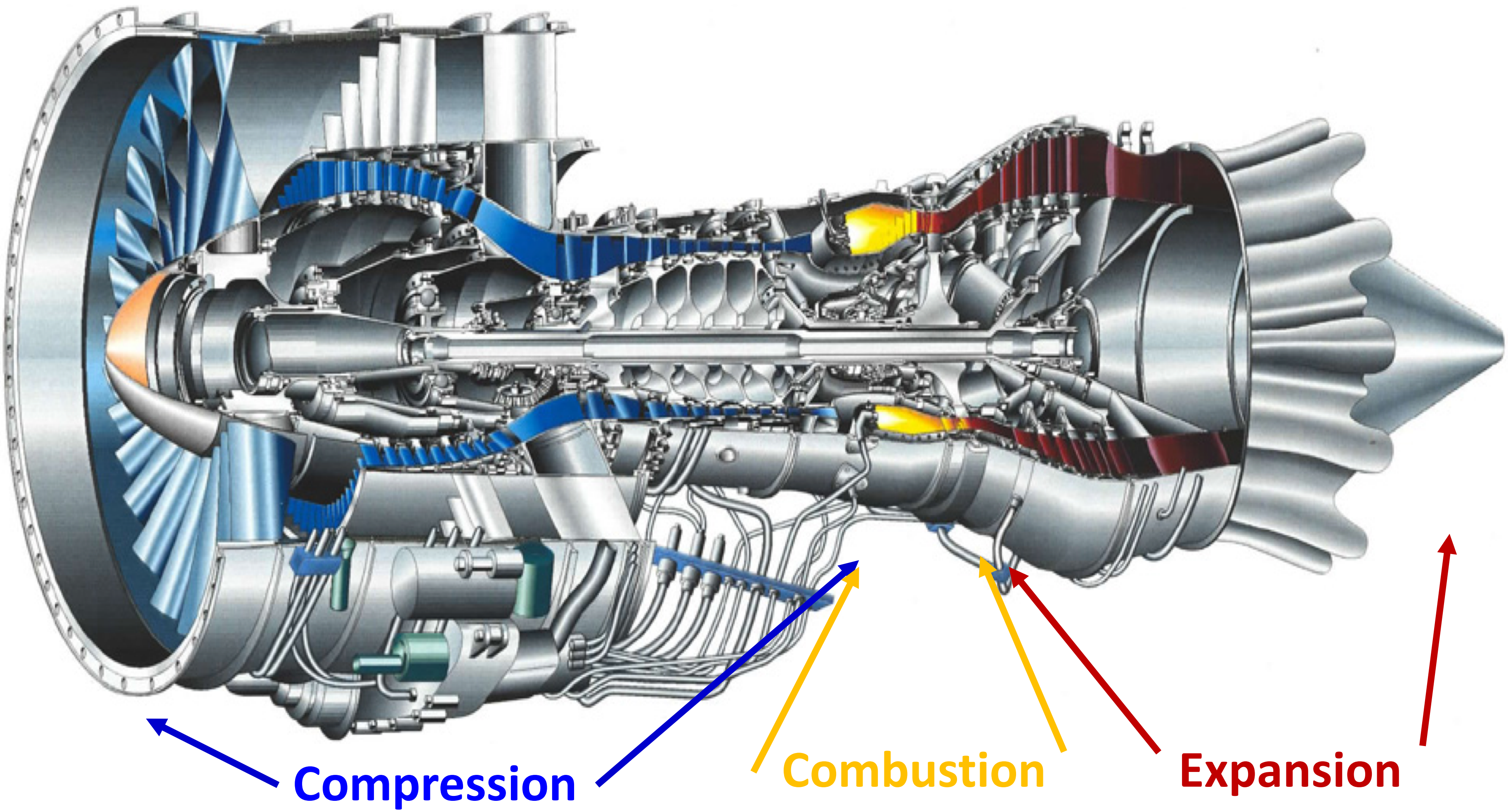
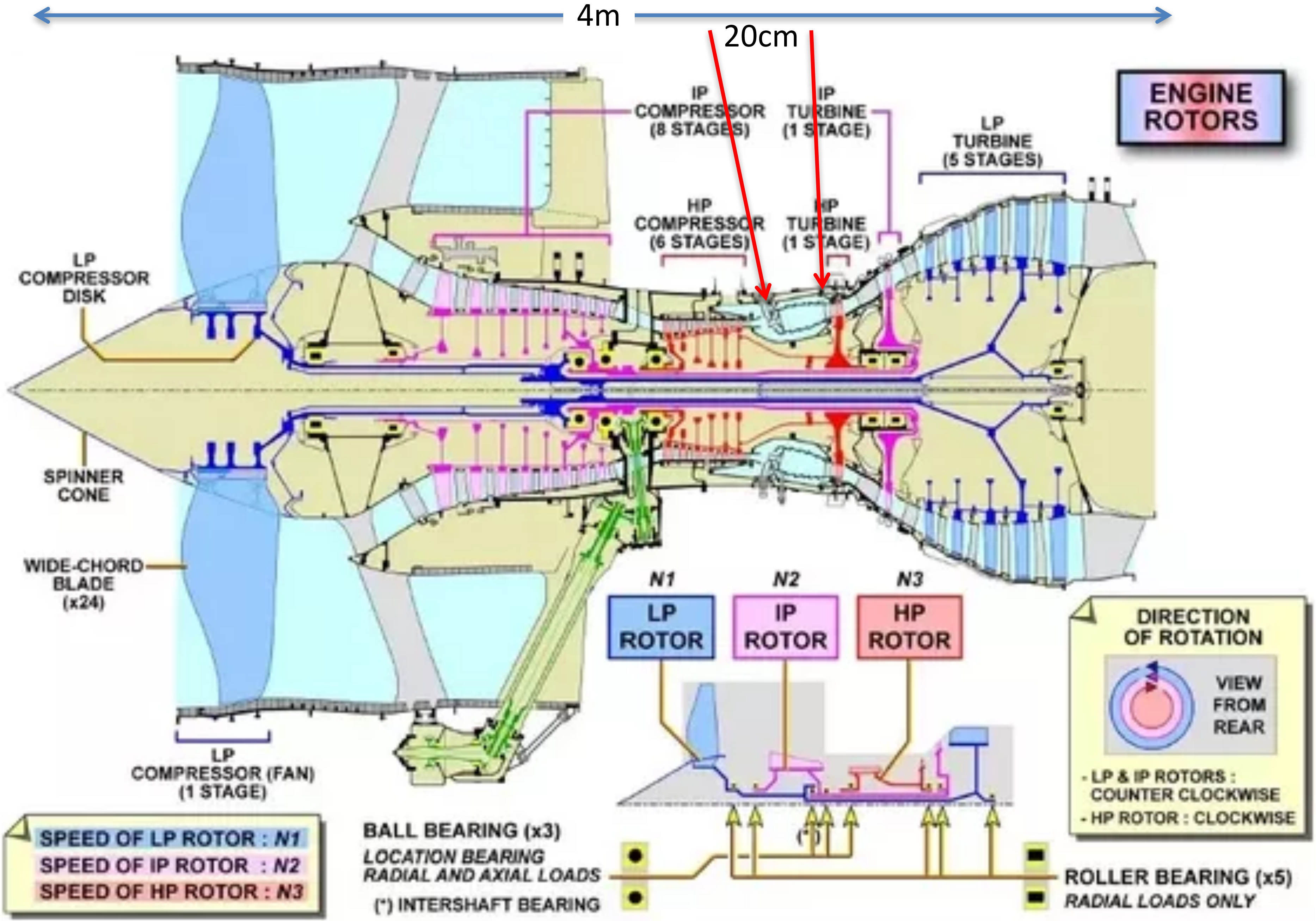
Lecture 21-22

Intro to Combustors, Combustion Thermodynamics

Cutaway of a Turbofan Engine

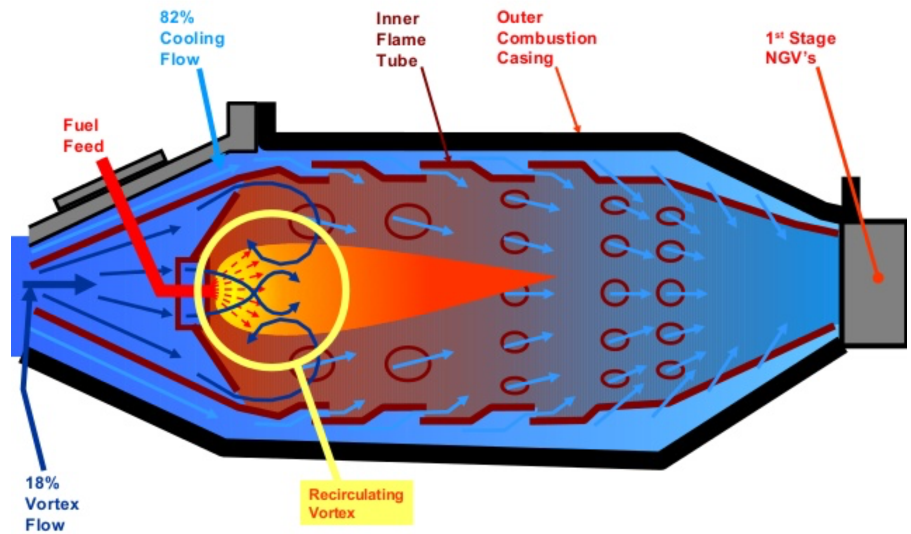


Combustors occupy a small fraction of the whole engine



Combustor Operation
Highly Non-Equilibrium, Dynamic Process

There is a lot happening in a very confined space



JET ENGINE – Combustion Process

fuel injection → atomization → vaporization → swirling/recirculation/mixing → ignition → combustion → <u>dilution</u> → flow adjustment

Combustor Design/Engineering/Physics

Requirements

- Output/ Efficiency
- Emission Control
- Fuel Flexibility
- Cost
- Size/Weig ht

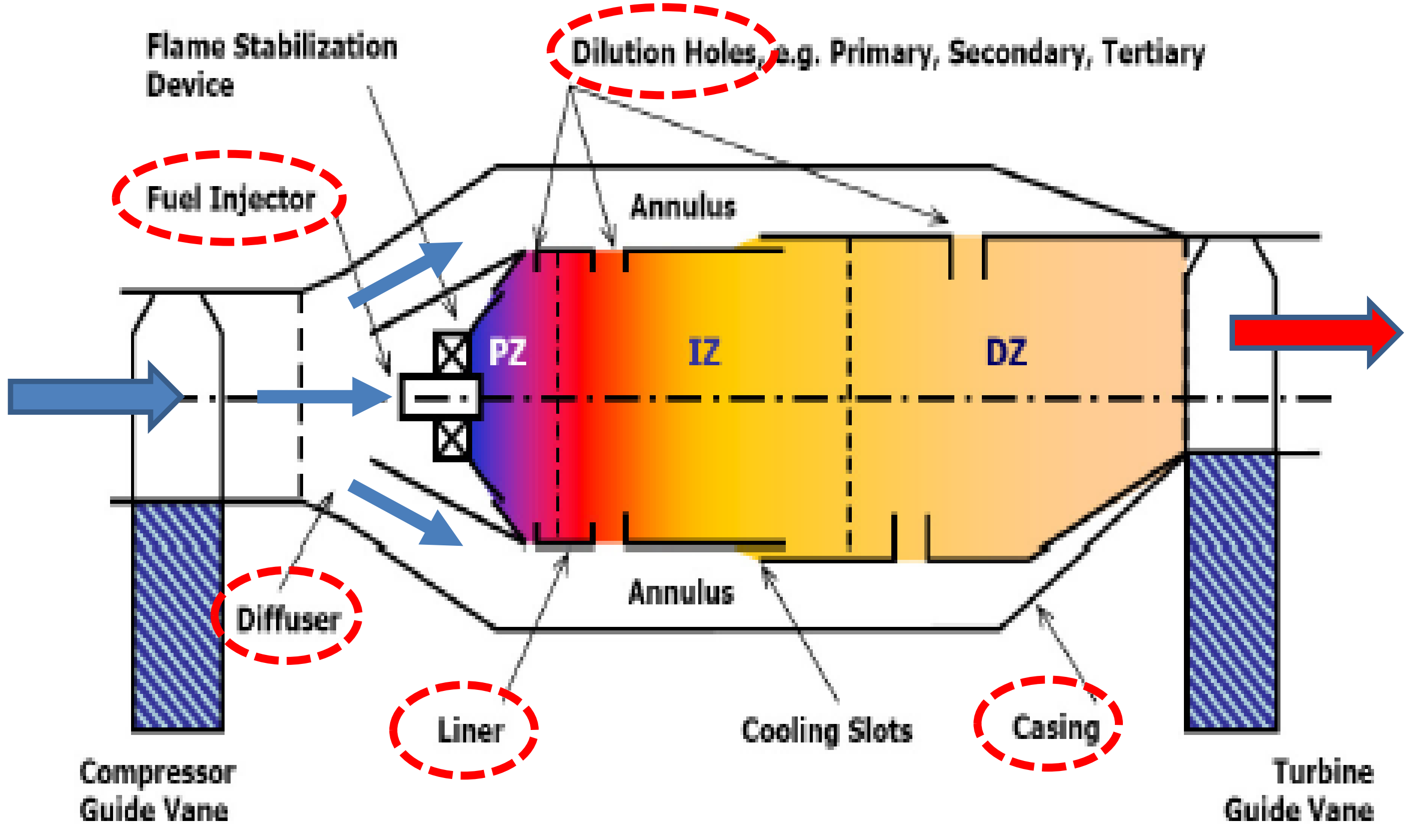
Practical Challenges

- Atomization
- Vaporization
- Mixing
- Ignition
- Flame Anchoring
- Instabilities
- Materials

Phenomena

- Multi-Phase Flow Dynamics
- Combusti on
- Thermo-Dynamics
- Chemical Kinetics
- Heat Transfer

Schematic of a Typical Combustion "Can"



•Guide vanes

•Diffuser

•Annulus(source of cooling and dilution air)

•Combustion Chamber

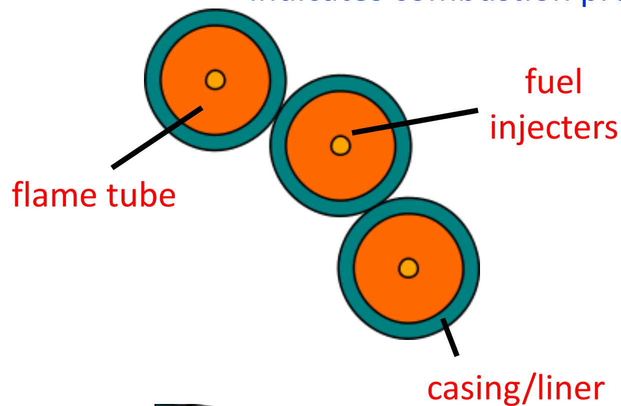
–primary zone (allows for mixing and atomization)

–secondary/intermediate zone allows for complete combustion)

–tertiary/dilution zone(reduces temperature at outlet, with impact on emissions)

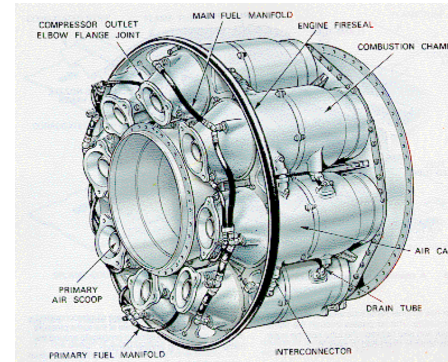
Gas Turbine Combustor Types

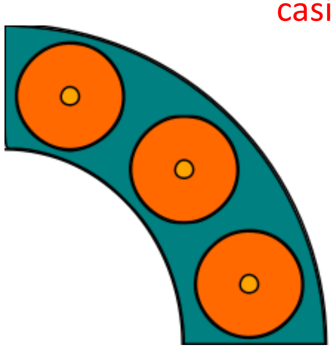
(looking axis on, through the exhaust, green indicates cooling flow path; orange indicates combustion product flow path)



Can-type combustor

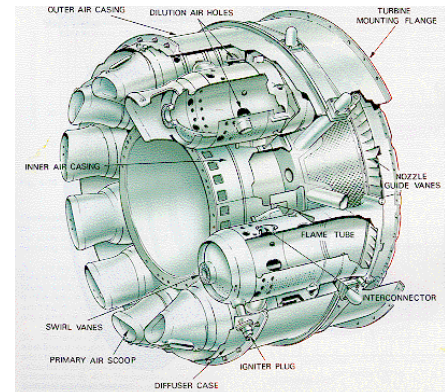
(mostly centrifugal machines; no longer used much in aircraft)

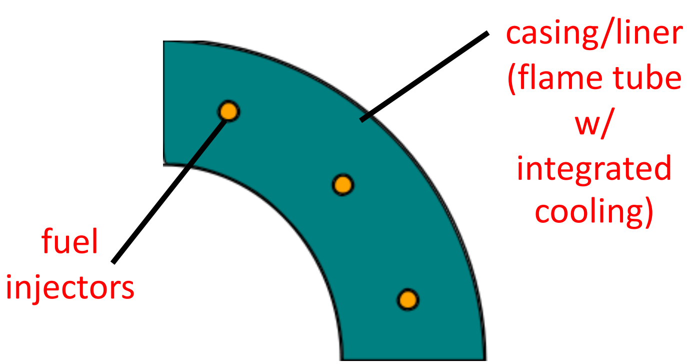




can-annular combustor

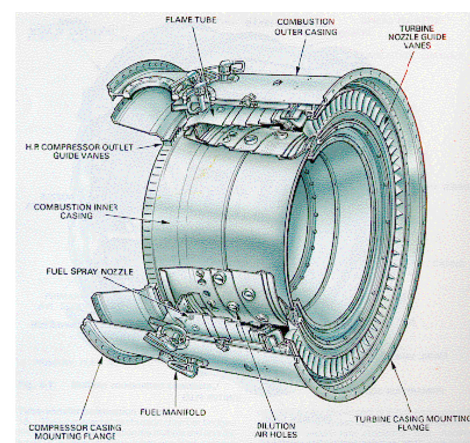
(single casing for all cans)





annular combustor

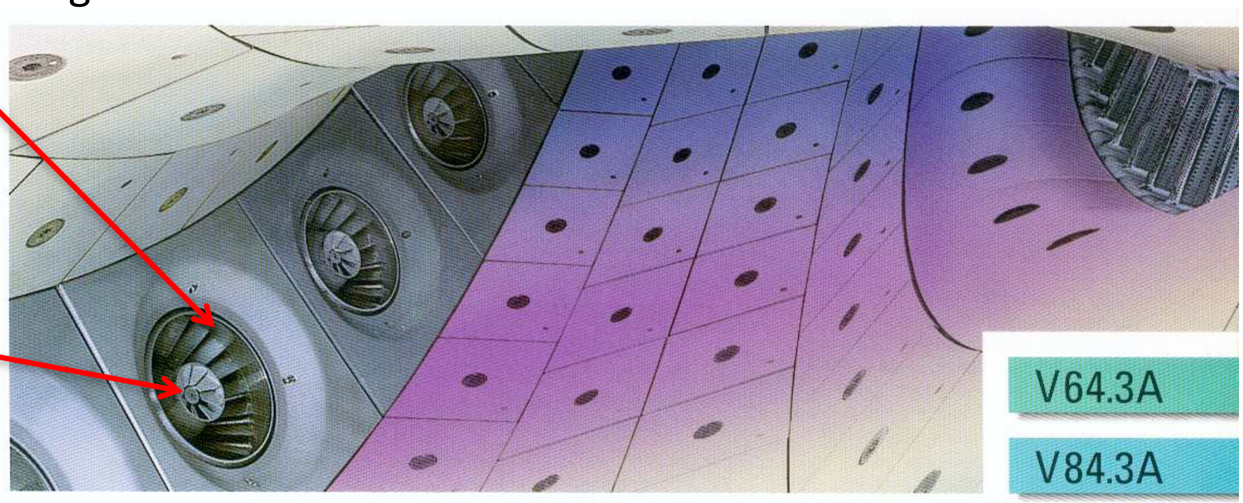
(open, no cans)



Combustor Interior

Swirl Inducing Vanes

Fuel
Injection



- Air flow through the combustor is divided into primary and secondary paths.
- 25 to 35 % of the incoming air is primary.
- 65 to 75 % of the incoming air is secondary.
- Primary or combustion air is directed inside the liner, passing through a set of swirl vanes which give the air a radial motion.
- As air is swirled the speed is reduced to about 2-3 m/s.
- Its important to slow the air to prevent flameout.

COMBUSTOR REQUIREMENTS

- Complete combustion ($\eta_b \rightarrow 1$)
- Low pressure loss ($\pi_b \rightarrow 1$)
- Reliable and stable ignition
- No flameouts - Flame stays lit over wide range of p, u, f/a ratio)
- Freedom from combustion instabilities
- Tailored temperature distribution into turbine with no hot spots
- Low emissions - Smoke (soot), unburnt hydrocarbons, NOx, SOx, CO
- Effective cooling of surfaces
- Low stressed structures, durability
- Small size and weight
- Design for minimum cost and maintenance
- Multiple fuel capability

Reference D.A. Kirk FIT Lecture MA5310

COMBUSTOR ANALYSIS

- Enthalpy rise across combustor = energy input from combustion
- Combustion efficiency, η_b = Actual Enthalpy Rise / Ideal Enthalpy Rise

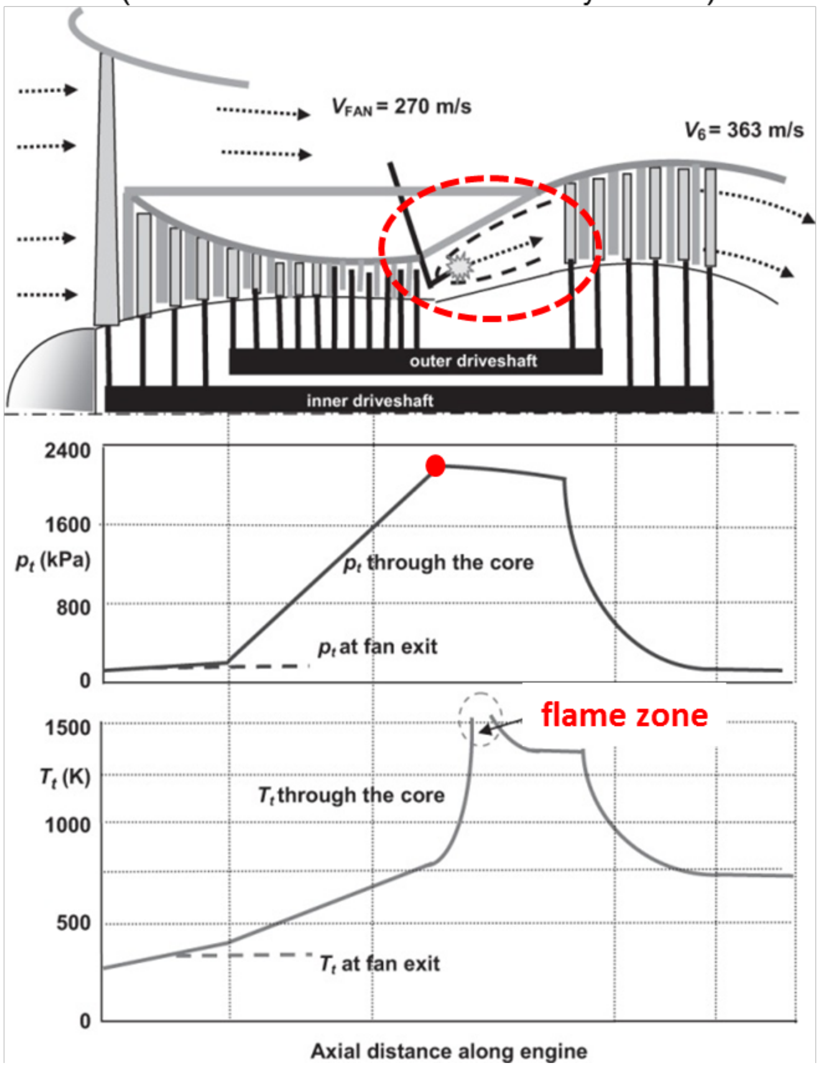
$$\eta_b = \frac{\bar{c}_P\left[\left(\dot{m}_a + \dot{m}_f\right)T_{04} - \dot{m}_a T_{03}\right]}{\dot{m}_f Qr}$$

- General Observations:
  1. $\eta_b \downarrow$ as p $\downarrow$ and T $\downarrow$ (because of dependency of reaction rate)
  2. $\eta_b \downarrow$ as Mach number $\uparrow$ (decrease in residence time)
  3. $\eta_b \downarrow$ as fuel/air ratio $\downarrow$
- Assuming that the fuel-to-air ratio is small

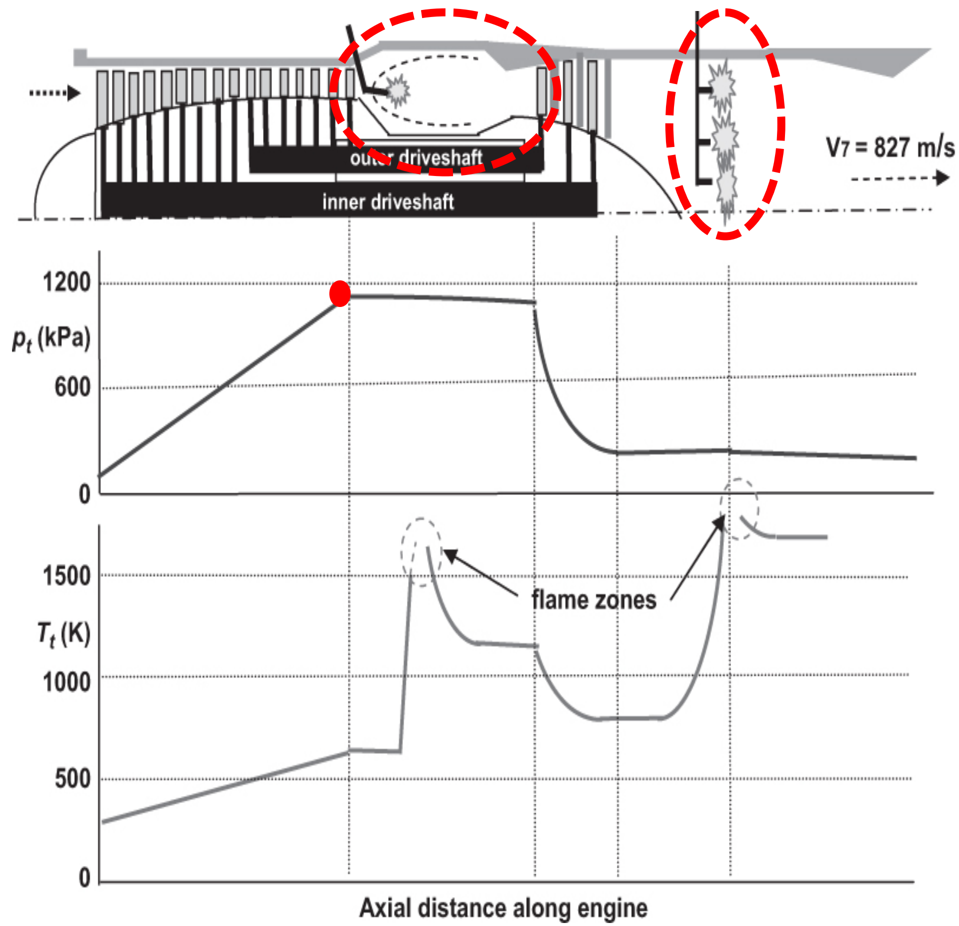
$$f \approx \frac{\bar{c}_P}{\eta_b Q_R}\left(T_{04} - T_{03}\right)$$

Axial Variation in Flow Properties

Dual-shaft, unmixed
high bypass turbofan
(similar to the Pratt & Whitney JT-9D)

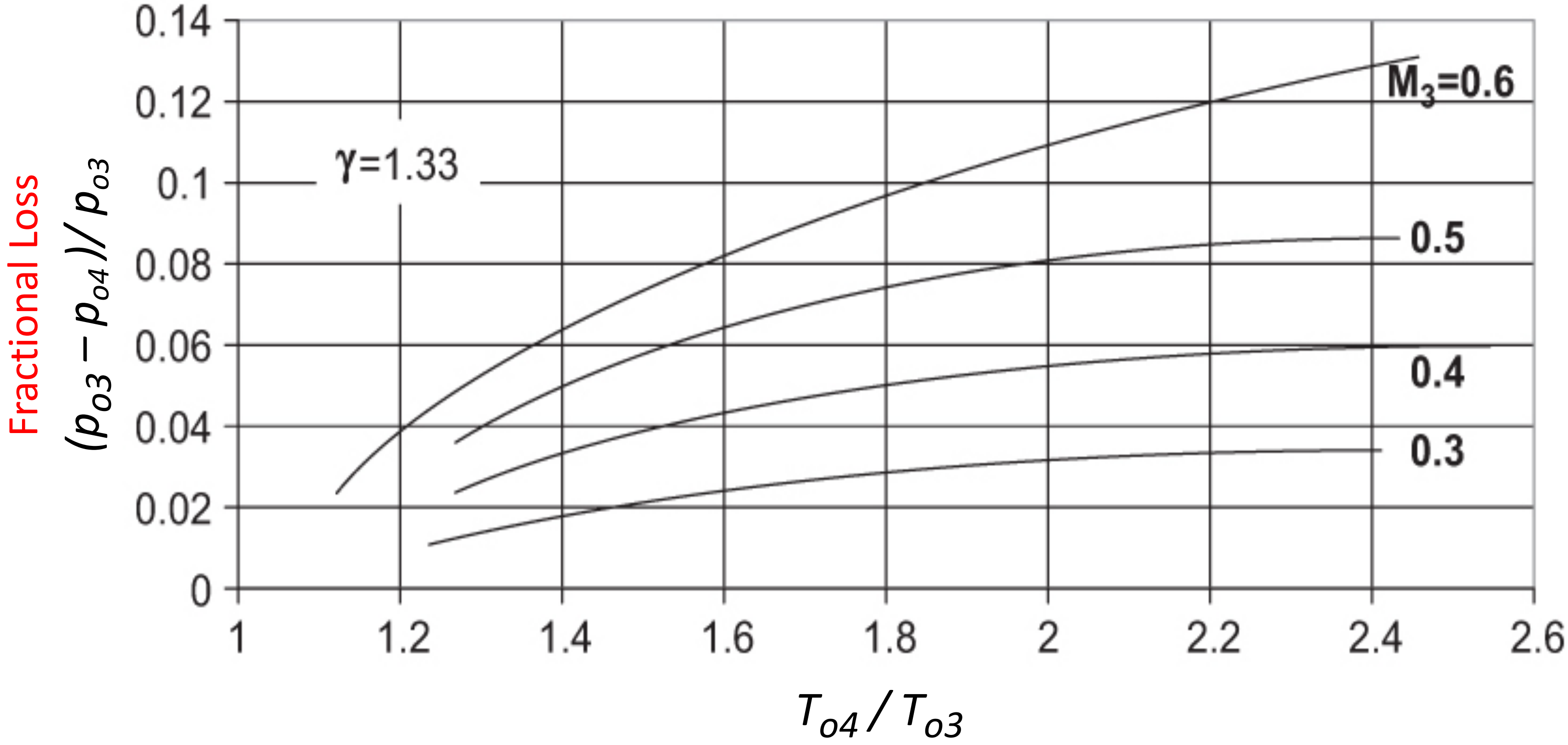


Dual-shaft
afterburning turbojet
(similar to the Pratt & Whitney J57-P-23)



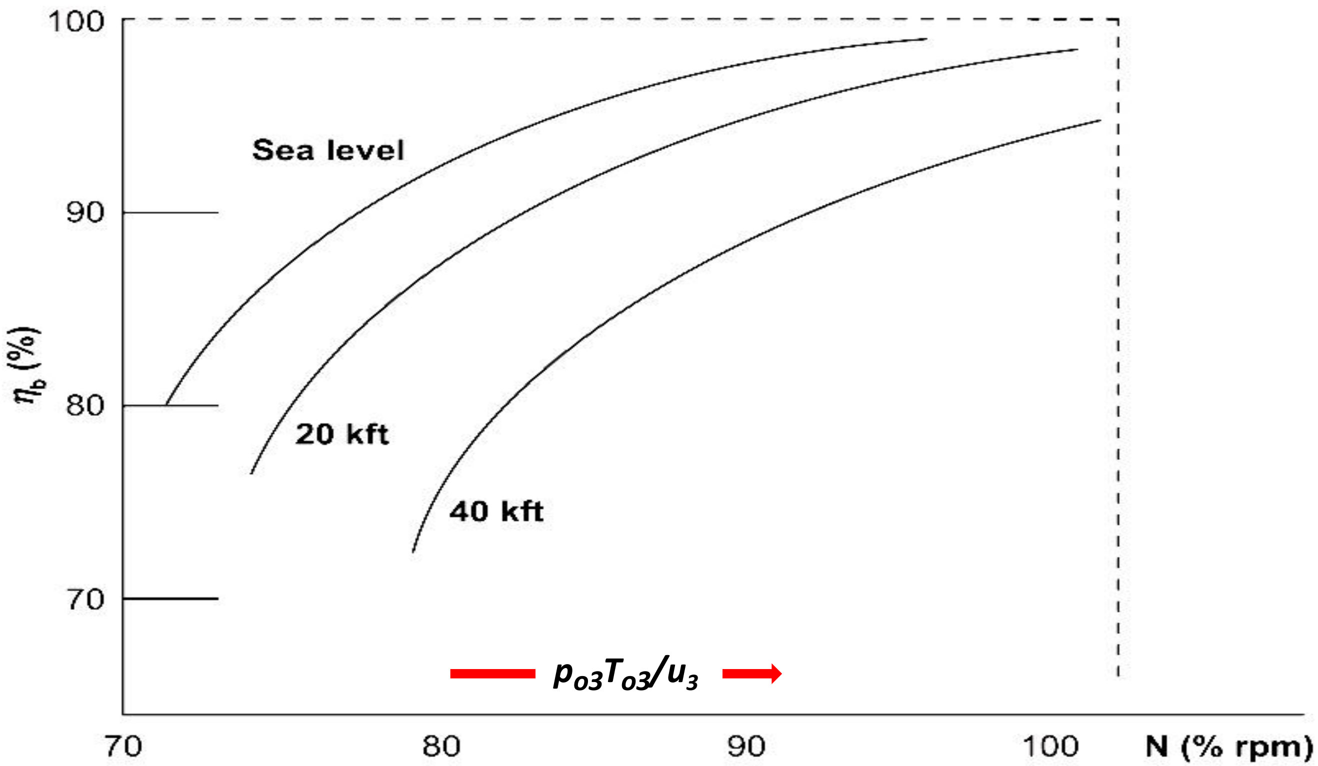
Stagnation Pressure Losses

Fractional loss of stagnation pressure across a constant area combustor as a function of burner stagnation temperature ratio for a constant γ of 1.33.



- Keep the speeds in the combustion chamber low
- Limit T04, i.e., burn away from stoichiometry

Effect of altitude and engine RPM on burner efficiency



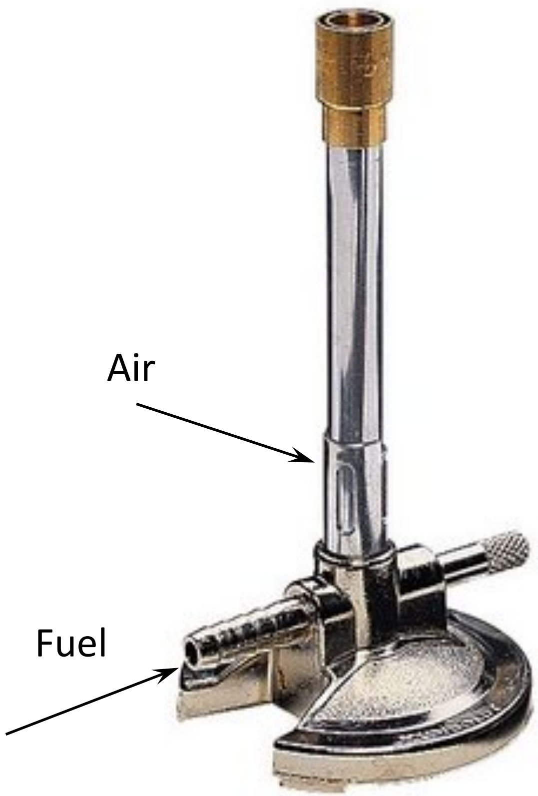
- The parameter $p_{o3}T_{o3}/u_3$ best describes good combustion performance, i.e.,
  - high inlet pressure
    - high inlet temperature
      - low *u* for long residence time (time for atomization, mixing, etc.)
- At altitude, fixed pressure ratio means lower combustor inlet *p* and *T*
- At part load, compressor pressure ratio is reduced, with the same effect

COMBUSTION MODES AND FLAME TYPES

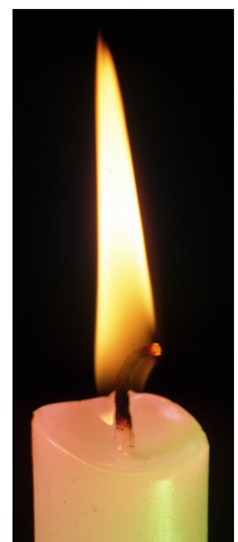
- Combustion can occur in flame mode
  - **Premixed** flames
  - **Diffusion** (non-premixed) flames
- Combustion can occur in non-flame mode (coal burning)
- What is a flame?
  - A flame is a self-sustaining propagation of a localized combustion zone at subsonic velocities
- Laminar vs. Turbulent Flames: both have same type of physical process and many turbulent flame theories are based on an underlying laminar flame structure

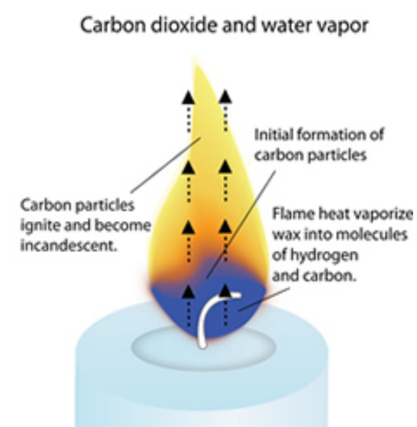
Flame Types: Pre-mixed and Diffusion

- Premixed: Fuel and oxidizer mixed at molecular level prior to occurrence of any significant chemical reaction



- Diffusion: Reactants are initially separated, and reaction occurs only at interface between fuel and oxidizer (mixing and reaction taking place)
- In turbulent diffusion flames, turbulent convection mixes fuel and air macroscopically, then molecular mixing completes the process so that chemical reactions can take place





Typically combustion in gas turbines is a combination of the two

FLAME OUT

- Flameout is uncommon in modern engine but the correct set of circumstances can cause engine die out.
- High air flow rate or very low airflow can extinguish the combustion flame.
- Turbulent weather, high altitude, slow acceleration, and high speed maneuvers can induce a flameout.
- Lean die-out occurs at high altitude where low engine speeds and low fuel pressure form a weak flame that can die out in normal airflow.
- Rich die-out occurs during rapid engine acceleration when an overly rich mixture causes the fuel temperature to drop below the combustion temperature or when there is insufficient airflow to support combustion.

Two conflicting requirements for f/a ratio

- Gas turbine can **<u>NOT</u>** operate at (or even near stoichiometric levels
  - Temperatures associated with stoichiometric combustion are too hot for turbine
  - Limited T_{04} implies roughly $\phi < 0.5$ (fuel-equivalency ratio)
- Most mixtures will **<u>NOT</u>** burn so far away from stoichiometric
  - Often called **<u>Flammability Limit</u>**
  - Highly pressure dependent
- Increased pressure, increased flammability lin
  - Requirements for combustion, roughly $\phi > 0.8$
- **What do we do?**
  - Burn (keep combustion going) near ϕ=1 with some of compressor exit air
  - Then mix very hot gases with remaining air to lower temperature for turbine

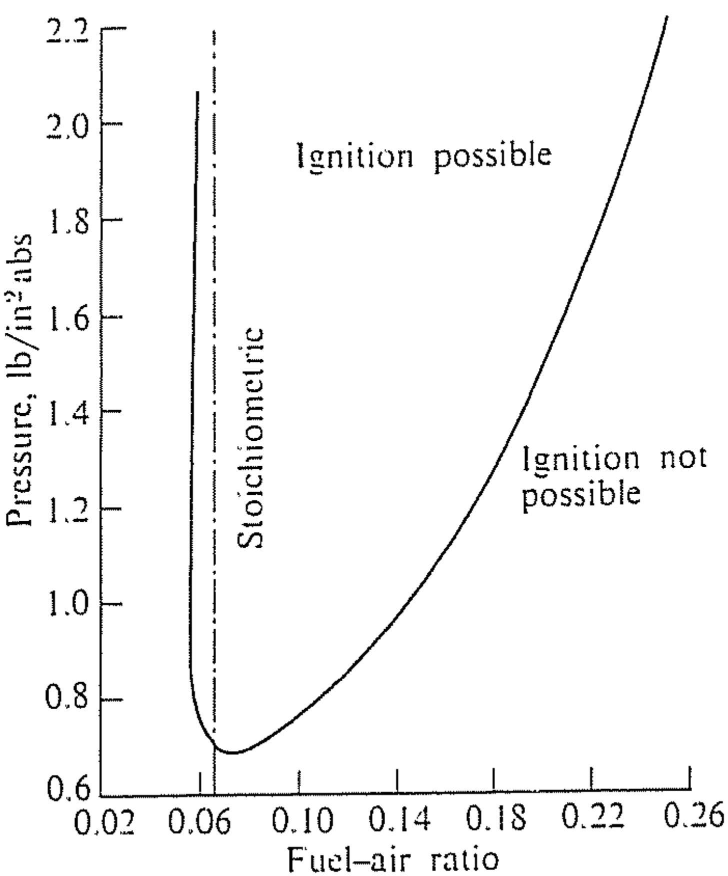
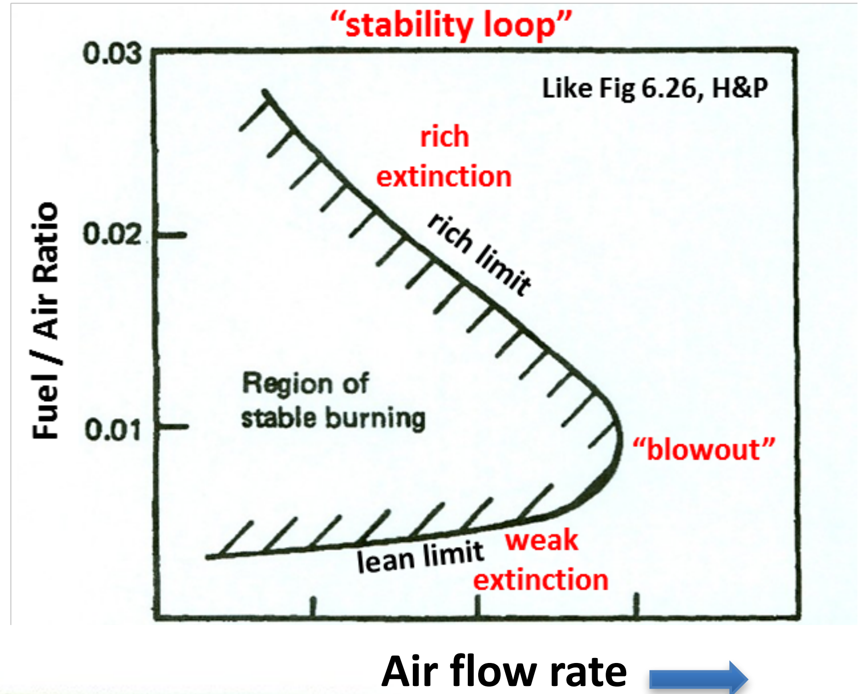
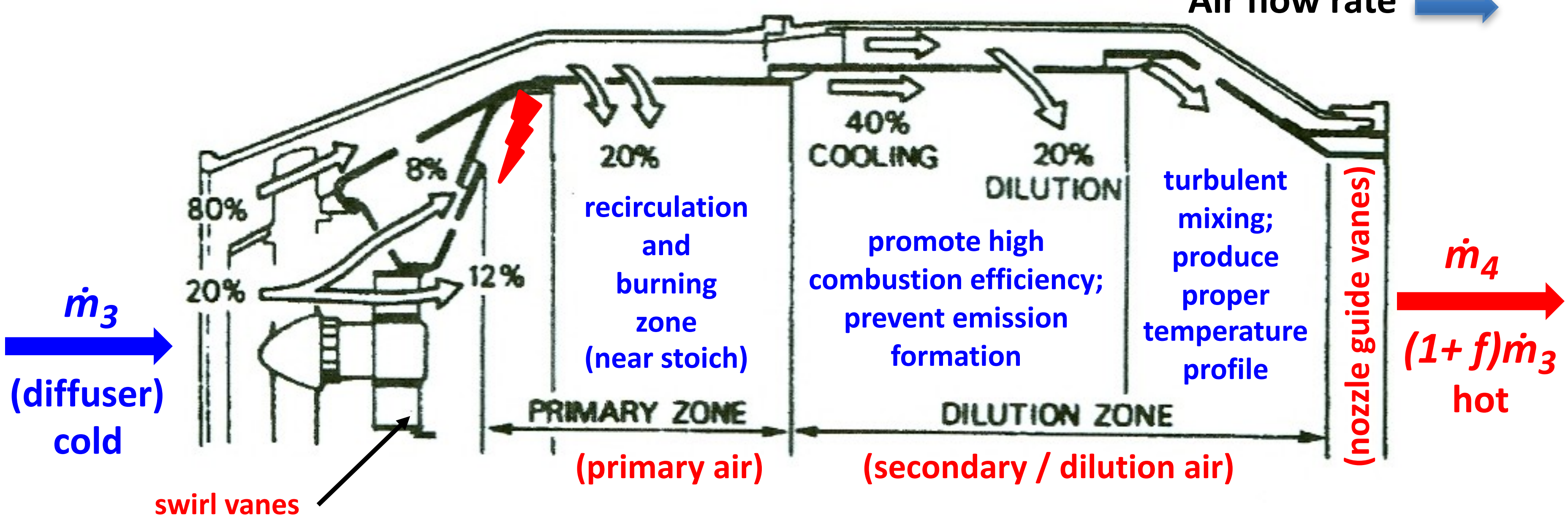


FIG. 7–24. Inflammability limits of gasoline–air mixtures. (Courtesy Olson, *et al.* [18].)

Distribution of Air in a Typical Can Combustor

Excess air for temperature (and emissions) control is absolutely essential for successful engine operation but flame stability has a very narrow range of flow rate requirement





CHEMISTRY REVIEW

- General hydrocarbon, C_nH_m (Jet fuel H/C~2)
- Complete oxidation, hydrocarbon goes to CO_2 and water
- For air-breathing applications, hydrocarbon is burned in air
- Air modeled as 20.9 % O_2 and 79.1 % N_2 (neglect trace species)
- Complete combustion for hydrocarbons means all C $\rightarrow$ CO_2 and all H $\rightarrow$ H_2O

$$C_nH_m + \left(n + \frac{m}{4}\right)\left(O_2 + 3.78N_2\right) \rightarrow nCO_2 + \frac{m}{2}H_2O + 3.78\left(n + \frac{m}{4}\right)N_2$$

Stoichiometric Mass fuel/air ratio

$$\boxed{\psi_s = \frac{(12n + m)}{\left(n + \frac{m}{4}\right)\left(32 + 3.78(28)\right)}}$$

Combustion with Dissociation

Without Dissociation

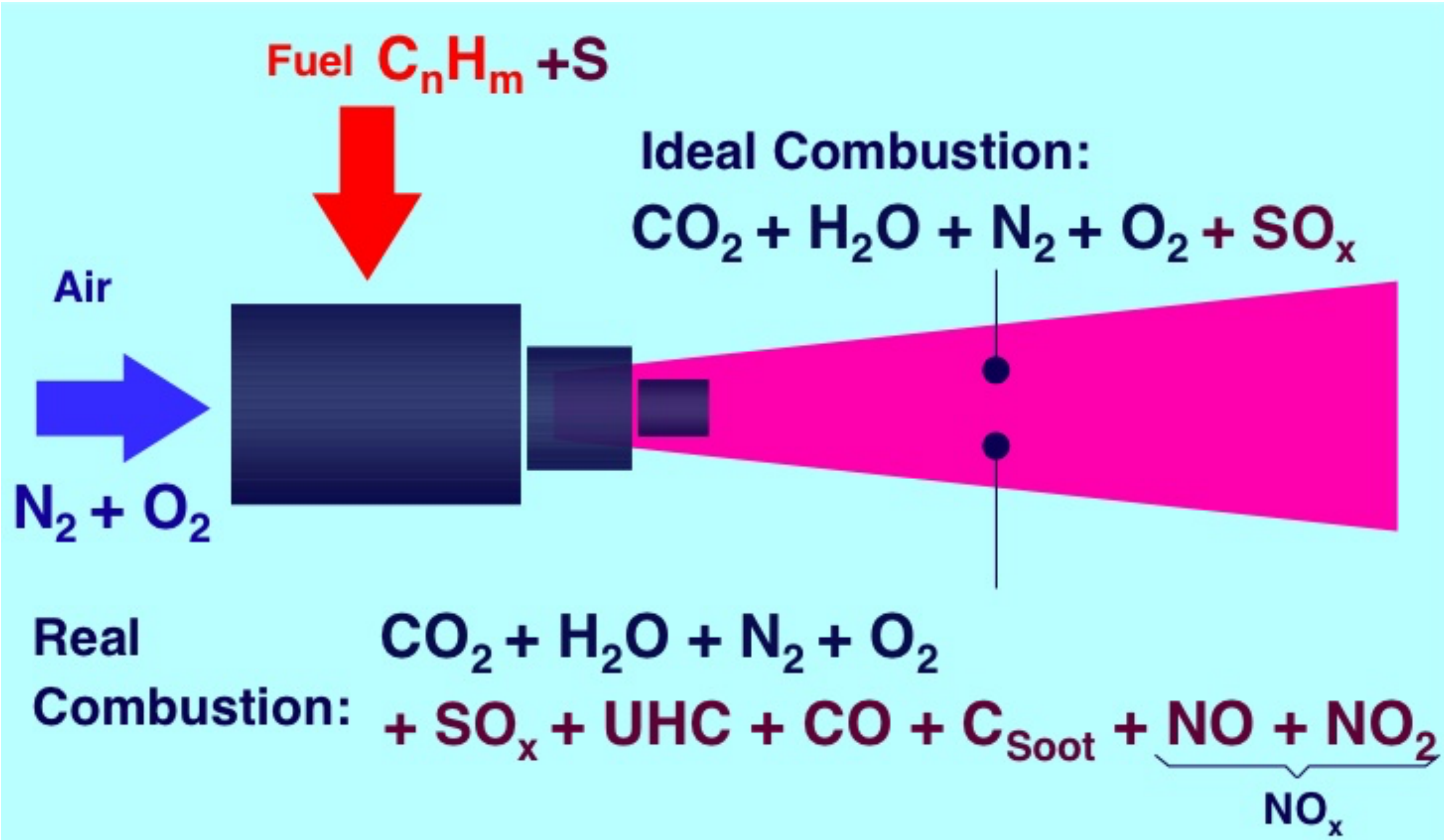
$$\phi H_2 + \frac{1}{2}\left[O_2 + \frac{79}{21}N_2\right] \rightarrow \phi H_2O + \frac{1}{2}(1-\phi)O_2 + \frac{1}{2}\frac{79}{21}N_2$$

With equilibrium dissociation: When the molecules break up and recombine into other species

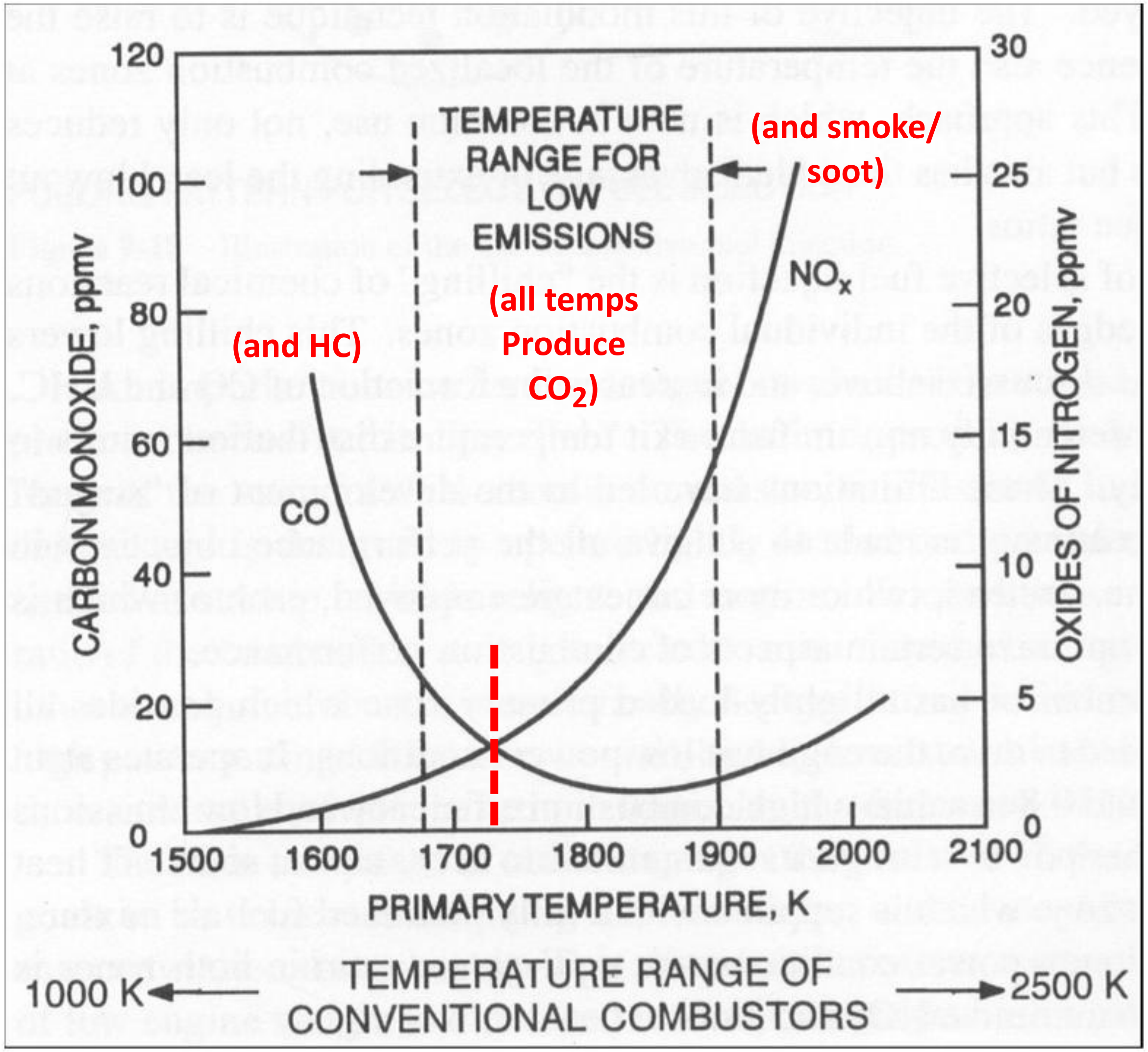
$$\phi H_2 + \frac{1}{2}\left[O_2 + \frac{79}{21}N_2\right]$$
$$\rightarrow n_{H_2O}H_2O + n_{N_2}N_2 + n_{O_2}O_2 + n_{H_2}H_2 + n_H H + n_O O$$
$$+ n_{OH}OH + n_{HO_2}HO_2 + n_{H_2O_2}H_2O_2 + n_{NO_2}NO_2 + etc.$$

Need to solve for transport of every possible species

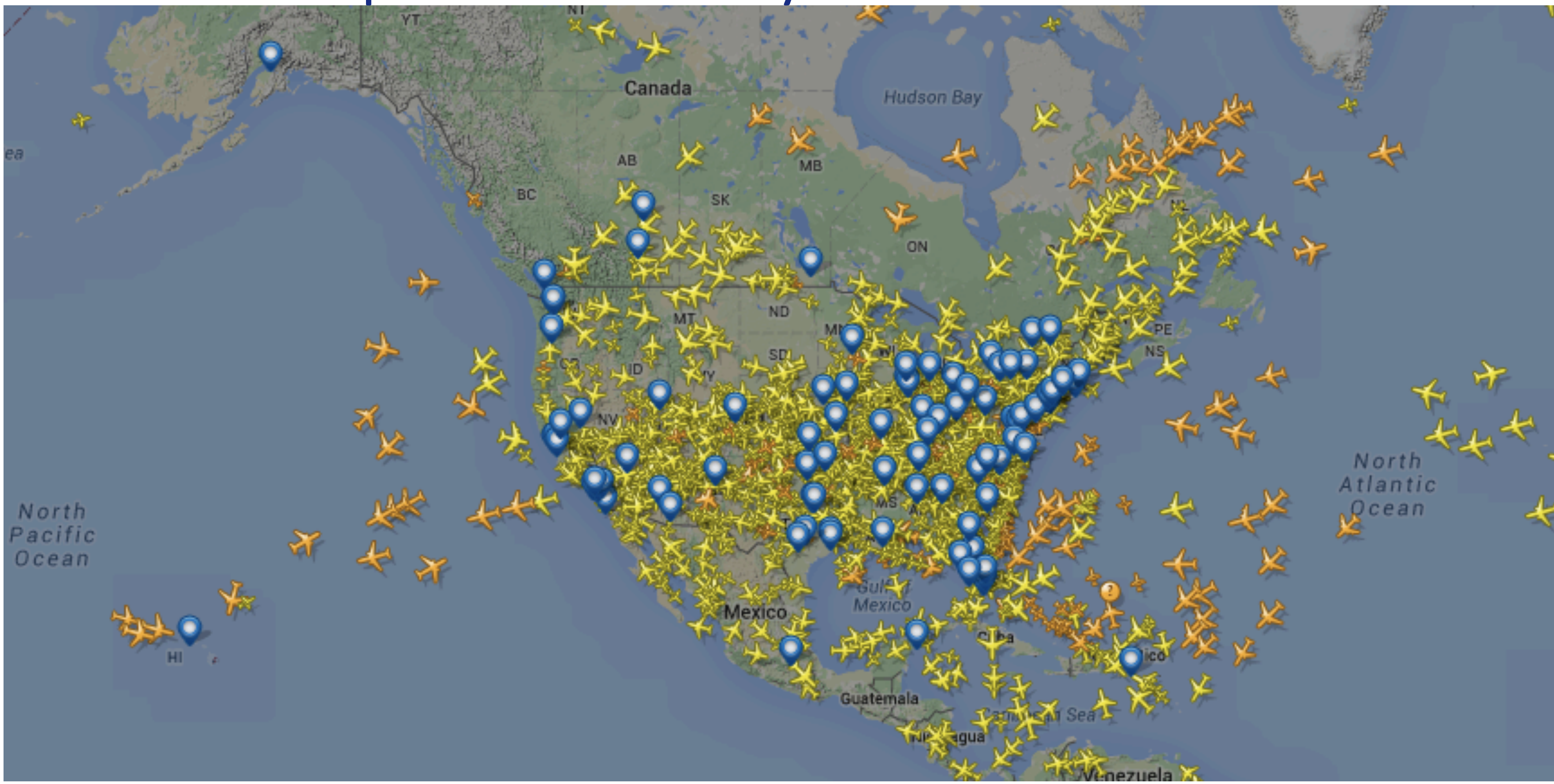
CHEMICAL EMISSIONS



Gas Turbine Emissions



Instantaneous Snapshot of number of planes in the sky over the US



So aircraft emissions are not insignificant, due to the sheer volume of flights

Complexity of combustion models

Aspects of Combustion Modeling