

NASA Aircraft Gas Turbine Combustor Emissions Research

Past, Present, and Future

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With thanks to K Ajmani, C Chang, J Klettlinger, C Lee, J Moder, R Moore, D Reddy, K Tacina

Motivation

- History of aircraft emissions reduction follows along with the public desire and demand for clean air and water, and low noise around airports, which ultimately led to…

  …Regulations (national and international): EPA, FAA, ICAO CAEP, etc.

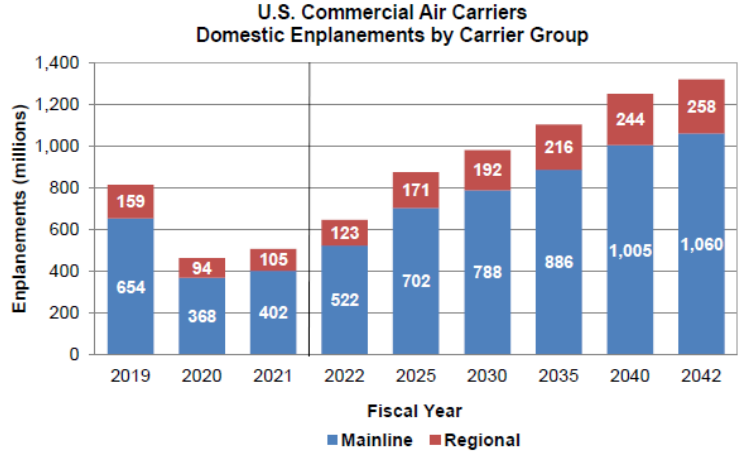
Other factors include:

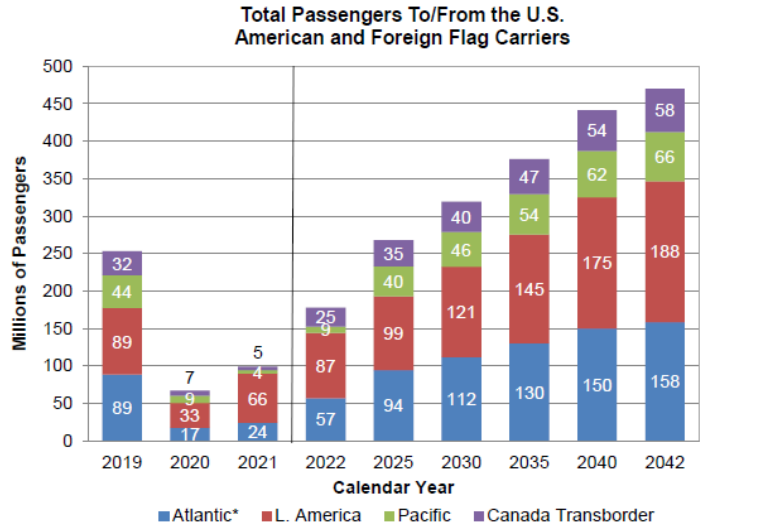
- Airlines, airframer/engine OEMs profitability
- More and more people around the world travel by air, which leads to more flights, therefore more total emissions from aircraft
- NASA is charged with pushing technology development to address national needs—advancing, collaborating, and transferring high-risk technology to the public and industry that are too risky or costly for them to do on their own

NASA Research Objectives—Emissions

- Meet or exceed noise and **emissions** regulations, fuel burn (CO_2) goals for aircraft through the years
- Focus on large aircraft—single aisle with > 90 passengers and twin aisle. These are the planes that most people fly on and would have the greatest environmental impact. Collaborate with airlines, airframe, engine and fuel injector OEMs, other government agencies (OGA), and universities to meet these goals
- Per FAA, System traffic in revenue passenger miles (RPMs) is projected to increase by 5.7 per-cent a year between 2022 and 2042.

From FAA Aerospace Forecast Fiscal Years 2022-2042:



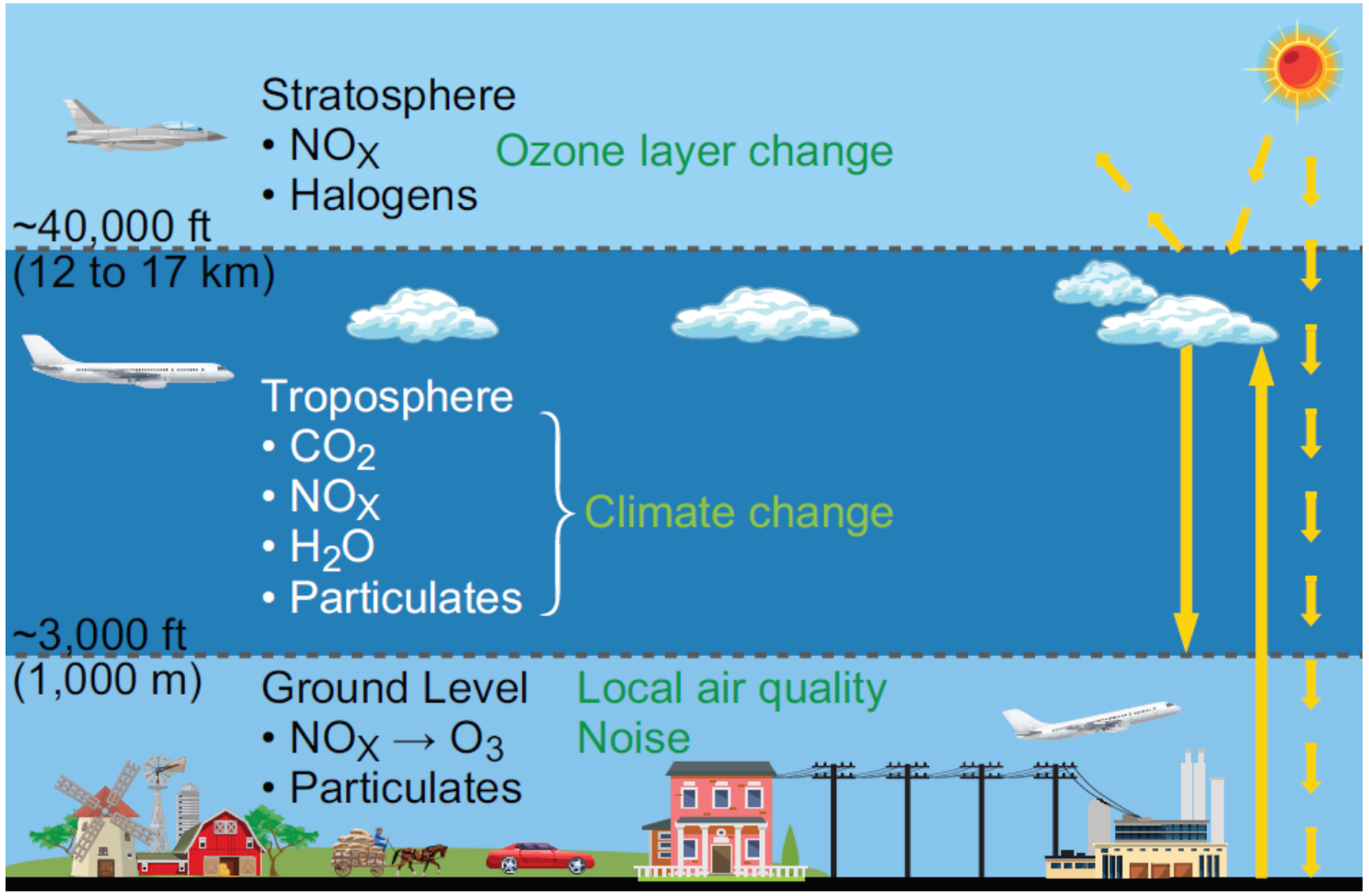


Source: US Customs & Border Protection data processed and released by Department of Commerce; data also received from Transport Canada
* Per past practice, the Mid-East region and Africa are included in the Atlantic category.

NASA has historically led the effort to reduce aviation environmental effects

For aircraft gas turbine engines

- Reduce NO_x emissions from future aircraft engines i.e., the combustors
- NO_x emissions increase smog and ozone in the lower troposphere and decrease the protective ozone layer in the stratosphere.
- More recently, we have added soot and particulate matter to the list of concerning species
- Next generation aircraft will have greater thermal and propulsive efficiency to reduce fuel burn and hence combustion emissions of CO_2 , H_2O, NO_x and particulates



Lee et al. 2021 notes that exhaust plumes contain gaseous sulfur compounds in addition to the major species and UHC Aerosol particles serve as nuclei for ice and cloud condensation. Contrails from in low-temperature ice-supersaturated air.

Outline

- Part 1. Background. A brief primer on aero engines and annular gas turbine combustors

- Part 2. Past GT Combustor research for reduced emissions. A historical look back with highlights

  ~ 1970 – 2015

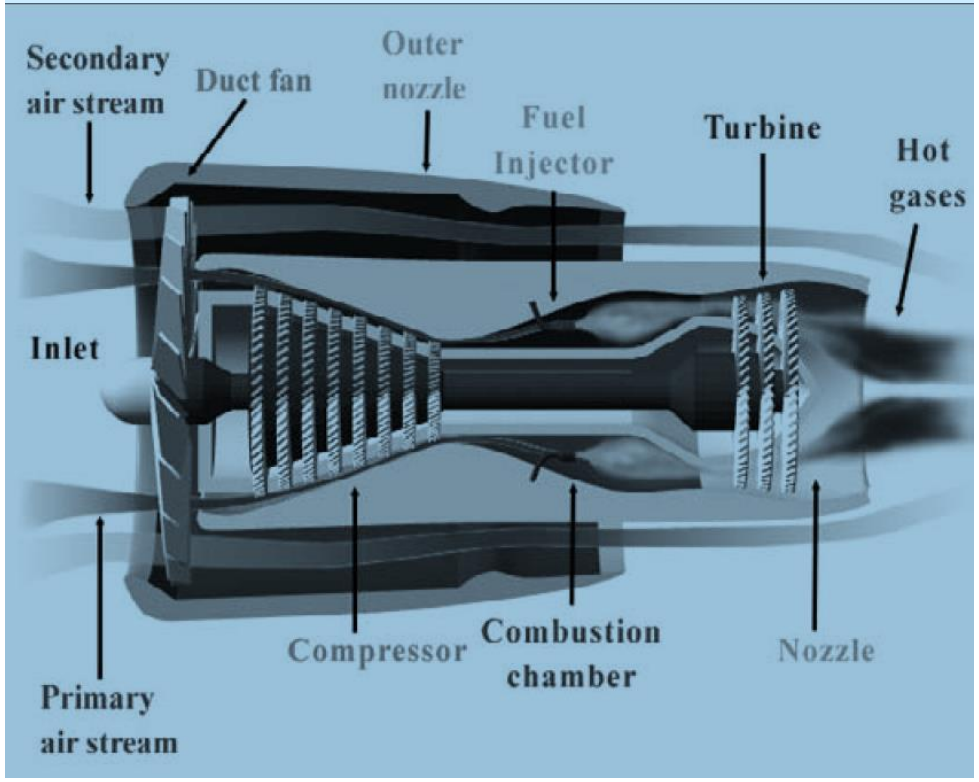
- Part 3. Present and future GT Combustor emissions-reduction research, from ~ 2015

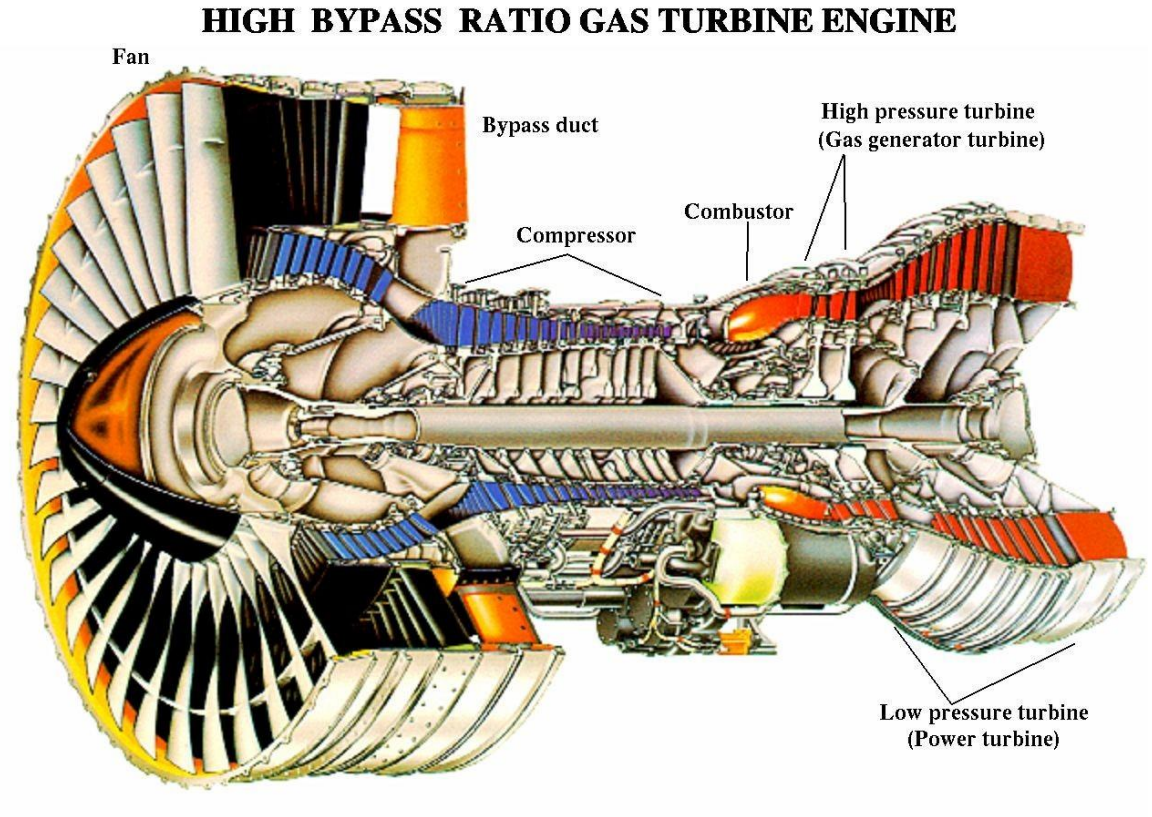
Part 1 Background information

- Aero engines and annular gas turbine combustors
  - Combustor elements
  - Combustor design requirements
  - Combustor emissions
  - Emissions regulations

Combustors in Aircraft Gas Turbine Engines

Cutaway view of a turbofan engine*



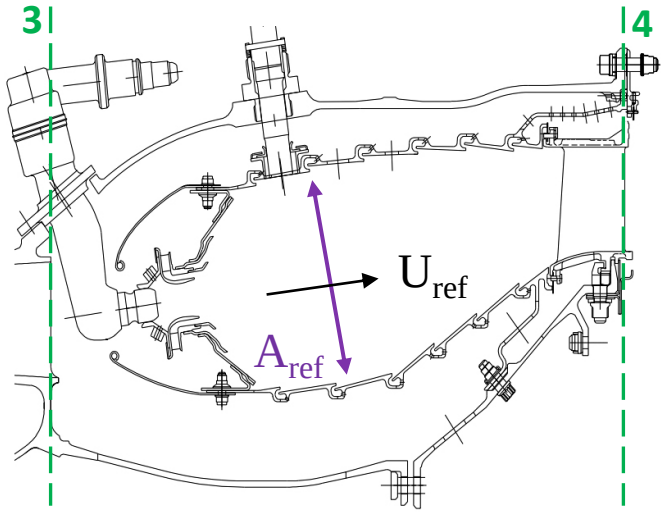


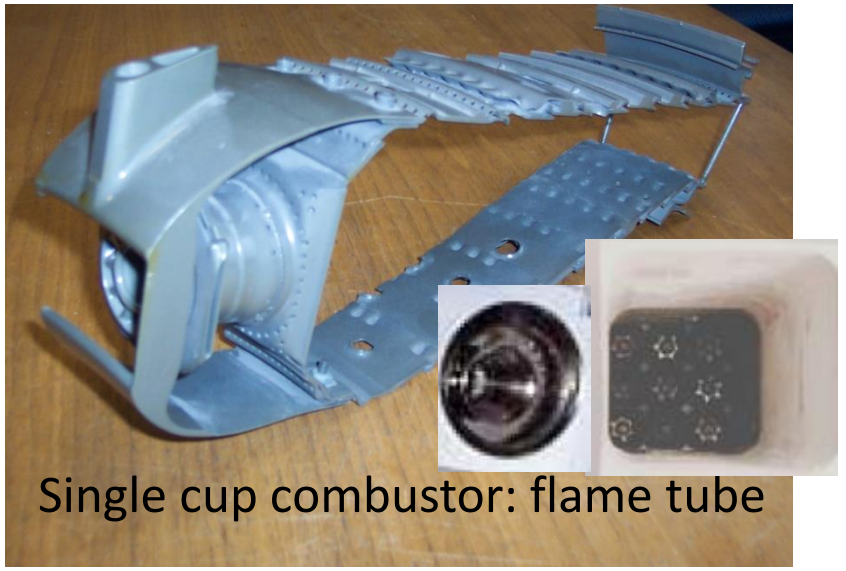
For more on aircraft engines, see

1. * “Pushing the Envelope: A NASA Guide to Engines” (2007). Publication EG-2007-04-013-GRC.
2. Mattingly (1996). *Elements of Gas Turbine Propulsion*, McGraw-Hill, Inc., New York.

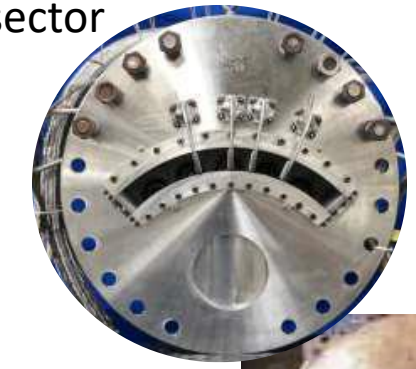
Some combustor terminology






Single cup combustor: flame tube

Multi-cup combustor: sector






A 22-cup full-annular combustor case

There also are dual annular combustors

- Stations 3 (inlet) and 4 (exit) define the combustor control volume for mass, temperature, pressure
- ΔP = combustor pressure drop = $P_3 - P_4$; typical % ΔP ~ 3 - 5
- Cold flow (unfueled, non-combusting) Reference Velocity U_{ref}: ~25-75 ft/s (7.6 – 22.9 m/s)

Upper left illustration from https://www.faa.gov/newsroom/continuous-lower-energy-emissions-and-noise-cleen-program#_Toc80621742

Combustor Air Flow Parameters

Effective Area: $ACd = \dot{m}_3 / (2P_3\Delta P/RT_3)^{0.5}$ (station 3 is combustor inlet)

where: A = geometric flow area

Cd = discharge coefficient

$\dot{m}_3$, P_3, T_3 = inlet air mass flow rate, pressure, temperature

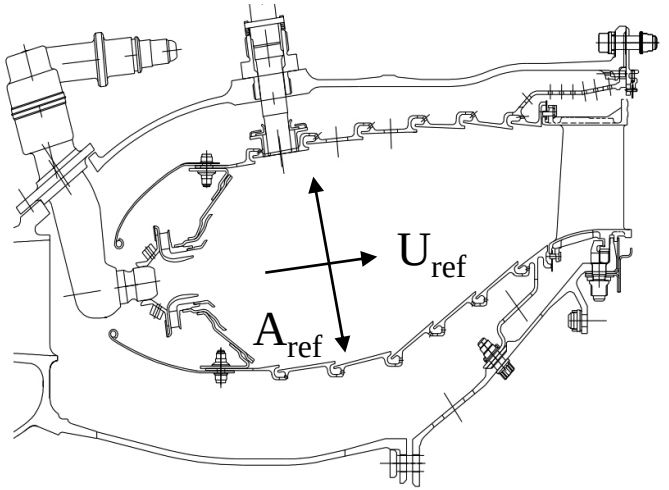
ΔP = combustor pressure drop = $P_3 - P_4$ (station 4 - exit)

R = gas constant

Corrected Flow: $\dot{m}_3^* = \dot{m}_3[(T_3/To)^{0.5}(P_0/P_3)]$

(different definitions on this)

To & Po sea-level static conditions



Reference Quantities:

$U_{ref} = \dot{m}_3 / (\rho_3 A_{ref})$ Reference Velocity ~25-75 ft/s

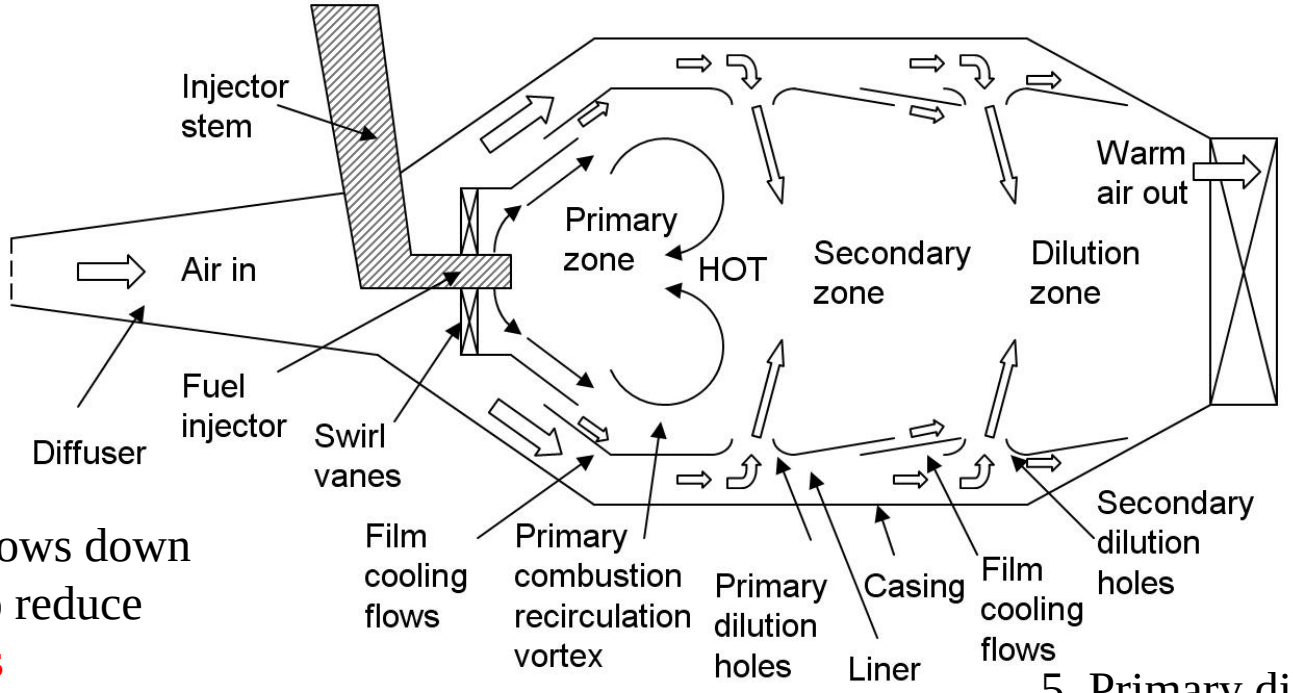
$M_{ref} = U_{ref}/(\gamma RT_3)^{0.5}$ Reference Mach Number

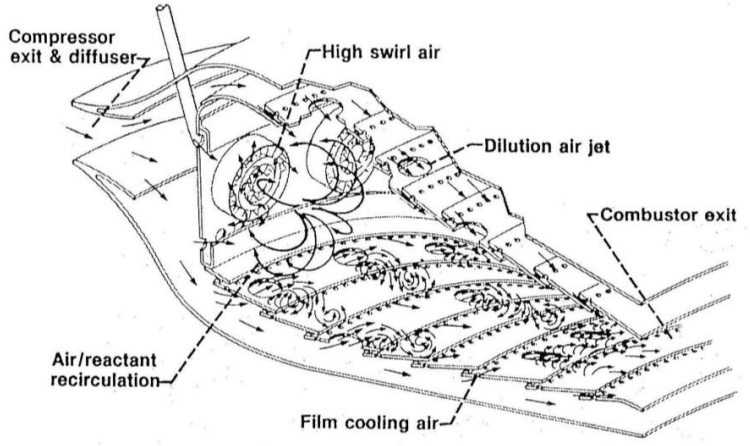
where: A_{ref} = area at plane of maximum cross-section

ρ_3 = inlet air density

γ = ratio of specific heats = ~1.4

Legacy Combustor Features (prior to ~1980)





1. Diffuser slows down flow speed to reduce Rayleigh loss

2. Fuel-nozzle turbulence speeds up ***atomization*** by break up liquid into droplets

3. Liner film-cooling decouples thermal loading from pressure casing

4. Swirling flow forms recirculation vortex to provide ***flame-holding***

5. Primary dilution holes provide dilution and vortex anchor

6. Secondary dilution holes add more air to bring T4 down and shape T_4 profile

We focus on fuel atomization/fuel-air mixing and primary zone combustion/flame holding

Combustor Design Requirements

Desired Characteristics

- High Combustion Efficiency at All Conditions
- Reliable and Smooth Ignition at All Conditions, including Altitude Relight
- Wide Stability Limits from idle to cruise, i.e. High Turndown Ratio for fuel injection
- Insensitive to Pressure Perturbations and Acoustic Feedback
- Free From Combustion Induced Instabilities
- Low Pressure Loss
- Exit Temperature Profile Tailored for Life of Turbine (Low Pattern and Profile Factors)
- Low Emissions (CO, UHC, NOx, Smoke, Particulates)
- Minimize Cost, Maximize Durability and Ease of Maintenance
- Size and Shape Compatible with Engine Requirements
- No coking of fuel lines or fuel injectors

Important Combustor Design Parameters

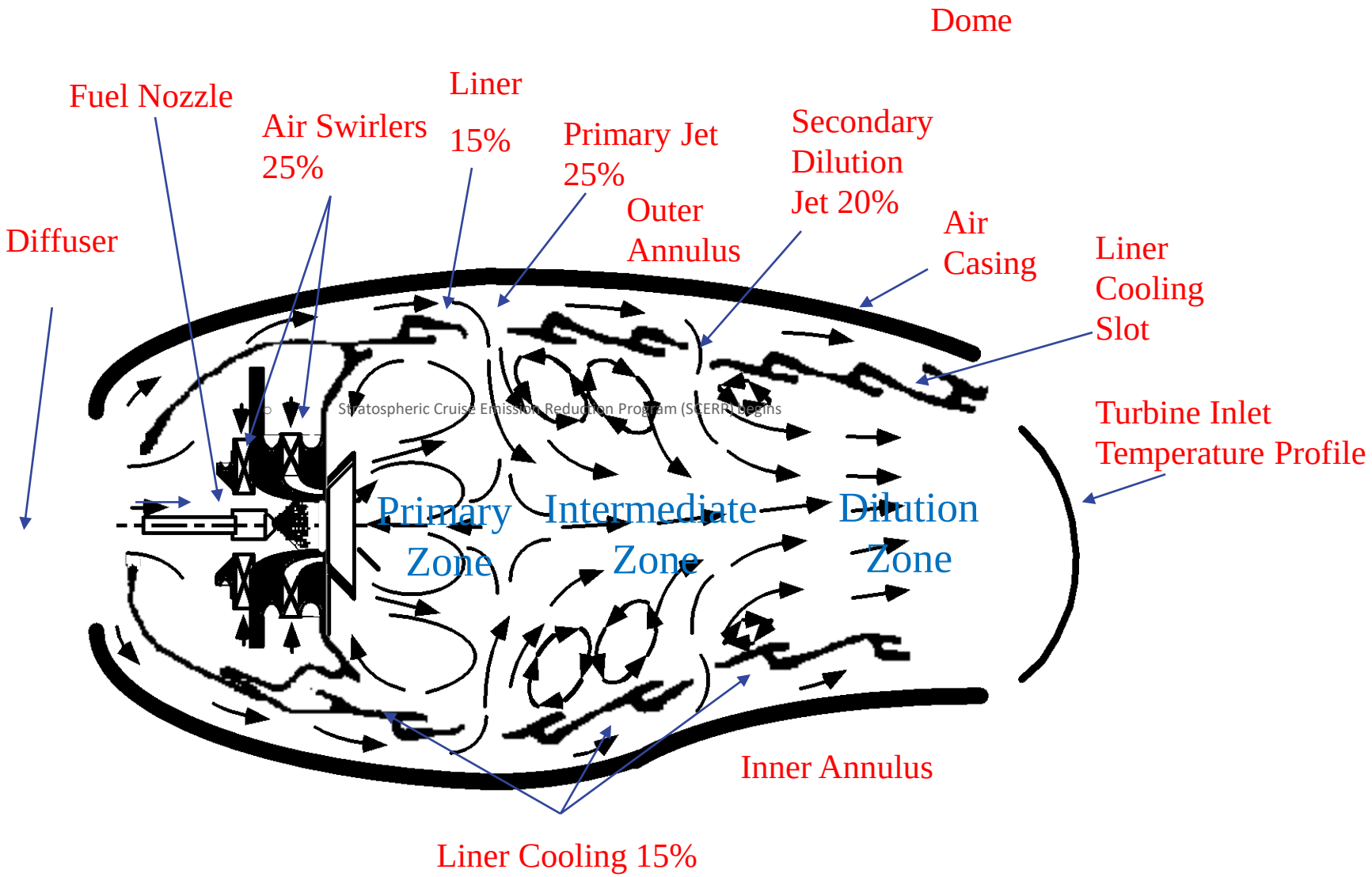
- Combustion Efficiency, $\eta_c > 99.9\%$ for all conditions
- Pressure Drop, $(P_3-P_4)/P_3 < 6\%$ (4% – 5% Typical)
- Pattern Factor = $(T_{max} - T_4)/(T_4 - T_3) \leq$ 0.25 @ Full Power
- Profile Factor = $(T_{mr} - T_4)/(T_4 - T_3) \leq$ 0.11 @ Full Power

Measures of combustor exit temperature variation

- Lean Blow-Out Limit, $\phi \leq$ 0.1 Low as Possible f/a ~ 0.005 - 0.008
- Altitude Re-Light $\rightarrow$ 30,000 Ft
- Emissions per the current International Civil Aviation Organization (ICAO) Standards for CO, HC, NOx, smoke or particulate matter (PM)

  "current" applies to entry into service (EIS) for the combustor

Air-Flow Distribution

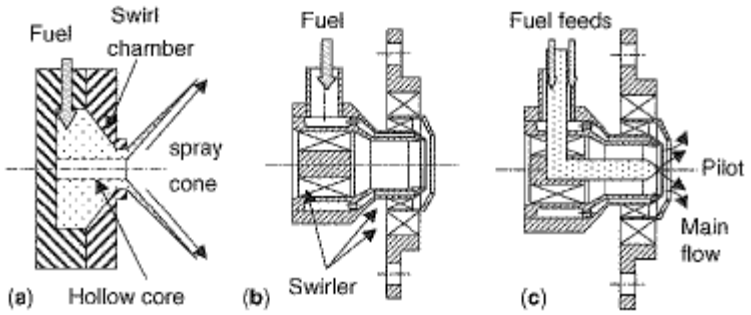


Fuel injection

How fuel is injected and mixed with the air is critical to keeping emissions low. For aircraft combustors, there are a few common fuel injector (nozzle) types used to achieve the objectives of flame stability, low emissions, engine operability for all parts of the flight envelope from idle to takeoff (turndown), and robustness. These are pressure atomizers and airblast injectors.

- Pressure atomizers rely on fuel pressure drop to achieve good atomization. Quite effective at low engine power, but as power increases, there is less available ΔP for good atomization
- Airblast nozzles rely on air momentum and shear to atomize fuel. Works great at high power, has relatively poor performance at low power (low air flow)
- These injection schemes are often combined into one fuel injector with more than one fuel circuit

Some fuel nozzle schema



(a) pressure-swirl nozzle, aka simplex
(b) Airblast nozzle with triple swirler
(c) Compound nozzle—pressure and airblast nozzles

Some representative aircraft fuel nozzles



https://www.collinsaerospace.com/what-we-do/Industries/commercial-aviation/power-controls-actuation/turbine-systems/

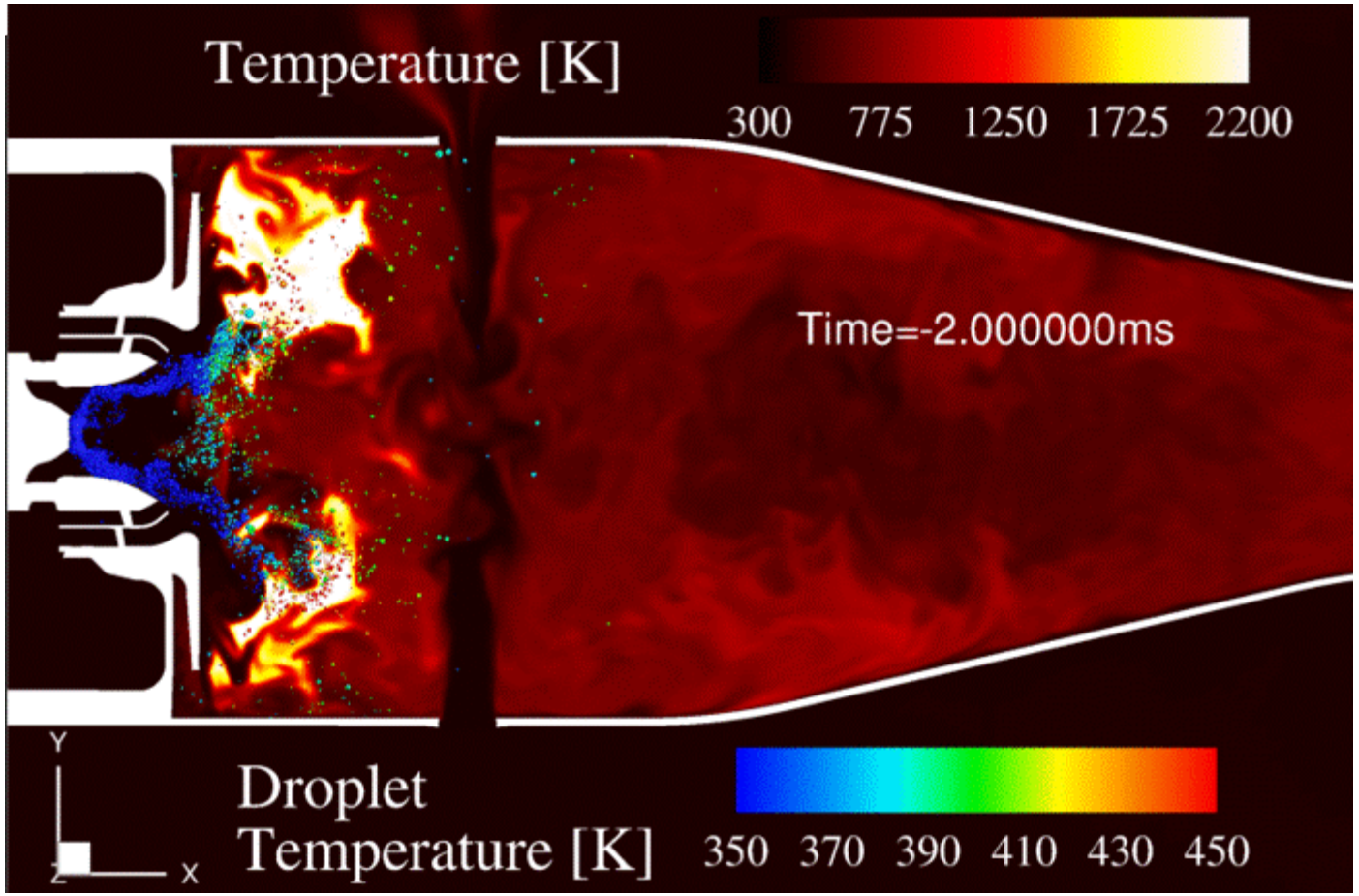


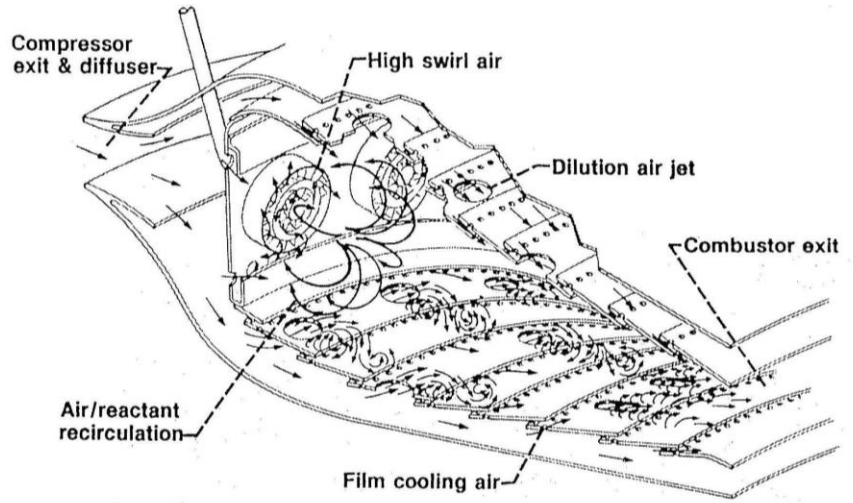
https://3dprintingindustry.com/news/ge-aviation-celebrates-30000th-3d-printed-fuel-nozzle-141165/



https://ph.parker.com/us/en/product-list/aerospace-engine-fuel-injectors

Combustor Physics Overview





- Liquid Fuel sprays
- Fuel vaporization and fuel-air mixing
- Chemical Reactions
- Low-Mach Number flows with large T, density gradients
- Turbulence impacts on aerodynamics, spray and chemistry
- Swirling Flows, recirculating Flows, and jets-in-Crossflows
- Soot, Radiation, Wall Heat Transfer
- Trace Species Emissions: NOx, soot, etc.

Fuel composition and Stoichiometry

Stoichiometric combustion ($\phi = 1$)

$C_{11.4}H_{22.1}$ (~Jet-A*)+ 16.925 (O_2 + 3.76N_2) →

11.4 CO_2 + 11.05 H_2O + 63.638 N_2

1 kg fuel burned → roughly 3.16 kg CO_2 and 1.25 kg water

Equivalence Ratio, ϕ, is defined using reactant *mass*

$\phi = (f/a)_{actual} / (f/a)_{\phi = 1}$ **$\phi > 1$: fuel-rich** **$\phi < 1$: fuel-lean**

Fuel-air mass ratio:

fuel = 11.4 * 12 + 22.1 *1 = 158.9

air = 16.925 * (32 + 3.76 * 28) = 2323.5

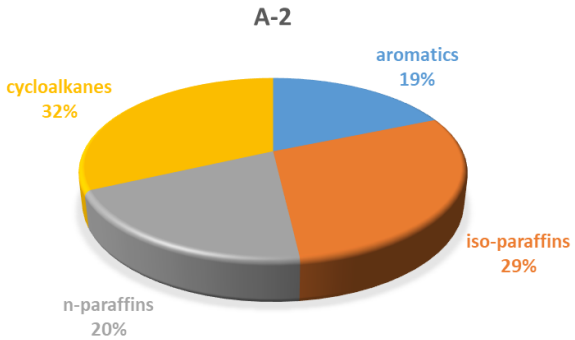
$(f/a)_{\phi = 1}$ = 159 / 2324 = *0.0684* or (a/f) = *14.6*

Non-Stoichiometric lean combustion ($\phi < 1$)

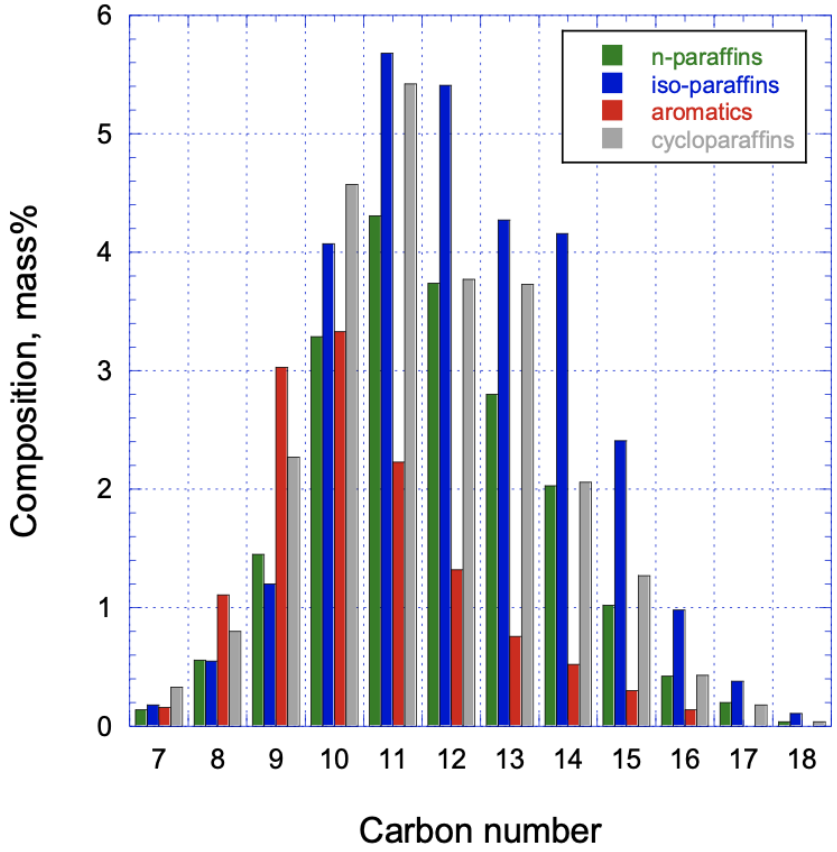
$\phi C_{11.4}H_{22.1}$ + 16.925 (O_2 + 3.76N_2) →

ϕ11.4 CO_2 + ϕ 11.05 H_2O + 63.638 N_2 + (1- ϕ) 11.75 O_2

* Jet fuels such as Jet-A and JP-8 are multicomponent, and overall composition depends on from where crude oil comes, time of year originating country federal regulations, etc., so this is an average formula



an Average Jet-A composition

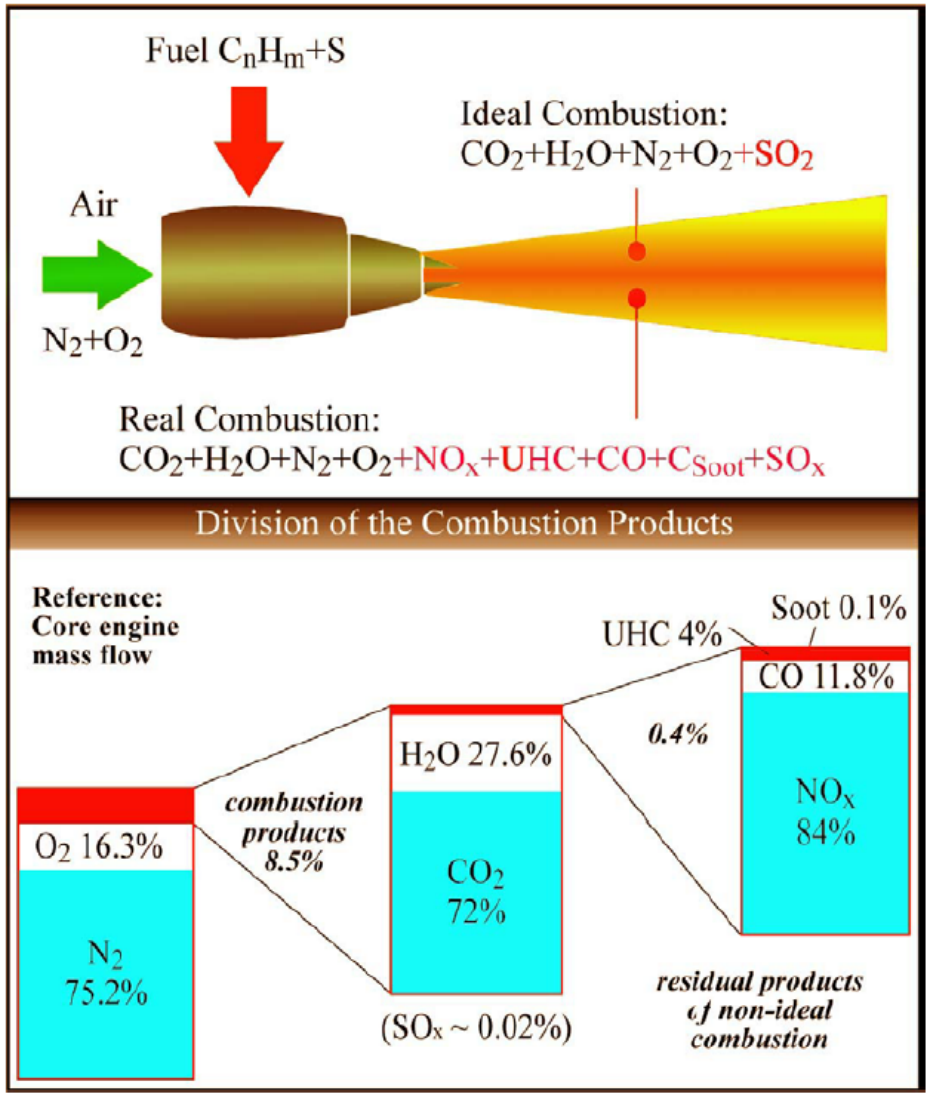


From Edwards, AIAA-2017-0146

Real Combustion

Jet Fuel: C_nH_m + Sulfur (trace amounts, ~1000 ppm)

Typical subsonic cruise emissions



Engine Emissions

Primary constituents: H_2O, CO_2, N_2, O_2

Secondary products: NO, NO_2, N_2O, SO_2, CO, stable HC, soot

Oxidation products of secondary combustion species: HNO_2, HNO_3, SO_3, H_2SO_4, H_2O_2, HNO

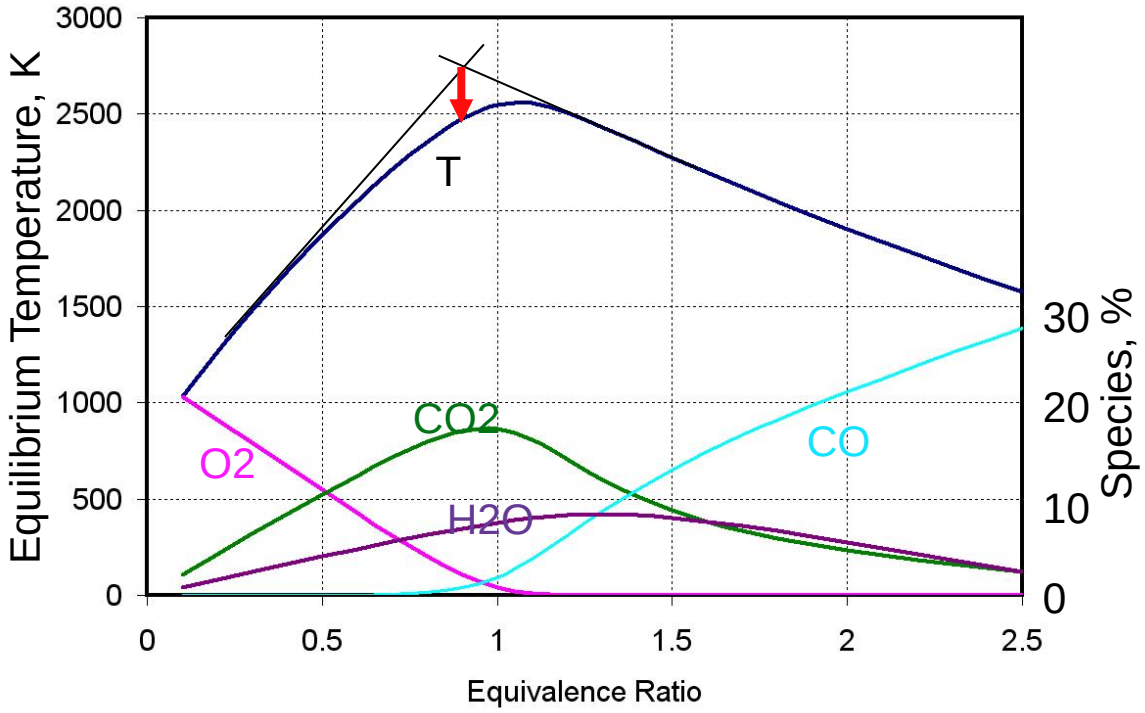
Reactive species: O, OH, HO_2, SO, H_2, H, N, CH

- Pollutant species (CO, HCs, NO_x, SO_x) measured in ppmV (parts per million by volume).
- CO_2, H_2O & O_2 in percent
- Required Regulations & Certification : CO, UHCs, NOx, Smoke/Soot

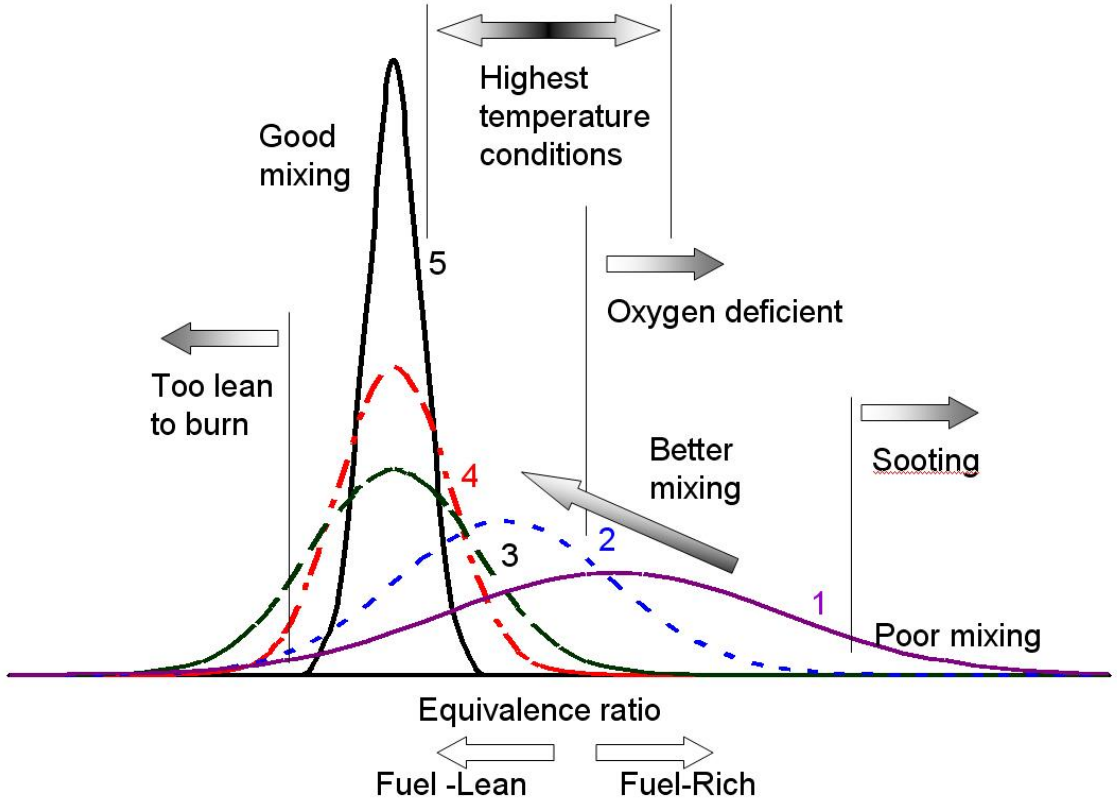
Influence of Fuel-Air Mixing on Combustor Operation

Equivalence Ratio and Equilibrium Temperature

What happens when you vary the fuel-air mixture

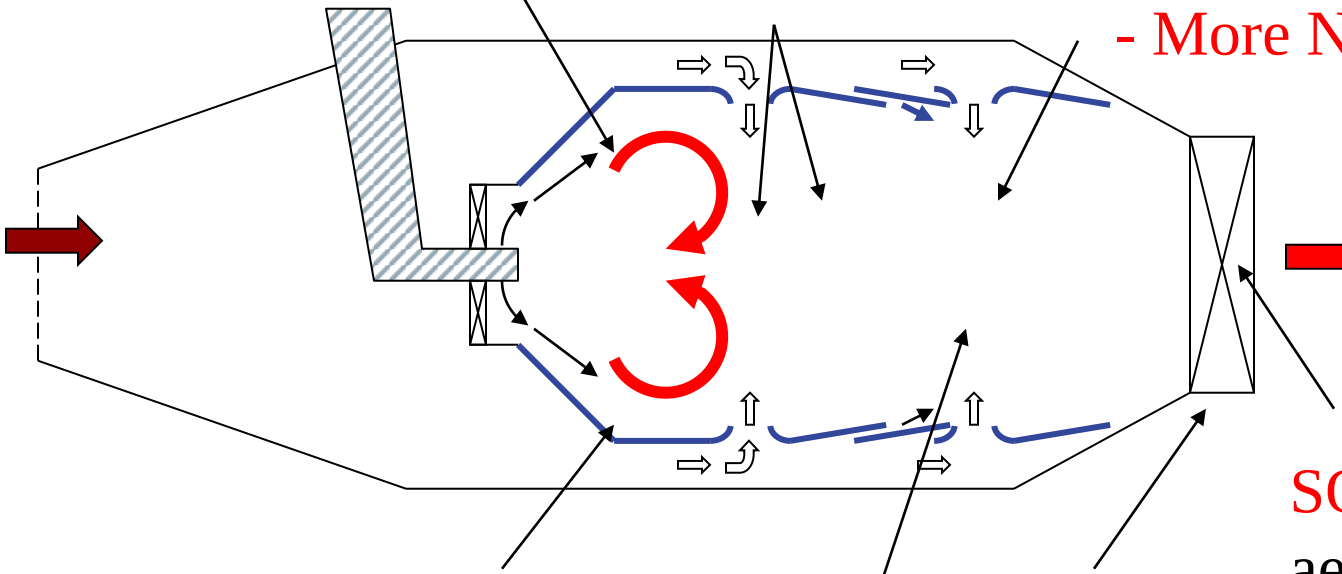


Influence of ϕ and Fuel-Air Mixing



Key to Low-NOx:
1. Avoid high temperature burning
2. Keep the exposure time short

Pollutant formation



Rich ϕ
CO, uHC
soot

High-Temp.
Zones –
NOx

Moderate
Temperature
Dilution Zones
- More NOx

Frozen
Chemistry

SOx &
aerosols

uHC near liner

Soot and CO
oxidation

Turbine
Stator

Actual hydrocarbon jet fuel may contain trace amounts of sulfur: CmHn + Sulfur (trace amounts, ~1000 ppm)

The Emission Index, EI

Calculating the Emission Index (EI) for Specie X_i:

$$EIX_i = [\text{Vol Fr}]_i \times [MW_{Xi}/MW_{exh}] \times [(1 + f/a)/(f/a)] \times 1000 \quad \{g\text{-}X_i/kg\text{-fuel}\}$$

where: $[\text{Vol Fr}]_i$ = Volume fraction of specie X_i, typically in ppm

MW_{Xi} = Molecular mass of specie X_i, kg/kg-mole

Mw_{exh} = Molecular mass of exhaust, kg/kg-mole

f/a = Fuel-to-air ratio, i.e. (mass flow fuel)/(mass flow air)

Calculated for each: CO, NOx, UHC's → EICO, EINOx, EIHC

EI normalizes the emissions w.r.t. fuel burned

Combustion Efficiency

Exhaust-gas analysis to calculate efficiency:

$$\eta_c = 1 - [X_{CO}(\Delta hc)_{CO} + X_{HC}(\Delta hc)_{HC} + X_{H2}(\Delta hc)_{H2}] / [(f/a)(\Delta hc)_f/(1 + f/a)]$$

where: X_i = mass fraction of species i

$(\Delta hc)_i$ = the heat-of-combustion for species i.

Note: X_{HC} = mass fraction of unburned hydrocarbons

The numerator represents unused chemical energy per mass of exhaust.

The denominator represents the chemical energy per mass of initial fuel-air mixture.

Another common means of expressing the inefficiency is by using the emission index, EIi, mass of species i per unit mass of fuel burned (g/kgf),

$$\eta_c = 1 - (0.232EICO + EIHC + 2.76EIH_2)/1000$$

Assumes unburned hydrocarbons (HC) come from the fuel.

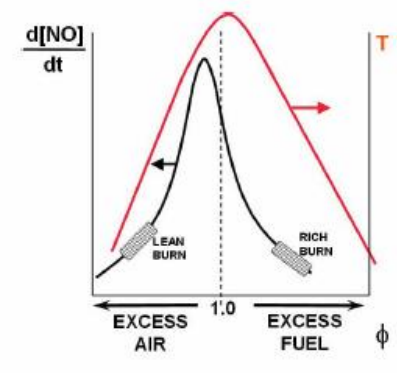
NOx reduction strategies

Several strategies exist to reduce NOx emissions. All involve staying away from stoichiometric combustion, temporally and spatially. The most common are

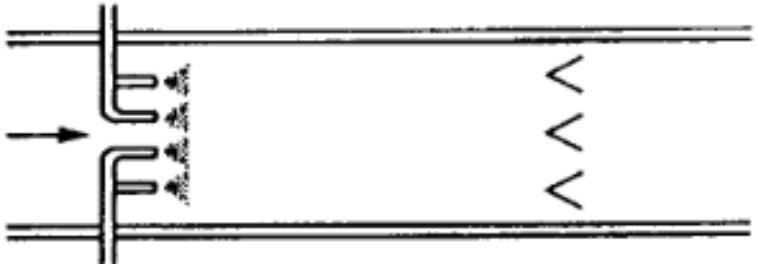
- Lean Premixed, Prevaporized (LPP)—this concept will have a very uniform fuel-lean mixture, to keep emissions of NOx, smoke, and particulate matter (PM) low. A major drawback is susceptibility to combustion instability and flashback. *This makes pure LPP less practical for aircraft combustors*.
- Rich-burn, quick-mix, lean burn (RQL)—RQL has good combustion stability because of its rich front end. The key to avoiding NOx is to rapidly mix in the air to spend as little time as possible near ϕ=1 and produce a uniform mixture in the lean zone. Many modern engines use this technology because it is simple and robust.
- Lean Direct Injection (LDI)—is a concept that replaces a single fuel cup with several smaller injectors that will enhance fuel-air mixing and fuel vaporization, resulting in smaller and shorter flame zones. The resulting system is partially-premixed, partially-diffusion, and flashback has not been observed. Like LPP, all fuel and air is injected in the front end, and since this concept runs typically fuel-lean, it can also be susceptible to combustion instabilities. There are also concerns about fuel system complexity.
- Staging fuel, air, or both—in this case, separate spatial zones are created to have a primary or pilot stage and a main stage. The pilot stage is primarily used at lower power, but is always fueled to maintain stability. The main stage is fueled at higher power conditions.
  - Axial staging generally involves a pilot stage in the front and a main stage, with fuel injection downstream
  - Radial staging may have the pilot stage closest to the center of the engine and the main stage outside or vice versa.

NOx reduction strategies, 2

A few concept sketches for LPP, LDI, RQL
For the latter two especially, the key is to keep the residence time short

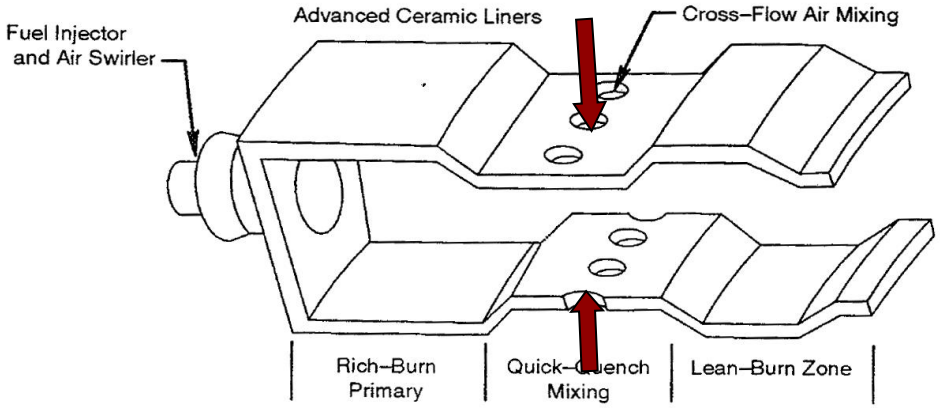


Lean, premixed, prevaporized



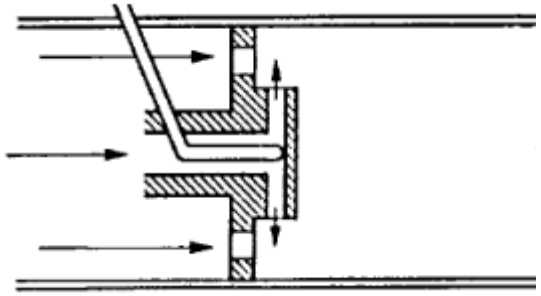
from NASA TM 103268 or AIAA-90-2400

Rich burn, quick quench, lean burn



from NASA CR-1998-207931

Lean-Direct Injection



from NASA TM 103268 or AIAA-90-2400

International regulations

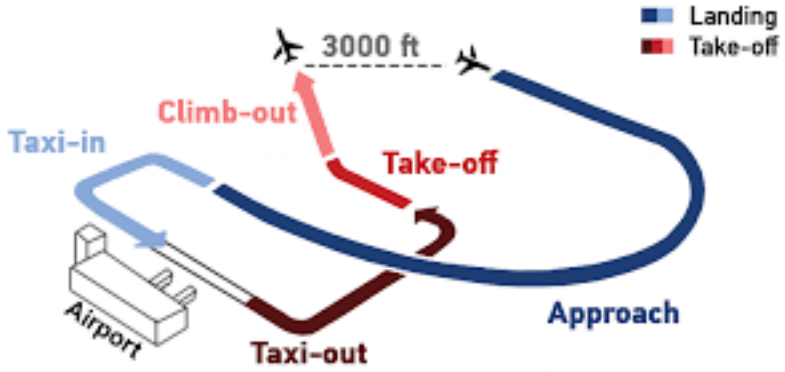
International Civil Aviation Organization (ICAO) established in 1947 and later became a specialized UN agency. The Committee on Aircraft Engine Emissions (CAEE) adopted first Standards and Recommended Practices (SARP) in 1981, adopting HC, CO, and NOx emissions limits. The Committee on Aviation Environmental Protection (CAEP) replaced CAEE. Meetings are triennial and standards are reviewed. These standards generally become more stringent as engine technology, measurement technology improves Typically, new SARPs are adopted then.

The CAEP/11 standard is in effect in 2023 and applies to all subsonic turbofan engines manufactured after 1 Jan 2023 with rated maximum takeoff thrust > 26.7 kN. CAEP/11 includes new rules for Particulate Matter mass

ICAO standards must be adopted into law independently by each country. In the U.S., the FAA is the representative member at annual CAEP steering group meetings and contribute technical expertise to working groups. The EPA serves both as advisor and advisee to the FAA.

ICAO Landing and Takeoff (LTO) Cycle

- Part of engine certification process, Annex 16, Volume II
- Addresses engine emissions: hydrocarbons, carbon monoxide, oxides of nitrogen, smoke or particulate matter (nvPM) for altitudes below 914m (3000 ft) and engines with rated thrust levels greater than 26.7 kN



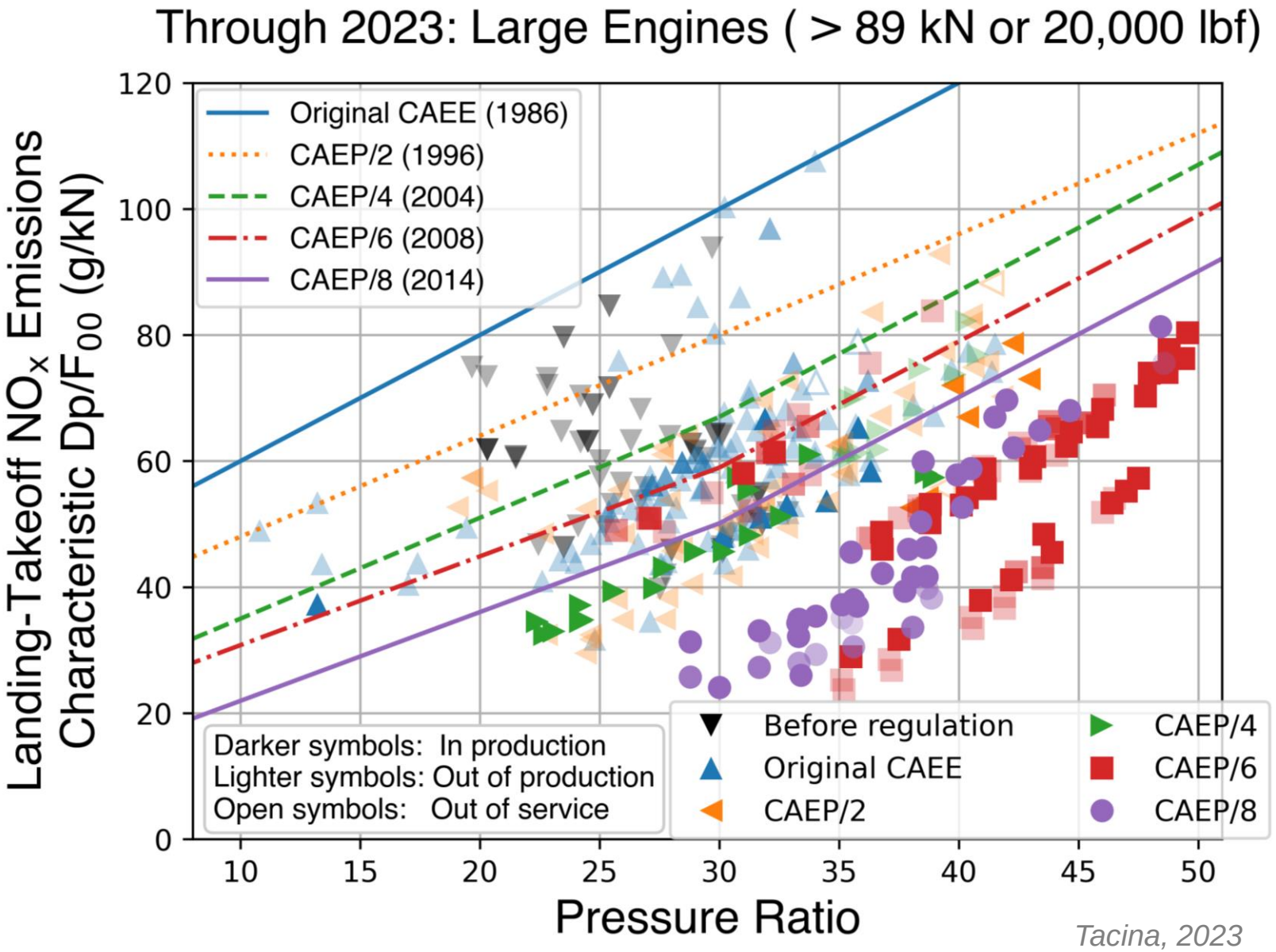
Mode	Power Setting % takeoff thrust	Time in mode minutes
Taxi/idle	7%	26
Approach	30%	4
Climb	85%	2.2
Takeoff	100%	0.7

$Dp(NOx)/F_{00}$ [g/kN]= (EINOx x fuel flow x time)/F_{00}

F_{00} is rated takeoff thrust.

Equation also applies to CO and UHC

Evolution of ICAO CAEP LTO NO_x regulations through CAEP/8 (latest NO_x reg) and the large engines that fall under those regulations



Tacina, 2023

Part 2—The Past

History of advancements in emissions reduction via NASA Aeronautics Programs and partnerships with other government agencies (OGA), industry, and academia

This covers a time frame roughly from 1970 to 2015.

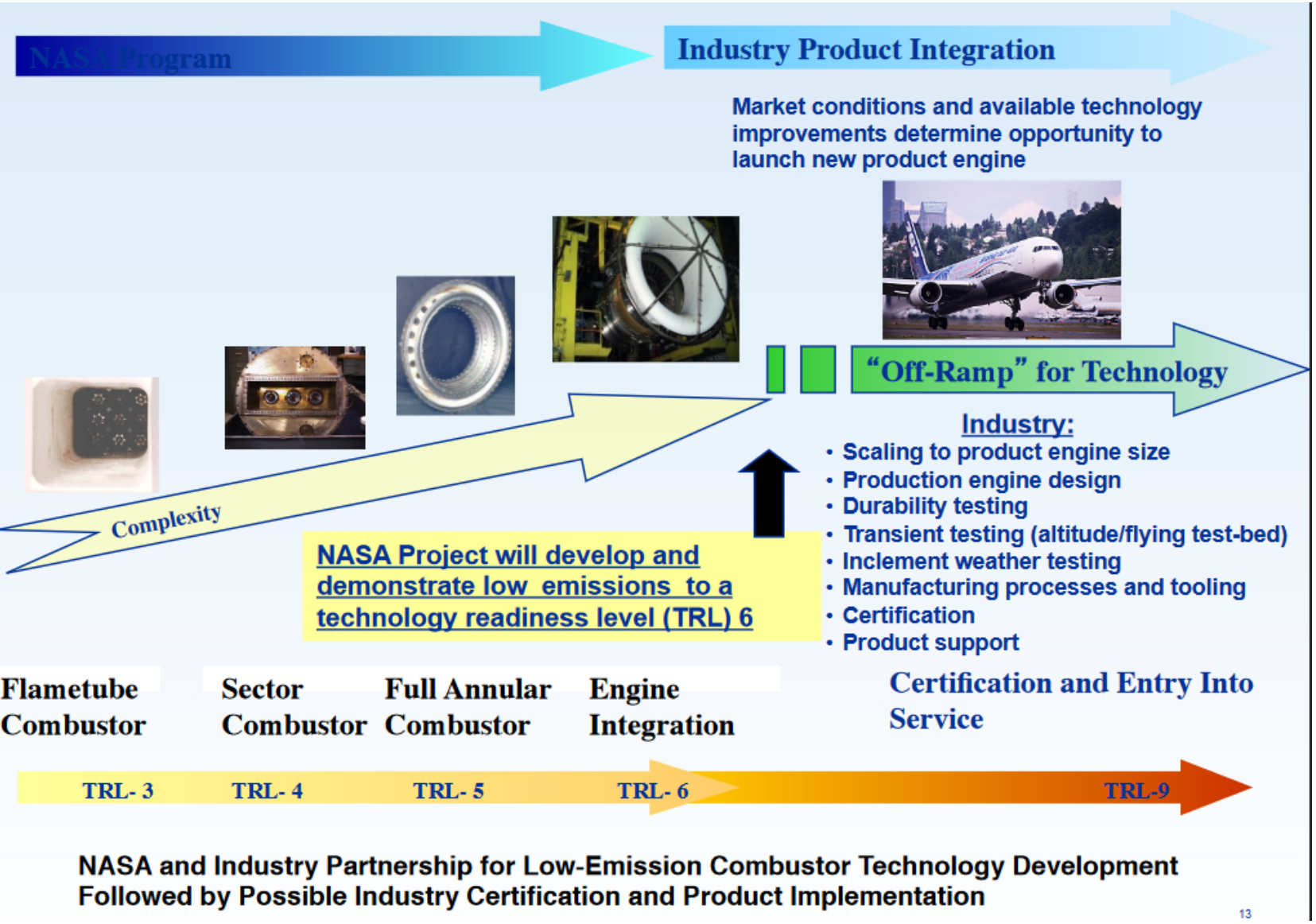
One may notice that some research is cyclical. Ideas that were problematic at first may later advance because of other technology that allowed the old idea to come to fruition. Or a new problem arose that the idea addressed.

overview of past NASA aero GT combustor research

Program name	Year	Engine class	Combustor concepts	Legacy
Experimental Clean combustor (ECC)	1973-1978	Large subsonic	Dual annular combustor (DAC), Vortex burning and mixing (Vorbix)	
Pollution Reduction Technology program (PRT)	1974-1979	Small to midsize subsonic	Vorbix	
Quiet Clean Short-Haul Experimental (QCSEE)	1974-1975	short-haul turboshaft		
Stratospheric Cruise Emission Reduction program (SCERP)	1977-1983	Supersonic	Lean prevaporized premixed (LPP)	
Energy Efficient Engine project (EEE, E^3)	1980-1984	Large subsonic, high OPR	DAC, axial-staged combustor	CFM56, GE90, V2500-A5
High-Speed Research (HSR)	1991–1999	large supersonic	LPP, rich-burn, quick-mixing lean-burn (RQL)	
Advanced Subsonic Transport (AST)	1994–1999	Large subsonic, 60 OPR	TALON II	PW4100, PW6000, GEnx
Ultra-Efficient Engine Technology (UEET)	1999-2004	Subsonic, 60 OPR	TALON X, twin annular premixing swirler (TAPS)	GEnx, GTF
Fundamental Aeronautics (FA)	2007-2015	Various	cutting-edge core comptencies for the long term	
Subsonic Fixed Wing (SFW)		Subsonic		
Subsonic Rotary Wing (SRW)				
Supersonics		Supersonic		
Hypersonics				
Environmentally Responsible Aviation (ERA)	2009-2015	Large subsonic, 55 OPR	Partially premix, lean direct injection (LDI)	

Beginning in the mid-1990s, NASA LDI concept has been pursued as a viable alternative to LPP, and has been on-going through the present

Emissions Reduction – Technology to Product Transition



TRL 3—Flametube Testing:

- Emissions (NOx, CO, HC)
- LBO performance
- Flame Stabilization
- Swirler Fuel Injector Design
- Injector Durability
- Preliminary Acoustics

TRL 4—Sector Combustor Testing

- Emissions (NOx, CO, HC, smoke)
- Liner design and durability
- Wall cooling
- 3d effects
- Combustor/flowpath design
- Injector interactions

TRL5—Full annular combustor testing

- Emissions (NOx, CO, HC, smoke, aerosols)
- LBO performance/Altitude relight
- Ignition/flame propagation
- Possible staging
- Exit profile/pattern factor
- Operability
- Combustion acoustics

A Brief review of NASA aircraft gas turbine combustor research, synopsized from Chang et al. 2013

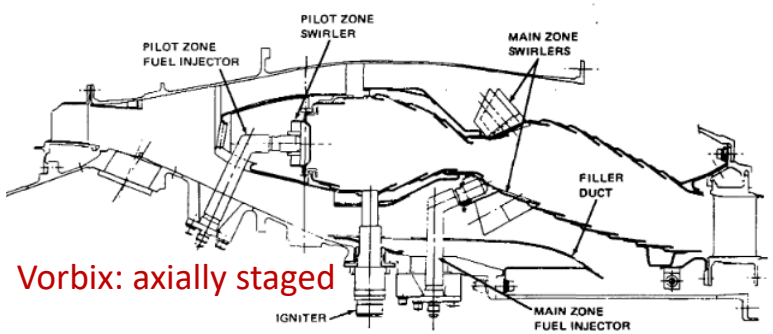
- 1940s – 1950s were devoted to reliability of aero-propulsion systems, primarily for military Late 1960s: *begin energy efficiency* + *environmental focus for civilian aircraft*
  - civilian engines at the time were based on the existing military engines, which ran fuel rich ($\phi > 1$), as they were designed for stable operation. But along with high ϕ comes high smoke count
- 1970 U.S. EPA established. Consolidation of several public health and pollution programs in the federal government. Modern era of consolidated U.S. emissions regulations begins

Review of NASA aero GT combustor research, cont.

- 1970s: *combustor development programs to reduce NOx, climate impact*
  - efforts to lean out ($\phi < 1$) primary zone to decrease smoke number; reduce high-power NOx and low-power CO and HC.
  - NASA research into fuel scheduling, airblast and air assist fuel nozzles; catalytic, partially premixed, and LPP combustion
  - Industry collaborations to incorporate NASA learnings and to develop low emissions combustor concept retrofits to existing engines (fuel-lean in main zone)
    - Experimental Clean Combustor Program → DAC, Vorbix
    - Pollution Reduction Technology Program → Vorbix
  - Stratospheric Cruise Emission Reduction Program (SCERP)
  - Climate impact studies done by DOT, NAS, NASA. Global Air Sampling Program (GASP) includes air sampling in lower stratosphere, upper troposphere from B-747 aircraft worldwide
  - Research begun for the Rich Burn, Quick-Mix, Lean Burn (RQL) combustor to reduce NOx emissions—Joint DOE/NASA effort (1980)

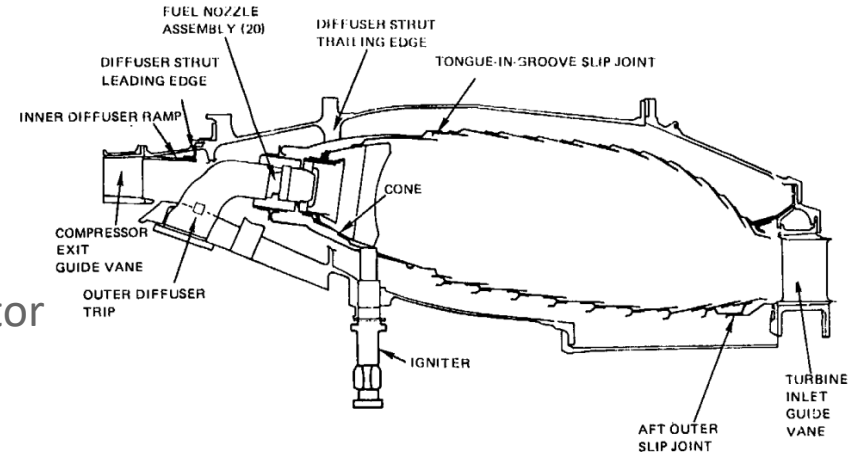
Experimental Clean Combustor: DAC and Vorbix retrofits

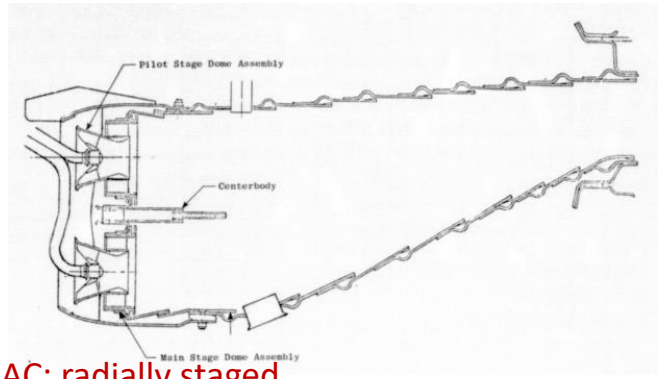
- GE developed the Dual Annual Combustor burner
- PW developed the Vortex Burning and mixing burner



Vorbix: axially staged

into JT9D-7A combustor

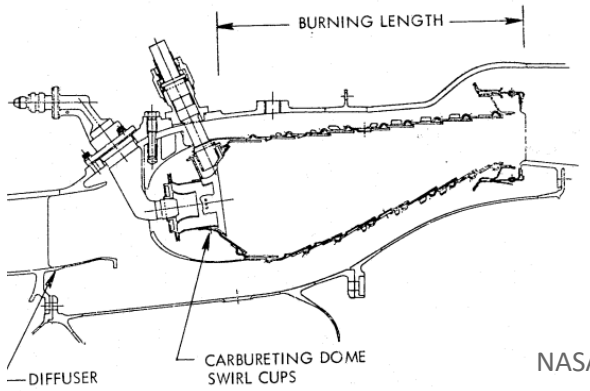




DAC: radially staged

NASA CR-134971

into CF6-50 combustor

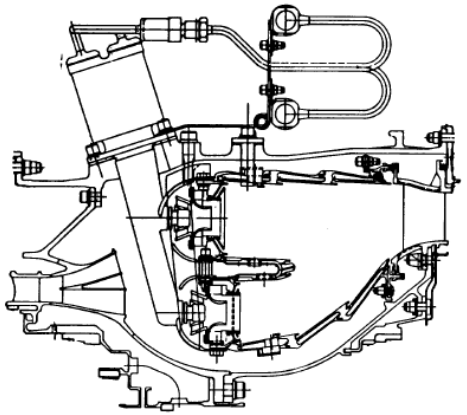


NASA CR-168219

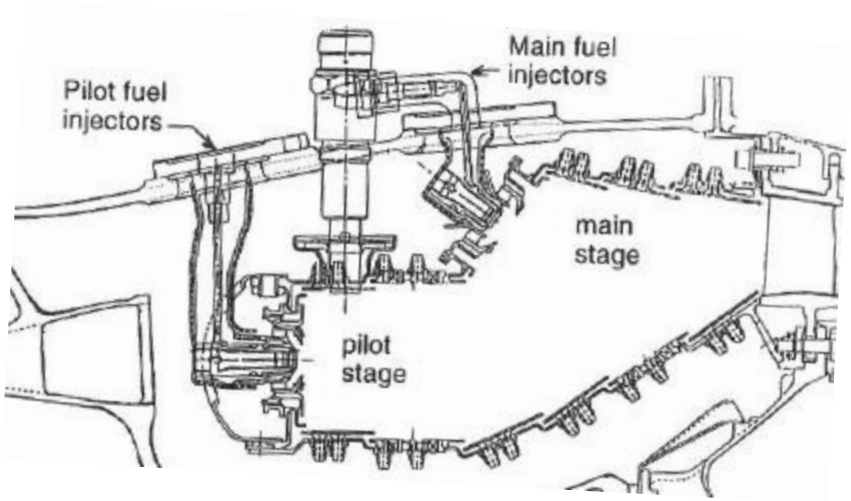
Review of NASA aero GT combustor research, cont.

- 1980s: *energy efficiency + environmental focus for civilian aircraft*
  - NASA studied combustor-diffuser interactions, air dilution, …
  - Energy Efficient Engine (EEE, E^3) Project was follow-on to ECCP
    - DAC concept pursued. Pilot outer, Main inner. Provided improved mixing, combustion, lower emissions, more robust liner led to longer maintenance intervals
    - DAC concept on CFM56 and future GE90 engines
    - Vorbix technology was iterated, revised, transformed into a different and better-performing (not named) axially staged combustor and can be found in the V2500 engine, EIS 1989

E^3 DAC



NASA CR-168219

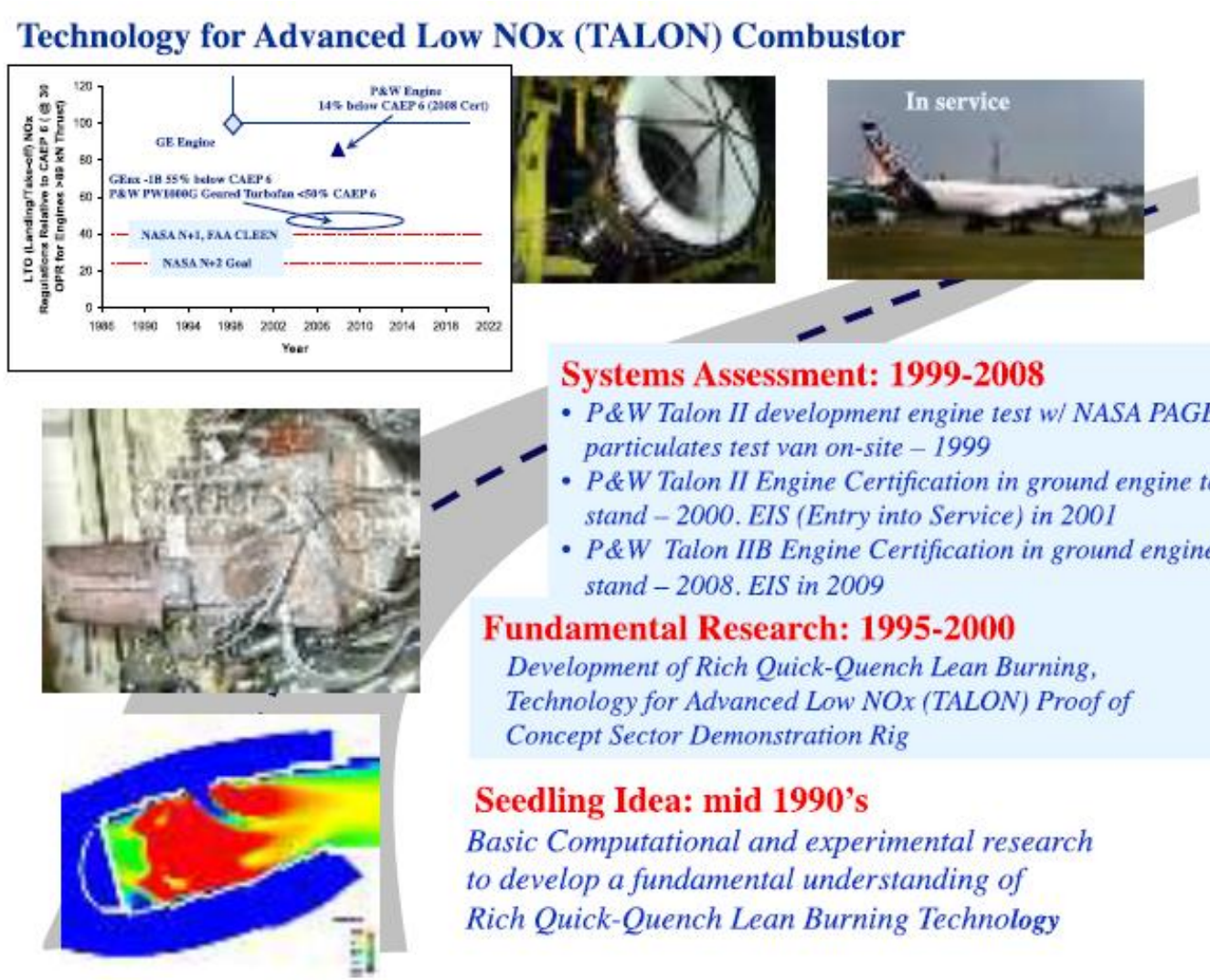


P&W V2500-AS combustor (Lefebvre, 1998; AIAA 2016-2121)

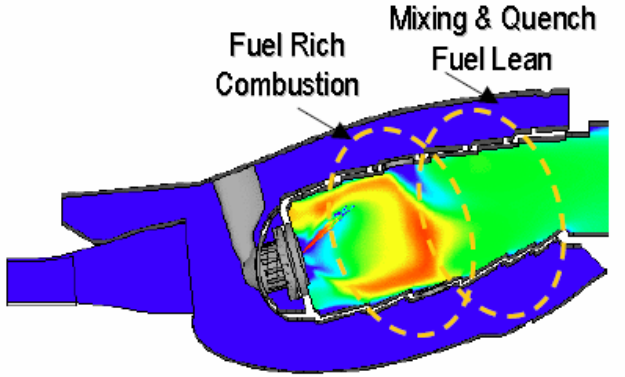
review of NASA aero GT combustor research, cont.

- 1990s: High Speed Research (HSR), Advanced Subsonic Technology (AST)
  - HSR program for civilian supersonic flight—emissions goal for EINOx ≤ 5 to help mitigate concerns for high altitude ozone depletion. RQL and LPP technologies were studied. A modified LPP-type strategy met the goal but had higher sensitivity to combustion instabilities during rapid transients.
  - AST research program had a main driver to improve engine efficiency by increasing the OPR over existing technology from 25 to between 60-75. This reduced fuel burn but increased OPR leads to higher NOx (higher T3) without new technology in fuel injection and
    - Continued work and refinement of RQL technology led to P&W TALON (Technology for Advanced Low NOx) combustors.
    - GE continued lean-front end technology led to development of the TAPS (Twin Annular Premixing Swirler) combustor, which replaced the lean-burn DAC.

Advancement of RQL technology to flight: PW Talon

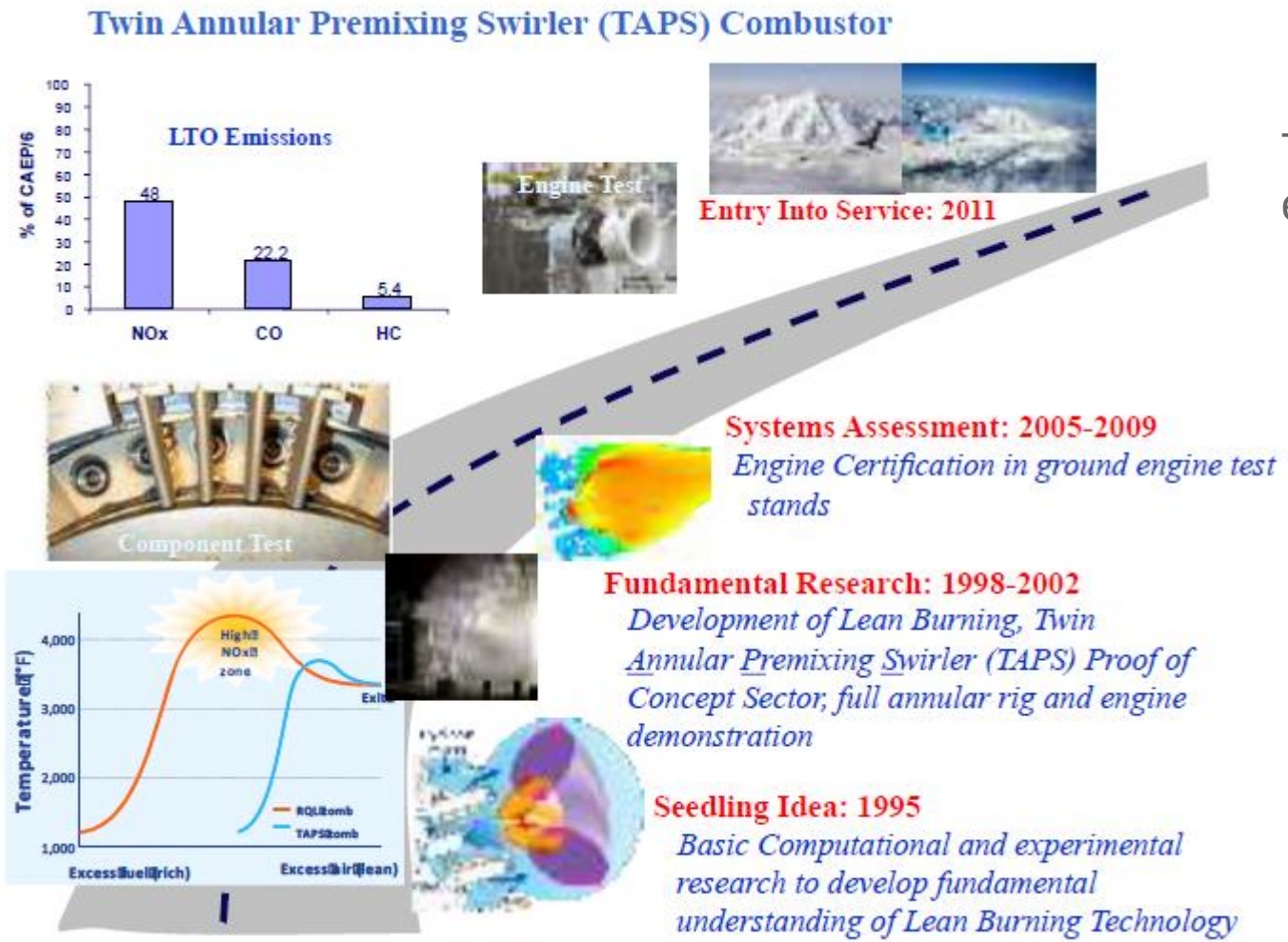


TALON combustors in PW4100, PW6000, Geared Turbofan GTF engines

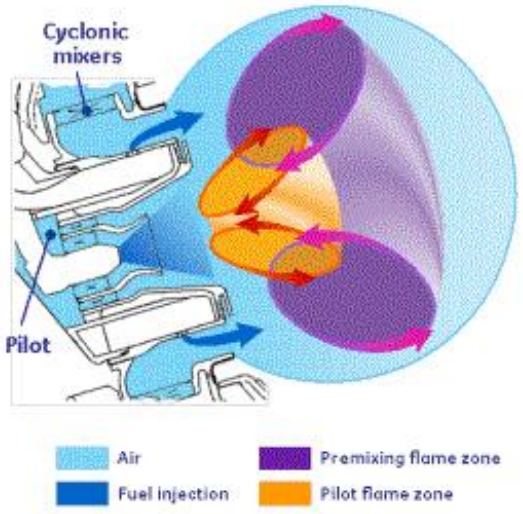


McKinney et al. (2007). The Pratt & Whitney TALON X low emissions combustor: revolutionary results with evolutionary technology. AIAA-2007-386

Advancement of “LPP” technology to flight: GEA TAPS



TAPS combustors in CFM LEAP, GEnx, GE9x engines

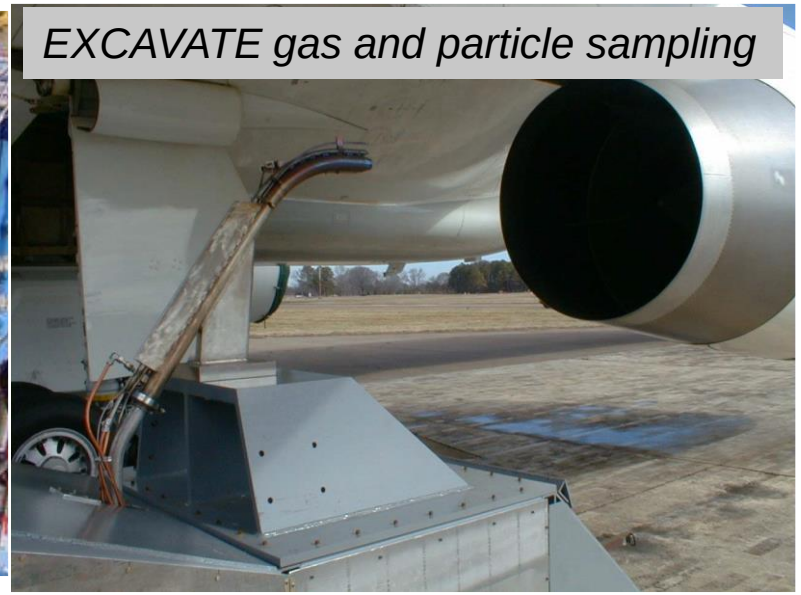


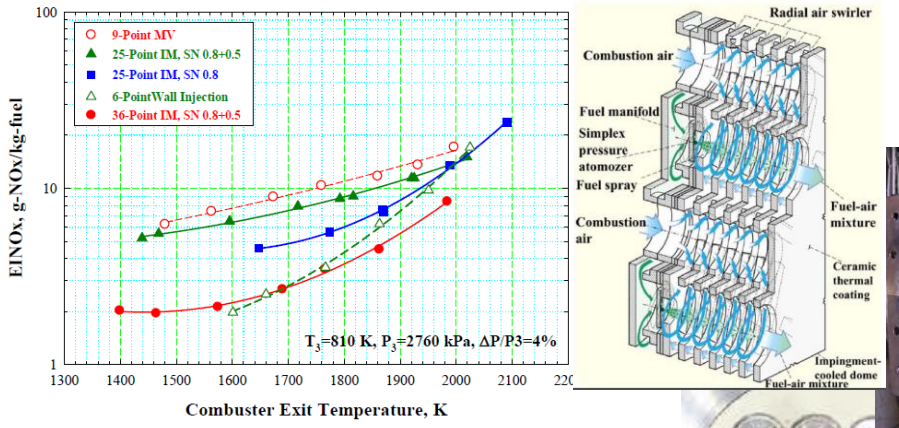
Foust, M.J, et al.(2012). “Development of the GE Aviation Low Emissions TAPS Combustor for Next Generation Aircraft Engines,” AIAA-2012-0936

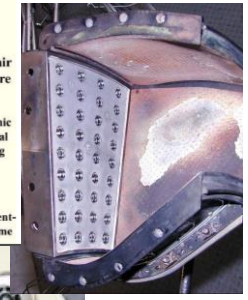
review of NASA aero GT combustor research, cont.

- 2000s: Ultra Efficient Engine Technology Program, UEET
  - Emissions Reduction was one of the UEET Projects. Goal to develop combustor technologies to reduce LTO NOx of 70% relative to 1996 ICAO standards (CAEP/2), applied to large and regional subsonic aircraft. Assess levels of aerosols and particulates. Improve and validate design codes to reduce design and development cycle time by 50%. Studies on LPP, RQL, and LDI technologies continued. Goal for ceramic matrix composite (CMC) material to meet 2700 F (1755 K). Continued work on atmospheric measurements and modeling. Alternative fuels effort.











Analyzing LDI configurations

review of NASA aero GT combustor research, cont.

- 2000s: Fundamental Aeronautics Program (FAP)
  - FAP Objective: Develop concepts and technologies to improve energy efficiency and environmental compatibility for sustained growth of commercial aviation
  - FAP has two focus areas of interest for combustion emissions: Subsonic Fixed Wing (SFW) and Supersonics (SUP). These projects took learnings from HSR, AST, and UEET and formulate plans and tasks projected to the future with a particular eye towards meeting the N+3 goals for SFW and for a supersonic business jet under SUP that can meet EINOx emissions goal of < 5.

NASA Subsonic Transport System Level Metrics

.... technology for dramatically improving noise, emissions, & performance

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-71 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

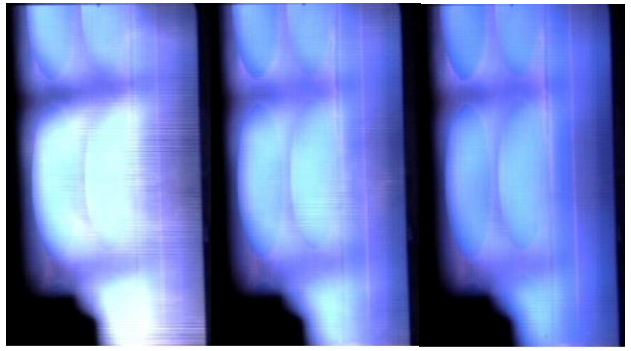
** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ CO_2 emission benefits dependent on life-cycle CO_{2e} per MJ for fuel and/or energy source used

SFW: Near-term research addressing revolutionary N+3 Goals

Subsonic Fixed Wing Project

Consideration of alternative fuels was a theme in both projects



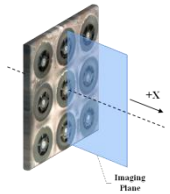
JP-8 50/50 FT

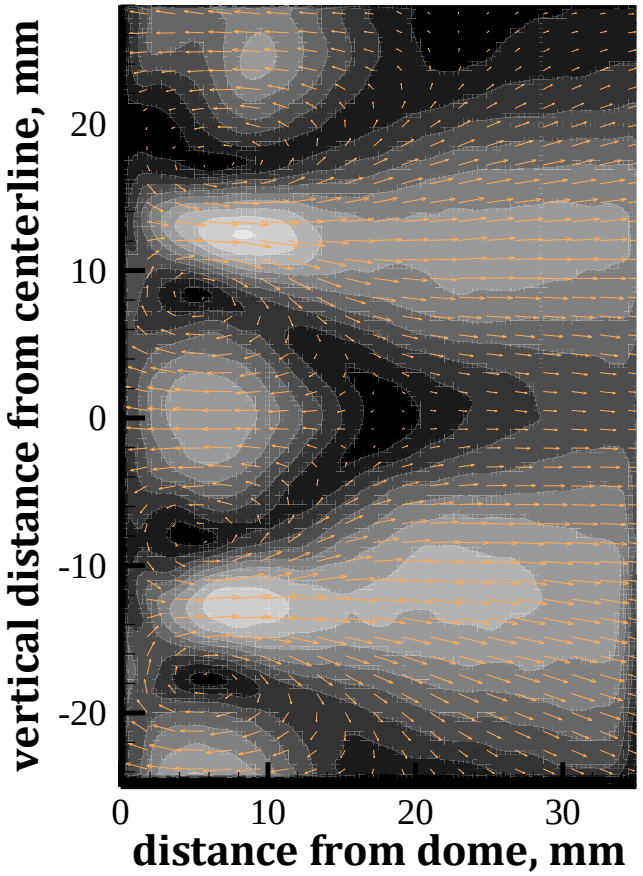
Color video of 9-pt LDI injector showing flame sootiness. From most to least sooty: JP-8/air flame, 50/50 blend, FT/air.

10.2 bar, 4% pressure drop, T_3=828 K, ϕ= 0.44

review of NASA aero GT combustor research, cont.

- 2000s: FAP SFW, SUP Characterizing fuel injection from NASA 9-pt LDI

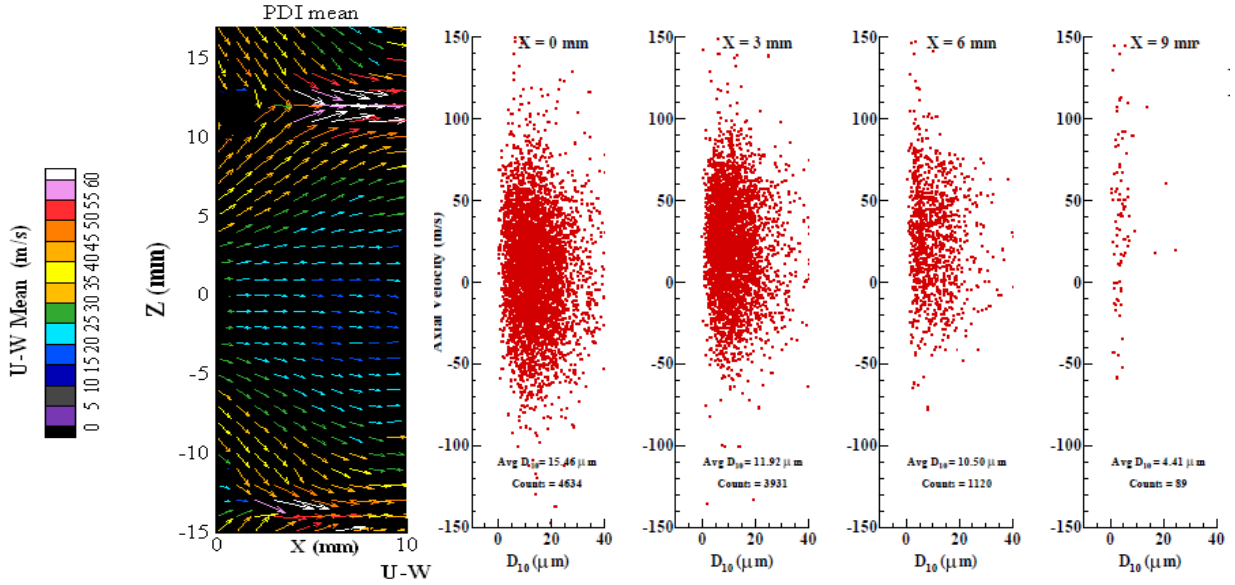




PIV result: Average axial-vertical velocity field of air in vertical center plane, from 500, 2d image pairs.

T_3 = 828 K, P_3 = 1034 kPa

Hicks et al. ISABE-2011-1106



Phase Doppler interferometry results during combustion around center swirler. Left (contour): Axial-vertical velocity vectors
Right: D_{10} vs Axial velocity

T_3 = 738 K, P_3 = 1034 kPa, ϕ = 0.45

Heath et al. GT2010-22960

review of NASA aero GT combustor research, cont.

- 2000s: Fundamental Aeronautics Program (FAP)

Alternative-Fuel Effects on Contrails and Cruise Emissions (ACCESS)

ACCESS objectives were to explore the potential of alternative fuels to
- reduce the impact of aviation on air quality and climate
- reduce impact on performance

Characterization done for flight tests, ground tests, lab tests

ACCESS benefits:
- Dramatically reduce environmental impact
- Support regulating agencies with real data

ACCESS II had two main goals:
- Measure and characterize the amount of soot and other pollutants generated by burning jet fuel (with either high or low sulfur content) that was blended with alternate biofuel.
- Gather basic data on contrail formation in the wake of a jet aircraft and study how or if burning blended fuel altered the contrail formation in any way.



Leverage prior ground tests


Lab studies


ACCESS 2 flight test campaign on-going (May 5-30, 2014)

- Establish effects of alternative fuels on engine emissions and thrust at cruise and examine the impact of aerosols on contrail formation
- In partnership with DLR (Germany), NRC (Canada), FAA (USA)

https://www.nasa.gov/aero/access-ii-confirms-jet-biofuel-burns-cleaner

review of NASA aero GT combustor research, cont.

- 2000s: Environmentally Responsible Aviation (ERA), a Project within the Integrated Systems Research Program
  - Had a focus on N+3 technology and considered many technical areas to support the objectives for EIS 2030-2035
    - *Hybrid electric and turbo electric*
    - *Truss-braced wing*
    - *Blended wing*
    - Reduced NOx
    - Alternative fuels
    - Ultra high bypass ratio engines with small core

NASA Subsonic Transport System Level Metrics

.... technology for dramatically improving noise, emissions, & performance

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
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Aircraft Fuel/Energy Consumption† (rel. to 2005 best in class)	-33%	-50%	-60%

  - ERA phase 1, from FY2010- FY2012 had the objective of meeting N+2 goals (TRL 4-6 by 2020) that included advanced engine combustor development via focused work under National Research Announcement (NRA) awards.
    - Multiple concepts were evaluated during phase 1, and most promising downselected to phase 2

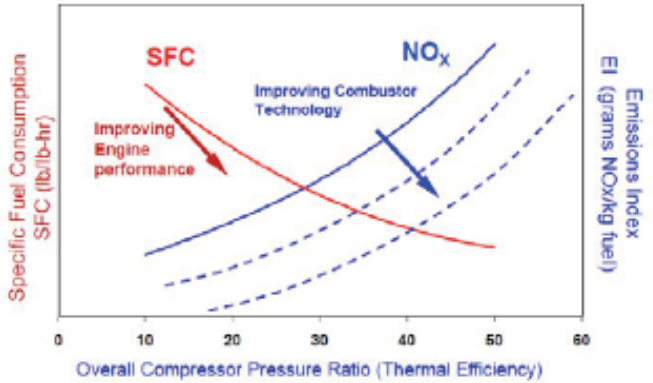
2000s: Environmentally Responsible Aviation (ERA) Project

LTO NOx

Core/Combustor Technology

Low NOx combustor concepts for high OPR environment

Increase thermal efficiency without increasing NOx emissions



Injector Concepts
- Partial Pre-Mixed
- Lean Direct Multi-Injection

Enabling Technology
- lightweight CMC liners
- advanced instability controls

- Improved fuel-air mixing to minimize hot spots that create additional NOx
- Lightweight liners to handle higher temperatures associated with higher OPR
- Fuel Flexibility

- DoD HEETE Program is developing higher OPR compressor technology
  .... ERA will focus on new combustor technology for reduced NOx formation

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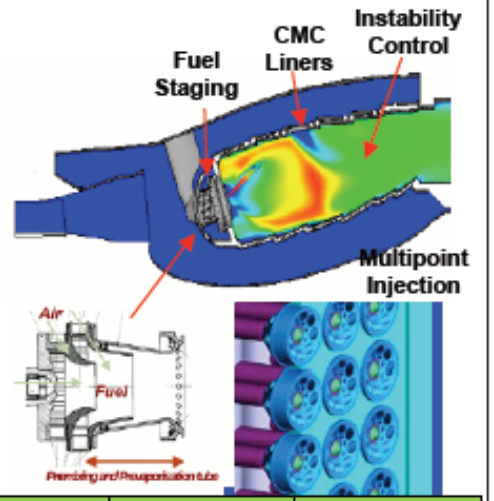
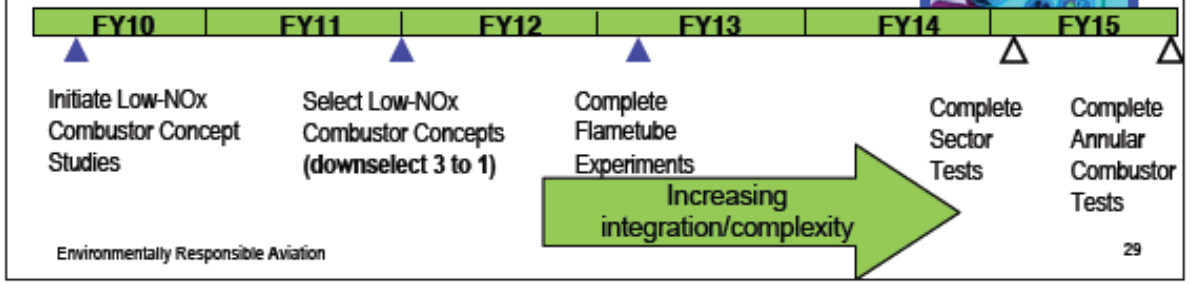
LTO NOx

Combustor Technology

- **Objective**
  - Extend maturation of technologies for reducing LTO NOx. Concepts must ensure fuel flexibility.
- **Approach**
  - Pursue 3 concepts: Lean Partial-Mixed Combustor, Lean Direct Multi-Injection, TBD from NRA.
  - Flametube, sector, and annular combustor tests.
  - Select single concept for engine tests.
  - Assume 50% cost share with industry.
- **Benefit**
  - Technologies to reduce LTO NOx by 75% below CAEP/6.



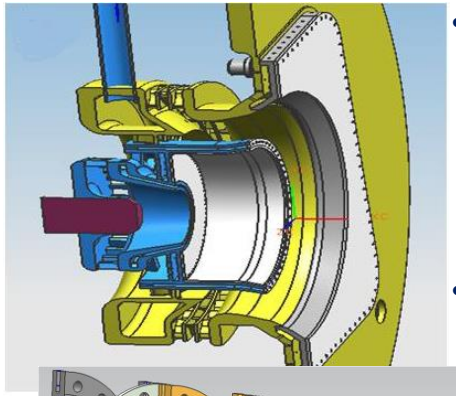


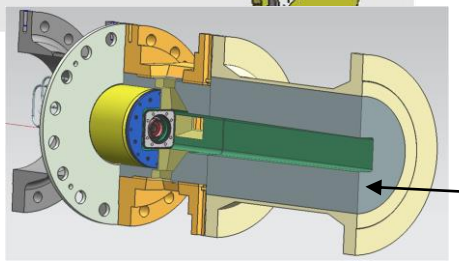
Environmentally Responsible Aviation 29

From Merlin (2020) Green light for green flight: NASA's contributions to environmentally responsible aviation
https://www.nasa.gov/connect/ebooks/aeronautics_ebooks_archive_1.html

2000s: FAP SUP and ERA subsonic test highlights

UTRC Pilot in Can Swirler (PICS) injector concept



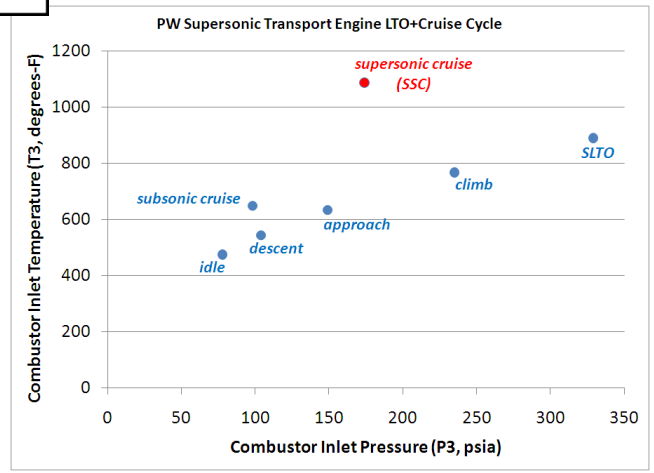


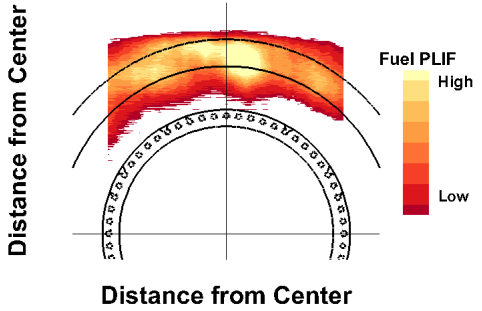
- Pilot
  - Low-power operation
  - Liquid fuel
  - Located in "can" inside the main swirler
  - can isolates pilot from main-stage flame
- Main-stage Supersonic flight
  - fuel used as heat sink
  - Flash vaporizes fuel for main swirler
  - low NOx emissions

Castable ceramic liner

	P3-psi	T3-F	FAR / FAR_{SLTO}
supersonic cruise 50k / M1.8	174	1087	1.10
subsonic cruise 35k / M0.8	98	648	0.77
SLTO	329	890	1.00
climb-66%	235	767	0.82
appoach-32%	149	634	0.66
descent-15%	104	544	0.59
idle	78	475	0.57

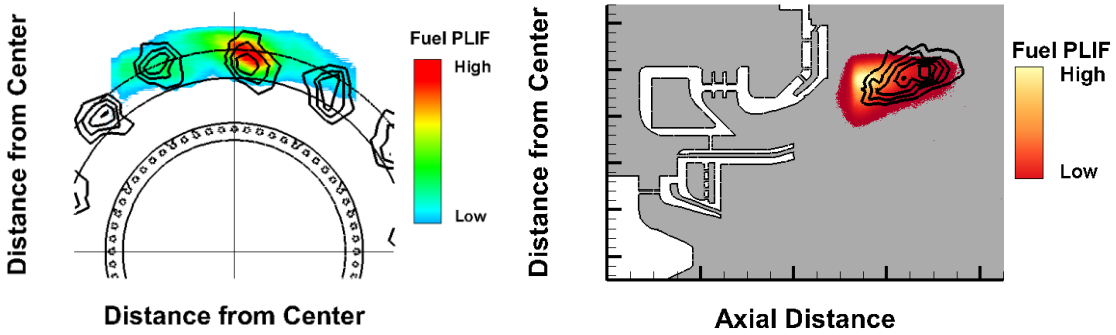
Differences between UTRC/NASA
- Supersonic cruise T3: 1087°F/ 975°F
- Subsonic cruise P3: 329/250 psia
- Fuel: *unheated* JP-5, ~ 70°F (UTRC used vaporized fuel)





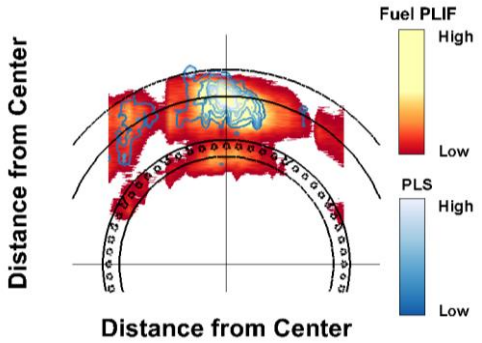
Subsonic Cruise Fuel Pattern

Results from NASA GRC testing

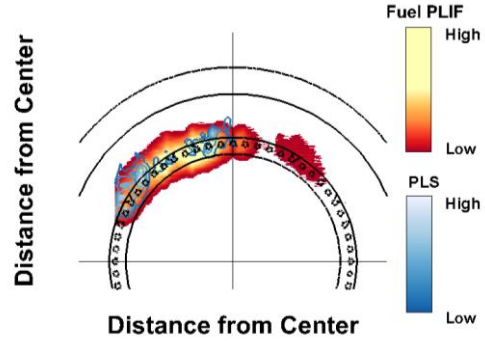


Distribution of Fuel (via PLIF) at N+3 Supersonic Cruise Condition
Line contours CFD; Color contours fuel PLIF
JP-8 enters as liquid at ~ 70°F, T3 = 975°F

Approach-1—Pilot + Main



Approach-2—Pilot Only



Note: UTRC is now RTRC

Hicks et al. AIAA-2014-3627

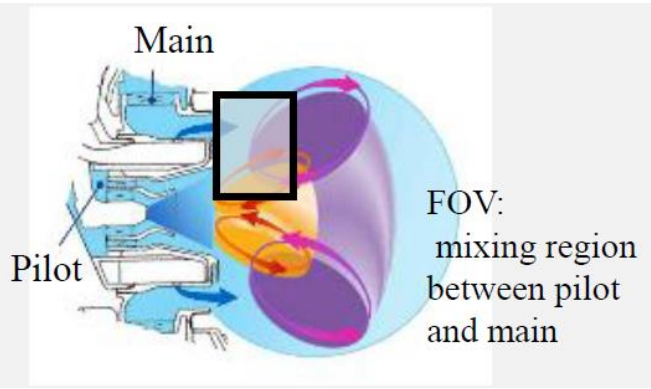
2000s: FAP SUP and ERA subsonic test highlights

Comparing Alternative BioFuel HRJ and JP-8 Fuel: Flame Tube Tests using a GE TAPS Injector Configuration

Test Point	P_3 psia	T_3 °F	Fuel Split % Pilot/Main	FAR/FAR_{SLTO}
1	166	650	100/0	0.48
2	200	925	10/90	0.94
3	200	1000	20/80	0.94
4	200	1000	10/90	0.94

Fuel settings:
100% HRJ,
100% JP8,
75% HRJ/25% JP8

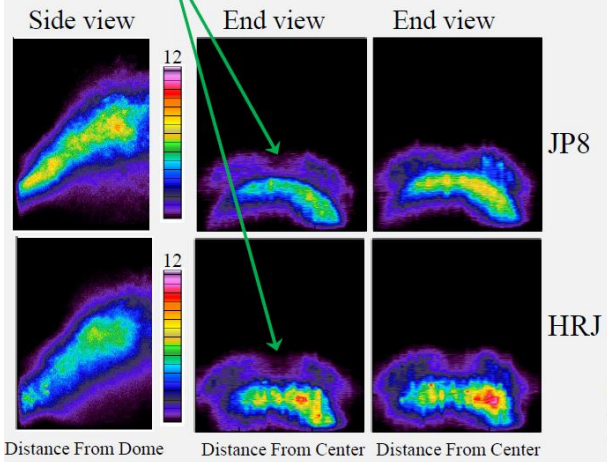
Fuel	JP-8	HRJ
Sulfur (ppm)	1148	<3
Olefins (%vol)	0.9	0.4
Aromatics (%vol)	18.6	0.4
Naphthalenes (%vol)	1.6	0
Initial boiling point, °	158	165
10%	176	179
90%	248	243
End Point	273	231
Flash Point °C	46	55
API Gravity	41.9	54
Specific Gravity	0.816	0.758
Freezing Point °C	-50	-62
Viscosity	4.7	5.3
Cetane Index	**41**	**67**
H Content (%mass)	13.6	15.3
Heat combustion (MJ/kg)	43.3	44.5
Fuel H/C ratio	**1.88**	**2.12**



Fuel PLIF

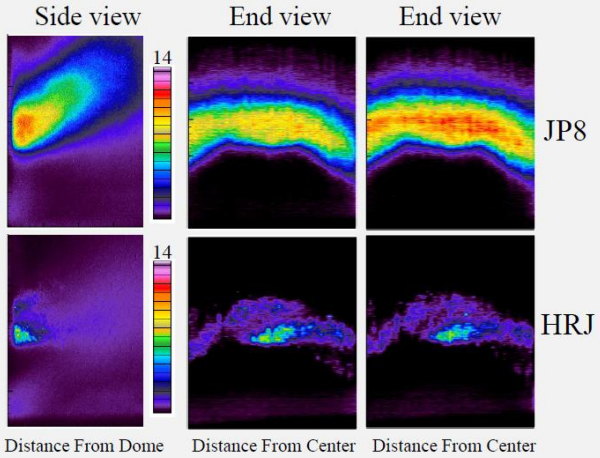
Point 1, pilot only

Notch due to N2 purge

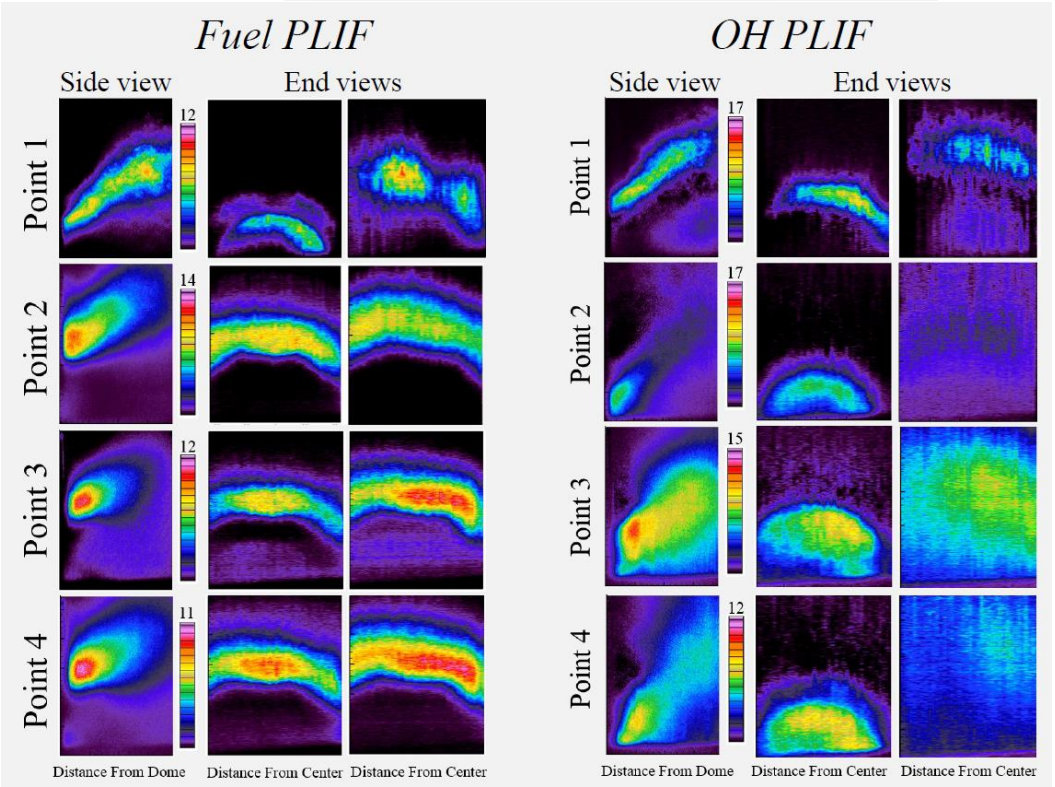


For pilot only, JP8, HRJ have similar spray pattern

Point 2, 10/90 split, T_{in} = 925°F

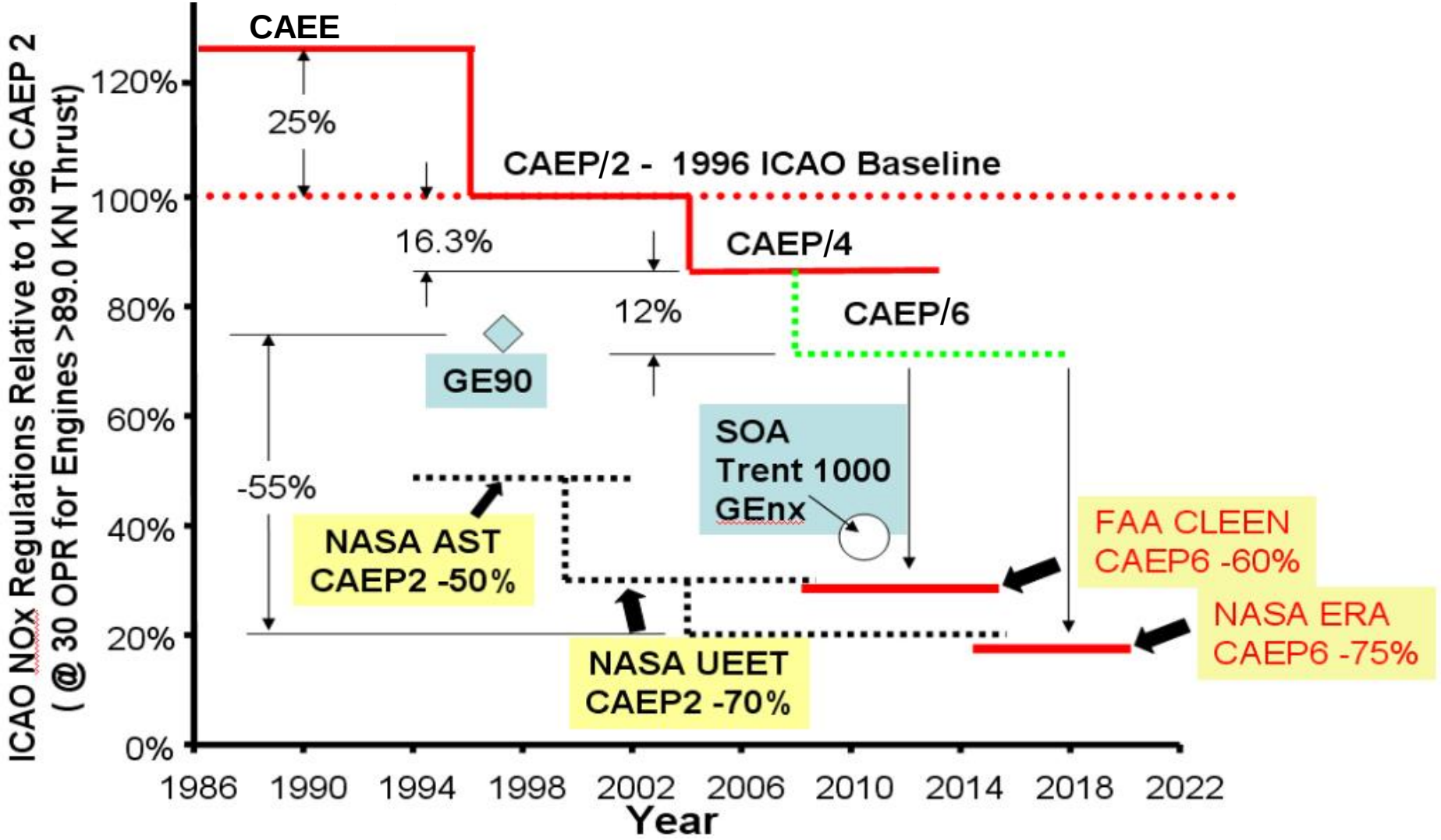


JP8: uniform distribution within annulus
HRJ: Most fuel observed near wetted annular walls
Possibly only HRJ liquid seen because greater number density than in gas phase



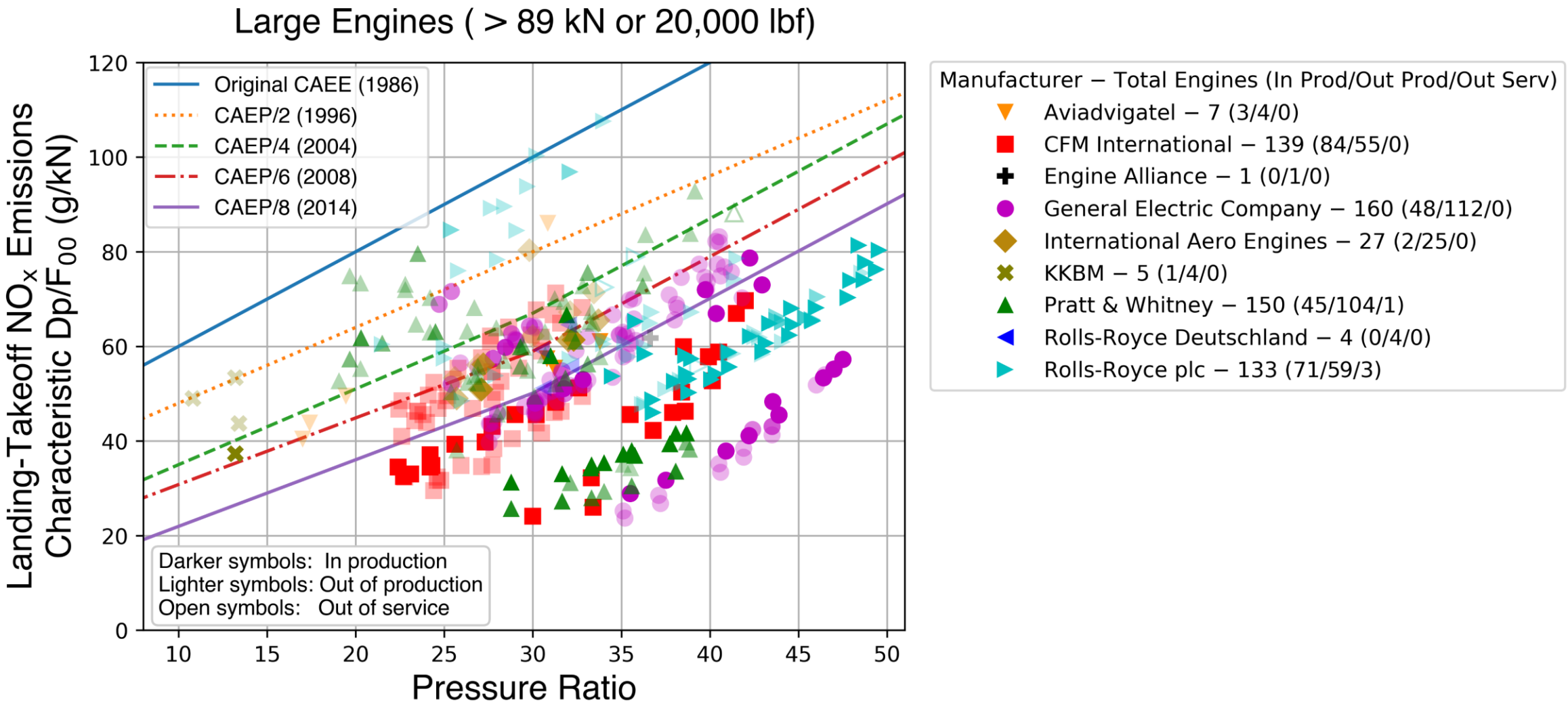
Hicks et al. AIAA-2016-4890

History of ICAO CAEP regulations for high thrust engine subsonic aircraft from CAEE through CAEP/6



Reddy and Lee GT2016-56100

Evolution of ICAO CAEP LTO NOx regulations through CAEP/8, along with engines by manufacturer



Part 3: Present and Future, since 2015

Present and future are combined here. One reason is that NASA looks forward to anticipate future needs, as was demonstrated in Part 2 and summarized in the last two slides that show the progress in emissions reduction.

The present comes from the past FAP N+3 and Integrated Systems Research Program ERA goals in other areas (such as for airframe and turbomachinery technologies). These in part led to the current Sustainable Flight National Partnership (SFNP) for subsonic aircraft, which has the objective of achieving net-zero carbon emissions by 2050. A key SFNP activity is the Hybrid Thermally Efficient Core (HyTEC) which will affect work in the Combustion and Emissions area.

The supersonic flight regime presents more Combustion and Emissions challenges to be met.

https://www.nasa.gov/sfnp/ https://www.nasa.gov/aeroresearch/programs/aavp/hytec/technical-portfolio/

Present → Future: Programs and Projects

Environmentally Responsible Aviation Project (ended 2015)

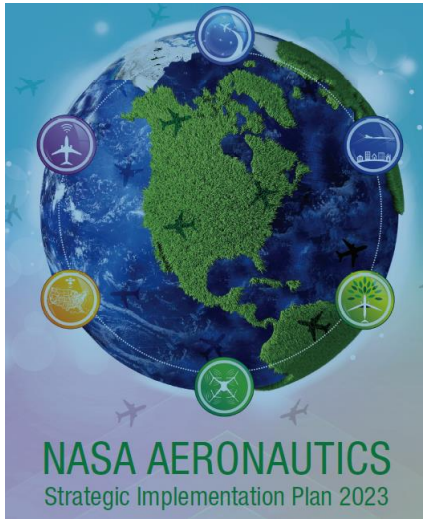
Advanced Air Vehicles Program (AAVP) began 2016

- Advanced Air Transport Technology (AATT)
- Commercial Supersonic Technology (CST)
- Hypersonic Technology (HT)
- Hybrid Thermally-Efficient Core (HyTEC)

Transformative Aeronautics Concepts Program (TACP) began 2015

- Transformative Tools and Technology (TTT, T^3)
- Convergent Aeronautics Solutions (CAS)
- University Innovation (UI)

NASA ARMD Strategic Implementation Plan. See Thrusts 2 and 3
https://www.nasa.gov/sites/default/files/atoms/files/sip-2023-final-508.pdf



Present → Future: AAVP

- AATT project: develop technologies for advanced fixed wing aircraft with high energy efficiency and environmental compatibility. Combustor related technical challenge (TC) is for a fuel-flexible combustor with NOx emissions 80% below CAEP/6 standard with minimal impacts on weight, noise or component life.
  - nvPM extractive & optical measurements
  - N+3 combustor emission measurement and simulations
- CST project: develop technologies that eliminate barriers to commercial supersonic flight. Relevant to combustion are NOx and particulate emissions.
  - Low NOx injector for supersonic cruise
- HyTEC project: develop small core engine tech that enables electrical power extraction (up to 20% at altitude), reduces fuel burn (5% - 10% compared to best-in-class turbofan), and is compatible with 80% - 100% sustainable aviation fuels.
  - Sustainable aviation fuel (SAF) combustor technologies

https://www.nasa.gov/aeroresearch/programs/aavp/aatt
https://www.nasa.gov/aeroresearch/programs/aavp/cs
https://www.nasa.gov/aeroresearch/programs/hytec

Present → Future: TACP

- T^3 project: develop state-of-art computational and experimental tools and technologies
  - Soot modeling and experiments
  - Fuel injector: X-ray atomization imaging experiments
  - Transcritical fuel sprays
  - Conjugate heat transfer

- UI project: provide opportunities for university-led teams to conduct research into transformative technology to support NASA ARMD goals via NASA Research Announcement awards. These include University Leadership Initiative (ULI), University Students Research Challenge (USRC), and Gateways to Blue Skies Competition (Blue Skies)

https://www.nasa.gov/aeroresearch/programs/tacp/ttt https://www.nasa.gov/aeroresearch/programs/tacp/ui/description/

Present → Future

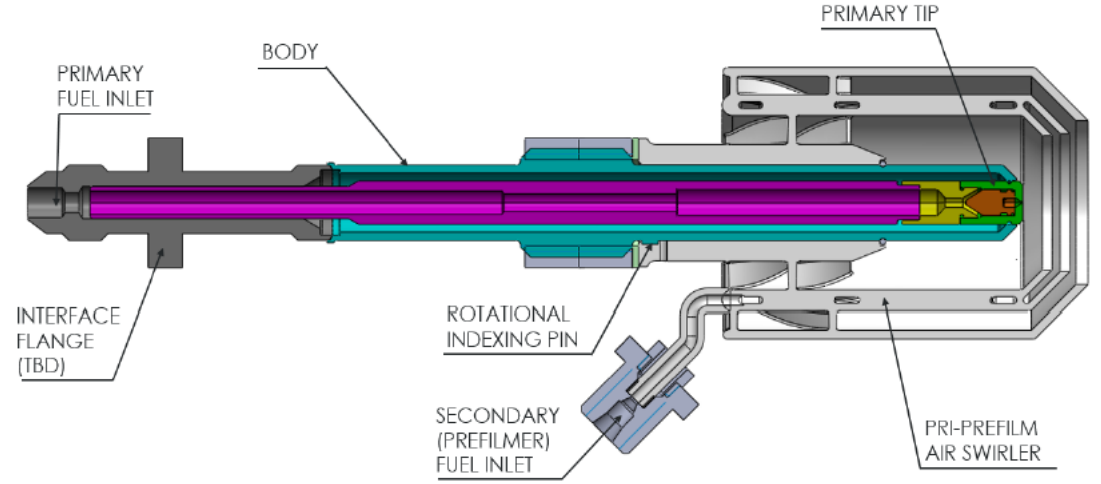
This last section will feature examples in areas not previously highlighted.

- Fuel injection research—Aero Spray Working Group collaboration
- NASA Sustainable Aviation Strategy and Sustainable flight
- Sustainable alternative fuels (SAFs) practicalities
  - Engine emissions
  - Stability: LBO, cold start, altitude relight
- Modeling
  - Fuel injection
  - LBO
  - Combustors

Fuel Injector Studies

A non-proprietary prefilming injector is being studied by a consortium called the Aero Spray Working Group (ASWG) that includes the US engine OEMs, AFRL, ARL, ONR, ANL, and NASA to better understand the fuel injection process as it proceeds from inside the injector and into the combustion chamber. X-ray techniques are being conducted by partners at Argonne National Lab that will help to answer these questions. Create detailed measurement database.

<u>Measurement phases</u>
Phase 1: 1 atm, 25°C
Phase 2: 50 atm, 25°C
Phase 3: 50 atm, 700°C

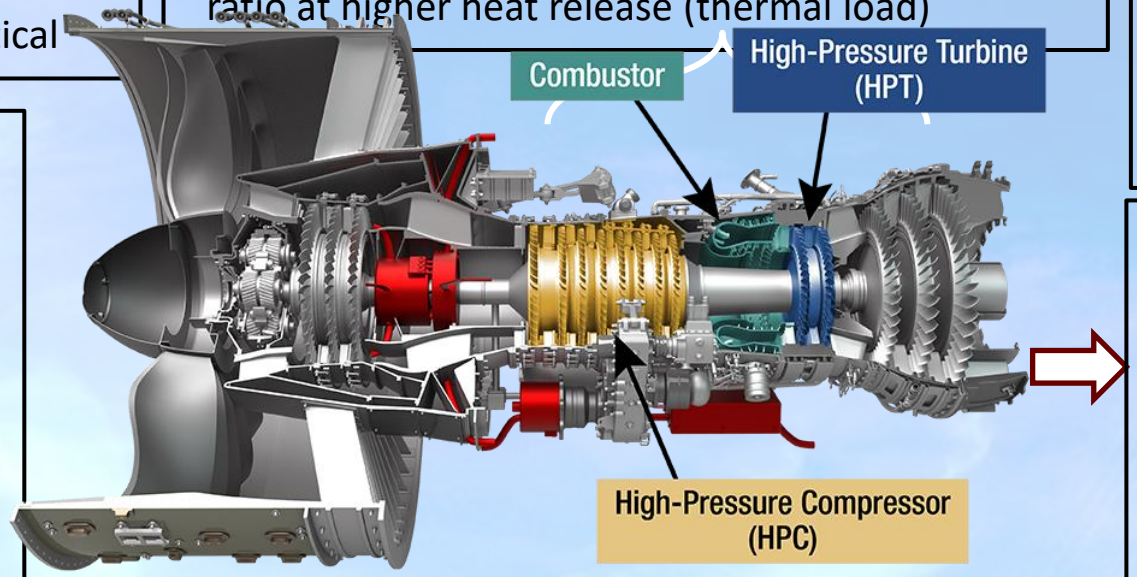


Non-proprietary fuel injector *Woodward FST*

Combustion and Emissions Challenges for Future Systems

High OPR
- Higher P3, T3 air into combustor creates challenges for
  - Low NOx
  - Durability
  - Fuel at trans/supercritical

Small Core Challenges
- Scaling combustor to smaller size (residence time, operability, emissions, fuel-nozzle orifice limits)
- Cooling with increased combustor surface/volume ratio at higher heat release (thermal load)



High-Speed Challenges
- Long Duration Cruise at harshest thermal condition
- High-altitude required to reduce fuel burn drives need for ultra-low NOx (to minimize ozone depletion)
- Strong drive to quickly get to 100% SAF

Heated Fuels
- Thermal management and/or cycle efficiency goals may drive use of fuel as heat sink (small core, high-speed)
- Fuel coking
- Fuel system control, injection, fuel-air mixing if fuel is trans/supercritical

Emission Challenges
- New CAEP/11 nvPM standards (LTO)
- More stringent future standards on LTO and potentially cruise (NOx, nvPM)
- Reducing non-CO2 aviation impacts on climate (NOx, particulates, contrail-cirrus formation)
- For Supersonic high-altitude, ultra-low NOx needed to reduce ozone depletion

Sustainable Aviation Fuels
- Scaling production of existing and new production pathways is largest challenge
- Further work needed to quantify/maximize SAF benefits (reduced soot, higher thermal stability), and evaluate operability and contrail impact for higher SAF blends

Hydrogen
- Different views on degree to which H_2 may contribute to meeting net-zero carbon 2050 aviation goals
- Combustion challenges include:
  - Low-NOx while preventing flashback
  - Fuel injection
  - Combustion dynamics

U.S. Aviation Climate Action Plan

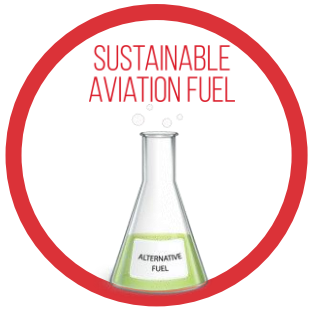
Global Context for Sustainable Aviation

U.S. aviation goal is to achieve
net-zero greenhouse gas emissions by 2050.

U.S. Aviation Climate Action Plan is aligned with
- U.S. economy-wide goal
- International Civil Aviation Organization
- Air Transport Action Group



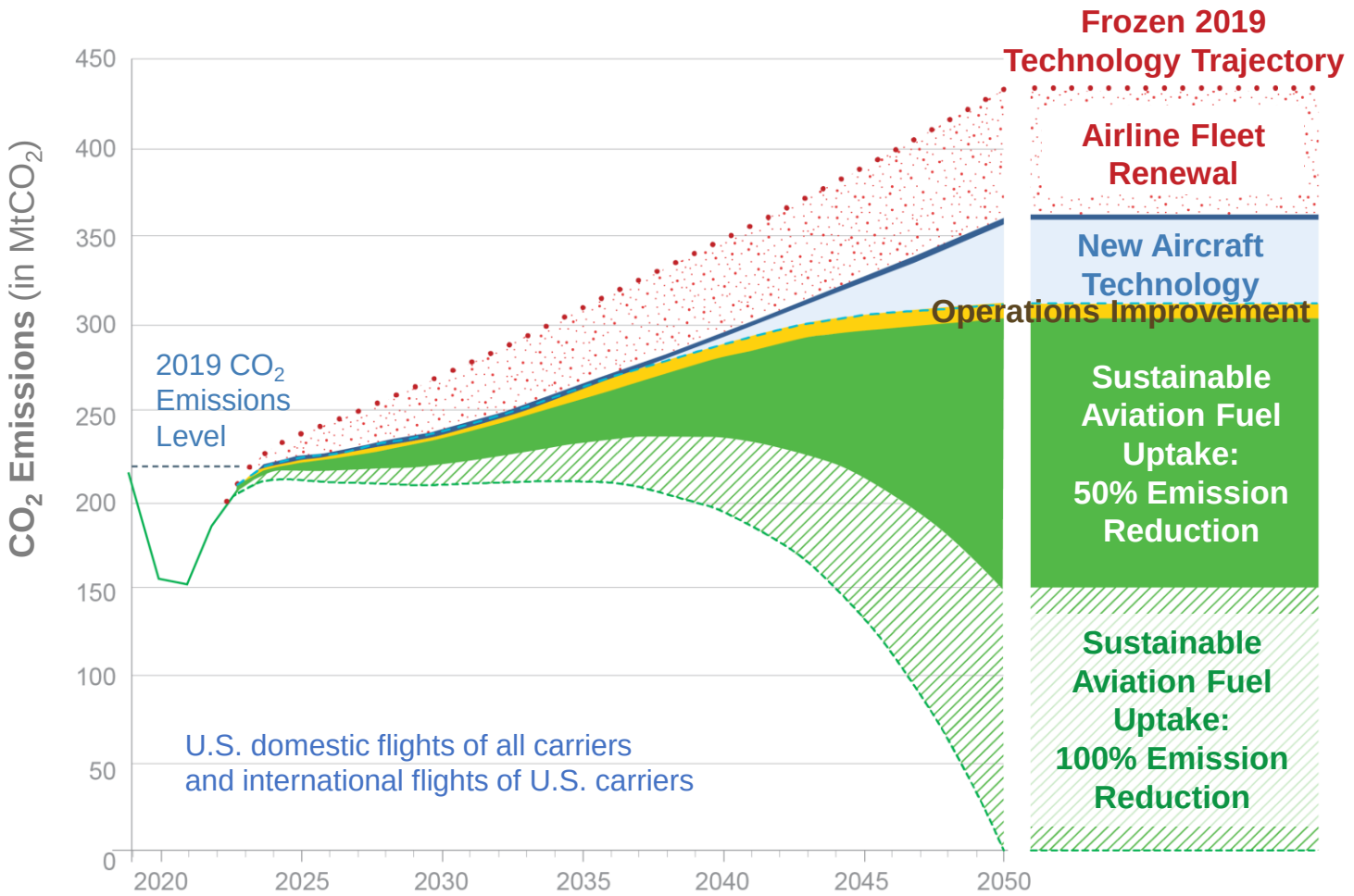
NASA = Primary Role



NASA = Supporting Role



NASA = Primary Role



https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf

Klettlinger and Moore, AEC roadmap mtg, May 2023

The U.S. is working with the global community to achieve net-zero greenhouse gas emissions by 2050 using a common basket of measures.

NASA Sustainable Aviation Strategy

2008-2013 | 2014-2019 | 2020-2025 | 2025-2030 | 2030+

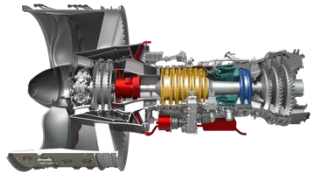
Subsonic Concept/Technology Studies
Electric Aircraft Propulsion,
Transonic Truss-Braced Wing
Blended Wing Body

Environmentally Responsible Aviation Project

Flight Demonstrator Studies

Advanced Composites Project





SUSTAINABLE FLIGHT NATIONAL PARTNERSHIP

Sustainable Flight National Partnership to mature and integrate key technologies for next-generation subsonic transports (2030s)

TODAY

ACCELERATING TOWARD NET-ZERO CARBON

Cast a wide net for zero-emission concepts and technologies

Select and develop promising concepts in partnership with universities, industry

Create a credible mission, architecture, and technologies for beyond next-generation subsonic transports for 2050 horizon

POWERING AVIATION TO NET-ZERO CARBON AND BEYOND

Klettlinger and Moore, AEC roadmap mtg, May 2023

Investment in innovation today paves the way to a net-zero carbon and beyond aviation future.

Sustainable Aviation Fuels (SAF)

Alternative Jet Fuels (AJF): Fuels produced from **non-petroleum** feedstocks

Sustainable Aviation Fuels (SAF): Fuels produced from **renewable** non-petroleum feedstocks in **sustainable** manner

"**sustainable**" typically includes*:

- Reducing net life-cycle CO2 emissions relative to petroleum-based jet fuel.
- Enhancing the sustainability of aviation by being superior to petroleum-based jet fuel in economic, social and environmental aspects.

SAFs also provide additional health and climate benefits:

- SAFs typically have low (or zero) aromatics content, leading to significant reductions in particulate emissions, which reduces health impacts from engine emissions and reduces contrail formation, a significant non-CO2 contributor to aviation's impact on climate warming.
- SAFs have zero sulfur content, thus removing the formation of sulfur oxides and sulfates resulting from engine emissions, reducing adverse health impacts from aviation

SAF composition and physical properties can vary significantly depending on the feedstock and process for creating a particular synthetic (non-petroleum) jet fuel.

* *CAAFI (Ccommercial Aviation Alternative Fuels Initiative)*: https://caafi.org

SAF Emissions and Contrails Research
October 2021 Emissions Ground Test at Boeing Field

- Goal to quantify on-wing emissions relevant for contrails & air quality
- Ultra-low-emitting CFM LEAP-1B engines on the 2021 ecoDemonstrator 737 MAX 9
- Four fuels:
  - 100% SAF HEFA (World Energy)
  - 50-50% SAF-Jet A
  - 30-70% SAF-Jet A
  - 100% Jet A
- Test covers a range of engine thrust conditions from engine idle to takeoff
- Burning 100% SAF in the LEAP-1B engines should give us the lowest possible emissions achievable with in-service technology!



Photo Credit: Boeing / Paul Weatherman

https://www.nasa.gov/aeroresearch/nasa-tests-sustainable-aviation-fuel-emissions

POC: Dr. Rich Moore, LaRC

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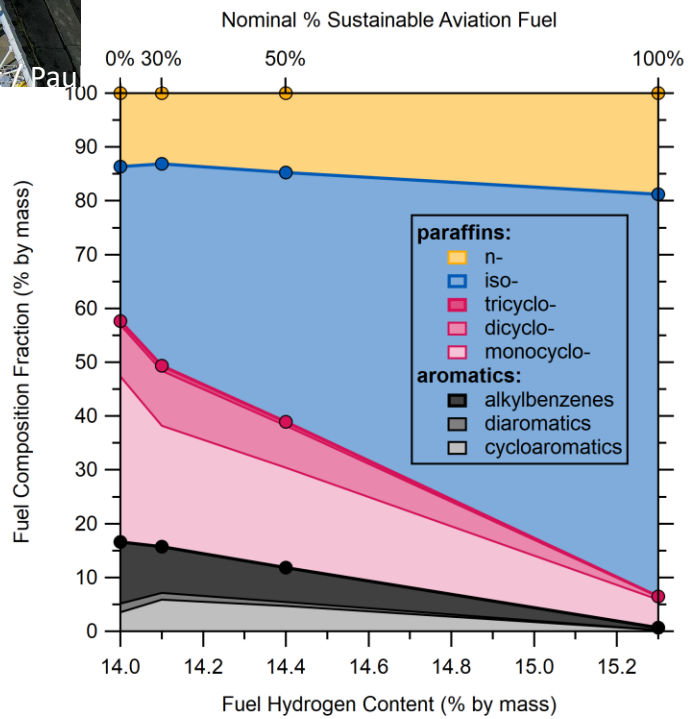
  - 100% Jet A
- Test covers a range of engine thrust conditions from engine idle to takeoff
- Burning 100% SAF in the LEAP-1B engines should give us the lowest possible emissions achievable with in-service technology!



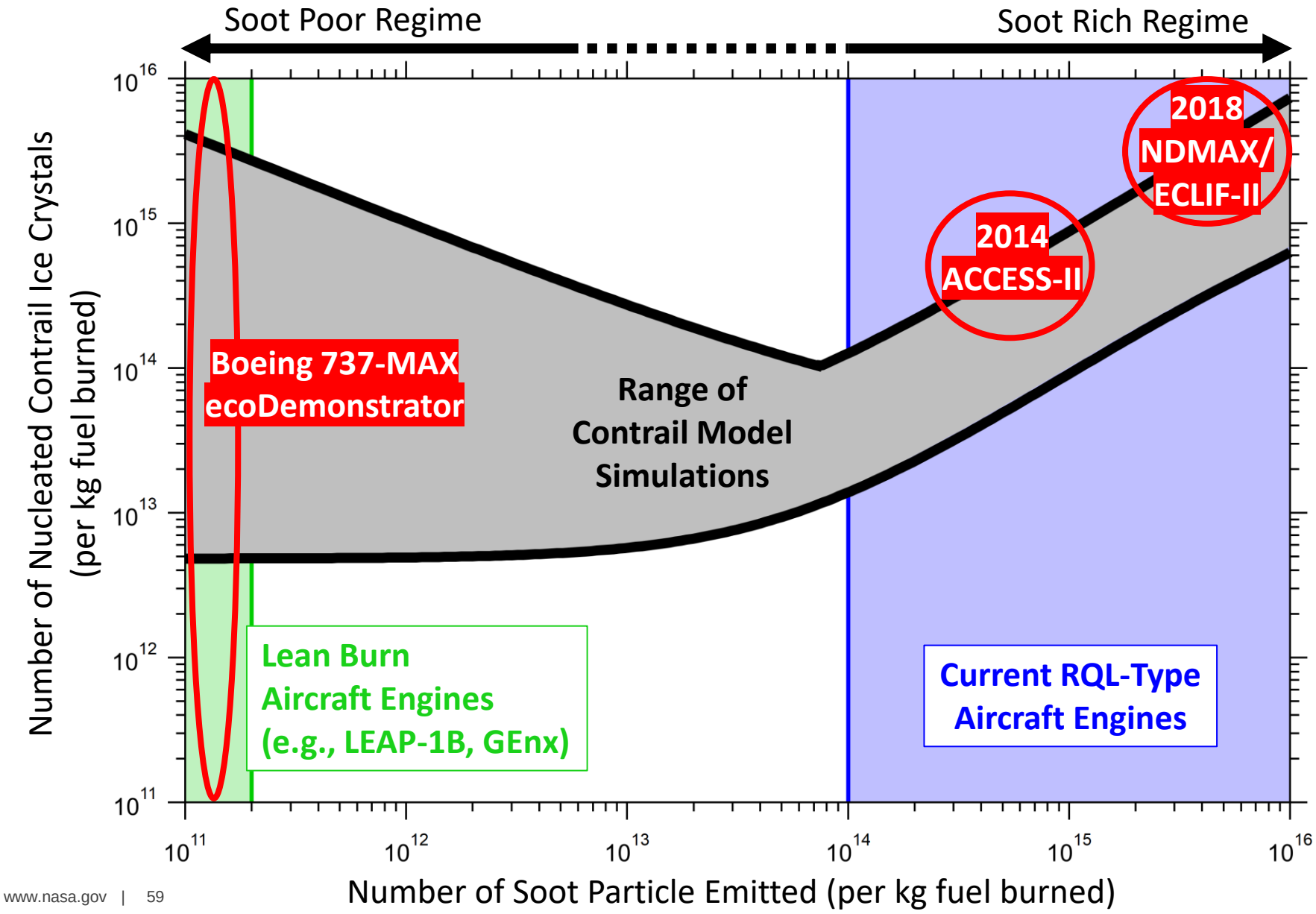
- Good linearity between aromatics and %hydrogen
- 50% SAF tested is NOT halfway between 0% and 100% in terms of aromatics or %hydrogen



https://www.nasa.gov/aeroresearch/nasa-tests-sustainable-aviation-fuel-emissions

POC: Dr. Rich Moore, LaRC

Motivation: Potential of SAF and Advanced Combustor Technology



Need to understand the "soot-poor" regime and do it at flight altitude to understand contrails

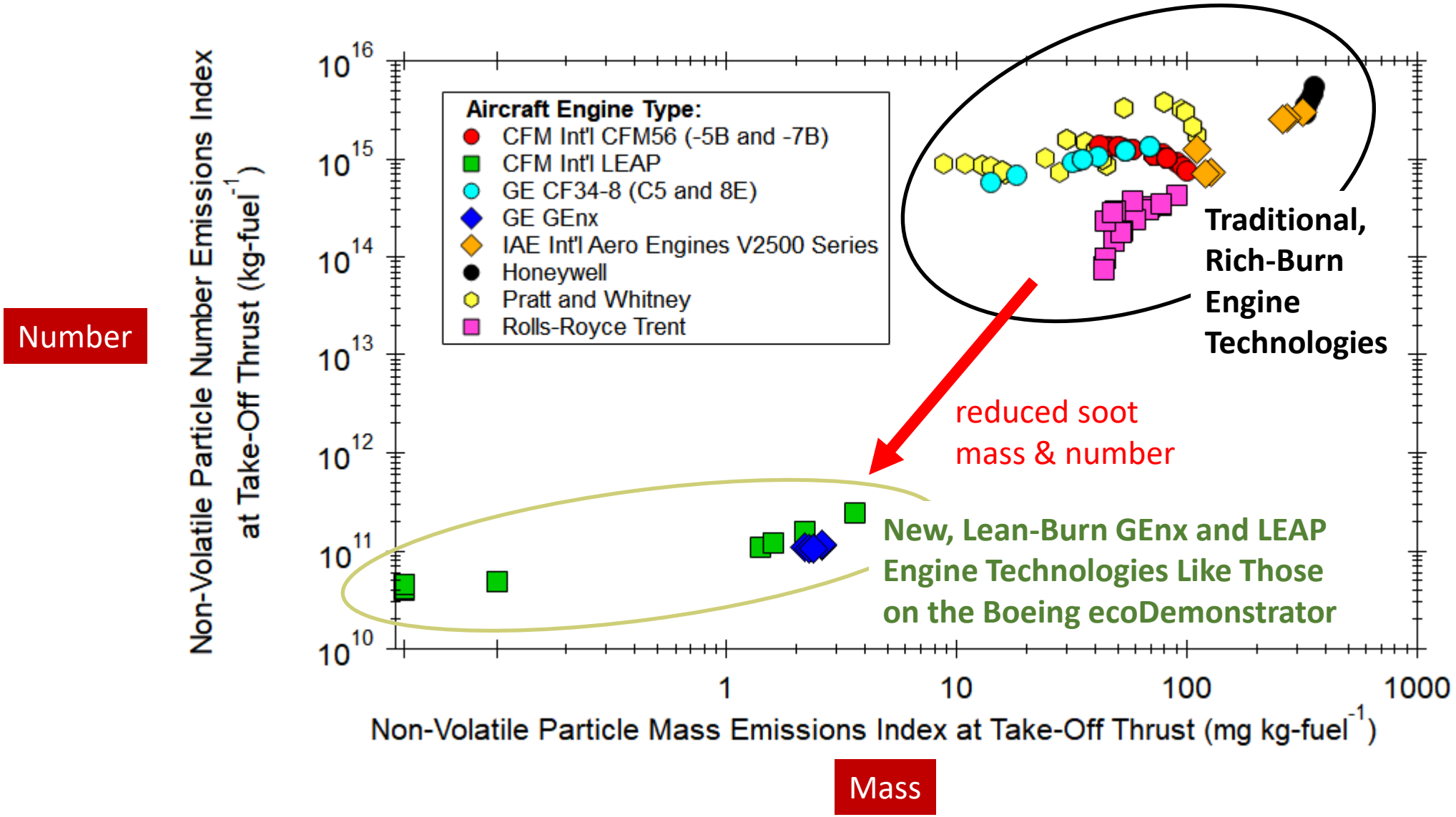
Need to fly aircraft with lean burn combustor (i.e. 737-MAX) at flight altitude to understand contrails

Figure adapted from Kärcher, *Nature Communications*, 2018.

Red circles show the approximate Number EIs observed during the 2014 ACCESS-II and 2018 ND-MAX/ECLIF-II flight test series.

Moore et al., Nature, 2017; Voigt et al., Nature Comms. Earth & Environ., 2021

Recent ICAO Engine Certification Data (released 12/2020) hint that reductions could be even greater for new combustor technologies!

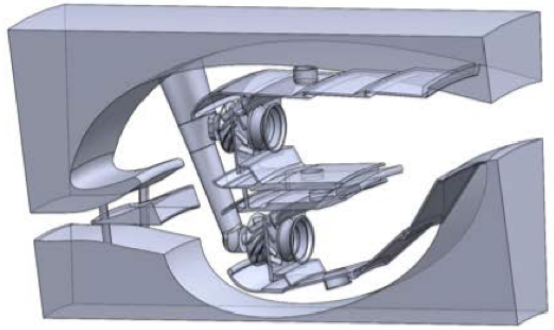


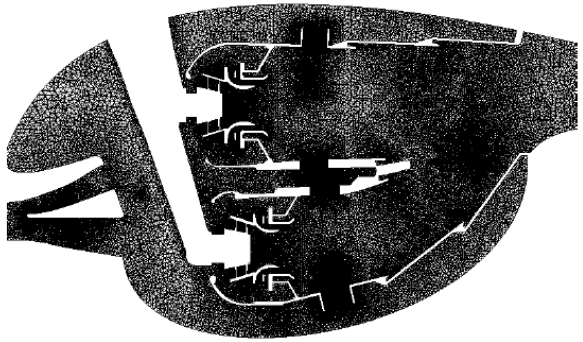
Combustor modeling examples

- TTT: computational study of combustor-turbine interactions
- CST: modeling of axially-controlled stoichiometry combustor—fuel effects
- CST: evaluation of Woodward FST LDI combustor design variations

Computational Flow Field in Energy Efficient Engine using OpenNCC

This work revisited the GE DAC combustor from E^3
Objective: better understand combustor-turbine interactions





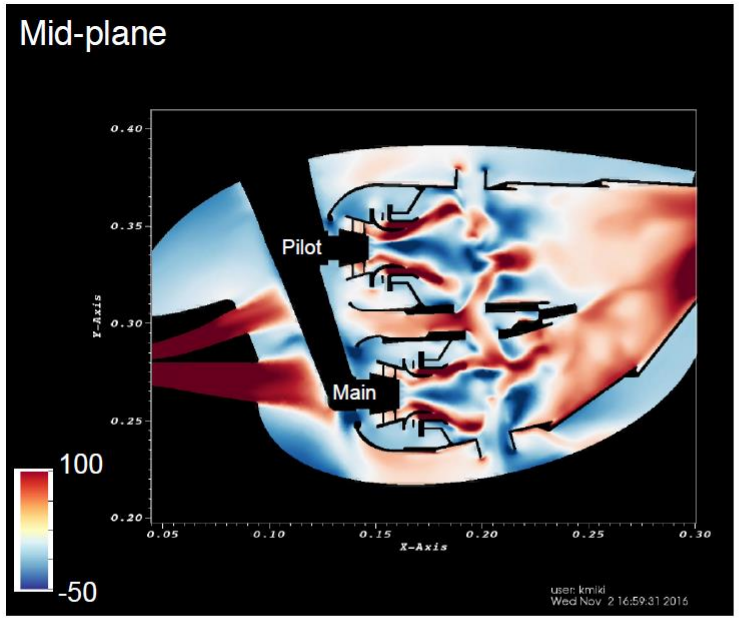
	Numerics	Steady?	Spray	Fuel	Chemistry
Case 1	JST/AUSM	Yes	Gas	C12H23	one-step
Case 2	JST/AUSM	Yes	Liquid	C11H21	14 species-18 reactions
Case 3	JST/AUSM	No	Liquid	C11H21	14 species-18 reactions

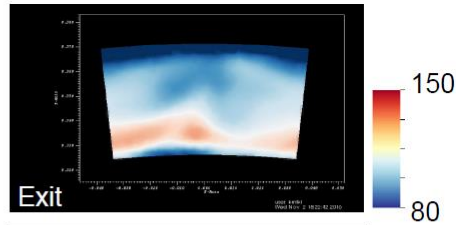
- One-cup (12 degree) E^3 geometry(1) is considered
- Tetrahedral mesh (~9.5M) is generated by Cubit (AMR is off)
- Used 960 processors of Pleiades at NASA Advanced Supercomputing facility
- Non-linear k-ε model and finite-rate chemistry
- Taken into consideration is the simulated sea level takeoff condition (SLTO)

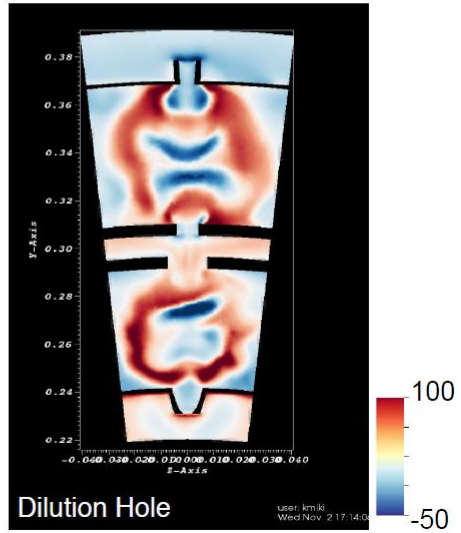
	P3 [atm]	T3 [K]	W3 [kg/s]	Wf_{total} [kg/s]	f/a	Wf_{pilot}/Wf_{total}	T_{fuel} [K]
SLTO	2.52	720	0.26	0.00364	0.014	0.5	520

(1) Burrus, D. L., et al, No. NASA/CR-1984-168301, (1984)

Unsteady flow fields. Contours of axial velocity







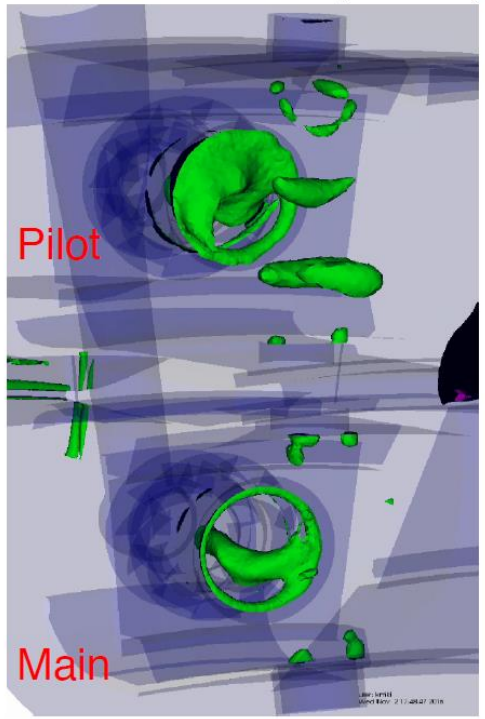
- Dilution airflow and swirling airflow interact and oscillate back and forth.
- There is a recirculation zone at the top of the dilution hole, enhancing the oscillation.

Miki, Moder, Liou 2016

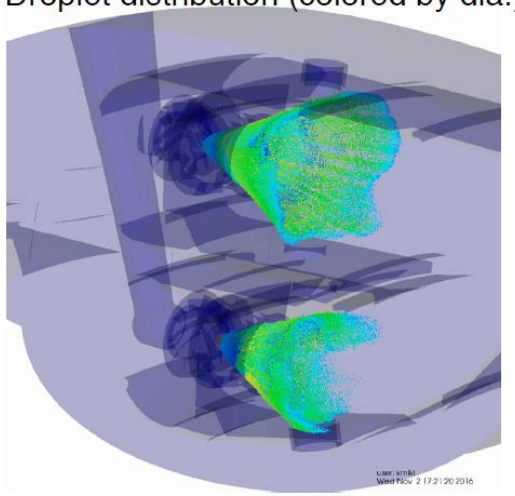
Computational Flow Field in Energy Efficient Engine using OpenNCC

Precessing vortex core

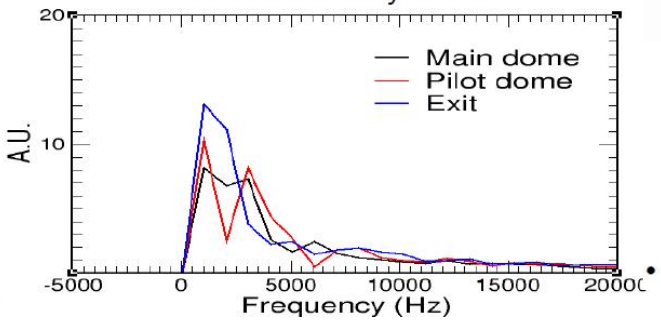
Pressure iso-surface (245K Pa)



Droplet distribution (colored by dia.)

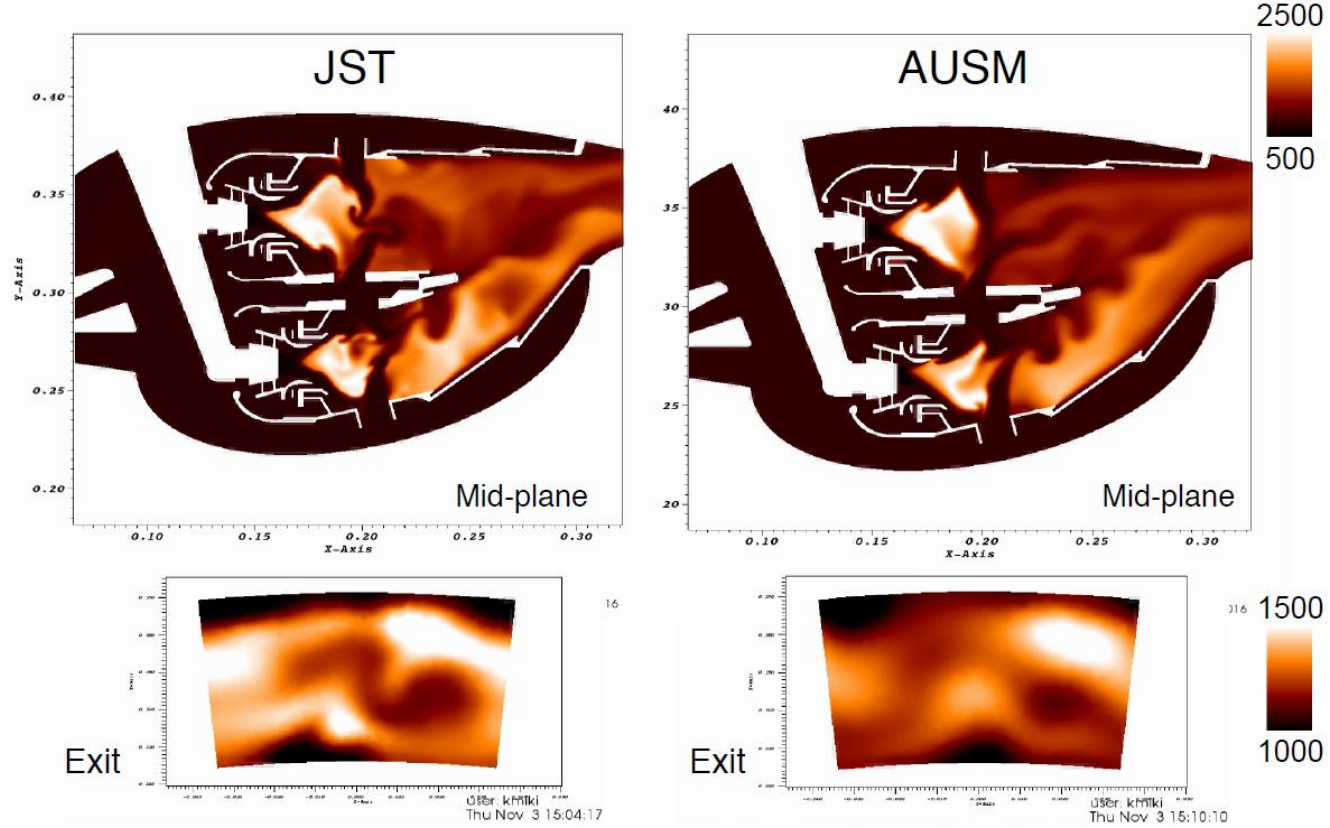


FFT of velocity fields



PVC greatly impacts on the particle motion and the combustion dynamics.

Temperature fields, time averaged



Temperature field is not uniform at the combustor exit and lots of hot/cold “spots” .

Miki, Moder, Liou 2016

CST High Altitude Emissions: CFD Evaluation of Advanced Fuel Blends

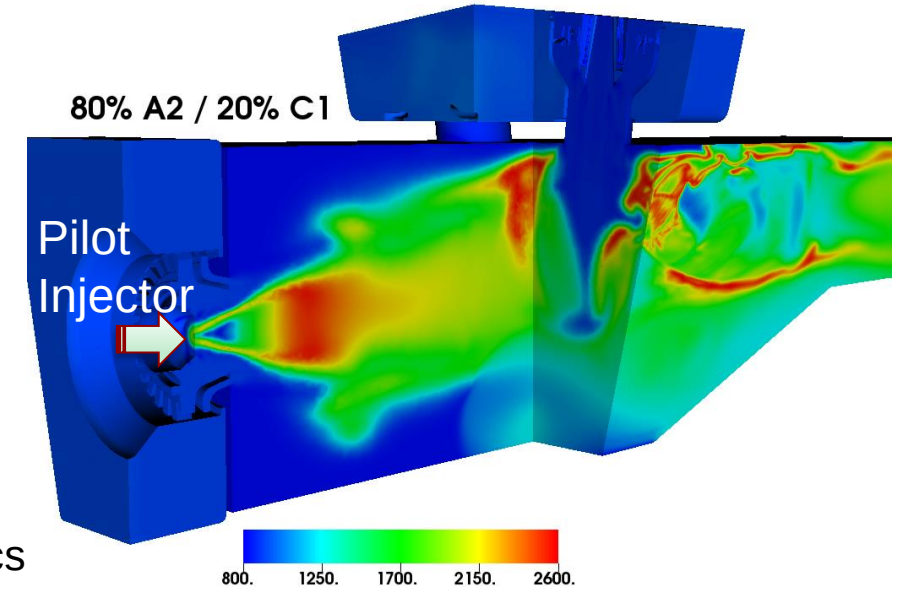
- **OpenNCC CFD Analysis of Fuel Blending. Use Sustainable Aviation Fuels (SAF) for CST**

  Combine faster-burning Jet-A (A2) with slower-burning SAF (Alcohol-to-Jet or ATJ C1) and assess the effects on Combustor Performance, Flame Stability, Emissions (CO and NOx)

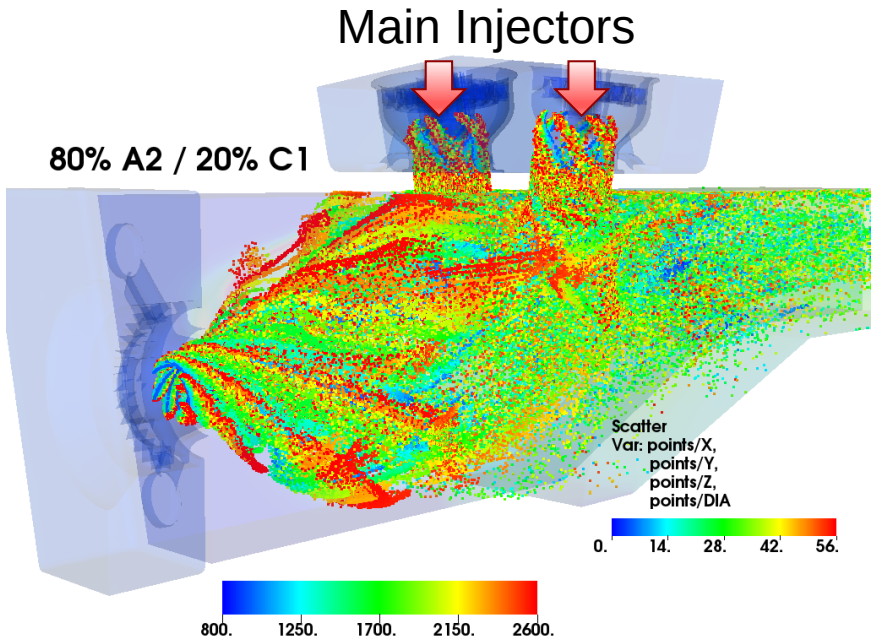
  Three blending ratios for A2/C1: 80/20, 50/50, 20/80

Composition	A2	C1
aromatics	20%	
iso-paraffin	20%	100%
n-paraffin	20%	
cyclo-paraffin	40%	
Derived Cetane Number	49	16

- Initial Flame w/ 51 Species Kinetics
- Add 30 Species for NOx
- Test and verify multi-component fuel evaporation model
- 1200hrs (1000 NAS cores) for each run



Typical Temperature (K) Contours



Typical Spray Droplet Pattern

Comparable Performance, Flame Stability, EINOx and CO for all three blends. 50/50 Blend shows some advantages.

POC: Kumud Ajmani, Jeff Moder, Jennifer Klettlinger

CST High Altitude Emissions: CFD Evaluation of Advanced Fuel Blends

Objectives

- CFD assessment of an axially-staged combustor (developed under ERA and AATT N+3 by PW/UTRC) at supersonic cruise with advanced fuel blends to assess fuel impacts on NOx emissions and flame structure

Summary Findings

- Three Fuel blends: 80/20, 50/50, 20/80 Jet-A (A2)/Gevo Alcohol-to-Jet (C1)

  CFD predictions of flame-structures for all three fuel blend mixtures are similar at CST Cruise conditions with similar flame holding and stability relative to Jet-A

  CFD predictions of NOx emissions for all three fuel blend mixtures are within 10% of each other at CST Cruise conditions.

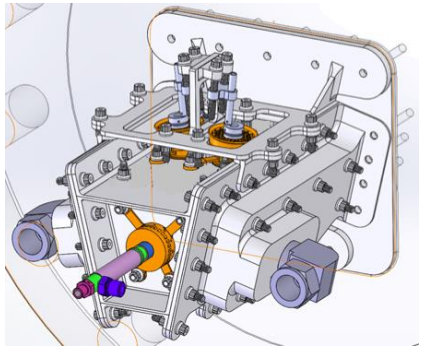
  CFD predictions of NOx emissions for all three fuel blend mixtures are within 10% of measured experimental values for 100% Jet-A fuel at CST Cruise conditions.

Significance

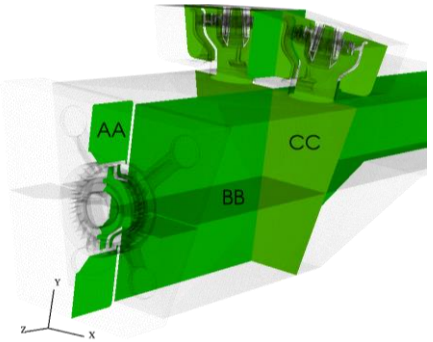
- Demonstrated capability to perform eddy-resolving CFD simulations including NOx chemistry for multiple LDI-4
- Consistent with previous experimental studies[1], CFD predicted only small var

CFD study demonstrated similar flame structures and NOx emissions for fuel blends covering large range of composition and combustion properties variation for a next-generation axially-staged combustor

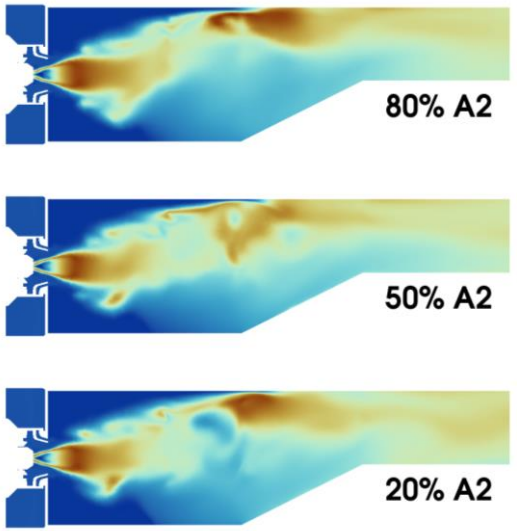
UTRC Hardware



CFD Geometry



CFD Flame Structure
(Slice AA)



Fuel Composition

Fuel Composition	A2 (Average Jet-A)	C1 (Gevo ATJ)
aromatics	20%	1%
iso-paraffin	20%	99%
n-paraffin	20%	
cyclo-paraffin	40%	

Predicted Emissions

A2 %	C1 %	EINOx
80	20	**15.5**
50	50	**14.5**
20	80	**16.0**

POC: Kumud Ajmani, Jeff Moder, Jennifer Klettlinger

CFD Evaluation of Woodward FST LDI Combustor Design Variations

Objectives

- CFD assessment of 3rd and 4th generation Lean Direct Injection (LDI) Combustors (Woodward, FST Inc) to predict the effects of injector design changes on NOx emissions and flame structure

Summary Findings

- Three Designs: Axial Air Swirlers (baseline, 3rd generation LDI-3), Radial Air Swirlers (co-rotating and counter-rotating, 4th generation LDI-4)

  CFD results predicted differences in flame-structures and similar stability between the axial (LDI-3) and radial air swirler (LDI-4) designs at CST Cruise.

  CFD predictions of NOx emissions for all three designs were within 25% of each other at CST cruise.

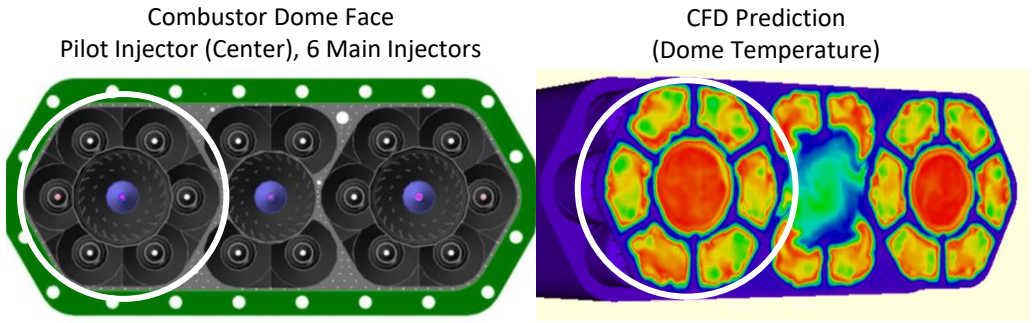
  CFD predictions of NOx emissions for a radial swirler design (LDI-4) were up to 25% lower than the baseline axial swirler design (LDI-3) at CST cruise.

Significance

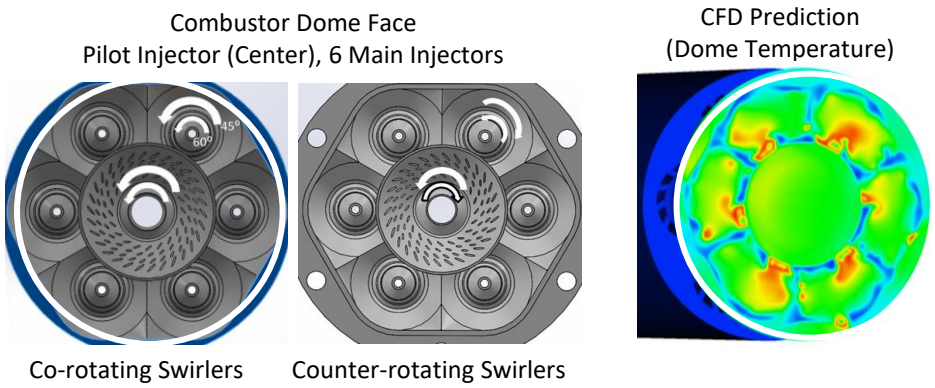
- Starting from a baseline lean direct injection (LDI) design previously tested at CST cruise conditions, this CFD study demonstrated the po
- Th

CFD study demonstrated different flame structures and up to 25% lower NOx emissions at CST Cruise conditions with fourth-generation Lean Direct Injection combustor designs

Axial Swirler Design (Baseline, LDI-3)



Radial Swirler Designs (LDI-4)



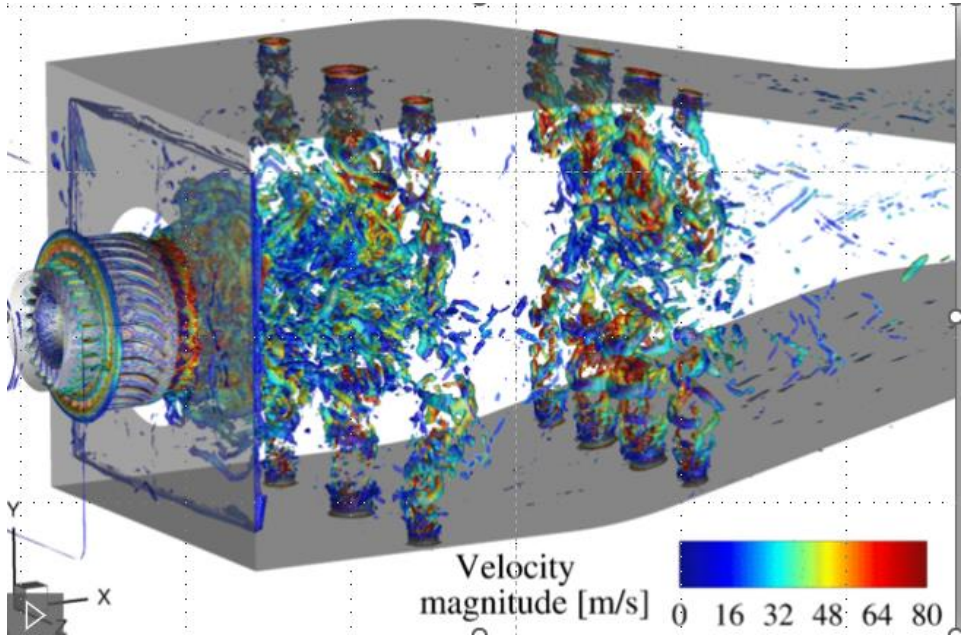
OpenNCC CFD NOx (CST Cruise)

LDI Designs	EINOx (g-NOx/kg-fuel)
Axial Swirlers (LDI-3, Baseline)	**16.5**
Radial Swirlers (LDI-4, Counter-Rotating)	**15.0**
Radial Swirlers (LDI-4, Co-Rotating)	**12.0**

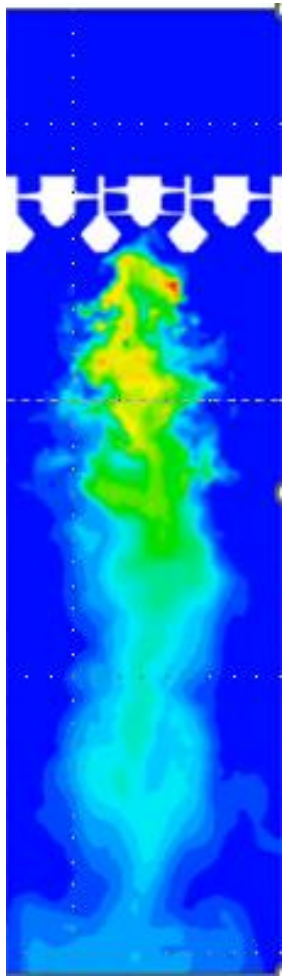
POC: Kumud Ajmani, Jeff Moder, Jennifer Klettlinger

Lean Blowout: experiment and CFD examples

- LDI: NASA 7-pt
- RQL: AFRL/UDRI Referee Rig



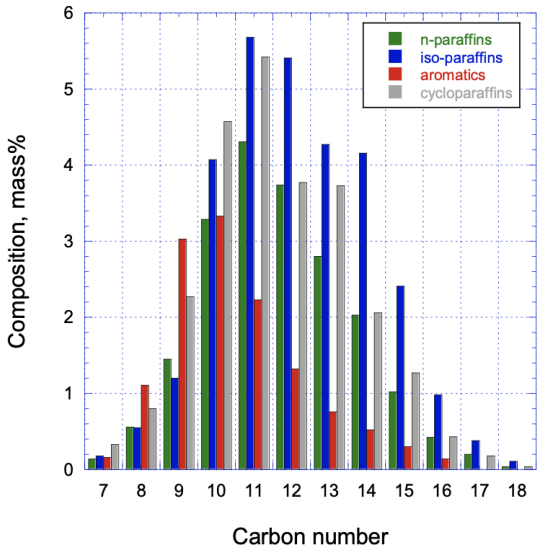




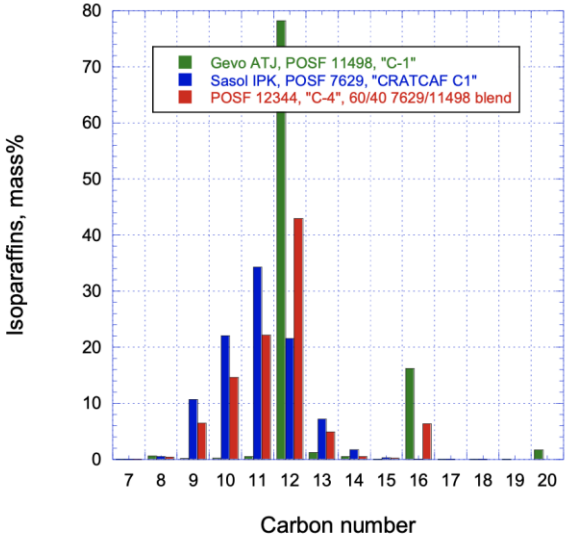
NASA LBO studies using three National Jet Fuel Combustion Program (NJFCP) fuels

Fuel	A-2	C-1	C-4
Composition	Average Jet-A	GEVO ATJ, highly branched C_{12} and C_{16} iso-paraffins	60% Sasol IPK (highly branched C_9-C_{13} iso-paraffins), 40% C-1
Description	Average/ Nominal jet fuel	Very low cetane number with unusual boiling range	Low cetane number with conventional, wide-boiling range
DCN	49	16	28
Vol % aromatics	17	1	2.3
Density, 288 K	803	760	760
Surface Tension, 300 K	24.6	23.4	22.4
Viscosity, 298 K	0.80	1.9	1.55
stoichiometric f/a	0.0680	0.0666	0.0665

A-2, Jet-A composition



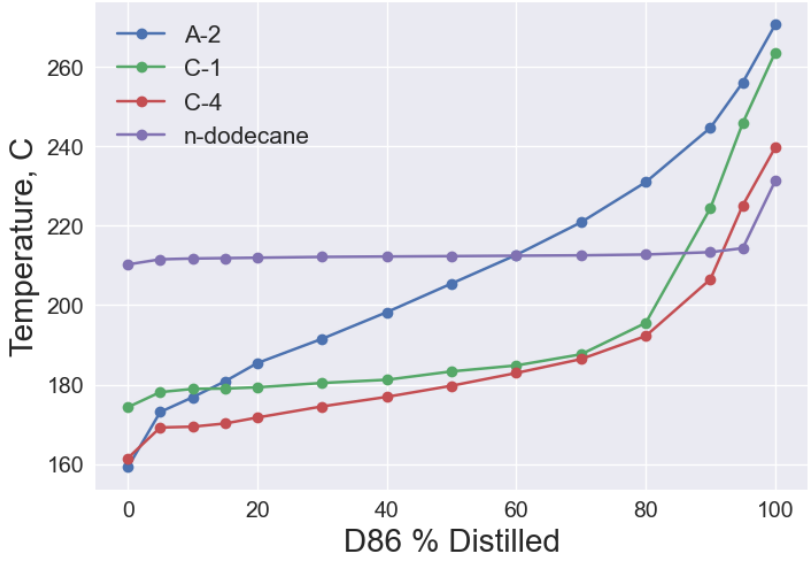
C-1 (Gevo), Sasol IPK, C-4 (Gevo/Sasol IPK blend) composition



Detailed description of fuels is provided in AIAA-2017-0146, Tim Edwards

Experimental LBO measurements conducted for both LDI and RQL

LBO modeling results are compared



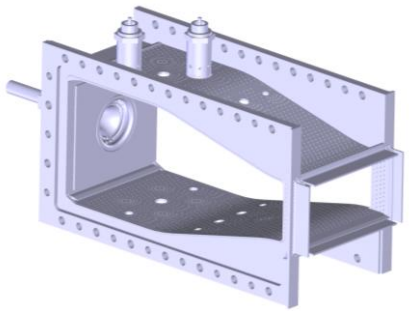
Rich-Burn and Lean-Burn Combustor LBO Experiments

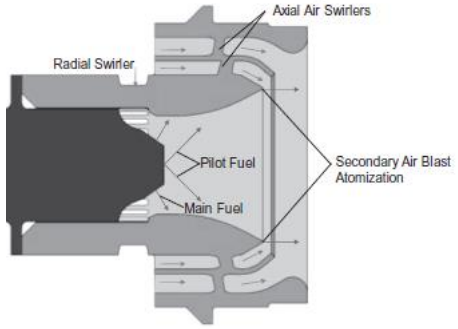
All LBO simulations are Large Eddy Simulations (LES)

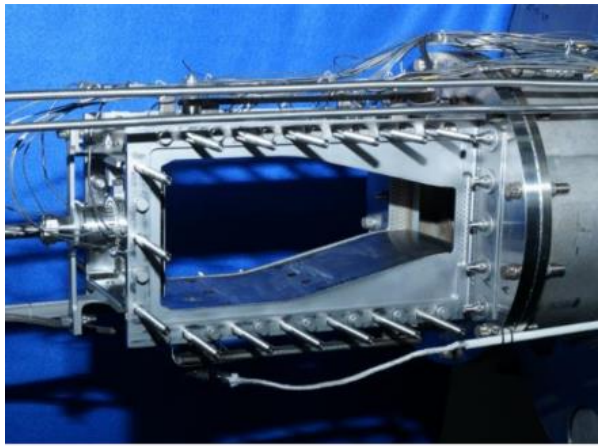
Rich-Burn

AFRL/UDRI Referee Rig

- Realistic combustor geometry
- Top and bottom liner
- Side windows
- Single cup, three swirler paths





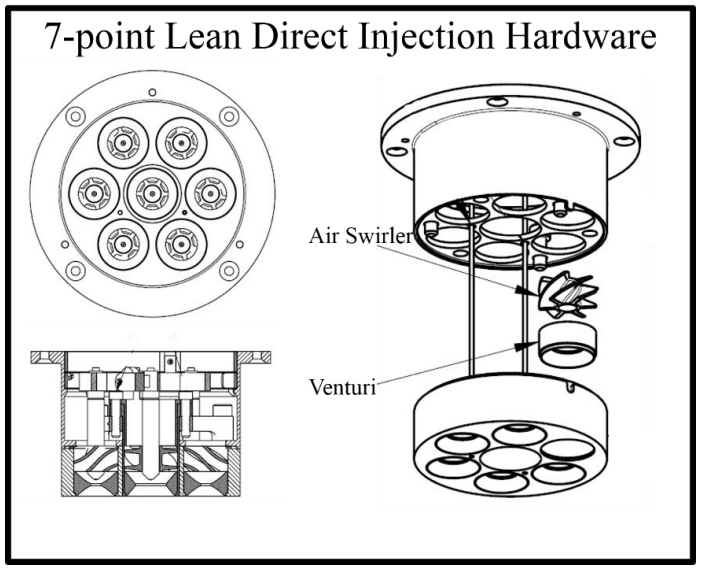


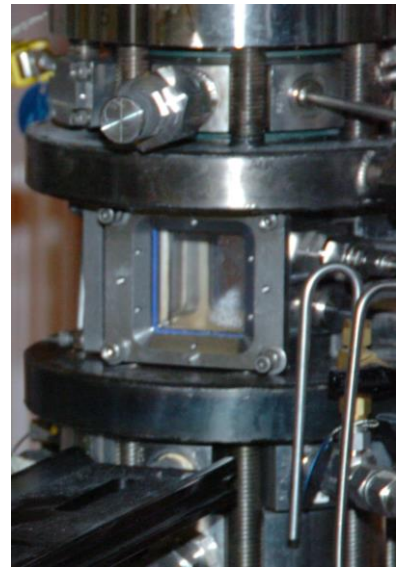
Several NJFCP Fuels are tested in both rigs (including A-2 and C-1)

Lean-Burn

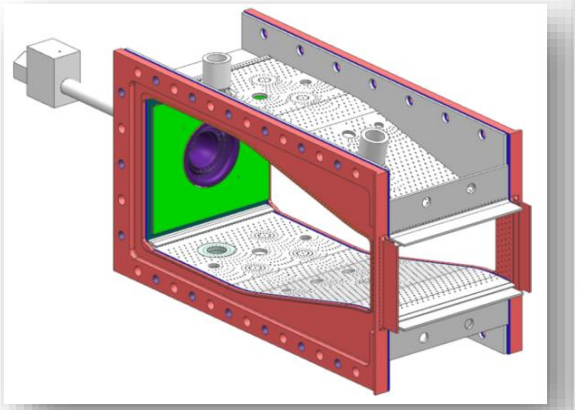
NASA GRC CE-13C

- Circular cross-section
- 3inch diameter
- Flow is downward
- 3 windows

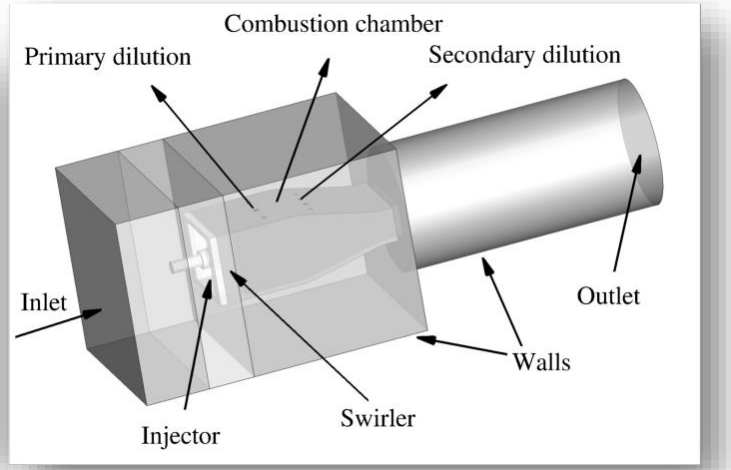




RQL CFD Domain and Boundary Conditions

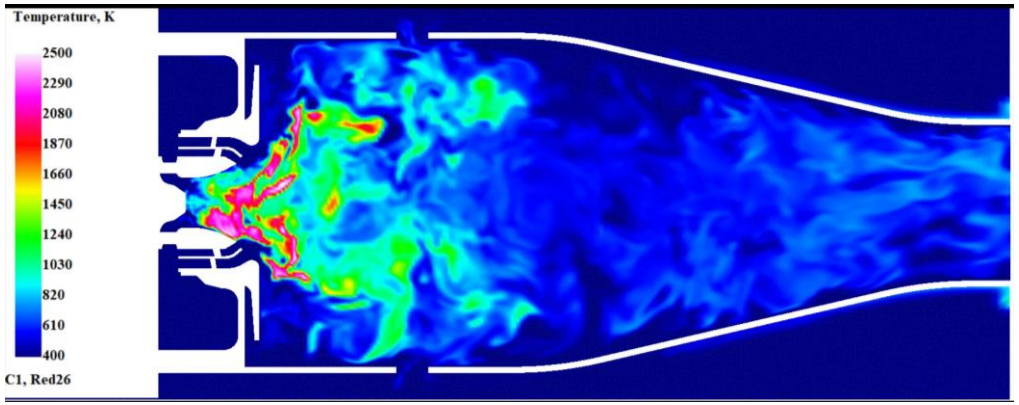


Experimental Combustion Chamber



Full Computation Domain

OpenNCC simulation of approach to LBO for C-1. *Decrease fuel, constant air*

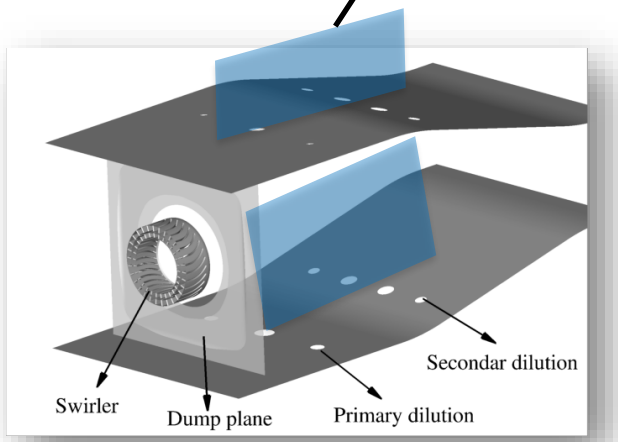


Instantaneous Temperature, K

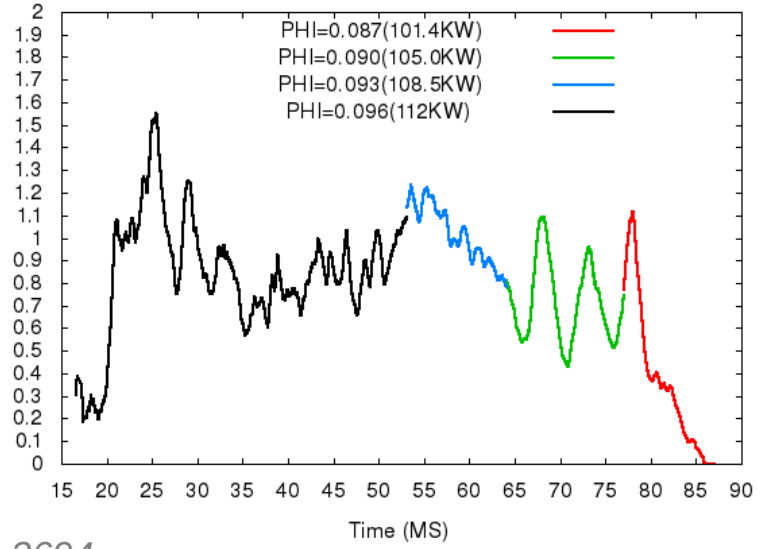
CONVERGE, Fluent, and a second set of OpenNCC simulations gridded all effusion holes

Parameter	Data
Exit pressure	207 kPa
Inlet mass flow rate	391.4 g/s
Inlet temperature	394 K
Effusion mass flow rate	241 g/s
Fuel mass flow rate (At start of LBO exp)	2.55 g/s (A-2), 2.50 g/s (C-1)
Wall temperature	Adiabatic
Spray conditions	Based on PDPA data

Cut Plane



Normalized Global Heat Release Rate



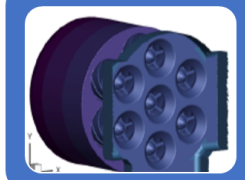
T. Wey, AIAA-2020-3694

Lean Blowout CFD Simulations: Predict LBO fuel sensitivity in a lean-burn combustor design.



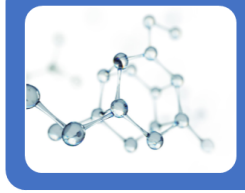
Experimental data: 2019 LDI results

- Fuels: A-2 average jet and C-1 Gevo



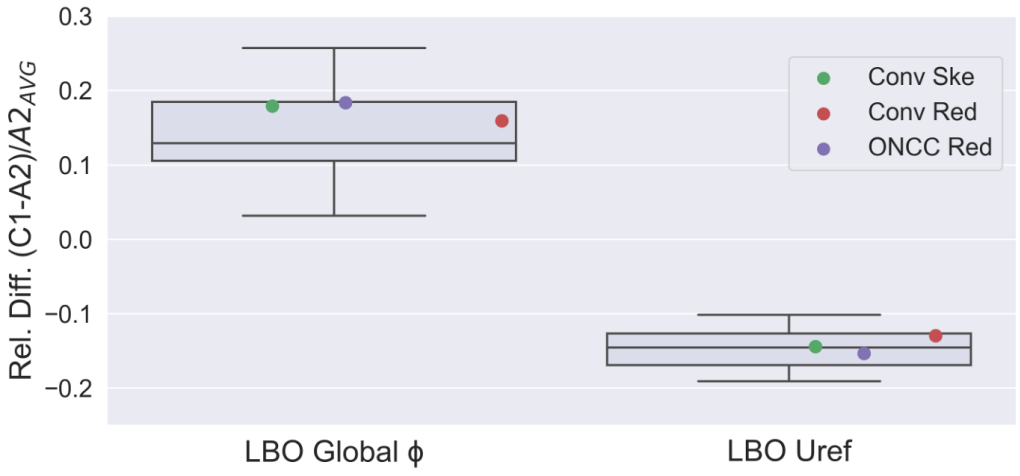
CFD codes

- **openNCC:** In-house unstructured mesh combustion CFD code
- **Converge:** Commercial combustion code, includes adaptive mesh refinement

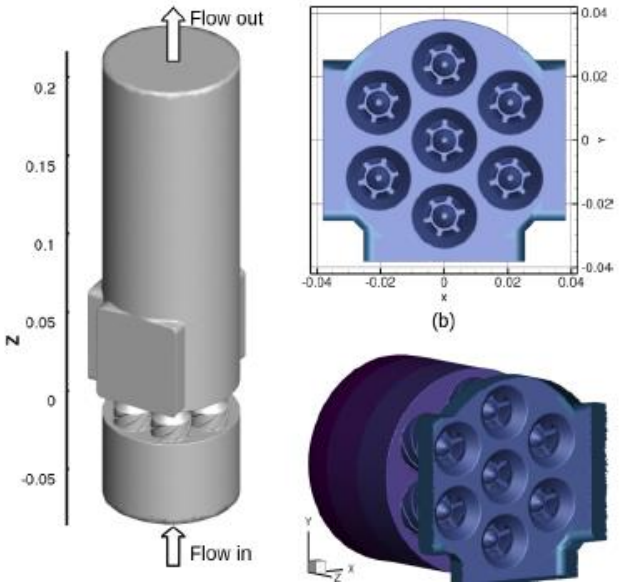


Chemistry: HyChem mechanisms

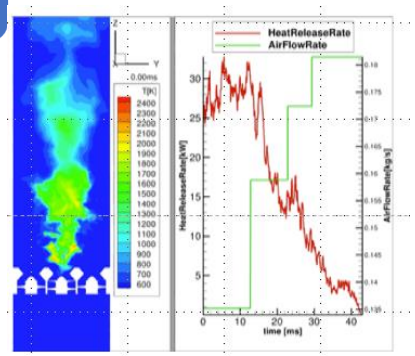
- **Skeletal:** based on directed relation graph and sensitivity analysis reduction; 41 species for A-2 **(Converge only)**
- **Reduced:** mechanism includes a second stage reduction using a quasi-steady-state approximation; 31 species for A-2 **(Converge and OpenNCC)**



CFD Domain and Boundary Conditions



- CFD boundary conditions are set to match the typical experiment conditions
- All surfaces are adiabatic.
- Swirlers are identical, additively-manufactured right-hand 60 deg
- Only the center injector is fueled at very low equivalence ratio.
- Fuel mass flow rates are fixed and the air mass flow rates are increased in step-wise manner until LBO occurs.
- LBO simulations performed for A-2 and C-1 fuels



Instantaneous Temperature

Simulation Boundary Conditions

	Cold Flow	A2	C1
Initial Air Flow Rate[kg/s]	0.2672	0.1356	0.1352
Fuel Flow Rate[g/s]	N.A.	1.784	1.716
Inlet Temperature(T3)[K]	700.4	506.8	503.7
Exit Pressure(P4)[kPa]	466.8	472.6	469.1

The box plots show range of the experimental results; points are CFD

Both the OpenNCC and CONVERGE simulations:

- Predict LBO within the experimental range of fuel relative difference in:
  - Equivalence ratio (ϕ) : $(\phi_{C-1} - \phi_{A-2}) / \phi_{A-2}$
  - Reference velocity (Uref) : $(Uref_{C-1} - Uref_{A-2})/Uref_{A-2}$

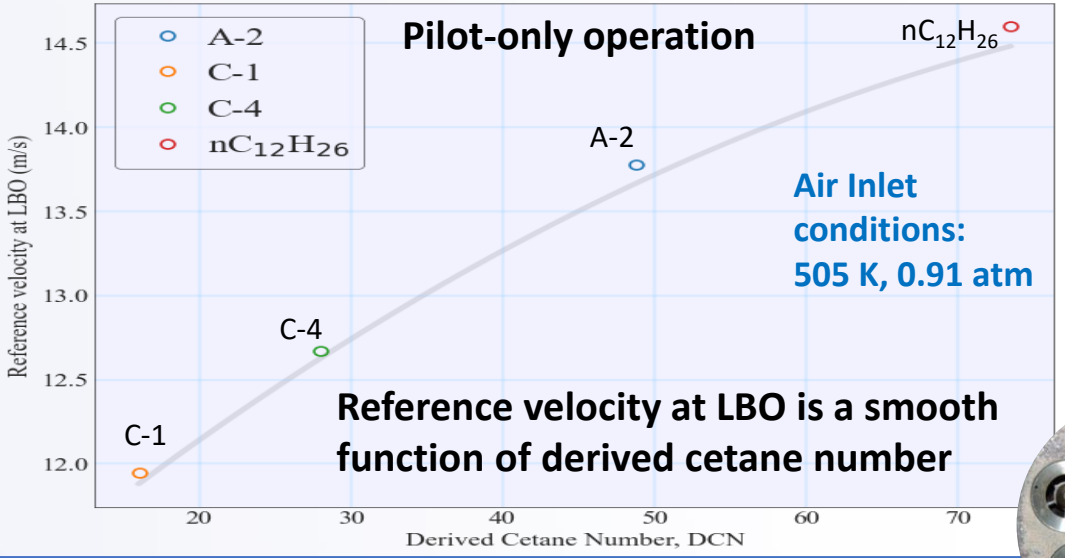
Endo et al. AIAA 2021-3458
Guzman et al. AIAA 2021-3459

Fuel Effects on Lean Blowout (LBO) and Flame Structure

- Support SAF certification
- Compare LBO and flame structure using NASA 7-pt LDI injector for 4 National Jet Fuels Combustion Program fuels:
  - A-2: “average” Jet-A
  - C-1: Gevo alcohol-to-jet
  - C-4: isoparaffinic kerosene (Gevo/Sasol blend)
  - n-$C_{12}H_{26}$ (n-dodecane)
- CFD compared well with experimental data†. Predicted the correct trend for fuels A-2 and C-1

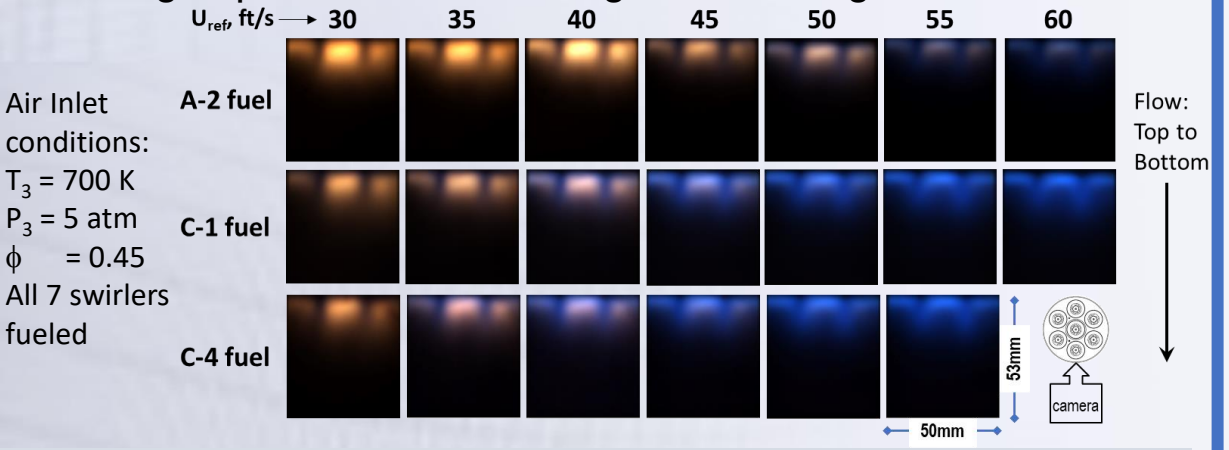
† Endo et al. Numerical simulation of LBO of alternative fuels in 7-element … injector. AIAA 2021-3458
Guzman et al. LBO predictions of a 7-point … array from large eddy simulations. AIAA 2021-3459

LBO: Increase air flowrate while keeping fuel flow constant.





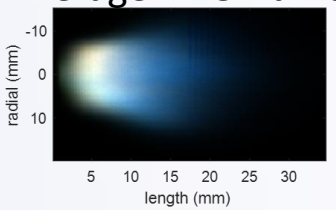
Color high speed camera average flame images, 40-50 kHz



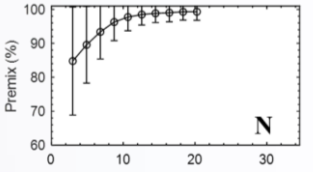
- Overall decreased soot with increased reference velocity for all fuels due to higher turbulence and mixing rates
- A-2 (Jet-A) contains polycyclic aromatic hydrocarbons known to promote soot
- Iso-paraffin fuels C-1 and C-4 have low DCN, where ignition delay and mixing timescales may affect local equivalence ratios and soot

C-4/air flame example

Average NBO flame



Avg NBO premixedness

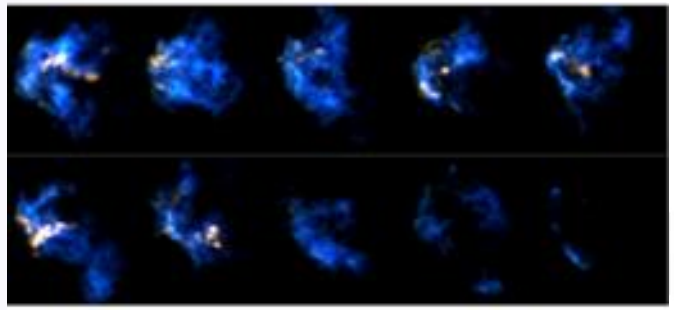


NLBO condition:
505 K, 4.8 bar,
m_f = 5 – 7.1 kg/h
m_{air}= 0.14 kg/s

Instantaneous color images, frame rate 40 kHz

At NBO →

Just before LBO →



Tacina, Capil, Hicks

Summary

- We saw a bit of combustion terminology and technology.
- Emissions
  - There have been tremendous gains over the last 50 years with more still possible
- Hydrocarbon fuels will be with us at least through 2050
  - SAF production is a key driver to achieve carbon neutrality
- Compact core combustors (such as with HyTEC), electrification, and supersonics offer challenges and opportunities.
  - Fuel injection for high OPR: fuel behavior trans to supercritical, effects on operability, measurements
  - Scaling: requires fuel-air mixing development and staging effects on emissions
  - Durability: injector, advanced materials, wall heat transfer tools, advanced liner materials and cooling strategies
  - Particulate measurement capabilities