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 exit diameter is about 15 in. The sea-level thrust was originally 120,000 lb, but was uprated to 135,000, then 150,000, and finally to 165,000 lb by increasing the flow and chamber pressure and strengthening and modifying the hardware. The cone-shaped exit zone 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. (Courtesy of The Boeing Company, Rocketdyne Propulsion and Power)*
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

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
LRE TCA

Combustion Chambers

- Main elements: injector head, wall cooling (+ baffles)
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 (N₂H₄) Injectors

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

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

*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

![Typical Injector Assemblies. These are the typical configurations used. They include doublets, triplets, concentric tubes, and the pintle injector. From Humble](image)

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](image)

adapted from Hazen and Huang

space.nss.org
### Historical Engine Examples

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Engine Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-1</td>
</tr>
<tr>
<td></td>
<td>RL-1B</td>
</tr>
<tr>
<td></td>
<td>LMDE</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>16,700 (vacuum)</td>
</tr>
<tr>
<td></td>
<td>7,776 (vacuum)</td>
</tr>
<tr>
<td></td>
<td>6,770 (vacuum)</td>
</tr>
<tr>
<td>Mass flow rate (kg/s)</td>
<td>2.27</td>
</tr>
<tr>
<td></td>
<td>2.40</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
</tr>
<tr>
<td>Total flow area ((\text{cm}^2))</td>
<td>403.7 (OX)</td>
</tr>
<tr>
<td></td>
<td>561.7 (Fuel)</td>
</tr>
<tr>
<td></td>
<td>5.16 (OX)</td>
</tr>
<tr>
<td></td>
<td>0.60 (Fuel)</td>
</tr>
<tr>
<td></td>
<td>3.10 (OX)</td>
</tr>
<tr>
<td></td>
<td>3.33 (Fuel)</td>
</tr>
<tr>
<td>Thrust (N)</td>
<td>67,700 (vacuum)</td>
</tr>
<tr>
<td></td>
<td>66,700 (vacuum)</td>
</tr>
<tr>
<td></td>
<td>43,800 (vacuum)</td>
</tr>
<tr>
<td>Chamber pressure (kPa)</td>
<td>265.1 (sea level)</td>
</tr>
<tr>
<td></td>
<td>304.8 (vacuum)</td>
</tr>
<tr>
<td></td>
<td>444 (vacuum)</td>
</tr>
<tr>
<td></td>
<td>304 (vacuum)</td>
</tr>
<tr>
<td>Oxidizer</td>
<td>Liquid oxygen</td>
</tr>
<tr>
<td></td>
<td>Liquid oxygen</td>
</tr>
<tr>
<td></td>
<td>N(_2)O(_4)</td>
</tr>
<tr>
<td>Fuel</td>
<td>RP-1</td>
</tr>
<tr>
<td></td>
<td>Liquid H(_2)</td>
</tr>
<tr>
<td></td>
<td>Ammonium - 90</td>
</tr>
</tbody>
</table>

**LMDE: Lunar Module Descent Engine**

#### hypergolics

<table>
<thead>
<tr>
<th>Injector type</th>
<th>Like doublet</th>
<th>coaxial</th>
<th>pintle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>like doublet</td>
<td>coaxial</td>
<td>pintle</td>
</tr>
</tbody>
</table>

#### Multi-element vs uni-element

*From Humble, Table 5.9*

---

### Multi-element Injector Head/Plate

![Multi-element Injector Head/Plate](image)

*From Sutton*

**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.

---

*AE6450 Rocket Propulsion*
Multi-element Injector Fabrication

- Can be as simple as holes drilled in injector face
  - US historic except LH₂

or

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

Shear Coaxial Injectors (Gas-Gas Examples)

- Use shear forces to entrain and mix jets

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)

\[ M \equiv \frac{\rho_g u_g^2}{\rho_l u_l^2} \]

Momentum Flux Ratio

\[ \text{M} \equiv \frac{\rho_g u_g^2}{\rho_l u_l^2} \]

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

Supercritical Injection

- Atomization no longer occurs

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)
Discharge Coefficients, Sizing

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

From Sutton

- Flowrates from $\Delta p$
  \[
  \frac{\dot{m}}{\rho} = Q = C_D A \sqrt{\frac{2\Delta p}{\rho}}
  \]
  \[
  \frac{\dot{m}_{\text{ax}}}{C_{D,\text{ax}}} A_{\text{ax}} \sqrt{\frac{\Delta p_{\text{ax}}}{\Delta p_f}}
  \]

- Generally, better atomization and resistance to combustion instability for higher injection velocity
  \[
  v_{\text{inject}} = Q = C_D \sqrt{\frac{2\Delta p}{\rho}}
  \]

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 ($\delta=0$)
  \[
  \sin \gamma_{\text{ax}} = \sin \gamma_f = \frac{\dot{m}_{\text{ax}} v_f}{\dot{m}_f v_{\text{ax}}}
  \]

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


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 (RP-1/LOx)

F-1 Engine
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, $V_{cc}$
  - combustion chamber length, $L_{cc}$
  - (average) c.c. cross-sectional area, $A_{cc}$

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

- \( V_{cc} = L^* A_t \)
  - \( L^* \) = 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.
**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

\[
\tau_{res} = \frac{L_{cc}}{\bar{V}_{cc}} = \frac{L_{cc}A_{cc}}{\bar{V}_{cc}A_{cc}} \Rightarrow \tau_{res} = \frac{V_{cc}}{m/\bar{P}_{cc}}
\]

from thrust requirement

"average" velocity in c.c.

from operating conditions

\[
\Delta p_o / p_o = (\frac{T_o}{T_{o,in}})^{\gamma - 1}
\]

\[
\gamma = 1.2 \quad M_{av} = 0 \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5
\]

\[
\gamma = 1.2 \quad T_o / T_{o,in} = 12 \quad = 8
\]

\[
\Delta p_o / p_o = \left( \frac{T_o}{T_{o,in}} \right)^{\gamma - 1}
\]

**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