What combustion fundamentals will real systems need?

We examine some relevant aspects of practical systems and show what fundamental combustion aspects control them.

- Reciprocating engines – diesel engine, carbureted gas engine – gasoline, natural gas or producer gas
- Gas turbine engine, military, earlier civil engines, modern civil engines
- Solid rocket engine – composite solid propellant combustion
- Liquid rocket engine – monopropellant engines, storable liquids, semi and full cryo liquids
- Atmospheric controlled combustion processes as steps to understand high pressure combustion phenomena and uncontrolled combustion processes in fire extinguishment strategies

NPTEL Combustion course, December 2019

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Reciprocating engines – diesel engine, carbureted gas engine – gasoline, natural gas or producer gas

- All these engines are required to perform with high efficiency and minimal undesirable emissions.
- High conversion efficiency to power implies low fuel usage and hence reduced CO_2 emissions.
- Reduced emissions of CO, NO_x, UHC and particulate matter call for fuel injection, combustion geometry and process modifications
- All these engines function by cyclic process. Periodic injection, ignition and combustion are expected to occur at periodic intervals of milliseconds (depending on the speed)
- Gasoline and diesel engines use compression ratios of 8 – 10 and 14 – 20 respectively
- Coal sometimes is also the solid fuel that is gasified to generate producer gas. However, biomass (renewable source) is the more common solid fuel to generate producer gas - a mixture of CO, H_2, CO_2, H_2O and N_2 obtained from a gasification process of biomass with air as the oxidant.
- Sometimes oxygen and steam are used to gasify biomass to produce a composition that will not have N_2. This gas is termed synthesis gas – allows obtaining liquid hydrocarbons with Catalytic processes (Fischer-Tropsch synthesis)

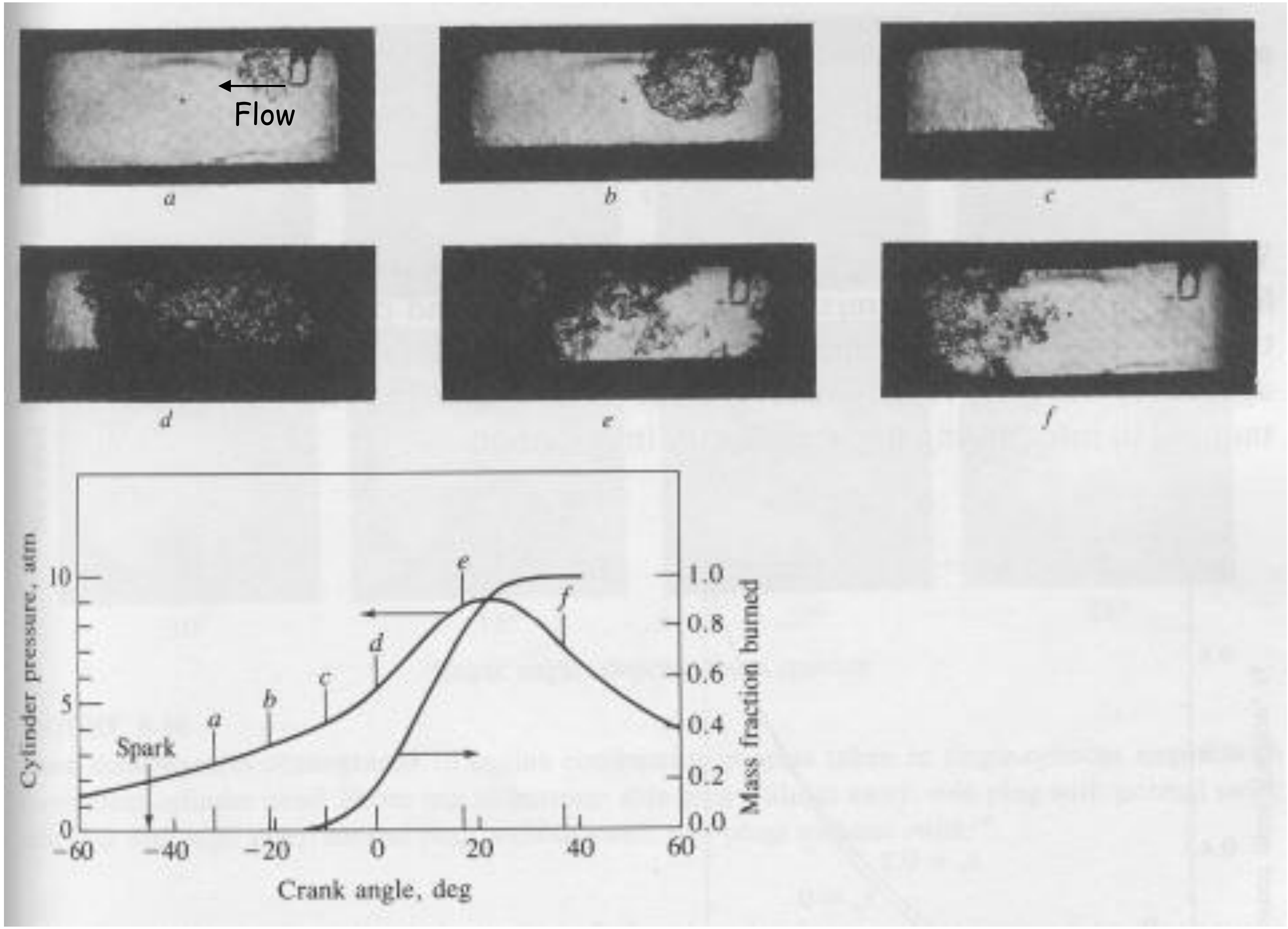
Spark Ignition Engine (gasoline & Producer gas)

After intake the fuel-air mixture (premixed) is compressed and then ignited (ignition process)
by a spark plug just before the piston reaches top center.

The flow conditions will be turbulent (turbulence?)

The turbulent flame spreads away from the spark discharge location and converts the reactant mixture to products and thus release heat.

This raises the pressure (nearly uniform) inside the chamber and the expansion process leads to power generation.

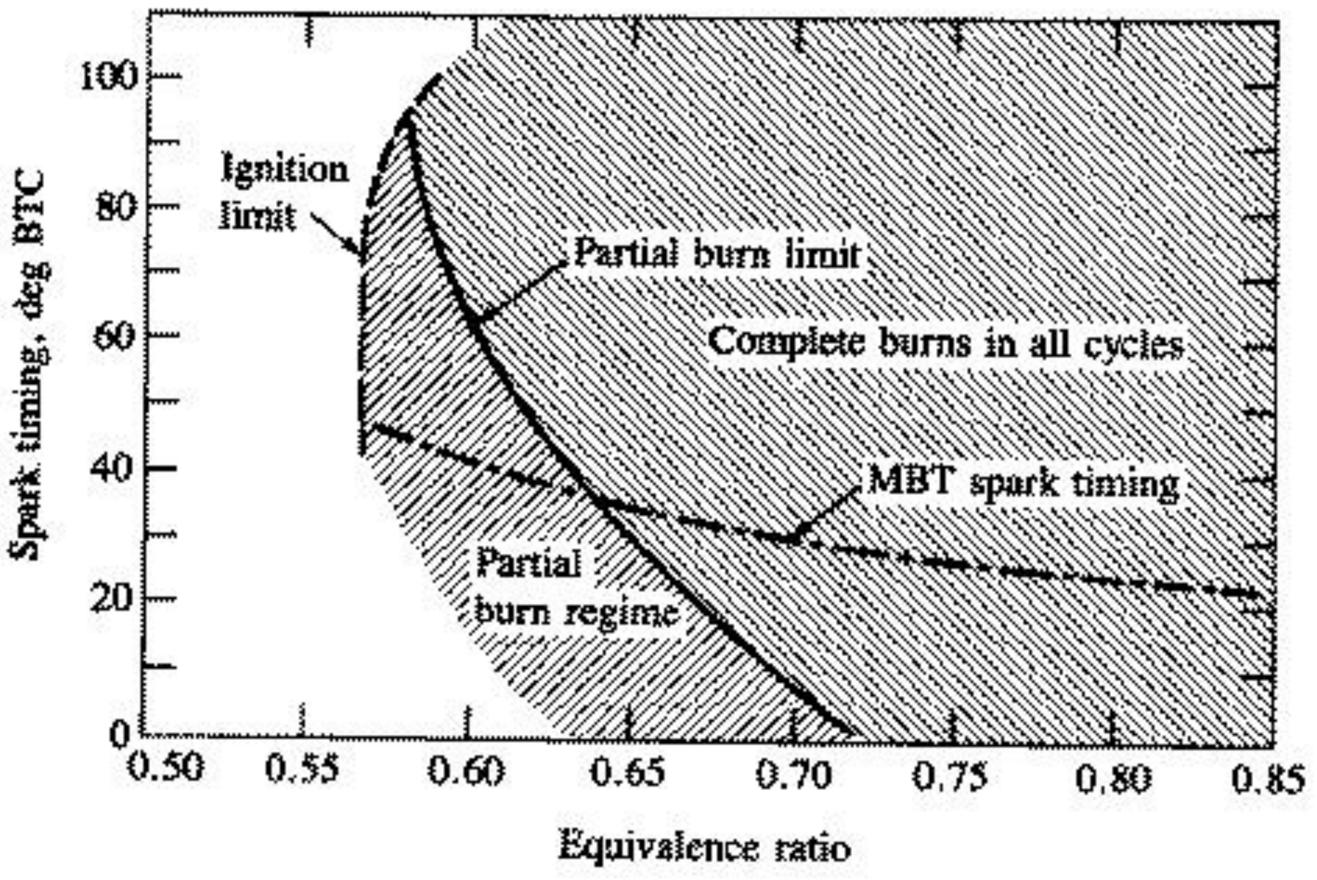


Effect of Fuel-air Dilution

If the spark timing is set for maximum brake torque (MBT) – typically about 20 to 30°, leaner mixture needs larger spark advance since burn time longer – burning velocity is lower {burning velocity vs. equivalence ratio – [fuel:air] / $[\text{fuel:air}]_{\text{stoichiometry}}$}.

Along MBT curve as you increase excess air reach partial burn limit (not all cycles result in complete burn) and then ignition limit (misfires start to occur). Ignition limit at low equivalence ratios corresponds to flammability limits of premixed fuel-air mixture

The whole combustion process is turbulent.

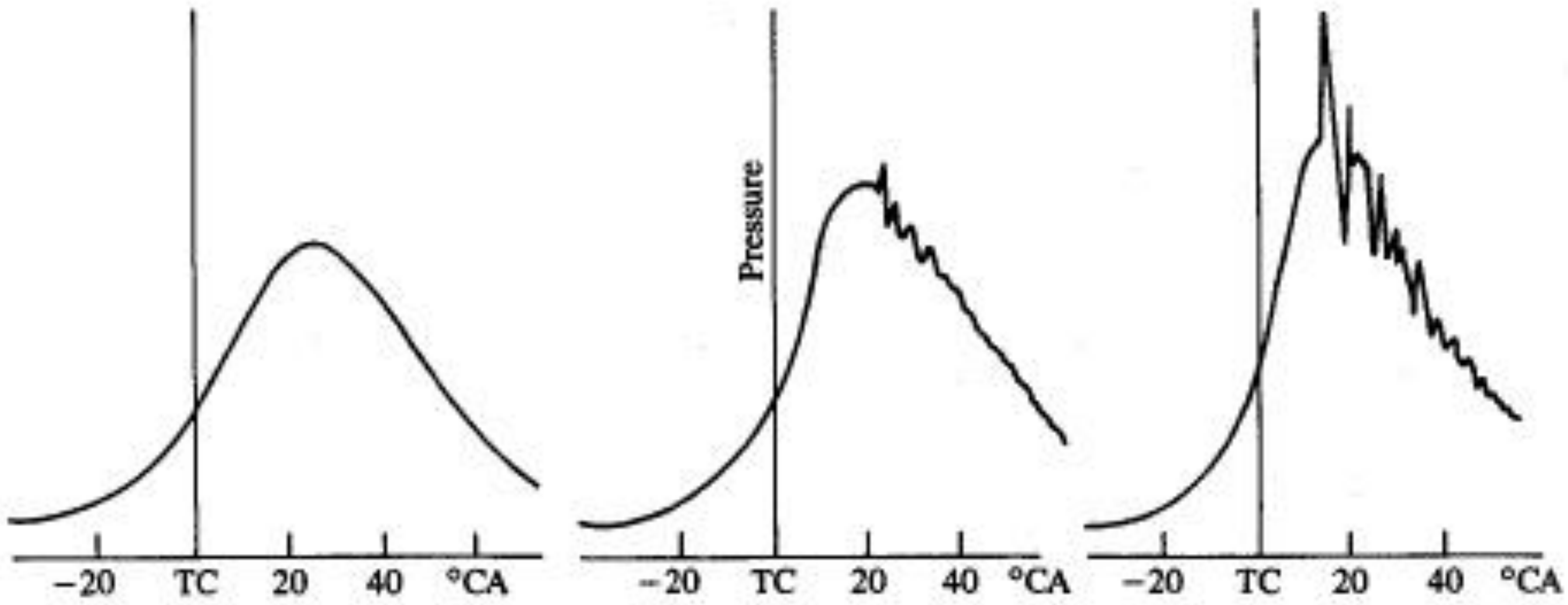


Knock in Spark Ignition Engine

Knock is essentially a pinging noise emitted from the engine undergoing abnormal combustion.

The noise is generated by detonation wave (shockwave in a reacting flow medium) produced inside the cylinder when unburned gas ahead of the flame auto-ignites. During this period, pressure is not uniform inside the combustion chamber.

There are many reasons for knock all related to reaction chemical kinetics.



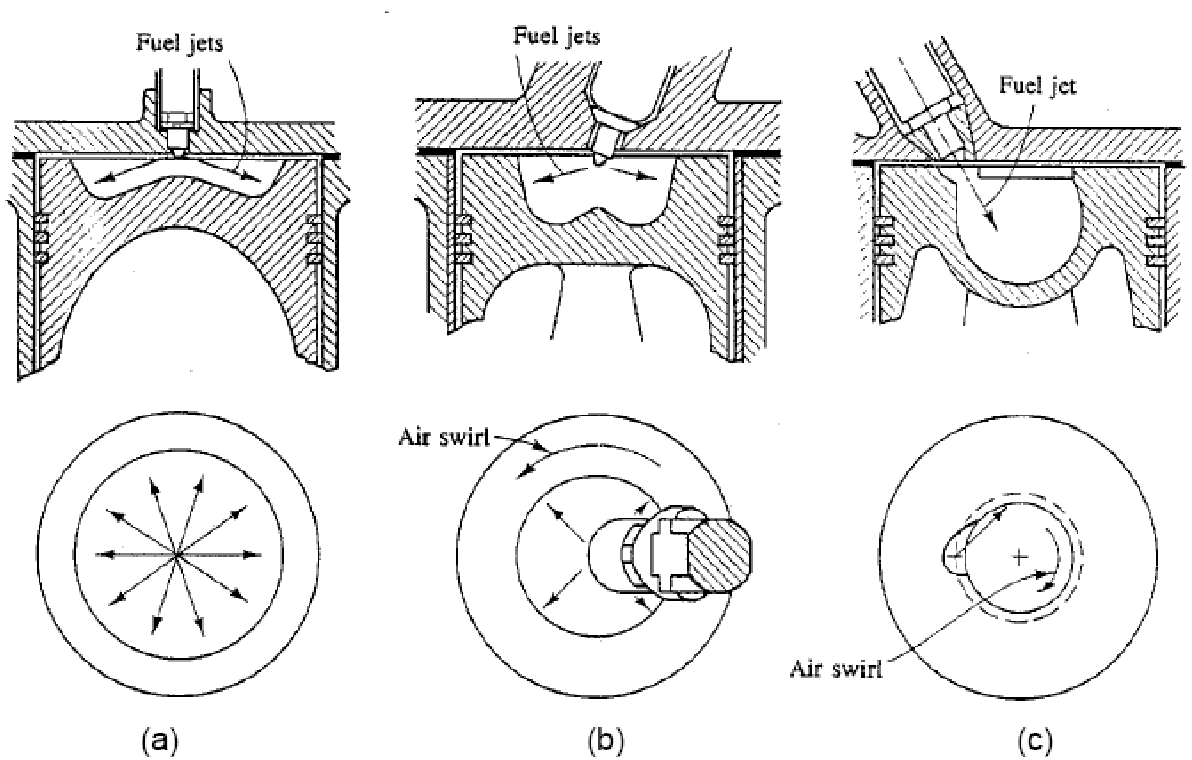
(*a*) Normal combustion, spark 28°BTC

(*b*) Slight knock, spark 28°BTC

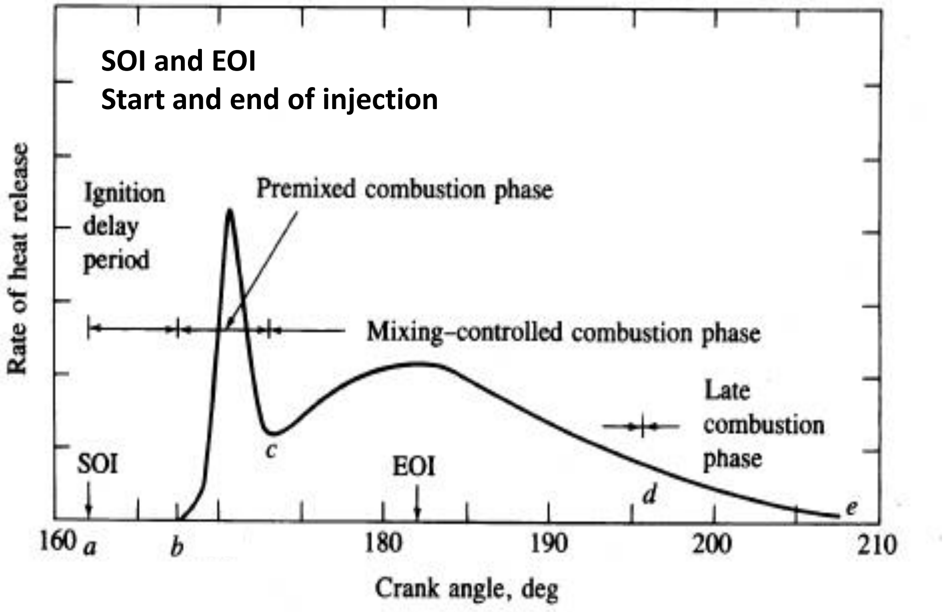
(*c*) Intense knock, spark 32°BTC

Premixed combustion systems are characterized by (a) burning velocity, and (b) flammability limits. They are controlled by chemical kinetics and conditions of pressure and initial temperature.

Combustion systems in CI Engines

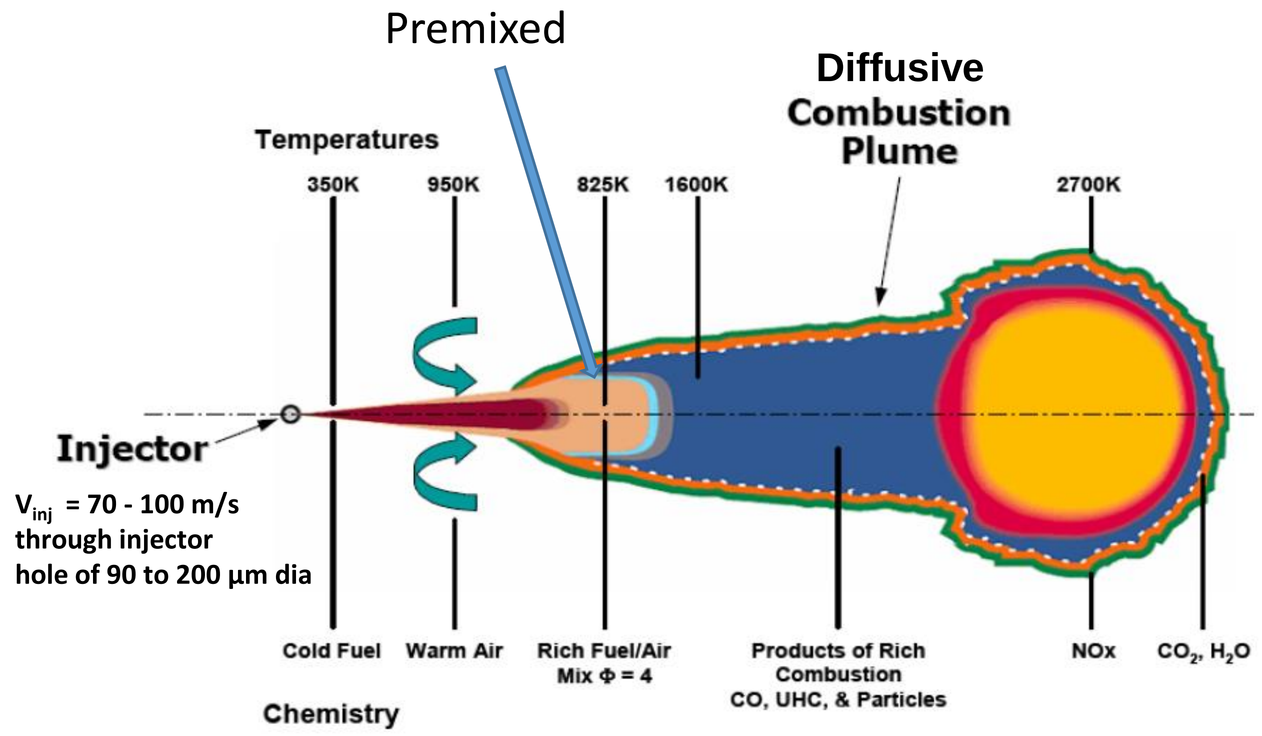


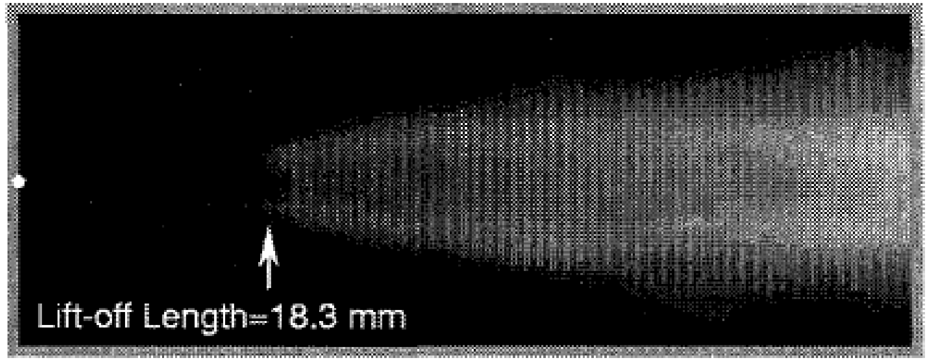
(a) Quiescent chamber with multihole nozzle typical of larger engines
(b) Bowl-in-piston chamber with swirl and multihole nozzle; medium to small size engines
(c) Bowl-in-piston chamber with swirl and single-hole nozzle; medium to small size engines

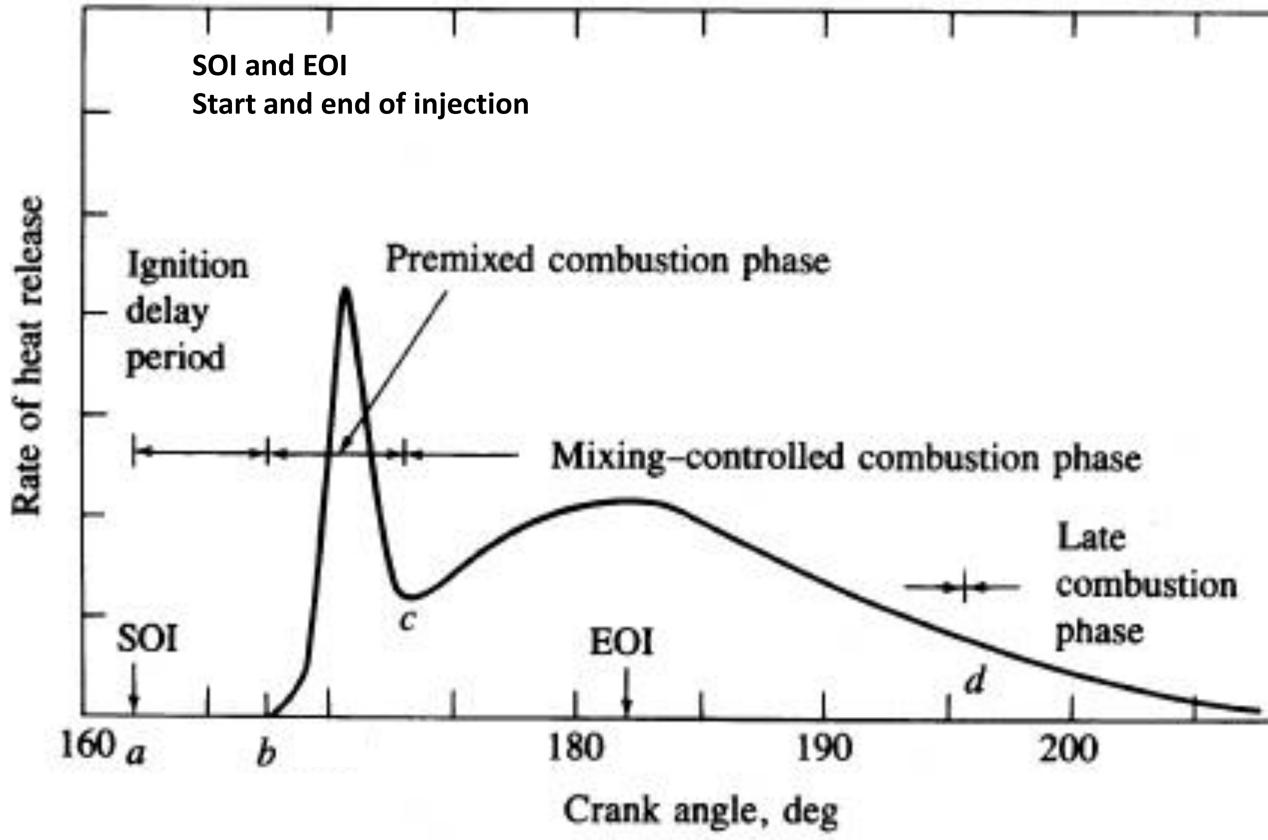


Engine-out NOx levels	Euro VI 04.g/kW-hr	~US2007 1.6g/kW-hr	Euro VI -90% deNOx ~US2010 -94% deNOx 3.2g/kW-hr
Fuel injection pressure, bar	3000 bar	2200 bar	1800 bar
Peak cylinder pressure	230 bar	180 bar	150 bar
EGR at full load	45%	27%	15%
Charge cooling relative to rated engine power	90%	50%	30%

Combustion process in large CI engine







Note: Both "rich premixed" and diffusive combustion Modes are involved at high pressures and temperatures – due to compression and exhaust gas recirculation which is adopted to reduce the emissions of NO_x largely

Gas turbine engine, military, earlier civil engines, modern civil engines

Do same engines go to civil and military aircraft? - Yes and No!...

Yes

- B52 Bomber has J57 engine;   Boeing 707 and DC 8 aircraft have JT – 3C engine
- Both J57 and JT- 3C engines are the same. Differences, if any are considered minor.

- C-5A Galaxy military transport has TF39 engine; Boeing 737 and Airbus 320 have CF6 engine
- Both TF39 and CF6 engines are essentially the same frame. Beginning as TF39, the engine benefited directly from new technology inputs in the form of components, materials, processes, manufacture, and repair processes that went into CF6 and also went into concurrent delivery of TF39 engines. Subsequently, TF39 was replaced by CF6.

Reason

The flight regimes are subsonic (M~0.8). Applications do not require maneuverability

While civil applications demand lower sfc that high bypass ratio engines promise, the military applications derive the same benefit – and why not?

Do same engines go to civil and military aircraft? - Yes and No!...

- The answer is NO for supersonic military aircraft – why?

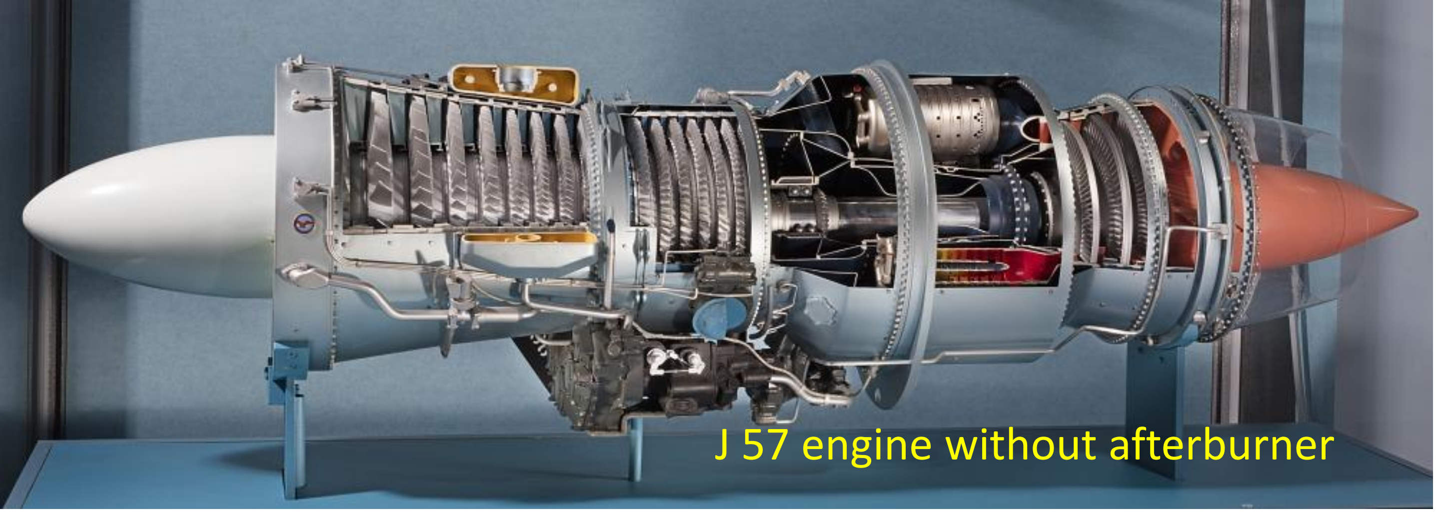
- Supersonic military aircraft need high maneuverability. This requires substantial Thrust/(drag at cruise speed) to enable sharp acceleration, deep turn and fast climb, stealth and thrust-vector control

- Such engines should be carried in the belly to ensure reduced radar exposure (stealth need)

- Reduction of aircraft drag is promoted by reducing the engine cross-sectional profile. This means that Thrust/air mass flow rate must be large.

- This feature can only be met with by turbojets or low bypass ratio turbofan.

- *Most military engines have a bypass ratio of 0.2 to 0.3.*



It is a twin spool axial flow turbojet engine.
0.78 kg/kgf h at take off and
0.9 kg/kgf h at cruise
Both dry and afterburner versions

J57 is military version – used on B52 bomber
It is also called JT 3C for civil version
used on Boeing 707

T.O. 1F-100D(I)-1

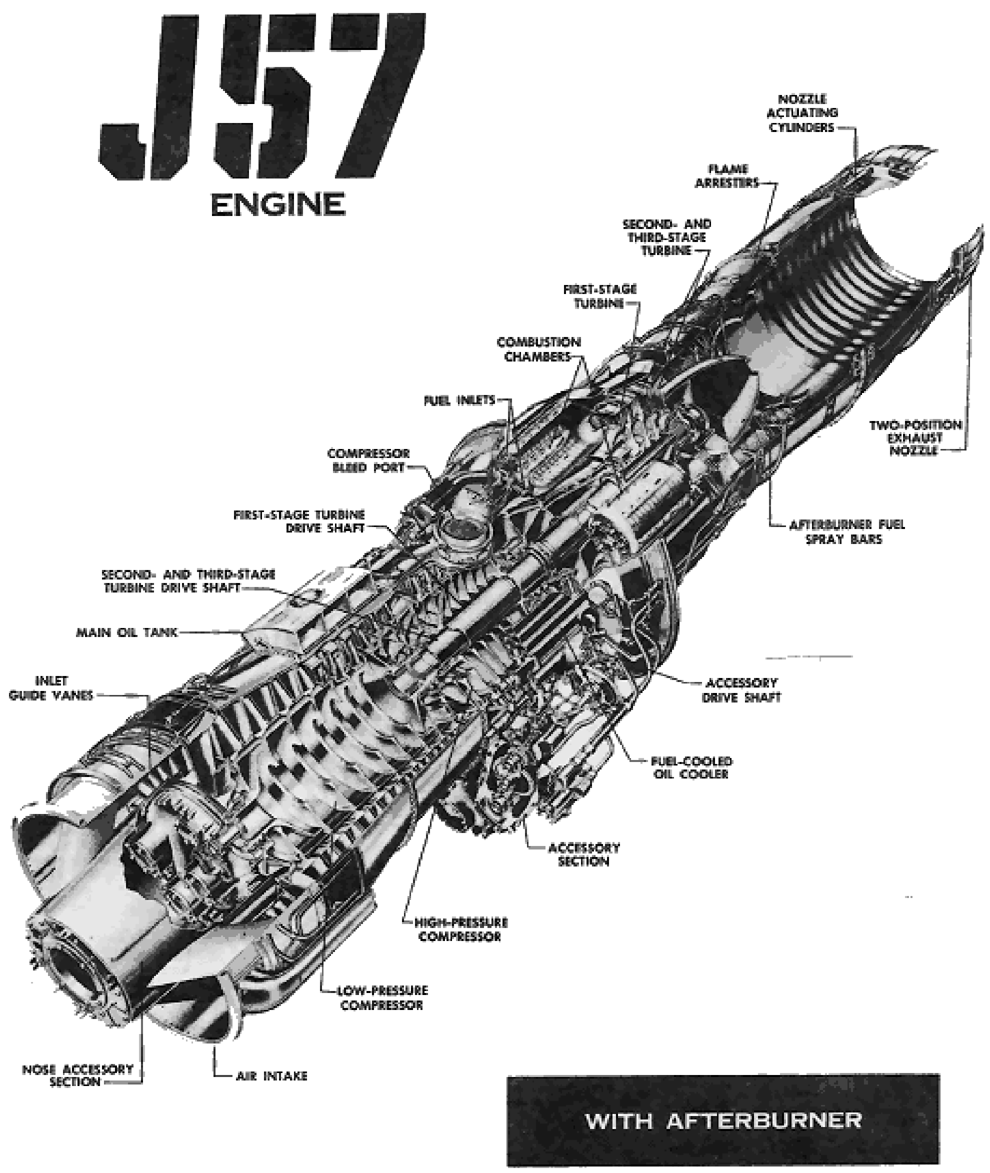
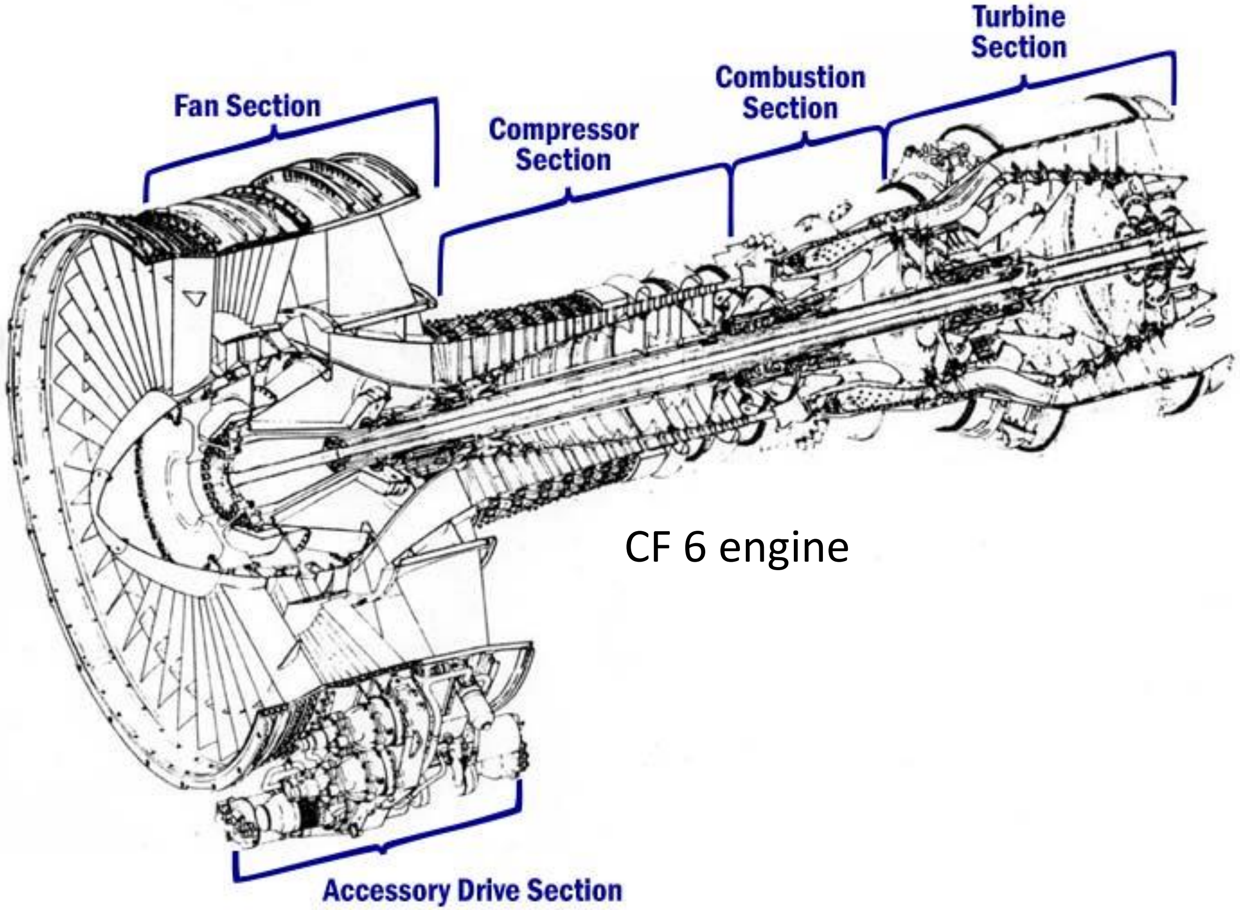
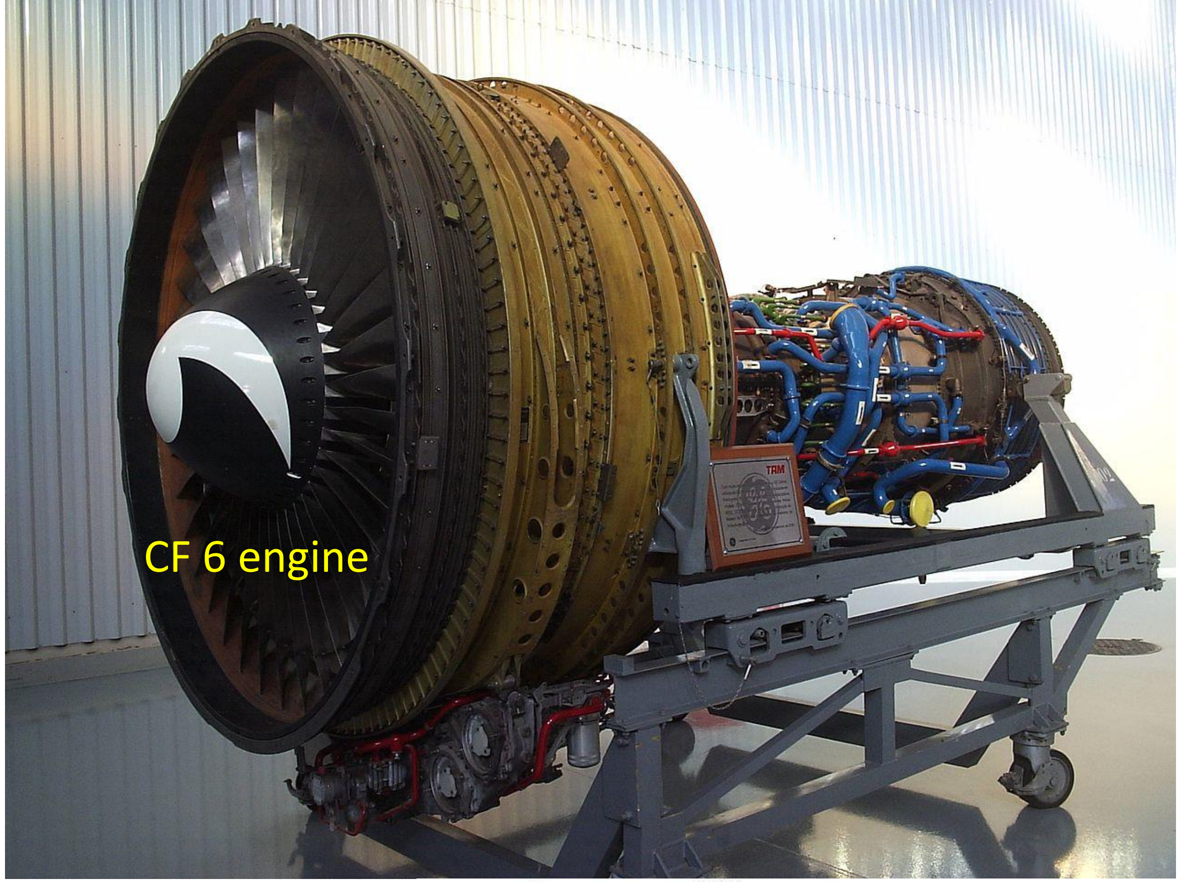


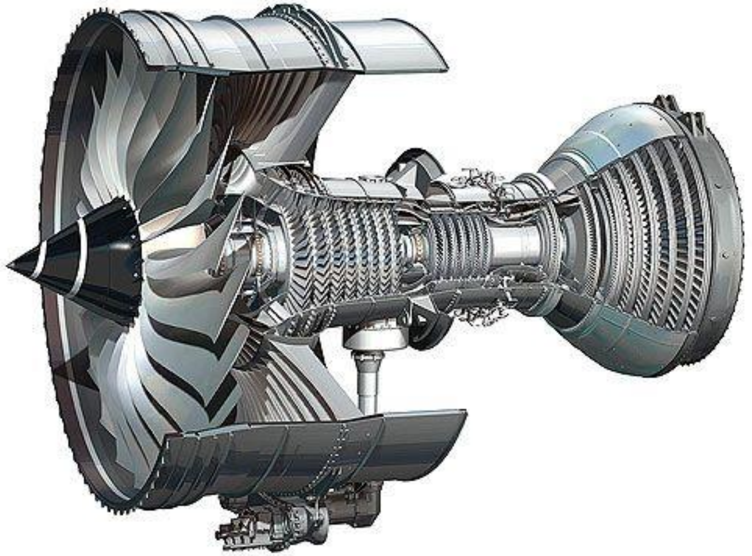
Figure 1-5



CF 6 engine



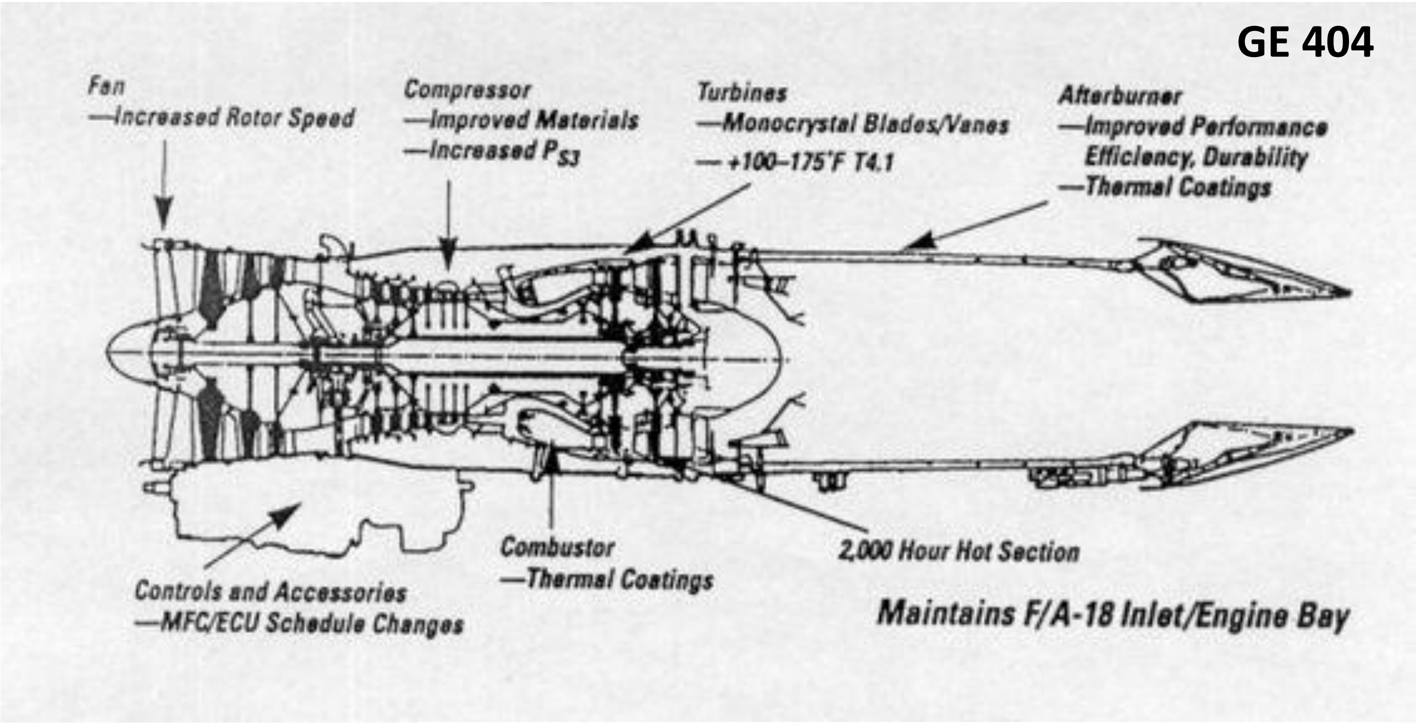
CF 6 engine

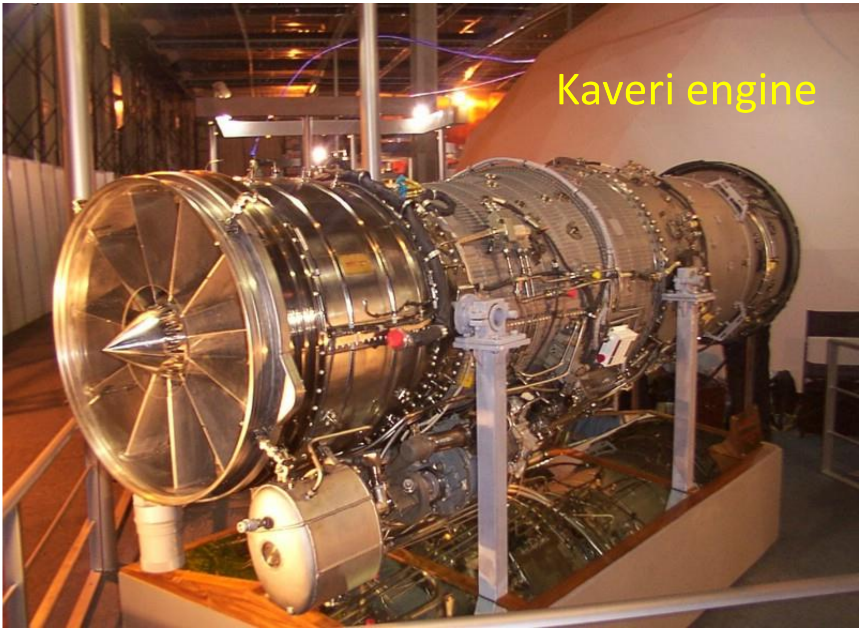


TF39 is what evolved into CF6

Bypass ratio ~ 8
CPR = 25

GE 404 – powers LCA aircraft





Military engines

Bypass ratio of original and variants ~ 0.2 to 0.3

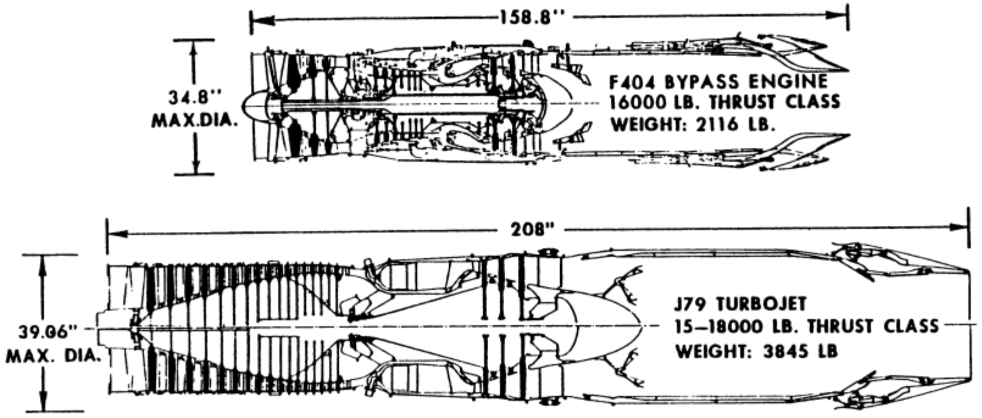
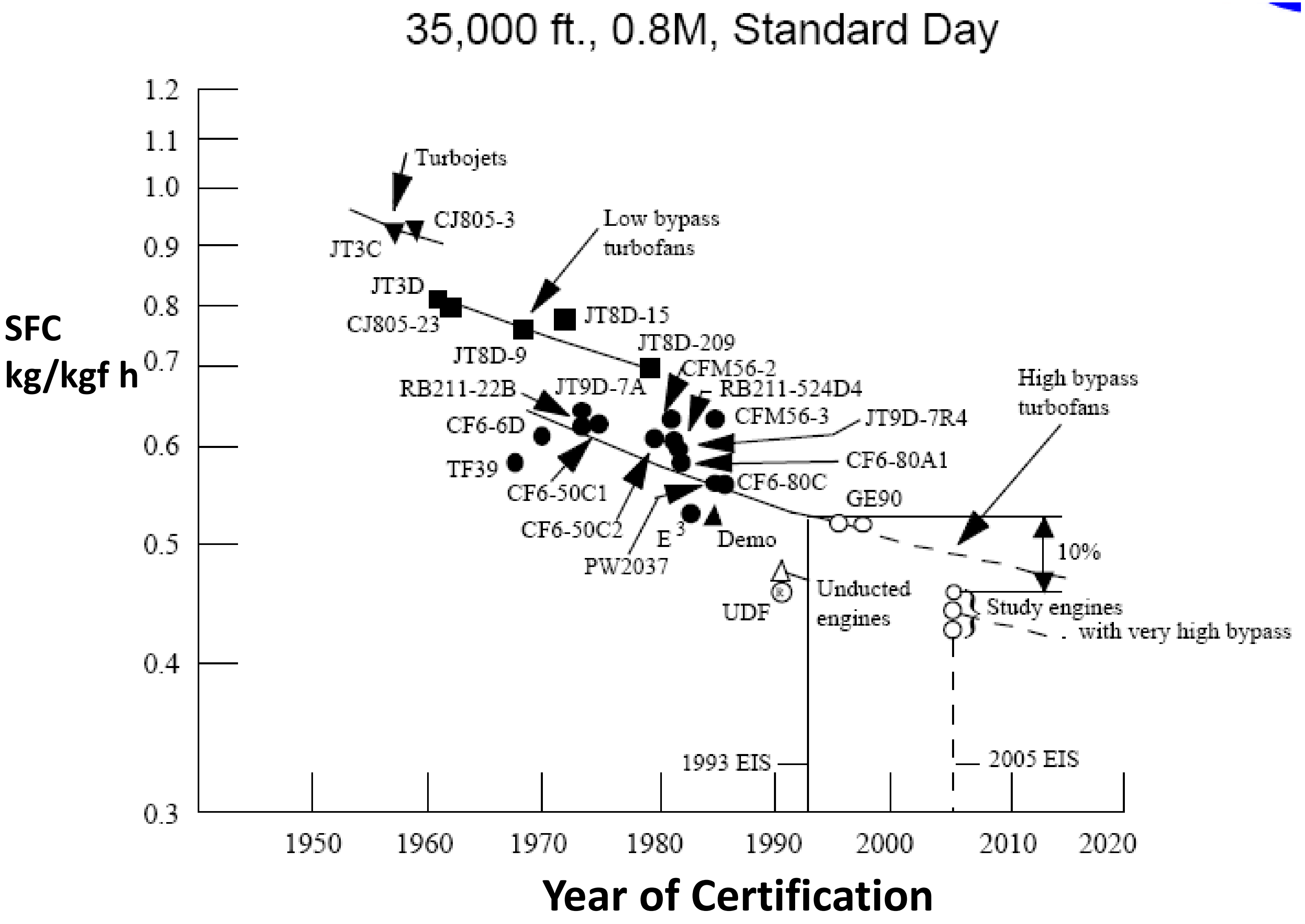
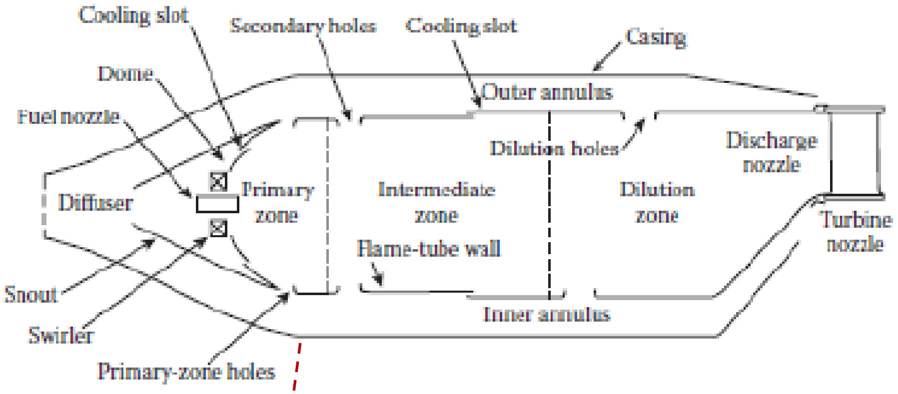


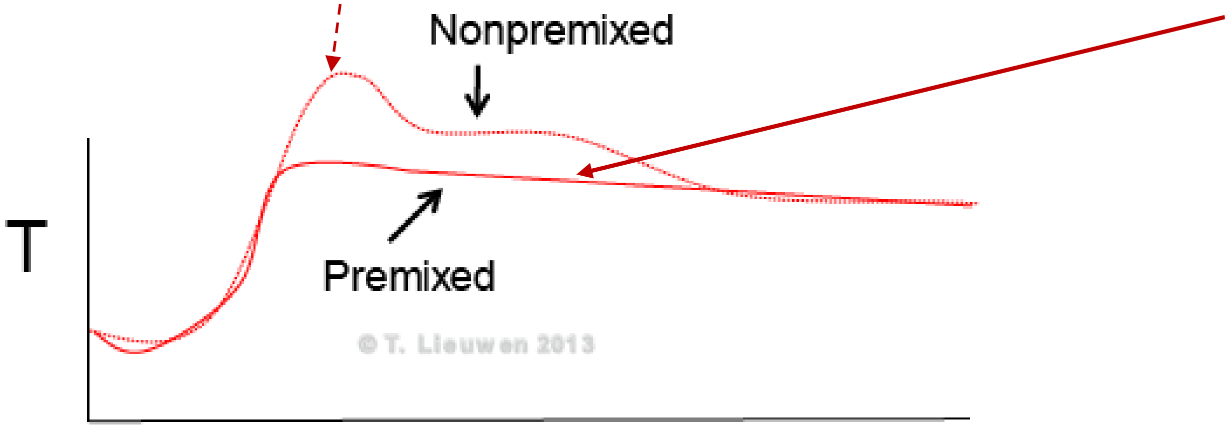
FIGURE 4-1. F404/J79 scaled cross-section comparisons.

Progress on engine efficiencies – reduction in specific fuel consumption



Old vs new approach to civil engine combustion chamber process





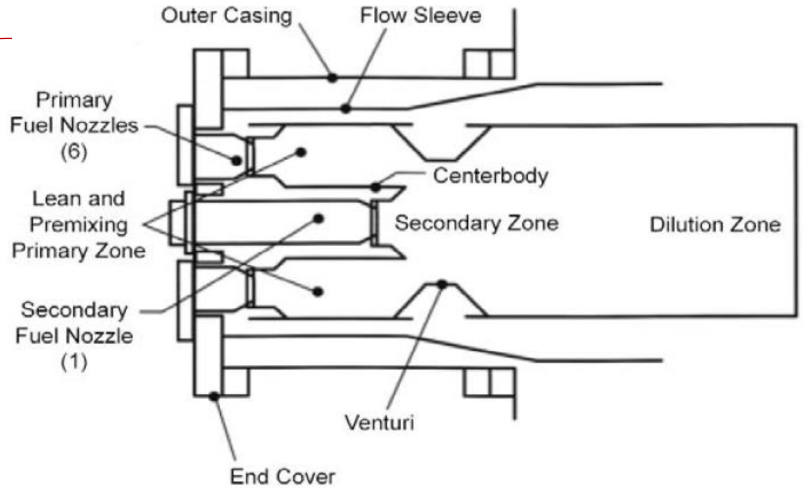
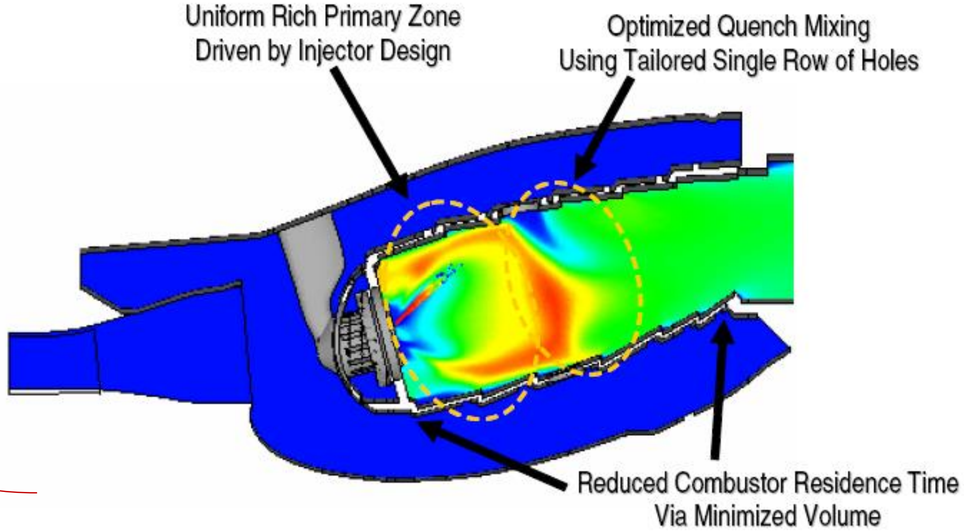


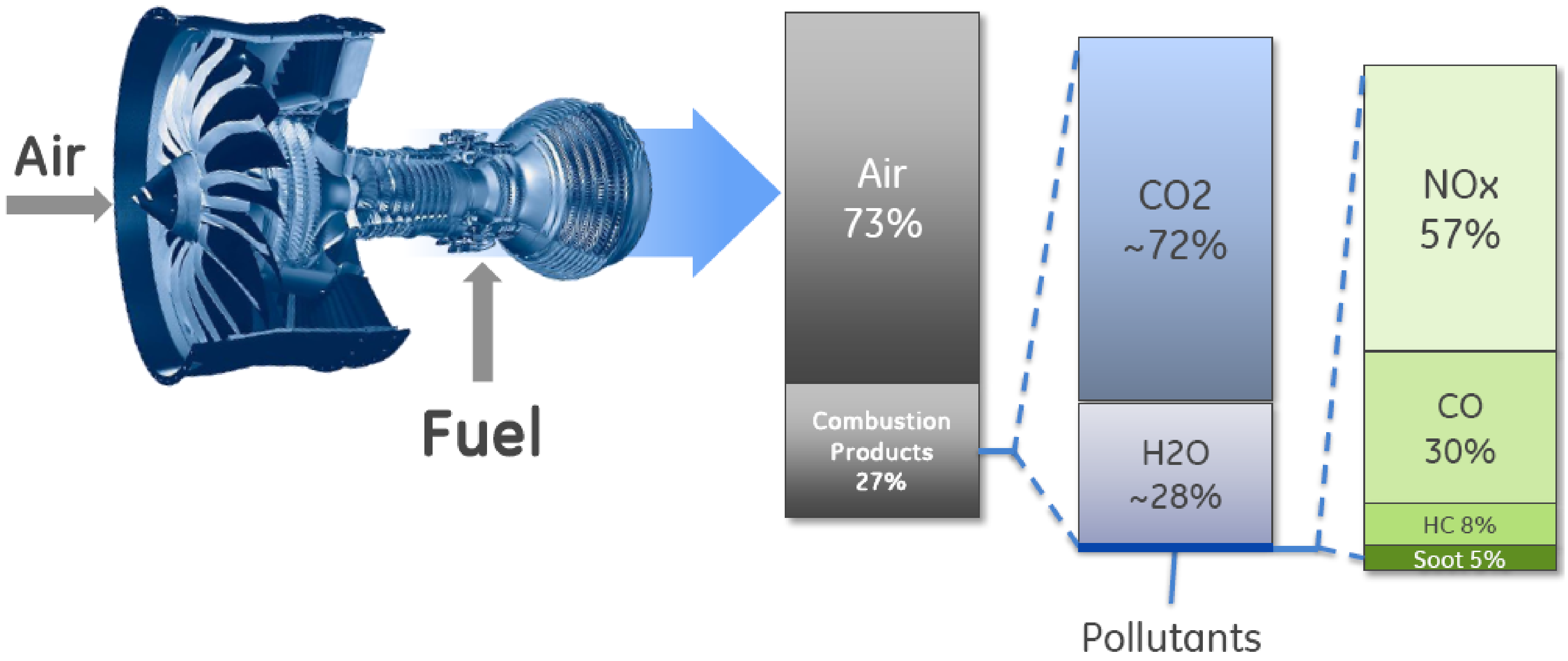
Fig. 1. Dry Low NO_x Combustor



Non-premixed flames are important even for current day military engines. The premixed combustion ideas to reduce the emissions. These have brought forth many problems of lean premixed combustion process and have

Reduction of other pollutants – NOx, CO, UHC, PM

Pollutant emissions from engines



Techniques required to reduce NO_x

NO_x production increases with temperature, But not that much under fuel rich conditions. This is because its generation is controlled by Zeldovich mechanism:

$$O + N_2 = NO + N,$$
$$N + O_2 = NO + H,$$
$$N + OH = NO + H,$$

$$d(NO)/dt = 2k_1 K_{c,f,o,Teq}(O_2)_{eq}^{1/2}(N_2)_{eq} \qquad k_f = 2\times10^{14}\exp(-315/RT)$$

Smaller residence time = smaller NO_x production
Typical residence time ~ 3 to 5 ms

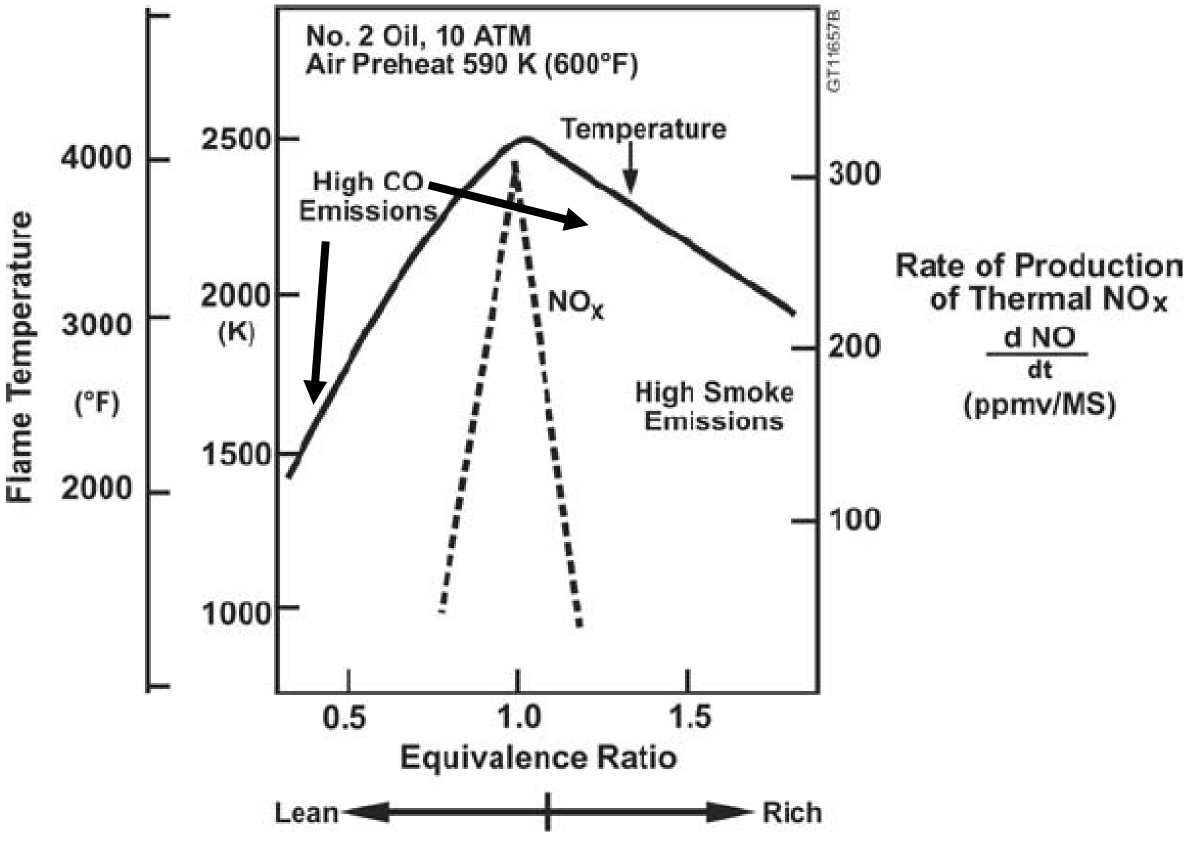
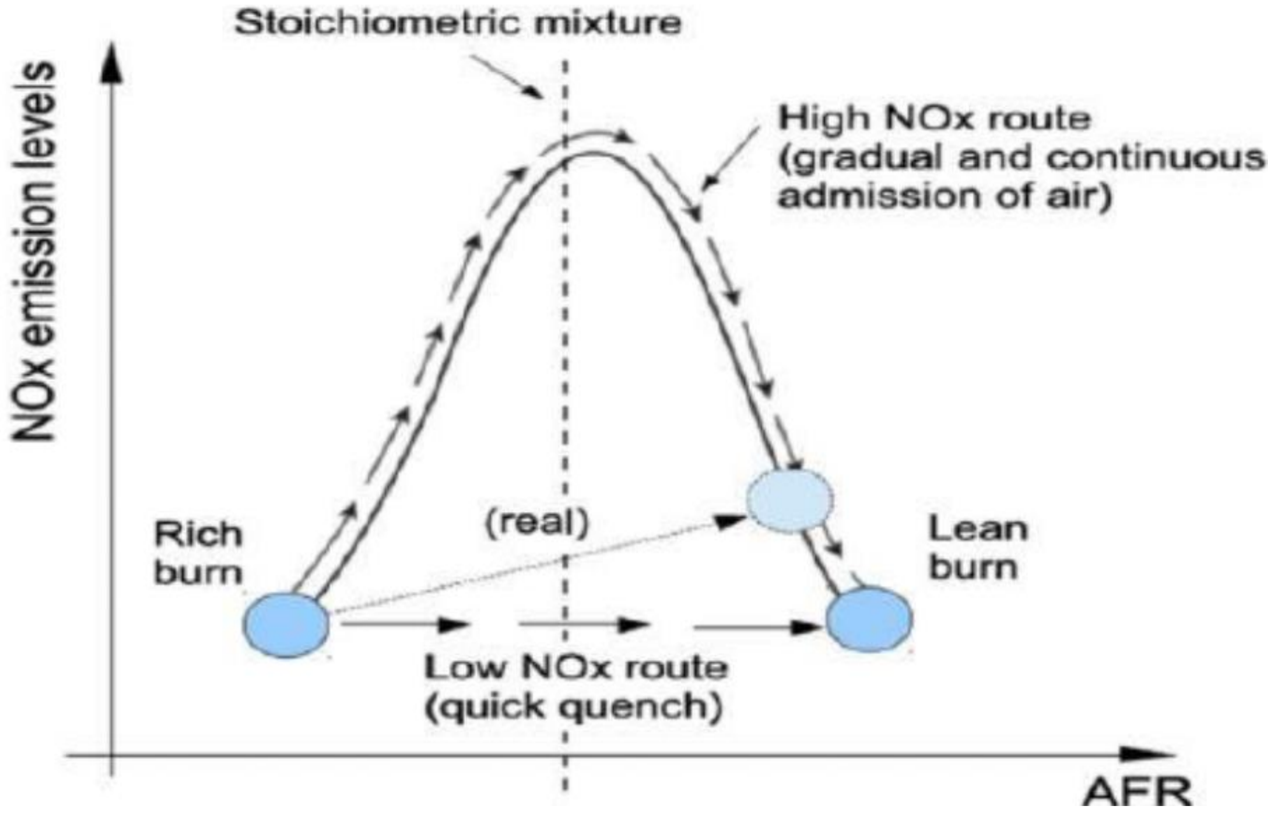


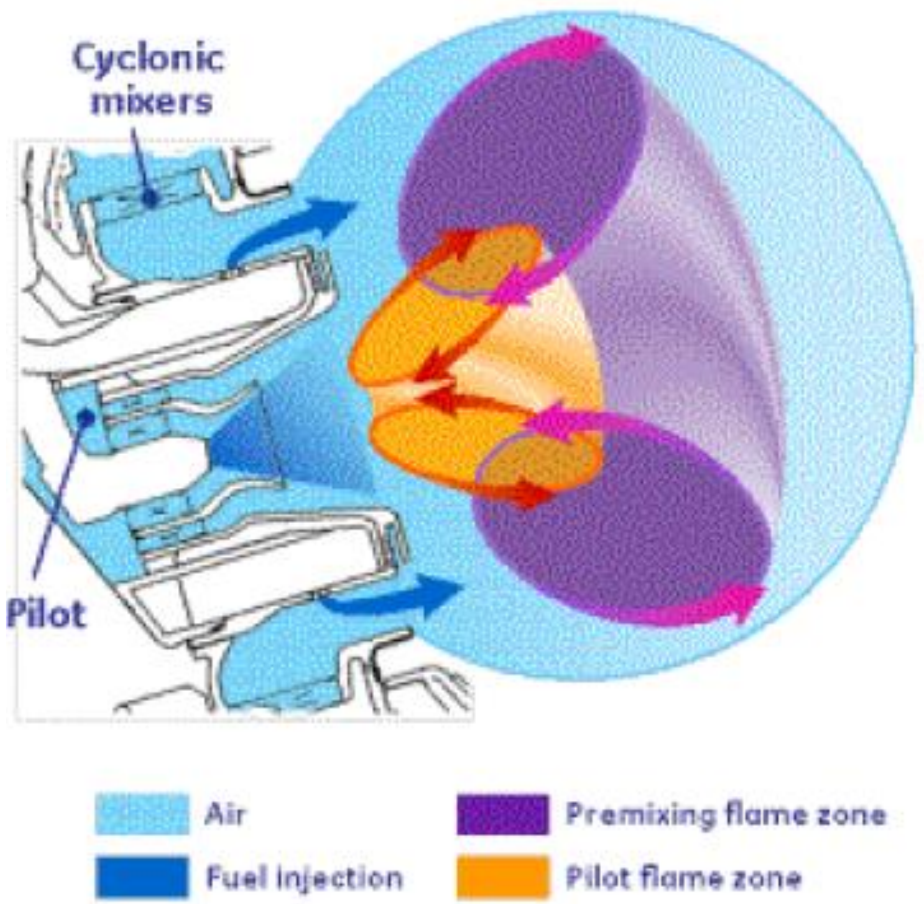
Fig. 3. NO_x Production Rate



On CO production and minimization

- There are two steps for the formation of CO. It is formed normally as a part of combustion process. Its oxidation is slower, even in a diffusion flame (another way of saying this is that its premixed burning velocity is low - 25 cm/s against 40 cm/s for methane – essentially because of chemistry).
- Even if cooling air is mixed, its conversion will not be high because of lower temperatures and reactivity. If, however, fuel rich combustion is created, its conversion will not occur and its production may be higher.
- Only if there are high temperature oxidizer rich zones, CO will come down.
- With lean operation with lower flame temperatures, and rich quench and short residence time, NOx will come down but managing CO will be a problem.
- This tight rope walk is what makes the design of new generation combustion systems for civilian applications – gas turbine based power generation and aircraft engines – very challenging.
- The fact that these have been achieved is something very heartening to note.
- Apparently, material advances may make it possible to reach higher operational temperatures (TIT), but limiting NOx may cause the operational limit.

Strategy towards minimal emissions and stable operation



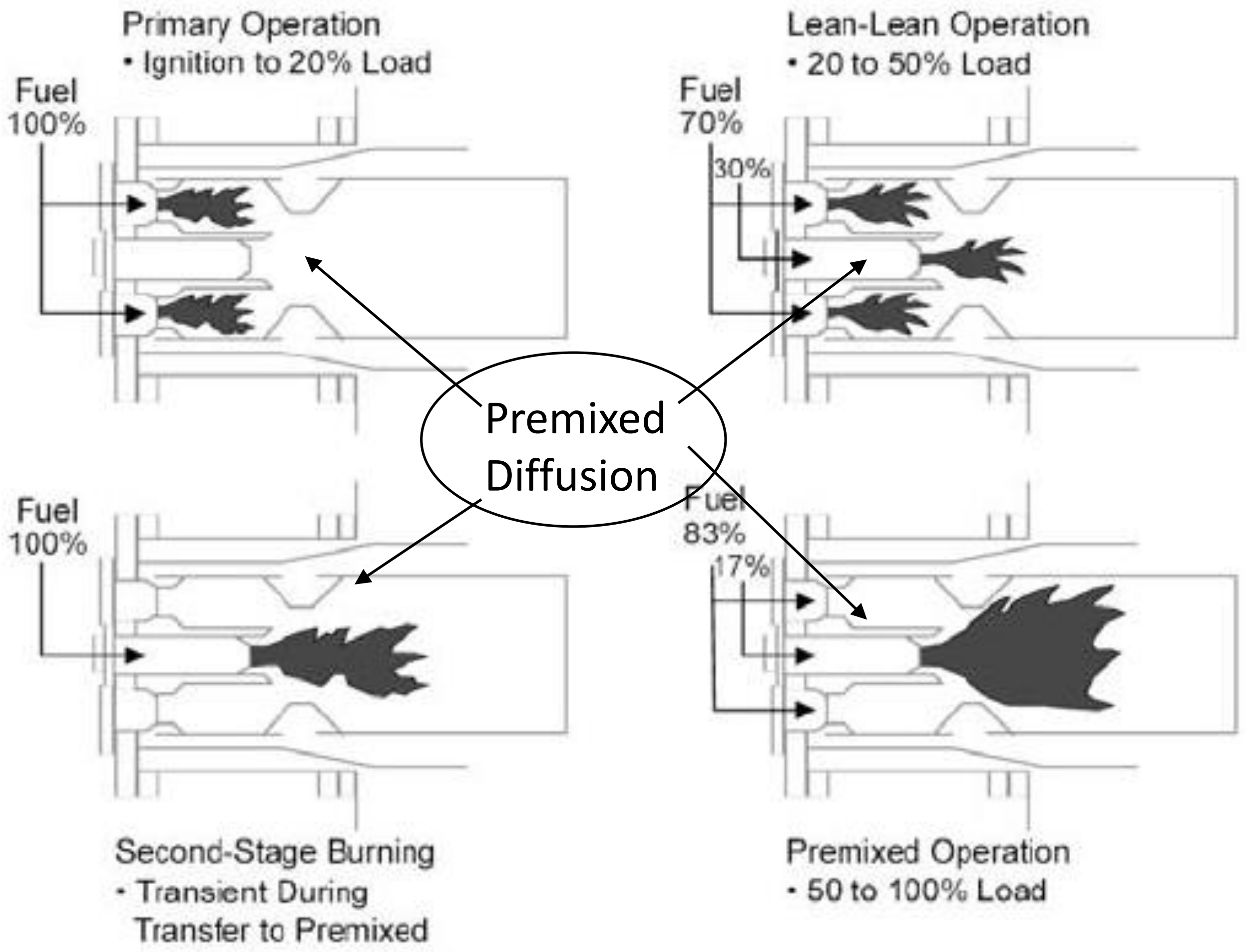


Fig. 2. Fuel-Staged Dry Low NO_x Operating Modes

We need to understand premixed combustion behavior - both steady and unsteady and also Diffusion flames

Circumferential pattern factor – F 100 engine

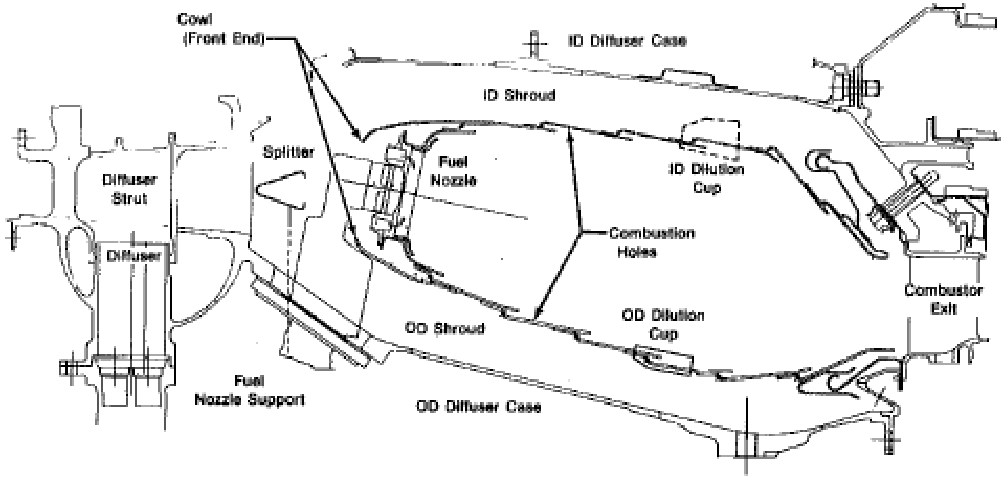


Fig. 1 F100(3) combustion system

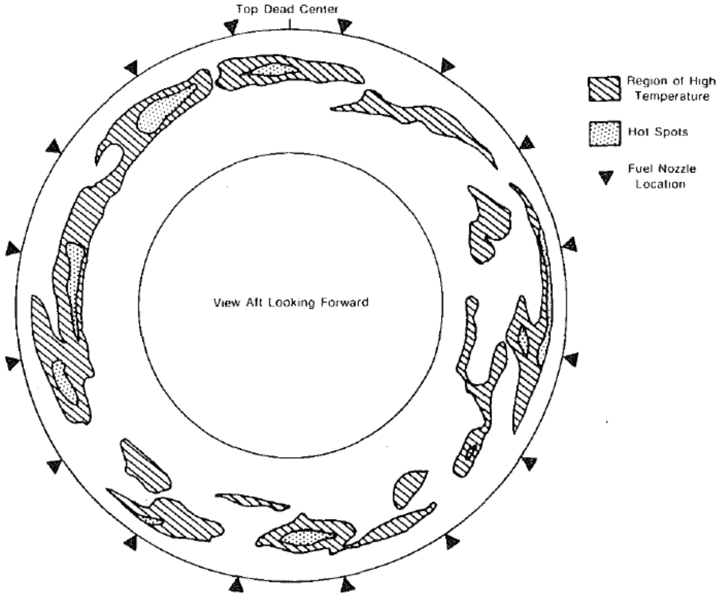


Fig. 3 F100(3) combustor exit temperature isotherm

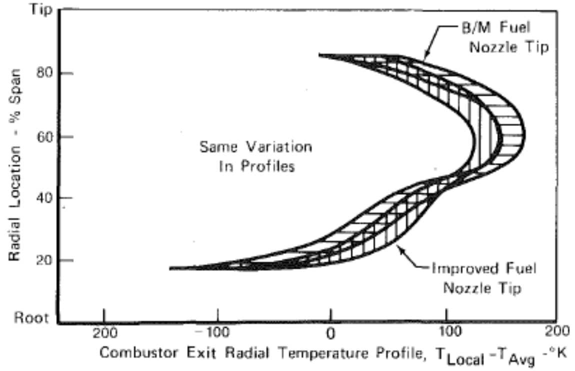


Fig. 7 **Combustor radial temperature profiles show shift in profile with improved fuel nozzle**

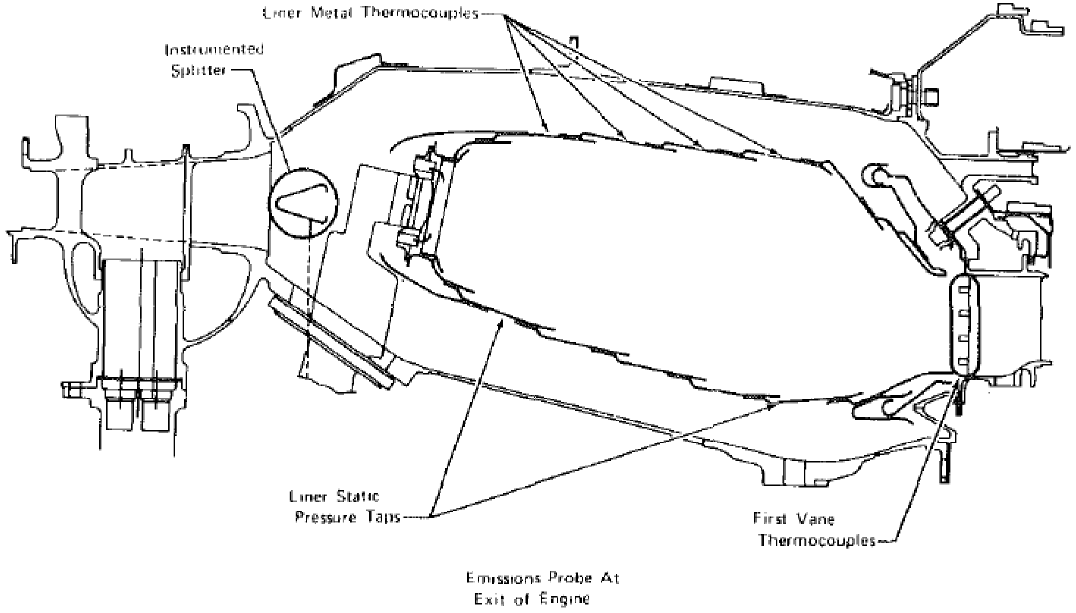
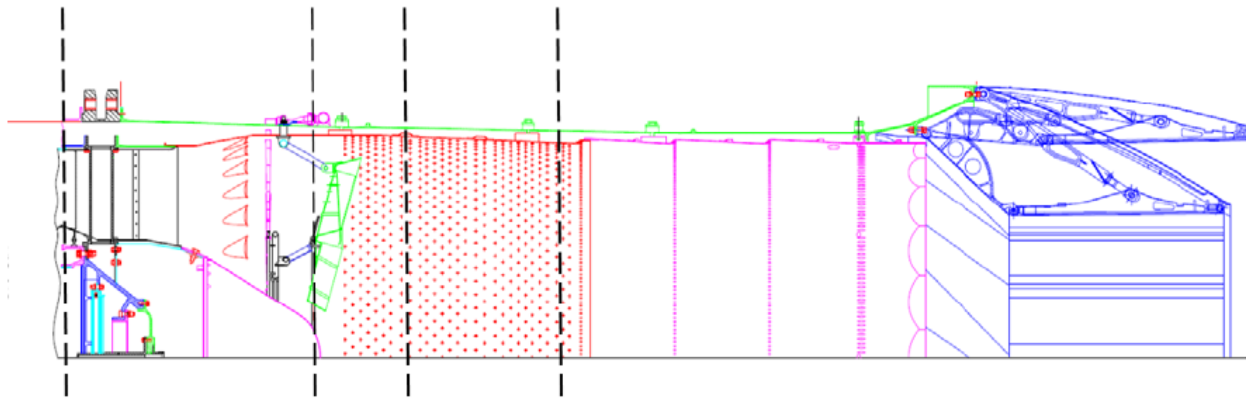


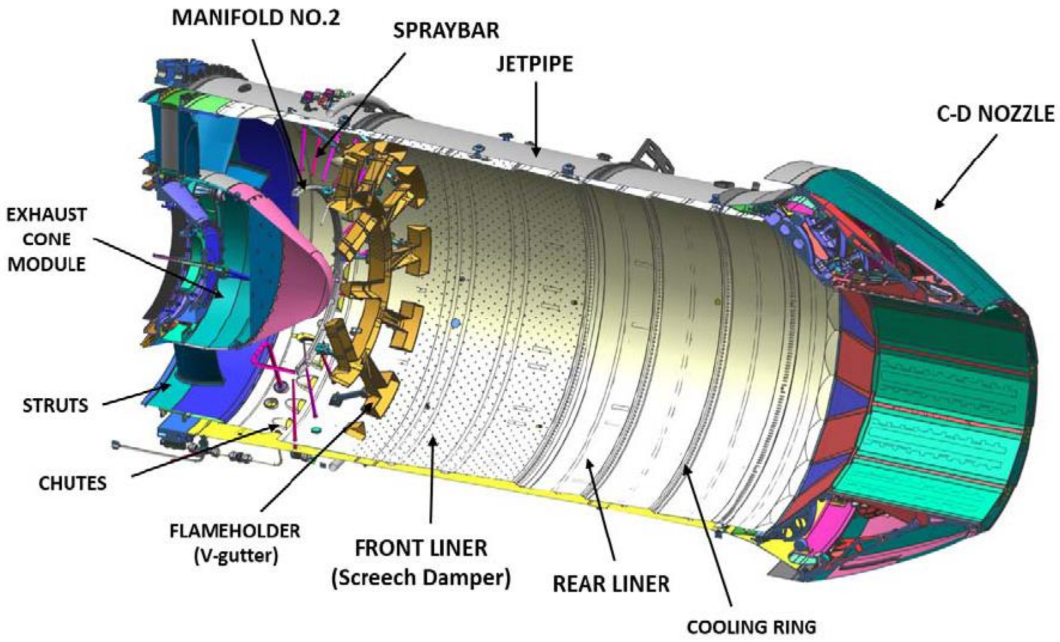
Table 1 **Combustor performance**

Heat release rate	6.65×10^8 Joules/m^3/MPa/s (6.5×10^6 Btu/ft^3/atm/hr)
Combustor temperature rise	856°C (1540°F)
Temperature pattern factor (with improved fuel nozzle)	0.35 average, 0.033 standard deviation
Liner pressure drop	2.5%
Overall pressure drop	3.8%
Front end loading	24% of combustion air
Combustor discharge temperature	1410°C (2570°F)

Subscale test rigs, full scale annular rig, and engine test program were all needed to resolve the problem. Similar problems require an additional tool – computational approach to be also brought in.

Screech (instability) in Gas turbine afterburners





- Screech is a serious problem in the afterburner of GT engines – 1st T mode, f ~ 2 kHz
- Afterburner operating conditions are: p ~ 3 - 5 atm, T ~ 2000 K.
- Heat release rates are much lower than in rocket engines where p ~ 100 atm, T ~ 3300 K.
- In rocket engines, instability is catastrophic to the hardware.
- In afterburners, it is unacceptable due to vibrations because the operation is man-rated
- The instability occurs despite acoustic damping provided by perforated liners
- The inference is that heat release (combustion) in the flow is phase-coupled with acoustics.
- Pursuit of this problem requires that the steady combustion process has to be computed accurately first.

Solid rocket engine –
composite solid propellant combustion

The rocket motor with solid propellant

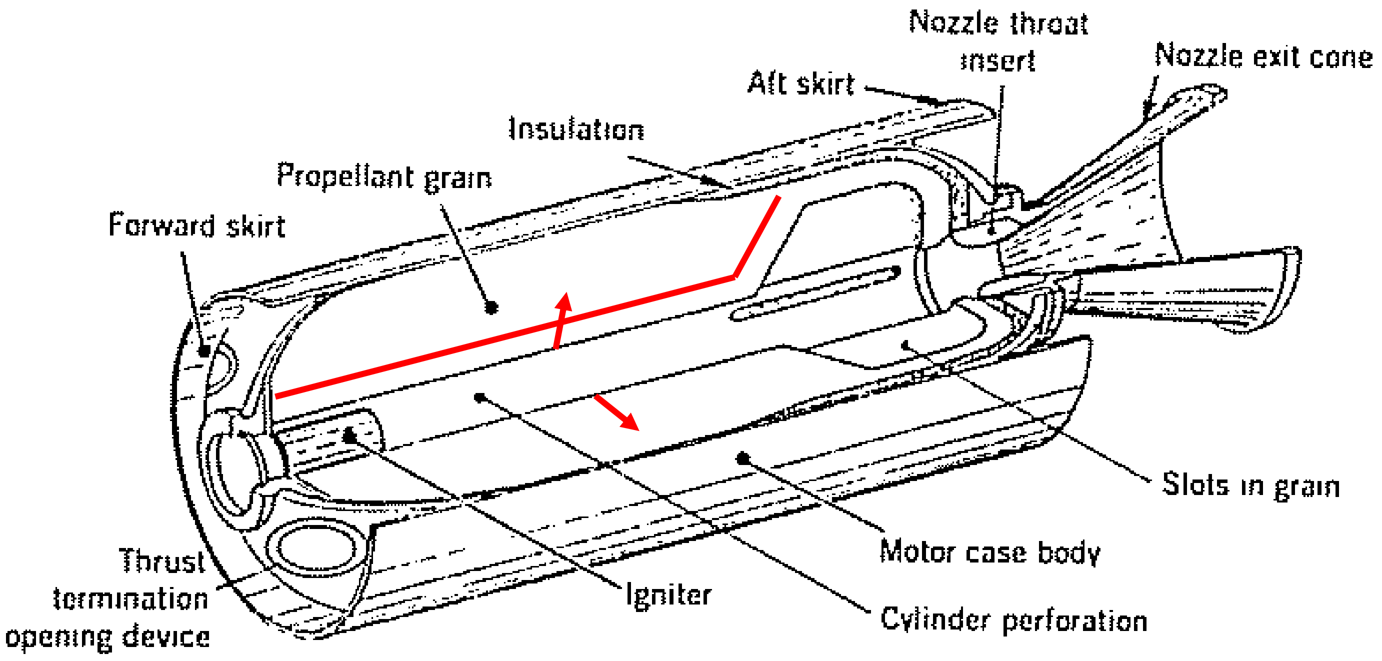
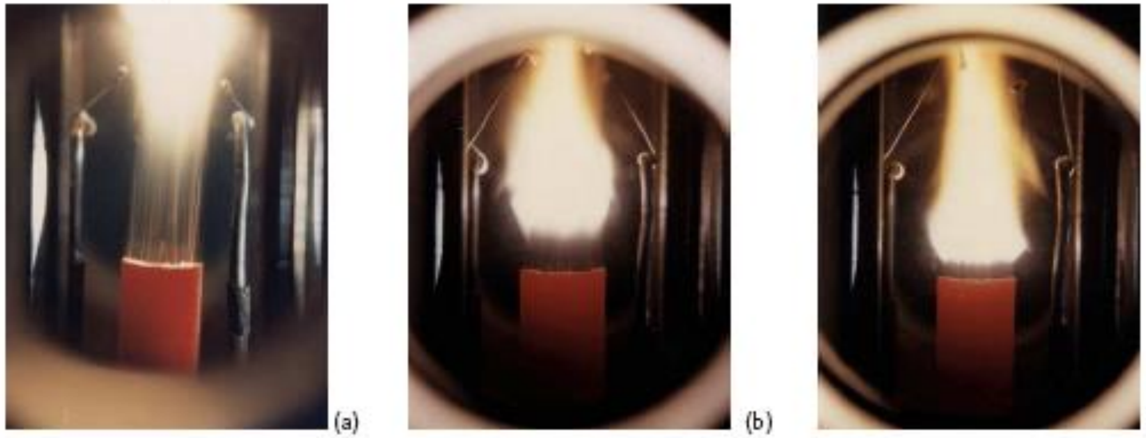


Fig. 11–1. *Simplified perspective quarter-section view of a typical solid propellant rocket motor with a case-bonded, perforated grain and a fixed nozzle. The cylindrical case with its forward and aft domes basically forms a pressure vessel. (Adapted with permission from Reference 11–1.)*

The solid propellant has both oxidizer and fuel elements in it. It burns on its own on ignition. It burns along the local normal at 1 to 30 mm/s depending on the composition, pressure (largely) and initial temperature. The flow

The Burn behavior



(a) (b) (c)

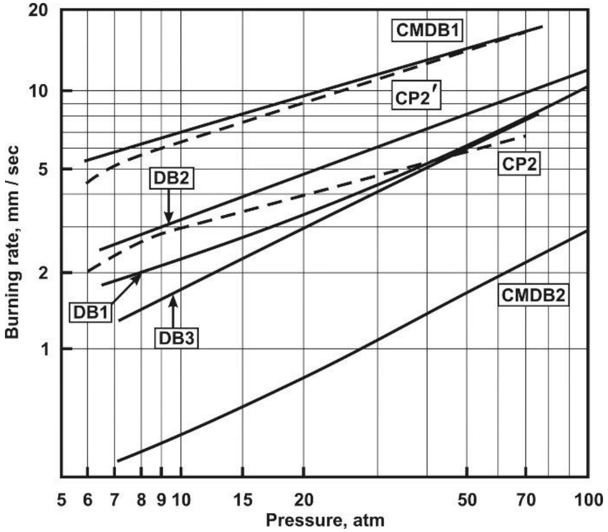
Fig. 6.4 Typical flame photographs of an NC-NG double-base propellant.

	p (MPa)	r (mm s^{-1})
(a)	1.0	2.2
(b)	2.0	3.1
(c)	3.0	4.0

7.2 Nitramine Composite Propellants

Fig. 7.34 Flame photographs of an AP composite propellant (a) and an RDX composite propellant (b) showing that the luminous flame front of the RDX composite propellant is distended from the burning surface:

	Mass fraction AP	RDX	PU	p MPa	r mm s^{-1}
(a)	0.80	–	0.20	2.0	5.3
(b)	–	0.80	0.20	2.0	1.1



$$\dot{r} = a\,p^n$$

Both a and n depend on composition

(a) (b) (c)

Fig. 7.4 Flame photographs of AP-HTPB composite propellants at low pressures:

	Mass fraction AP	HTPB	p MPa	r mm s^{-1}
(a)	0.86	0.14	0.07	1.2
(b)	0.86	0.14	0.10	1.5
(c)	0.80	0.20	0.10	1.0

Burning behavior of homogeneous and heterogeneous Propellants as a function of pressure, composition and ingredients

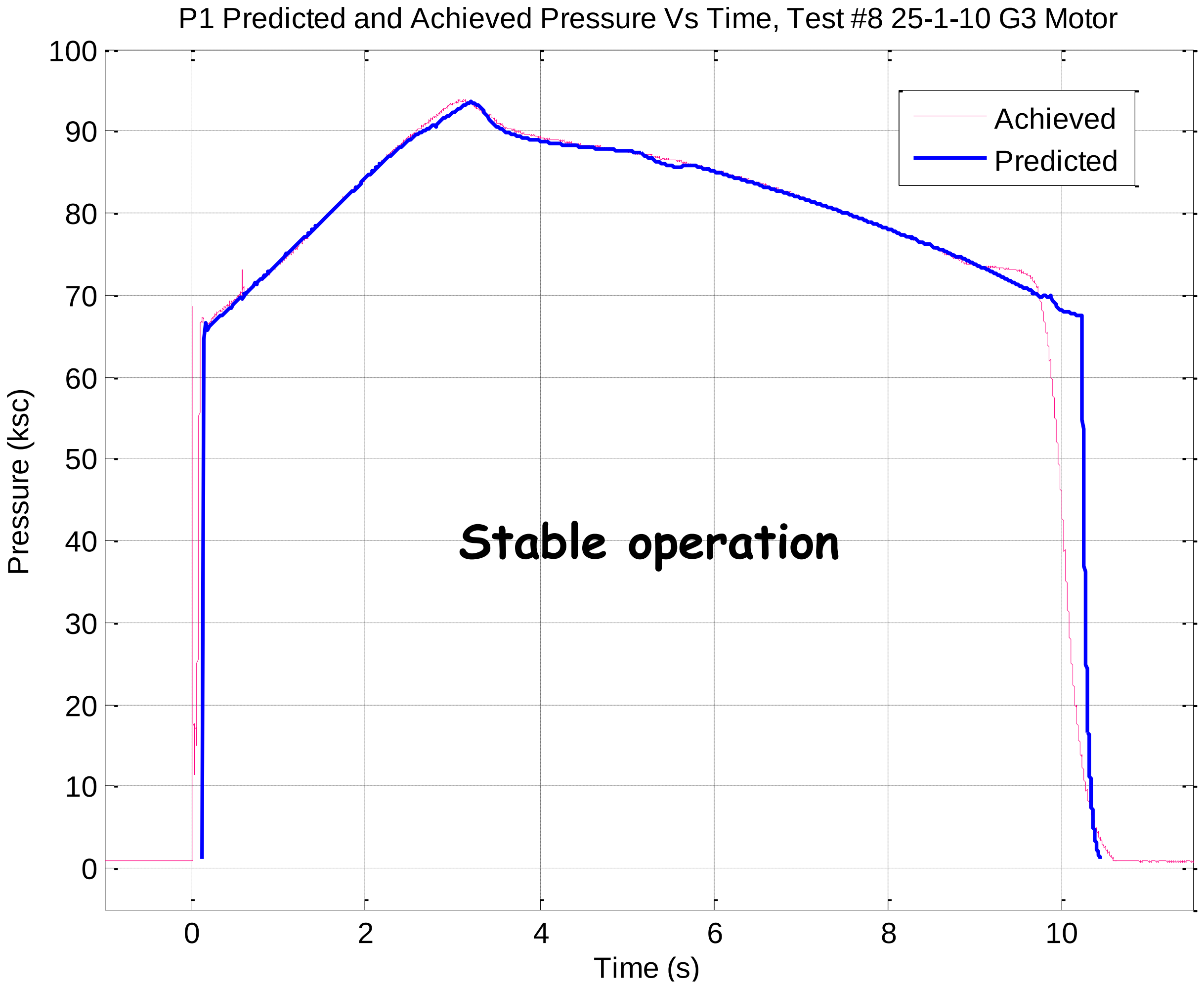
Premixed combustion – homogeneous propellant
Premixed + Diffusion in heterogeneous propellants
Rate of temperature rise - 10^4 K/mm to 10^5 K/mm
10^4 K/s to 10^5 K/s

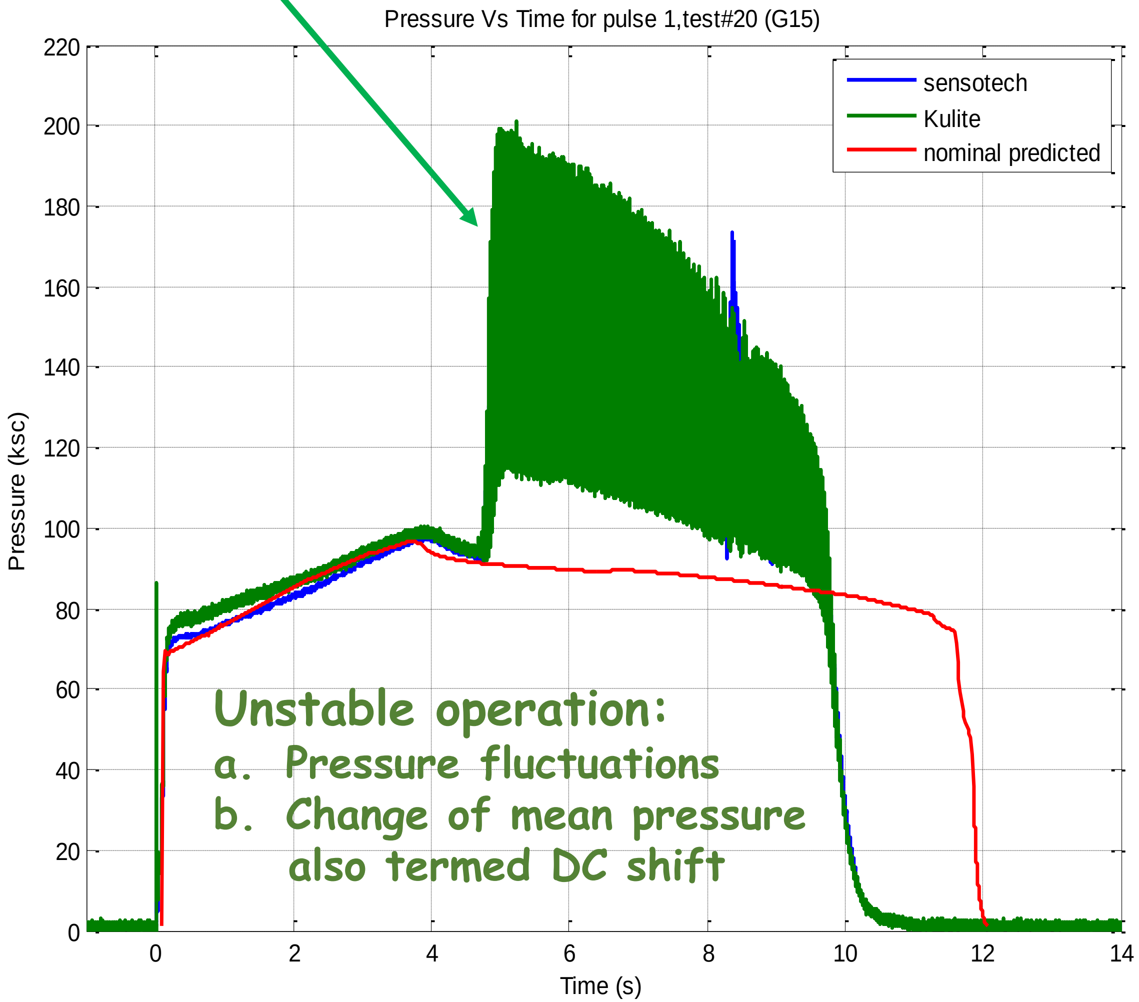
Can we predict the burn rate using combustion

Stable and unstable combustion

A composite solid propellant rocket – 2 m long, 68 mm ID, 200 mm OD

During development roughly half the time longitudinal instability was found





Why does instability occur? – Mechanisms? and how to overcome…..

Liquid propellant rockets

An overview

- Liquid propellant rockets come in a variety of sizes and for different applications.
- Monopropellants like catalytically decomposed hydrazine are used to provide thrust for satellite control (catalyst – iridium coated porous alumina particle bed)
- Relatively small rockets using storable hypergolic bipropellants – MMH (mono-methyl hydrazine) - N_2O_4 combination is used for delivering satellite into the orbit or orbit transfer maneuvers with inert gas (helium or nitrogen) pressure fed arrangements for the liquid feed system (hypergolic – self-igniting – no need for separate ignition system)
- Larger rockets use other storable hypergolic bipropellants as second or third stage propulsion systems, but with turbo pump fed arrangements with gas generator –turbine – pumps approach. The hot turbine exhaust goes through separate nozzles. p_c ~ 50 to 60 atms.
- Upper stage larger rockets use liquid oxygen and liquid hydrogen usually in the more complex, but more efficient staged combustion cycle – the products of combustion of turbo-pumps will also go into the main combustion chamber taking the chamber pressures to even up to 300 atms.
- Large lower stages use liquid oxygen and kerosene in staged combustion cycle.
- In LOX-Kerosene and LOX-LH2 systems, ignition system has to be separately included.
- Engines become very compact with increased p_c, making design difficult. One feature is supercritical operating conditions needing different equation of state and combustion behavior.

The Large thrust Engines…

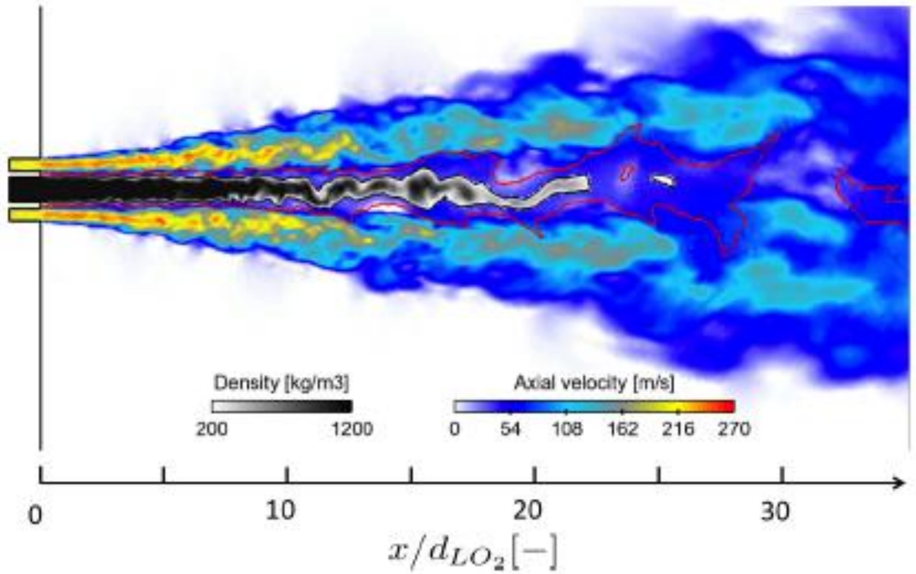
F-1 Engine (USA)
Saturn V
0.68 MN thrust (SL)
LOX/Kerosene

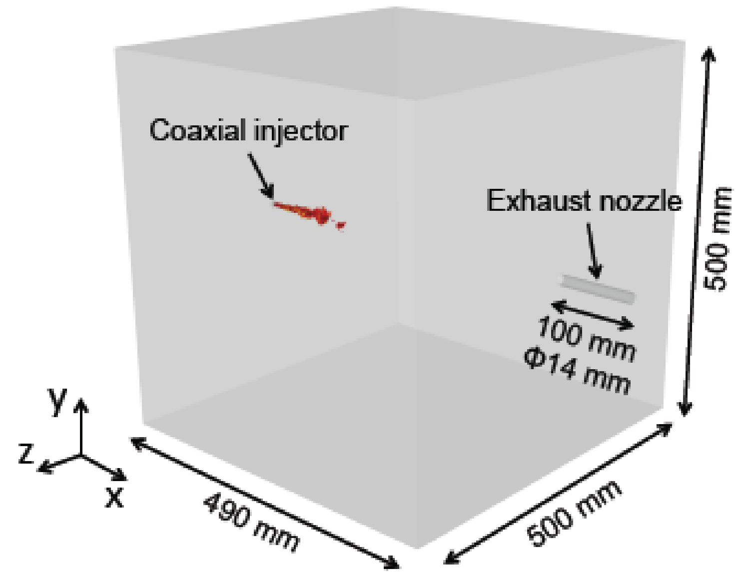
Main Engine (USA)
Space Shuttle
1.7 MN thrust (SL)
LOX/H_2

RD-170 (Russia)
8 MN thrust (SL)
LOX/Kerosene

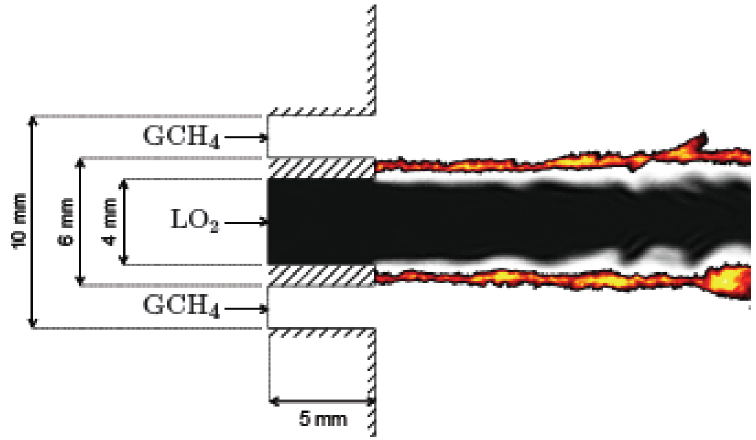
Table 1: Load point describing parameters.

LOx post		GCH_4 post		Global parameters	
$\dot{m}_{O_2}$ [g.s^{-1}]	423	$\dot{m}_{CH_4}$ [g.s^{-1}]	860	p_c [MPa]	11.7
$T^0_{O_2}$ [K]	100	$T^0_{CH_4}$ [K]	300	E [-]	0.492
$\rho^0_{O_2}$ [kg.m^{-3}]	1122	$\rho^0_{CH_4}$ [kg.m^{-3}]	88	J [-]	3.29
$u^0_{O_2}$ [m.s^{-1}]	30.0	$u^0_{CH_4}$ [m.s^{-1}]	194.4		
Re_{O_2} [-]	7.80×10^5	Re_{CH_4} [-]	5.48×10^6		





(a)



(b)

Processes in the combustion chamber of a liquid rocket engine

Issues of importance in LPRs

Injectors - coaxial or impinging variety generate liquid droplets.

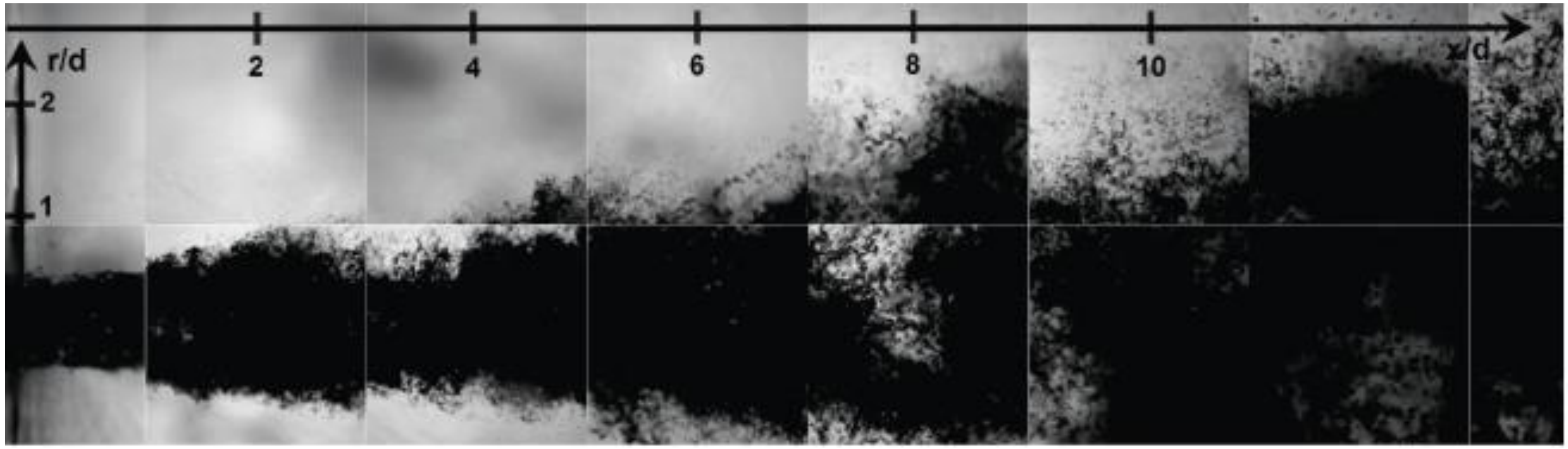
In coaxial systems, gaseous oxygen – liquid kerosene interact to generate kerosene droplets

In case of impinging jets, the impingement process generates liquid drops

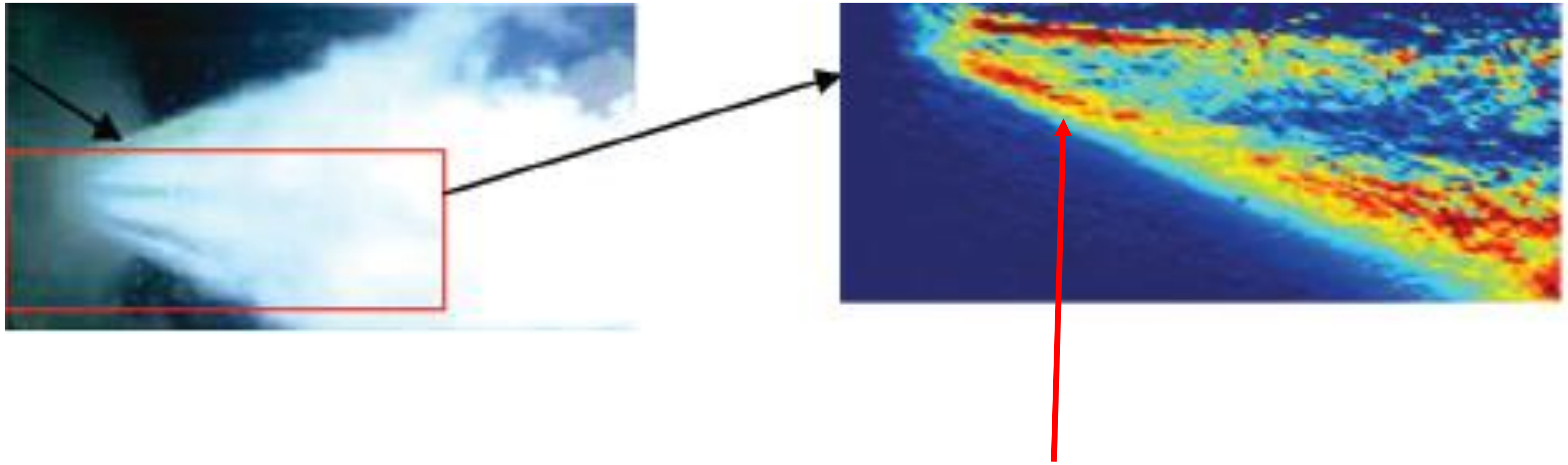
Larger injector hole diameter creates larger drops – SMD ~ d_{inj}.

This is the more accessible feature used to get better Atomization.

Injector pressure drops are typically 10 to 15 atm and cannot be varied at will, since the pressure budget gets fixed by pumps

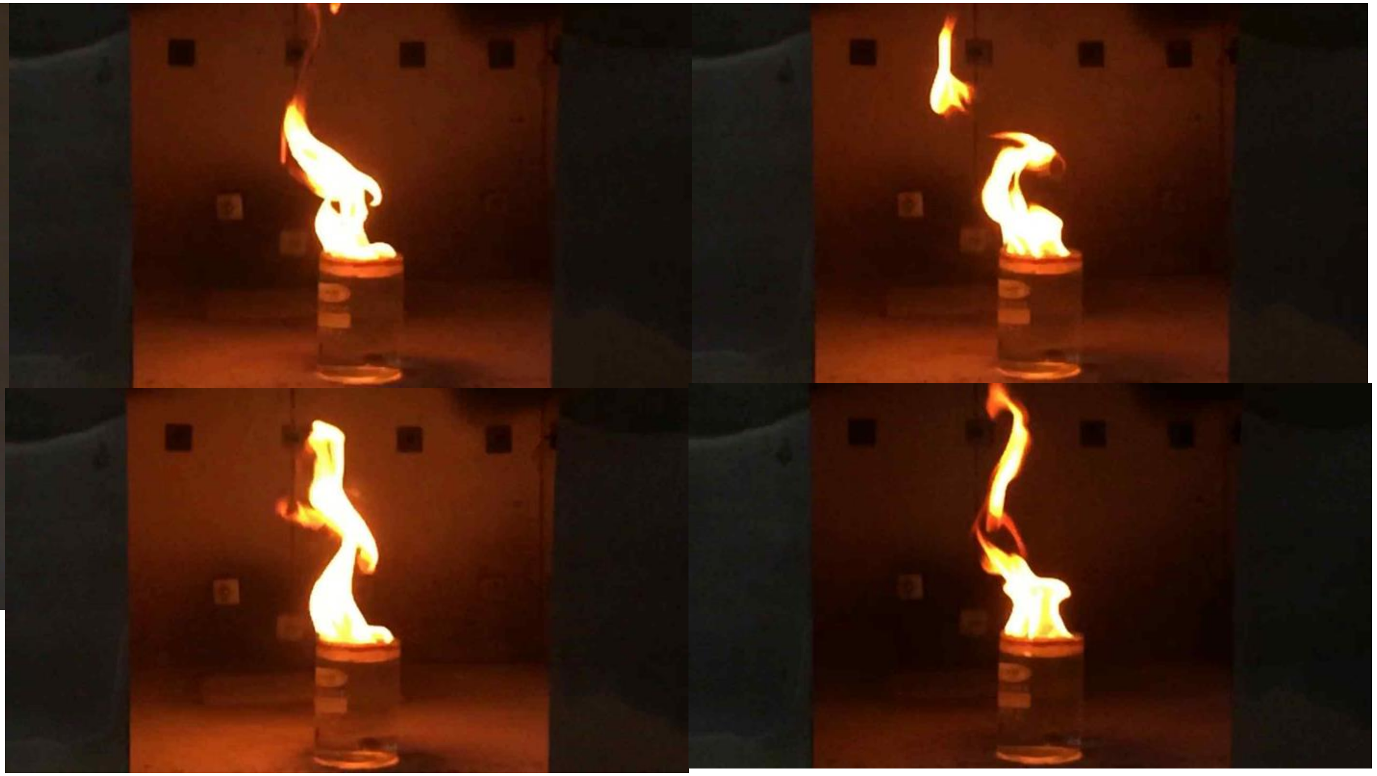


LOX injector under a Δp = 9 atm



OH* chemiluminiscence showing reaction zone

Fires – uncontrolled combustion
- Free convection dominated



Whether it is 90 mm pool fire as it is above or 2 m pool fire, all have puffs with a frequency $\sim 0.5\sqrt{g/d}$.
The latter pictures are at every 5 ms intervals. Notice the flame extinction at some points and ignition at others
This is more easily noticed since the frequency is 5 Hz or lower. For forced convection, this would be very much higher frequency

The key question is to determine the burn rate of the fuel given the geometric parameters of the pan and why the flame becomes extinguished or not extinguished in the gas phase and what controls the flame extinguishment when foam is applied.

Thus, the variety on combustion has the following fundamental aspects – at the least

- Flames are either premixed, partially premixed or diffusion.
- They have different fundamental behavior in terms of ignition, steady combustion and extinction influencing the combustion process in terms of efficiency, emissions, stability in most practical systems….It is therefore important to understand them.
- Premixed systems at stoichiometry have high heat release, but larger emissions.
- Premixed systems near limits (of lean flammability) are unstable.
- Diffusion flames are stable, but not as clean burning as premixed types.
- Practical combustion systems can be beset with local ignition and extinction phenomena – fires, higher speed combustion systems, composite solid propellants or liquid rocket engines. These need to be understood as well.

References

1. https://webpages.uidaho.edu › mindworks › IC_Engines › Sessions › SI_Engine
2. 2012, Arai, M., Physics behind diesel sprays, 12th Trienniel Int. Conf, Liquid atomization and spray systems,
3. https://webpages.uidaho.edu › mindworks › IC_Engines › Sessions › CI_Engine
4. https://ocw.mit.edu › courses › lecture-notes › MIT2_61S17_lec15
5. web.mit.edu › 2.61 › www › Lecture notes › Lec. 10 SI engine combustion II
6. https://netl.doe.gov › sites › default › files › gas-turbine-handbook
7. 2019, NASA Project develops next-generation low emissions combustor technologies, Lee etal, https://ntrs.nasa.gov/search.jsp?R=20150007508 2019-08-21T03:51:50+00:00Z
8. 2012, Development of the GE Aviation low emissions TAPS combustor for next generation aircraft engines, AIAA 2012-0936
9. 1981, Cox Jr, G. B. et al., Pattern factor improvementin the F100 primary combustion system, J. of Engg for power, p. 739+
10. 1996, Mayer, W and Tamura, H., Propellant injection in a liquid oxygen/gaseous hydrogen rocket engine, J. Prop. Power, p. 1137+
11. 2009, Haidn, O., Flame stabilization in high pressure liquid oxygewn/methane rocket engine, J. Prop. Power, p. 15+