Liquid Rocket Engine TCA

Thrust Chamber Assembly (TCA)

- **TCA**=combustion chamber+nozzle
- **Design goals**
  - produce desired thrust with high efficiency
    - high combustion efficiency and uniformity into nozzle
  - meet desired throttling range
  - minimize weight and size
    - small cc, light materials with high strength at high T and/or cooling, rapid mixing injectors
  - durability and reusability
  - relights, min. burn time
  - stable operation

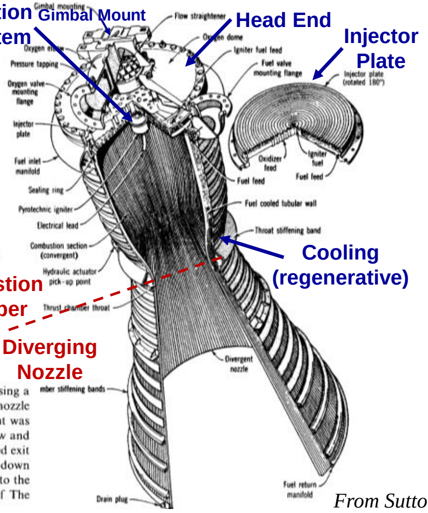


FIGURE 8–1. Construction of a regeneratively cooled tubular thrust chamber using a kerosene-type fuel and liquid oxygen, as originally used in the Thor missile. The nozzle inside diameter is about 15 in. The sea-level thrust was originally 120,000 lbf, but was uprated to 135,000, then 150,000, and finally to 165,000 lbf by increasing the flow and chamber pressure and strengthening and modifying the hardware. The cone-shaped exit cone was replaced by a bell-shaped nozzle. Figure 8–9 shows how the fuel flows down through every other tube and returns through the adjacent tube before flowing into the injector. Figure 8–4 shows the flow passages in a similar injector. (Courtesy of The Boeing Company, Rocketdyne Propulsion and Power.)

From Sutton

Combustion Chamber: Zones

- Processes in LRE (bipropellant) combustion chambers
  - – injection: liquid-liquid, liquid-gas, gas-gas
  - – vaporization, mixing
  - – heat release
    - primary compact zone
    - secondary burnout zone

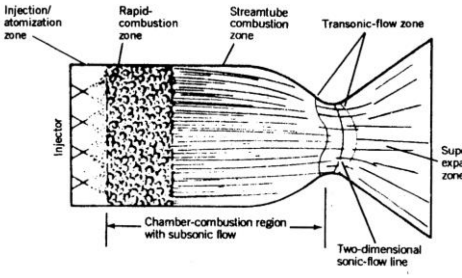


FIGURE 9–1. Division of combustion chamber into zones for analysis. (Reprinted with permission from Ref. 8–1, copyright by AIAA.)

From Sutton

Combustion Chamber Cooling Approaches

- Combustion temperatures too high for uncooled materials (high pressure = high stress)
- What needs the most cooling?
- Comb. chamber
  - – hottest and highest pressure part of TCA
- Nozzle throat
  - – hot and high heat transfer rate

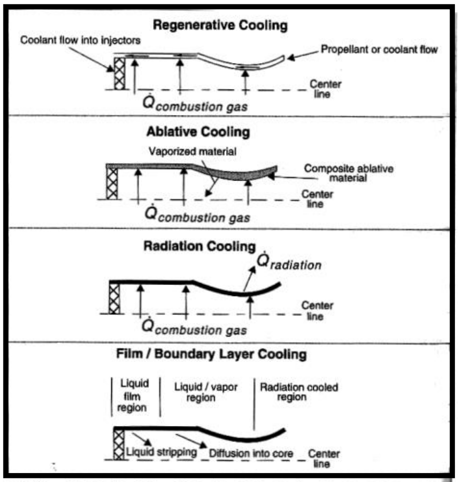


Fig. 5.28. Sketch of Techniques for Cooling the Combustion Chamber. This figure shows each of the cooling techniques work [$\dot{Q}$ = heat flow (W)].

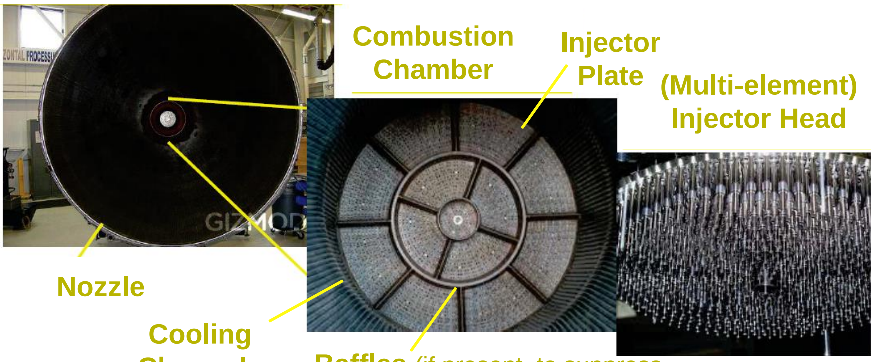
From Humble

LRE TCA

Combustion Chambers

Combustion Chambers

- Main elements: injector head, wall cooling (+ baffles)



Combustion Chamber

Injector Plate

(Multi-element) Injector Head

Nozzle

Cooling Channels

Baffles (if present, to suppress combustion instability)

From West et al., NASA MSFC

Injector (Plate) Requirements

- **Distribute propellants across combustor**
  - – uniformity
- **Rapid mixing of (fuel and oxidizer) flows**
  - – reduce combustor length
- **For subcritical liquids, good atomization**
  - – small droplets evaporate (and mix) more rapidly
  - – reduce combustor length
- **Additional constraints/goals**
  - – non-excessive pressure drop
  - – low start-up and shut-down (dribble) transients
  - – minimize sensitivity to acoustic fluctuations

Example Monopropellant (N_2H_4) Injectors

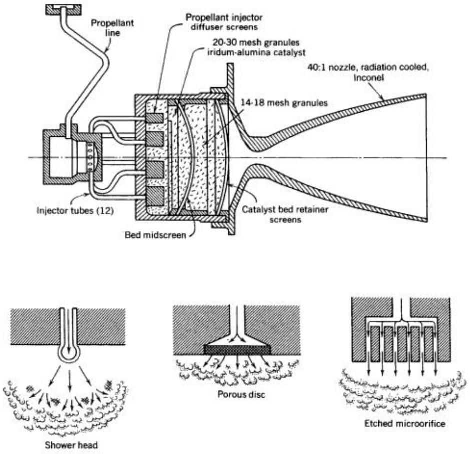


FIGURE 8–16. Typical hydrazine monopropellant small thrust chamber with catalyst bed, showing different methods of injection.

- Liquid injected into catalytic reaction chamber
- Disperse propellant across bed

From Sutton

Example Bi-propellant Injectors

- Impinging type
  - use (liquid) momentum to atomize and mix
- Coaxial type
  - liq.-liq., gas-liq. or gas-gas
  - also use momentum (shear) to induce mixing, breakup liquid
  - can include swirl

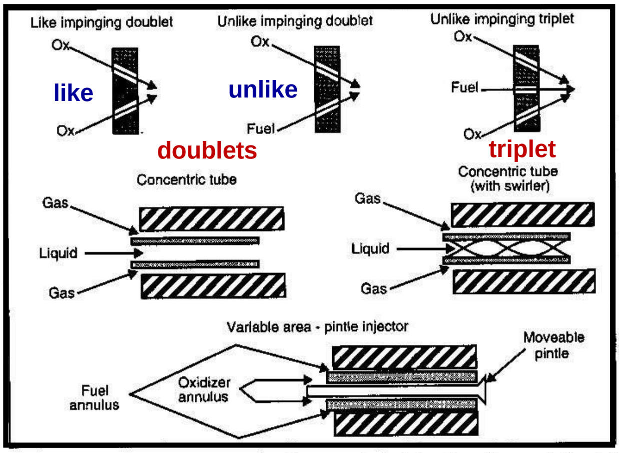


Fig. 5.27. **Typical Injector Assemblies.** These are the typical configurations used. They includ doublets, triplets, concentric tubes, and the pintle injector.

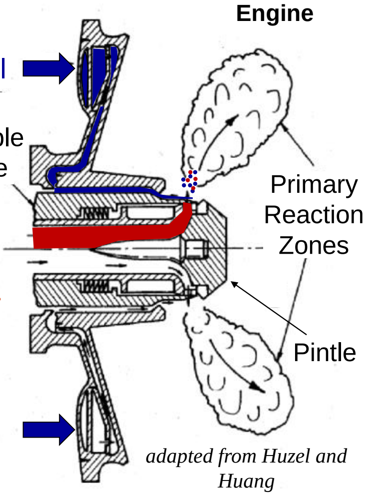
From Humble

Film/Crossflow Injectors

- Can also use crossflow momentum instead of coaxial momentum to induce breakup and mixing
- Thin liquid sheets/films can produce small droplets

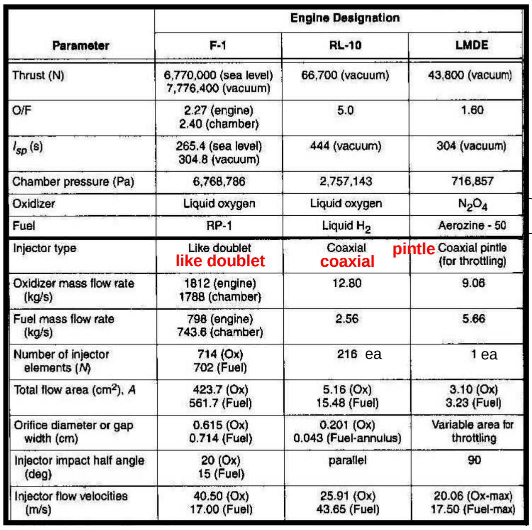
Apollo Lunar Module Descent Engine

space.nss.org



adapted from Huzel and Huang

Historical Engine Examples



Parameter	Engine Designation F-1	RL-10	LMDE
Thrust (N)	6,770,000 (sea level) 7,776,400 (vacuum)	66,700 (vacuum)	43,800 (vacuum)
O/F	2.27 (engine) 2.40 (chamber)	5.0	1.60
I_{sp} (s)	265.4 (sea level) 304.8 (vacuum)	444 (vacuum)	304 (vacuum)
Chamber pressure (Pa)	6,768,786	2,757,143	716,857
Oxidizer	Liquid oxygen	Liquid oxygen	N_2O_4
Fuel	RP-1	Liquid H_2	Aerozine - 50
Injector type	Like doublet like doublet	Coaxial coaxial	pintle Coaxial pintle (for throttling)
Oxidizer mass flow rate (kg/s)	1812 (engine) 1788 (chamber)	12.80	9.06
Fuel mass flow rate (kg/s)	798 (engine) 743.6 (chamber)	2.56	5.66
Number of injector elements (*N*)	714 (Ox) 702 (Fuel)	216 ea	1 ea
Total flow area (cm^2), *A*	423.7 (Ox) 561.7 (Fuel)	5.16 (Ox) 15.48 (Fuel)	3.10 (Ox) 3.23 (Fuel)
Orifice diameter or gap width (cm)	0.615 (Ox) 0.714 (Fuel)	0.201 (Ox) 0.043 (Fuel-annulus)	Variable area for throttling
Injector impact half angle (deg)	20 (Ox) 15 (Fuel)	parallel	90
Injector flow velocities (m/s)	40.50 (Ox) 17.00 (Fuel)	25.91 (Ox) 43.65 (Fuel)	20.06 (Ox-max) 17.50 (Fuel-max)

LMDE=Lunar Module Descent Engine

hypergolics

Multi-element vs uni-element

From Humble,Table 5.9

Multi-element Injector Head/Plate

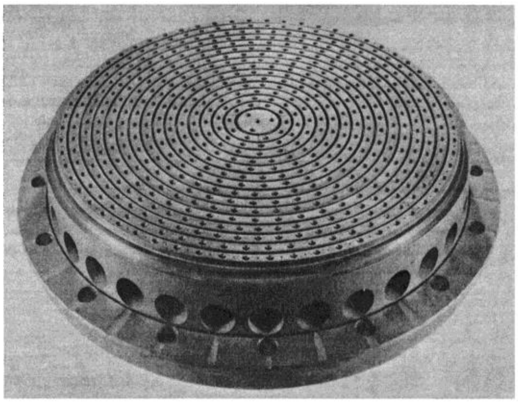


FIGURE 8–4. Injector with 90° self-impinging (fuel-against-fuel and oxidizer-against-oxidizer)-type countersunk doublet injection pattern. Large holes are inlets to fuel manifolds. Pre-drilled rings are brazed alternately over an annular fuel manifold or groove and a similar adjacent oxidizer manifold or groove. A section through a similar but larger injector is shown in Fig. 8–1.

From Sutton

Multi-element Injector Fabrication

- Can be as simple as holes drilled in injector face
  - US historic except LH_2

or

- More complex spray-type injectors that are inserted and/or fastened (e.g., welded) into injector face
  - LH2 + historic Russian + …

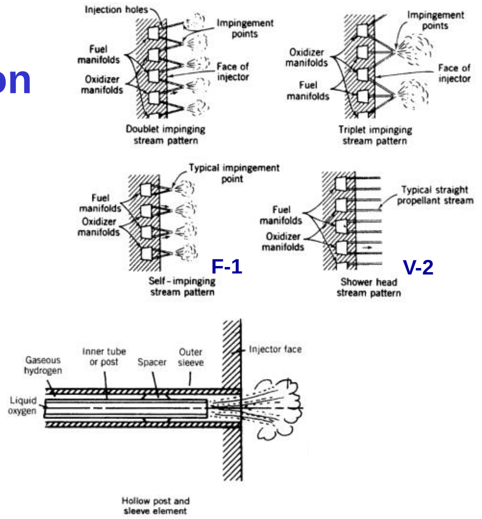


FIGURE 8–3. Schematic diagrams of several injector types. variable thrust injector is adapted from Ref. 8–1.

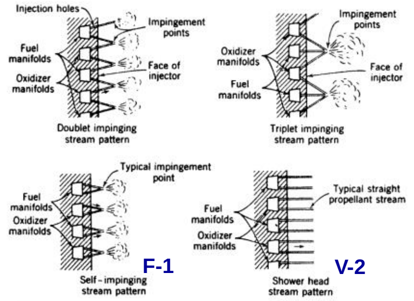
From Sutton

Multi-element Injector Fabrication

- Can be as simple as holes drilled in injector face
  - US historic except LH_2

or

- More complex spray-type injectors that are inserted and/or fastened (e.g., welded) into injector face
  - LH2 + historic Russian + …



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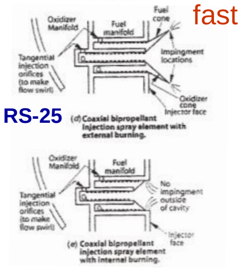


(*d*) Coaxial bipropellant injection spray element with external burning.

(*e*) Coaxial bipropellant injection spray element with internal burning.

From Sutton

New Fabrication Approaches

- Can lower manufacturing and development costs, and allow for more complex designs
    - monolithic structures formed from stacked, etched plates (platelets) bonded together (Aerojet)
    - additive manufacturing

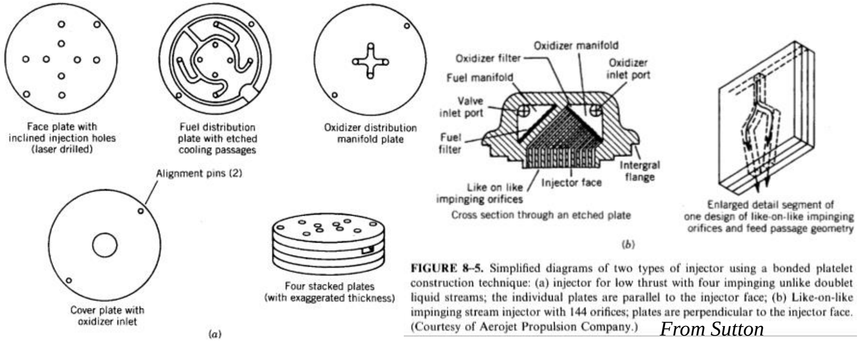
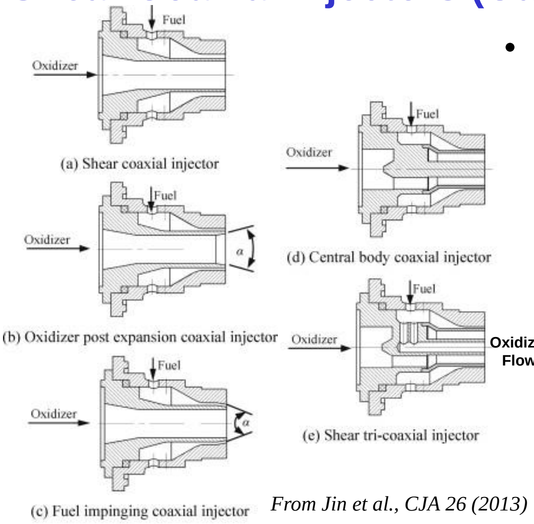


FIGURE 8–5. Simplified diagrams of two types of injector using a bonded platelet construction technique: (a) injector for low thrust with four impinging unlike doublet liquid streams; the individual plates are parallel to the injector face; (b) Like-on-like impinging stream injector with 144 orifices; plates are perpendicular to the injector face. (Courtesy of Aerojet Propulsion Company.)

From Sutton

Shear Coaxial Injectors (Gas-Gas Examples)

- Use shear forces to entrain and mix jets



(a) Shear coaxial injector

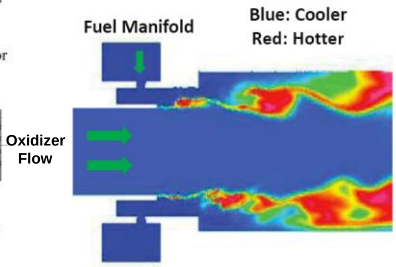
(b) Oxidizer post expansion coaxial injector

(c) Fuel impinging coaxial injector

(d) Central body coaxial injector

(e) Shear tri-coaxial injector

From Jin et al., CJA 26 (2013)

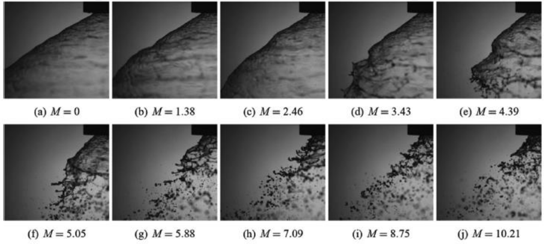


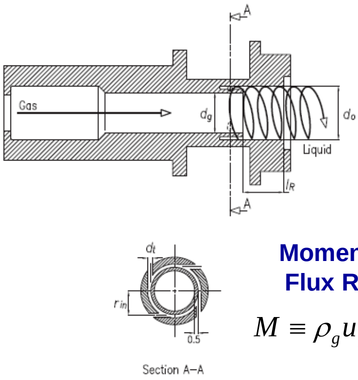
From West et al., NASA MSFC

Swirl Gas-Liquid Injector

- Swirl and shear ⇒ enhanced atomization and mixing
  - common for LH2/LOX
  - also HC fuels

Example for subcritical injection (p=1 atm)





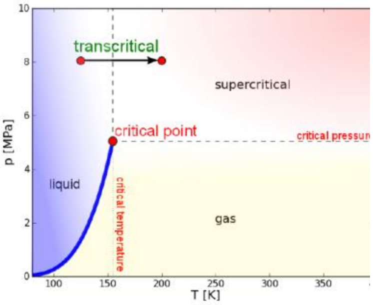
Momentum Flux Ratio

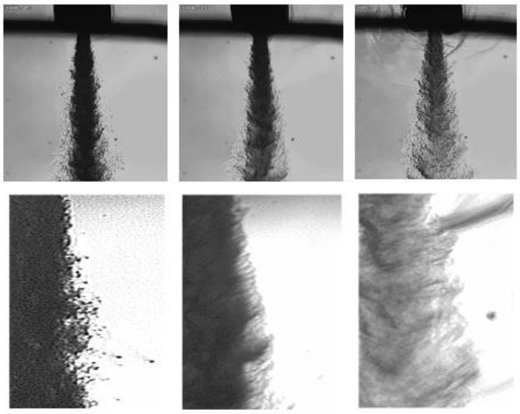
$$M \equiv \rho_g u_g^2 \big/ \rho_l u_l^2$$

From Jeon et al., J. Fluids Engin. 133 (2011)

Supercritical Injection

- Atomization no longer occurs





(a) Pr=0.91 Re=75,281

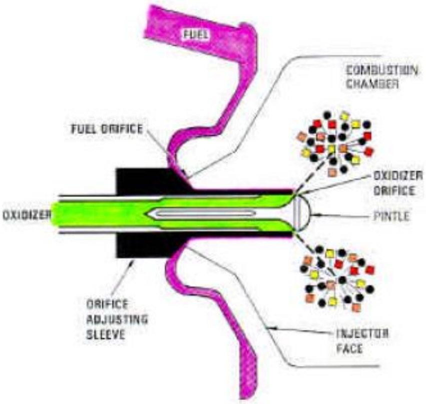
(b) Pr=1.22 Re=66,609

(c) Pr=2.71 Re=42,830

Right from Chehroudi et al., 5th International Conference on Liquid Rocket Propellant (2003)

Pintle Type Injector

- Origin in mid 1950's at JPL
- Pros
  - allows for deep throttling and injector face shutoff
  - potentially reduced development costs
  - resistance to combustion instability
- Cons
  - non-optimized mixing and uniformity
  - requires fine control of moving parts
- Examples: LMDE, Merlin



From Dressler and Bauer, AIAA 2001-3871

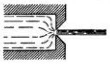
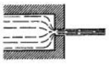
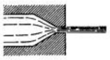
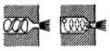
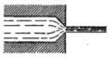
Choosing Injector Type

- Assuming bipropellant LRE, major considerations are
  - hypergolic or not
    - must prevent any premixing of propellants
    - historically impingement-type, pintle on LMDE
  - physical state
    - liquid-liquid (e.g., RP-1/LOX gas generator)
    - gas-liquid (e.g., LH2/LOX expander)
    - gas-gas (e.g., full-flow staged-combustion)

not impingement type

Discharge Coefficients, Sizing

TABLE 8–2. Injector Discharge Coefficients

Orifice Type	Diagram	Diameter (mm)	Discharge Coefficient
Sharp-edged orifice		Above 2.5 Below 2.5	0.61 0.65 approx.
Short-tube with rounded entrance $L/D > 3.0$		1.00 1.57 1.00 (with $L/D \sim 1.0$)	0.88 0.90 0.70
Short tube with conical entrance		0.50 1.00 1.57 2.54 3.18	0.7 0.82 0.76 0.84–0.80 0.84–0.78
Short tube with spiral effect		1.0–6.4	0.2–0.55
Sharp-edged cone		1.00 1.57	0.70–0.69 0.72

From Sutton

- Flowrates from Δp

$$\frac{\dot m}{\rho} = Q = C_D A\sqrt{\frac{2\Delta p}{\rho}}$$

$$\frac{\dot m_{ox}}{\dot m_f} = \frac{C_{D,ox}}{C_{D,f}}\frac{A_{ox}}{A_f}\sqrt{\frac{\Delta p_{ox}/\Delta p_f}{\rho_{ox}/\rho_f}}$$

- Generally, better atomization and resistance to combustion instability for higher injection velocity

$$\mathrm{v}_{inject} = Q = C_D\sqrt{\frac{2\Delta p}{\rho}}$$

Impingement Injectors: Angles

- Good atomization typically found for mostly axial momentum after jet impingement
  - for unlike doublet-impinging injector with jet momentum conserved and no net transverse momentum (δ=0) $\Rightarrow$ $\boxed{\frac{\sin\gamma_{ox}}{\sin\gamma_f} = \frac{\dot m_f \mathrm{v}_f}{\dot m_{ox}\mathrm{v}_{ox}}}$

like-injector will typically use symmetric angles

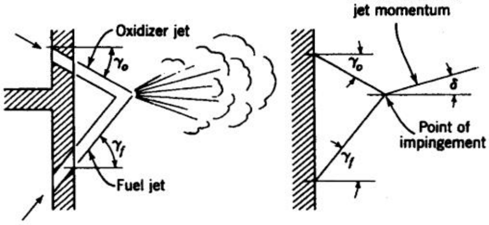
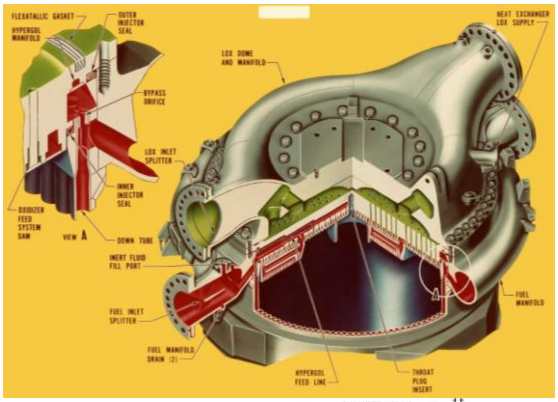


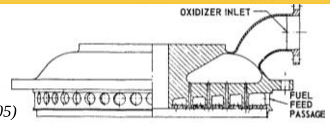
FIGURE 8–7. Angular relation of doublet impinging-stream injection pattern.

From Sutton

Multi-element Manifold

- Tradeoffs in manifold volume
- Larger ⇒
  - ☺ more uniform distribution
  - ☺ lower p drops
  - ☹ longer transients (slow start and dribble)
  - ☹ more sensitivity to instability



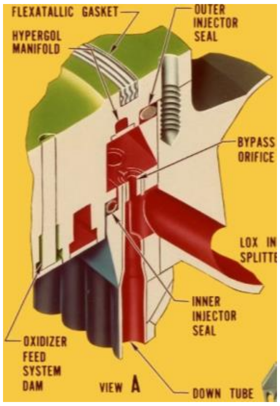


F-1 Engine (RP-1/LOx)

Wheelock and Kraemer, Rocketdyne: Powering Humans into Space (2005)

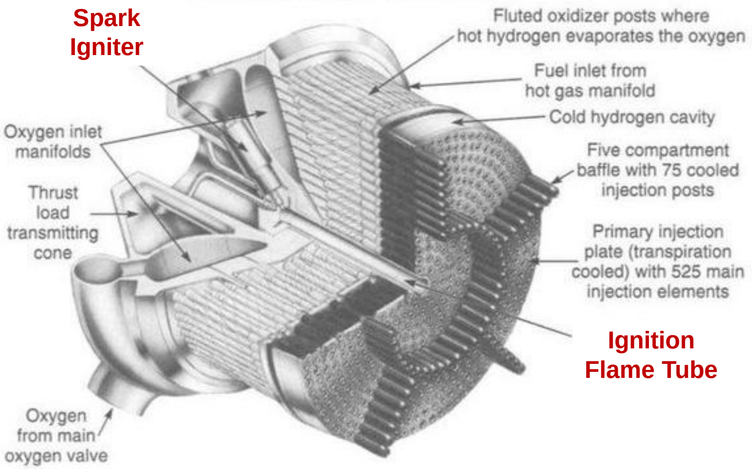
Ignition

- Hypergolics
  - – self-igniting
- Otherwise typically 3 options
  - – use pyrotechnics
    - typically only for single-start option
  - – use hypergolic ignition
    - e.g., F-1 triethylboron with 10-15% triethylaluminium + LOx but single-start cartridge
  - – spark igniter



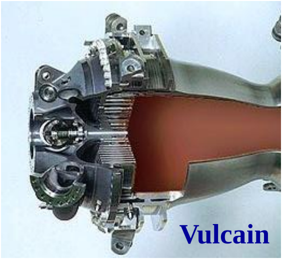
F-1 Engine

RS-25 (SSME) Injector Assembly



Combustion Chamber Sizing

- LRE combustion chambers typically described by near-cylindrical shape
  - – reasonable for high pressures (reduce stress concentrations)
  - – some tapering as c.c. becomes part of converging section of nozzle
- So sizing of combustion chamber can be described by
  - – combustion chamber volume, $\boldsymbol{V_{cc}}$
  - – combustion chamber length, $\boldsymbol{L_{cc}}$
  - – (average) c.c. cross-sectional area, $\boldsymbol{A_{cc}}$



From Fröhlich et al., AIAA93-1826

$$V_{cc} = L_{cc} A_{cc}$$

Combustor Sizing: Characteristic Length

- One approach to combustion chamber sizing is to use historical values for combustion chamber volume **scaled to nozzle throat size**
  - since throat area is typical design parameter based on thrust requirement
- $V_{cc} = L^* A_t$
  - $L^* \equiv$ characteristic length
  - V_{cc} includes all volume up to throat
- Values of L^* found for different types of propellants using historical information from different rocket engines

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Characteristic Combustion Chamber Lengths

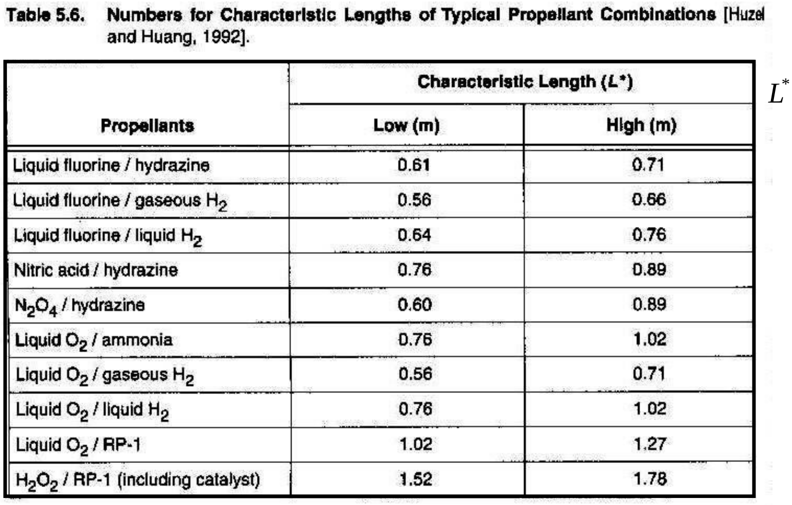

Table 5.6. Numbers for Characteristic Lengths of Typical Propellant Combinations [Huzel and Huang, 1992].

Propellants	Characteristic Length (L^*)	
	Low (m)	High (m)
Liquid fluorine / hydrazine	0.61	0.71
Liquid fluorine / gaseous H_2	0.56	0.66
Liquid fluorine / liquid H_2	0.64	0.76
Nitric acid / hydrazine	0.76	0.89
N_2O_4 / hydrazine	0.60	0.89
Liquid O_2 / ammonia	0.76	1.02
Liquid O_2 / gaseous H_2	0.56	0.71
Liquid O_2 / liquid H_2	0.76	1.02
Liquid O_2 / RP-1	1.02	1.27
H_2O_2 / RP-1 (including catalyst)	1.52	1.78

$$L^* = \frac{V_{cc}}{A_t}$$

From Humble

Combustor Sizing: Residence Time

- Another approach to sizing combustor is based on making sure the length (L_{cc}) is sufficient for the **residence time** to exceed the time required to finish all the combustion processes, e.g.,

$$\tau_{res} \geq \tau_{vap} + \tau_{mix} + \tau_{chem}$$

  - at high pressures, typically a few ms or more
  - required residence time increases as operating pressure drops

$$\tau_{res} = \frac{L_{cc}}{\bar{v}_{cc}} = \frac{L_{cc} A_{cc}}{\bar{v}_{cc} A_{cc}} \Rightarrow \tau_{res} = \frac{V_{cc}}{\dot{m}/\bar{\rho}_{cc}}$$

"average" velocity in c.c.

from thrust requirement

from operating conditions

Combustor Sizing: Area

- Cross-sectional area should be large enough to keep Mach number reasonably subsonic ($3 \times A_t$?)
  - p_o loss occurs if heat release (burning) occurs at high M
  - e.g., simple tpg/cpg approximation
- Increasing A_{cc} will reduce L_{cc} for fixed V_{cc}
  - tradeoff influenced by heat transfer and mechanical design/stresses