Overview of Gas Turbine Generated Pollutants

Gas Turbine Combustion Short Course

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Contents

- Products of combustion and their consequences
  - Mechanisms of formation
  - Effects on the environment and/or human health
  - Overview of limitation strategies

- Emissions legislation and targets:
  - ICAO
  - ACARE Vision 2020 and FlightPath 2050 goals

Products of Combustion:
CO_2

Mechanism of formation:

- Complete combustion of any carbon containing fuel

Effects on the environment and/or human health:

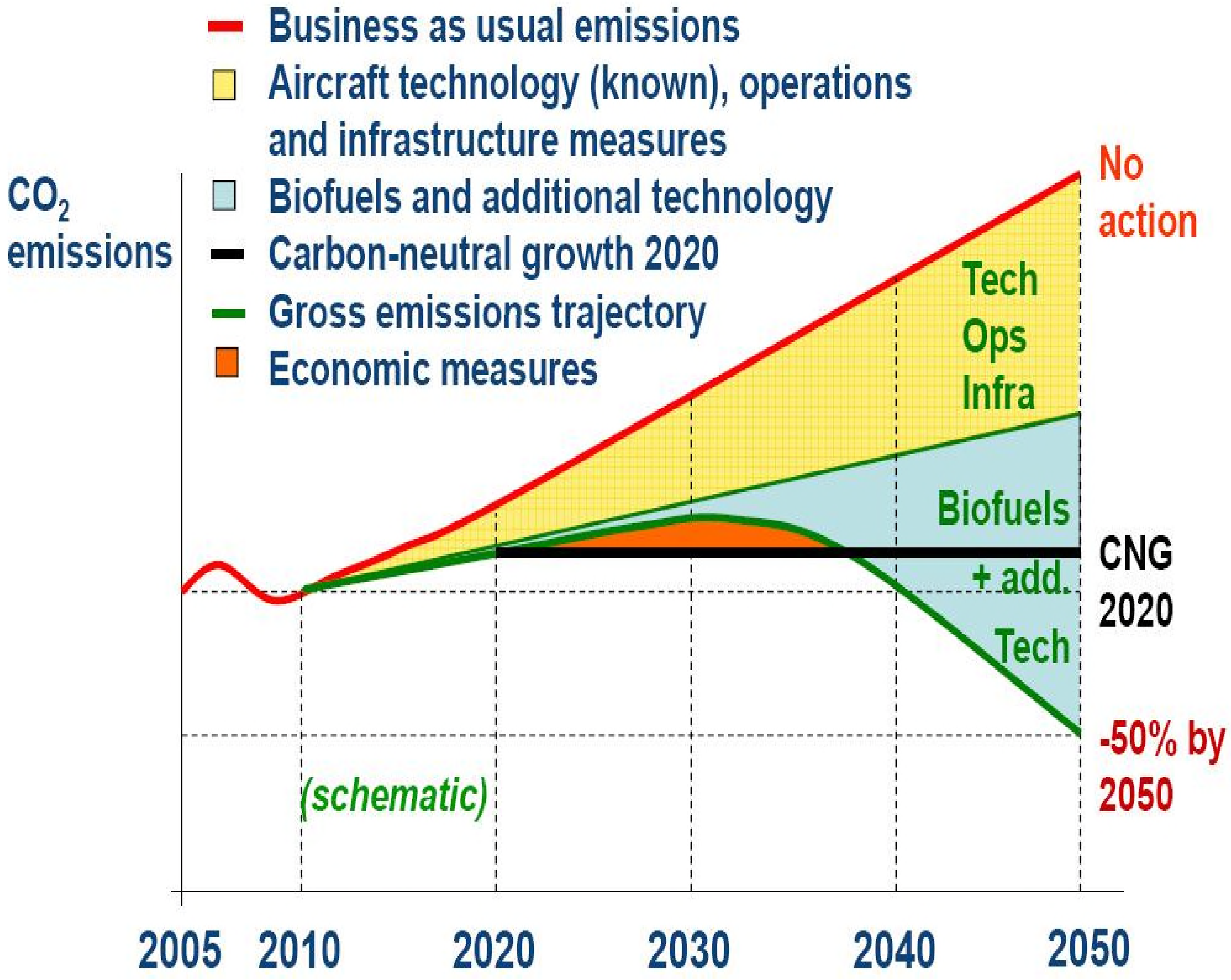
- Greenhouse gas – contributes to global warming

Overview of limitation strategies:

- Increase thermodynamic efficiency of engine/aircraft system
- Improve operations – smart operations on ground and trajectory optimisation
- Move to alternative fuels (e.g., Hydrogen, Biofuels…)*

*(Provided manufacturing processes, and use result in lower overall carbon footprint)

ICAO CO_2 Reduction Goals



Ref: ICAO Environmental Report (2010) Environmental Branch, International Commercial Aviation Organisation, Montreal, Canada

Products of Combustion:
SO_x

Mechanism of formation:

- Oxidation of sulphur content of fuel

Effects on the environment and/or human health:

- Acid rain – toxic, corrosive

Overview of limitation strategies:

- Use minimum amount of sulphur in fuel - required to maintain fuel lubricity (inhibit corrosion) in fuel distribution systems
  (maximum permitted concentration for aviation kerosene – 0.3% by mass)
- Research sulphur free lubricity improver additives (LIA)

Products of Combustion:
CO and UHC

Mechanism of formation:

- Inadequate burning rates in primary zone (PZ) due to low FAR or t_{res}
- Inadequate mixing of fuel and air (local fuel rich regions)
- Quenching of post-flame products by entrainment with liner wall cooling air
- *CO may also be produced at high temperature due to dissociation and chilling of products of combustion

Effects on the environment and/or human health:

- Toxic

Overview of limitation strategies:

- Improved fuel atomisation (more homogeneous mixing)
- Redistribution of air flow to allow lean PZ FAR
- Increase in PZ volume (t_{res})
- Reduction of film cooling air (more efficient cooling technology)
- At low power, bleed compressor air to increase FAR in PZ ($\uparrow$ PZ temperature)
- Avoid high primary zone temperatures that favour dissociation

Products of Combustion:
Smoke / Soot

Mechanism of formation:

- Produced in fuel rich regions of the flame
- Produced in any part of the combustion zone where mixing is inadequate
- PZ governs rate of formation, IZ and DZ determine rate of consumption
- Smoke/Soot comprises 96% C and mixture of H, O and other species
- Aromatic H/C produce soot via:
  - Condensation of aromatic rings into a graphite like structure
  - Break up into small H/C $\Rightarrow$ polymerise to form larger H-deficient molecules $\Rightarrow$ nucleate to form soot

Effects on the environment and/or human health:

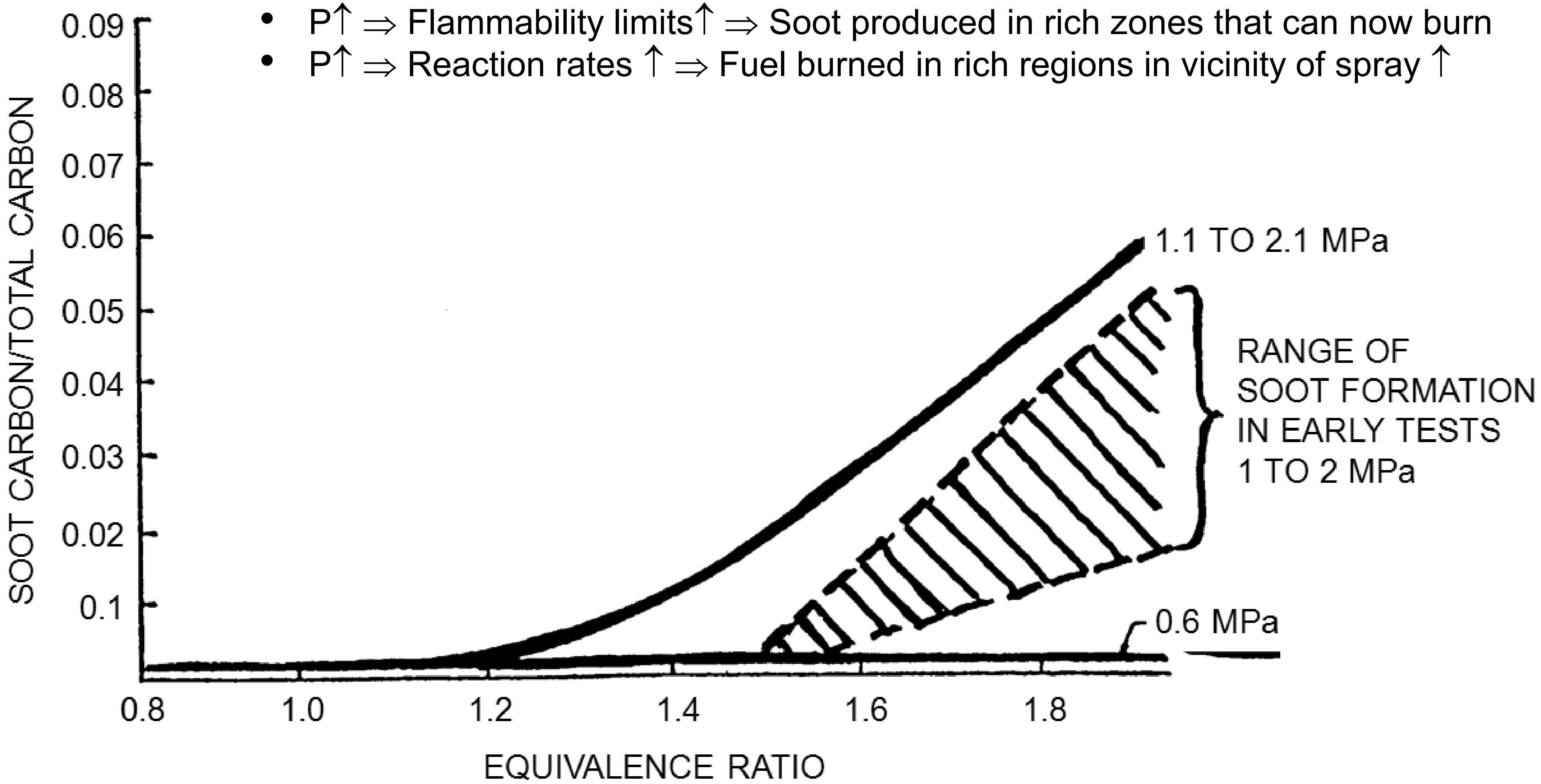
- Toxic, Visible

Overview of limitation strategies:

- Use fuels with minimum required amount of polycyclic H/Cs - required for sealing effectiveness (No more than 20-25%)
- Avoid local fuel rich zones (more homogenous mixing)

Smoke / Soot Production:
Effects of Pressure and ϕ

- P↑ ⇒ Flammability limits↑ ⇒ Soot produced in rich zones that can now burn
- P↑ ⇒ Reaction rates ↑ ⇒ Fuel burned in rich regions in vicinity of spray ↑



Mechanisms of Formation of NO_x:

Fuel NO_x and Prompt NO_x

Fuel NO_x:

Mechanism of formation:

- Oxidation of nitrogen content if fuel contains organically bonded nitrogen

Overview of limitation strategies:

- Use of fuels with little/no organically bonded nitrogen (not a big problem for aero)

Prompt NO_x:

Mechanism of formation:

- Under certain conditions, low temperature and fuel rich flames
- Mechanisms not yet fully understood

Overview of limitation strategies:

- Under investigation (relatively small concentrations relative to thermal NO_x)

Formation of Thermal NO_x:
The Zeldovich Mechanism

Zeldovich Mechanism

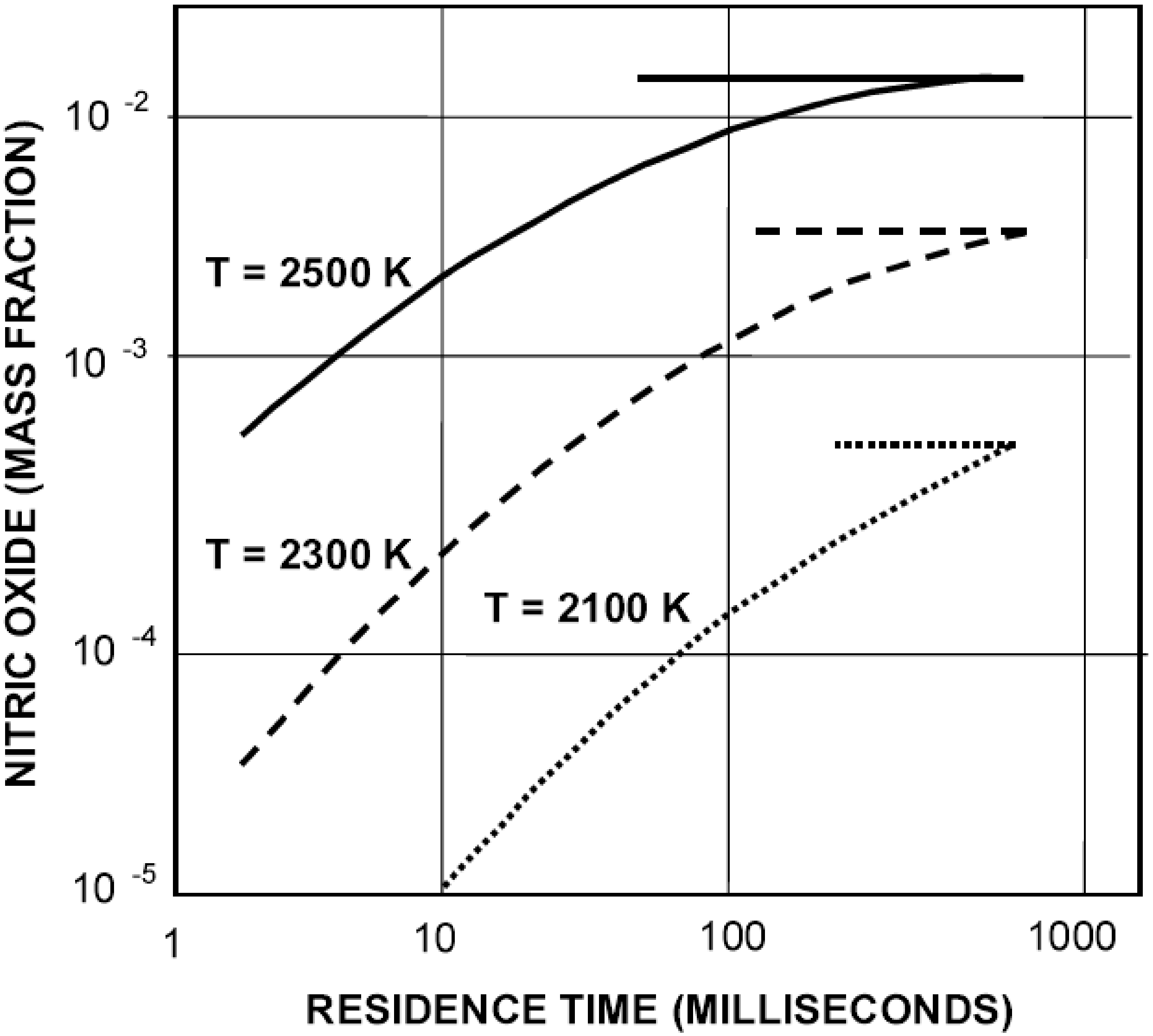
$$O_2 \rightleftharpoons 2O$$

$$O + N_2 \rightleftharpoons NO + N$$

$$N + O_2 \rightleftharpoons NO + O$$

At Lower Temperatures

$$2NO + O_2 \rightleftharpoons 2NO_2$$

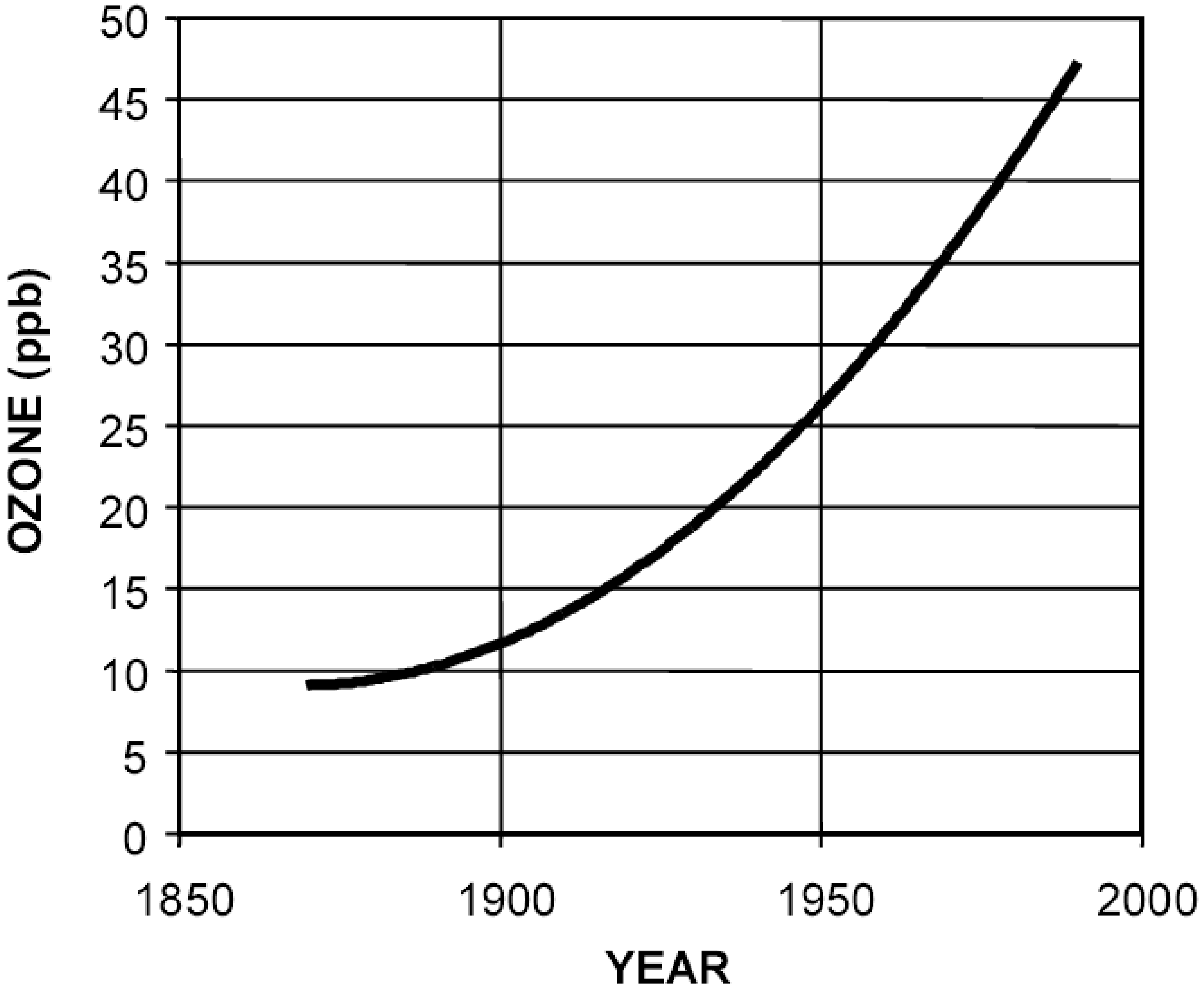


Effects of Products of Combustion:
NO_x

Ozone Formation in the Troposphere
(0km – 10/15km)

$$NO_2 + h\nu \rightleftharpoons NO + O$$

$$O + O_2 \rightleftharpoons O_3$$



Consequences

- Respiratory illness
- Impaired vision
- Headaches
- Hearing disorders
- Allergies

Effects of Products of Combustion:

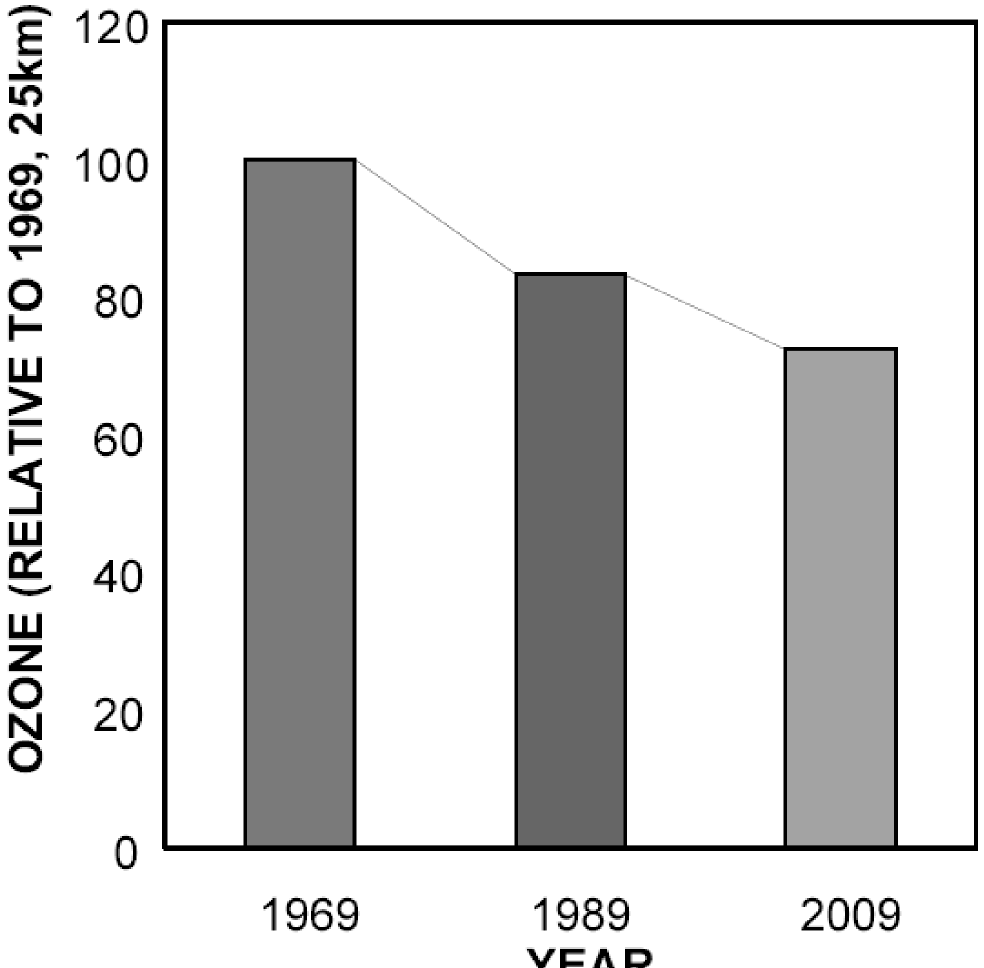
NO_x

<u>Ozone Depletion in the Stratosphere</u>

(10/15km – 50/60km)

$$NO + O_3 \rightleftharpoons NO_2 + O_2$$

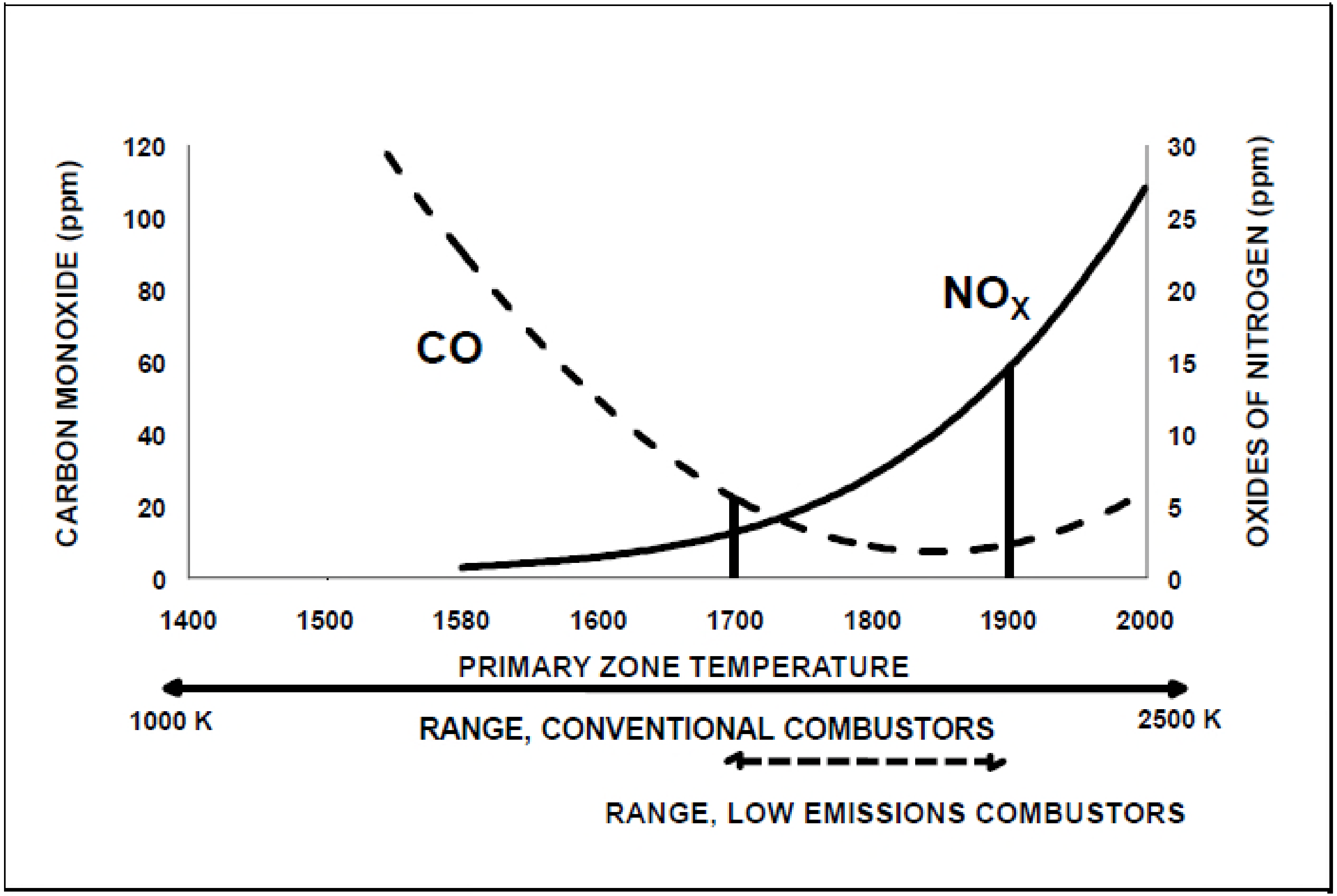
$$NO_2 + O \rightleftharpoons NO + O_2$$



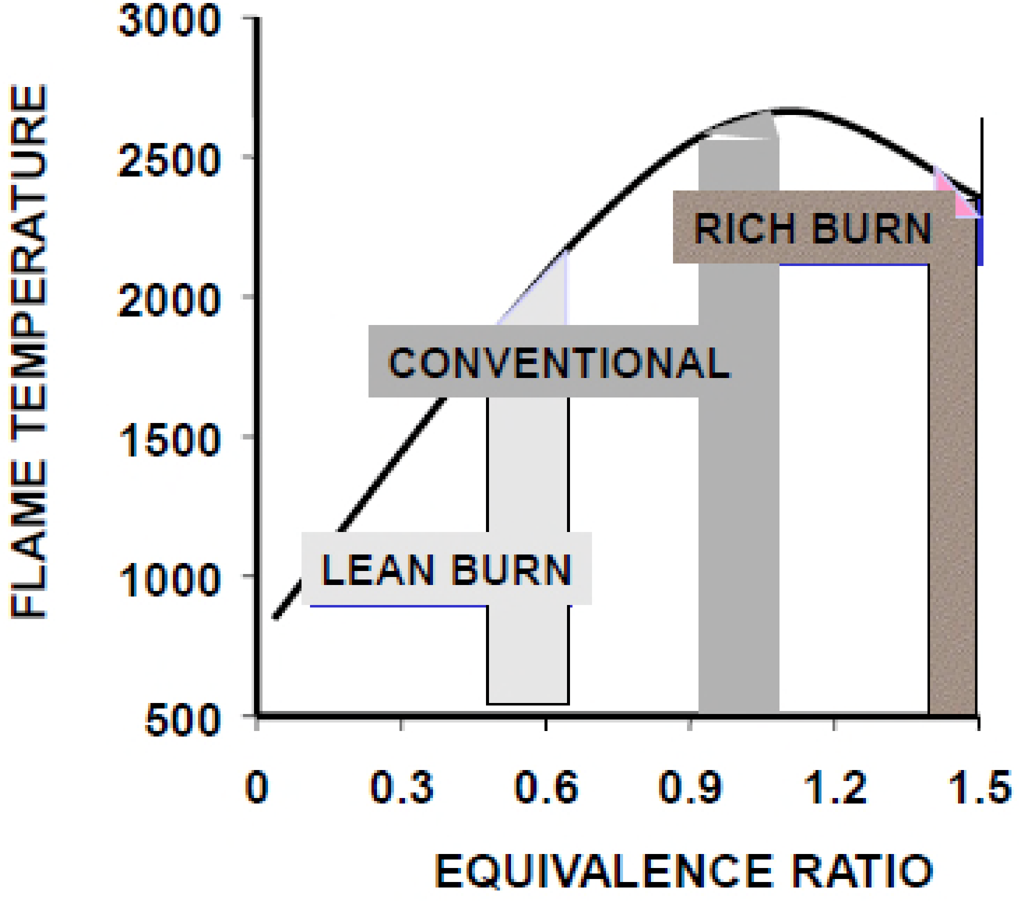
<u>Consequences</u>

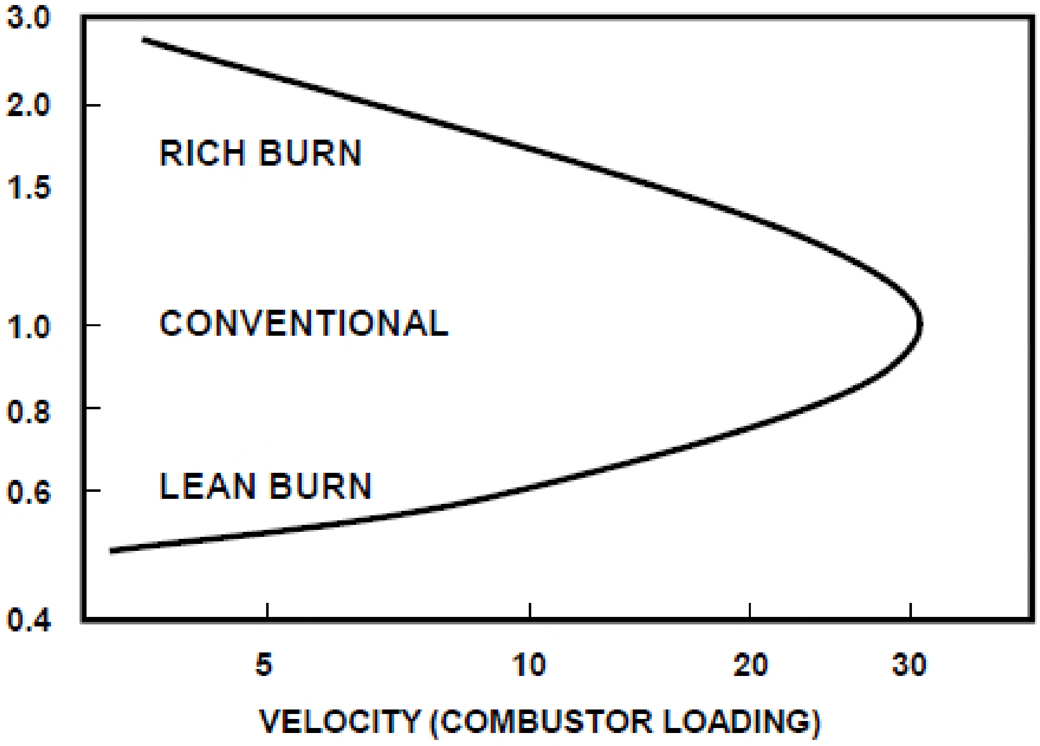
- Increase in ground level UV radiation
- Skin cancer
- Eye disease

Effects of Primary Zone Temperature:
NO_x and CO



Effect of ϕ on Flame Temperature and Stability

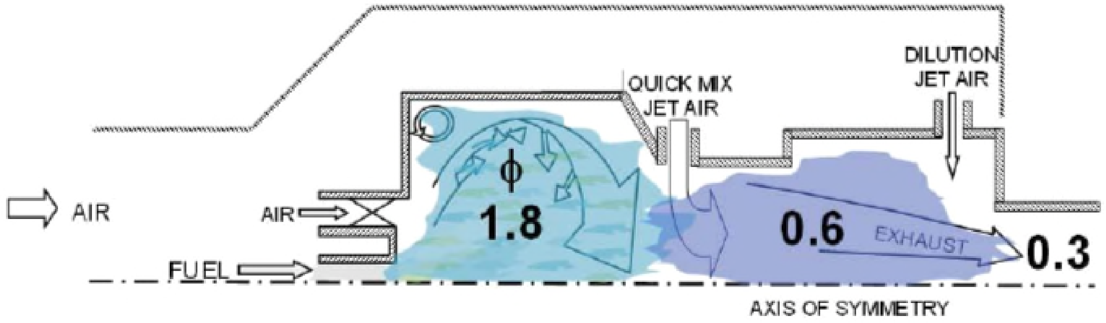




<u>Effect of ϕ on Flame Temperature</u>

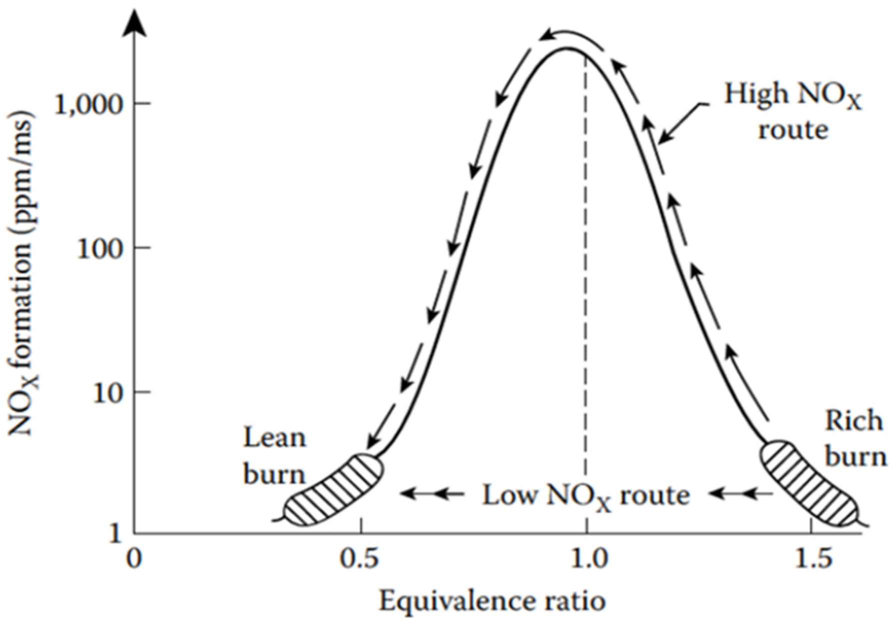
<u>Effect of ϕ on Stability</u>

Low Emissions Combustors:
RQL – Rich Burn Quick Quench Lean Burn



RQL Principle

Ref: Peterson, C.O., Sowa, W.A and Samuelsen G.S., "*Performance of a model rich burn-quick mix-lean burn combustor at elevated temperature and pressure*". University of California, Irvine, California 2002 .NASA CR/2002-211992



Ref: Lefebvre, A. H. and Ballal, D. R. (2010), "*Gas Turbine Combustion Alternative Fuels and Emissions"*, Third edition, CRC Press.

Advantages:

- Low NOx due to rich burn
- More stable than purely lean burn
- High TRL (9)
- Less complex fuel control than fuel staged combustors

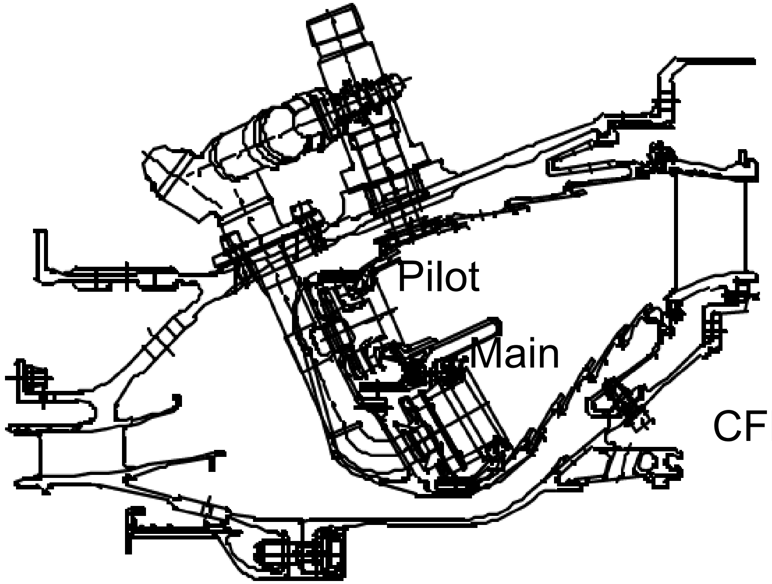
Design challenges:

- Quick quench region design critical
- Good atomisation required to reduce soot formation
- Liner durability issues due to high luminous radiation
- Careful design for dome front end cooling (may approach Stoichiometric FAR)

Low Emissions Combustors:
Double Annular Combustor (DAC)

DAC Principle:

- At low power (e.g. idle) only Pilot operates:
  - $\phi \approx 1 \Rightarrow T\uparrow$, $\eta\uparrow$, CO and UHC $\downarrow$ (rel. conventional combustor at idle)
  - NOx $\downarrow$ (rel. low T_3 and P_3)
- At high power both Pilot and Main operate
  - $\phi < 1$ (lean burn) $\Rightarrow$ $T\downarrow$, NOx and Soot $\downarrow$



CFM-56 DAC

Ref: Mongia, H., *"TAPS: A Fourth Generation Propulsion Combustor Technology for Low Emissions"*, AIAA International Air and Space Symposium and Exposition: The Next 100 Years, International Air and Space Symposium (Evolution of Flight)

Advantages:

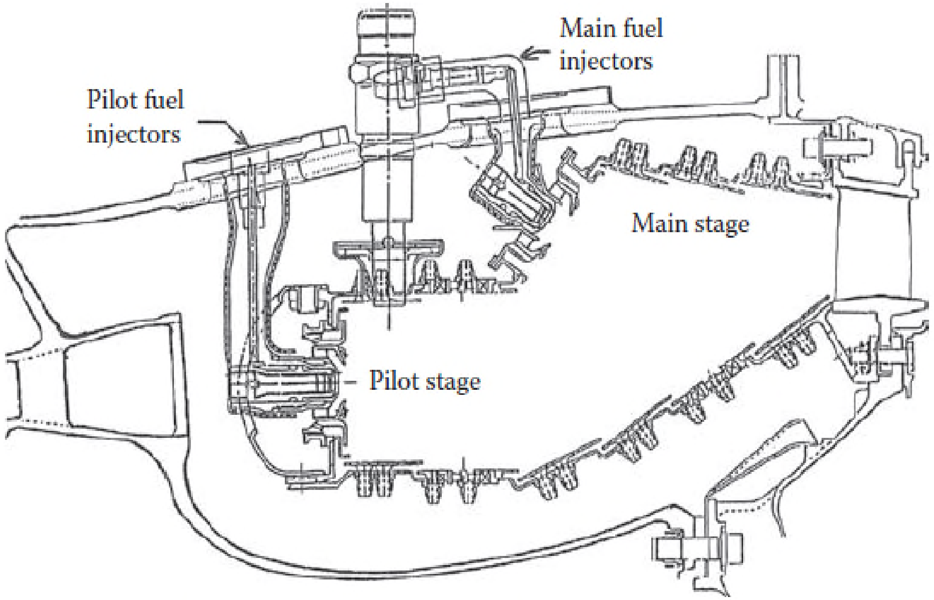
- Lower NOx at high power and lower CO and UHC at low power rel. conventional combustors
- High TRL (9)
- Similar length as conventional combustor
- Less fuel coking (both fuel injectors share same arm and main injectors are cooled by pilot fuel)

Design Challenges:

- Local chilling of reacting gas during "Pilot only" operation (CO & UHC higher than RQL)
- Control of OTDF/RTDF
- Efficiency issues during transition $\Rightarrow$ acceleration affected (more staging points may help)
- Prone to combustion instability (pressure oscillation due to heat release difference)
- Larger surface area (i.e., more cooling air required)

Low Emissions Combustors:
Axially Staged Combustors

Axially Staged Principle:
- Similar to DAC but axially staged
- Main is placed downstream of Pilot
- Relative lower CO and UHC during transition than DAC



Axial staged combustor for IAE V2500-A5 engine

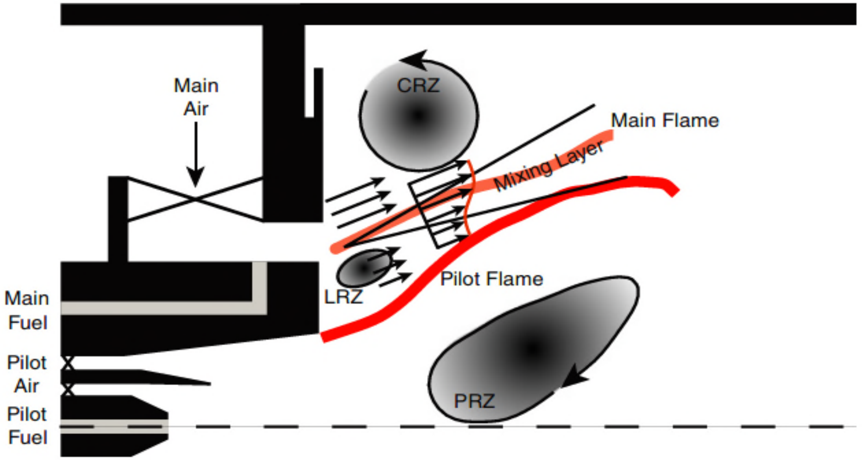
Ref: Koff, B. L., *"Aircraft Gas Turbine Emissions Challenge"*, J. Eng. Gas Turbines Power 116(3), 474-477 ASME 93-GT422, 1993.

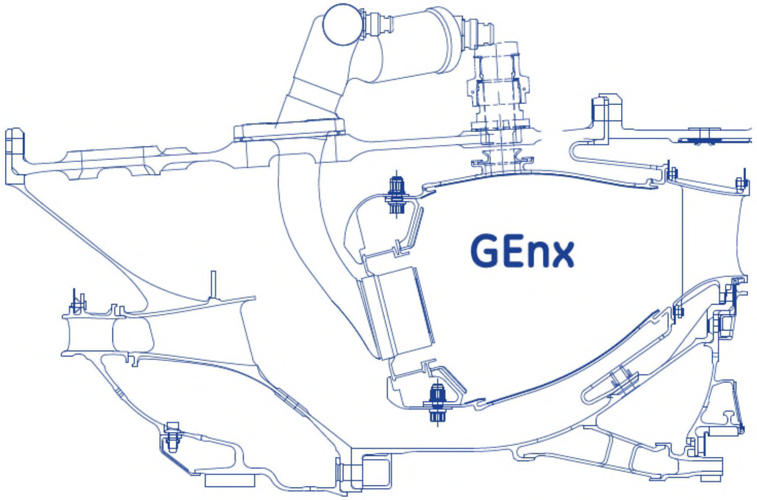
Advantages:
- Improved ignition, stability and combustion efficiency (Main supplied with hot air from Pilot)
- Improved RTDF and hence turbine life
- Inboard location of pilot $\Rightarrow$ less water ingestion and therefore better stability during heavy rain
- Outboard location of Main, peaks the temperature towards the tip $\Rightarrow$ easier to achieve designed temperature profile.

Design Challenges:
- Longer axial length
- Offset Pilot and Main may result in higher pressure loss
- Fuel injector coking at main (hot incoming gas from pilot)
- Reduced casing stiffness (The two fuel feed arms require separated penetrations of the combustion casing)

Low Emissions Combustors:
TAPS – Twin Annular Premixing Swirler (GE)

TAPS Principle:
- Partially premixed main stage
- Internally staged
- Concentric pilot and main stages





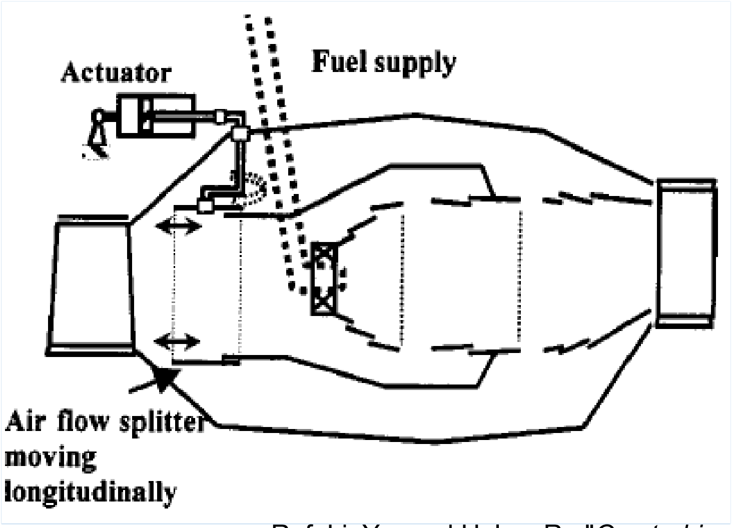
Ref: Dhanuka, S.K., Temme, J.E., Driscoll, J.F., and Mongia, H., *"Vortex shedding and mixing layer effects on periodic flashback in a lean premixed prevaporized gas turbine combustor"*, Proceedings of the Combustion Institute, 32(2):2901–2908, 2009

Advantages:
- Low NOx and soot due to lean partial premixing (small cavities reduce risk of auto-ignition)
- Easier control of RTDF rel. to DAC
- Pilot zone recess improves stability (reduces quenching from Main)
- Other than fuel injector design, combustor general arrangement similar to conventional
- High TRL (9)

Design Challenges:
- Ignitor location critical
- Complex fuel injection system
- Relatively larger frontal area of fuel injector ⇒ more prone to coking
- Control of periodic unsteadiness resulting from Corner Recirculation Zone (CRZ)
- Control of Lip Recirculation Zone (LRZ) critical to provide good continuous ignition to main (but not too large to increase Tres ⇒ NOx↑)
- Thermoacoustic issues (Main and Pilot heat release rates)

Low Emissions Combustors:
Variable Geometry

VG Principle:
- Combustion temperature controlled by regulating air flow in PZ
- Air directed downstream at low power $\Rightarrow \eta\uparrow$
- Air directed upstream at high power $\Rightarrow NOx\downarrow$



Ref: Li, Y., and Hales, R., "*Gas turbine emissions control using variable geometry combustor and fuel staging*", 40th AIAA Aerospace Sciences Meeting & Exhibit, Aerospace Sciences Meetings

Advantages:
- Potential for rel. wider stability limits and improved altitude relight performance
- Combined with staged/LPP $\Rightarrow$ rel. very low emissions (CO, UHC and NOx)

Challenges:
- Increased complexity in control and feedback mechanisms (i.e., weight and cost)
- Annulus air flow distortion and rel. larger pressure loss
- Liner durability (as cooling air is frequently changed)
- Problem of achieving the desired temperature pattern if liner pressure drop is allowed to vary too much (change in C_D of liner holes)
- Rel. lower TRL (5)

Overview of Possible Limitation Strategies:

Thermal NO_x

- Staged combustion (Fuel or Air Staging)
  - Lean primary zone
  - Rich primary zone

- More homogenous combustion
  - Better fuel atomization and mixing

- Reduction of residence time? (Implications?)

- Water injection
  - More effective if injected directly into primary zone
  - Additional weight, complexity and safety aspects need to be assessed
  - Can have adverse effect on fuel bound NO_x

- Hydrogen Availability
  - Potential to facilitate much leaner FAR mixtures - wider stability limits
  - Micromix combustors (less risk of auto-ignition and flashback with good mixing)

The Case for LH_2 for Civil Aviation

Alternative Fuels and Production Routes		Drop-in replacements		LNG			LH_2	
		Bio-fuels (from algae)	Synthetic Kerosene	Conventional / Fracking	Biomass	Synthetic LNG	Non-renewable	Renewable / Nuclear
Effect on Emissions relative to Jet-A1								
At Mission Level	CO_2							
	Energy Efficiency							
	NO_x							
	CO and UHC							
	Soot / Particulates							
	Water Vapour							
	Contrails							
Over the Life Cycle (well to wake)	CO_2 emissions							
	CH_4 emissions (leakage)							
	Long Term Sustainability							
Effect on Costs relative to Jet-A1								
Short-Medium Term (up to 2050)	Fuel Production Costs							
	Aircraft Engineering Costs							
	Airport Integration Costs							
	Life Cycle Costs							
Long Term (beyond 2050)	Fuel Production Costs							
	Aircraft Engineering Costs							
	Airport Integration Costs							
	Life Cycle Costs							
Effect on Safety relative to Jet-A1								
Actual Safety Record in Transportation								
Likely Public Perception of Safety								

Key						
				Inferior to Jet-A1		No clear benefit re. Jet-A1
		Indicates greater uncertainty		Superior to Jet-A1		Significant benefit re. Jet-A1

Hydrogen Micromix Combustion:

Why Hydrogen?

No Carbon

No CO_2/CO/UHC/Soot

Less Luminous Radiation

Better liner durability

Wider stability limits

Leaner combustion

Lower flame temperature

Higher burning velocity

Higher reaction rate

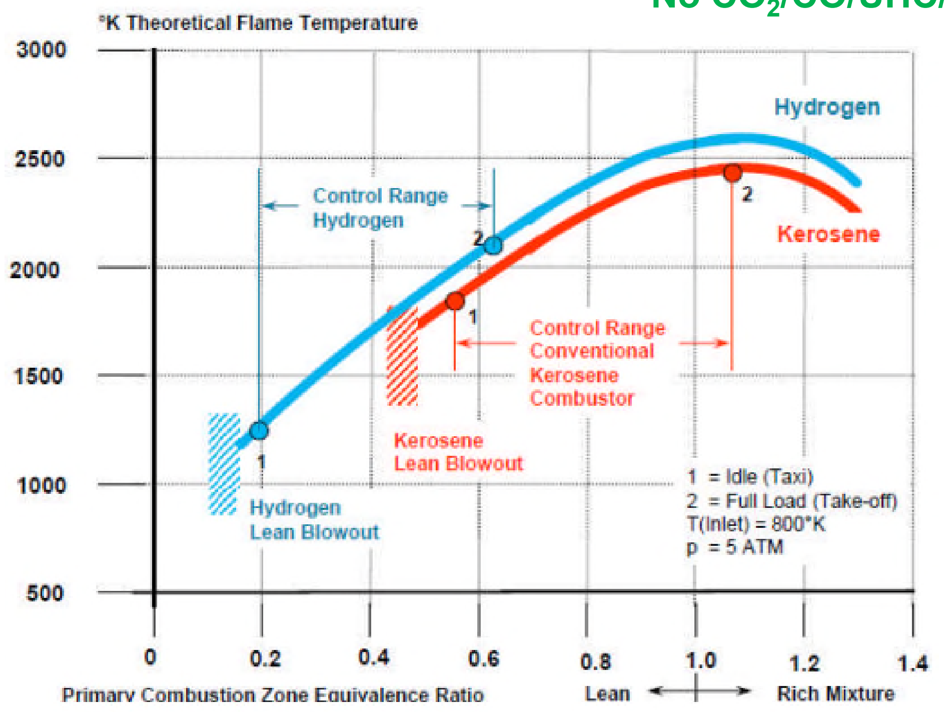
Lower residence time

Higher diffusivity

Faster mixing

Lower thermal NOx

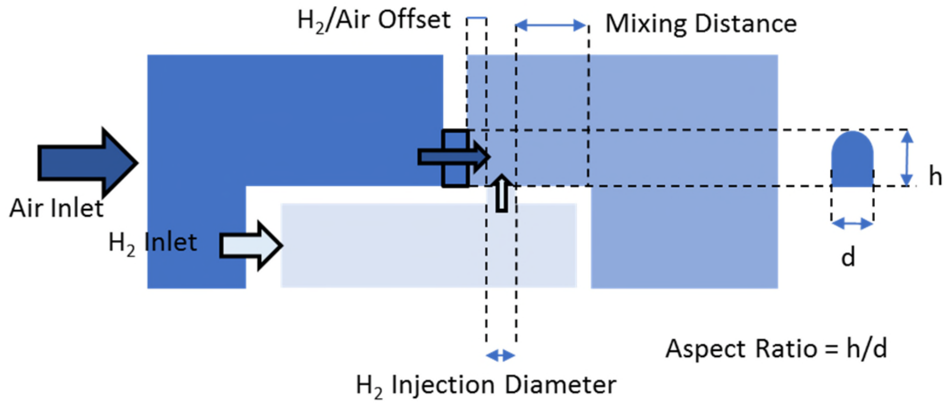
Shorter combustor

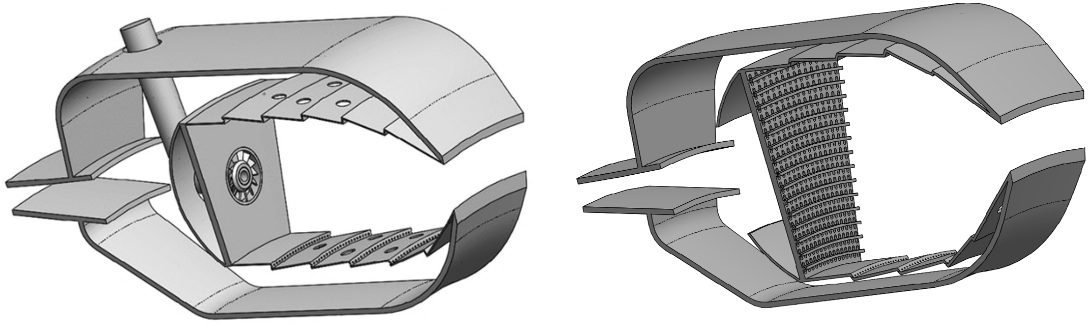


Ziemann J, Mayr A, Anagnostou A, Suttrop F, Lowe M, Bagheri SA, et al. Potential use of hydrogen in air propulsion. EQHHPP, Phase III.0-3. Final report, submitted to European Union (contract no. 5077-92-11 EL ISPD).

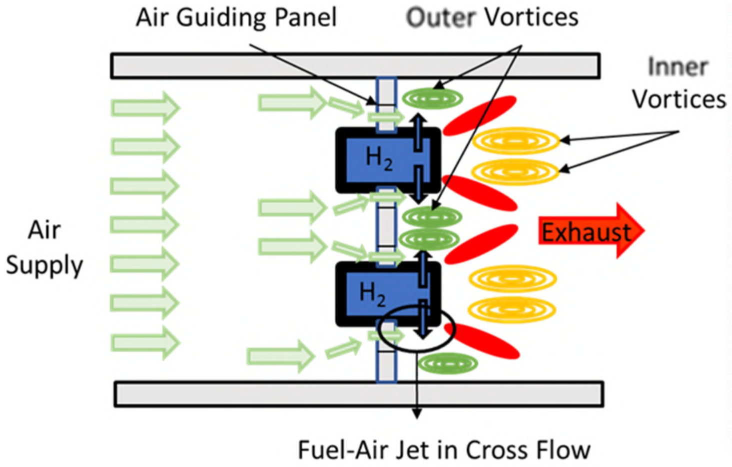
Hydrogen Micromix Combustion:
Why Micromix?

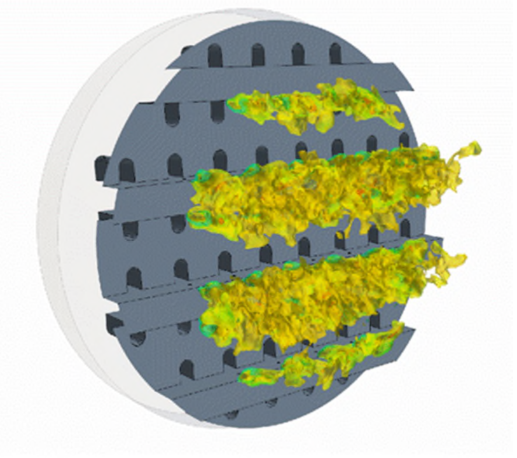
- Mixing length scale minimised while mixing intensity maximised
- Diffusion flame - reduces risk of flashback
- More flexibility for customised fuel scheduling:
  - Tailor outlet temperature distribution (without dilution zone)
  - Control of thermoacoustic instabilities





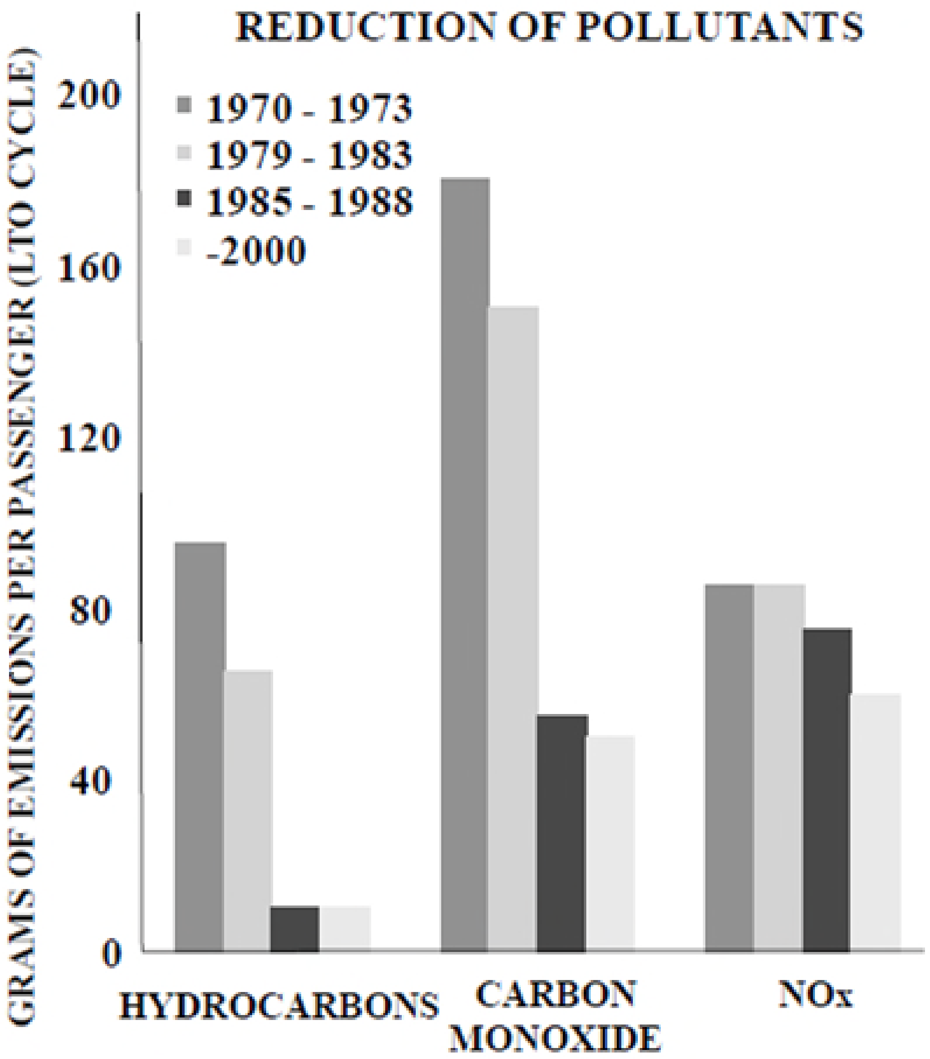
Conventional annular kerosene ***vs*** micromix combustor (conceptual)

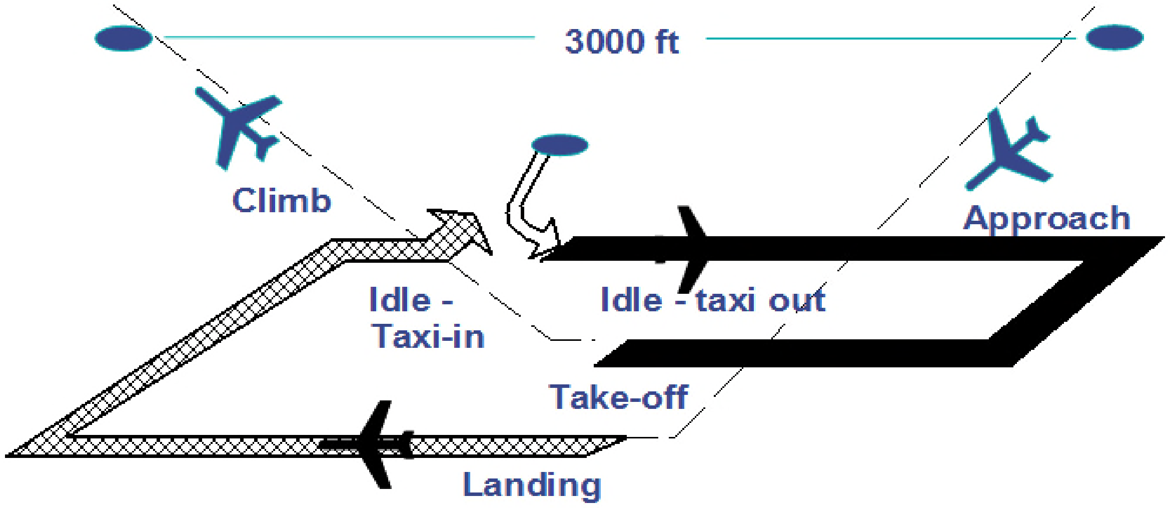




NOx Legislation

Landing and Take-Off (LTO) Cycle (Airport Environment)



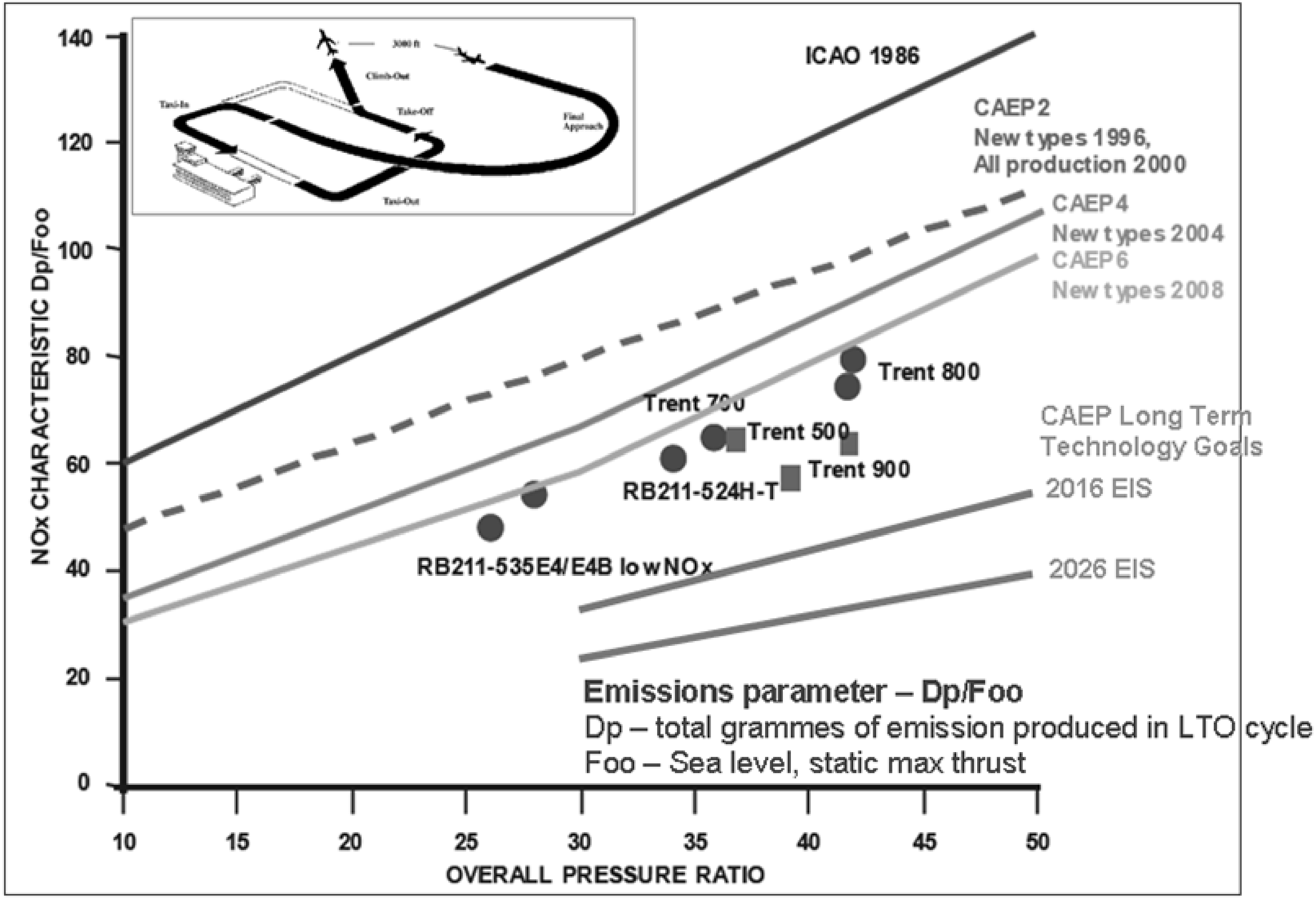


Typical Operation

	Power Setting (%)	Time in Mode (min)
Taxi (In and Out)	7	26
Final Approach	30	4
Take-Off	100	0.7
Climb	85	2.2

NOx Legislation

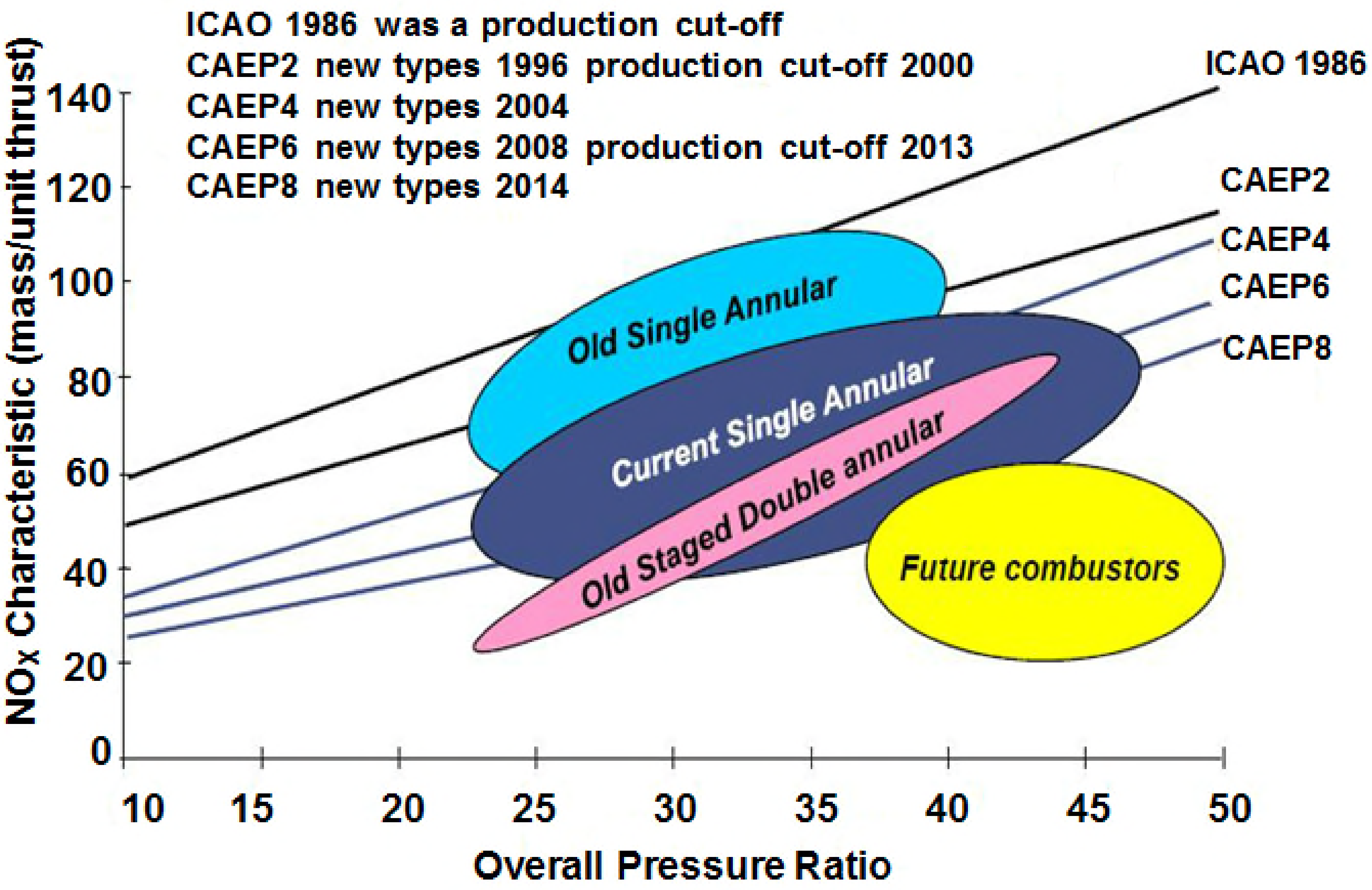
Certification Requirements and Challenges



ICAO Emissions Data Bank

NOx Legislation

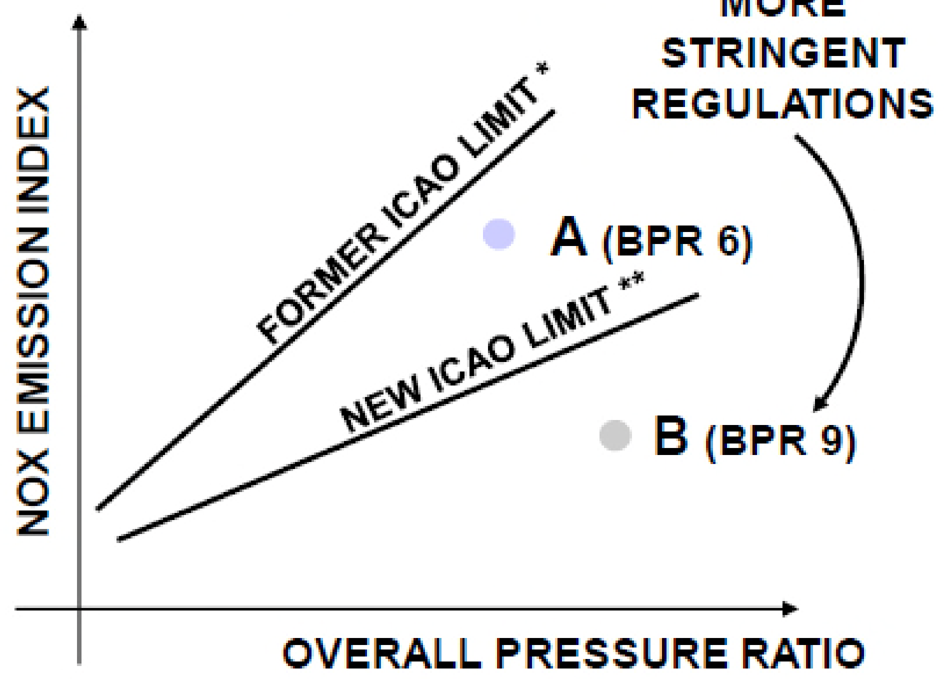
Technology Goals



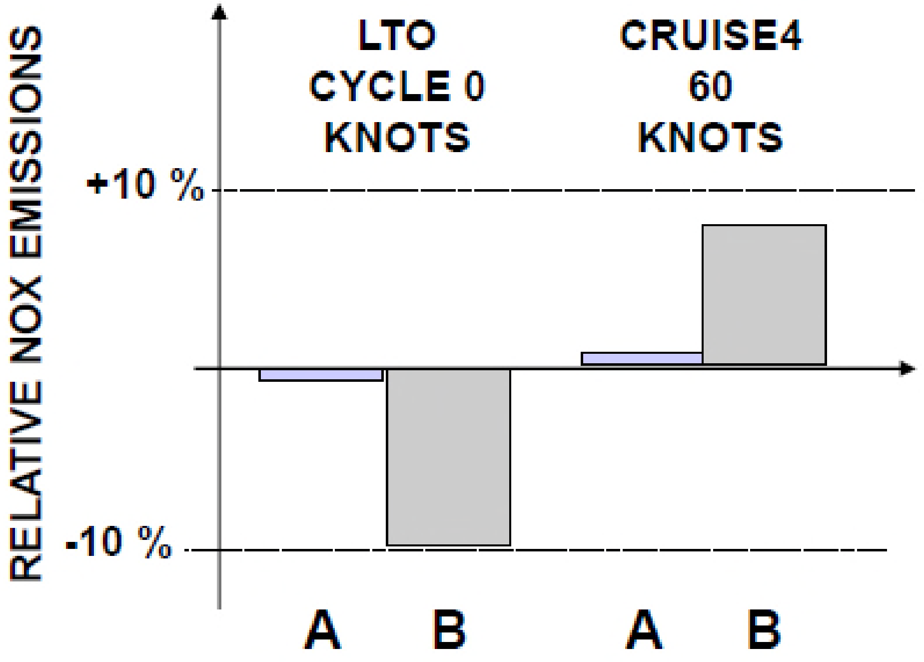
P. Madden, "CAEP Combustion Technology Review Process and CAEP NOx Goals," Rolls-Royce, 7 2014.

Cruise NO_x Legislation?

ENGINE B COMPLIES WITH NEW REGULATION...**



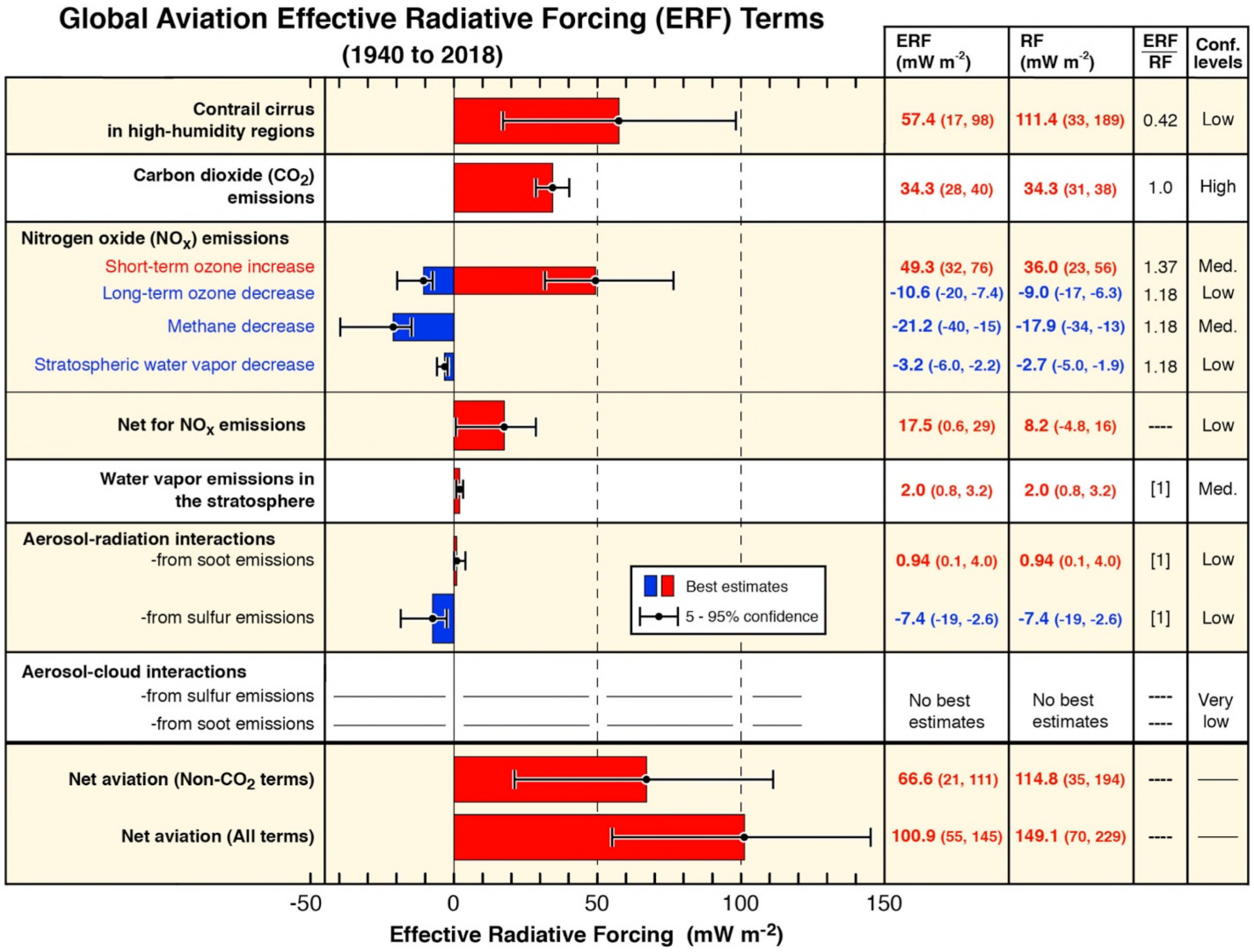
...AND STILL PRODUCES MORE NOX DURING CRUISE.



* : CAEP1
** : CAEP2

COURTESY: ROLLS-ROYCE

Contrails and Cirrus Clouds

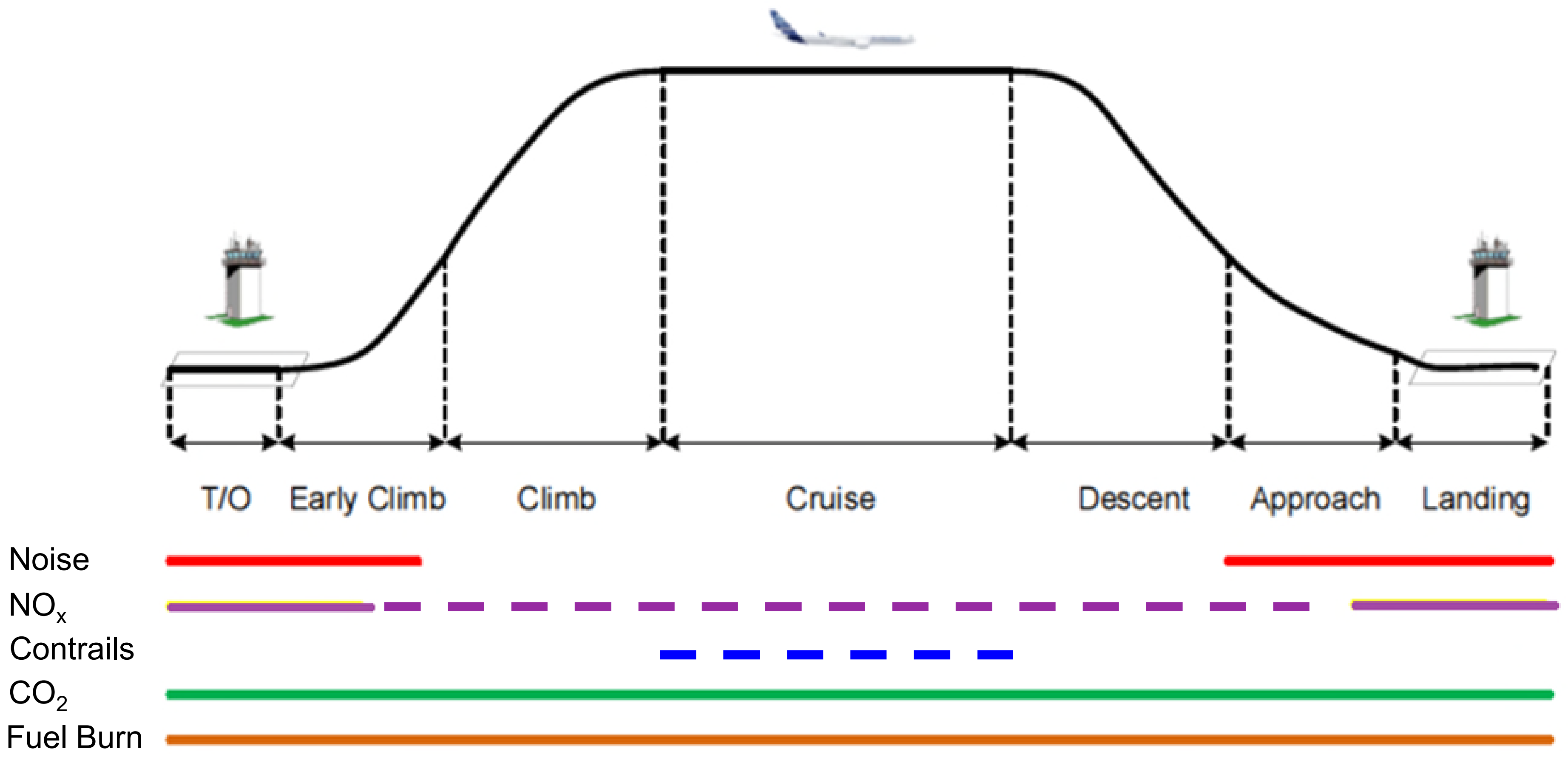


LH_2 – What about contrails?

- Significantly higher water vapour emissions
- Fewer emissions of particulates
- Appropriate mission management (persistent contrail avoidance trajectories)
- Less aggressive cycles?

Ref: D.S. Lee, D.W. Fahey, A. Skowron, M.R. Allen, U. Burkhardt, Q. Chen, S.J. Doherty, S. Freeman, P.M. Forster, J. Fuglestvedt, A. Gettelman, R.R. De León, L.L. Lim, M.T. Lund, R.J. Millar, B. Owen, J.E. Penner, G. Pitari, M.J. Prather, R. Sausen, L.J. Wilcox, “The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018”. Atmospheric Environment, Volume 244, 2021, 117834, ISSN 1352-231

Aircraft Trajectory Optimisation Criteria



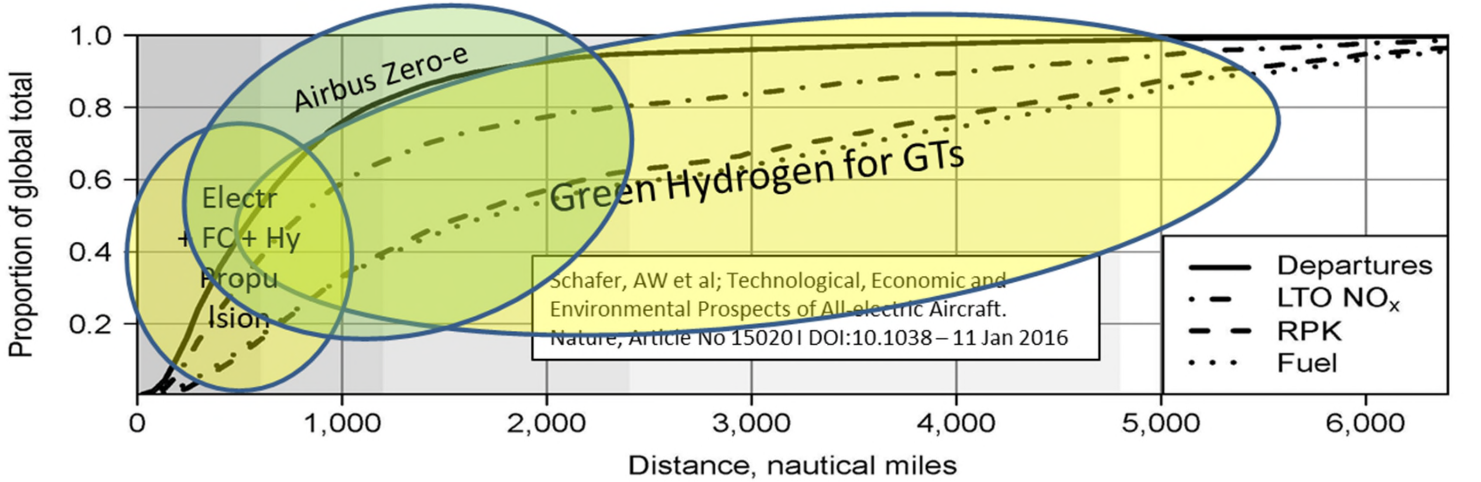
ACARE Flightpath 2050 Goals

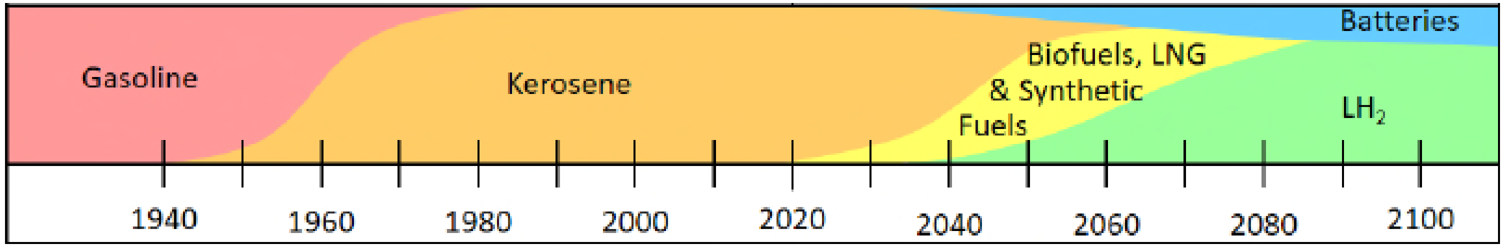
Aggressive Enough?

- Advisory Council for Aeronautical Research in Europe Flightpath 2050 goals (relative to Y2000 technology)
    - Reduction in CO_2 : 75%
    - Reduction in NO_x : 90%
    - Reduction in External Noise by: 65%
    - Cruise NO_x and Contrails considerations
    - Emissions free taxiing
    - Alternative fuels
- EU ETS

Sustainable Aviation = Protecting the Environment + the Economy

Decarbonise Aviation and Minimise Non-CO_2 Emissions!





Abbreviations
Electr: Electric
FC: Fuel Cells
GTs: Gas Turbines
Hy Propulsion: Hybrid Propulsion
LNG: Liquefied Natural Gas
LTO: Landing and Take-Off Cycle
RPK: Revenue per Passenger Kilometre

Green Propulsion Technologies are Key!

Sustainability

Decarbonise ⇒
Zero Carbon – Not “Net Zero”!

Minimise Non-CO_2 Emissions ⇒
NOx, Contrails, Noise

Improve Energy Efficiency ⇒
Advanced, Disruptive Tech.

Do not Curb Aviation Growth ⇒
Protect the economy!

Invest and Attract Diverse Talent ⇒
Infrastructure, R&D, Education