6. LIQUID ROCKET PROPULSION (LRP) SYSTEMS
6.1 INTRODUCTION
Thrust Chamber or Thruster
- Injector, combustion chamber, nozzle.
- Liquid propellants are metered, injected, atomized, mixed and burned to form hot gaseous reaction products, which are accelerated and ejected at high velocity.

Cooling:
- Propellant cooled: fuel is circulated through cooling jackets
- Radiation-cooled: high-temperature material radiates away excess heat
- Ablative-cooled: heat-absorbing materials

Tanks: Propellant storage,

Feed Mechanism: Force propellants from tanks to thrust chamber(s),
- Pressure-fed
- Pump-fed

Power Source: Furnish energy for feed mechanism,

Plumbing/Piping: Transfer of liquids,

Structure: Transmit thrust force,

Control Devices: Initiate and regulate propellant flow and thus thrust.
### Applications

<table>
<thead>
<tr>
<th>Type</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Booster Engines</td>
<td>Sea Level Operation</td>
</tr>
<tr>
<td>Core Engines</td>
<td>Sea Level Operation in combination with Boosters</td>
</tr>
<tr>
<td>Sustainer Engines</td>
<td>2nd Stage Operation</td>
</tr>
<tr>
<td>Upper Stage Engines</td>
<td>2nd, 3rd or 4th Stage Engines</td>
</tr>
</tbody>
</table>

### Requirements

<table>
<thead>
<tr>
<th>Type</th>
<th>Thrust</th>
<th>Isp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boosters</td>
<td>Very High</td>
<td></td>
</tr>
<tr>
<td>Core</td>
<td>High</td>
<td>+ High</td>
</tr>
<tr>
<td>Sustainers</td>
<td>Medium</td>
<td>+ High</td>
</tr>
<tr>
<td>Upper Stage</td>
<td>Low</td>
<td>+ Very High</td>
</tr>
</tbody>
</table>

For an exhaustive list of rocket systems, see [http://www.astronautix.com/spaceflt.htm](http://www.astronautix.com/spaceflt.htm)
Propellant Types/Systems

**Bipropellant**
- Two separate liquid propellants: oxidizer and fuel,
- Stored separately and mixed in combustion chamber.

**Monopropellant**
- Single substance containing oxidizing agent and combustible matter.
- Stable at atmospheric conditions, but decompose when heated or catalyzed.

**Cold Gas Propellant**
- Stored at very high pressure.

**Cryogenic Propellant**
- Liquefied gas at low temperatures,
- Issues: venting and vaporization losses.

**Gelled Propellant**
- Liquid with gelling additive behaving like jelly or thick paint.
PROPELLANT FEED SYSTEM

Functions:
★ Raising pressure of propellants.
★ Feeding propellants to one or more thrust chambers.

★ Pump-Fed System
★ Pressure-Fed System
## Applications of LRP

<table>
<thead>
<tr>
<th>System Type</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Launch</td>
</tr>
<tr>
<td>Pump-Fed Biprop System</td>
<td>X</td>
</tr>
<tr>
<td>Pressure-Fed Biprop System</td>
<td>X</td>
</tr>
<tr>
<td>Monopropellant</td>
<td>X</td>
</tr>
<tr>
<td>Monopropellant (electrical heating)</td>
<td></td>
</tr>
<tr>
<td>Cold Gas</td>
<td></td>
</tr>
</tbody>
</table>
### Engine Cycles

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Application</th>
<th>Specifics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Drive</td>
<td>Upper Stage, Space Propulsion</td>
<td>Low Pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low Thrust</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 2 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 40 kN</td>
</tr>
<tr>
<td>Gas Generator</td>
<td>Booster, Core, Upper Stage</td>
<td>Medium Pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 15 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large Thrust Range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60 kN - 7 MN</td>
</tr>
<tr>
<td>Expander</td>
<td>Upper Stage</td>
<td>Low-Medium Pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 - 7 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Small Thrust Range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 - 200 kN</td>
</tr>
<tr>
<td>Staged Combustion</td>
<td>Booster, Core, Upper Stage</td>
<td>High Pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13 - 26 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large Thrust Range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 kN - 8 MN</td>
</tr>
<tr>
<td>Full Flow Staged Combustion</td>
<td>Booster, Core (nothing’s flying yet)</td>
<td>High Pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 30 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large Thrust Range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>up to 10 MN</td>
</tr>
</tbody>
</table>
6.2 PRESSURE–FED SYSTEMS
## Types of Rocket Engines

<table>
<thead>
<tr>
<th>Complexity</th>
<th>Pressure–Fed</th>
<th>Pump–Fed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Blowdown</td>
<td>Expander</td>
</tr>
<tr>
<td></td>
<td>Regulated pressure</td>
<td>Gas generator</td>
</tr>
<tr>
<td></td>
<td>More reliable</td>
<td>Staged combustion</td>
</tr>
<tr>
<td>Weight</td>
<td>Heavier tanks – $p_{tank} \approx 1.5 \ p_{chamber}$</td>
<td>Extra weight of TPA</td>
</tr>
<tr>
<td>Performance</td>
<td>Cold gas and monprop &lt; 200 s</td>
<td>Gain from higher $p_c$ allowing</td>
</tr>
<tr>
<td></td>
<td>Biprop up to 340 s</td>
<td>higher $\varepsilon$, for same $p_a$ or $\varepsilon$</td>
</tr>
<tr>
<td>Applications</td>
<td>Upper stages, space engines, small thrusters (sat prop &amp; RCS); ‘big dumb booster’</td>
<td>Booster engines and upper stages; extreme space engines</td>
</tr>
</tbody>
</table>
Pressurization Options

Pressurant Tank

Press Valve

Oxidizer Tank

Fuel Tank

Pre-valve

Engine

Blowdown Pressurization

Flow Control Valve

Oxidizer Tank

Fuel Tank

Pre-valve

Engine

Autogenous Pressurization
Some rules/issues to consider when deciding on a pressurization mechanism:

- Lack of pumps drives a higher tank pressure.
- Large propellant-tank volume drives the use of pumps.
- In general, big systems use pumps, small systems don’t.
- With larger system size, decreasing tank mass (lower pressure $\Rightarrow$ thinner wall thickness) justifies additional complexity and cost of pumps.
- The larger the tank, the bigger the mass savings (inert mass fraction!).
- New/advanced/improved tank material and manufacturing technologies must be evaluated.
6.2.1 MONOPROPELLANT SYSTEMS
Since Earth storable bipropellants have so much better performance, why ever use monopropellant systems?

The answer is simplicity and cost!!

★ Biprop systems need twice as many tanks, components, etc.
★ Biprop systems can only operate over a tight range of mixture ratios and inlet pressures:
  ✦ Mixture Ratio \( (\tau) \) is defined as oxidizer/fuel flowrate.
  ✦ Tight \( \tau \) control implies tight thermal control of tanks, etc.
★ Small biprop thrusters are not available.
★ Biprop systems cost approximately an order of magnitude more than monoprop systems.

★ Dual mode propulsion (NTO/N\(_2\)H\(_4\)) allows high performance main engines and monoprop attitude control thrusters with shared fuel storage and control.
  ✦ NTO: nitrogen tetroxide
  ✦ N\(_2\)H\(_4\): hydrazine

★ An interesting fact about NTO/MMH thrusters is that the typical mixture ratio \( \tau \) for these thrusters results in roughly equal-volume propellant tanks.
  ✦ MMH: monomethyl hydrazine
Basic Blowdown Monoprop System

Legend
- Filter
- Inlet/Outlet filter
- Pressure transducer
- Service valve
- Temperature transducer
- Latch Valve
- Flow Control Orifice
**Description:** A single liquid propellant feeds into a catalyst bed in a thruster where it catalytically and/or thermally decomposes to create a hot gas that is exhausted through a nozzle.

**Benefits:**
- Low system complexity (no combustion and often a regulator is not even needed),
- Relatively inexpensive,
- Requires only one set of tanks, components, and plumbing,
- Good storability.

**Drawbacks/Issues:**
- Moderate to poor performance,
- Moderately dangerous from a handling standpoint,
- Contamination of a spacecraft’s external surfaces from exhaust gases.

**Typically chosen as the propulsion system when:**
- Small thrust levels, minimum impulse bits, and/or \( \Delta v \) are required,
- Operational lifetime of the system is long,
- Science dictates known and quantifiable contamination of external body.
**Examples**

**Typical Monopropellant Thruster**

**Typical Monopropellant Gas Generator**
Important Considerations

 dez Stable operation of monopropellant thrusters over a wide range of inlet pressures typically allows operation in blow-down mode.

 dez Catalyst bed and valve heaters are usually required on all monopropellant thrusters:
  dez For thermal catalyst beds, propellant decomposition will not take place unless cat bed is pre-heated.
  dez The firing duty cycle will dictate how long and often the cat. bed heaters are required.
  dez If cat. bed heaters are not wanted in the design with a spontaneous catalyst, a warming pulse (“cold start”) could be used before the maneuver(s) are conducted to “gently” warm up the cat. beds.
  dez Cold starts rapidly degrade the catalyst bed and are not recommended unless operational lifetime is short.

 dez A diaphragm positive expulsion device (PED) is typically used for hydrazine systems:
  dez Several elastomers which are compatible with hydrazine exist,
  dez HAN-based monoprop systems cannot use elastomeric diaphragms/bladders yet.
  dez HAN: hydroxylammonium nitrate

 dez Monopropellant systems will always have some hold-up/residual remaining in the propellant tanks at the end of the mission that must be accounted for.
Blow-down systems typically pay a mass penalty for their simplicity:

- Option for reducing propellant tank mass are:
  - Recharge systems
  - Regulated systems.

If off-the-shelf tanks are slightly too small, “ullage tanks” can be used to increase effective tank volume.

Pumps can also be considered to allow storage of propellant at low pressure and with minimal beginning-of-life-ullage.
6.2.2 BIPROPELLANT SYSTEMS
**Description:** Liquid oxidizer and liquid fuel feed into a thrust chamber where they mix and react chemically; the combustion gases then accelerate and are exhausted through a converging-diverging nozzle.

**Benefits:**
- Relatively high achievable performance for chemical propulsion.

**Drawbacks/Issues:**
- High cost and complexity (“twice” as many components as a monopropellant system, many more variables to be controlled/analyzed),
- Bipropellants are often dangerous from a system safety/handling standpoint,
- Reaction temperatures are often high enough that combustion temperatures are too high to be accommodated by the thruster materials,
  - Sometimes need extremely tight mixture ratio control
- Nasty exhaust products (contamination of spacecraft’s external surface or the surface of an ephemeral body).

**Typically chosen as the propulsion system when:**
- High thrust levels, total impulse, and/or ΔVs are required to offset dry mass,
- Operational lifetime of the system is long,
- The spacecraft temperature is tightly maintained.
Pressure-Fed System Types

Basic Biprop Propulsion System

Legend:
- Filter
- Inlet/Outlet filter
- Pressure transducer
- Service valve
- Temperature transducer
- Latch Valve
- Flow Control Orifice
Unless thruster inlet conditions are carefully controlled, thrusters can burn through or otherwise fail.

- Not a problem with monoprop thrusters,
- Many variables affect thruster inlet conditions:
  - Schematic
    - Magnitude and location of pressure drops
    - Relative pressure drops in oxidizer and fuel feed systems
  - Propellant and propellant tank temperature and pressure,
  - Propellant vapor pressure and state of pressurant saturation.

Due to typically large propellant masses and need to carefully control inlet conditions, most biprop systems include a pressurization system.

- Usually can’t afford the mass or volume penalty, or large excursion in inlet pressures associated with blow-down operation for the entire mission.
- Oxidizer is not compatible with most elastomers, so all-metal Propellant Management Devices are typical in oxidizer tanks.
- Separate propellants need to be kept apart
  - Both in liquid and vapor forms.
Important Considerations

- Bipropellant systems will always have some hold-up/residual remaining in the propellant tanks at the end of the mission that must be accounted for (more so than monopropellant systems due to mixture ratio uncertainties),
- Chugging (feed system frequency interaction with engines),
- Vapor migration in the feed system,
- Center of gravity shift during operation (must number, locate, and size tanks to account for this),
- A repeatable minimum impulse bit is difficult to achieve due to mixture ratio and combustion uncertainties,
- The design of the propellant management devices (PMDs) in the tanks are much more complicated than with monopropellant systems due to tighter propellant management control and material incompatibilities (e.g., NTO is incompatible with many elastomeric materials),
- Bipropellant engines typically have tight operating boxes (mixture ratio, pressure, temperatures),
  - tighter the operating box, the more complex the overall propulsion system.
Design Considerations:

- Plumbing in the pressurization system has to:
  - Provide isolation of the high pressure pressurant tank(s) from the relatively low pressure propellant tanks.
  - Prevent migration and mixing of propellant vapors, if a pressurization system common to both propellants is used.
- Prevent mixing of propellants (except in thrusters, of course).
- Maintain control of the flow of both propellants such that the thruster inlet conditions stay within acceptable limits.
- Control pressure drops in the system such that effects associated with pressurant coming out of solution are within acceptable limits.
- Biprop systems often provide for the isolation of the pressurization system during long periods of system inactivity, or after enough of the propellant has been expelled that blow-down operations are possible.
  - Dual mode systems often provide for the isolation of the oxidizer system after the biprop main engine has been used, either leaving the hydrazine tank in blow-down, or keeping the hydrazine tank at regulated pressure.
Viking Orbiter Bipropellant & Cold-Gas Propulsion System

Legend
- Check valve
- Pyrotechnic valve (normally closed)
- Filter
- Pyrotechnic valve (normally open)
- Field Joint
- Burst Disc / Relief
- Flexible line
- Valve Assembly
- Service valve
- Gas regulator
- Latch valve
- Orifice
- Temperature transducer
- Pressure transducer

1323 N Main engine
Propulsion Subsystem

Cold Gas Attitude Control Subsystem (ACS)
6.3 CYCLE DEFINITION FOR BIPROP SYSTEMS
<table>
<thead>
<tr>
<th>Cycle</th>
<th>Application</th>
<th>Specifics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Drive</td>
<td>Upper Stage, Space Propulsion</td>
<td>Low Pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low Thrust</td>
</tr>
<tr>
<td>Gas Generator</td>
<td>Booster, Core, Upper Stage</td>
<td>Medium Pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 15 MPa</td>
</tr>
<tr>
<td>Expander</td>
<td>Upper Stage</td>
<td>Low-Medium Pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 - 7 MPa</td>
</tr>
<tr>
<td>Staged Combustion</td>
<td>Booster, Core, Upper Stage</td>
<td>High Pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13 - 26 MPa</td>
</tr>
<tr>
<td>Full Flow Staged Combustion</td>
<td>Booster, Core (nothing’s flying yet)</td>
<td>High Pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 30 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large Thrust Range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>up to 10 MN</td>
</tr>
</tbody>
</table>

- High Pressure: > 30 MPa
- Large Thrust Range: up to 10 MN
- Medium Pressure: 3 - 7 MPa
- Small Thrust Range: 80 - 200 kN
- Low Pressure: < 2 MPa
- Low Thrust: < 40 kN
Open Cycles

- **Gas Generator Cycle**
  - Open cycle
  - GG burns non-stoichiometric to eliminate turbine cooling
    + Fairly simple
    + Wide thrust operating range
    - Turbine exhaust gives low Isp = effective loss in performance
    - GG required
  - RS-27, MA-5, STME, Titan

- **Combustion Tap-Off Cycle**
  - Open cycle similar to GG, but uses chamber pressure rather than GG to drive turbine
    + No GG required
    - Difficult to throttle, start
    - Narrow thrust operating range
    - Saturn V

- **Coolant Bleed Cycle**
  - Open cycle similar to combustion tap-off, but uses coolant bleed (vaporized) to run turbine
    + No GG required
    - Limited to cryogenic fuels
    - Pressure and thrust limited by thermal properties
**Closed Cycles**

- Closed cycle; most of coolant fed to low pressure ratio turbines
  - Good performance, i.e. closed cycle efficiency
  - Simple design
  - Low weight
  - Self starting
    - Limited to low $p_c < 1,100$ psi
    - Limited to cryogenic fuel

- Closed cycle with preburner replacing GG
  - High performance
  - High $p_c$ and thrust capability
    - Very complex, lesser reliability
    - Advanced turbine/pump required for high $p_c$ (boost pumps)
Thermodynamic cycle chosen is hopefully the optimal for the application.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Main Turbopumps</td>
<td>3-4</td>
<td>3-4</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Number of Boost Pumps</td>
<td>3-4</td>
<td>3-4</td>
<td>0-2</td>
<td>0-2</td>
<td>0-2</td>
<td>0-2</td>
<td>0-2</td>
</tr>
<tr>
<td>Number of major valves (typical)</td>
<td>11-16</td>
<td>7-9</td>
<td>5-7</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Number of GG/PB's</td>
<td>2</td>
<td>2-3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Number of Thrust Chambers</td>
<td>2+</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of Main Injectors</td>
<td>2+</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of Nozzles</td>
<td>2+</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Increasing Complexity

Decreasing Complexity
# Pump-Fed Propulsion System

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>High performance from altitude compensation and/or propellant bulk density benefits. Can use combination of open and closed cycles</td>
<td>Highest integrated performance available (closed cycle). Maximizes propellant bulk density and Isp.</td>
<td>High performance (closed cycle). Very attractive for reusable applications. Easier MR and thrust level throttling characteristics.</td>
<td>High performance (closed cycle). Simpler than multi preburner options to left. Very attractive for reusable applications</td>
<td>Simple cycle, low production costs, easier to develop</td>
<td>High reliability, benign failure modes (containted), simple cycle</td>
<td>Simple cycle with fewer parts, lower production costs, easier maintainability</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>Essentially 2 engines in one. Very complex and difficult to develop. Very costly to produce. Production cost makes reusable applications mandatory. Vehicle must be very performance driven such as SSTO.</td>
<td>Most difficult to develop. Will be very expensive. Production cost makes reusable applications mandatory. Vehicle must be very performance driven such as SSTO.</td>
<td>More difficult to develop than single PB. Tends to be very expensive. Failure modes tend to be more involved. Production cost makes reusable applications almost mandatory.</td>
<td>More difficult to develop. Tends to be more expensive. Failure modes tend to be more involved.</td>
<td>Lower performance because of open cycle. Performance level makes this unattractive for most reusable applications.</td>
<td>Limited to LOX/LH2 propellants only. Limited performance because of heat transfer limitations.</td>
<td>Hot gas duct that taps off from the MCC and mixes diluent fuel to regulate gas temperature. Lower performance (Open cycle).</td>
</tr>
<tr>
<td><strong>Potential Applications</strong></td>
<td>Reusable SSTO.</td>
<td>Reusable SSTO.</td>
<td>Booster or upperstage, reusable or expendable rockets (May depend on propellant choices)</td>
<td>Booster or upperstage, reusable or expendable rockets</td>
<td>Booster or upperstage, reusable or expendable rockets</td>
<td>Booster or upperstage, reusable or expendable rockets</td>
<td>Booster or upperstage, expendible rockets</td>
</tr>
</tbody>
</table>
6.4 COMPONENTS OF LRP SYSTEMS
All liquid propellant systems require tanks for storage of propellants.

- Separate fuel and oxidizer tanks in bipropellant systems,
- Single tanks for monopropellant systems,
- Number of tanks dictated by system redundancy and control of vehicle’s center of gravity.

Tank Shape:

- Launch Vehicle: cylindrical shape to reduce frontal area and thus minimize drag,
- Space Vehicle: spherical shape to increase packaging efficiency.

Tank Arrangement:
Surface Area vs. Shape:

\[ \frac{A_{\text{sphere}}}{A_{\text{cylinder}}} = \frac{\frac{2}{3} \cdot 2 (L/D)^3}{1 + 2 \cdot (L/D)} \]

where \( L/D \) = length-to-diameter of cylindrical tank

Volume Requirement is dictated by:

- Required mass of liquid propellant: \( V_{\text{prop}} \)
- Changes in liquid density due to temperature the tank might encounter (Ullage): \( V_{\text{ullage}} \)
- Boil-Off of given propellants: \( V_{BO} \)
- Trapped propellant in tanks or/and feed lines: \( V_{\text{trap}} \)

\[ V_{\text{total}} = V_{\text{prop}} + V_{\text{ullage}} + V_{BO} + V_{\text{trap}} \]
**Tank Sizing**

- **Pressure at the bottom of tank**
  \[ p_{\text{total}}(t) = p_{\text{ ullage}}(t) + \rho_{\text{propellant}} g_{\text{ earth}} \cdot a(t) \cdot h(t) - p_{\text{ ambient}}(t) \]

- **Case Thickness**
  \[ t_{\text{case}} = p_{\text{ total}} \frac{R}{\sigma} \]  
  Max. Allowed Stress

- **Buckling Analysis**
  - **Static Equilibrium of Forces on Tank**
    \[ \sum F_z = \pi R^2 \left( p_{\text{ ullage}} - p_{\text{ ambient}} \right) - F_{\text{ axial}} \]
  - **Stress in Thin-Walled Tank**
    \[ \sigma \equiv \frac{F}{A} = \frac{\pi R^2 \left( p_{\text{ ullage}} - p_{\text{ ambient}} \right) - F_{\text{ axial}}}{2\pi R t} \]
  - **Critical Stress in Thin-Walled Tank**
    \[ \sigma_{\text{critical}} = -E \left[ 9 \cdot \left( \frac{t_{\text{case}}}{R} \right)^{1.6} + 0.16 \cdot \left( \frac{t_{\text{case}}}{L} \right)^{1.3} \right] \]  
    Young's Modulus

  \[ \sigma_{\text{critical}} > \sigma \]  
  Non-Buckling Condition
Propellant Management throughout Mission Profile

- Supplying engines with gas-free propellant,
- Draining maximum amount of loaded propellant minimizing residuals,
- Preventing propellant slosh: no forces or moments transmission to spacecraft structure which might overwhelm attitude-control system,
- Changing acceleration environment of the mission profile complicates propellant management.

Propellant-Expulsion Devices:

- Positive-expulsion devices use physical barriers between propellant and pressurant gas.
  - Examples: bladders, pistons, diaphragms, bellows.
- Passive-expulsion devices use surface tension on propellant to keep the fluid in contact with the propellant drain.
  - Examples: vanes, porous sheets, screens.

Gas can accumulate at the outlet and keep engines from starting.
Positive-Expulsion Devices for Propellant Management

★ Comparison of Different Technologies ★ Examples of Different Technologies
Propellant Choice is a strong influence on Sizing the Combustion Chamber.

Cross-sectional area is dictated by injector design.

Length of the combustion chamber is determined by the residence time to ensure complete combustion of the propellants.

Residence Time:

$$t_{\text{residence}} = \frac{l_{\text{chamber}}}{v_{\text{propellant}}} = \frac{\rho_{\text{propellant}} A_{\text{chamber}} l_{\text{chamber}}}{m} = \frac{c^*}{RT_{\text{propellant}}} \cdot \frac{A_{\text{chamber}} l_{\text{chamber}}}{A_{\text{throat}}}$$

Characteristic Chamber Length:

$$L^* = \frac{A_{\text{chamber}} l_{\text{chamber}}}{A_{\text{throat}}}$$
Combustion Instabilities

★ Low Frequency: Chugging Mode
   Characteristic Frequency range is between 10 and 200 Hz. This instability occurs due to an interaction between chamber and feed system.

★ Medium Frequency: Buzzing Mode
   Characteristic Frequency range is (arbitrarily) placed between 20 and 1000 Hz. This instability is a result from either flow instabilities or resonance with chamber structure.

★ High Frequency: Screaming Mode
   Characteristic Frequency range is above 1000 Hz. This instability is due to interactions of the combustion process with chamber acoustics.
Injectors are responsible for metering, distributing, and atomizing propellants for efficient combustion within the combustion chamber.

**Injector Classification:**

- Doublet & Triplet Impinging Stream Patterns,
- Self-Impinging Stream Pattern,
- Shower Head Stream Pattern,
- Spray Injection Pattern,
- Splash Plate Pattern,
- Coaxial Type, etc.

**Injector Sizing**

- Mass Flow Rate of an Injector Element (Bernoulli’s Equation)
  \[
  \dot{m}_{\text{element}} = c_D A_{\text{element}} \sqrt{2 \rho g \Delta p}
  \]

- Number of Elements
  \[
  N = \frac{\dot{m}_{\text{total}}}{\dot{m}_{\text{element}}}
  \]

- Injector Face Area
  \[
  A_{\text{chamber}} = \frac{N_{\text{ox}} + N_{\text{fuel}}}{N_D}
  \]

- \( N_D = \frac{N}{A} \) = # of elements per area due to design
6.5 EXAMPLES OF LRP CYCLES
Pump-Fed Propulsion System

Rated Conditions

- **LH₂**
  - P = 24.5 psia
  - T = 37.8° R
  - m = 226 lb/s
  - N = 25566 RPM

- **GOX Repress**
  - P = 1200 psia
  - T = 1600° R
  - m = 31.2

- **Internal Mixer**
  - Pc = 1200 psia

- **LOX**
  - P = 47 psia
  - T = 162.7° R
  - m = 1356 lb/s
  - N = 10223 RPM

- **OTBP**

F (vac) = 669Klb
F (sl) = 570Klb
Isp (vac) = 423 sec
Isp (sl) = 360 sec
MR = 6.0
EPS = 22
Weight = 8030 lbs

Legend:
- Pump Stage
- Turbine Stage
- Shutoff Valve
- Dual Position Valve
- Orifice

- LH₂
- LOX
- Gas
# Gas Generator Engines - Production Line

<table>
<thead>
<tr>
<th>ENGINE</th>
<th>HM 7B</th>
<th>VIKING VO</th>
<th>HM 60</th>
<th>LR 87</th>
<th>LR 91</th>
<th>MA-5A BOOSTER</th>
<th>MA-5A SUSTAINER</th>
<th>RS-27</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contractor</td>
<td>SEP</td>
<td>SEP</td>
<td>SEP</td>
<td>Aerojet</td>
<td>Aerojet</td>
<td>Rocketdyne</td>
<td>Rocketdyne</td>
<td>Rocketdyne</td>
</tr>
<tr>
<td>Stage</td>
<td>Ariane 4</td>
<td>Ariane 4</td>
<td>Ariane 5</td>
<td>Titan IV</td>
<td>Titan IV</td>
<td>Atlas II</td>
<td>Atlas II</td>
<td>Delta II/III</td>
</tr>
<tr>
<td></td>
<td>3rd Stage</td>
<td>1st Stage</td>
<td>1st Stage</td>
<td>2nd Stage</td>
<td>1st Stage</td>
<td>1st Stage</td>
<td>1st Stage</td>
<td>1st Stage</td>
</tr>
<tr>
<td>Propellant</td>
<td>LOX/LH₂</td>
<td>N₂O₄/UH25</td>
<td>LOX/LH₂</td>
<td>N₂O₄/Aerozine 5</td>
<td>N₂O₄/Aerozine 5</td>
<td>LOX/RP1</td>
<td>LOX/RP1</td>
<td>LOX/RP1</td>
</tr>
<tr>
<td>Thrust</td>
<td>Sea Level [lbf]</td>
<td>14,100</td>
<td>152,000</td>
<td>198,000</td>
<td>447,300</td>
<td>429,500</td>
<td>60,500</td>
<td>199,945</td>
</tr>
<tr>
<td></td>
<td>Vacuum [lbf]</td>
<td></td>
<td>171,000</td>
<td>250,500</td>
<td>552,500</td>
<td>106,200</td>
<td>85,000</td>
<td>237,067</td>
</tr>
<tr>
<td>Throttle</td>
<td>fixed</td>
<td>fixed</td>
<td>fixed</td>
<td>fixed</td>
<td>fixed</td>
<td>fixed</td>
<td>fixed</td>
<td>fixed</td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>Sea Level [lbf]</td>
<td></td>
<td>445.1</td>
<td>248.5</td>
<td>340</td>
<td>263.3</td>
<td>265</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td>Vacuum [lbf]</td>
<td></td>
<td>278.4</td>
<td>340</td>
<td>304</td>
<td>318</td>
<td>308</td>
<td>302.1</td>
</tr>
<tr>
<td>Mixture Ratio</td>
<td>4.77</td>
<td>1.70</td>
<td>5.30</td>
<td>1.91</td>
<td>1.86</td>
<td>2.25</td>
<td>2.27</td>
<td>2.245</td>
</tr>
<tr>
<td>Chamber Pressure</td>
<td>521.8</td>
<td>876</td>
<td>1647</td>
<td>827</td>
<td>827</td>
<td>719</td>
<td>736</td>
<td>521.8</td>
</tr>
<tr>
<td>Area Ratio</td>
<td>62.5</td>
<td>10.48</td>
<td>45</td>
<td>15</td>
<td>49.2</td>
<td>8</td>
<td>25</td>
<td>12</td>
</tr>
<tr>
<td>Dry Weight [lb]</td>
<td>341</td>
<td>1953</td>
<td>3571</td>
<td>4583</td>
<td>1284</td>
<td>3336</td>
<td>1035</td>
<td>2528</td>
</tr>
<tr>
<td>Thrust/Weight</td>
<td>Sea Level</td>
<td>41.3</td>
<td>77.8</td>
<td>55.4</td>
<td>97.6</td>
<td>128.7</td>
<td>58.5</td>
<td>79.1</td>
</tr>
<tr>
<td></td>
<td>Vacuum</td>
<td>87.5</td>
<td>70.1</td>
<td>120.6</td>
<td>82.7</td>
<td>82.1</td>
<td>93.8</td>
<td></td>
</tr>
</tbody>
</table>
Saturn V/J-2 Engine

Saturn II

- GIMBAL
- FUEL INLET DUCT
- FUEL BLEED VALVE
- GAS GENERATOR
- HIGH PRESSURE FUEL DUCT
- ELECTRICAL CONTROL PACKAGE
- PRIMARY FLIGHT INSTRUMENTATION PACKAGE
- MAIN FUEL VALVE
- THRUST CHAMBER
- ANTI-FLOOD CHECK VALVE
- HEAT EXCHANGER
- PROPELLANT UTILIZATION VALVE
- PNEUMATIC CONTROL PACKAGE
- OXIDIZER INLET DUCT
- START TANK
Tap-Off Cycle

Fuel Pump → Main Chamber
Fuel Pump Hot Gas Tap-off Flow to Drive TPA's

Oxygen Pump

Legend:
- Pump Stage
- Turbine Stage
- Fuel
- Oxygen
- Main Chamber Hot Gas
Expander Cycle

Fuel cool-down and pressure relief valve

Liquid Oxygen

Main propellant valves

Liquid Hydrogen

Venturi

Turbine

Fuel bypass and thrust control valve

Oxidizer flow control valve

Regenerative cooling channels
## RL-10 Evolution

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Contractor</td>
<td>P &amp; W</td>
<td>P &amp; W</td>
<td>P &amp; W</td>
<td>P &amp; W</td>
<td>P &amp; W</td>
<td>Rocketdyne</td>
<td></td>
</tr>
<tr>
<td>Stage</td>
<td>Centaur</td>
<td>Centaur</td>
<td>Centaur</td>
<td>Centaur</td>
<td>Centaur</td>
<td>Centaur</td>
<td>Centaur</td>
</tr>
<tr>
<td>Propellant</td>
<td>LOX/LH₂</td>
<td>LOX/LH₂</td>
<td>LOX/LH₂</td>
<td>LOX/LH₂</td>
<td>LOX/LH₂</td>
<td>LOX/LH₂</td>
<td>LOX/LH₂</td>
</tr>
<tr>
<td>Thrust</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sea Level [lbf]</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>13,352</td>
</tr>
<tr>
<td>Vacuum [lbf]</td>
<td>15,000</td>
<td>15,000</td>
<td>15,000</td>
<td>15,000</td>
<td>16,500</td>
<td>20,800</td>
<td>14,560</td>
</tr>
<tr>
<td>Specific Impulse</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sea Level [lbf]</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>334.8</td>
</tr>
<tr>
<td>Vacuum [lbf]</td>
<td>424</td>
<td>429</td>
<td>433</td>
<td>442.4</td>
<td>444.4</td>
<td>449</td>
<td>365.1</td>
</tr>
<tr>
<td>Mixture Ratio</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5.5</td>
<td>6</td>
</tr>
<tr>
<td>Chamber Pressure</td>
<td>475</td>
<td>475</td>
<td>475</td>
<td>475</td>
<td>475</td>
<td>570</td>
<td>578</td>
</tr>
<tr>
<td>Area Ratio</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>57</td>
<td>61</td>
<td>84</td>
<td>4.28</td>
</tr>
<tr>
<td>Dry Weight [lb]</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>370</td>
<td>316</td>
</tr>
<tr>
<td>Thrust/Weight</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sea Level</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>42.3</td>
</tr>
<tr>
<td>Vacuum</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>55</td>
<td>56</td>
<td>46</td>
</tr>
</tbody>
</table>
## RL60 Engine Requirements

### RL10B-2 vs. RL60 Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>RL10B-2</th>
<th>RL60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust (lb.) vac.</td>
<td>25,000</td>
<td>60,000</td>
</tr>
<tr>
<td>Isp (sec.) vac.</td>
<td>482</td>
<td>485</td>
</tr>
<tr>
<td>Weight (lb.)</td>
<td>664</td>
<td>1,100</td>
</tr>
<tr>
<td>Chamber pressure (psia)</td>
<td>640</td>
<td>1,200</td>
</tr>
<tr>
<td>Propellants</td>
<td>LOX / LH2</td>
<td>LOX / LH2</td>
</tr>
<tr>
<td>Inlet mixture ratio</td>
<td>6.0 to 6.0</td>
<td>5.0 to 6.0</td>
</tr>
<tr>
<td>NPSH (psia) LOX / H₂</td>
<td>6.0 / 6.0</td>
<td>2.0 / 1.5</td>
</tr>
<tr>
<td>Maximum diameter (ft.)</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Installed Length (ft.)</td>
<td>7.3</td>
<td>7.3</td>
</tr>
<tr>
<td>Growth margin</td>
<td>0%</td>
<td>10%</td>
</tr>
<tr>
<td>Life</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Firings (starts)</td>
<td>15</td>
<td>45</td>
</tr>
<tr>
<td>- Time (sec.)</td>
<td>3,500</td>
<td>4,050</td>
</tr>
<tr>
<td>Reliability</td>
<td>0.998</td>
<td>0.998</td>
</tr>
</tbody>
</table>

The RL60 has twice the thrust of an RL10B-2 in a comparable envelope.
RL-60 Combustion Chamber

RL60 Combustion Chamber

Structural Jacket

VPS Copper

Seamless Jacket Cross Section

Partial Combustion Chamber Cross-Section

Chamber Tube Stack
# Staged Combustion Engine - Production Line

<table>
<thead>
<tr>
<th>ENGINE</th>
<th>KUD-7.5</th>
<th>LE-7</th>
<th>RD-0124</th>
<th>RD-0120</th>
<th>RD-0210</th>
<th>RD120</th>
<th>RD170 / RD171 / RD172</th>
<th>RD253</th>
<th>SSME Block I</th>
<th>SSME Block II</th>
<th>RD180</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellants</td>
<td>LOX/LH2</td>
<td>LOX/LH2</td>
<td>Ox/Kerosene</td>
<td>Ox/Kerosene</td>
<td>Ox/Kerosene</td>
<td>Ox/Kerosene</td>
<td>Ox/Kerosene</td>
<td>Ox/Kerosene</td>
<td>Ox/LH2</td>
<td>Ox/LH2</td>
<td>Ox/Kerosene</td>
</tr>
<tr>
<td>Thrust Sea Level, lbf</td>
<td>197,637</td>
<td>187,637</td>
<td>347,500</td>
<td>141,500</td>
<td>1,631,000</td>
<td>350,000</td>
<td>394,000</td>
<td>418,600</td>
<td>860,200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vacuüm, lbf</td>
<td>242,300</td>
<td>63,600</td>
<td>440,850</td>
<td>120,861</td>
<td>1,779,000</td>
<td>385,000</td>
<td>488,800</td>
<td>512,950</td>
<td>933,400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrrottle 5% to 100%</td>
<td>16,524</td>
<td>25% to 114%</td>
<td>100%</td>
<td>40% TO 100%</td>
<td>162,500</td>
<td>1,779,000</td>
<td>Continuous to 306,000</td>
<td>Continuous to 343700</td>
<td>Continuous from 100% to 40%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>--</td>
<td>349.0</td>
<td>358.5</td>
<td>264.0</td>
<td>309.0</td>
<td>285.0</td>
<td>355.1</td>
<td>368.9</td>
<td>311.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sea Level, sec</td>
<td>461.0</td>
<td>446.0</td>
<td>359.0</td>
<td>455.0</td>
<td>327.0</td>
<td>341.0</td>
<td>337.0</td>
<td>316.0</td>
<td>452.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vacuum, sec</td>
<td>5.00</td>
<td>6.00</td>
<td>2.60</td>
<td>6.00</td>
<td>2.60</td>
<td>2.60</td>
<td>2.67</td>
<td>6.00</td>
<td>6.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixture Ratio</td>
<td>853.8</td>
<td>1910.5</td>
<td>2370</td>
<td>3170</td>
<td>2175.0</td>
<td>2360.0</td>
<td>3456.0</td>
<td>2160</td>
<td>3100.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chamber Pressure</td>
<td>642.4</td>
<td>3779</td>
<td>990</td>
<td>7606</td>
<td>1248</td>
<td>2609</td>
<td>26375</td>
<td>1248</td>
<td>7004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stagnation, psia</td>
<td>49.7</td>
<td>0.0</td>
<td>45.7</td>
<td>54.2</td>
<td>61.4</td>
<td>56.3</td>
<td>56.0</td>
<td>72.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area Ratio</td>
<td>25.7</td>
<td>64.1</td>
<td>64.2</td>
<td>58.0</td>
<td>104.9</td>
<td>70.0</td>
<td>66.9</td>
<td>308.5</td>
<td>69.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrust/Weight (Sea Level)</td>
<td>25.7</td>
<td>64.1</td>
<td>64.2</td>
<td>58.0</td>
<td>104.9</td>
<td>70.0</td>
<td>66.9</td>
<td>308.5</td>
<td>69.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrust/Weight (Vacuum)</td>
<td>25.7</td>
<td>64.1</td>
<td>64.2</td>
<td>58.0</td>
<td>104.9</td>
<td>70.0</td>
<td>66.9</td>
<td>308.5</td>
<td>69.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Space Shuttle Main Engine

Hydrogen fuel inlet

Low pressure fuel (booster) turbopump driven by hot gasified H₂

Low pressure oxygen turbopump driven by liquid oxygen turbine

Oxygen inlet

Preburner and high pressure oxygen turbopump

Main LO₂ valve

Main injector

Regeneratively cooled main combustion chamber

Part of oxygen flow is pressurized to a higher pressure with a separate impeller

Fuel valve

Preburner and Fuel turbopump with 3-stage Hydrogen pump

Coolant control valve

Regeneratively cooled tubular nozzle

Thrust chamber gas exhaust
Components and Subcomponents
SSME Powerhead

- Fuel Preburner
- High-Pressure Fuel Turbopump
- Main Combustion Chamber
- Oxidizer Preburner
- High-Pressure Oxidizer Turbopump
Ox-Rich Staged Combustion (ORSC)

Ox rich preburner eliminates sooting issue in turbopump drive turbine. Significant advantage for reusable application.

Legend

- Pump Stage
- Turbine Stage
- RP-1
- Oxygen
- Ox Rich Hot Gas
RD-180 Engine Characteristics

★ Characteristics demonstrate heritage to RD-170

★ Two chamber derivative of the RD-170,
★ Identical chambers, scaled turbopumps,
★ Staged combustion cycle - LOX rich PB,
★ LOX/kerosene propellants,
★ 2 thrust chambers (+/- 8° gimbal),
★ LOX & fuel boost pumps,
★ Single shaft high pressure turbopump
  ✶ 2 stage fuel pump,
  ✶ single stage LOX pump,
  ✶ single stage turbine,
★ Self contained hydraulic system (valves, TVC)
  powered with kerosene from fuel pump,
★ Hypergolic ignition.
<table>
<thead>
<tr>
<th></th>
<th>Full Power (100%)</th>
<th>Minimum Power (47%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber Pressure (psi)</td>
<td>3,722</td>
<td>1,755</td>
</tr>
<tr>
<td>Flow Rate (lb/s)</td>
<td>2,756</td>
<td>1,152</td>
</tr>
<tr>
<td>Total Sea Level Thrust (lb)</td>
<td>860,200</td>
<td>365,500</td>
</tr>
<tr>
<td>Total Vacuum Thrust (lb)</td>
<td>933,400</td>
<td>438,700</td>
</tr>
<tr>
<td>Sea Level Isp (sec)</td>
<td>311.9</td>
<td>278.7</td>
</tr>
<tr>
<td>Vacuum Isp (sec)</td>
<td>338.4</td>
<td>334.6</td>
</tr>
<tr>
<td>Mixture Ratio</td>
<td>2.72</td>
<td></td>
</tr>
<tr>
<td>Nozzle Area Ratio</td>
<td>36.9</td>
<td></td>
</tr>
<tr>
<td>Throat Area (in²)</td>
<td>67.5</td>
<td></td>
</tr>
<tr>
<td>Engine Length (in)</td>
<td>141</td>
<td></td>
</tr>
<tr>
<td>Circumscribed Exit Diameter (in)</td>
<td>124</td>
<td></td>
</tr>
<tr>
<td>Single Nozzle Exit Diameter (in)</td>
<td>56.9</td>
<td></td>
</tr>
<tr>
<td>Gimbal Angle</td>
<td>+/- 8 deg</td>
<td></td>
</tr>
<tr>
<td>Weight, Dry (lb)</td>
<td>12,225</td>
<td></td>
</tr>
<tr>
<td>Weight, Wet (lb)</td>
<td>13,260</td>
<td></td>
</tr>
<tr>
<td>Thrust/Wt (Sea Level, with TVC )</td>
<td>70.4</td>
<td></td>
</tr>
<tr>
<td>Thrust/Wt (Sea Level, No TVC )</td>
<td>74.5</td>
<td></td>
</tr>
</tbody>
</table>
Full-Flow Staged Combustion

Dual preburner with like on like MR eliminates key failure modes in turbomachinery and repress systems.

Legend:
- Pump Stage
- Turbine Stage
- Hydrogen
- Oxygen
- Fuel Rich Hot Gas
- Ox Rich Hot Gas