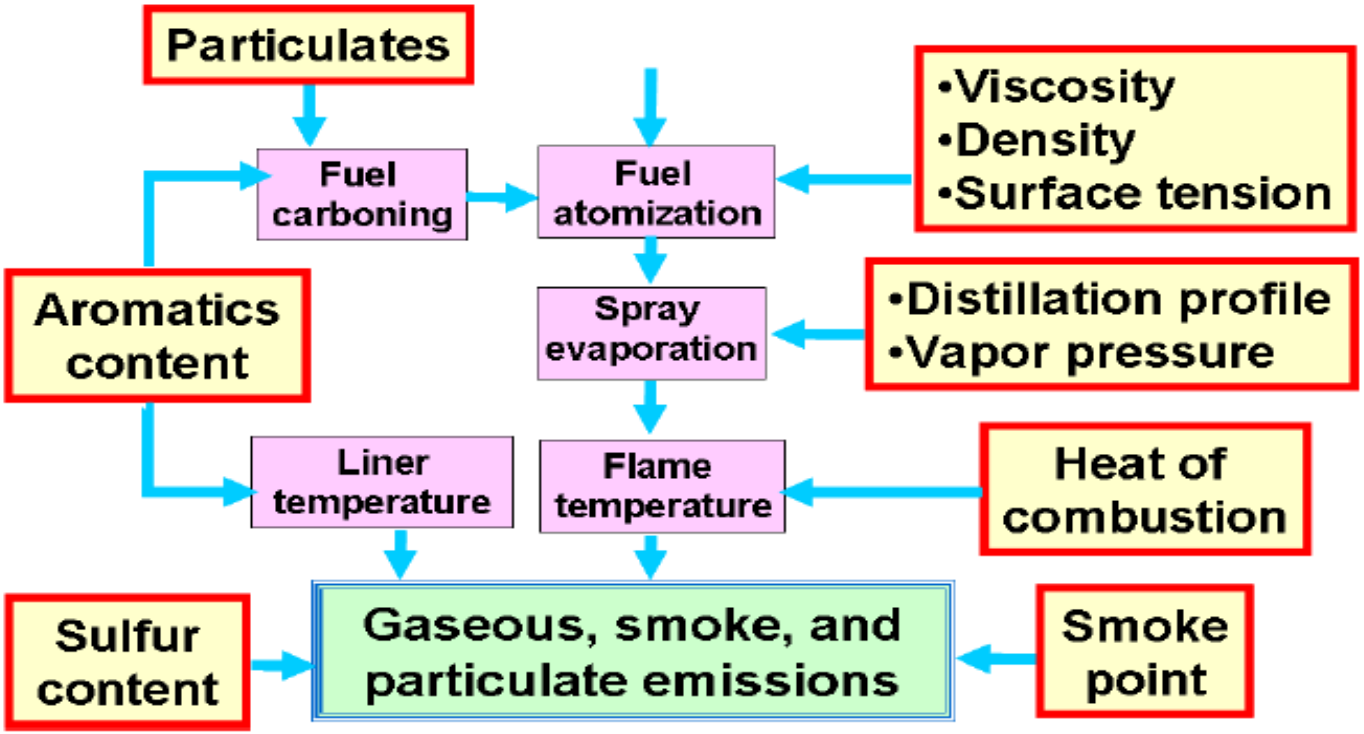
- Advanced Injector Concept
- Fuel/Air Mixing
- Ignition

Fischer-Tropsch & Jet A Fuel Analysis

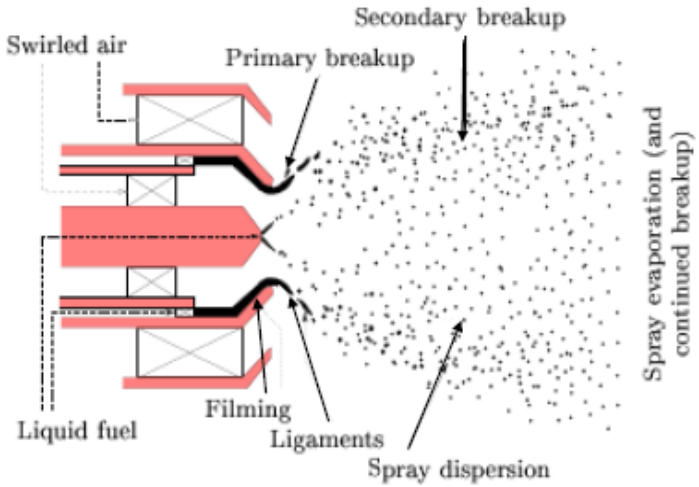
Test	F-T	Jet A
Total Acid Number (mg KOH/g)	0.002	0.00
Aromatics (% vol)	0.0	19
Mercaptan Sulfur (% mass)	0.000	0.000
Total Sulfur (% mass)	0.00	0.0
Distillation		
Initial Boiling Point (°C)	149	
10% Recovered (°C)	162	180
20% Recovered (°C)	163	
50% Recovered (°C)	168	212
90% Recovered (°C)	184	251
End Point (°C)	196	
Residue (% vol)	0.9	1.3
Loss (% vol)	0.4	0.9
Flash Point (°C)	44	51
API Gravity @ 60°F	60.5	
Freezing Point (°C)	-55	-48
Viscosity @ -20°C (mm^2/s)	2.6	5.2
Net Heat of Combustion (MJ/kg)	44.2	42.8

Test	F-T	Jet A
Hydrogen Content (% mass)	15.6	13.0
Smoke Point (mm)	40.0	21
Copper Strip Corrosion (2 h @ 100°C)	1a	
Thermal Stability @ 260°C		
Change in Pressure (mmHg)	0	1
Tube Deposit Rating, Visual	1	0
Existent Gum (mg/100 mL)	<1	0.2
Particulate Matter (mg/L)	0.4	0.2
Filtration Time (min)	2	
Water Reaction Interface Rating	1	1
FSII (% vol)	0.00	0.00
Conductivity (pS/m)	217	10
Lubricity Test (BOCLE) Wear Scar (mm)	0.75	
Net Heat of Combustion (MJ/kg)	44.0	43.2
Workmanship	Pass	Pass

Impact of fuel properties on emissions



Fuel properties impact on atomization



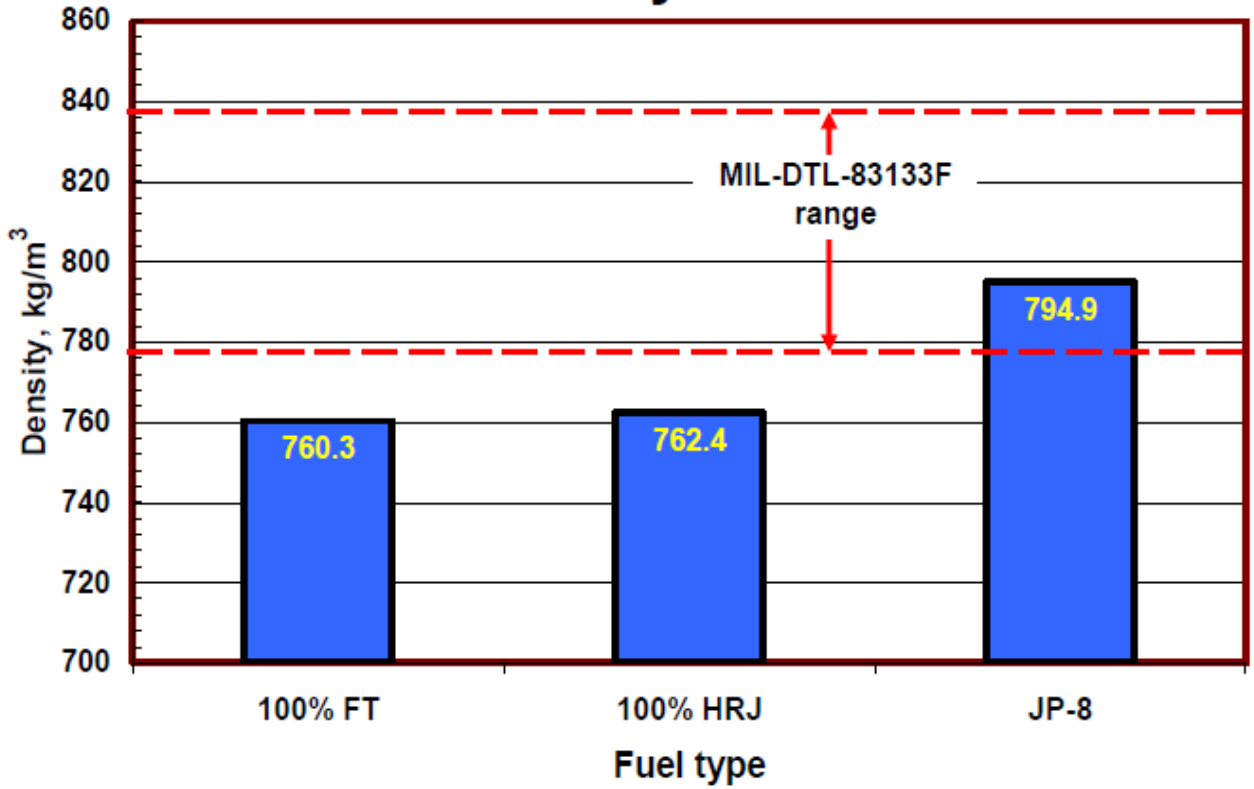
- Notable expression for airblast atomizers is given by:

$$SMD = (1 + FAR)\left(0.33 \left\{\frac{\sigma}{\rho_A D_p U_A^2}\right\}^{0.6} \left\{\frac{\rho_L}{\rho_A}\right\}^{0.1} + 0.068 \left\{\frac{\mu_L^2}{\rho_L \sigma D_p}\right\}^{0.5}\right) D_h$$

- Notable expression for pressure swirl atomizers is given by:

$$SMD = 2.25\,(\sigma \,.\, \mu_L \,.\, W_L)^{0.25} \,.\, \Delta P_L^{-0.5} \,.\, \rho_A^{-0.25}$$

Alternative fuels density



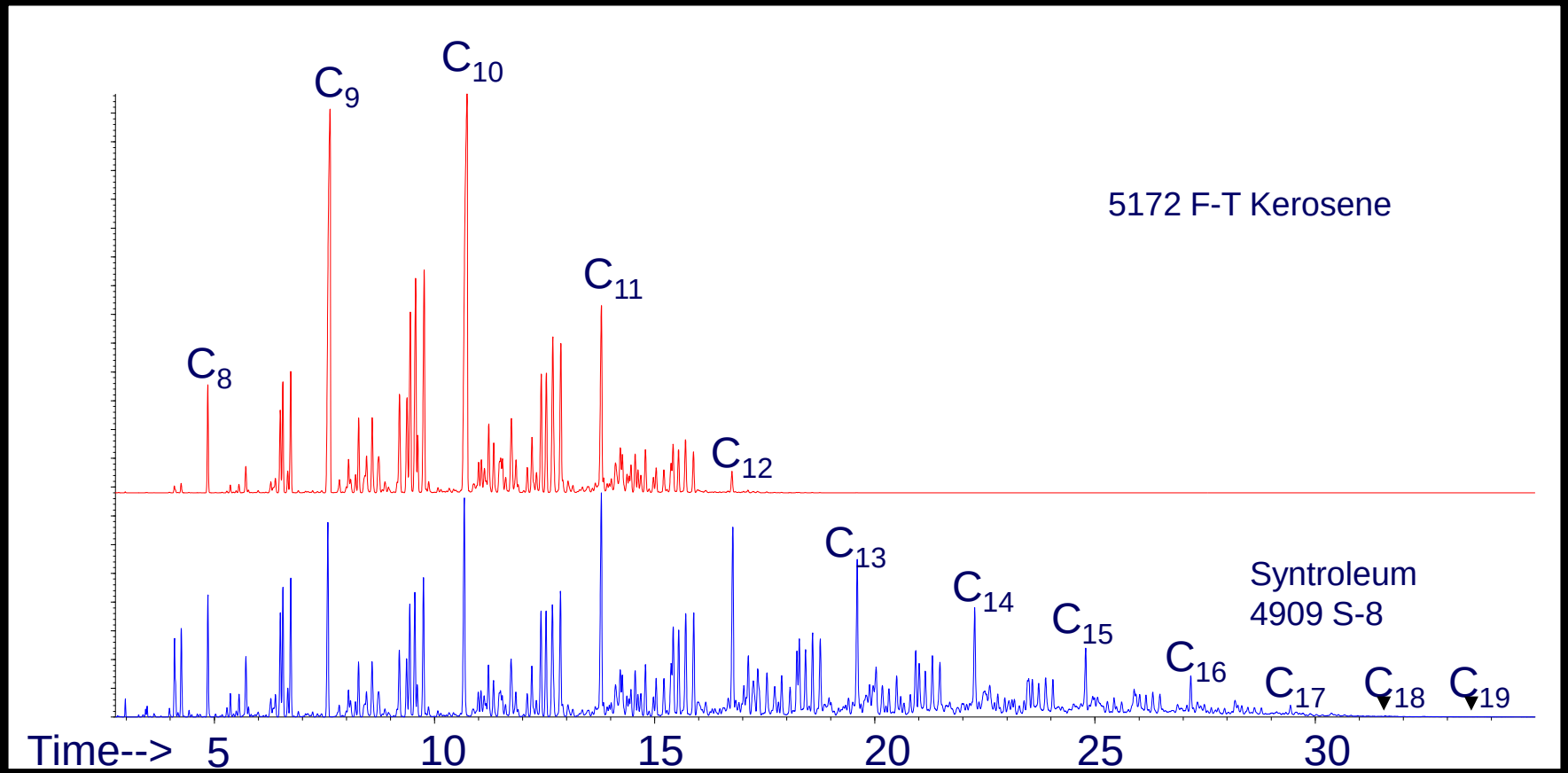
- Density of JP-8 tested is close to mean value
- Both FT and HRJ fuels are below density specifications

Additional key fuel

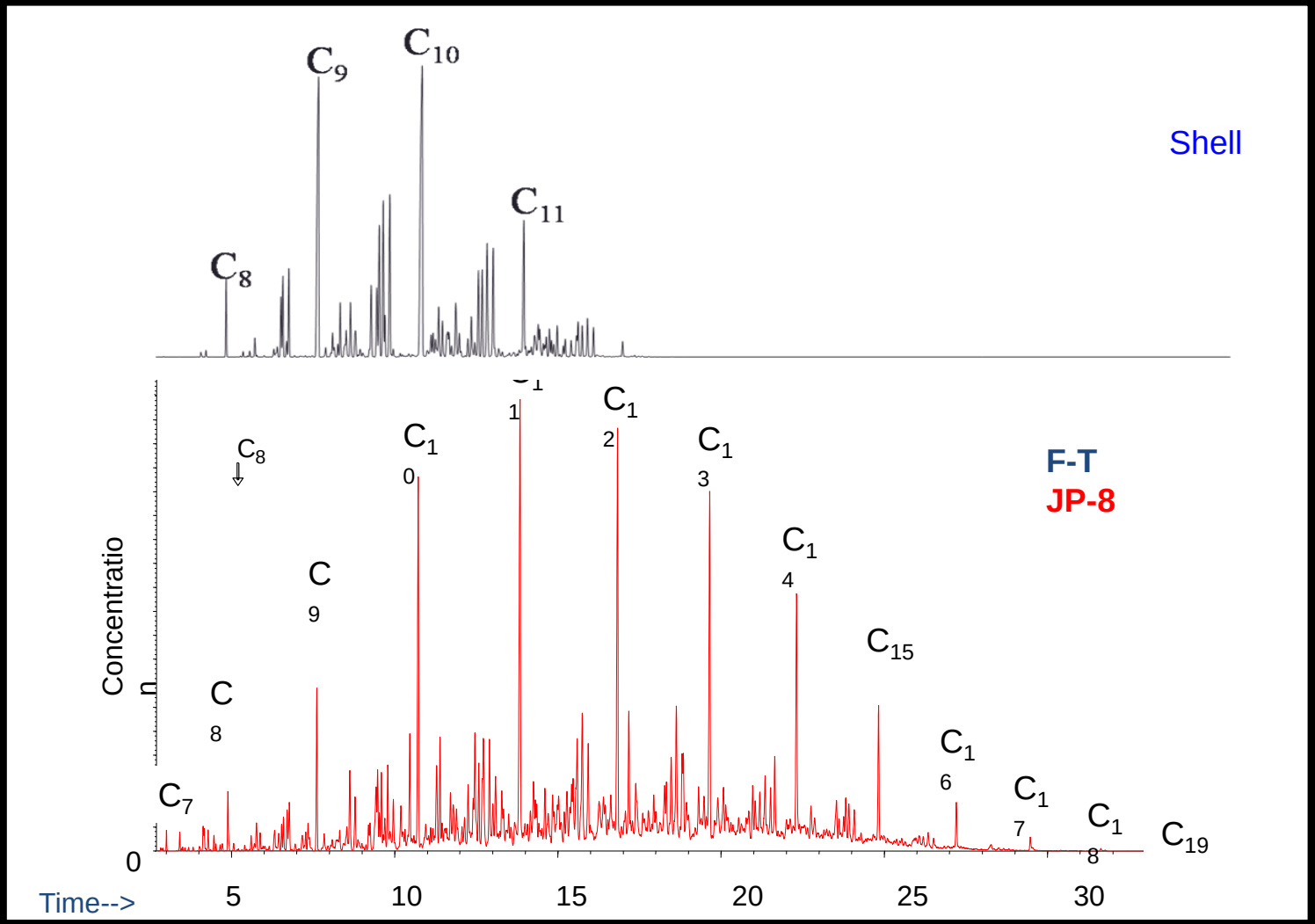
Property	Units	Limits	MIL-DTL-83133F JP8	100% FT	100% HRJ	JP-8
Aromatics	%v/v	Max	25.0	0.6	0.0	18.0
Specific energy (NHC)	MJ/kg	Min	42.8	44.3	44.3	43.5
Smoke point	mm	Min	25.0	50.0	>40.0	25.0
Hydrogen content	%w/w	Min	13.4	15.1	15.3	13.9

- HRJ has lowest aromatics and highest hydrogen content
- JP-8 has lowest specific energy, SP, and hydrogen content

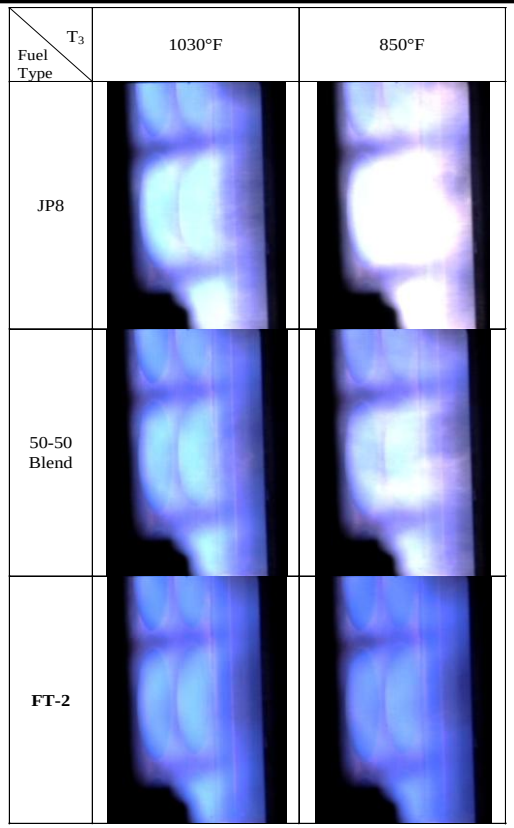
F-T Fuel Analysis



Fischer-Tropsch & JP-8 Fuel Analysis

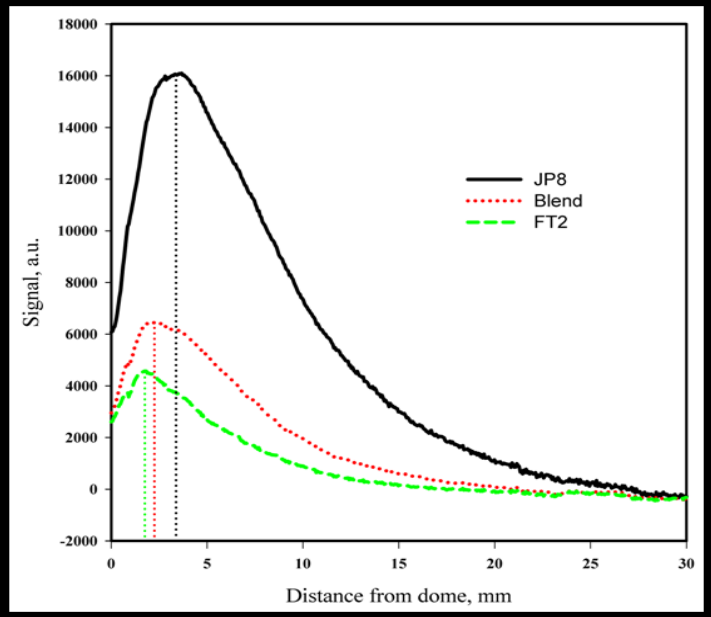


JP8, 50-50 Blend, and FT-2 Comparisons

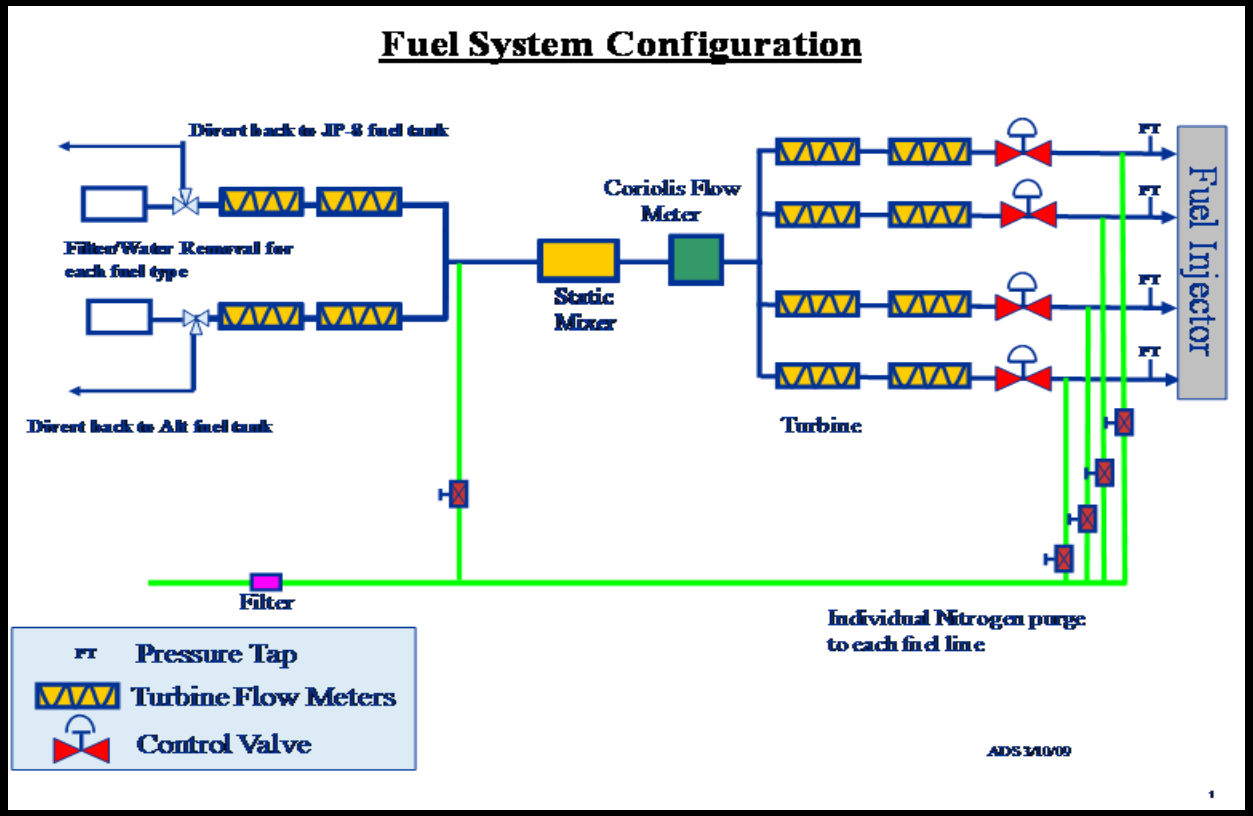


Video Images, with flow from left to right

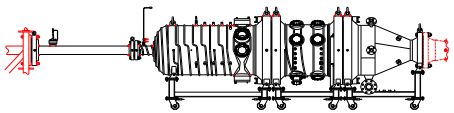
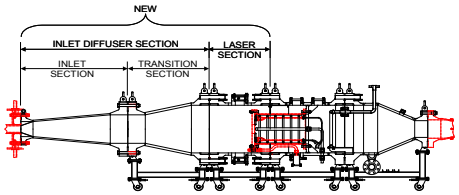
Comparison showing average flame length and luminous intensity for T3 = 1030°F



Advanced Subsonic Combustor Rig (ASCR) Alternative Fuels Establishment (cont'd)

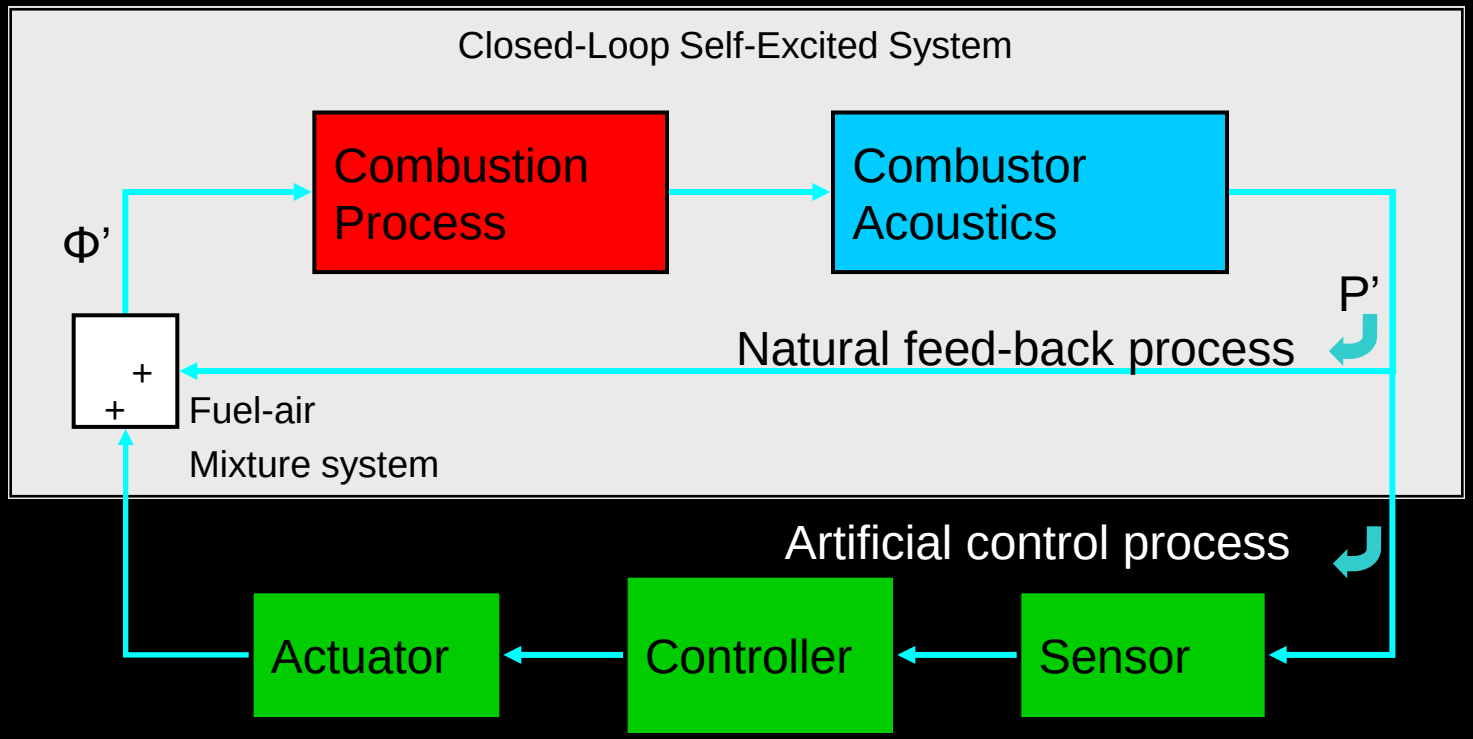


ASCR Plenum Design and Fabrication (cont'd)

EXISTING AND REVISED CONFIGURATIONS	 **Existing ASCR Sector Rig Assembly 28470M43A000**	 **Revised ASCR Sector Rig Assembly Concept**
Inlet Temperature @ Pressure	1100°F @ 600-psig	1300°F @ 900-psig
Flow Conditions	5 to 50 pound per second	5 to 50 pounds per second
Operating Pressure	30 to 900-psig	30 to 900psig
Maximum Allowable Working Pressure	1100-psig	1100-psig
Combustion Flow Temperature	3400°F	3400°F
Exhaust Flow Temperature	500°F	500°F

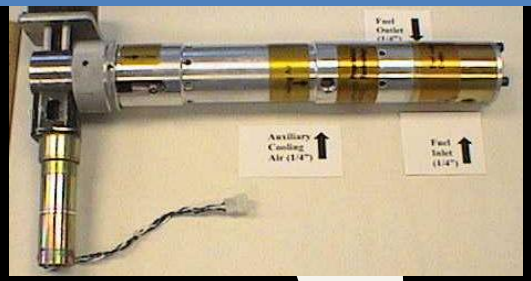
Combustion Instability Control Strategy

Objective: Suppress combustion thermo-acoustic instabilities when they occur

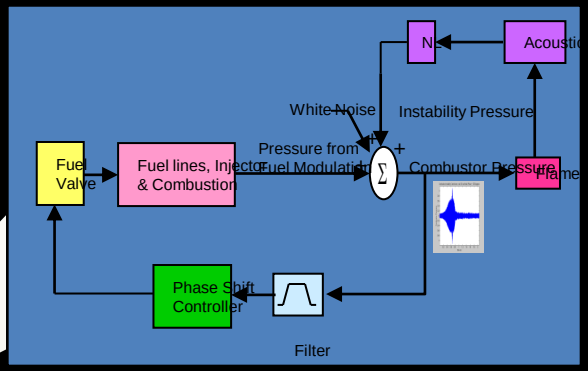


Active Combustion Instability Control Via Fuel Modulation

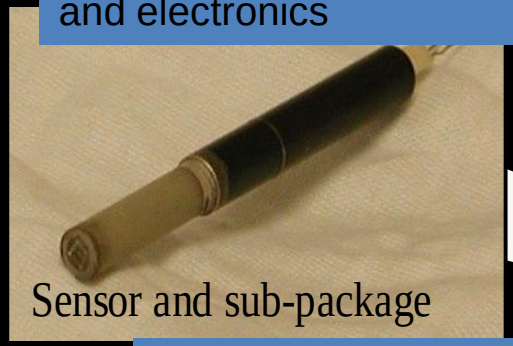
High-frequency fuel delivery system and models



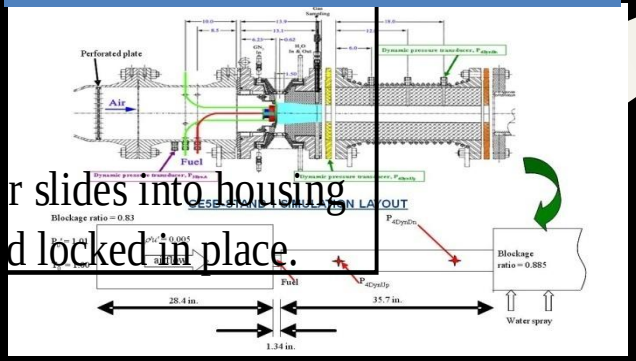
Advanced control methods



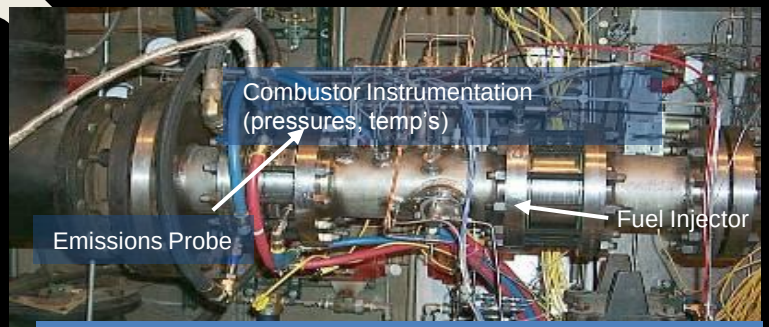
High-temperature sensors and electronics



Physics-based instability models



r slides into housing
d locked in place.



Realistic combustors, rigs for research

High Temperature Combustor Liner Challenge

Issues for CMC Liner –

Durability –

Insufficient data – both long term coupon and relevant engine environment

Mitigation – In-house durability testing, coupon creep/fatigue/etc testing, HPBR, Subcomponent (NRA) testing.

Advanced Coatings – improved coating compositions, erosion, spallation, *repairability*

Mitigation - In-house research effort on advanced coatings, HPBR investigations, insufficient funds for repairability

Integration – Attachment design & fretting coatings

Mitigation - NRA for attachment design, in-house investigation in fretting coatings, coeff friction, various materials etc

Low NO_x, Fuel-Flexible Combustion System

Hybrid Wing-Body Aircraft

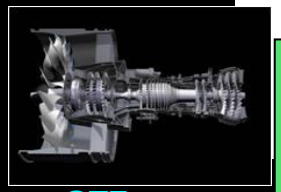
Advanced Aircraft Concept

System Design

Systems modeling
- Flexible fuel staging
- Mission profiling for emissions management

Experimental validation / verification
- Emissions and atmospheric mixing sampling
- In-flight measurement

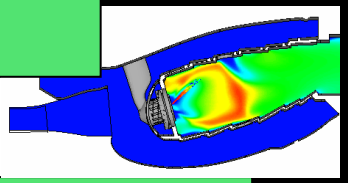
Multi-Discipline Capabilities



GTF Engine

Propulsion Contributions
- Improved propulsion efficiency
- Higher thermal efficiency

Combustion System Contributions
- Improved thermal mgt
- Light weight structures



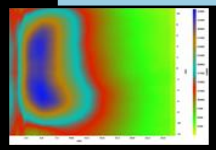
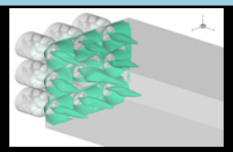
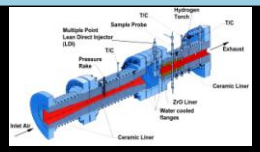
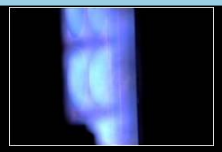
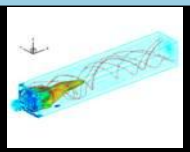
Low-NOx Combustor

Discipline Level Capabilities

Combustion Contributions
- Lower NOx Emissions
- Improved fuel-air mixing
- Advanced Active Controls
- Fuel Flexibility

Materials Contributions
- CMC combustor liners with reduced cooling
- Improved high temperature durability

Foundational Physics & Modeling

Fundamental research

CFD modeling; improved diagnostics; experimental techniques; acoustics physics; materials, etc