Class Agenda

- Propulsion subsystem selection and sizing
- Basics of rocket propulsion
- Types of rockets
- System sizing

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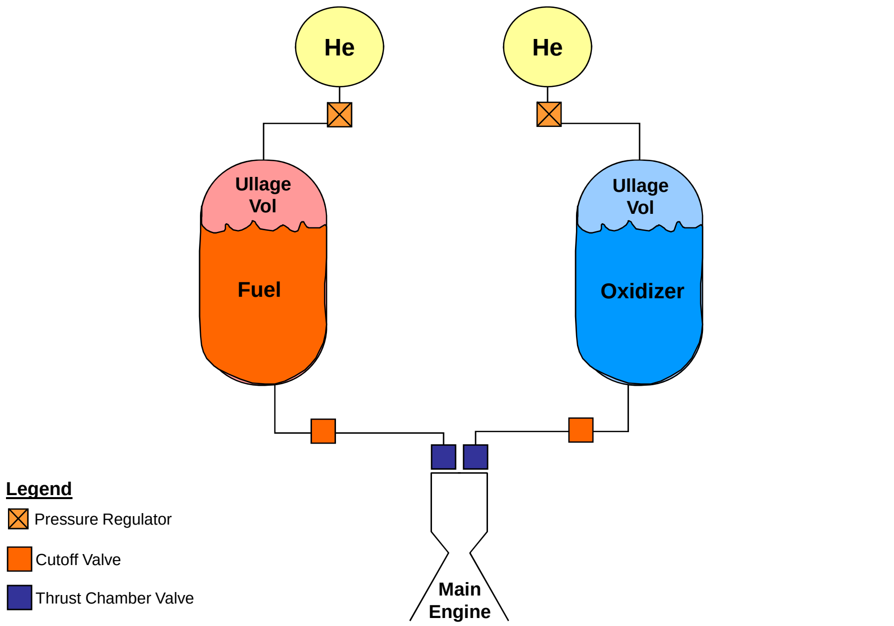
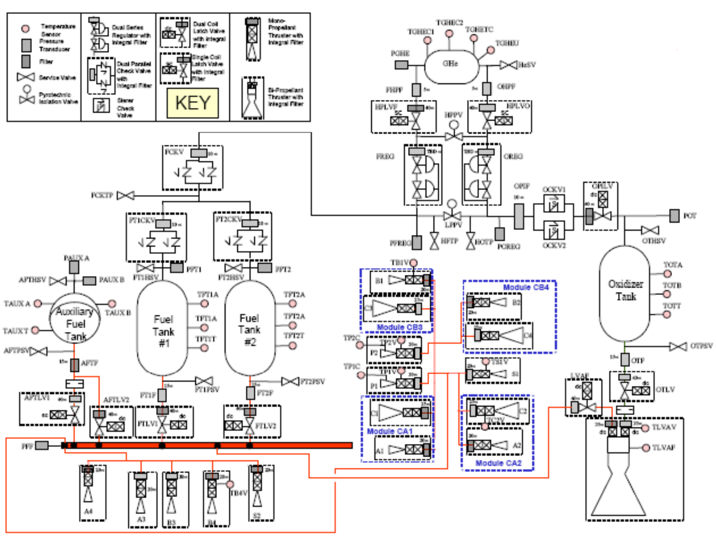
Spacecraft Propulsion System



Spacecraft Propulsion System



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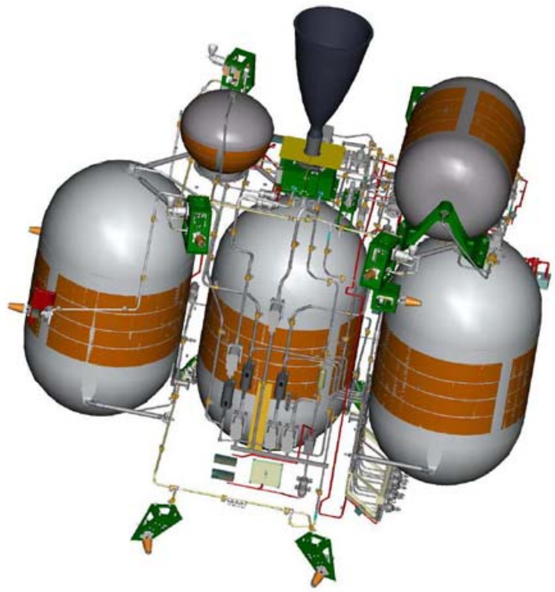
Spacecraft Propulsion System



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Introduction

- Tsiolkowski – observed that rocket propulsion was a prerequisite for space exploration
- 1883 – noted that gas expulsion could create thrust – rocket could operate in vacuum
- 1903 – published paper describing how space flight could be accomplished with rockets
  - Described staged rockets and showed mathematically that space exploration would require staging
  - Created Tsiolkowski's equation

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Introduction

- Goddard – observed space flight would require liquid rocket propulsion
- Goal – design, build, and fly a liquid rocket – over 200 patents in process
- 1926 – 1st liquid rocket launch, LOX/Gasoline – flew for 2.5 s, altitude of 41 ft, 63 mph
- Developed pump-fed engines, clustered stages, quick disconnects, pressurization systems, gyro stabilization
- By the time he died in 1945 – all equipment developed for Saturn V

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Units

- Rockets like English units
  - lbf = 4.448N
  - lbm = 0.4535kg
  - psia = 6894.75kPa
  - Remember
    - 1lbf = 32.2 lbm*ft/sec^2

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Propulsion

- Three functions
  - Lift launch vehicle and payload from launch pad and place payload in LEO
  - Transfer payloads from LEO into higher orbit
  - Provide thrust for attitude control and orbit corrections
- Performance parameters
  - Thrust, F
  - Total impulse, I_T
  - Duty cycle

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Propulsion

- In-space propulsion system parameters driven by performance and weight efficiency
  - Weight (mass)
  - Size
  - Volume
- Other parameters
  - Specific impulse, Isp
  - Propellant density
  - Stage mass fraction

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Propulsion Selection and Sizing

1. List applicable spacecraft propulsion functions
2. Determine ΔV budget and thrust level constraints for orbit insertion and maintenance
3. Determine total impulse for attitude control, thrust levels for control authority, duty cycles (% on/off, total number of cycles) and mission life requirements
4. Determine propulsion system options
   – Combined or separate propulsion systems for obit and attitude control
   – High vs. low thrust
   – Liquid vs. solid vs. electric propulsion

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Propulsion Selection and Sizing

5. Estimate key parameters for each option
   – Effective Isp for orbit and attitude control
   – Propellant mass
   – Propellant and pressurant volume
   – Configure subsystem and equipment list
6. Estimate total mass and power for each option
7. Establish baseline propulsion subsystem
8. Document results and iterate as required

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Propulsion Options

Propulsion Technology	Orbit Insertion (Perigee)	Orbit Insertion (Apogee)	Orbit Maintenance and Maneuvering	Attitude Control	Typical Steady State Isp (sec)
Cold gas			✓	✓	30-70
Solid	✓	✓			280-300
Monopropellant			✓	✓	220-240
Bipropellant	✓	✓	✓	✓	305-310
Dual mode	✓	✓	✓	✓	313-322
Hybrid	✓	✓	✓		250-340
Electric		✓	✓		300-3,000

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Basics of Rocket Propulsion

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Basics of Rocket Propulsion

- Rockets generate thrust by accelerating high-pressure gas to supersonic velocities in a converging-diverging nozzle
- Most cases – high-pressure gas generated by high-temperature combustion of propellants
- Rockets
  - Combustion chamber
  - Throat
  - Nozzle

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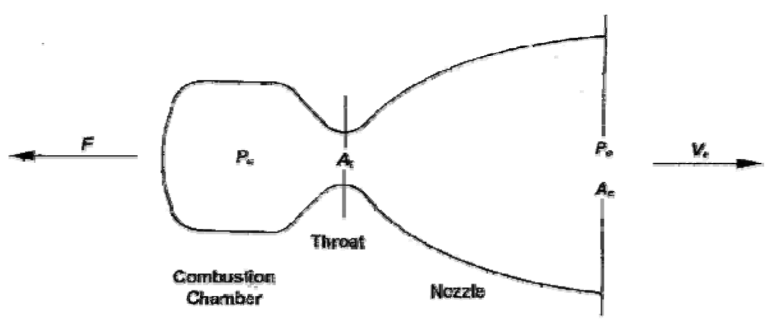
Basics of Rocket Propulsion



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Basics of Rocket Propulsion

- Bipropellant rocket engine – gases are generated by rapid combustion of liquid oxidizer and liquid fuel in combustion chamber (LOX/LH2)
- Monopropellant system – only one propellant is used, high-pressure, high-temperature gases are generated by decomposition of single propellant (N2H4)
- Solid system – solid fuel and oxidizer mechanically mixed and cast as a solid-propellant grain, grain occupies most of volume of combustion chamber (HTPB, AP)
- Cold gas system – no combustion involved, gas stored at high pressure and injected into chamber without combustion (He, N2)

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Thrust

- Rocket thrust generated by momentum exchange between exhaust and vehicle and by pressure imbalance at nozzle exit
- Thrust caused by momentum exchange derived from Newton’s second law:

$$F_m = ma$$

$$F_m = \dot{m}_p \left(V_e - V_0 \right)$$

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Thrust

- In addition to thrust caused by momentum, thrust generated by pressure-area term at nozzle exit
- If nozzle were exhausting into vacuum, pressure-area thrust would be

$$F_p = P_e A_e$$

- If ambient pressure is not zero

$$F_p = P_e A_e - P_a A_e$$

$$F_p = \left(P_e - P_a\right) A_e$$

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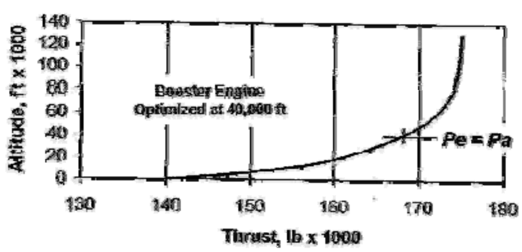
Thrust

- Total thrust – sum of thrust caused by momentum exchange and thrust caused by exit plane pressure

$$F = \dot{m} V_e + \left(P_e - P_a\right) A_e$$



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Ideal Rocket Thermodynamics

- Somewhat idealize flow of rocket engine – thermodynamics can be used to predict rocket performance parameters within a few percent of measured values
- 7 assumptions
  - Propellant gases are homogeneous and invariant in composition throughout nozzle, requires good mixing and rapid completion of combustion
  - Propellant gases follow perfect gas laws; high temperature of rocket exhaust is above vapor conditions, these gases approach perfect gas behavior
  - No friction at nozzle walls, no boundary layer
  - No heat transfer across nozzle wall
  - Flow is steady and constant
  - All gases leave engine with an axial velocity
  - Gas velocity is uniform across any section normal to nozzle axis

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Ideal Rocket Thermodynamics

- Assumptions 3,4,6,7 permit use of one-dimensional isentropic expansion relations
- Assumption 1 defines frozen equilibrium condition
- Gas composition can vary from section to section – shifting equilibrium calculation

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Specific Impulse

- Specific impulse (Isp) – describes how much thrust is delivered by an engine per unit propellant mass flow rate (engine fuel efficiency)
- Premier measurement of rocket performance
- Common to assume that an extra second of Isp was worth a million dollars in engine development

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Specific Impulse

- Isp equation

$$I_{sp} = \frac{F}{\dot{m} g_O}$$

- Thermodynamic expression for theoretical vacuum Isp

$$I_{sp} g_O = \sqrt{\frac{2kRT_c}{(k-1)}\left[1-\left(\frac{P_e}{P_a}\right)^{\frac{k-1}{k}}\right]} + \frac{P_e A_e}{P_c A_t}\sqrt{\frac{RT_c}{kg_O\left(2/k+1\right)^{\frac{k+1}{k-1}}}}$$

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Specific Impulse

- To fully define specific impulse, necessary to state
  - Ambient pressure
  - Chamber pressure
  - Area ratio
  - Shifting or frozen equilibrium conditions
  - Real or theoretical
- Real engine – 95-93% of theoretical
  - Want to go higher – lots of research into ways to eliminate losses

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Area Ratio

- Area ratio of rocket engine is ratio of exit area to throat area

$$\varepsilon = {A_e}/{A_t}$$

- Measure of gas expansion provided by engine
- Optimum area ratio provides an exit-plane pressure equal to local ambient pressure (no shock)
- Sea-level engine – near midpoint of flight – 12 common area ratio
- Spacecraft engine – optimum is infinite – largest allowed by space and weight is used – range between 50 and 300

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Mass Flow Rate

- Mass flow rate through a supersonic isentropic nozzle

$$\dot{m}_p = \frac{P_c A_t k}{\sqrt{kRT_c}} \sqrt{\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}$$

- Assumes choked flow at throat!

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Thrust Coefficient

- Useful term which first arose during rocket engine testing
- Proportionally constant between thrust and product of chamber pressure and throat area

$$F = P_c A_t C_f$$

$$C_f = \sqrt{\frac{2k^2}{k-1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\left[1-\left(\frac{P_e}{P_c}\right)^{\frac{k-1}{k}}\right]} + \left(\frac{P_e - P_a}{P_c}\right)\frac{A_e}{A_t}$$

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Total Impulse

- Impulse – change in momentum caused by force acting over time, for constant thrust

$$I = Ft = m_p g_O Isp$$

- Propulsion system size is rated based on total impulse – particularly useful in solid systems

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Mixture Ratio (MR)

- Important parameter for bipropellant systems
- Ratio of oxidizer to fuel flow rate, on a weight basis

$$MR = \frac{\dot{m}_o}{\dot{m}_f}$$

- Volumetric MR sometimes used in conjunction with tank sizing

$$VMR = MR\frac{\rho_f}{\rho_o}$$

- Volumetric MR – major effect on system design because it determines relative sizes of propellant tanks
- Loaded MR designed off optimum in order to have both ox and fuel tanks same volume – Isp loss is slight, two identical tanks are cheaper than two individually sized tanks

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Bulk Density

- Often convenient to use bulk density of propellant combination to expedite approximate calculations
- Bulk density – mass of a unit volume of propellant combination “mixed” at appropriate mixture ratio

$$\rho_b = \frac{MR + 1}{MR/\rho_o + 1/\rho_f}$$

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Translational Velocity Change

- Main products of mission design – ΔV required for maneuvers for mission
- To convert ΔV maneuver requirements to propellant requirements – need Tsiolkowski equation

$$\Delta V = g_O I_{sp} \ln\left(\frac{m_i}{m_f}\right)$$

$$m_p = m_i\left[1 - \exp^{\left(\frac{-\Delta v}{g_O I_{sp}}\right)}\right] = m_f\left[\exp^{\left(\frac{\Delta v}{g_O Isp}\right)} - 1\right]$$

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Translational Velocity Change

- Assumptions
  - Thrust is only unbalanced force on vehicle, force of gravity balance by centrifugal force and drag is zero
  - Thrust is tangential to vehicle trajectory
  - Exhaust gas velocity is constant, implies a fixed nozzle throat area and sonic velocity at throat

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Types of Rockets

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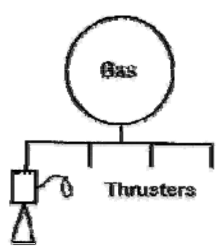
Types of Rockets

- Propulsion choices
  - Cold-gas system
  - Liquid rockets
    - Monopropellant
    - Bi-propellant
    - Dual-mode
  - Solid motor
  - Hybrid rockets
  - Electric
- Selection of propulsion system type has substantial impact on total spacecraft and is key selection in early design

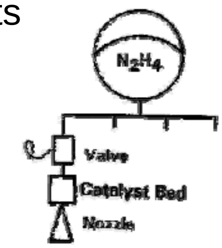
Cold-Gas Systems

- Almost all spacecraft of 1960s used this system
- Simplest choice and least expensive
- Can provide multiple restarts and pulsing
- Low Isp (40 s) and low thrust level (>1N) – major disadvantage



Monopropellant Systems

- Next step in complexity and cost
- Can supply pulsing or steady-state thrust
- Isp ~ 225 sec
- F ~ 0.5 – 100s N
- Common choice for attitude control and midrange impulse requirements
- Propellant – N2H4



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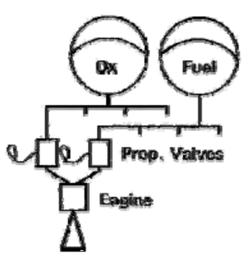
Bipropellant Systems

- Top of complexity and expense scale
- Very versatile and high performance system
- Provide Isp < 310 sec and wide range of thrust capability
- Can be used in pulsing or steady-state modes
- Most common propellant combo – N2O4/N2H4



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Dual-Mode Systems

- Designed for situations that require high-impulse burns in addition to low-impulse attitude control pulses
- High-performance high-impulse burns are provided by bipropellant N2O4/N2H4
- Fuel, N2H4, used as a monopropellant for low-impulse attitude control pulses
- Ideal for geosynchronous orbit and require low-impulse attitude control and station keeping
- Planetary spacecraft that required orbit insertion burns as well as attitude control are good candidates for this system as well

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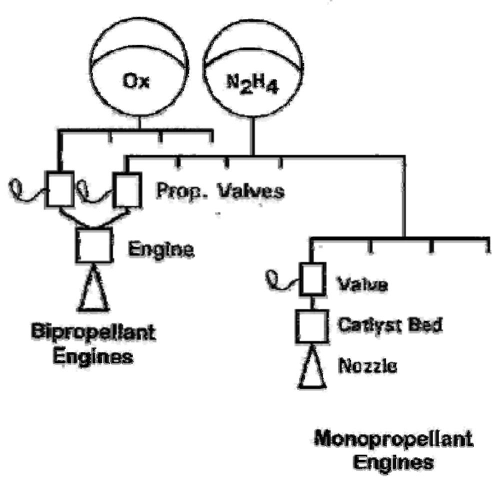
Dual-Mode Systems



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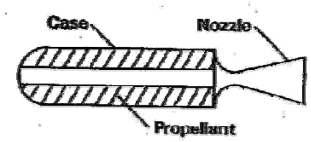
Solid Motor Systems

- Candidates when all of impulse is to be delivered in a single burn and impulse can be accurately calculated in advance
- Examples
  - Planetary orbit insertion
  - Geosynchronous apogee burns (kick motors)
- If criteria met, solids provide simplicity and reasonable performance (Isp)



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Hybrid Rockets

- Fuel – solid
- Oxidizer – liquid or gas
- Features
  - Safety – impossible to create explosive mixture
  - Throttling – change oxidizer flow rate to change burn rate of solid
  - Restart – shut off and on
  - Storability – fuel storable, most oxidizers as well
  - Environmentally clean – no harmful by-products

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Electric Propulsion

- Uses externally provided power (solar or nuclear) to accelerate working fluid to produce useful thrust
- Propulsion system mass varies
  - Isp (exhaust velocity)
  - Thrust level
  - Total impulse
- Propellant mass decreases with Isp increase
  - Power source requirements increases with Isp increase

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Electric Propulsion

- Power required

$$P = \frac{F^2}{2\dot{m}\eta} = \frac{FI_{sp}g_o}{2\eta}$$

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System Sizing

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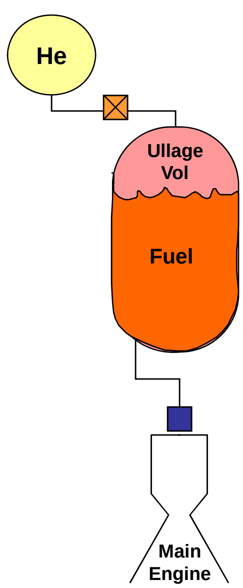
Monopropellant System



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Monopropellant System Design Steps

- Define requirements
- Calculate propellant required, add margin
- Select propellant control device
- Decide dual-vs single-propellant tanks
- Decide propellant tank type, sphere, barrel, conosphere
- Select pressurant – He is mass is critical
- Select pressurization system type and set performance parameters – max tank pressure and blowdown ratio
- Design propellant tank
- Design engine modules and general arrangement
- Design system schematic; plan redundancy
- Calculate system mass
- Conduct trade studies of system alternatives; repeat process

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Propellant Inventory

- Propellant inventory subdivided tabulation of loaded propellant weight
- Usable propellant – portion of propellant loaded, which is actually burned
  - Quantity required for all maneuvers and all attitude control functions
  - Important that usable propellant quantity be calculated under worst-case conditions
- Trapped propellant – propellant remaining in feed lines, tanks, valves, hold-up in expulsion devices, and retained vapor left in system with pressurizing gas
  - About 3% of usable propellant
- Uncertainty – added to load to ensure that usable propellant can be no less than worst-case requirement
  - About 0.5% of usable propellant

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Propellant Inventory

- Propellant reserves are very valuable commodity
- More of project reserves placed in propellant – the better
- 3 primary reasons
  - Propellant is usually life-limiting expendable on spacecraft
  - Often desirable to make unplanned maneuvers in response to unexpected results or emergency conditions
  - Usually extended mission objectives that can be achieved after primary mission

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Tankage Weight

- Major dry weight component in liquid propellant propulsion system is tankage
- 1st – volume of tank must be established and maximum tank pressure set
- Tank weight can then be estimated
- Four components to volume
  - Initial ullage
  - Useable propellant volume
  - Unusable propellant volume – 3-4% of usable
  - Volume occupied by zero-g device

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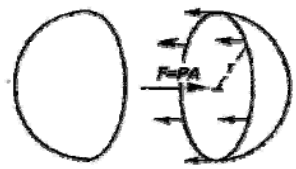
Spherical Tanks

- Common tank configurations
  - Spherical
  - Barrel with hemispherical domes
- Tank weights are byproduct of structural design of tanks
- For spheres – load in walls is pressure times area

$$PA = P\pi r^2$$



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Spherical Tanks

- Stress is load divided by area carrying load

$$\sigma = \frac{P\pi r^2}{2\pi r t} = \frac{\Pr}{2t}$$

$$t = \frac{\Pr}{2\sigma}$$

- Knowing wall thickness – weight of tank membrane calculated

$$R = r + t$$

$$W = \frac{4}{3}\pi\rho\left(R^3 - r^3\right)$$

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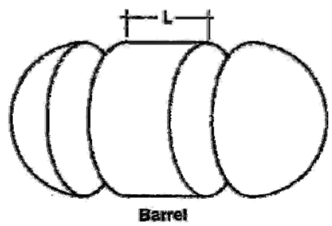
Cylindrical Tanks

- Hoop stress is twice that in spherical shell

$$t = \frac{\Pr}{\sigma}$$

- Weight of barrel

$$W = \pi L \rho \left(R^2 - r^2\right)$$



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Penetrations and Girth Reinforcements

- Membrane weight is a perfect pressure shell
- Areas of reinforcement (land areas)
  - Girth welds – weld between two hemispheres
  - Penetration welds – welds for inlet and outlets
  - Bladder attachment – attachment between bladder and tank wall
  - Structural mounting of tank
- Weight must be added to membrane weight to account for these reinforcements

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Penetrations and Girth Reinforcements

- Weld areas must be reinforced because of reduction in material properties near welds
- Mounting pads on tank add about 2% of supported weight
- Penetrations, girth land areas, and mounting pads normally add about 25% to shell weight

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Tank MER

- Following mass estimating relationship can be used for tanks

$$M_{Tank} = 0.0116 P(kPa) * V(m^3)$$

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Pressurization Subsystems

- Purpose – to control gas pressure in propellant tanks
- Tank pressure must be higher than engine chamber pressure by amount equal to system losses
- Significant delta pressure must be maintained across injector for combustion stability

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Pressurization Subsystems

- Pressurants
  - Must be inert in presence of propellants
  - Low molecular weight desirable
  - Two pressurants – N2 and He
  - He – provides lightest system – difficult to prevent He leakage
  - N2 – used if weight situation will allow it
- Ullage
  - Volume that pressurant occupies above propellant

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Blowdown System

- Two systems
  - Regulated
  - Blowdown
- Blowdown – tank is pressurized to an initial level and pressure is allowed to decay as propellant is used
- Advantages
  - Simplest method – more reliable
  - Less expensive – fewer components
- Disadvantages
  - Tank pressure, thrust, and propellant flow rate vary as function of time
  - Isp is 2nd order function of chamber pressure and drops as function of time
- Variability of flow rate and engine inlet pressure make blowdown system difficult to use with bipropellant systems

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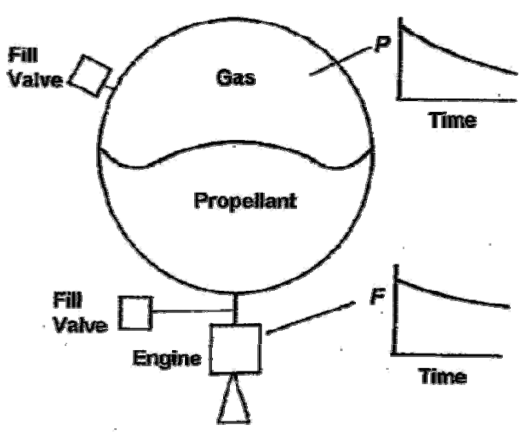
Blowdown System



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Tank Gas Thermodynamics

- Blowdown ratio – ratio of initial pressure to final pressure

$$B = \frac{P_{gi}}{P_{gf}} = \frac{V_{gf}}{V_{gi}}$$

$$V_{gi} = \frac{V_u}{B-1}$$

$$V_{gi} = \frac{W_u}{\rho(B-1)}$$

- Maximum blowdown ratio is determined by inlet pressure range engines can accept
- Ratios of 3 or 4 common – can be as high as 6

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Tank Gas Thermodynamics

- Equation of state
  - An ideal gas at any state point – product of tank pressure and ullage volume

$$PV = mRT$$

$$m = \frac{PV}{RT}$$

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Tank Gas Thermodynamics

- Isothermal expansion
  - Outflow of propellant is usually slow and heat transfer will keep gas temperature fixed at or near propellant temperature – process is isothermal

$$P_2 = P_1 \frac{V_1}{V_2}$$

  - During blowdown process, tank pressure at time t

$$P(t) = P_{gi}\left(\frac{V_{gi}}{m_p(t)/\rho + V_{gi}}\right)$$

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Tank Gas Thermodynamics

- Isentropic expansion
  - If propellant withdrawn rapidly – translational burn – gas expansion in ullage will be isentropic and temperature will drop during process

$$P_1 V_1^{\,k} = P_2 V_2^{\,k}$$

$$P(t) = P_{gi}\left(\frac{V_{gi}}{m_p(t)/\rho + V_{gi}}\right)^k$$

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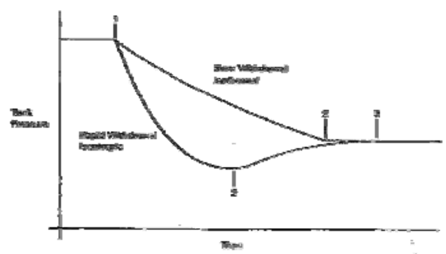
Tank Gas Thermodynamics

- Isentropic expanison – temperature drops more rapidly and drops below propellant temperature
- After engine shutdown – gas temperature warms up to propellant temperature
- Tank pressure and thrust will be lower during portion of burn than isothermal calculations would predict



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Thruster Mass

- Least-squares curve fit of actual monopropellant thruster/valve designs

$$M_T = 0.4 + 0.0033F(N)$$

- For low thrust levels thruster weight approaches valve weight
- Use 0.3 kg as minimum thruster/valve weight for low thrust levels
- Estimated weight must be increased if redundant valves are used

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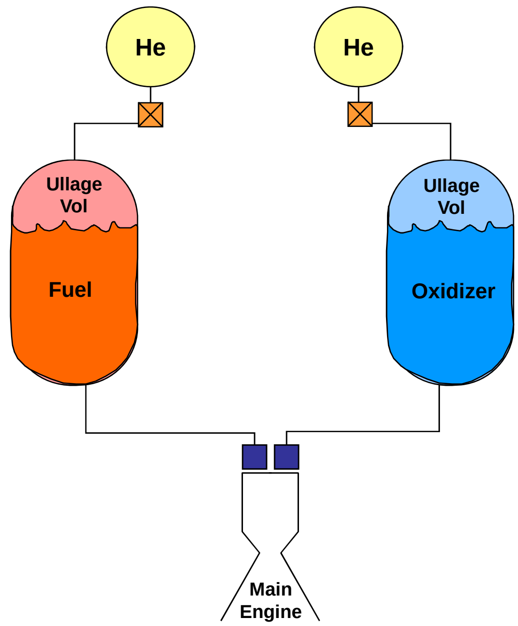
Bipropellant System



Bipropellant System Sizing

- Define requirements
- Calculate propellant required, add margin
- Decide propellant tank type, sphere, barrel, conosphere
- Select pressurant – He is mass is critical
- Design pressurization system
- Design propellant tank
- Design engine modules and general arrangement
- Design system schematic; plan redundancy
- Calculate system mass
- Conduct trade studies of system alternatives; repeat process

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Bipropellants

- Goddard
  - LOX/Kerosene
- Germans
  - LOX/Alcohol
- Post WWII
  - Kerosene – RP-1
  - LOX not used – storability issue
  - Storable propellants
    - Nitric acid – corrosive, still used by Russia
    - NTO developed
  - Fuels
    - N2H4 & UDMH
    - 50/50 mixture of N2H4 & UDMH – Aerozine 50
    - MMH – properties of Aerozine, but with mixing problems

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Bipropellants

- Saturn series
  - LOX/LH2
  - Fluorides – too energetic for metal tank containment
- F2, O2, & H2 – cryogenics
  - Extremely low temperatures at which they are liquids
- Cryogenics never used in spacecraft
  - Only in launch vehicles to date
  - Ongoing studies to show benefits of systems

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Bipropellants

- Nitrogen tetroxide (N_2O_4)
  - Equilibrium solution of NO_2 and N_2O_4
  - Equilibrium state varies with temperature
  - Relative of nitric acid – smells like it
  - Reddish brown and very toxic
  - Hypergolic with N_2H_4, Aerozine 50, MMH
  - Pulsing performance practical
  - Compatible with stainless steel, aluminum, and Teflon
  - Incompatible with all elastomers

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Bipropellants

- Monomethylhydrazine (MMH)
  - Clear water-white toxic liquid
  - Sharp decaying fish smell
  - Not sensitive to impact or friction
  - More stable than hydrazine when heated
  - Decomposes with catalytic oxidation
  - N_2O_4/MMH – dominant spacecraft propellant combination for bipropellant spacecraft propulsion

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Bipropellants

- Hydrazine (N_2H_4)
  - Dual-mode propulsion systems made N_2H_4 propellant of choice
  - Provides slightly higher Isp with N_2O_4 than MMH
  - Can be used as monopropellant for pulsing

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Propellant Inventory

- Subdivided tabulation of loaded propellant weight
- Usable propellant first subdivided into oxidizer and fuel
- NTO/MMH ~ 1.6
- NTO/N2H4 ~0.9

$$MR = \frac{m_o}{m_f}$$

$$m_f = \frac{m_u}{1 + MR}$$

$$m_o = m_u - m_f$$

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Propellant Inventory

- Usable propellant – portion of propellant loaded that is actually burned
- Trapped propellant – propellant remaining in feed lines, tanks, valves, hold up in expulsion devices and related vapor left in system with pressurizing gas
  - About 3% of usable propellant in small bipropellant systems
- Two primary activities for required propellant
  - Propellant required for velocity change maneuvers as dictated by mission design
  - Propellant required for control attitude
- Tsiolkowski equation used to determine propellant requirements

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Propellant Inventory

- Outage – caused by difference between mixture ratio loaded and mixture ratio at which engine actually burned
- Always some of one propellant left when other propellant is depleted – remaining propellant called outage
- Outage depends on loading accuracy and on burn-to-burn repeatability of engine MR
- 1% used for initial estimates
- 5% JPL requirement
- Calculate propellant requirements under worst-case conditions – show propellant inventory as stated

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Propellant Inventory

- Reserves shown as separate item in propellant inventory
- Reserves are valuable commodity
- 3 reasons
  - Propellant is usually life-limiting expendable
  - Often desirable to make unplanned maneuvers in emergency conditions
  - Usually extended mission objectives that can be achieved after primary mission
- Measurement uncertainty in propellant loading – 0.5%
- Added to load to ensure usable propellant can be no less than worst-case requirement

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Propellant Control and Tankage

- Titanium, aluminum, and stainless steel all compatible with NTO and N2H4
- Titanium – lightest and most common
- Usually use identical tank shells for oxidizer and fuel as cost-saving measure
- NTO – not compatible with elastomers – propellant control devices limited to metals and Teflon

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Pressurization

- Blowdown pressurization not used with bipropellants
  - Difficulty in keeping both tanks at same pressure
  - Difficulties with varying inlet pressure to bipropellant engines
- He or N2 systems used
  - He most frequent choice
- Regulated system controls pressure in propellant tanks at preset pressure
- Pressurant stored at high pressure (3000-5000 psia)
- Engine supplied propellant at tightly controlled lower pressure and flow rate
- Thrust does not vary during propellant consumption
- Regulation is essential in order to keep flow rate of each propellant constant and at correct mixture ratio

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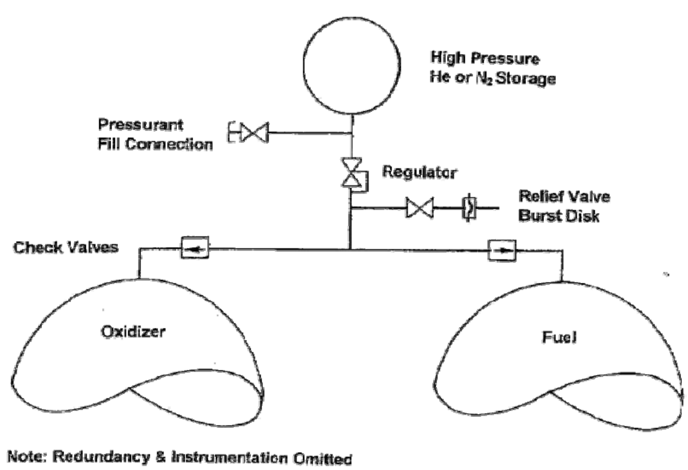
Pressurization



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Pressurization

- Pressurant tank weight is essentially constant for any initial pressure for a given gas weight
  - Takes 3.2 kg of tank to contain 1 lb of He
- Initial storage pressure selected is 2nd order trade
- Regulator requires inlet pressure around 100 psi higher than outlet pressure in order to operate properly
- Unusable pressurant is trapped in pressurant tank at or above minimum regulator inlet pressure

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Pressurization

- Typical pressure profile for a regulated system
  - Maximum pressurant tank pressure – 4500 psia
  - Minimum pressurant tank pressure – 650 psia
  - Minimum regulator inlet pressure – 600 psia
  - Nominal propellant tank pressure – 500 psia
  - Minimum engine valve inlet pressure – 450 psia
  - Nominal chamber pressure – 350 psia
- Minimum ullage volume must be about 3% of propellant tank volume in order for regulator to have stable response when outflow starts
- Relief valves necessary to protect tank in case regulator fails open
- Good practice to place burst disk upstream of relief valve so that pressurant is not lost overboard at valve seat leakage rate
  - Particularly important if He is pressurant
- Each propellant tank ullage must be isolated to prevent vapor mixing

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Pressurization

- Pressurant mass

$$m_{gi} = \frac{P_p V_p}{RT_i}\left[\frac{k}{1-\left(P_g / P_i\right)}\right]$$

- k = 1.67 for He
- R = 2077.3 J/(kg-K) for He

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Pressurization

- Careful considerations should be given to propellant vapor mixing between check valves after permeation of check valve seals
- Propellant vapor mixing between check valves have been issues with previous missions
  - Viking I – still successfully landed
  - Mars Observer – did not enter Mars orbit
- Positive mixing prevention particularly important on long duration missions

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Unusable Propellant

- Unusable propellant greater with bipropellant systems than monopropellant systems
- Difference between loaded mixture ratio and burned mixture ratio results in residual of one or the other propellants
- Residual – called outage
- Unusable propellant is about 4% of total load by weight

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Bipropellant Thruster Mass

- Thruster mass

$$M_T = 0.0073 * F(N) + 1.95$$

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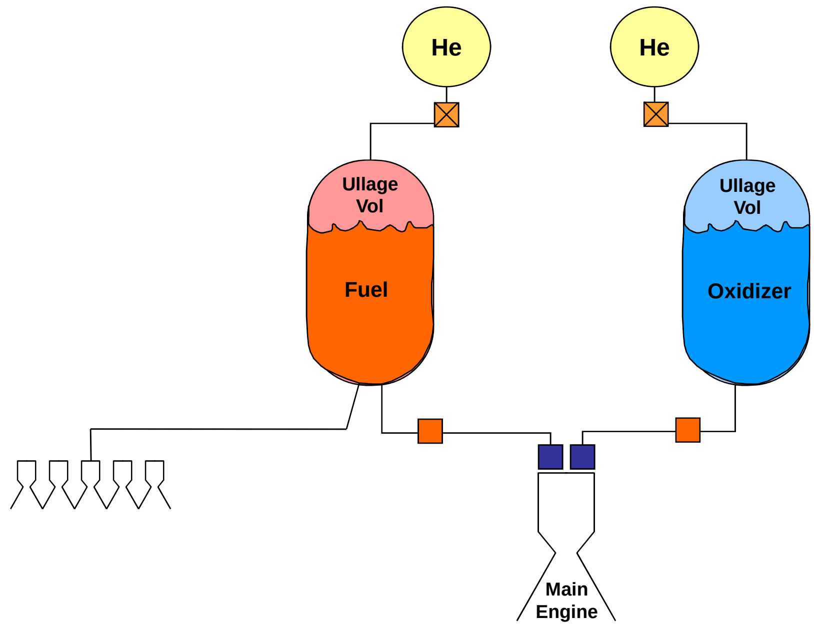
Dual Mode System



Solid Rocket Systems

- Oxidizer and fuel are stored in combustion chamber as a mechanical mixture in solid form
- When propellants are ignited, they burn in place
- Used extensively where
  - Total impulse requirement is known accurately in advance
  - Restart is not required
- Kick stage of geosynchronous spacecraft

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Propellants

- Solid rockets over 700 years old
  - Chinese invented in 1232
- Basis of Chinese rockets – black powder
- Smokeless powder invented by Alfred Nobel in 1879
  - Not used as rocket fuel until 1918 by Goddard
- Double-base propellant
  - Combination of nitrocellulose dissolved in nitroglycerin
- Composite propellant
  - Modern, high-performance propellants made in 1942 by JPL

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Propellants

- Composite propellants
  - Composed of one of several organic binders, aluminum powder, and an oxidizer – usually AP
  - Binders – rubber-like polymers – serve dual purpose as fuel and bind aluminum with AP
  - Common binders
    - HTPB, PBAN
  - Contain small amounts of chemical additives to improve physical properties
    - Burn rate, smooth burning, casting characteristics, structural properties, absorb moisture during storage

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Propellants

- Solid propellants produce vacuum Isp of 300 sec or lower
  - Somewhat lower than bipropellants
- Solid propellant densities are higher
  - Smaller systems for a given impulse
- Higher Isp – less stable ingredients
  - Boron
  - Nitronium perchlorate

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Burning Rate

- Control of exhaust gas flow by precise control of exposed grain surface area and burning rate of propellant mixture
- Solid transformed into combustion gases at grain surface
- Surface regresses normal to itself in parallel layers
- Rate of regression – burning rate
- Burning rate – measured by measuring flame front velocity on a strand

$$\dot{m}_p = \rho A_p \dot{r}$$

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Burning Rate

- Pressure effect
  - Grain density is constant during burn, gas flow rate is controlled by grain area and burning rate
  - Gas flow rate, thrust, and chamber pressure go up with an increase in burn area
  - Burning area goes up exponentially with pressure

$$\dot{r} = cP^n$$

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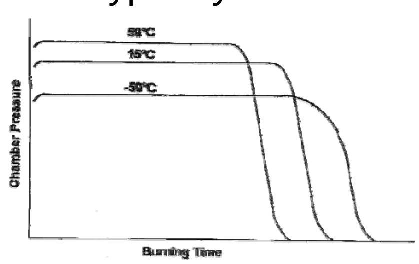
Burning Rate

- Temperature effect
  - Chamber pressure increases nonlinearly with grain temperature because burning rate increases with temperature and pressure
  - Sensitivity of chamber pressure to temperature is typically 0.12 to 0.50% per °C



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Burning Rate

- Temperature effect
  - Two reasons to control temperature
    - Limit variation in performance
    - Minimize thermal stress in grain and minimize possibility of grain cracks
  - Typical temperature control is 15 - 38°C
  - Control range can be tightened before motor firing

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Grains

- Solid motor – propellant tank and combustion chamber are same vessel
- Viscous propellant mixture is cast and cured in mold to achieve desired shape and structural strength
- After casting – propellant called grain
- Most frequent method of casting is done in place in motor case using a mandrill to form central port
  - Grain called case bonded

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Grains

- Grains also cast separately and loaded into case at later time
  - Called cartridge loaded
- Large grains cast in segments – then stacked to form motor
  - SRBs on shuttle and Titan IV
- Segmented grains solve transportation issue, but require high-temperature case joints
  - Serious failure source
  - *Challenger* accident
- Liner used in grain to case interface to inhibit burning as flame front arrives at case wall
- Liner composition usually binder without added propellants
- Areas in case where no grain interface (ends of motor), insulation used to protect case for full duration of firing

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Grains

- Grain shape
  - Primarily cross section
  - Determines surface burning area as function of time
  - Burning area, along with burning rate, determines thrust
  - For given propellant, surface area vs time determines shape of thrust time curve
  - Cylindrical grain inhibited on sides – called an “end burner” would have constant burning area and constant thrust
  - Grain with essentially constant burning surface area and thrust time curve is called neutral burning

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Grains

- Grain shape
  - Progressive – grain that has increasing surface area with time
  - Primary disadvantage – as mass decreases thrust increases – higher acceleration loads
  - Cylindrical grain inhibited on ends and burning from sides would be regressive
  - Neutral burning is most common design for spacecraft

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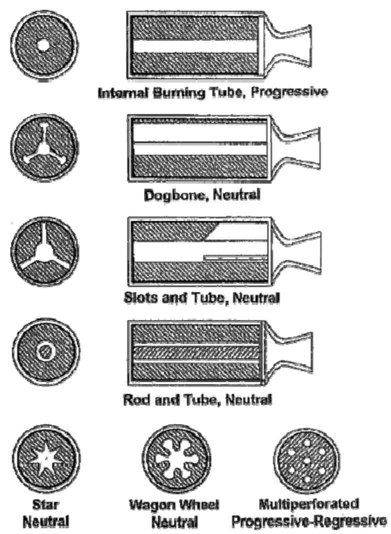
Grain Configurations



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Grains

- Crack in grain provides unplanned increase in exposed area with resultant sudden increase in pressure – can lead to failure
- Numerous precautions
  - Limits on grain temperature extremes
  - Limits on shock loads on grain and bond line
  - Final set of grain x rays at launch site just before launch
- Star grain most commonly used shape and nearly neutral
  - Flame does not reach liner in all locations at same time
  - When flame front reaches liner, chamber pressure starts to decay
  - At given pressure aggressive burning or deflagration can no longer occur
  - Residual propellant (remains after combustion) – called sliver
  - Sliver – about 2% of grain weight

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Motor Weight

- Total weight can be expressed as

$$m = \frac{m_p}{\eta}$$

- Average propellant mass fraction of 23 current motors is 0.93 with correlation of 0.954
- Useful equation

$$m_{SRM} = \frac{m_p}{0.93}$$

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