5. The Aerothermodynamics of Rocket Propulsion

or the means for high speeds

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M26 Rocket – cluster munition

- Length: 3.94 m
- Diameter: 0.227 m
- Weight: 306 kg
- Warhead: 644 M77 DPICM bomblets
- Range: 32 km
- Propulsion: Solid-fueled rocket

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Missile - AGM 65 cutaway diagram

A rocket motor produces thrust by ejecting mass at high speeds (Newton’s 3\textsuperscript{rd} law)

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### AGM 65 Rocket Motor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1.02 m.</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.28 m.</td>
</tr>
<tr>
<td>Weight</td>
<td>47.2 kg</td>
</tr>
<tr>
<td>Propellant</td>
<td>Reduced Smoke HTPB*</td>
</tr>
<tr>
<td>Speed</td>
<td>320 m/s</td>
</tr>
<tr>
<td>Range</td>
<td>27 km</td>
</tr>
</tbody>
</table>

* HTPB: Hydroxy-terminated polybutadiene, a stable synthetic rubber

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Parts of a rocket motor

- Aluminum Blast Tube
- Nozzle
- Bondliner
- Aluminum Case
- Igniter
- Initiator
- Propellant Grain
Propulsion basics

Definition of impulse of a force

1. From Newton’s second law

\[ F = \frac{d}{dt} (mv) \]

2. Integrate from time 0 to time t

\[ \int_{0}^{t} F \, dt = (mv)_{t} - (mv)_{0} \]
Figure of merit for missile propulsion systems

Specific impulse $I_s$

This is the total impulse (change in momentum) per unit weight of propellant

Note: total impulse $\Rightarrow$ over the burning time of the propellant

Question  What does this figure of merit measure?
\[ I_s = \frac{\int_{0}^{t} F dt}{g \int_{0}^{t} m \ dt} \]

**Question**: What’s the unit for specific impulse?

Specific impulse is measured in s

**Question**: What are typical specific impulse for rockets?
Specific impulse for current propulsion systems
Exercise: Estimate the specific impulse, average thrust and average burn rate for a 2 stage vertical launch AMM

<table>
<thead>
<tr>
<th>Propellant mass (kg)</th>
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<tbody>
<tr>
<td>Burn time (s)</td>
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<tr>
<td>Thrust impulse (kN s)</td>
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Booster

weight of propellant =

specific impulse = thrust impulse / propellant weight

average thrust = thrust impulse / burn time

average burn rate = propellant mass / burn time
Sustainer

weight of propellant = 10g

specific impulse = thrust impulse / propellant weight

= 25,500 / 10g

= 260 s

average thrust = thrust impulse / burn time

= 25,500 / 3.5

= 7285 N

average burn rate = propellant mass / burn time

= 10 / 3.5

= 2.86 kg/s
## Summary

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<th>Sustainer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant (kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burn rate (kg/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrust (N)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific impulse (s)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Question**: What can you conclude?

**Answer**: 
Comparison: AGM84 - Harpoon

- Teledyne *turbojet* sustainer rated at 660 lbf = 2936 N
- Solid propellant booster for surface and submarine launch
Exercise: Can you estimate the air flow rate for the AGM 84 (Harpoon) turbojet rated at 2936 N?
Rocket thrust equation

Thrust equation

1. Applying the conservation of momentum to the control volume defined by the rocket motor ...

\[
\text{Thrust} = \frac{d}{dt}(m_e) V_e + (P_e - P_{atmo}) A_e
\]

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Design altitude for rockets

1. From the thrust equation:

\[
\text{Thrust} = \left(\frac{dm_e}{dt}\right) V_e + (P_e - P_{atmo}) A_e
\]

**Question:** What do we need for large thrust?

**Answer:**
Area-velocity relation

*or why nozzles converge and diverge*

1. For a variable area nozzle, the flow velocity $u$ and the cross-section area $A$ are related by:

$$\frac{dA}{A} = (M^2 - 1) \frac{du}{u}$$

2. This follows from the conservation of mass, momentum and the assumption of isentropic flow

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Question: We want accelerating flow ($du > 0$), so what happens in the converging-diverging nozzle?

$$\frac{dA}{A} = (M^2 - 1) \frac{du}{u}$$

$M = 1$

throat $dA = 0$
Ram jets

• A ramjet compresses incoming air by virtue of high forward speed.

• Unlike a turbojet, there is no need for a compressor.

• The catch is that the carrying platform must have another means of propulsion to get the ramjet up to speed.
Bristol Bloodhound

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Thor ramjet cutaway diagram

Design for operation at Mach 2

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Scramjet is an acronym for Supersonic Combustion Ramjet.

- The scramjet differs from the ramjet in that combustion takes place at supersonic air velocities through the engine.

- Designed for hypersonic Mach numbers $M > 5$

- Typically fuelled by hydrogen
NASA X-43 Scramjet

- Mach 9.6, or nearly 7,000 mph world record on Nov. 16, 2004
- Compare with the SR-71 Mach 3.2

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ONR/DARPA – Hypersonic Flight Demonstrator (HyFly)

- Missile demonstrator at Mach 6, 600 nautical miles (1110 km) range using liquid hydrocarbon fuel.

- First ground test on May 30, 2002 at NASA LRC

- Test simulated hypersonic cruise conditions at Mach 6.5, 90,000 feet altitude