Propulsion

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Origins of Rocketry

- 7th Century AD
  - Chinese recordings of the mysterious Tao, a mixture of potassium nitrate, sulfur, arsenic, and honey
  - This is the earliest form of black powder
- 1500 – Optimum formulation of black powder
  - Potassium nitrate 60%
  - Charcoal 30%
  - Sulfur 10%
  - Formula for black powder is essentially the same in present day manufacturing of black powder
- 1647 – Canonical book *Great Art of Artillery* is published
  - Polish author (Kazimierz Siemienowicz) studies the use of rocketry for military applications

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Rocketry in the 1800s

- 1804 – William Congreve made a major change to rocket design by introducing iron casings
  - Prior to this, paper casings were used
  - The new rockets were faster, weighed 40 pounds and had a range of 3000 yards
  - Used in Napoleonic Wars as well as the war of 1812
- Advances in thermodynamic theory leads to advances in rocketry
  - 1890 – Gustaf de Laval (Swede) patents "isoentropic" nozzle
  - 1895 – Liquification of hydrogen (Dewar)

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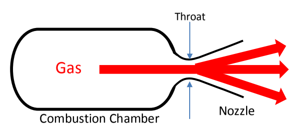
The Isoentropic Nozzle

- The pinched area of the nozzle (throat) is characteristic of the de Laval nozzle
  - Greatly increased the rocket thrust
  - Based upon the concept of constant gas entropy
- The nozzle is designed such that gas entropy is constant on either size of the throat
  - Mass flow rate of the propellant is constant
  - Gas temperature and gas pressure are reduced and gas velocity increases as the gas passes through the throat and is expelled from the nozzle



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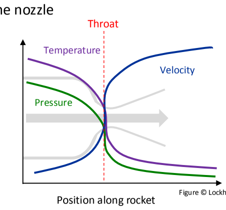

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Rocketry in the Twentieth Century

- World War I – Little use of rocketry
  - Artillery weapons provided greater accuracy and range
- World War II – Prolific use of rockets from both allied and axes forces
  - Germans
    - V-2
    - HS293 air launched, solid propelled, radio controlled anti-ship rocket
    - ME163 (Komet) liquid propelled aircraft interceptor
  - Japanese
    - Yokosuka MXY-7 *Ohka*
  - Russians
    - Katusha artillery rocket
  - U.S.
    - Bazooka
- Post World War II is the modern age of rocketry

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Modern Propulsion Systems

- Types of propulsion systems
  - Rocket engine
  - Air breathers
    - Turbo jet
    - Ram jet
- Common Principles
  - Propellant
    - Fuel and oxidizer
  - Combustion
    - Converts fuel energy to thermal energy
  - Mass Expulsion
    - Combustor product expelled at high velocity through nozzle
    - Directed kinetic energy

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Rocket Propulsion vs Air Breathers

- Rocket engines
  - Carry an oxidizer as part of its propellants
    - Not reliant upon atmospheric air passing through the system
  - Thrust is
    - Dependent upon the jet exhaust velocity (can be fixed by design)
    - Independent of the flight speed
    - Independent (nearly) of the outside air pressure
  - Thrust per unit of frontal area is the largest of all known engine types
- Air breathers
  - Require atmospheric air (oxidizer) to pass through the system
  - Thrust is
    - Dependent upon the rate at which the air stream enters the
    - Fully throttleable

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Liquid Propulsion Systems

- Propellant feed systems
  - Stored gas
  - Gas generator
  - Turbo pumps
- Operational Aspects
  - Easy to regulate thrust, shut off and allow intermittent operation
  - Provide better performance than solids due to combination of energy fuels and lighter overall power plant weight
  - Suitable for space missions due to high performance and controllability
  - Not suitable for tactical mission with high maneuvers due to loss of propellant feed through sloshing
  - Susceptible to corrosion with long storage periods
  - Relatively low reliability
  - Relatively high reaction time

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Limitations of Air-Breathers

- Ram jets and pulse jets do not produce static thrust
  - Air must be forced into the system to produce thrust
- Design and operation of inlet is very critical to performance
  - Inlet must be reconfigured for different flight speeds
- Overall design optimized for limited range of flight conditions
- Angle of attack limits are very narrow
  - Required to allow continued flow of air into the system
  - Precludes high maneuver capability

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Types of Propulsion Systems

Modern Propulsion Systems

Type	Description	Advantages	Disadvantages
Rocket motor	liquid or solid fuel	Very high thrust, Unlimited altitude	Limited in range
Ramjet	jet engine with scoop air injection	Few moving parts, Efficient	Must be boosted to operational speed
Turbojet	jet engine with air intake turbine	Very efficient, long range. Lower IR signature	Limited to relatively slow speeds and altitudes.

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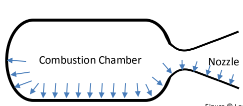
Operating Principles and Components of a Rocket Motor



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- Combustion chamber
  - Pressure vessel: 300 psi (liquid system); 2000 psi (solid system)
  - Temperature range: 3000 R to 8000 R
  - Energy: 100,000 BTU/sec/ft^3; 10,000 BTU/sec/ft^3 (air breathers)
- Nozzle
  - Converts thermal energy to mechanical energy by aligning random motion into ordered motion to create high exit velocity

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Solid Propellant Systems

- Grain configuration
  - Endo burner
  - Radial burner
  - Combination end/radial burner
- Propellants
  - Double base (homogeneous)
  - Composite (heterogeneous)
- Operational Aspects
  - No moving parts
  - Easily stored and transported
  - Highly reliable
  - Low reaction time
  - Adaptable to high maneuvering tactical missiles

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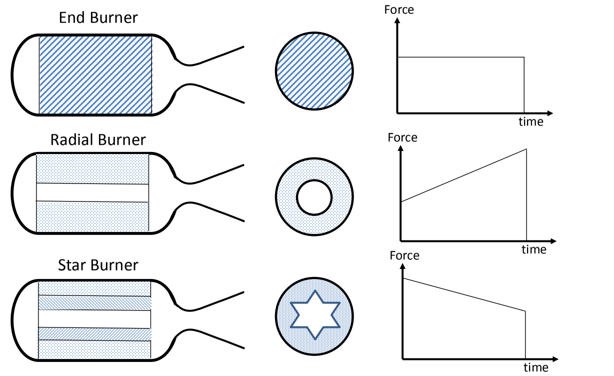
Basic Grain Configurations

Solid Propellants



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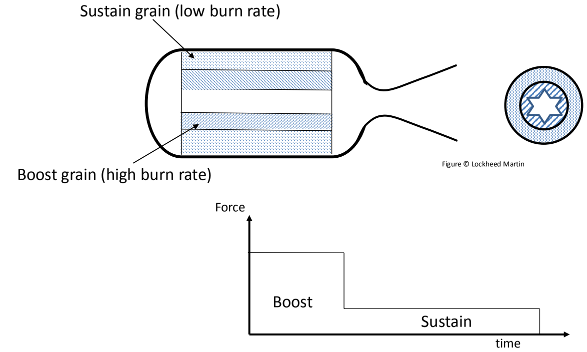
Dual Thrust Grain Configuration

Solid Propellants



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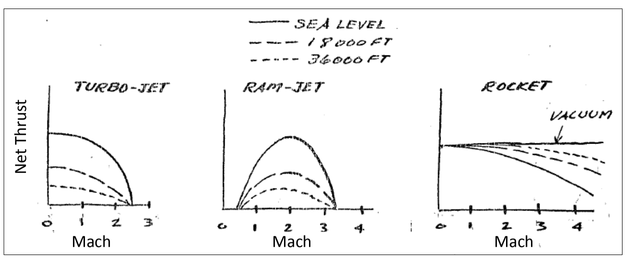
Air Breathers vs Rockets



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- Air breathers decrease their thrust as altitude increases
- Rockets increase their thrust as altitude increases

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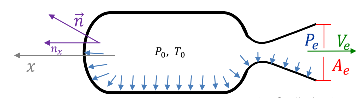
Rocket Motor Thrust

- Thrust is the force used to overcome the weight of the rocket and propel it through the air
- Can be computed by two separate methods
  - Integration of pressure around the motor case

    $\vec{F}_x = \oint (p - p_a)\, \vec{n}_x \, dA$



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  - Momentum considerations

    $F = \frac{\dot{W}\, V_e}{G} + (P_e - P_a)\, A_e$

    - This is the more common means of computing thrust
    - It is often referred to as the "Rocket Thrust Equation"

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Rocket Thrust Equation

$$F = \frac{\dot{W}\, V_e}{G} + (P_e - P_a)\, A_e$$

- Where
  - F = thrust (N) (lb)
  - $\dot{W}$ = propellant weight flow rate (N/sec) (lb/sec)
  - V_e = exhaust exit velocity (m/sec) (ft/sec)
  - P_e = exit pressure (Pa) (psi)
  - P_a = outside pressure (Pa) (psi)
  - A_e = nozzle exit area (m²) (ft²)
- Sometimes, the equation is shown using mass flow rate, $\dot{m}$

  $\dot{m} = \frac{\dot{W}}{G}$

Please be careful with your units, as weight refers to a force, not mass.
When using English units, this can be confusing

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Propellant Weight Flow Rate ($\dot{W}$)

- Rate at which propellant mass is expelled from the nozzle
- Flow rate depends upon
  - P_0 - Chamber pressure (controlled by design of case and grain)
  - A^* - Throat area (controlled by design)
  - C^* - Characteristic velocity of burned propellants (depends upon the propellant)
- Flow rate is computed as

  $\dot{W} = G \frac{P_0\, A^*}{C^*}$ N/sec (lb/sec)

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Characteristic Velocity, C^*

- Depends upon molecular characteristics of burned propellant

  $$C^* = \frac{223}{K}\sqrt{\frac{T_0}{m}} \qquad \text{m/sec} \qquad \text{(ft/sec)}$$

  - Where
    - m is molecular weight
    - K is function of specific heat ratio (typically between 0.63 and 0.73)
    - T_0 flame temperature
- Working value of C^* for most solid propellants ≈ 5200 ft/sec
- In space applications, C^* for liquid propellants can be as high as ≈ 8000 ft/sec
- Using C^*, we can write an alternate form of the rocket thrust equation
- $F = \frac{P_0 A^*}{C^*} V_e + (P_e - P_a)\, A_e$

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Specific Impulse, I_{SP}

- Specific Impulse if defined as

  $$I_{SP} = \frac{F}{\dot{W}} \qquad \text{seconds}$$

- I_{SP} relates to thermochemical energy inherent in the particular propellant
  - I_{SP} can range from 130 sec (end burners) to 260 sec (radial burners)
- Range of I_{SP} for liquids is greater than for solids (as high as 350 sec)
- I_{SP} has two practical uses
  - Easily measured in tests
  - Provides missile designer with convenient parameter to determine missile performance
- The effective exit velocity (V_e) can be expressed in terms of specific impulse

  $$V_e = G\, I_{SP}$$

Specific Impulse Describes Propellant Efficiency (like MPH for cars)

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Total Impulse, I_T

- Total impulse is the integral of the thrust-time curve

  $$I_T = \int_0^{t_{BO}} F\, dt \qquad \text{N-sec} \qquad \text{(lb-sec)}$$

- Total impulse can also be calculated from the produce of propellant weight (W_P) and I_{SP}

  $$I_T = W_P\, I_{SP} = constant$$

- Total impulse remains constant for a given rocket, regardless of the motor being a “hot soak” or “cold soak”
  - Different thrust-time curves, but equal areas under the curve
  - Missile designer may select a desired thrust-time curve to achieve desired trajectory characteristics

Total Impulse is Analogous to the Amount of Gas in the Tank of a Car

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Ideal Burnout Velocity

- Represents the rocket speed that can be realized assuming no drag and no work against gravity

  $$V_{BO_I} = G\, I_{SP} \ln\left(\frac{W_L}{W_{BO}}\right)$$

  - Where
    - W_L is the weight of the vehicle at launch
    - W_{BO} is the weight of the vehicle at burn out
  - Typical values for the vehicle mass ratio (W_L/W_{BO}) > 2
- A more realistic value of burnout velocity for long burn times can be obtained by including gravity and drag effects

  $$V_{BO} = G\, I_{SP} \ln\left(\frac{W_L}{W_{BO}}\right) - G \sin(\bar{\gamma})\, T_{BO}$$

  - Where
    - $\bar{\gamma}$ is the average flight path angle

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Computing Burnout Velocity

- We can approximate burn out velocity of a rocket as a function of time

  $$\frac{dv}{dt} = \frac{F_{thrust}}{m} - \frac{F_{drag}}{m} - G$$

- Assumptions:
  - For simplicity we assume that the drag is small compared to the thrust ($F_{drag} = 0$)
  - Difference in pressure in the thrust equation is zero ($T_{thrust} = -v_e \frac{dm}{dt}$)
  - $\bar{\gamma}$ is the average flight path angle

  $$\frac{dv}{dt} = \frac{T_{thrust}}{m} - \sin(\bar{\gamma})\, G \quad = \quad -\frac{v_e}{m}\frac{dm}{dt} - \sin(\bar{\gamma})\, G$$

  $$dv = -v_e \frac{dm}{m} - \sin(\bar{\gamma})\, G\, dt$$

- Integrating:

  $$v(t) = v_0 + v_e \ln\left(\frac{m_0}{m(t)}\right) - \sin(\bar{\gamma})\, G\, t,$$

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Missile Propulsion / Radar Interactions

- Plume effects
  - Certain propellant materials (especially aluminum oxide) influence frequency and modulation of radar signals
- Thrust variation
  - Results in time/position variation of missile, which influence radar range gate settings for missile acquisition after launch
- Thrust misalignment
  - Influences guidance
- Missile roll
  - Vortex swirling with certain propellants may induce roll oscillations due to an inadequate autopilot response
  - Can affect missile beacon track as missile receiver can be rotated to a less desirable orientation (null)

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References

1. *Propulsion*. Missile System Engineering Fundamentals, Lockheed Martin Lectures (circa ~1984)

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