AA 284a
Advanced Rocket Propulsion

Lecture 11
Solid Rocket Propulsion

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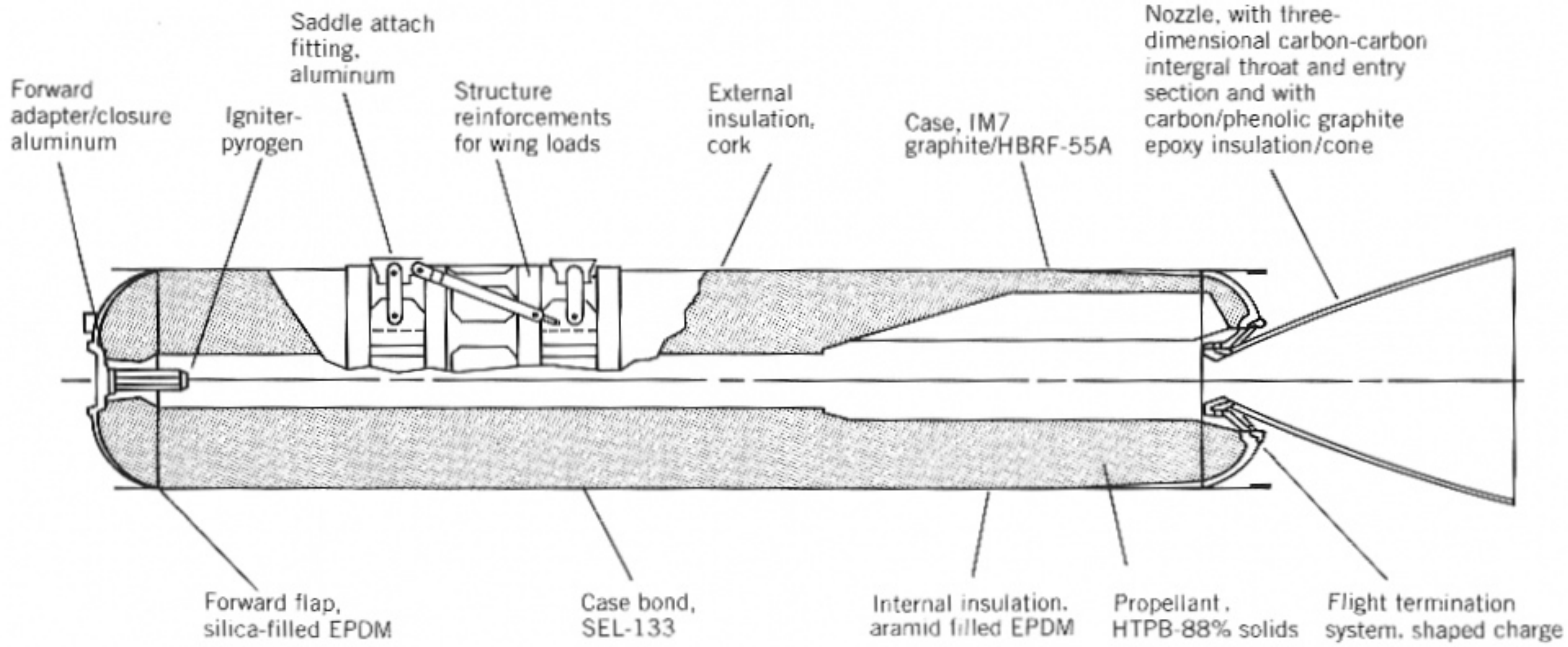
Solid Rocket Systems

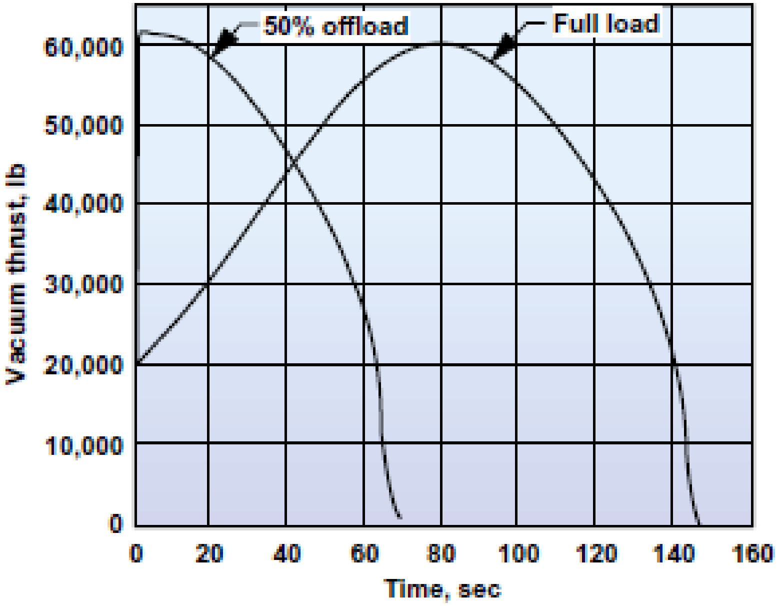


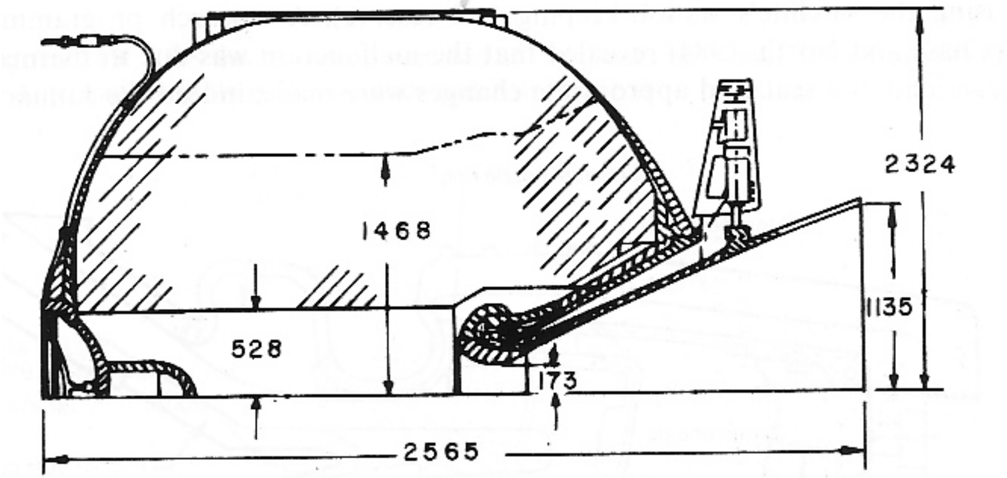
Pegasus solid rocket motor

- Propellant in solid phase
- No moving parts, very simple mechanical design
- Structural mass fraction: 0.84-0.94 (0.90 typical)

- Difficult manufacturing, transportation, operations due to explosive nature of the propellant charge
- Compact design, high density system
- Low Isp due to low energy oxidizers (260-300 seconds)

ORBUS 21 Space Motor (CSD/UTC)





3-D Fuel grain geometry determines F-t

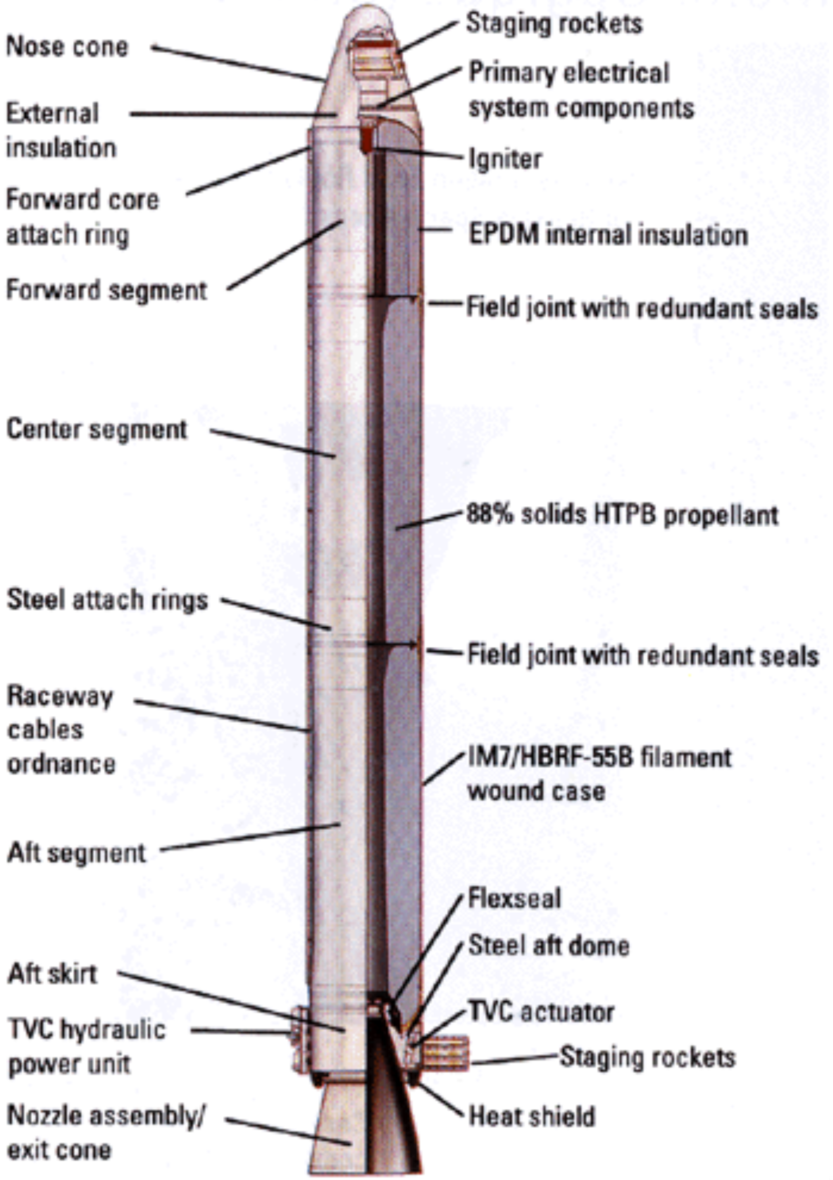
Active control is very hard to implement

Offloading is possible (use same motor for different missions)

Flex joint for Thrust Vector Control (TVC)

Segmented Solids

- Limit the propellant mass for large boosters
  - Manufacturing
  - Transportation
- Conceived by UTC/CSD in the late 1950's
- Implemented to
  - Titan 4
  - Shuttle SRB's
  - Ariane V boosters
- Requires field joints

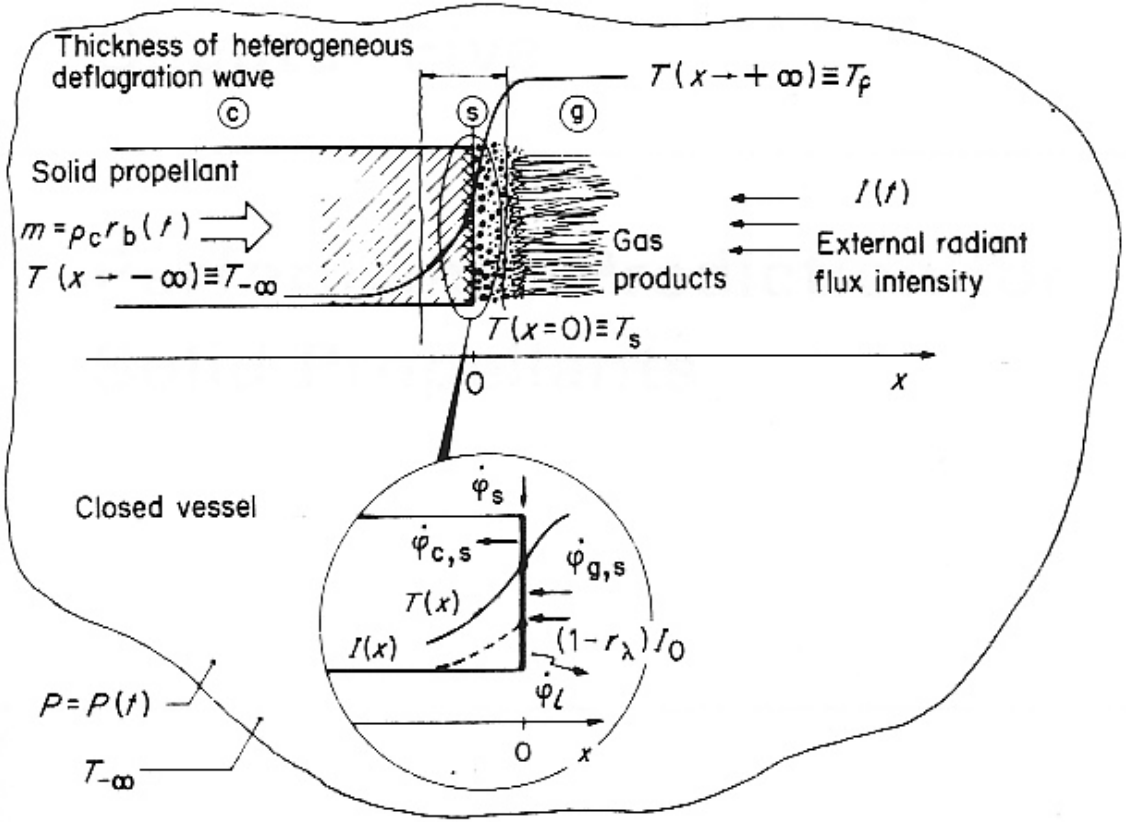


Titan 4

Classification of Solid Propellants

- Classification of solid rockets based on propellants
  - Homogeneous Propellants
    - Oxidizer and fuel belong to the same molecule
    - Double–base propellants: Two explosive materials are homogenously mixed
      - Nitrocellulose (white fibrous solid), nitroglycerine (oily liquid) (JPN propellants)
      - Stoichiometric ratio is 8.57 (nitroglycerine/ nitrocellulose)
      - Can not use more than 43.5% of nitroglycerine
  - Nitramine Propellants
    - RDX (cyclotriethylene trinitramine)
    - HMX (cyclotetramethilene teranitramine)
    - 85% nitramines, HTPB or PU as binders
    - Low smoke
  - Heterogeneous Propellants (Composite)
    - Most modern solid systems use composite propellants
    - Crystalline oxidizer (AP, AN), binder (HTPB, PBAN, PU), metal fuel (Al)
    - Mixed and held together by typically a rubbery substance, binder (HTPB)
    - Binder is also the fuel component
  - Composite Modified Double Based Propellants (CMDB)
    - Double based with crystalline oxidizers, Al fuel or nitramines

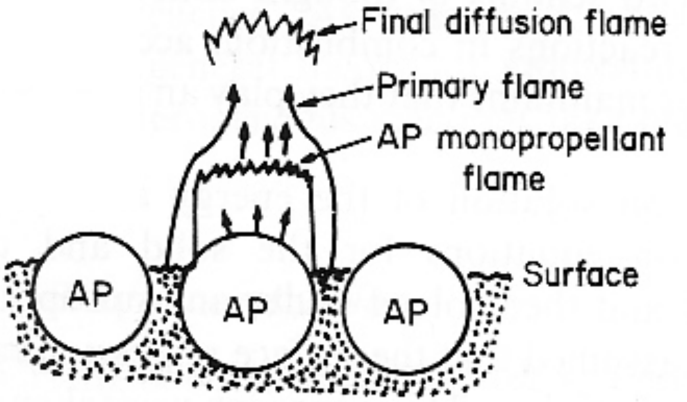
Solid Rocket Combustion/Composite Propellants



- Globally premixed flame
- Deflagration wave
- Locally modeled by multiple diffusion flames (i.e. Beckstead)
- Solid phase and heterogeneous reactions are important

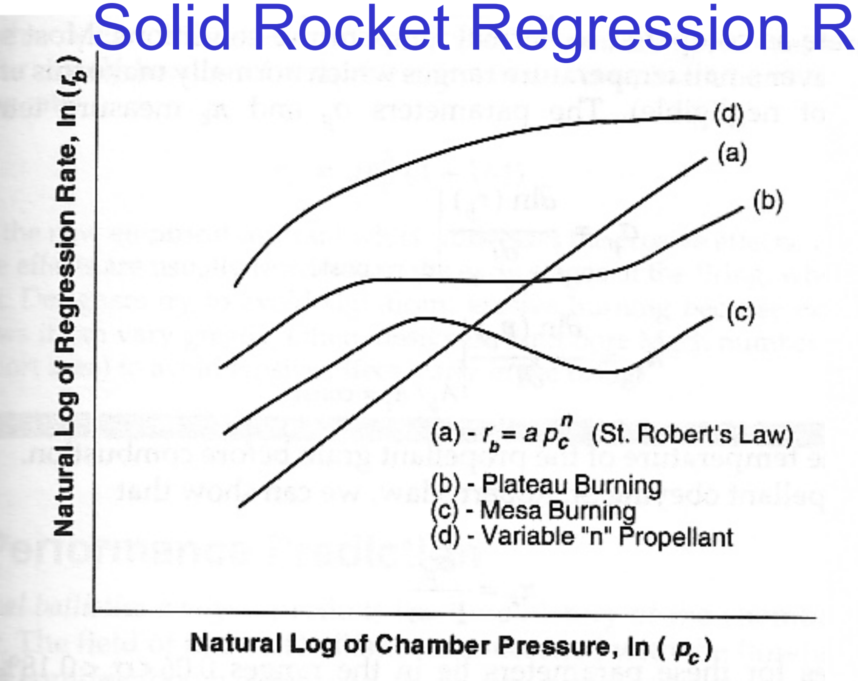
- Chemical kinetics is important
- High regression rates
- Pressure dependent regression rate

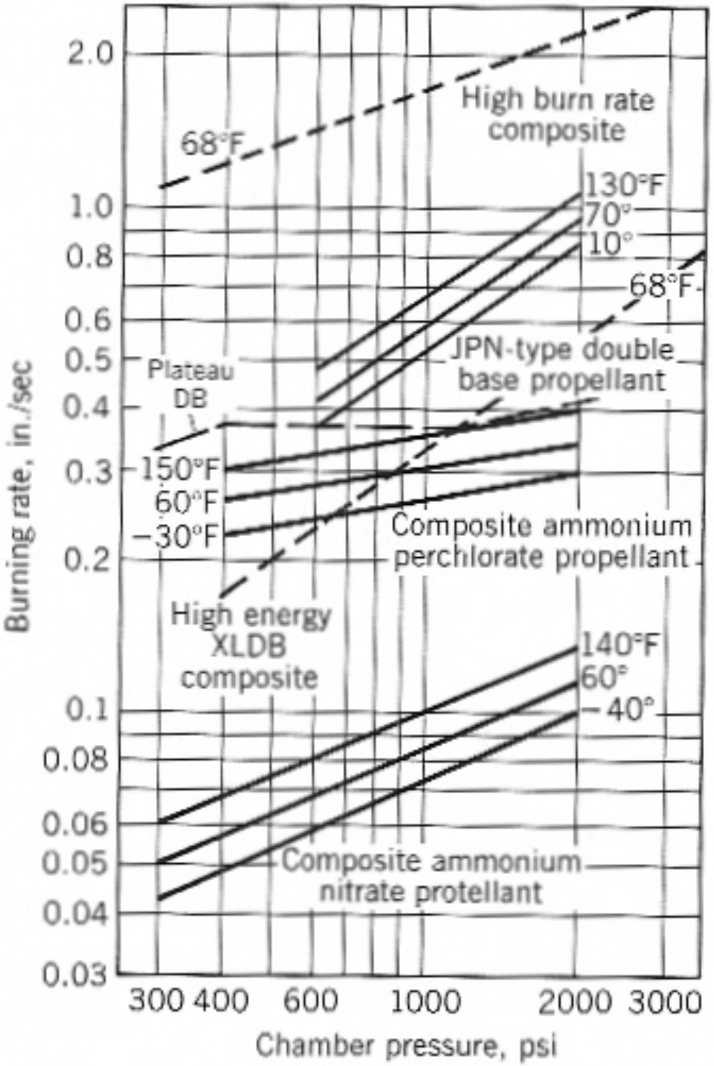
$$\dot{r} = a\ P^n$$



Multiple-flame model
(Beckstead *et al.*)

Solid Rocket Regression Rate Law





- The regression rate law coefficient, a, is temperature dependent
- The regression rate does not depend on the mass flux (to the first order)
- For modern composite propellants n is 0.3-0.4
- Mass generation is proportional to the fuel surface area

Solid Rocket Regression Rate Factors

- **Ambient temperature:** Solid regression rate increases with increasing ambient temperature. Define a regression rate temperature sensitivity factor

$$\sigma_P = \left(\frac{\partial \ln(\dot{r})}{\partial T_a}\right)_P$$

T_a : Ambient Temperature

  - The sensitivity parameter is in the range of 0.06-0.18 %/K for composite propellants. Can be higher for double base propellants
  - Temperature sensitivity is important since the thrust time profile changes with changing temperature.
  - Example: Increasing temperature increases the average thrust but reduces the burn time. Vehicle acceleration may become critical.

- **Erosive Burning:** Mass flux increases the heat transfer and the regression rate

$$\dot{r} = a\ P^n + \alpha\ G^{0.8} D^{-0.2} e^{-\beta\ \dot{r}\rho_p / G}$$

D : Port Diam

ρ_p : Propellant Density

G : Mass Flux

α, β : Cons.

  - Must be eliminated or must be repeatable and controlled

Solid Rocket Regression Rate Factors

- **Acceleration:** Acceleration normal to the burning surface enhances the regression rate
  - Spin along the longitudinal axis for a circular grain
- **Combustion Instability:** Pressure oscillations increase regression rate due to an effect called the “DC Shift”
- **Addition of Conductive Metal Rods:** Increases heat conduction and thermal profile thickness in the solid
- **Burn Rate Modifiers:** Influences the combustion phenomenon
  - Example: FeO for composite propellants
- **End Burning Grains:**
  - End burning grains have higher regression rate close to the case wall
    - Due to microcracks formed at stress concentration areas
    - Due to the migration of the burn rate catalyst towards the insulator
  - Results in coning of the burn surface. Neutral burning is compromised.

Solid Rocket Ballistic Analysis

- Assume cylindrical grain design
- Total pressure drops along the length of the grain due to mass and energy addition
- The conservation of momentum requires

$$d\left(\dot{m}V\right)=d\left(\rho_g A_p V^2\right)=-A_p dP$$

ρ_g : Gas Density
A_p : Port Area
V : Axial Velocity
$\dot{m}$: Flow Rate
M : Mach Number

- For constant port area along the length and perfect gas

$$\frac{dP}{P}=-\frac{\gamma d\left(M^2\right)}{1+\gamma M^2}$$

- The static pressure ratio between the aft and fore end of the motor

$$\frac{P_{aft}}{P_{fore}}=\frac{1}{1+\gamma M_{aft}^2}$$

P_{aft} : Aft Static Pressure
P_{fore} : Fore Static Pressure
M_{aft} : Aft Mach Number

Solid Rocket Ballistic Analysis

- The stagnation pressure ratio can be written as

$$\frac{P_{oaft}}{P_{ofore}} = \frac{\left(1+\frac{\gamma-1}{2}M_{aft}^{2}\right)^{\gamma/(\gamma-1)}}{1+\gamma\, M_{aft}^{2}} \equiv \phi$$

P_{oaft} : *Aft Stagnation Pressure*

P_{ofore} : *Fore Stagnation Pressure*

- Note that the Mach number at the exit of the grain increases with increasing port to nozzle throat area, *Ap/At*. Thus *Ap/At* ratio must be more than 2.0 to minimize the total pressure loss.
- Also note that for a nozzleless solid *Ap/At* is 1 and the choking takes place in the port.
- The regression rate law is based on the static pressure. The difference between the static and stagnation pressures is small for most solids. Thus fuel production rate can be written as

$$\dot{m}_{in} = a\ P_{ofore}^{n}\rho_{p}A_{b}$$

$\dot{m}_{in}$: *Gas Mass Generation*

A_b : *Burning Surface Area*

Solid Rocket Ballistic Analysis

- The mass flow rate through the nozzle is

$$\dot{m}_{out} = \frac{P_{oaft} A_{nt} C_d}{c^* \eta_c} = \frac{P_{ofore} A_{nt} C_d \phi}{c^* \eta_c}$$

$\dot{m}_{out}$: *Mass Rate Exiting Motor*

A_{nt} : *Nozzle Throat Area*

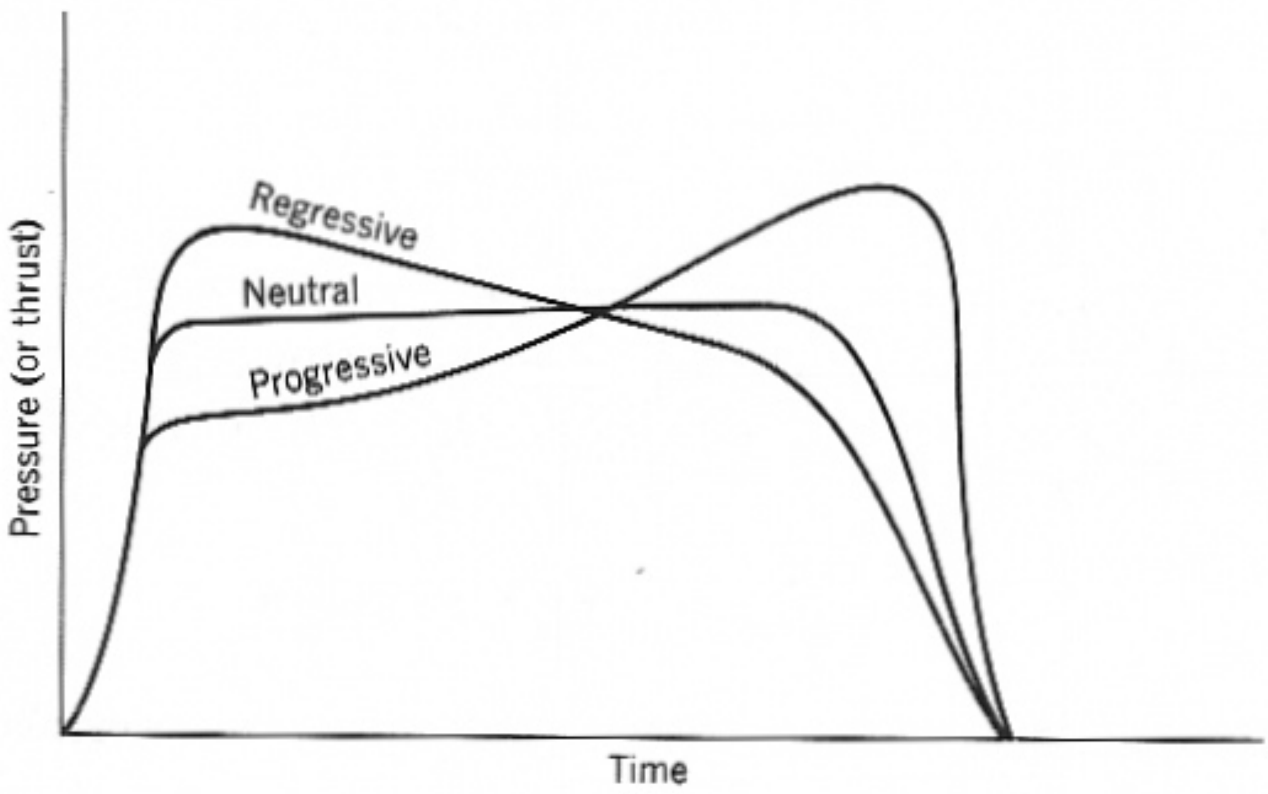
- During steady state operation $\dot{m}_{in} = \dot{m}_{out}$
- Which yields

$$P_{ofore} = \left(\frac{a\ \rho_p A_b c^* \eta_c}{\phi\ A_{nt}} \right)^{1/(1-n)}$$

$$\dot{m}_{in} = \dot{m}_{out} = \dot{m}_p = \left(\rho_p a\ A_b\right)^{1/(1-n)} \left(\frac{c^* \eta_c}{\phi\ A_{nt}} \right)^{n/(1-n)}$$

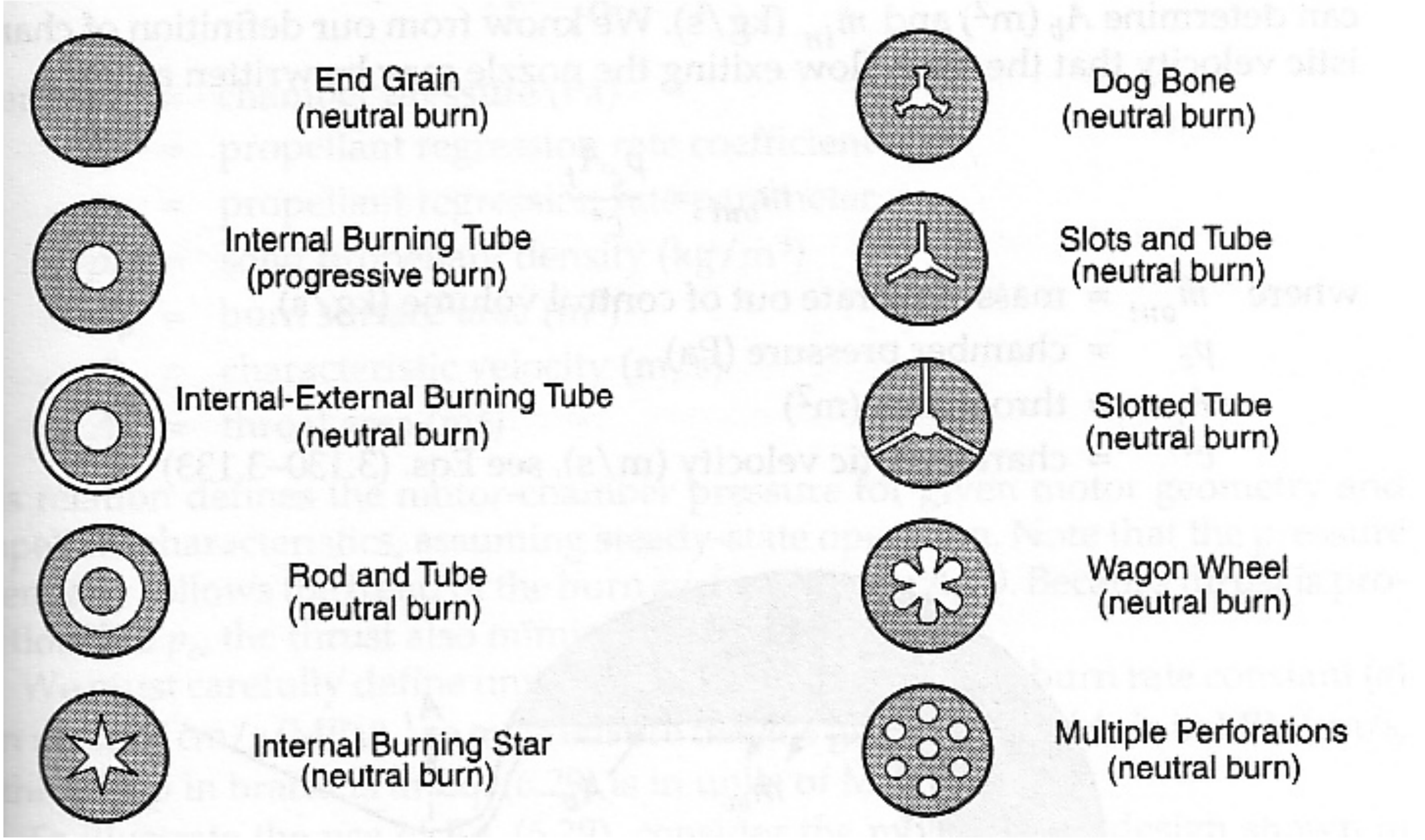
- Design process:
  - Propagate the burning surface to update the geometry. Note that all exposed surfaces are regressing (approximately) at the same rate.
  - Calculate the new burning surface area (all grain area exposed to the pressure-uninhibited surface area)
  - Calculate the chamber pressure, propellant mass flow rate and thrust

Solid Rocket Thrust Time Behavior



- Grain geometry dictates the shape of the thrust (pressure) time curves
- If the burn surface is increasing with time, the thrust is progressive

Solid Rocket Grain Design



Common Cylindrical Grain Shapes

Solid Rocket Propellant Formulation Issues

- Composite Propellant Ingredients
  - Oxidizer: Oxidizer source, AP-AN (0-70 %)
  - Metal Fuel: Primary fuel source, Al, B, Be, Zr, (0-30 %)
  - Fuel Binder: Holds the grain in one piece, also fuel, (HTPB, PU, PVC), (5-18 %)
  - Curing Agents: Polymerization and cross linking agents, DDI, (1-3.5 %)
  - Burn Rate Modifiers: Combustion mechanisms, FeO (0.2-3 %)
  - Explosive Fillers: Smoke control, HMX, RDX (0-40 %)
  - Plasticizers: Improve elongation capability, ease of processing (various liquids)
- Oxidizer and fuel particle size distribution is critical
  - AP: <1 micron to 400 micron mean size
  - Al: 2-60 microns
  - Monomodal/Bimodal (enhances loading capability)
  - Regression rate increases with decreasing particle size

Solid Rocket Propellant Formulation Issues

- Hazard Class
  - Class 1.1: Deflagration to detonation transition is possible (Grains containing HMX, RDX)
  - Class 1.3: Can not detonate. Fire and explosion hazard
  - Class 1.4: Lower grade propellants (low AP loadings)
- Detonation vs Deflagration
  - Detonation wave speed: 2,000-9,000 m/sec
  - Deflagration wave speed: 0.002-0.05 m/sec
- Typical Composite Propellant: AP (70% by weight), Al (16% by weight), Binder (12% by weight)
- Typical Double-Base Propellant (JPN): Nitrocellulose (51.5% by weight), Nitroglycerine (43.0 % by weight)
- Typical Composite Modified Double-Base (CMDB): AP (20.4% by weight), Al (21.1% by weight), Nitrocellulose (21.9% by weight), Nitroglycerine (29.0 % by weight)
- Gas Generators: Alkali Azides (NaN3 or KN3) with oxides (low temperature products)
- Igniters: Mg+Teflon, B+KN+Binder (Rapid heat release)

Solid Rockets-Summary

Summary

- Mechanically simple
- Hazardous processing, transportation and operation
- Expensive propellant
- Low Isp performance
- Good structural mass fraction
- High density impulse
- Ideal for volume limited applications
- Mature technology

Challenges

- Improve Isp performance - metal hydrides
- Throttling
- Find a replacement for AP