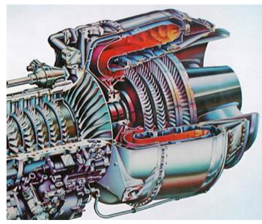
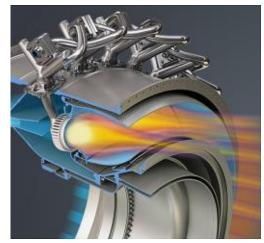
Jet Engine (Main) Combustors

- Long history of jet engine combustors and design advances

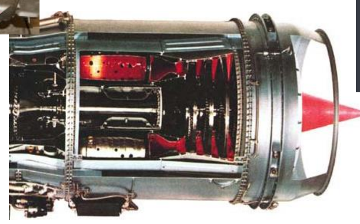


T53 (1959)
(UH-1A, AH-1,…)

Jumo004b (1942)
ME262,...



GE90 (1995)
B777



JT8D (1963)
B727,737,DC-9

Combustors: Requirements

- Convert chemical energy (fuel) to thermal energy (T) with
  - high combustion (conversion) efficiency
  - low pressure losses
  - good stability (flame is “stationary”, no “flame outs”)
  - reliable ignition (takeoff and relight)
  - short length (lower weight, shorter shafts,…)
    $\Rightarrow$ low residence time (few ms to complete combustion)
  - long lifetime (cool or insulated surfaces)
  - “uniform” exit temperature profile (pattern factor) to maintain turbine lifetime
    - actually need cooler flow at rotor root (stress) and tip (seals)
  - low emissions
  - reasonable cost, manufacturable and maintainable

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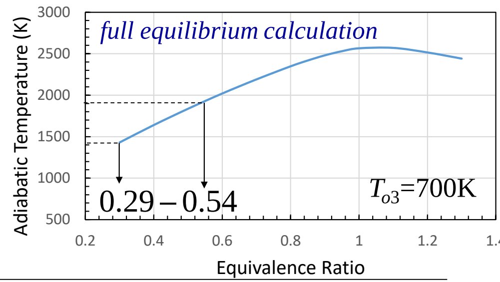
T4 and Fuel-Air Ratio

- In main combustors, we inject fuel into “warm” air
- What is the desired fuel-air ratio?
  - simplified combustor energy equation *e.g.*, III.10 $f \cong \dfrac{T_{o4} - T_{o3}}{\Delta h_R / c_p - T_{o4}}$
  - **equivalence ratio**, $ER \equiv f / f_{stoich}$
  - for jet fuel, f_{stoich} ~0.067 $\Delta h_R \cong$43.4 MJ/kg
  - more accurate to use non-cpg and equilibrium composition
  - for $T_{o4,max}$= 1400-1900K, relatively lean



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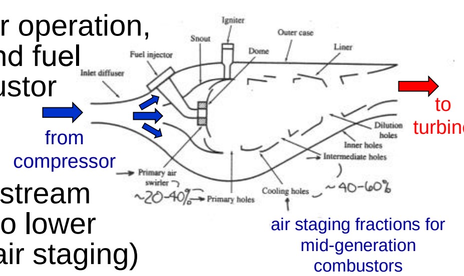
Flammability Limits and Dilution

- For premixed jet fuel-air at typical T3 values, can’t sustain a flame (without “help”) below E.R. ~ 0.35-0.43 = the **lean flammability limit**
  - for lower range of our operation, can’t premix all air and fuel at entrance to combustor
  - run richer in primary zone (**more stable**)
  - add dilution air downstream (intermediate zone) to lower temperature (called air staging)
  - also use some of the excess air to cool the combustor walls, keep flame and hot gases away from liner



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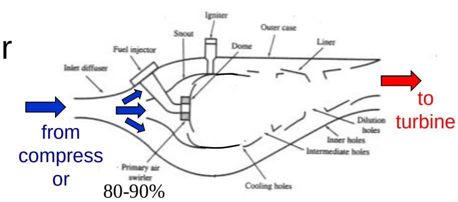
Air Staging Options

- To reduce soot and NOx emissions, some combustor designs have moved to increasing the fraction of air introduced near the head end of combustor (lean burn)
- Reduction in dilution air
  - less air for cooling
  - can be harder to reduce hot streaks
  - leaner primary zone susceptible to stability problems
  - can require complicated fuel management for turndown (reduced f)



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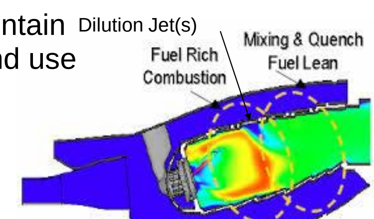
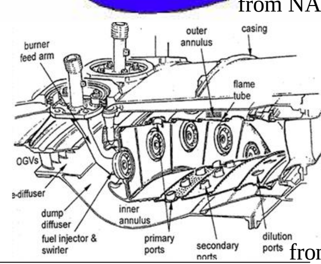
Air Staging Options

- Alternate approach is to maintain original rich primary zone and use strong dilution air jets
  - RQL (Rich burn – Quick quench – Lean burn)
- Can keep emissions levels low and promote exit uniformity while maintaining stability advantages of rich primary zone
  - may not be able to achieve as low emissions as lean burn designs



from NASA



from RR

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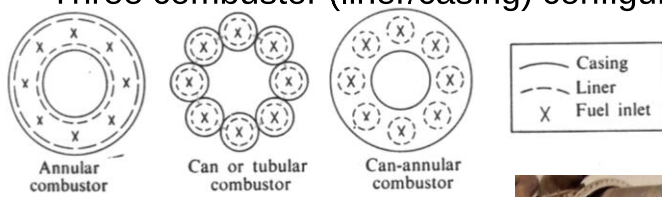
Main Combustor (Axial) Configurations

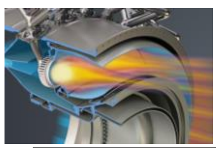
- Three combustor (liner/casing) configurations



↑ modern engines

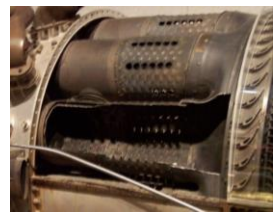
↑ earliest engines

↑ still in service



GE90

Jumo004b



GE79

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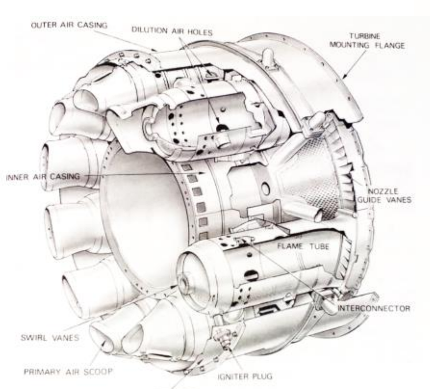
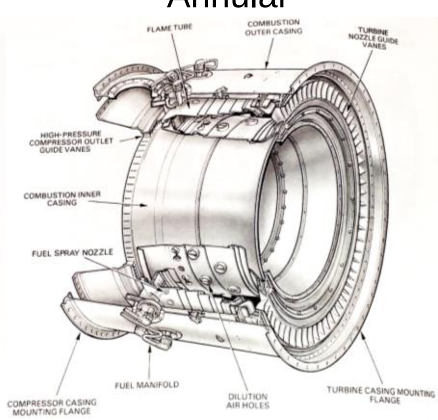
Main Combustor Configurations

Can-annular

Annular

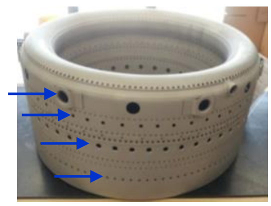




From Rolls-Royce (similar to Figs. 6.28 and 6.29 in Hill and Peterson)

Annular Combustor Liners

Dilution Holes

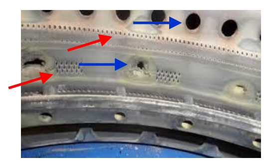


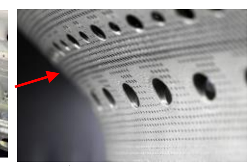
PT6 (PW Canada, Turboprop, King Air, Cessna)

KJ66 Pegasus (RR, Harrier)

JT9D (PW, 747, 767, A300)

Effusion (film) Cooling





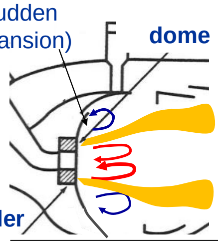
CFM56 (GE/Safran, 737, A320, A340)

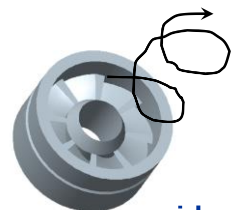
Main Combustor Configurations

	Can	Can-Annular	Annular
Pros	• Simple control of fuel-air ratio • Very modular (replacement and testing)	• Moderate p loss (6%) • Intermediate cross-sectional area (casing weight) • Intermediate liner mass • Some ducting • Intermediate modularity (liner replacement, sector testing)	• Lowest p loss (5%) • Lowest liner surface area • Improved uniformity • Smallest cross-sectional area (less weight and shorter)
Cons	• Heavier, larger volume • More ducting • Higher p loss (7%) • Hard to get uniformity (θ)		• Greater need for full-rig testing • Must replace complete liner (expensive)

Flame/Combustor Static Stability

- Also want to make sure flame does not leave combustor, e.g., blowoff and move into the turbine
  - need to make sure flame is anchored stably near the front of the combustor
  - standard approach* relies on swirling incoming air and having sudden expansion
    - expansion creates outer recirculation zone
    - swirl produces low velocity regions and central recirculation of hot gases back towards the entrance
    - also improves mixing of fuel and air





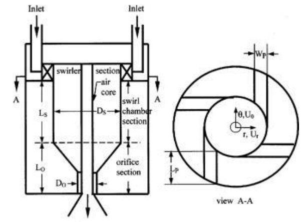
alternatives include trapped vortex combustor (TVC)

Fuel Atomization

- Liquid hydrocarbon fuels will burn only AFTER becoming a gas/vapor
- Prevaporizing fuel in heat exchanger would
  1. require additional weight
  2. lead to fuel coking; heated fuel pyrolyzes and forms carbon residue that clogs fuel lines
- So combustors employ atomizers to produce **fine** liquid fuel droplets
  - time required to evaporate a HC fuel droplet of diameter d, $t_d = d^2/K$ with $K \sim 10^2\text{-}10^3\ \mu m^2/ms$
  - $t_d(200\ \mu m) = 40\ ms$; $t_d(10\ \mu m) = 0.1\ ms$

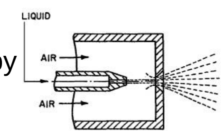
Fuel Injection/Atomization

- **Pressure atomizers**
  - swirl-pressure (**simplex**) common in aircraft APUs and staged pilots (plain orifice for diesels)
  - rely on large Δp to atomize
  - poor performance at reduced fuel flow rates (low Δp)
- **Air-blast atomizers**
  - typical main combustors
  - rely less on fuel Δp and more on shear induced by air flow
  - worse atomization at reduced air flow rates

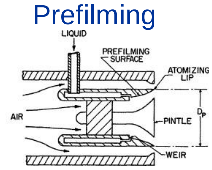


J. Eng. Gas Turbines Power 129, 945 (2007)

Plain Jet



Prefilming

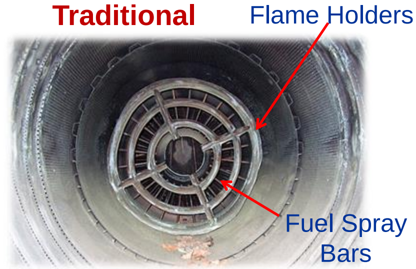


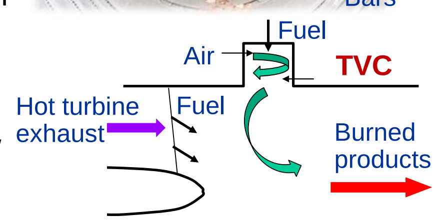
Lefebvre, Gas Turbine Combustion

Augmentors (and Ramjets)

- Fuel is being injected into high temperature flow
  - combustion products for augmentor
- Fuel needs to be distributed
  - radially and azimuthally
- Need flame holding for high velocity flow
- Concern for signatures
  - infrared radiation, radar
- Choking of high speed flow (heat addition)

Traditional





Choking Due to Heat Addition

- Heat addition increases entropy
- For **enough heating**, M_e=1
  - heat addition can lead to choked flow
  - additional heating lowers mass flux
- Requires sufficient area increase (diverging) to offset heat addition
  - variable area nozzle to account for augmentor power setting