Aerospace Propulsion

Lecture 15

Airbreathing Propulsion V

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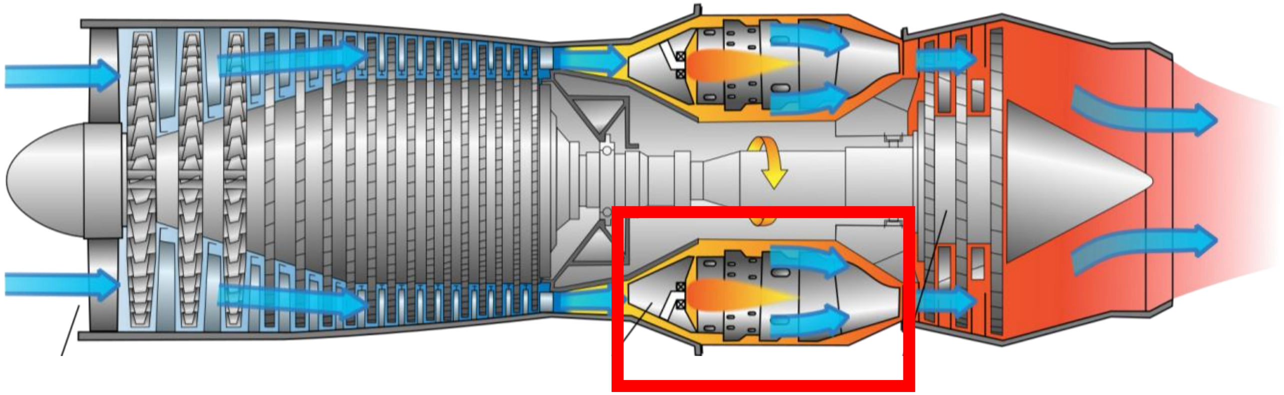
Airbreathing Propulsion: Part V

- Combustor Geometry
- Flame Behavior
- Combustor Emissions
- CO_2 Emissions

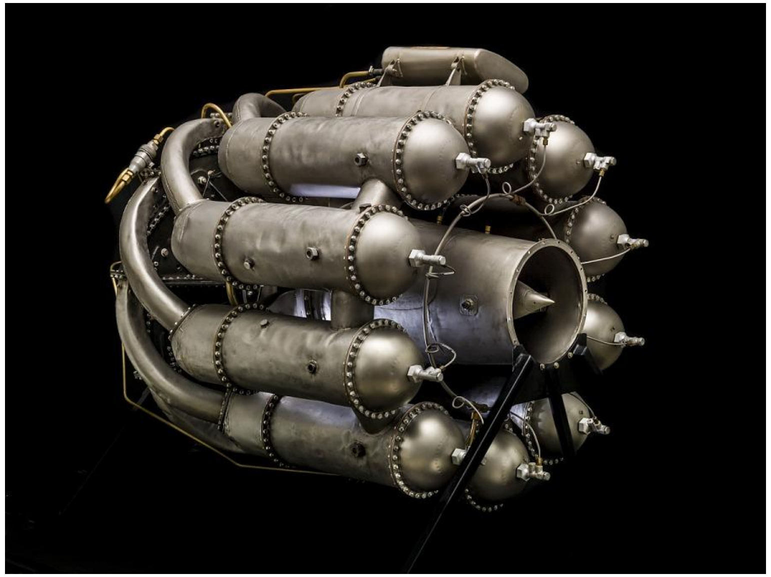
Combustors

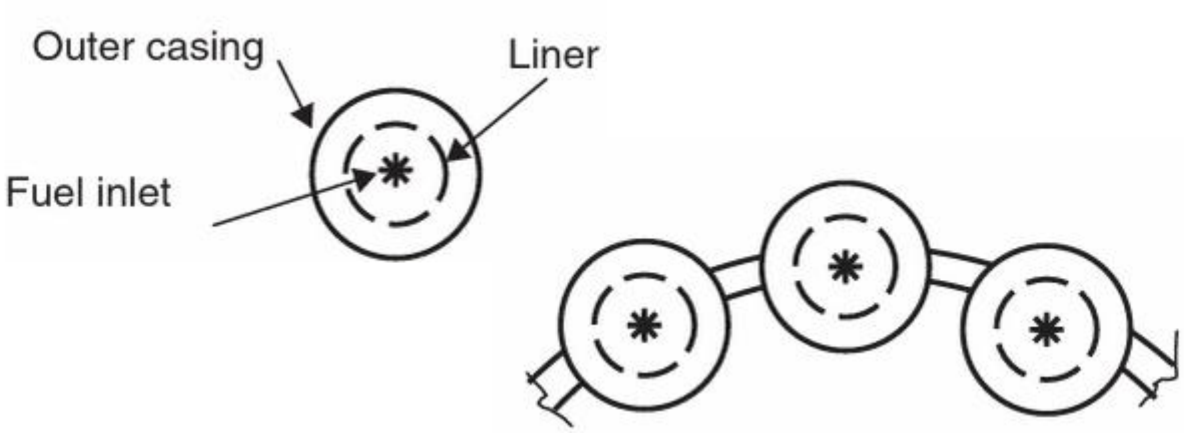


- Purpose and considerations
  - Primary
    - Add energy to compressed air to drive compressor/fan and provide thrust
      - Energy extraction is highly efficient (99%)
  - Secondary
    - Low drop in stagnation pressure (will not discuss)
    - Flight requirements: Ignition, relight, stability, noise, etc.
    - Low emissions of NO_x and soot (last few decades)
    - Low-to-no emissions of CO_2 (last decade)
    - Avoid damage to engine
    - Provide uniform temperature flow to turbine

Combustor Geometry

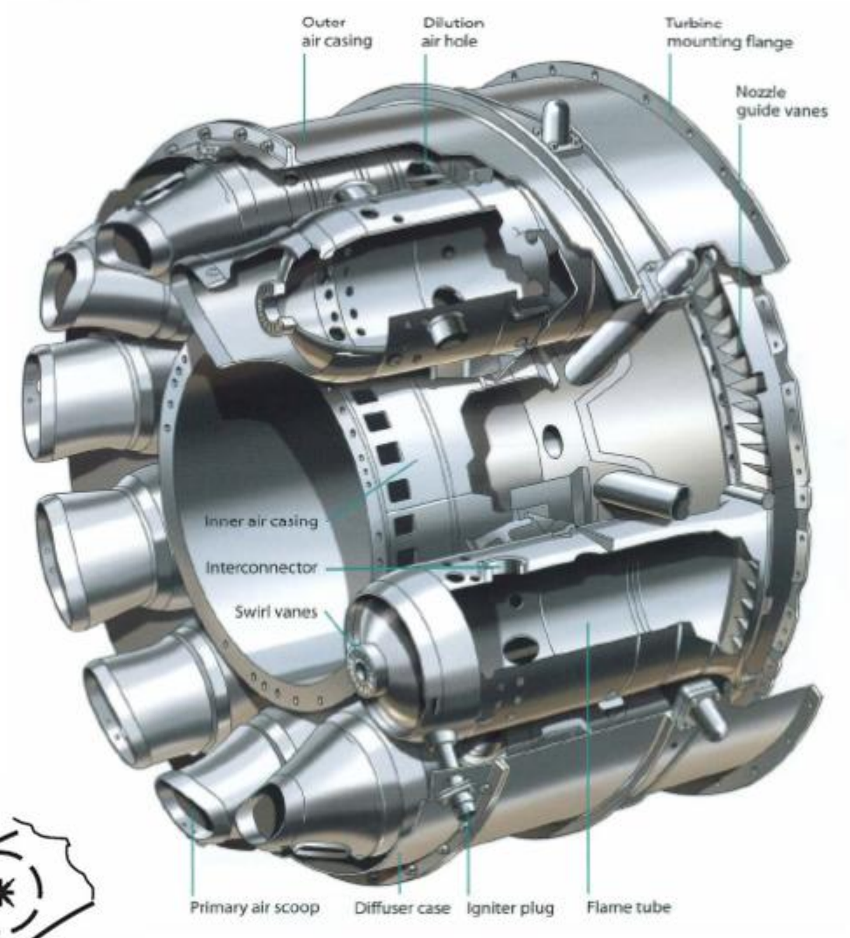
- Can
  - Fuel+Air mixed in a single "can"
  - Primary geometry for early combustors
  - Advantages
    - Easy to design and scale up and down
      - More power? More cans!
    - Easy maintenance of individual cans
  - Disadvantages
    - Each burner needs separate ignition
    - Large and heavy

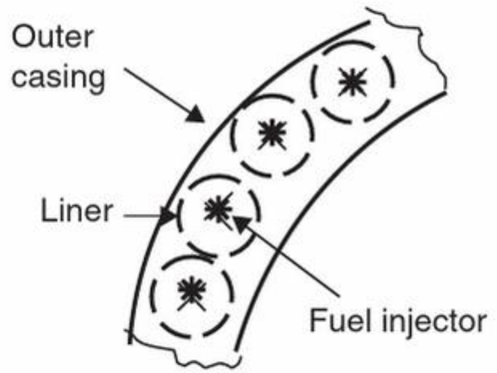




Combustor Geometry

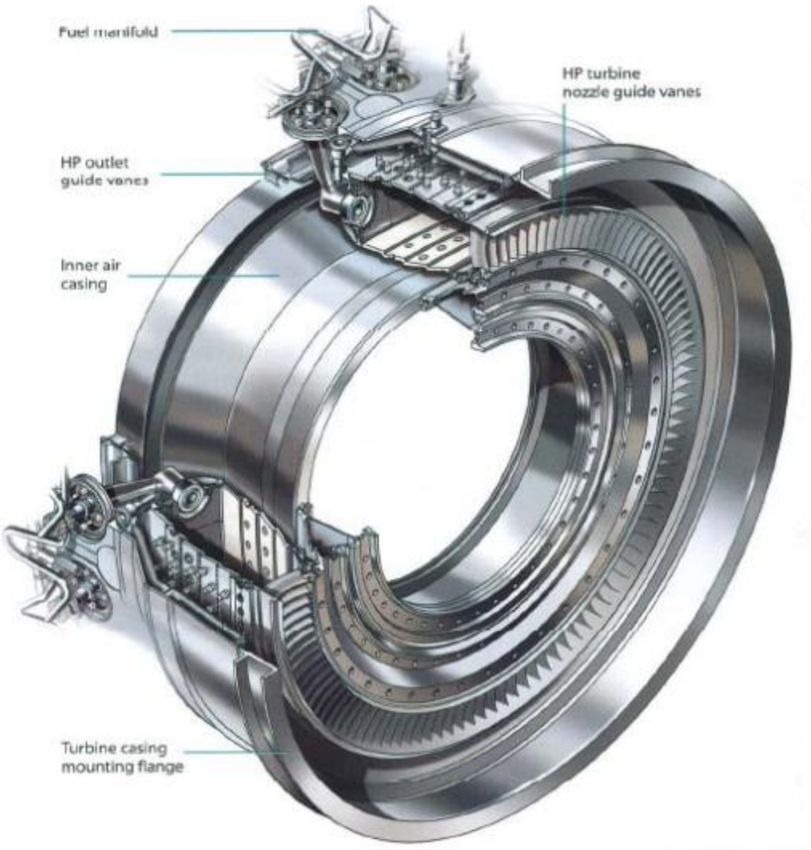
- Can-Annular
  - Independent combustion chambers, but shared annulus for dilution air
  - Popular in 1940's and 1950's
  - Advantages
    - More compact than can geometry
  - Disadvantages
    - Similar to can combustors

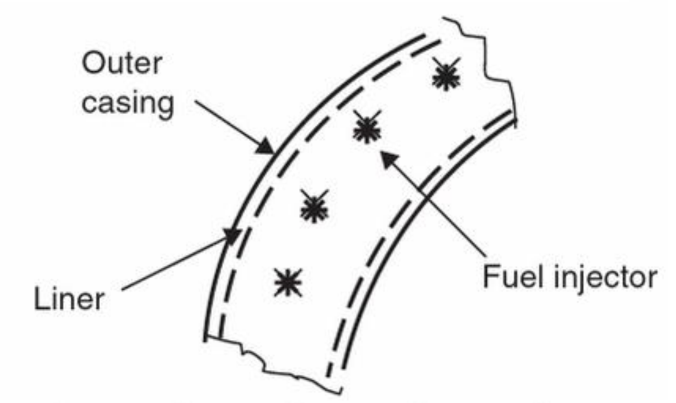




Combustor Geometry

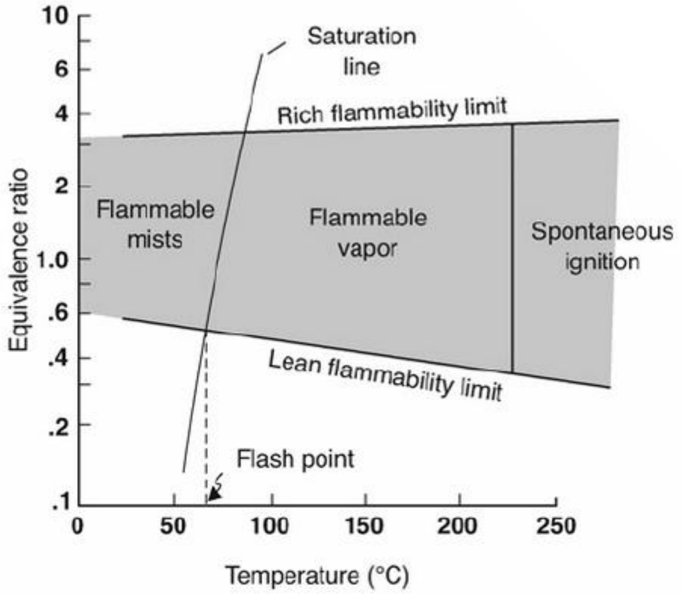
- Annular
  - Single annular combustor
  - Most modern combustors
  - Advantages
    - Most compact
    - Low pressure losses
    - Only need single igniter
  - Disadvantages
    - Harder to maintain
      - Can’t remove a single can

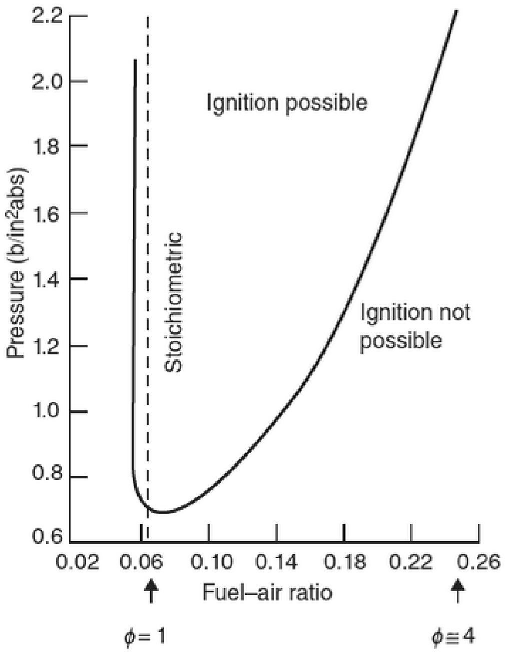




Flame Behavior

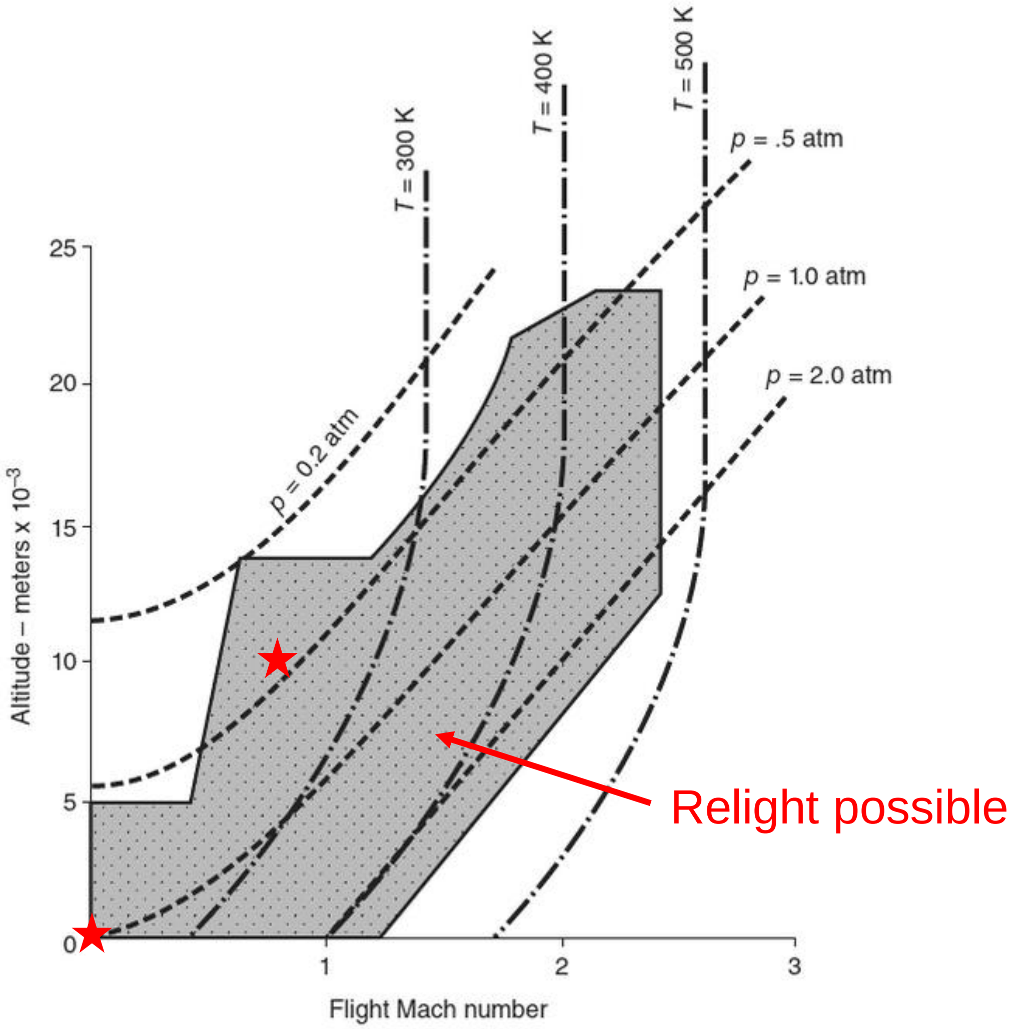
- Ignition
  - Recall that reaction rate is a function of
    - Temperature (always)
    - Pressure (depends on reaction)
  - Reaction timescale estimate
    - $\tau_r \sim p^{-n} T^{-m} \exp \frac{E_a}{RT}$
    - $n \sim 1.2$
    - $m \sim 2$
  - Ignition is easier:
    - At high preheat temperatures
    - At higher pressures (rich combustion)
  - Overall, ignition is not problematic on ground





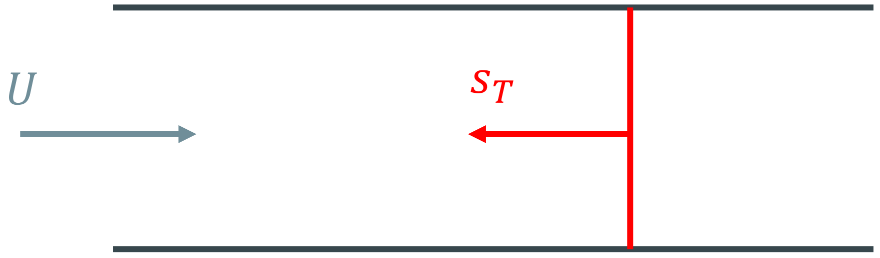
Flame Behavior

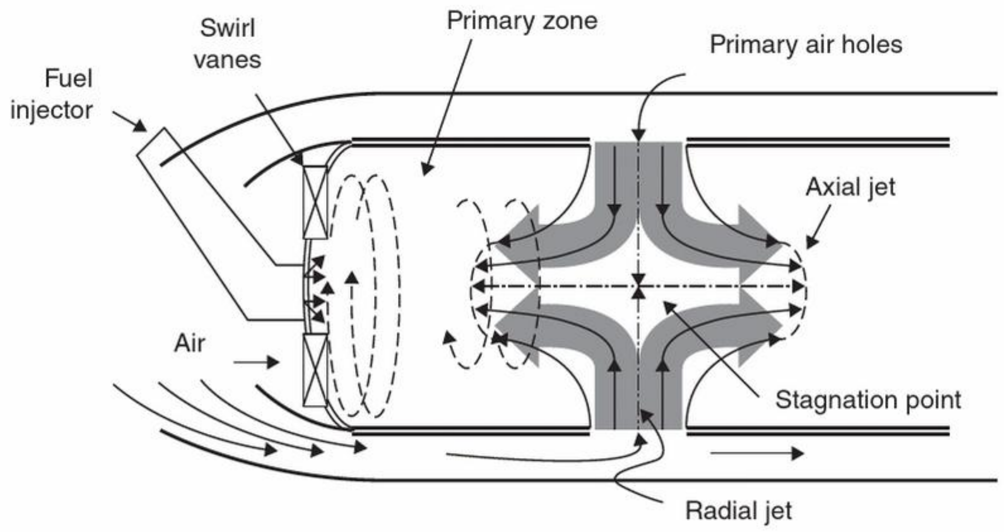
- Relight
  - In extreme case, flame can extinguish while in flight
    - Flight conditions are highly unsteady
  - At flight altitude, lower pressure and temperature
  - Relighting is harder at altitude
    - Long chemical time-scale



Flame Behavior

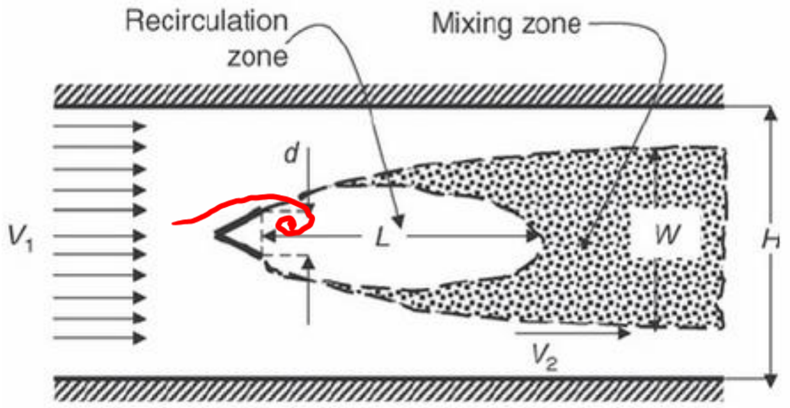
- Flame stabilization
  - Recall premixed flames propagate at
    - Laminar flame speed $s_L \sim$ O(0.1-1.0 m/s)
    - Turbulent flame speed $s_T \sim s_L *$ O(1-100)
  - Flame stability cannot be guaranteed, for example, in channel-like flow
  - Combustors utilize various methods to stabilize flame
    - Swirling flows
    - Radial jets
    - Overall, strong vortices that "break-down" and lead to "reversed-flow"

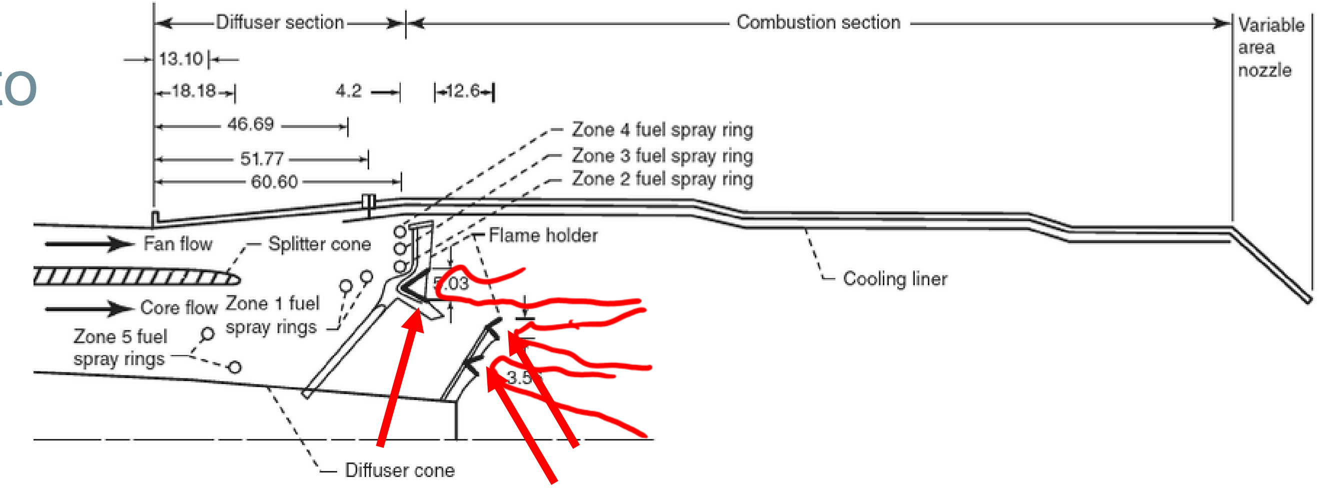




Flame Behavior

- Afterburner flame stabilization
  - Fluid is just before nozzle, already moving fast
    - More extreme stabilization necessary
  - Utilize “bluff-bodies” that lead to strong recirculation zones
  - Flow after bluff body is slow
    - Negative velocity component



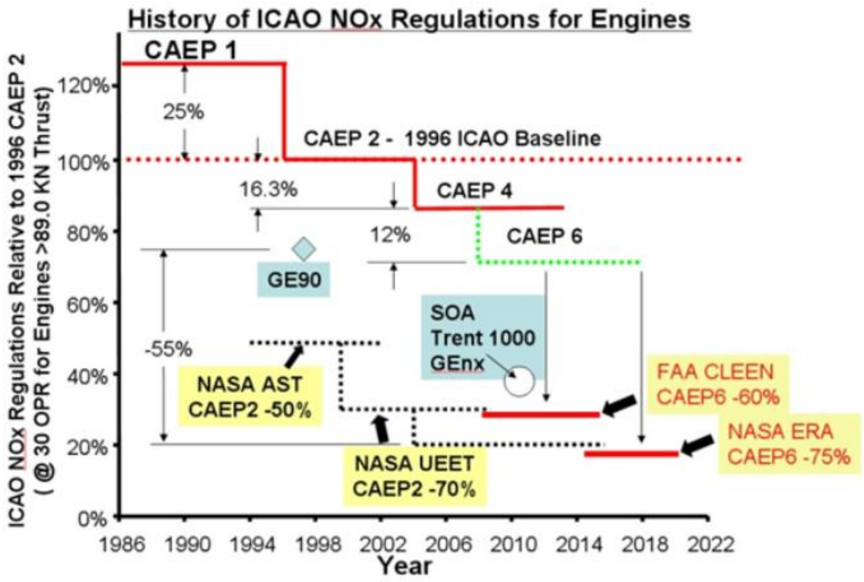


Combustor Emissions

- Emissions Review: Three rules of pollutants
  - **Rule #1**: Formation of pollutants is kinetically (chemistry) controlled
    - "Long" residence times are required for pollutant formation
  - **Rule #2**: Once formed, NO_x is difficult to remove via combustion
    - Avoid forming NO_x as much as possible
  - **Rule #3**: Once cold, soot is difficult to remove via combustion
    - Try to destroy any formed soot before it reaches cold gases
- Ideal combustor designs
  - Option A: Rich combustion followed by lean combustion
    - Avoid stoichiometric mixtures
  - Option B: Lean premixed combustion

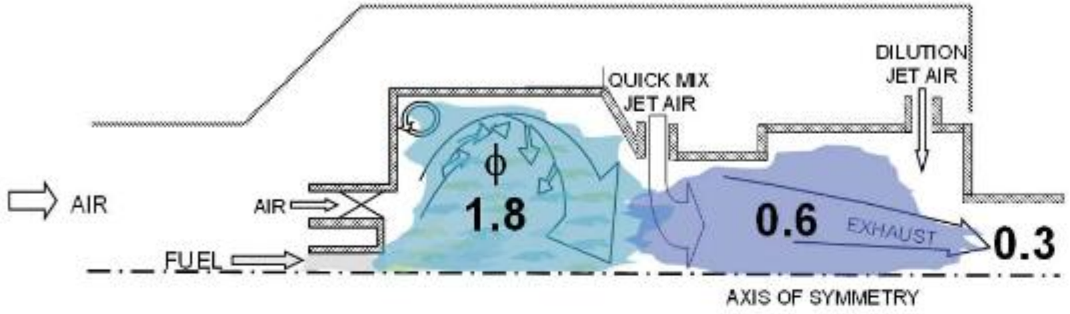
Combustor Emissions

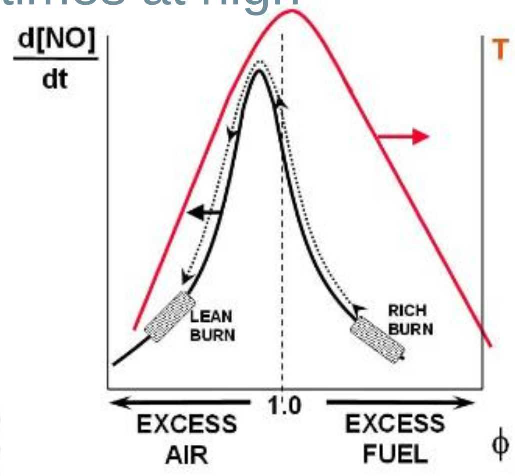
- Rich Burn – Quick Quench – Lean Burn (RQL) combustor
  - Used by Pratt and Whitney, Rolls Royce since ~ 1996
  - What happened in 1996?
    - ICAO: International Civil Aviation Organization
    - CAEP: Committee on Aviation Environmental Protection
    - CAEP/2 Adopted by EPA in 1997
  - New standards continue to be released
    - CAEP11 released in 2019



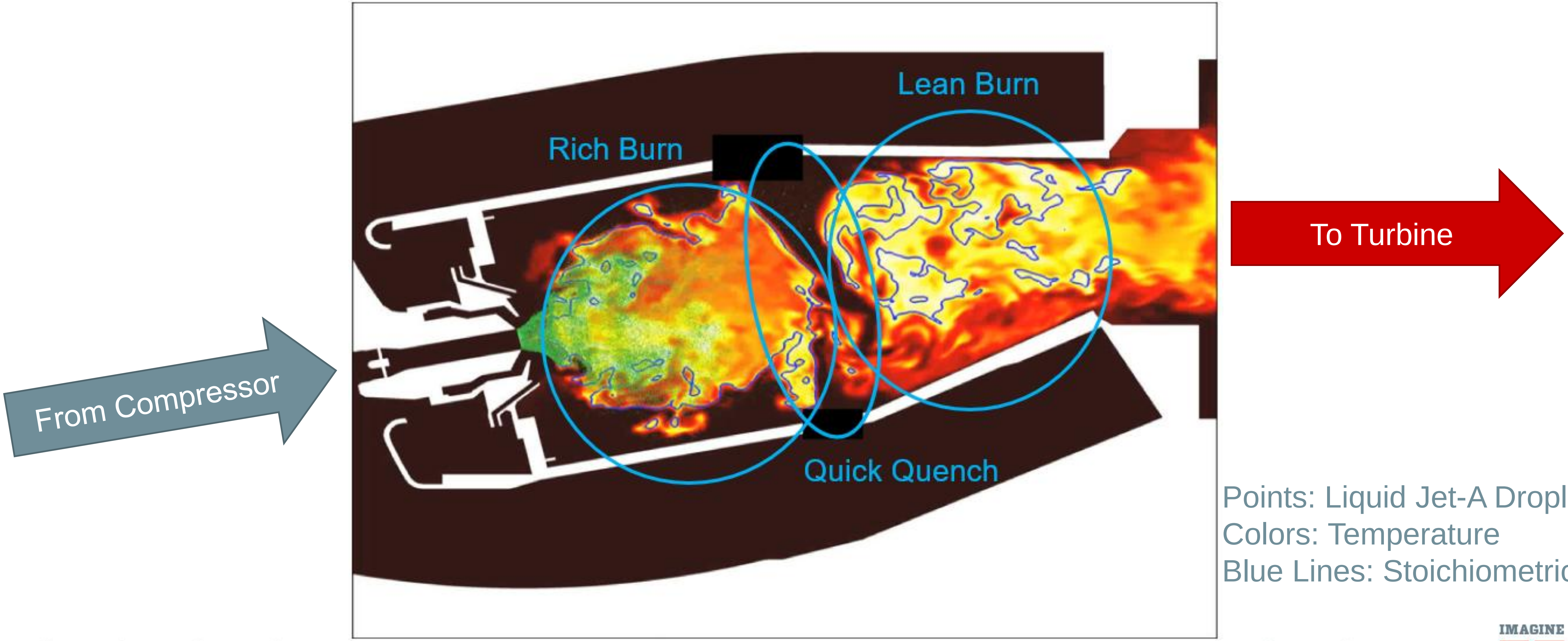
Combustor Emissions

- Rich Burn – Quick Quench – Lean Burn (RQL) combustor
  - Primary combustion zone
    - Fuel rich (very stable flame, see slide 7)
    - Forms a lot of soot (very rich)
    - Forms very little NO_x (little oxygen)
  - Quenching
    - Rapidly add dilution air (cold) and mix to minimize residence times at high temperature and stoichiometric conditions
  - Secondary combustion zone
    - Fuel lean combustion
    - Burn most previously formed soot away (a lot of oxygen)
    - Forms very little NO_x (low temperature)





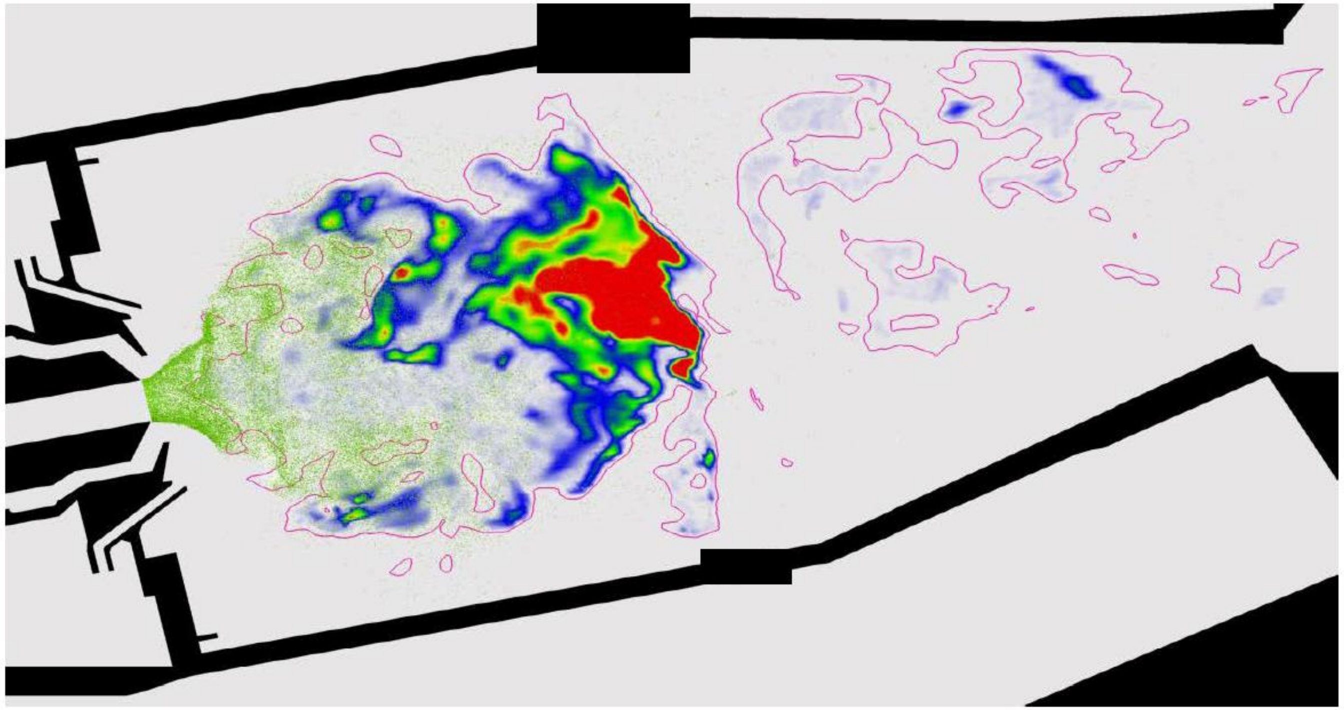
Combustor Emissions



Points: Liquid Jet-A Droplets
Colors: Temperature
Blue Lines: Stoichiometric

Combustor Emissions

From Compressor



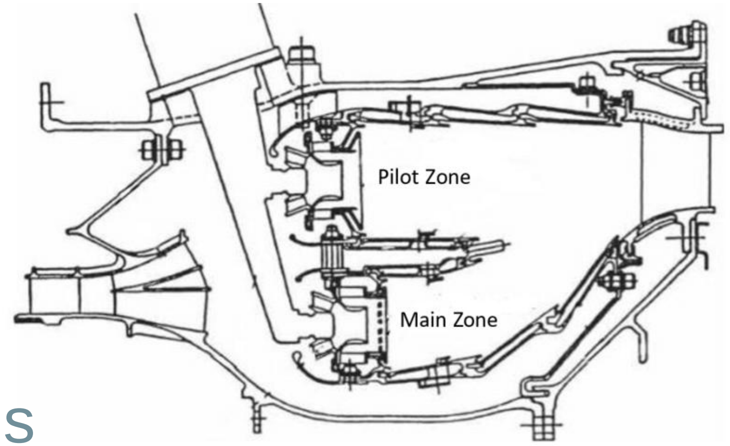
To Turbine

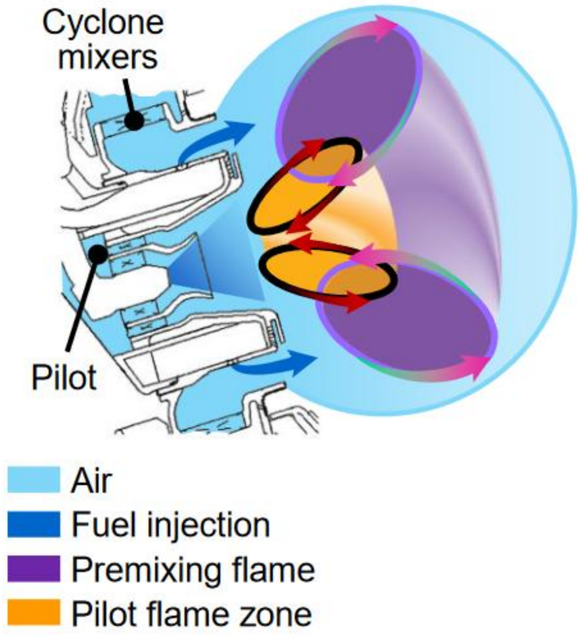
Points: Liquid Jet-A Droplets
Colors: Soot
Purple Lines: Stoichiometric

Combustor Emissions

- Lean Premixed Pre-vaporized (LPP)
  - Approach taken by GE to meet emissions standards

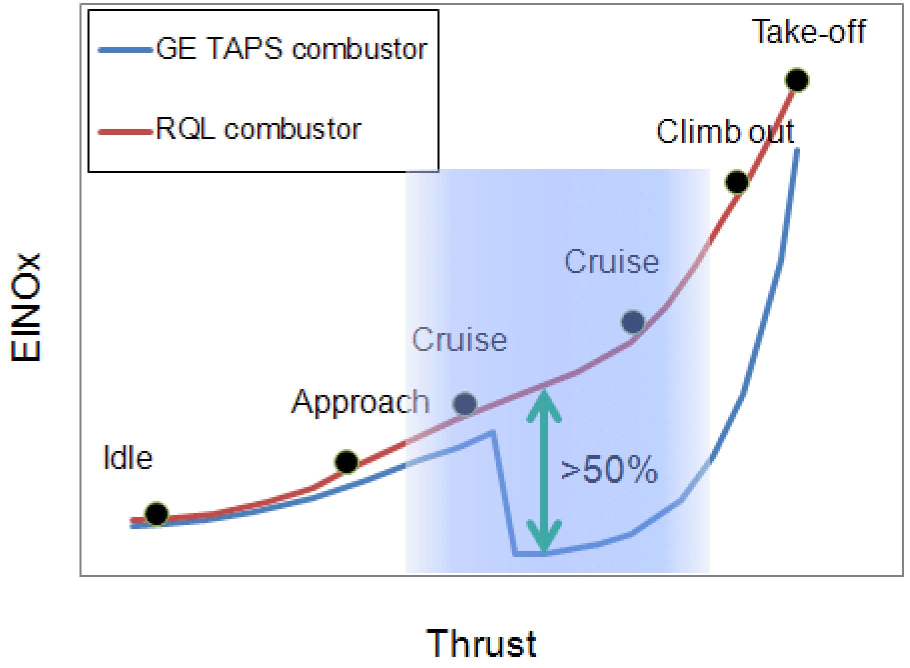
  - 1995: Double Annular Combustor (DAC)
    - Two burners (pilot and main) both operating lean
    - Pilot zone provides low power and ignites main zone
    - Main zone used for high power
  - 2008: Twin Annular Premixed Swirler (TAPS)
    - Pilot and main zones combined
    - Essentially a single lean burner at both low/high power





Combustor Emissions

- Lean Premixed Pre-vaporized (LPP)
  - All combustion at lean conditions so low NO_x and soot
  - Advantages
    - Cleaner than RQL for NO_x
  - Disadvantages
    - Lean combustion is less stable (slide 7)
      - Flame may extinguish
    - Lean combustion susceptible to instabilities
    - Fuel must be well vaporized/mixed
      - Un-vaporized liquid droplets cannot burn lean
      - Increases combustor mass and volume



CO_2 Emissions

- Net-zero carbon emissions by 2050 (US)
- CO_2 emissions are controlled by
  - Flight efficiency
  - What goes into the combustor
- Any carbon-containing fuel will release CO_2
  - We **want** this for the heat release
- Options
  - Move away from combustion
  - Use a net-zero carbon fuel
  - Use a non-carbon fuel

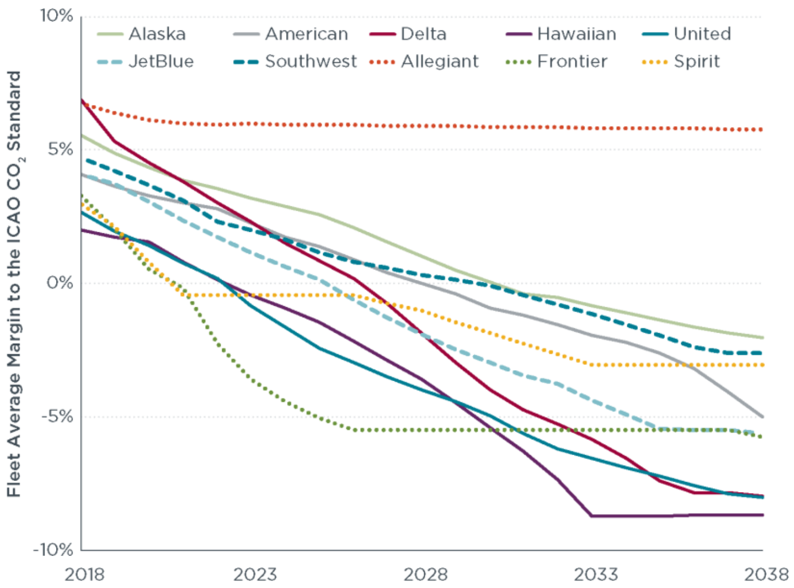


Figure 5. Average margin to the ICAO CO_2 standard for jet aircraft in the fleet of U.S. mainline carriers, 2018 to 2038.

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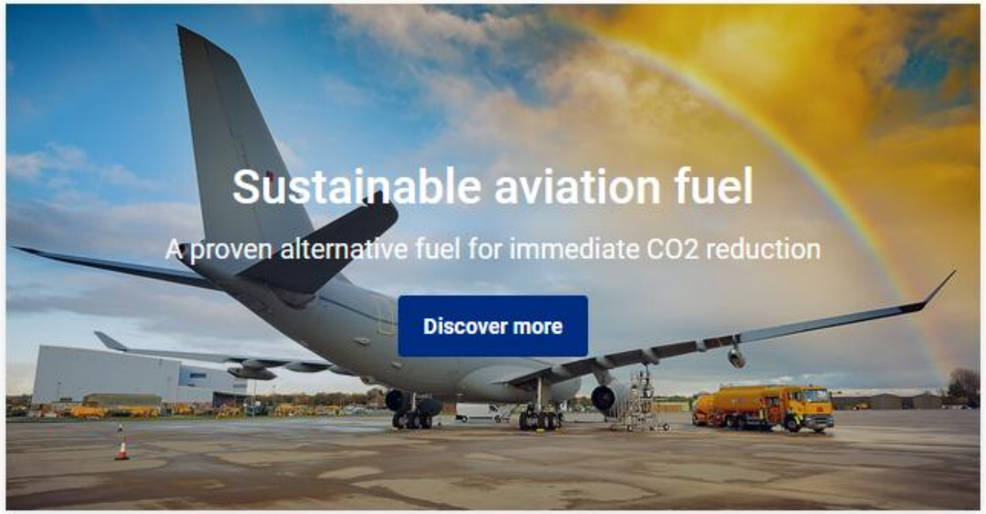
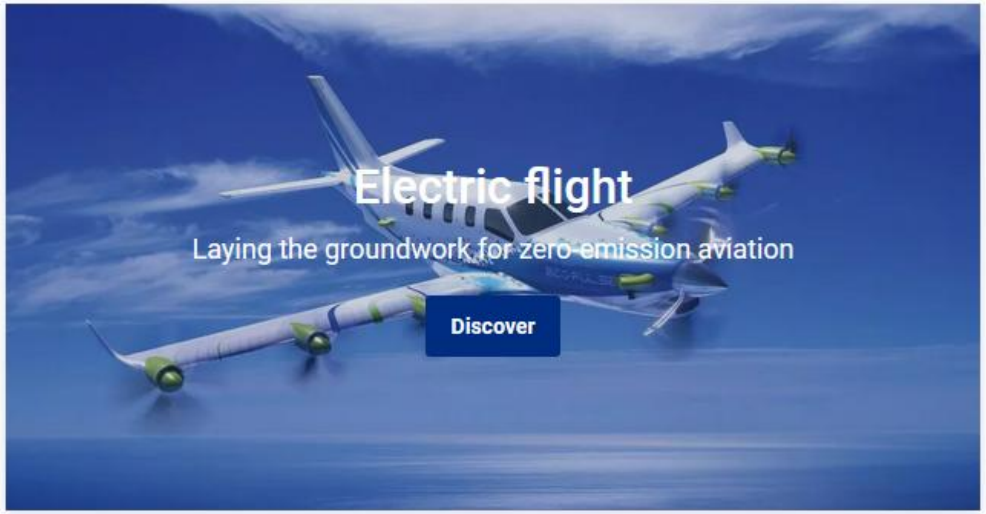
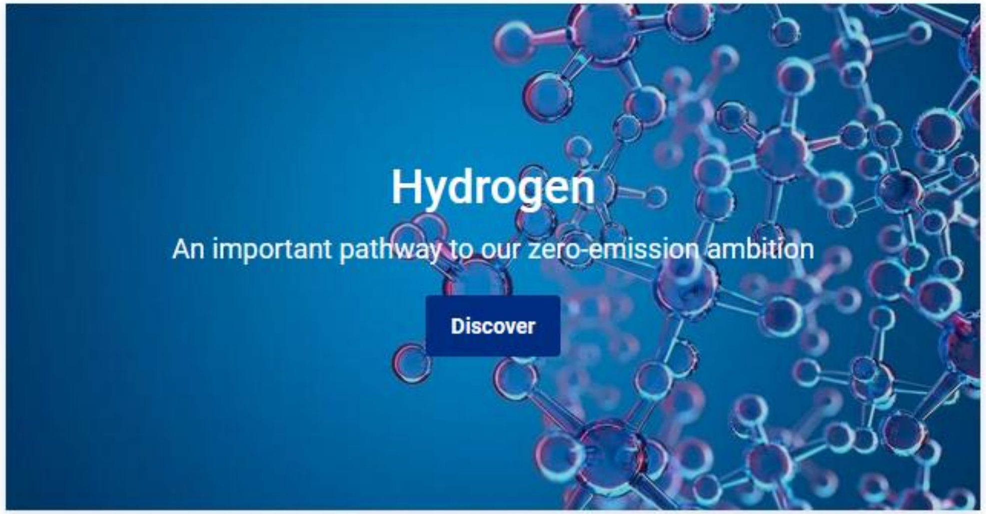
CO_2 Emissions (2023)

https://www.airbus.com/en/innovation/zero-emission-journey

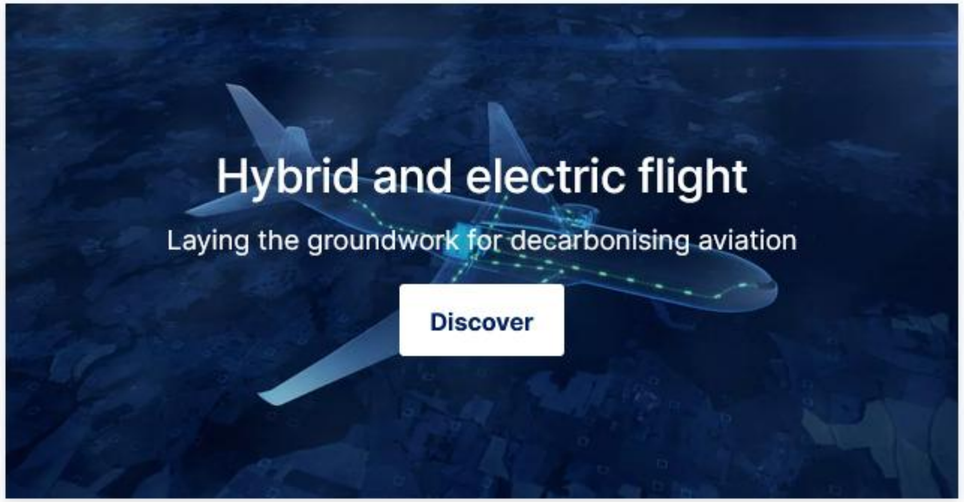


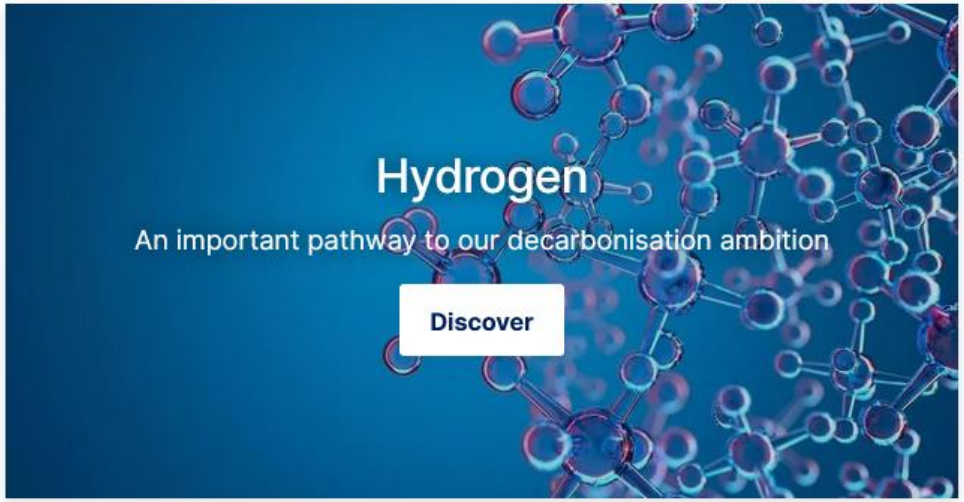




CO_2 Emissions (2024)

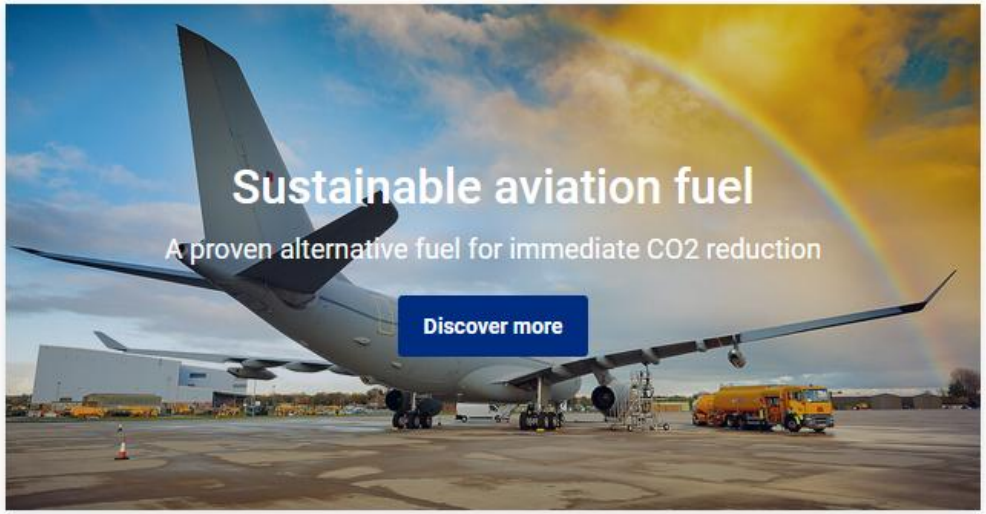
https://www.airbus.com/en/innovation/zero-emission-journey

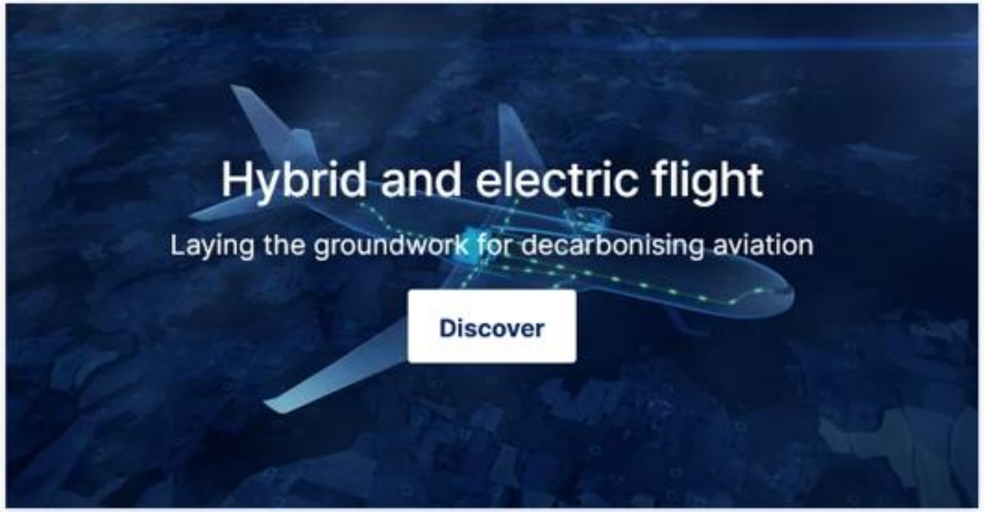


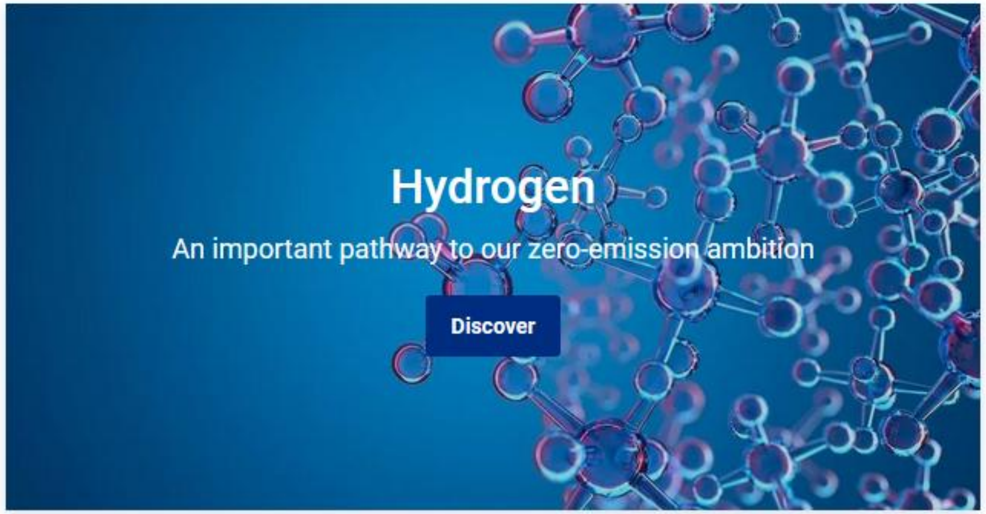


CO_2 Emissions (2025)

https://www.airbus.com/en/innovation/energy-transition

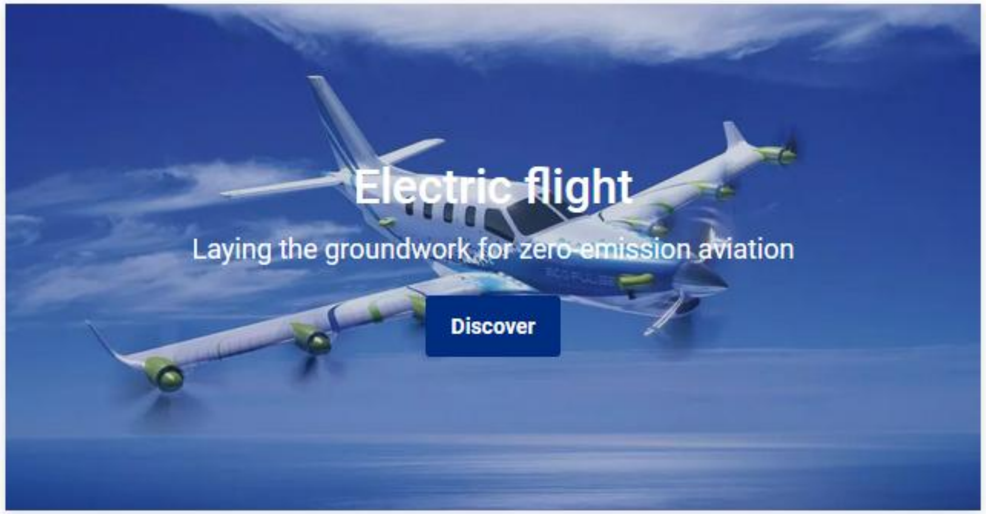






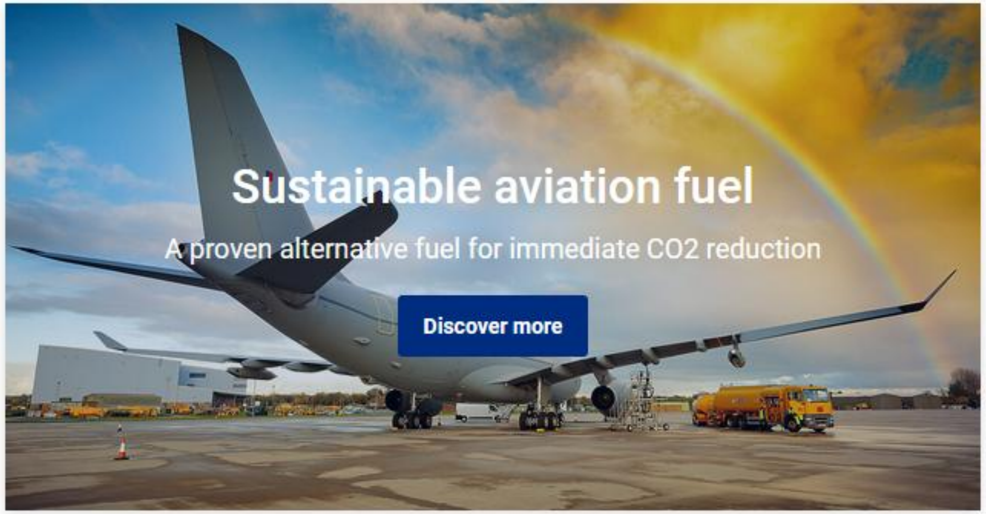
CO_2 Emissions

- Not covered here, completely different type of propulsion
- Battery energy storage density not high enough for anything beyond short-haul
    - Note airbuses change from “electric” to “hybrid and electric”



CO_2 Emissions

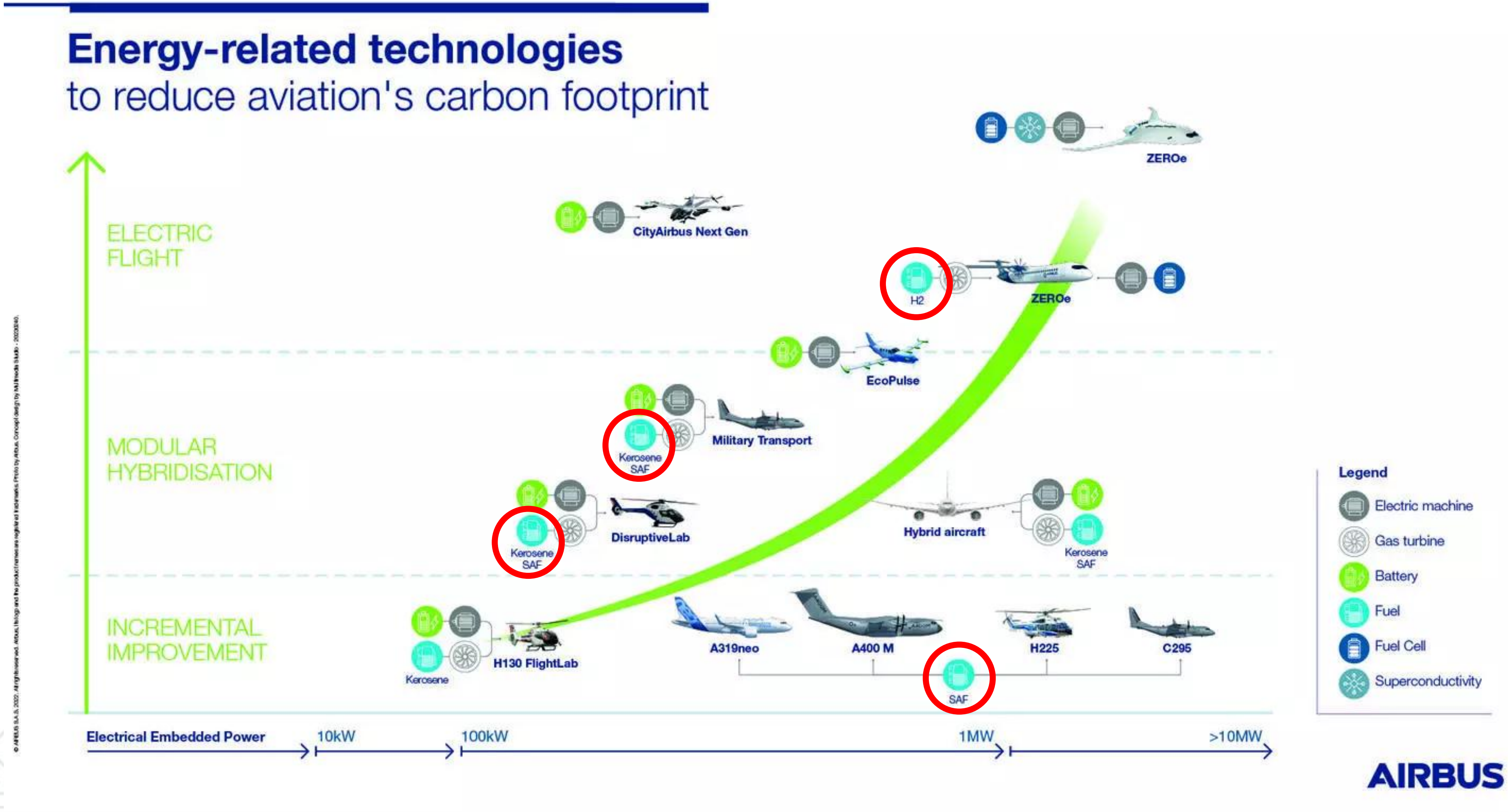
- Sustainable aviation fuels (SAF)
  - Designed to be "drop-in" fuels
  - Net-zero carbon emissions
  - Mixture of standard aviation fuel with renewable fuel
    - Agricultural and forestry waste
    - Used fat, oil, grease
    - Municipal waste



- This is "easy"
  - No major combustor changes needed

CO_2 Emissions (2024)

https://www.airbus.com/en/innovation/zero-emission-journey



CO_2 Emissions

- Hydrogen (H_2)
  - Contains no carbon – no CO_2 release
  - Issues with storage, transport, density
  - High energy per mass
  - Low energy per volume
- Ammonia (NH_3)
  - Easier to store and transport
  - Can be converted to hydrogen
- Both **must** be formed with renewable energy to make any sense

Fuel Type	MJ/kg	MJ/L	$/MJ
Li Battery	0.3	0.3	0.03
Honey	14	20	0.29
Goose Fat	38	35	0.26
Jet A	44	36	0.018
Natural Gas	45	19	0.005
Hydrogen	117	8.3	0.44

CO_2 Emissions

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Li Battery	0.3	0.3	0.03
Honey	14	20	0.29
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Jet A	44	36	0.018
Natural Gas	45	19	0.005
Hydrogen	117	8.3	0.44

- (117 MJ/kg)*(0.44 $/MJ) = 51.48 $/kg
- Hydrogen Earthshot seeks to dramatically reduce this number

1 Dollar   1 Kilogram   1 Decade

https://www.energy.gov/eere/fuelcells/hydrogen-shot

CO_2 Emissions

- Airbus has flown using pure H2 combustion in late 2023
  - Blue Condor, 7,000 ft

CO_2 Emissions

- SAF mimic AF fuel properties
  - Combustion occurs very similarly
- Hydrogen combustion is very different
  - Shorter chemical timescales
    - Ignition promoted
    - Higher flamespeed
  - ✓Relight envelope is increased
  - ✓Flame extinction less likely
  - × Flame flashback more likely
    - Damages/destroys combustor