Lecture 11.

Turbulent Combustion in Gas Turbine Engines

Content

- Development of gas turbine
- Types of gas turbines
- Gas turbine cycle
- Gas turbine combustor
- New gas turbine combustors for clean environment

History of gas turbine/jet propulsion engine

Hero of Alexandria, Egypt
130 BC

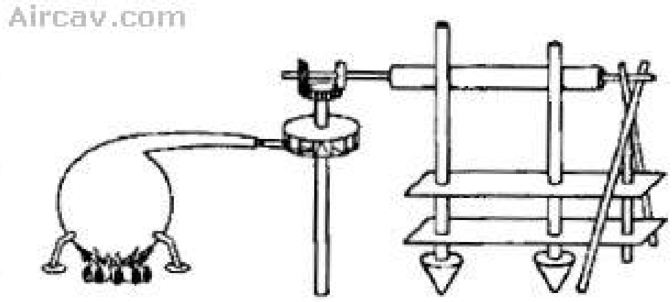
Hero's Aeolipile

Newton's Steam Wagon

Chinese solid fuel rocket, 1000 AD

Leonardo Da Vinci's chimney jack, 1500

Giovanni Branca, Italy, 1629



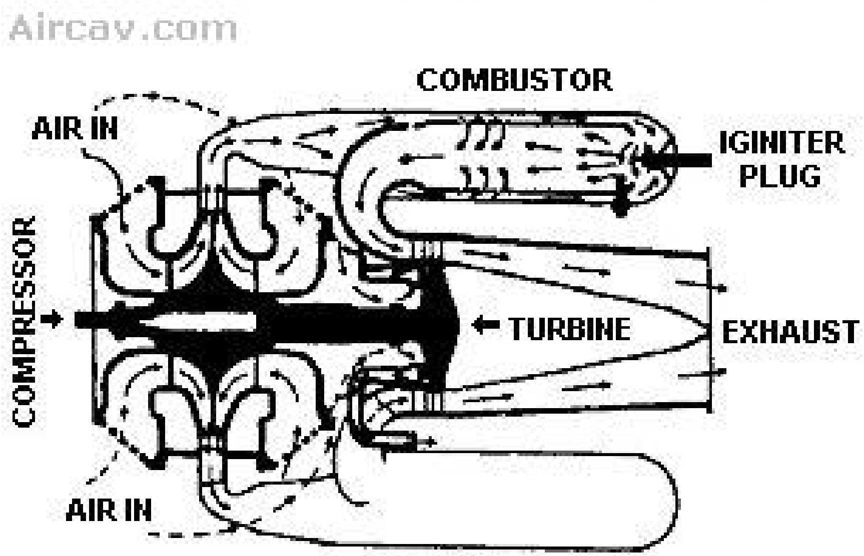
Branca's Jet Turbine

Isaac Newton's steam wagon, 1687

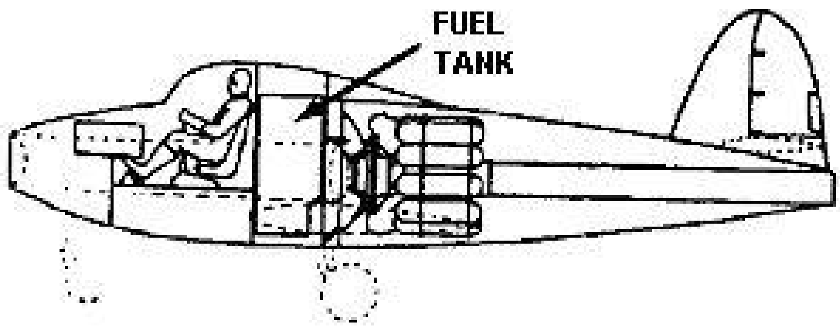
Johan Barber made first patent, 1791

Gas turbine for modern aviation

Frank Whittle, 1930, UK, submitted a patent for a gas turbine for jet propulsion
Power Jets Ltd got contract from Air Minsistry
In May 1941, the Whittle W1 engine made its first flight



Whittle's Reverse-Flow
Combustion Chamber



Fuselage Arrangement of the
E28/39 Experimental

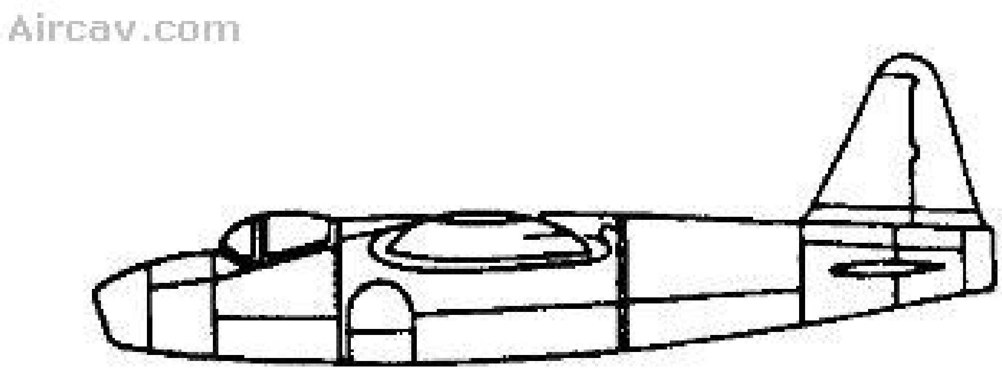
Gas turbine for modern aviation

Gloster Whittle E28

Gas turbine for modern aviation

Hans von Ohain and Max Hahn, 1936, Germany, submitted a patent for a gas turbine for jet propulsion

Ernst Heinkel Aircraft Company made first true jet propulsion aircraft in 1939, Aug - Sept



The German Heinkel HE-178

Secundo Campiri, Italy, made a gasturbine engine for the CC-2 aircraft, 1940

American (with the help of the British) made W.IX engine in 1941, GE

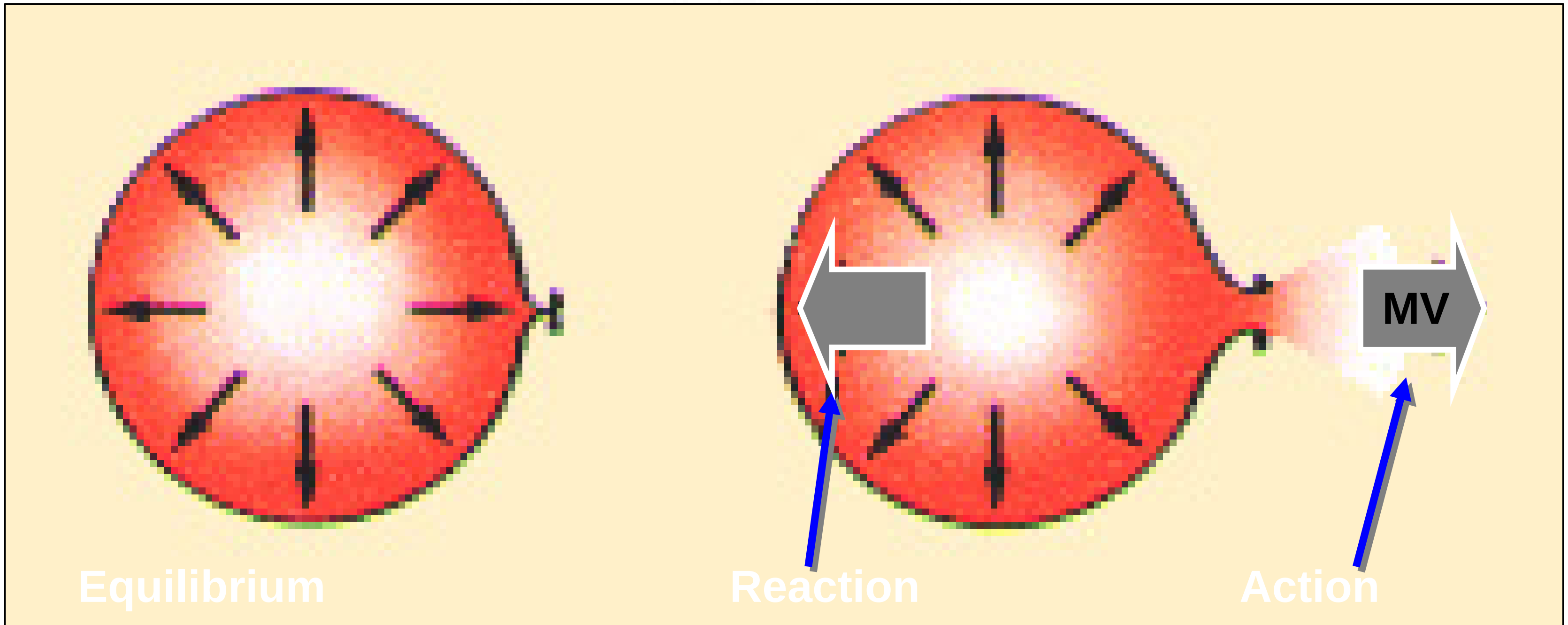
Later Westinghouse Corporation made contiuous development

Gas turbine for modern aviation

Rolls-Royce Today

- aero-engines
- marine propulsion systems
- energy business
- Annual sales of over £4.5 billion
- Orders of over £13 billion

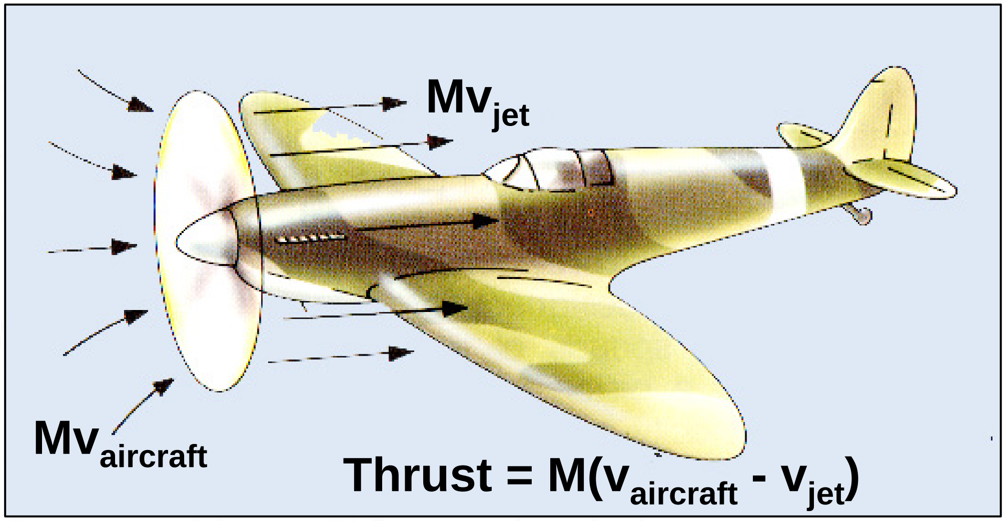
Newton’s 3rd Law: principle of propulsion

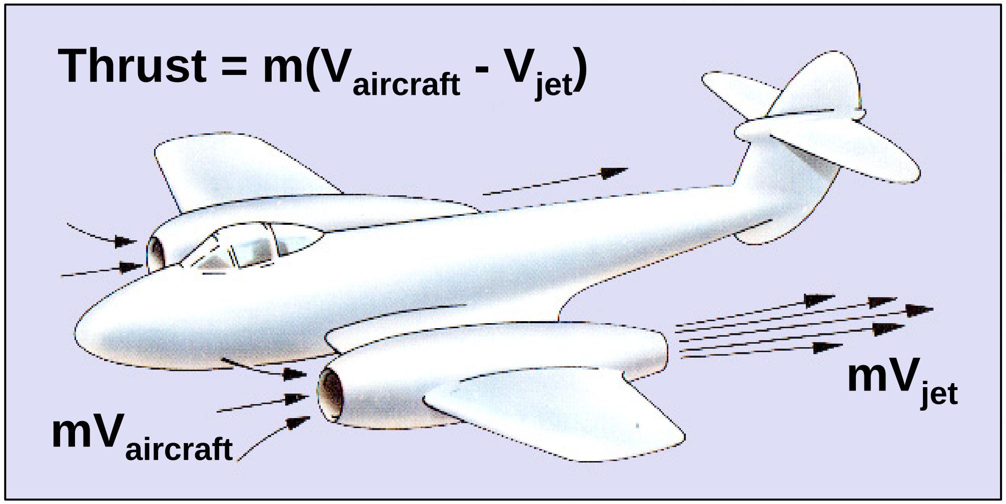


Thrust = Mass x Velocity (MV)

Propeller versus Jet Propulsion

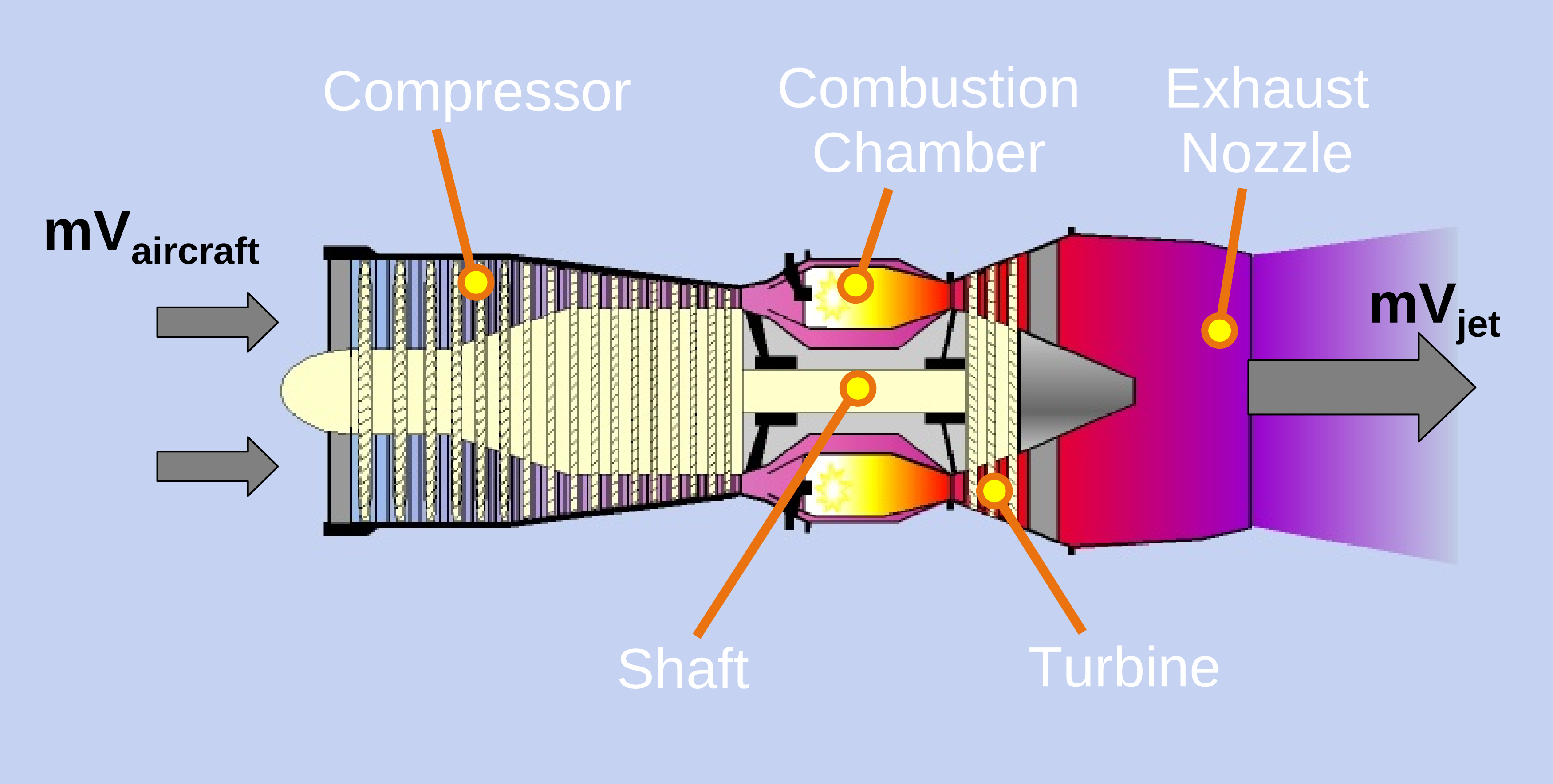
Propeller - moves LARGE MASS of air at low velocity





Jet - moves small mass of gas at HIGH VELOCITY

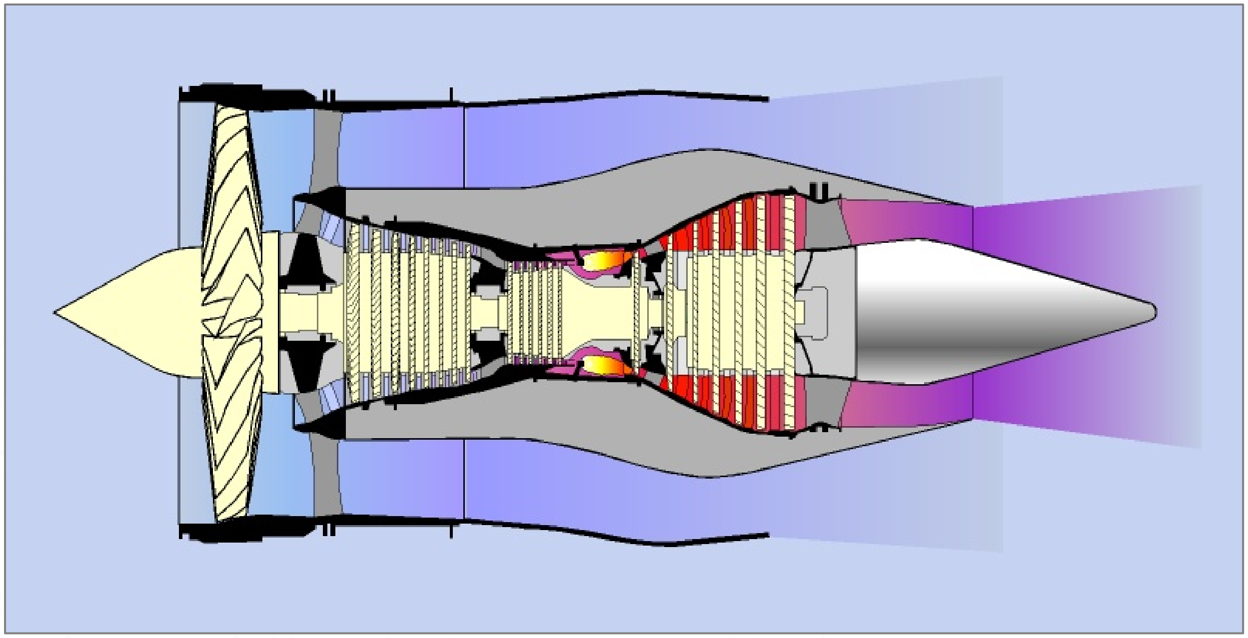
Jet Engine Layout



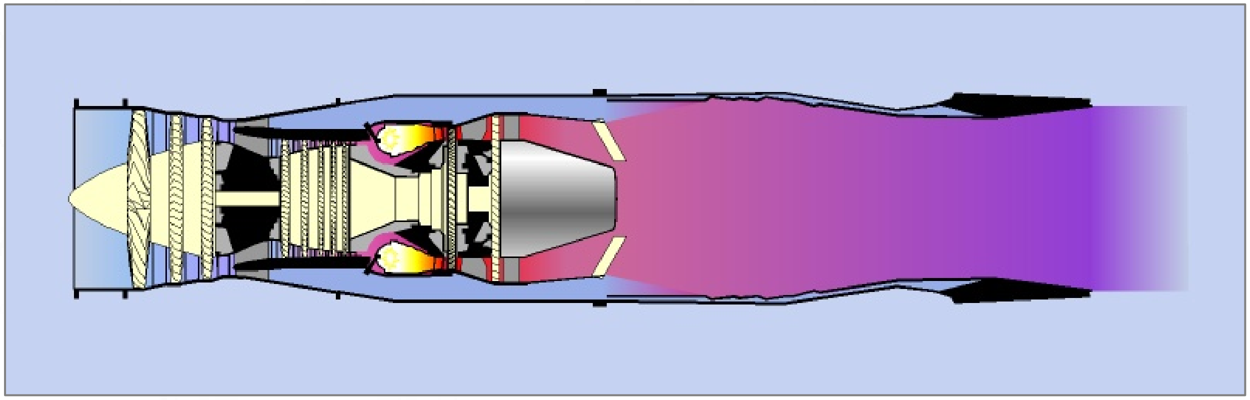
'Straight-through' configuration

Different Jet Engine Types

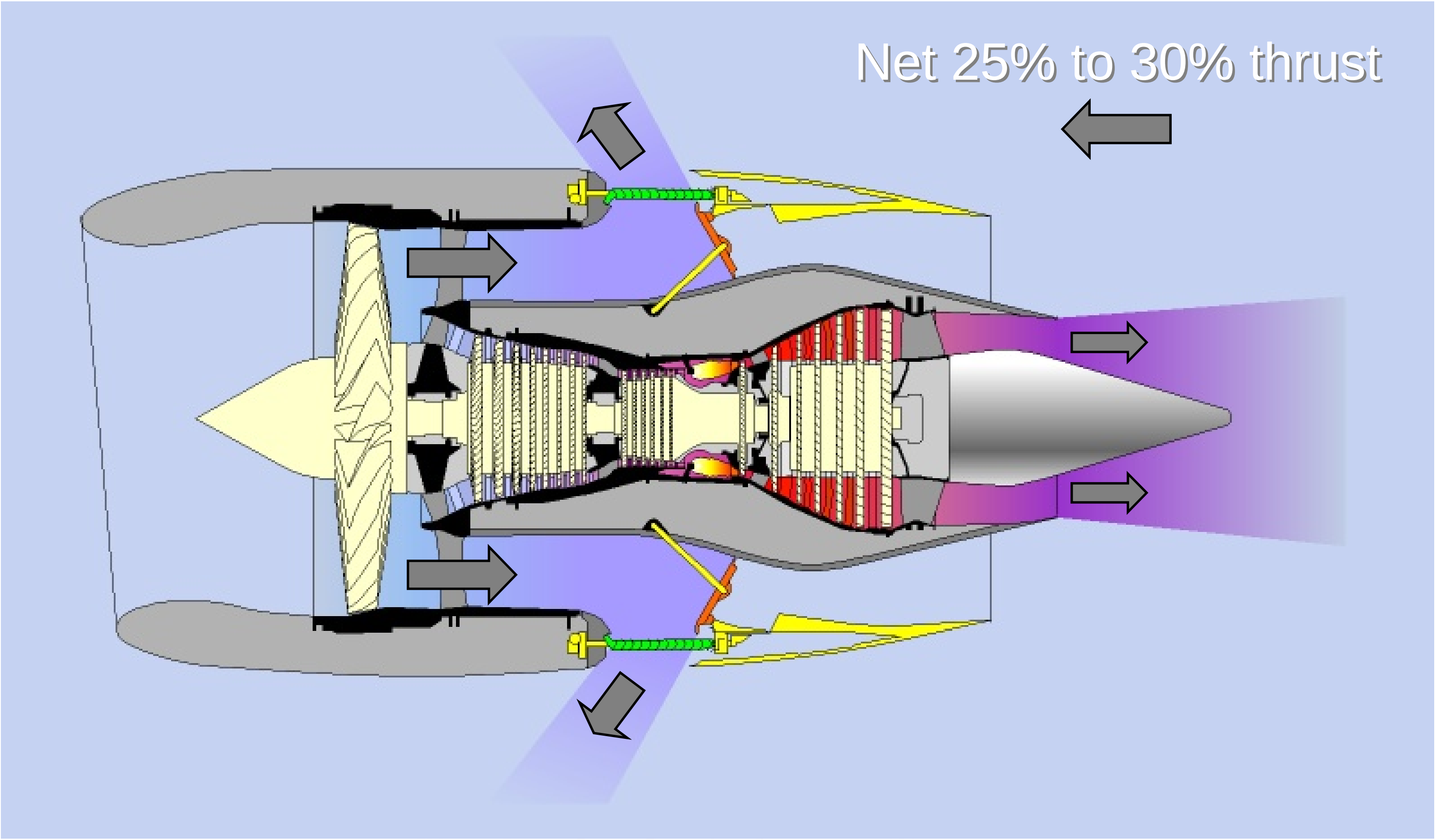
Civil turbofan - Trent



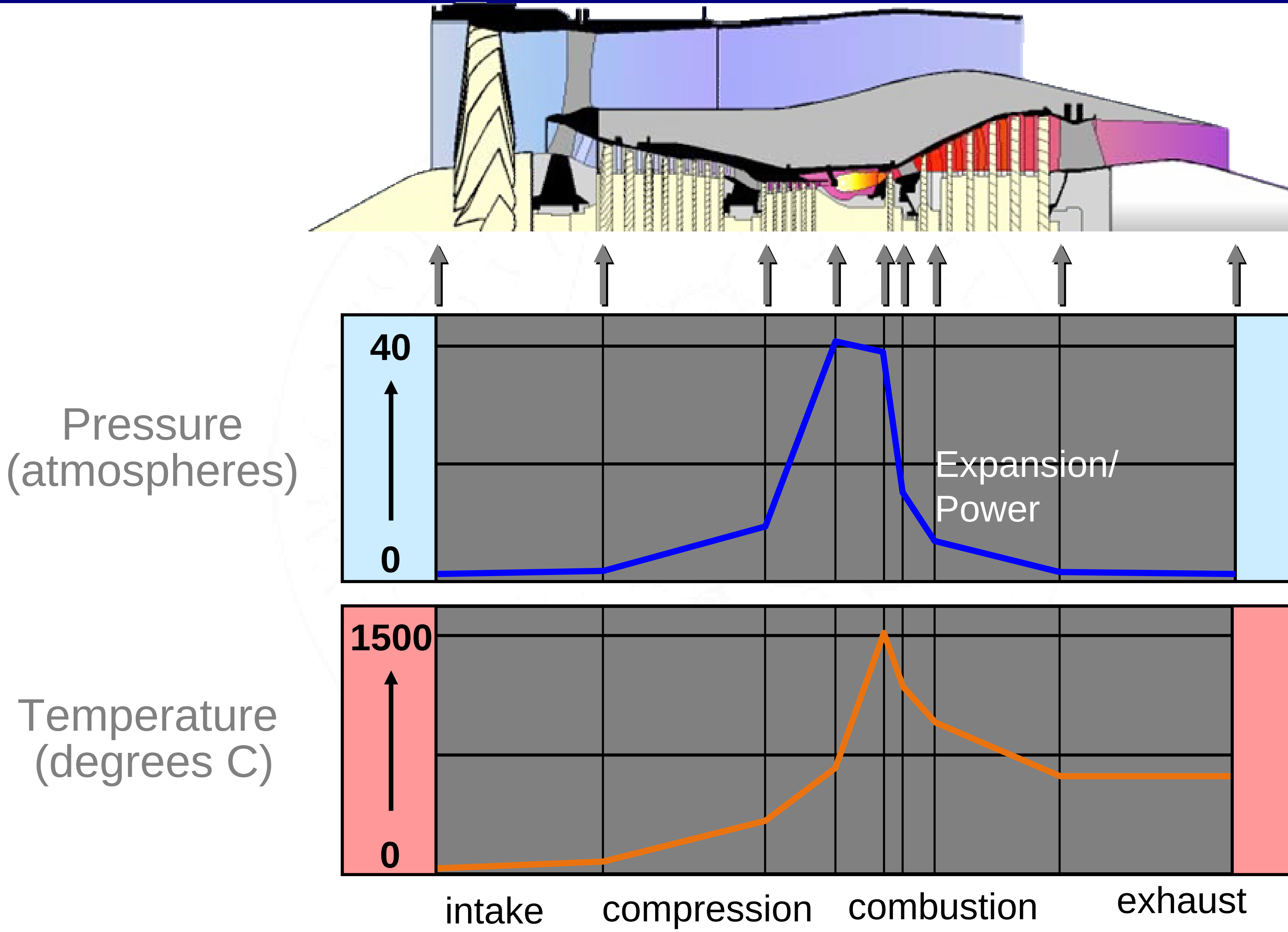
Military turbofan - EJ200



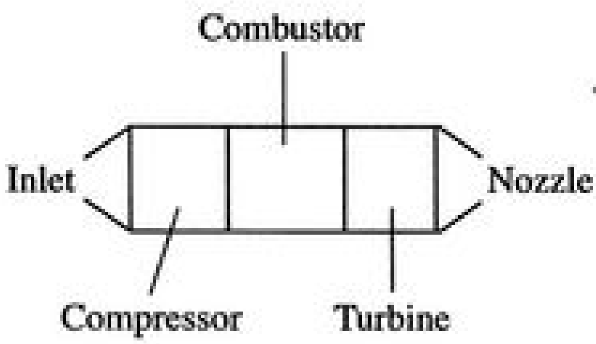
Reverse Thrust

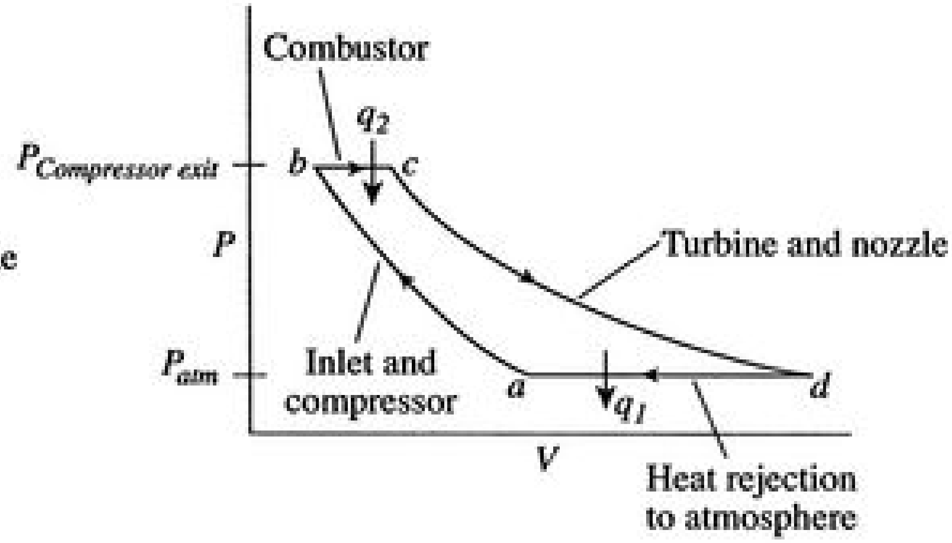


Gas turbine cycle: Brayton cycle



Gas turbine cycle: Brayton cycle





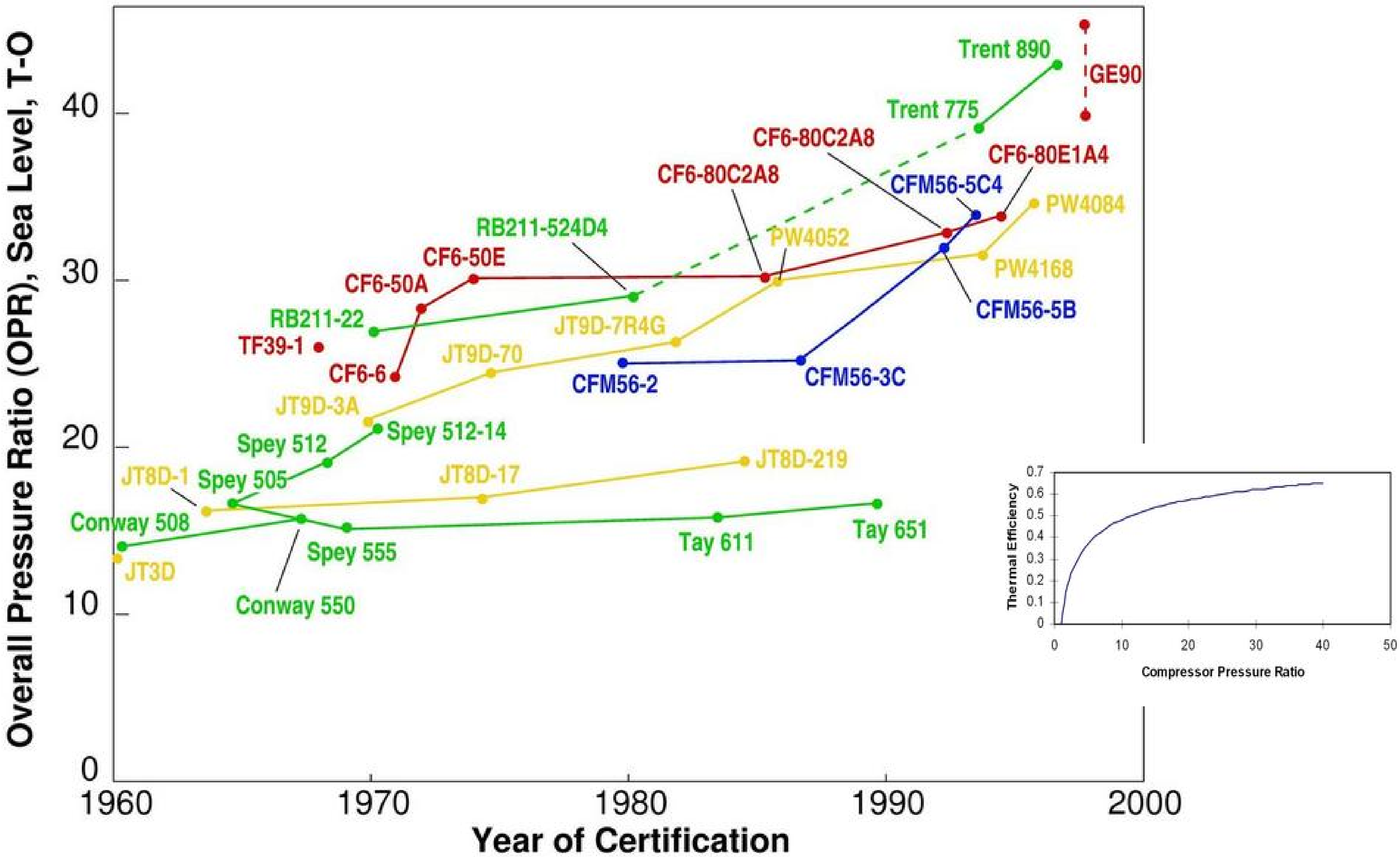
$$\eta = \frac{\text{Net work}}{\text{Heat in}} = \frac{c_p[(T_c - T_b) - (T_d - T_a)]}{c_p[T_c - T_b]} = 1 - \frac{(T_d - T_a)}{(T_c - T_b)} = 1 - \frac{T_a(T_d/T_a - 1)}{T_b(T_c/T_b - 1)}.$$

$$\text{Ideal Brayton cycle efficiency: } \eta_B = 1 - \frac{T_a}{T_b} = 1 - \frac{T_{\text{atmospheric}}}{T_{\text{compressor exit}}}.$$

$$\eta_B = 1 - \frac{1}{TR} = 1 - \frac{1}{PR^{(\gamma-1)/\gamma}}.$$

TR: temperature ratio a-b
PR: pressure ratio a-b

Trend of gas turbine development



Gas turbine running conditions

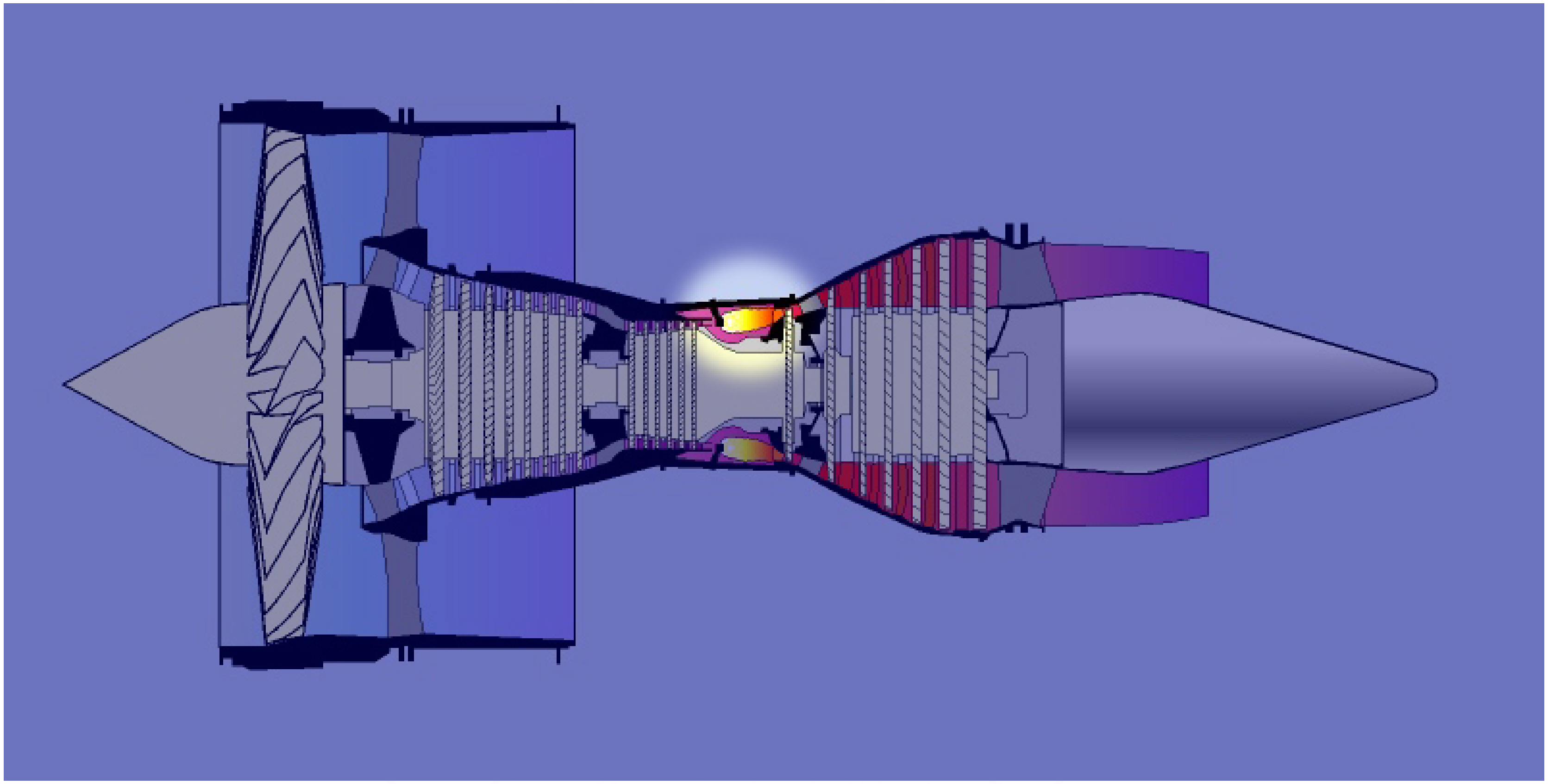
Gas turbines
Typical running conditions

	Pressure Bar	Turbine Inlet Temperature °C	Combustor inlet temp. °C
Industrial - Combined and Simple cycle	10-40	→ 1500	300-650
Recuperated	< 10	→ 1300	600-800
Aero	20-40	→ 1600	450-650
Microturbines	4-6	1000-1150	600-800
Automotive. Research projects	4-6	1150-1350	800-1000

Gas turbine combustor

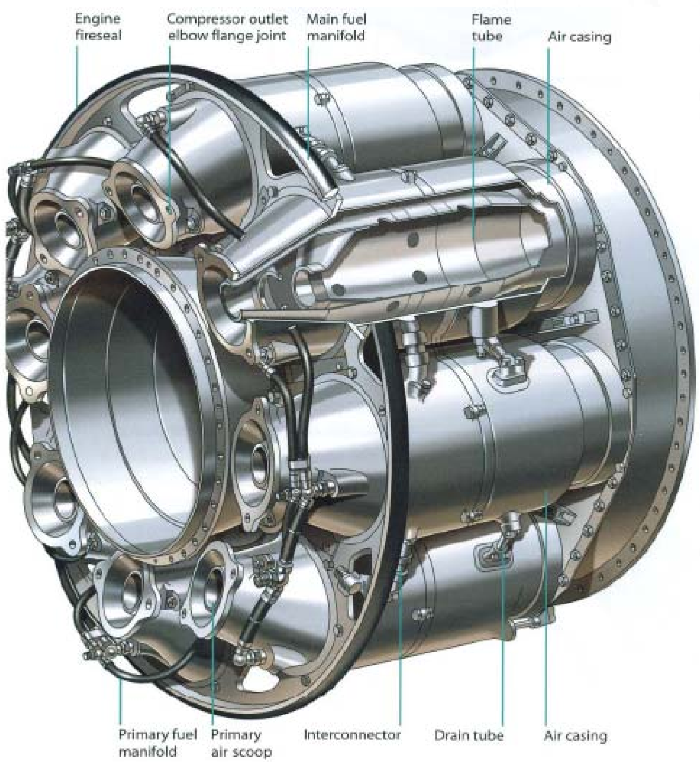
- Stright pipe
- Diffuser
- Flame stabilization
- Optimal air supply

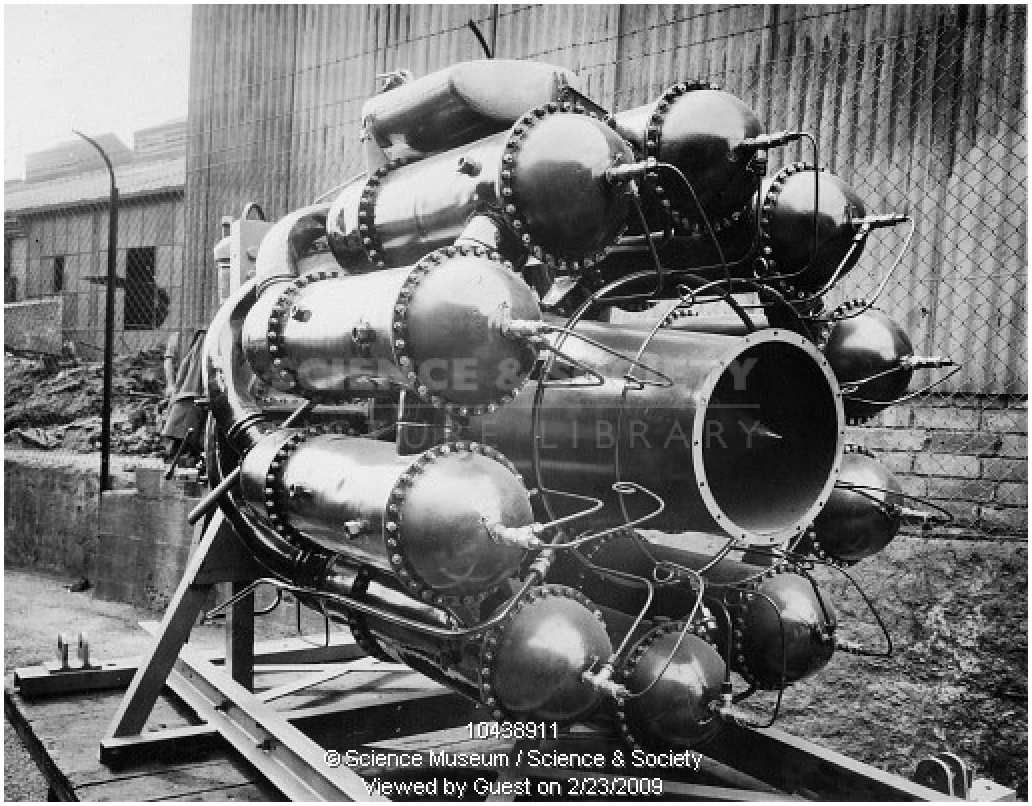
Combustor Operation



Jet Engine Layout

Can combustor

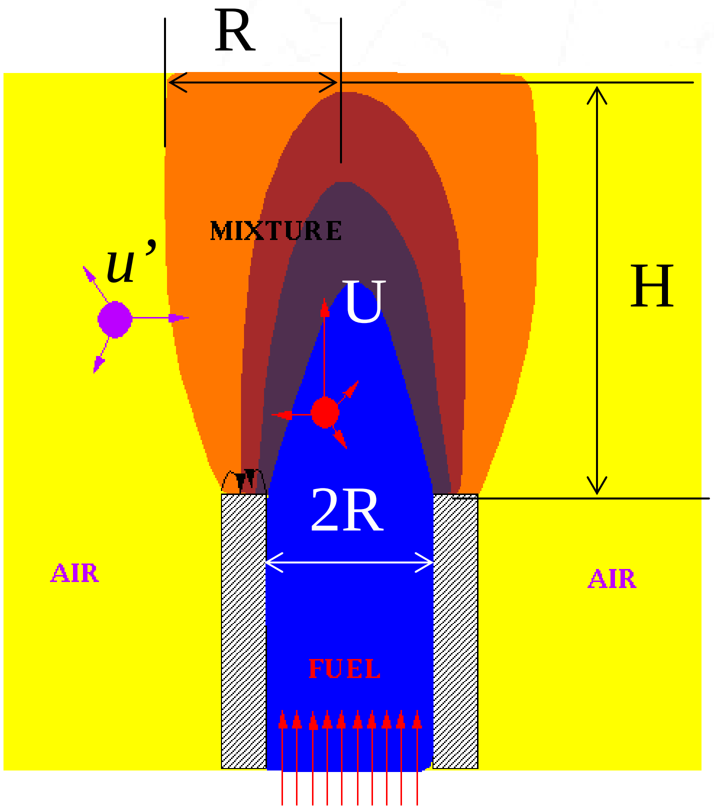




Whittle W1 engine, 1941

Turbulent flame shape and flame height (3)

order of estimation



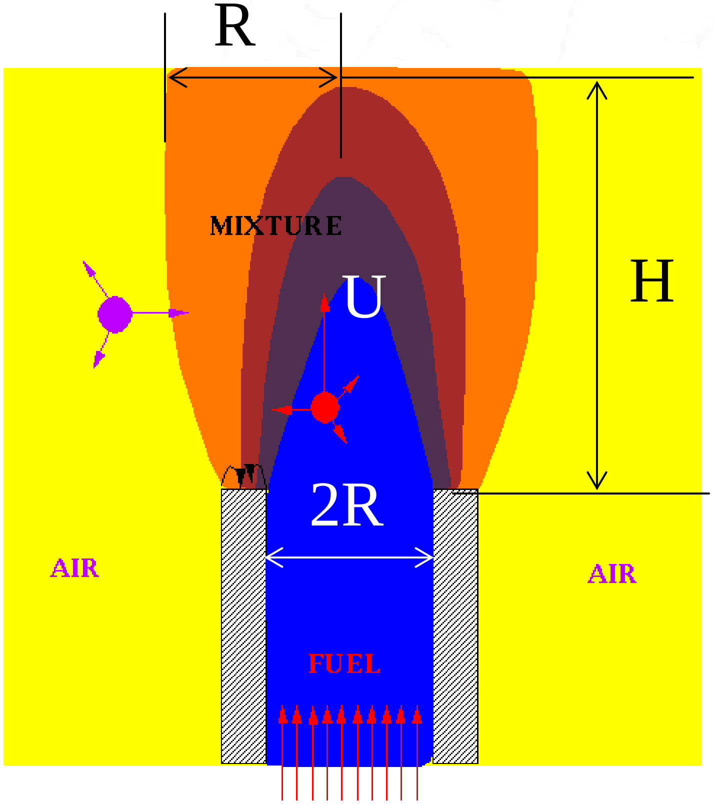
During time Δt, fuel molecule is convected from inlet to the tip of flame at a speed U, and oxygen molecule is transport by turbulence from air stream to the flame tip at a speed *u'*.

$$\Delta t \propto \frac{H}{U} \propto \frac{R}{u'}$$

$$\Rightarrow H \propto \frac{RU}{u'} \propto \frac{R}{I}$$

$I = u'/U$: intensity of turbulence

Recall: Laminar flame shape and flame height - *order of estimation*

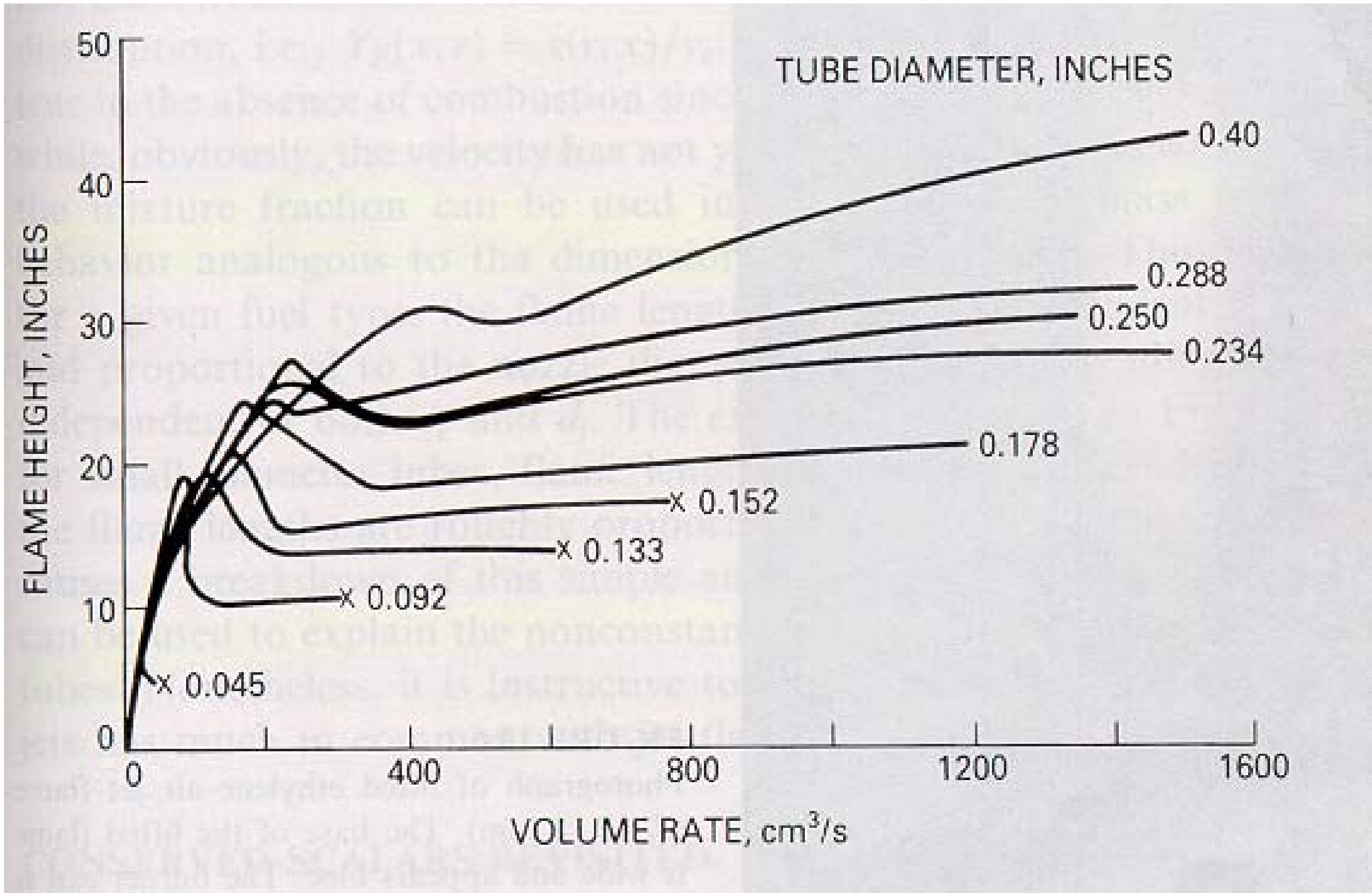


During time Δt, fuel molecule is convected from inlet to the tip of flame at a speed U, and oxygen molecule is diffused from air stream to the flame tip. D is diffusion coef.

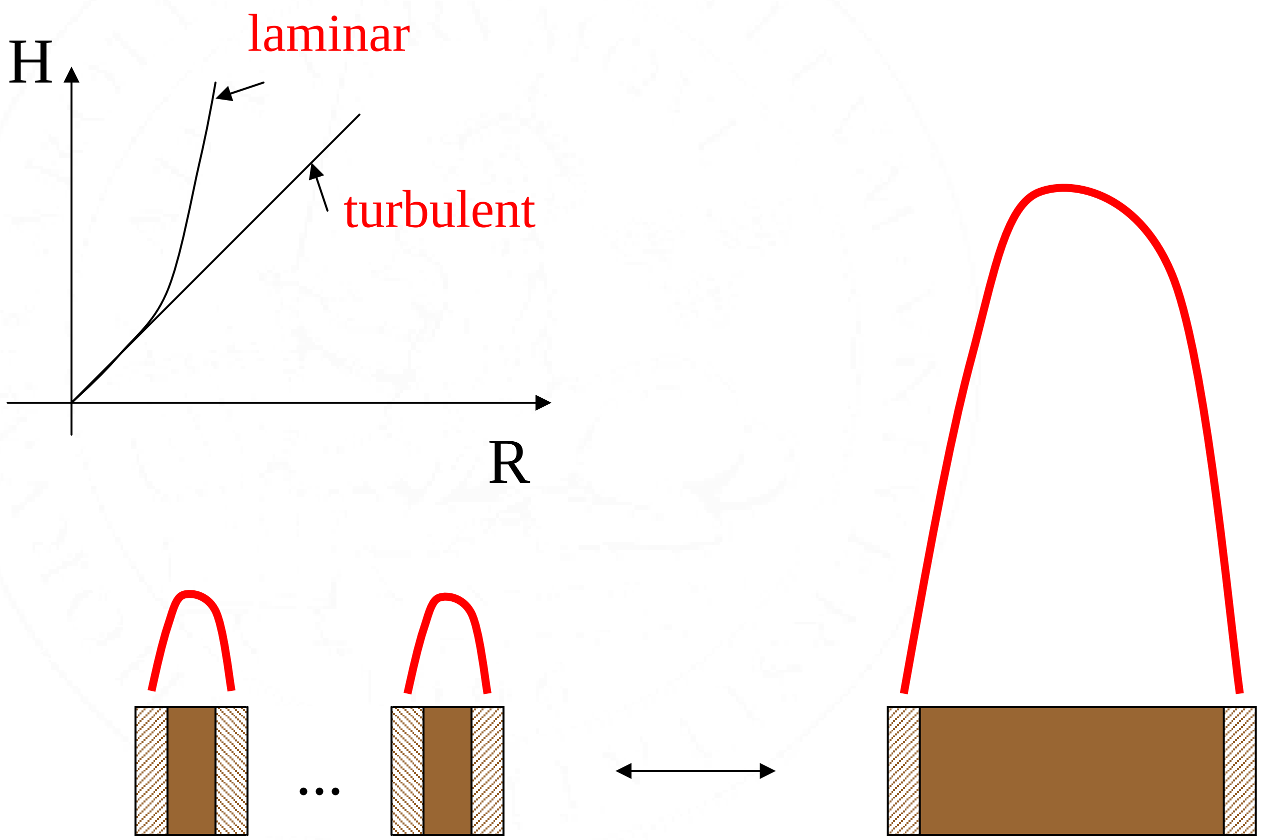
$$\Delta t \propto \frac{H}{U} \propto \frac{R^2}{D}$$

$$\Rightarrow H \propto \frac{R^2 U}{D}$$

Dependence of flame height on injection speed

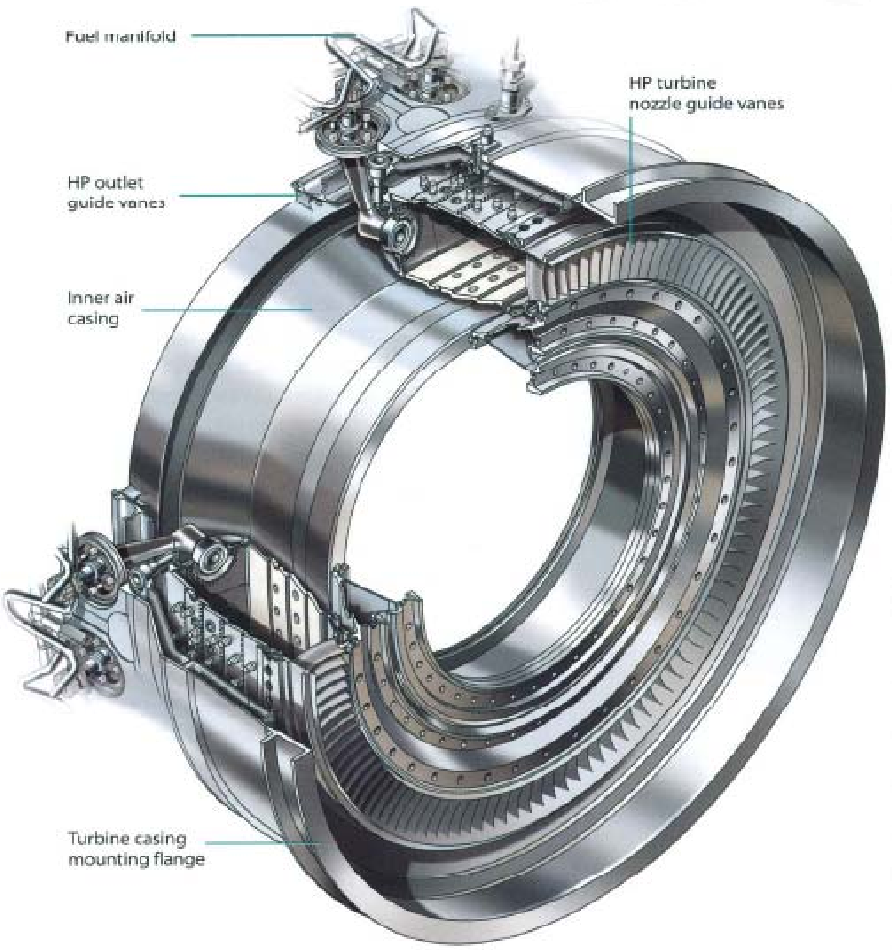


Dependence of flame height on burner diameter

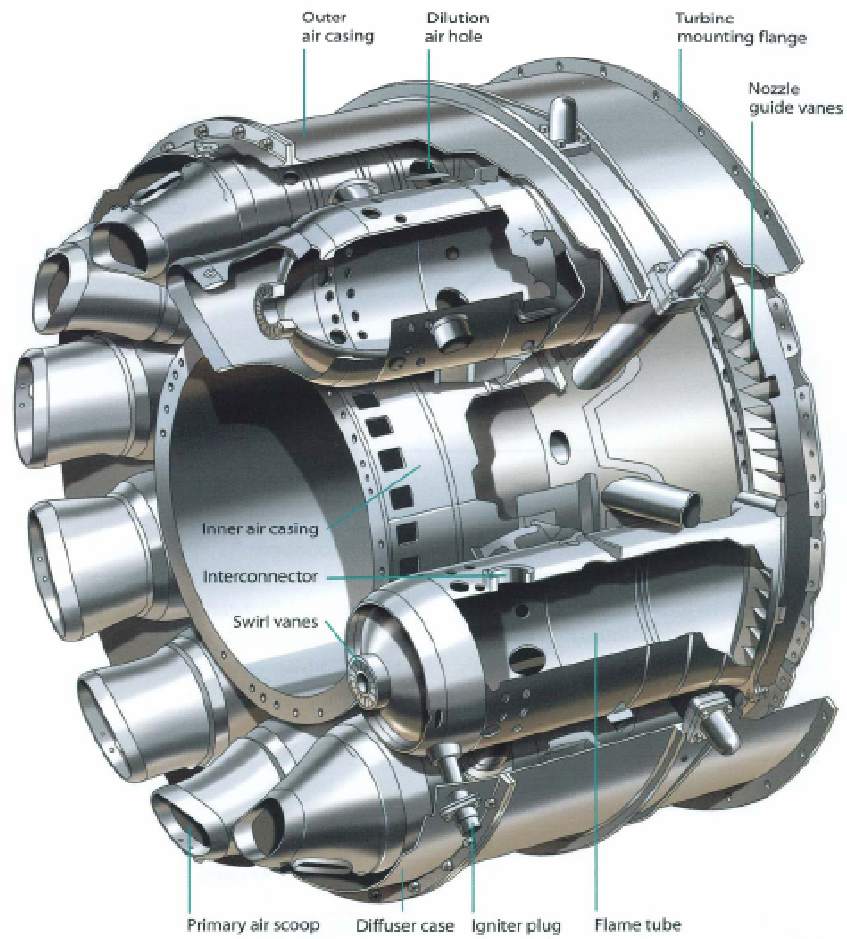


Jet Engine Layout

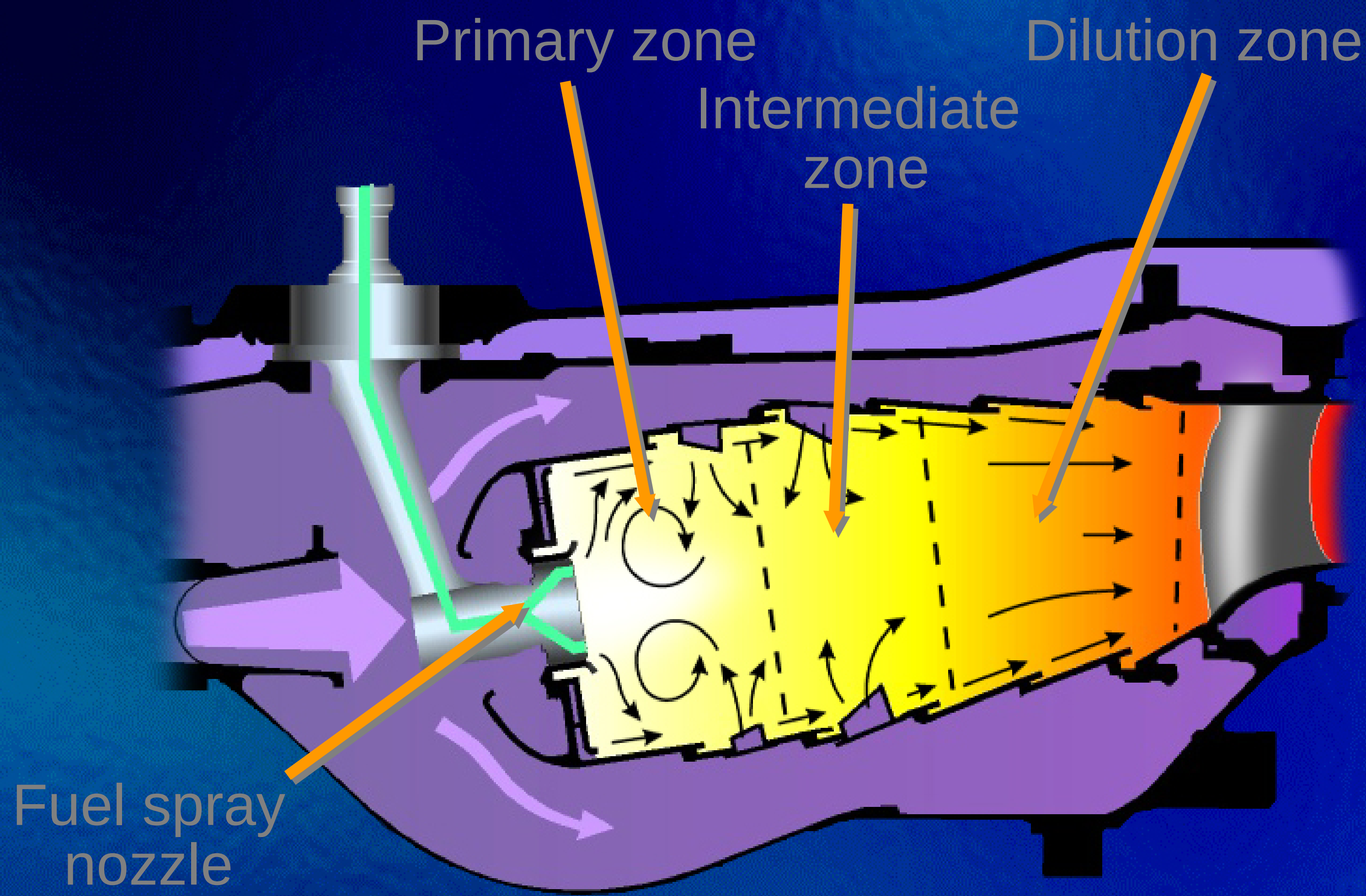
Annular



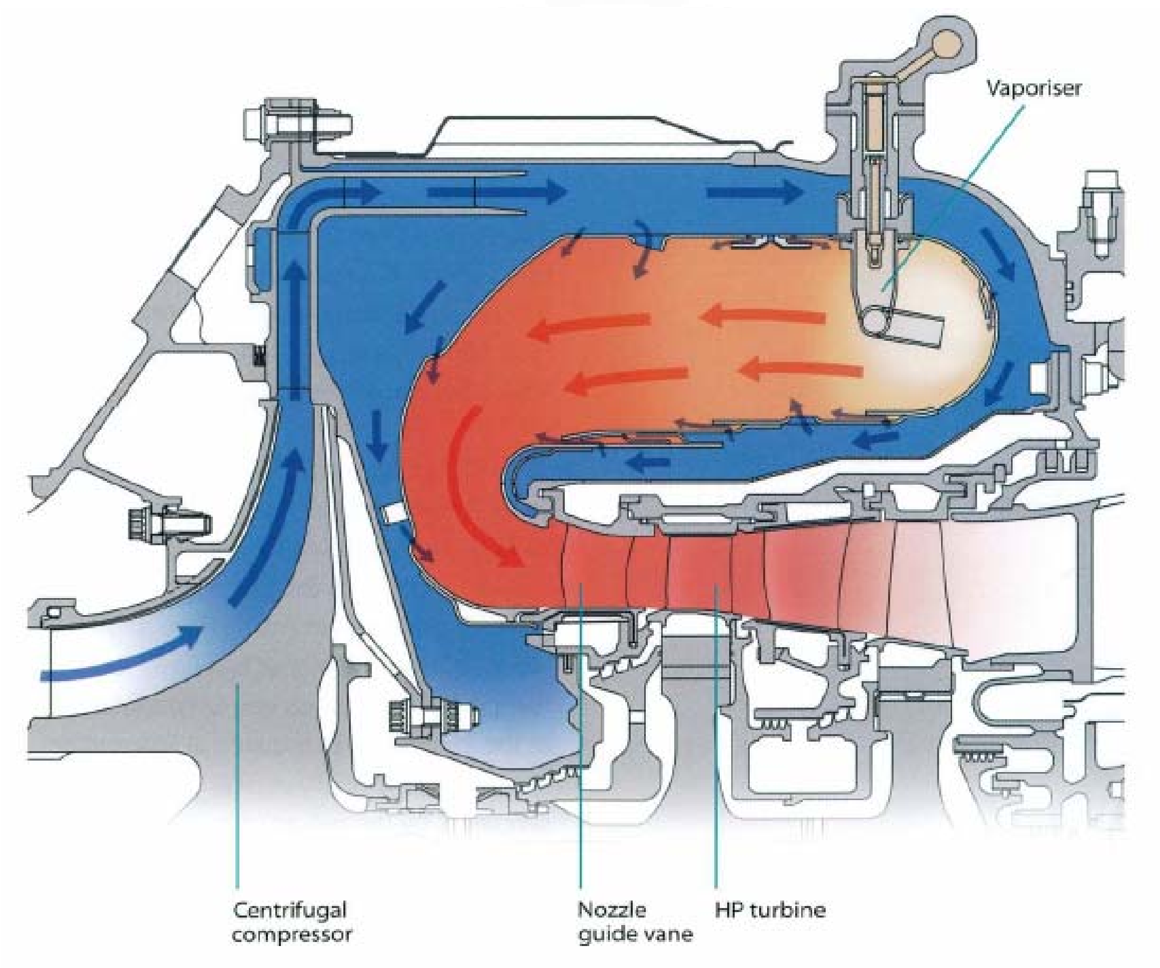
cannular



Combustor Operation

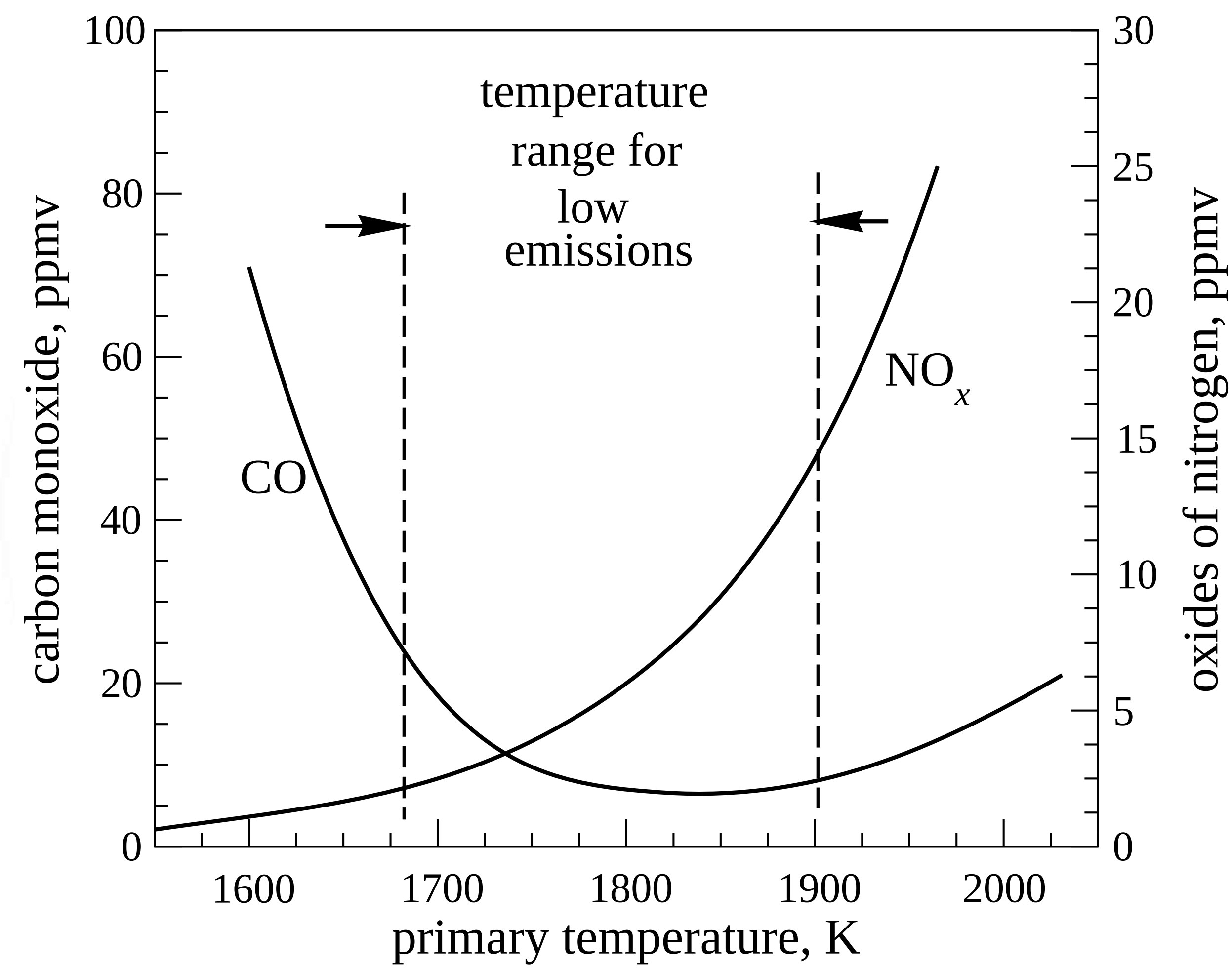


Reverse flow combustor



Development of modern gas turbine for clean environment

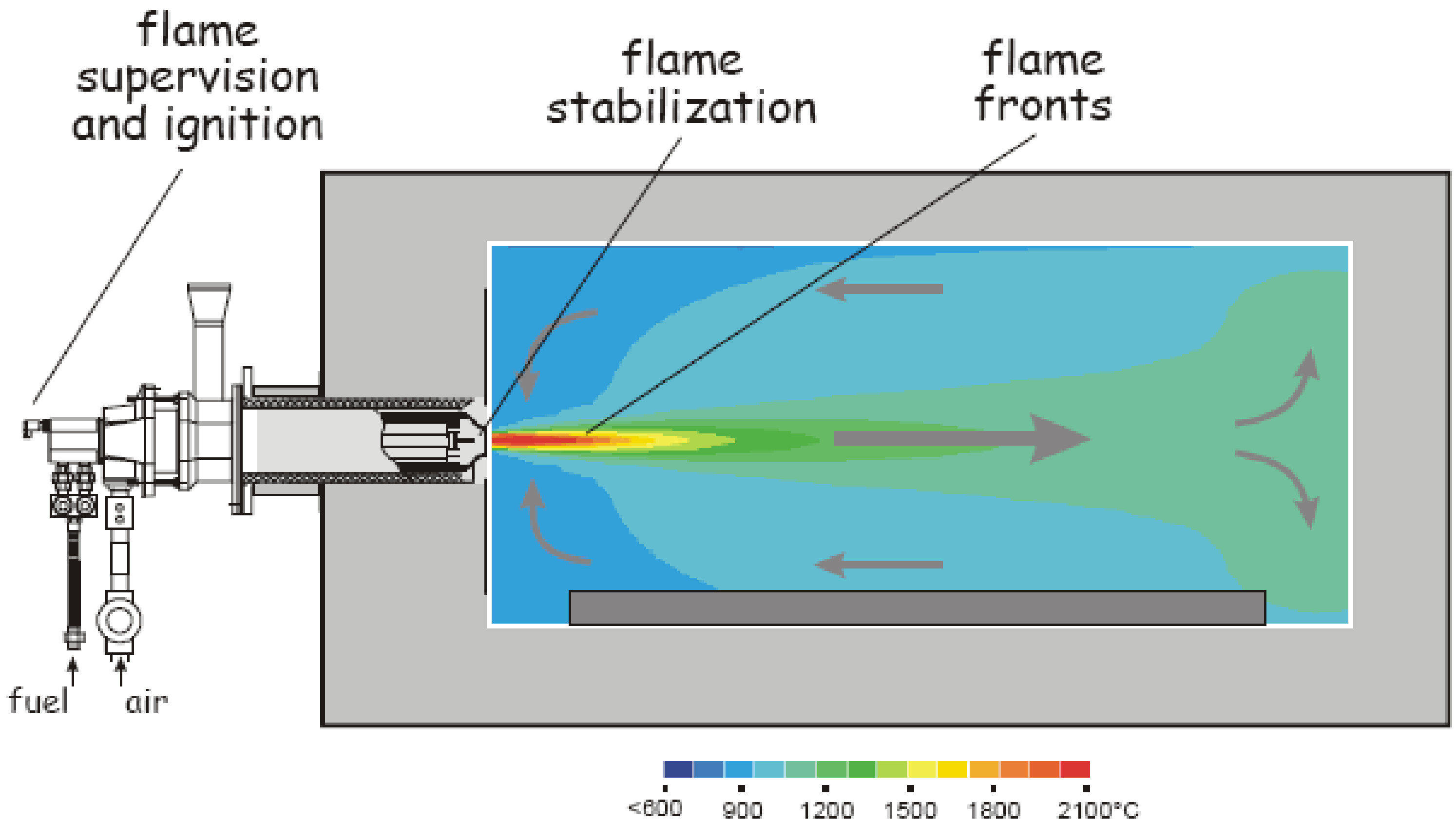
General consideration



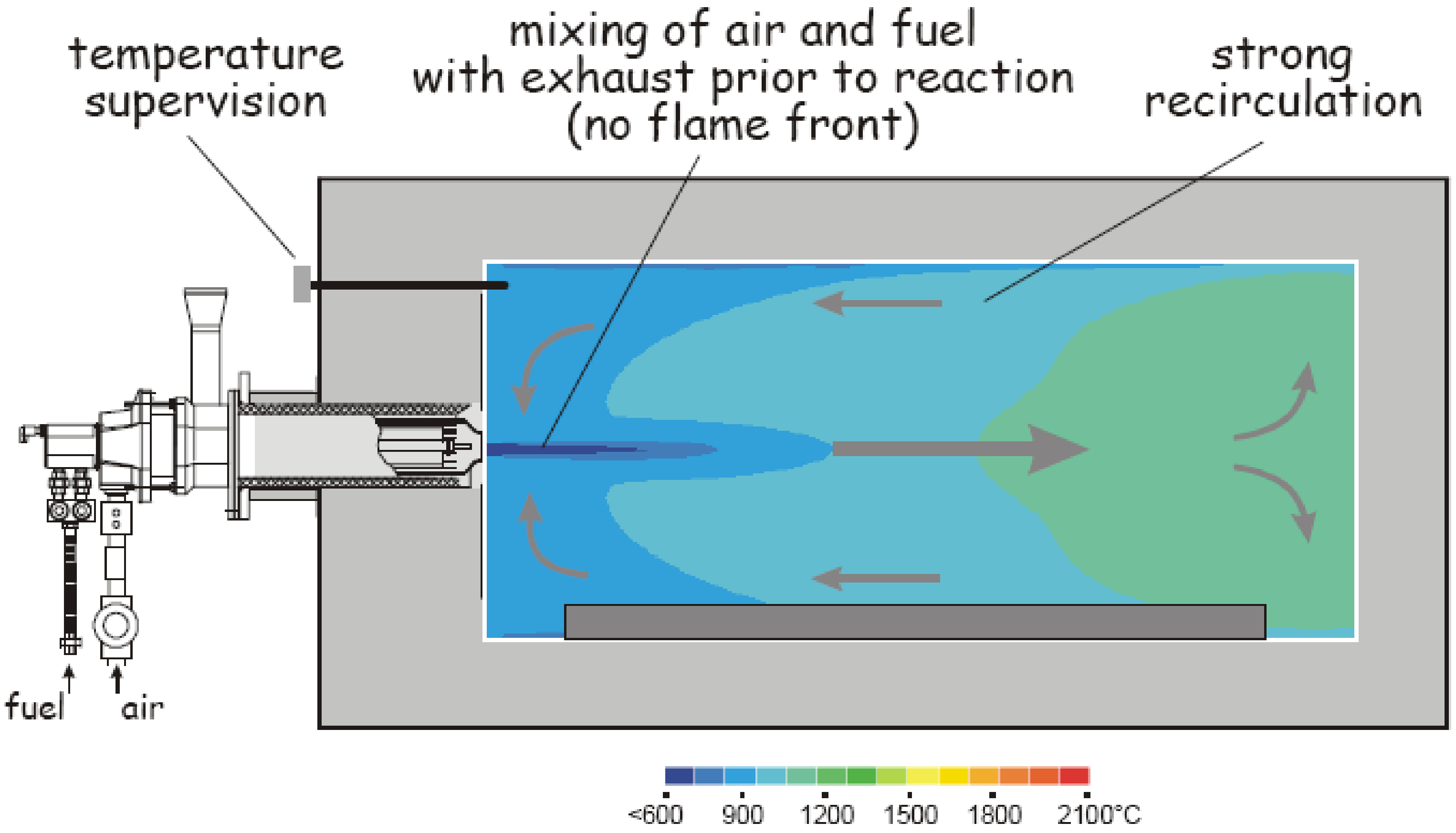
Other cocnepts

- Variable geometry
- Dry low NOx (DLN) combustion & lean prevaporized premixed (LPP) combustion
- Humid air combustion
- Rich burner, quick quench, lean burn (RQL) (premixed)
- Catalytic combustion
- Flameless combustion

Diffusion Flames

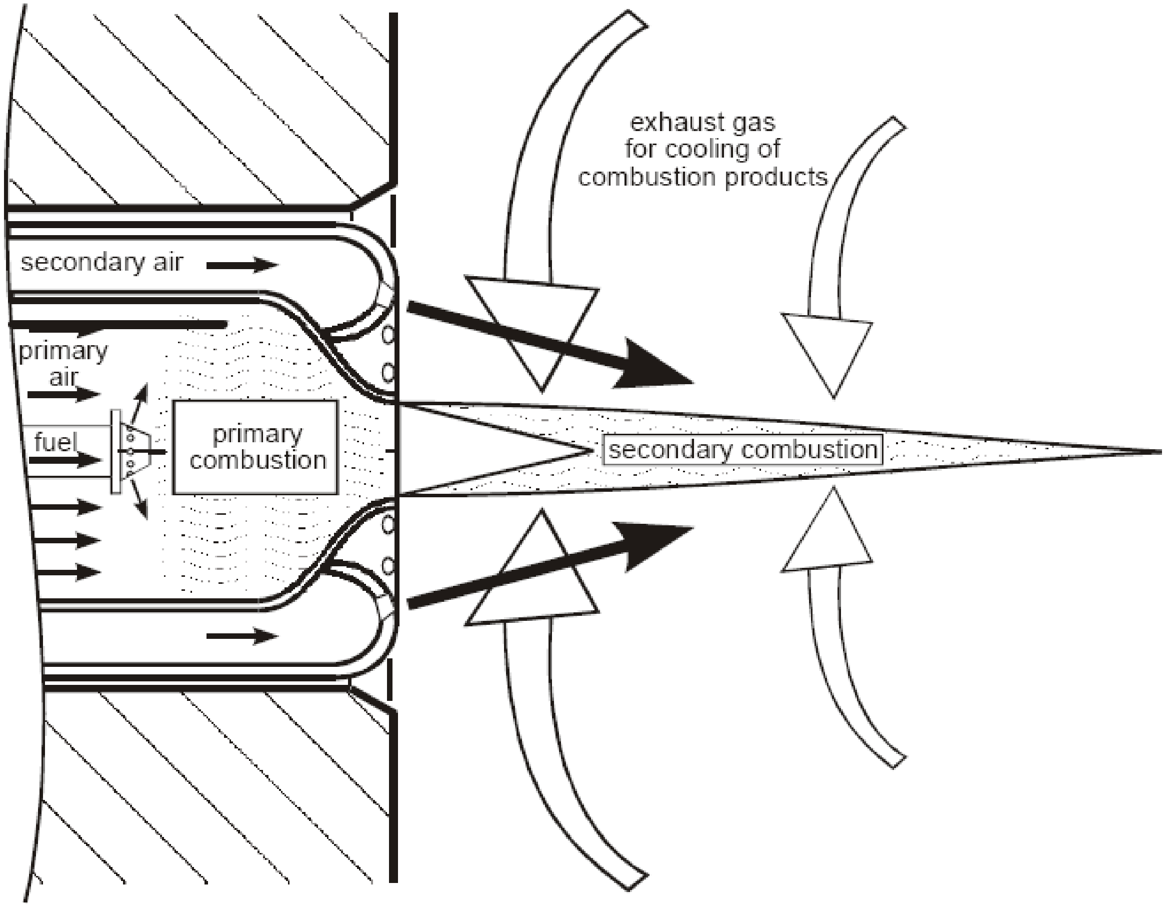


FLOX

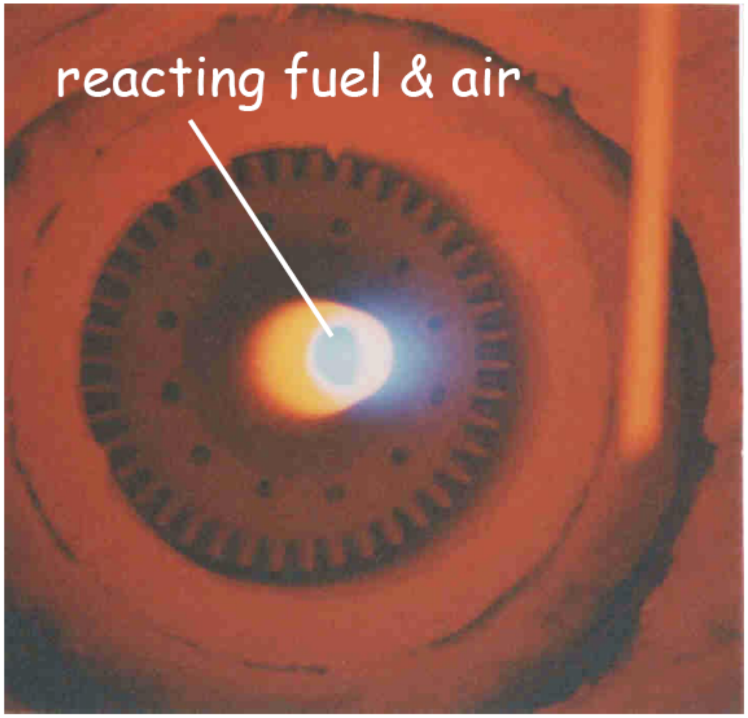


temperature supervision
mixing of air and fuel with exhaust prior to reaction (no flame front)
strong recirculation
fuel
air
<600
900
1200
1500
1800
2100°C

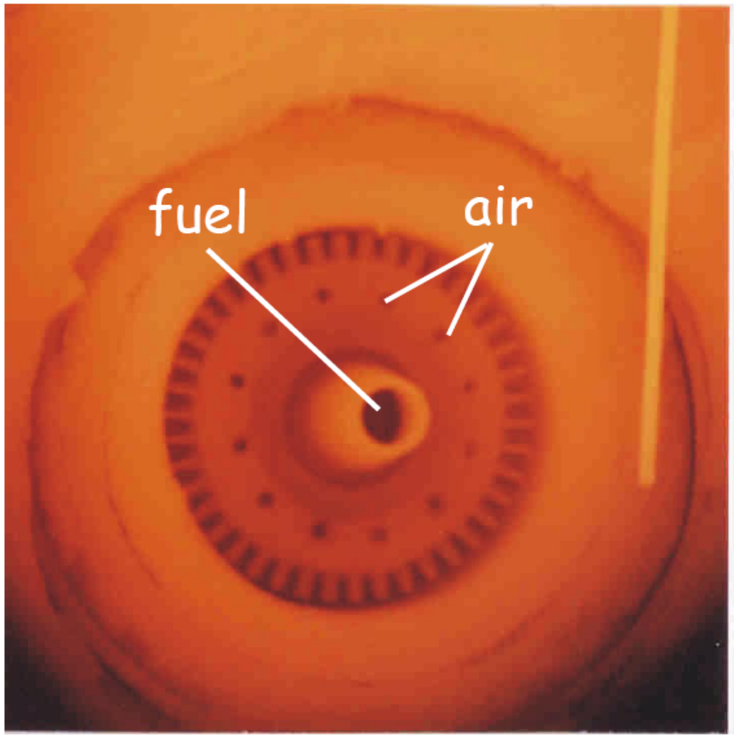
Flameless: air staged combustion



Flames and flameless

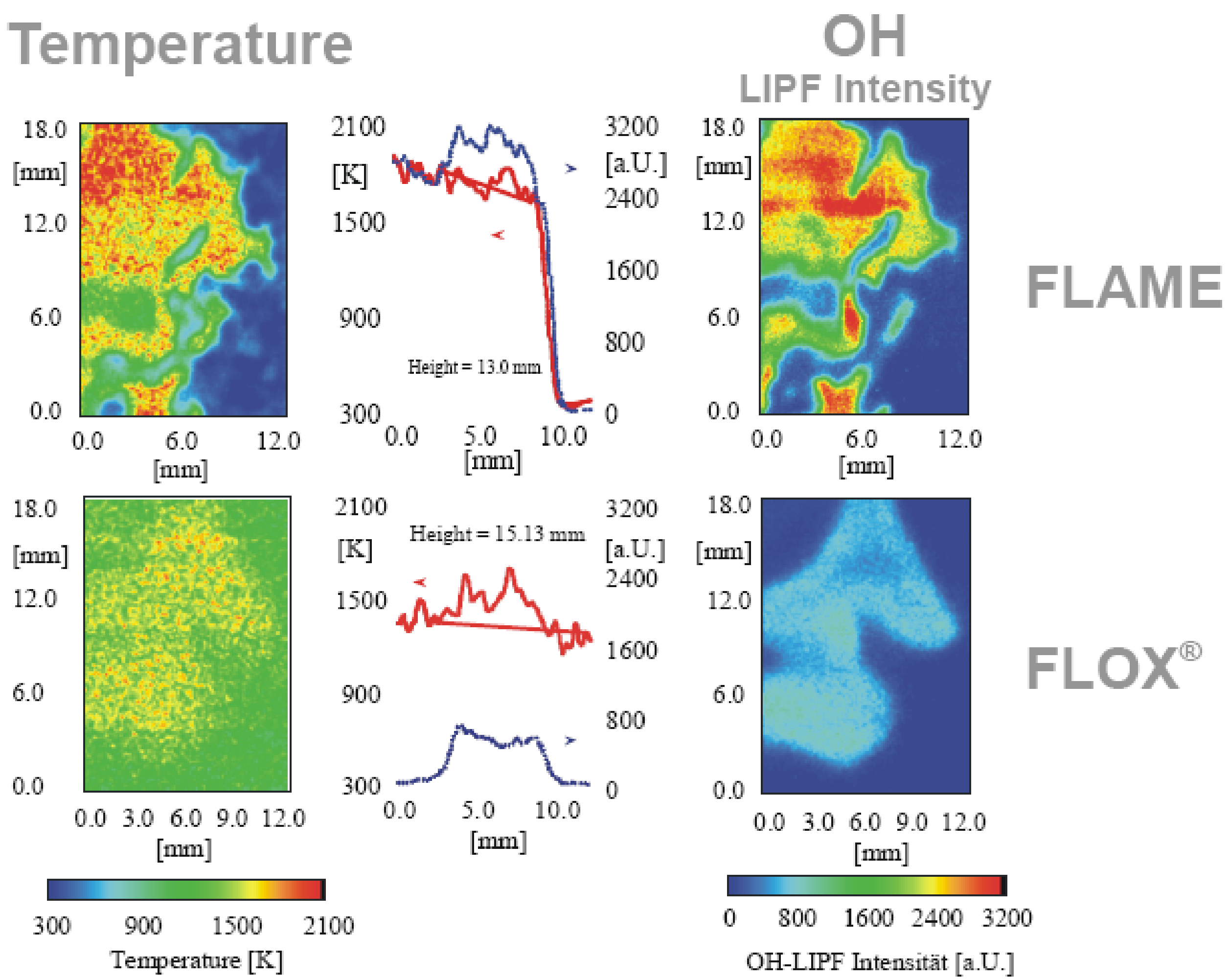


flames



FLOX

Flames and FLOX



Flames and flameless