AE 330 Rocket Propulsion
Solid Rocket Motors

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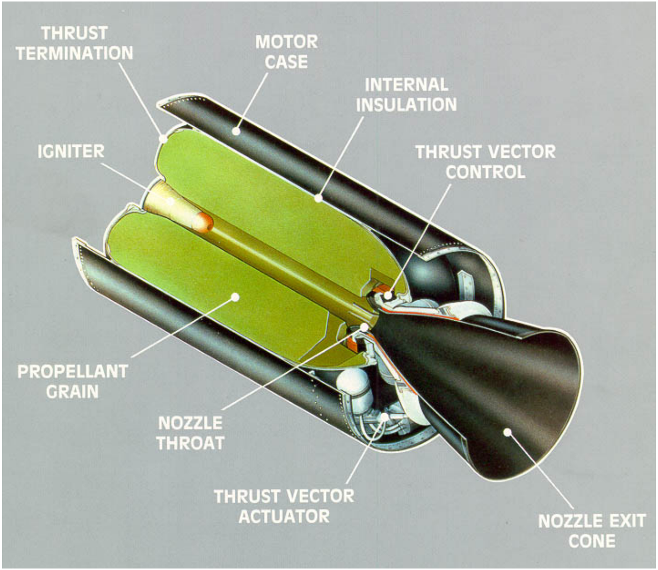
Solid propellant Rocket Motor (SRM)



Propellants for SRMs – Requirements

Fuel + Oxidizer **mixture** should be a rigid solid

Survives stresses (thermal & mechanical) during storage & operation

No/negligible reaction of the mixture during storage

Sustainable combustion only at $T \sim T_c$

Bad heat absorber(radiation)/conductor

Exhaust gases should not be *track*able (for missiles)

Propellants for SRMs

Homogeneous: fuel and oxidiser are contained in the same molecule

Heterogenous/Composite: mixtures of oxidising crystals in an organic plastic-like fuel binder

Propellants for SRMs

- Oxidizer
- Fuel
- Binder
- Plasticizer
- Curing-Agent

Propellants for SRMs – Oxidizers, Inorganic

Oxidizing capacity: F $>$ O $>$ Cl

Perchlorates $-(ClO_4) >$ Nitrates $(-NO_3)$

Perchlorates

Ammonium Perchlorate (AP): NH_4ClO_4

Most widely used

Available as small white crystals

Exhaust has HCl $\rightarrow$ corrosive

Nitrates

Ammonium Nitrate (AN): NH_4NO_3

Hygrospcopic $\rightarrow$ phase/volume changes

low-cost, smokeless, non-toxic exhaust

Usage: low burning-rate applications,

low performance applications,

gas-generators

Propellants for SRMs – Oxidizers, Organic

-NO_2

NitroGlycerine (NG)

Liquid form

Acts as solvent for Nitrocellulose (fuel) etc.

Nitramines

RDX: CycloTriMethyleneTriNitramine

HMX: CycloTetraMethyleneTetraNitramine

White crystalline solids

Added for higher performance

Explosives

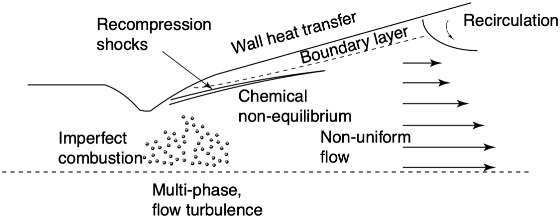
Careful handling required

Propellants for SRMs – Fuels, Inorganic

Powdered spherical Aluminium

Oxidized into Al_2O_3

- Liquid droplet form during combustion
- Solidifies in nozzle $\rightarrow$ heat release
- Liq. Al_2O_3 can form slag near nozzle
- $\rightarrow$ intermittent ejection of large mass of Al_2O_3



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Boron

- Lighter than Al, higher melting point
- Efficient only at small particle-sizes

Beryllium

- More efficient than Boron
- Oxides are toxic

Propellants for SRMs – Fuels, Organic

Nitrocellulose (NC)

Crystalline
Retains fiber structure of organic cellulose
Mixed with NG to form a propellant

Propellants for SRMs – Binder & Burn-rate Modifier

Binder

Structural glue/matrix to hold Fuel-Oxidizer mixture
Polyethers, Polyesters, Polybutadienes

Grain: Binder + Fuel + Ox. $\rightarrow$ Hard, rubber-like material

Older options: Poly-vinyl-chloride (PVC),
Poly-urethane (PU)

Present-day: Hydroxyl-Terminated Poly-Butadiene (HTPB)
Allows larger solids fraction($\sim 88 - 90\%$) for fuel (Al)/oxidizer(AP)

Propellants for SRMs – Burn-rate Modifier

Burnrate Modifier

Tailor the burnrate for the mission of the vehicle

Modifies burning rate vs time profile

Stabilizer

Prevents reactions during storage

Propellants for SRMs – Plasticizer & Curing-Agent

Plasticizer

Low viscosity liquid, organic, also a fuel
Improves processing properties of the propellant mixture

Curing-Agent

Causes the formation of long polymeric chains from the ingredients, & solidification of mixture

Propellants for SRMs – Homogenous Propellants

Ingredients are usually large molecules, with both fuel and oxidizer elements

Fuels: Chemicals that can get oxidized

Double-base (DB)/Homogeneous Propellants

Fuel and Oxidizer are parts of the same molecule.

Nitrocellulose (NC) – fuel rich (12.9%), **(s)**
+ Nitroglycerine (NG) – ox. rich (0.04%), **(l)**
Stoichiometric ratio: NG:NC$\approx 6.5:1$ is a slurry
Typical NG:NC$\approx 0.8:1$ is a rigid solid $\rightarrow$ **Fuel Rich**

NC-NG propellant can be transparanent$\rightarrow$ radiative heat absorption$\rightarrow$ internal damage/"bore-holing"

$\rightarrow$ Add Carbon-black (Opacifying Agent)

CMDB: Composite Modified Double-base Propellant

Modified with HMX, and AN composites

$\rightarrow$ Higher energy content

$\rightarrow$ Nearly Smokeless

Composite/Heterogeneous Propellants

Fuel and Oxidizer are macroscopically mixed, forming a composite solid propellant.

Convnetional composition

Crystalline Oxidizer, AP: $60 - 72\%$
Metallic Fuel, Al: $\sim 22\%$
Elastomeric Binder + Plasticizer: $\sim 8 - 16\%$

Modifications

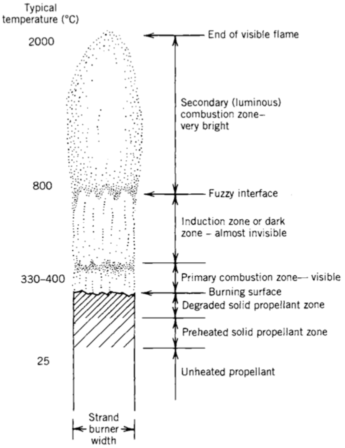
Higher Energy: Energetic Nitramine (HMX/RDX)
Energetic Plasticizer (NG/HMX)
Lower energy: AN instead of AP

Propellant Combustion – visualized using Strand burners

$p_{expt} < p_c \rightarrow$ lower burning-rates ($\sim 4 - 12\%$) than in a motor

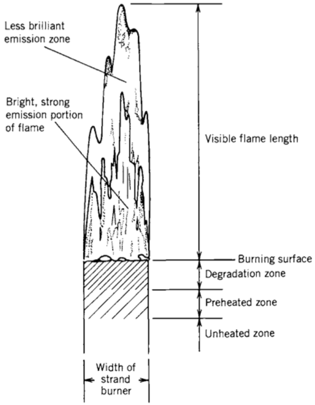
Doublebase/Homogeneous

premixed – Steady



Composite/Heterogeneous

Unsteady/Irregular



Doublebase/Homogeneous Propellant Combustion – visualized using Strand burners

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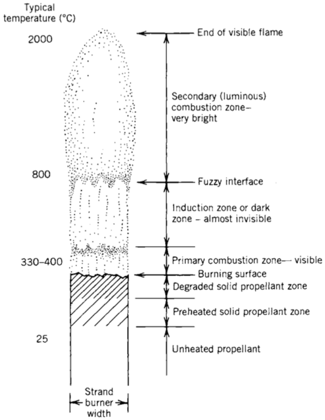
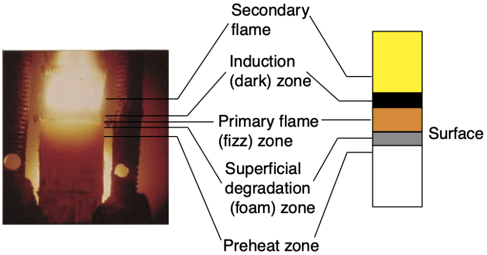
Premixed – Steady





Double-base propellant flame

Composite/Heterogeneous Propellant Combustion – visualized using Strand burners

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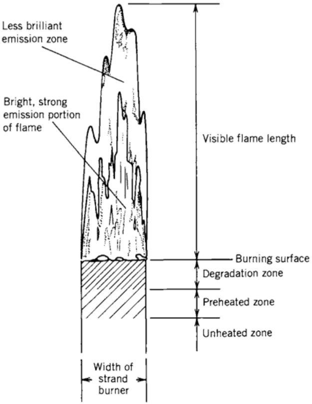
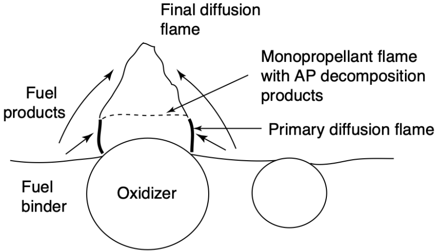
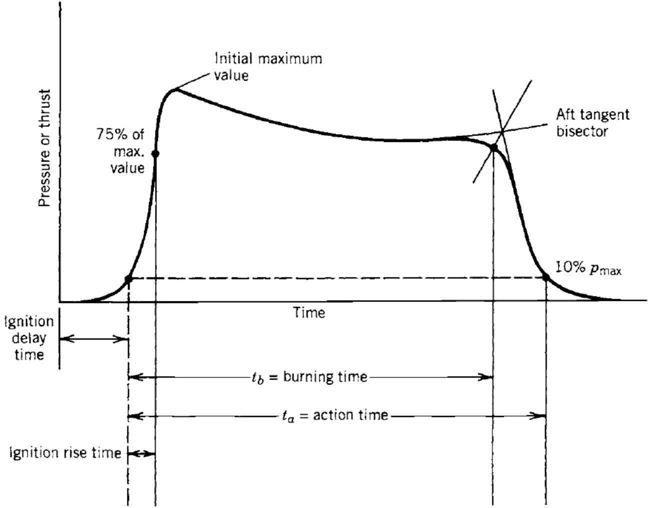
Diffusion – unteady



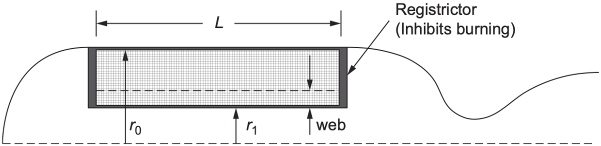


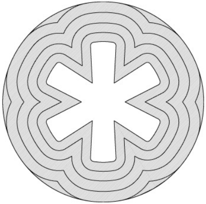
Composite propellant flame

Basic Performance: $\mathcal{T} = C_{\mathcal{T}} p_c A_t = \dot{m} c^* c_{\mathcal{T}}$



Propellant burning rate, r





$$\mathcal{T} = \dot{m} c^* c_{\mathcal{T}}$$

$$\dot{m} = \rho_p A_b \, r$$

Propellant burning rates

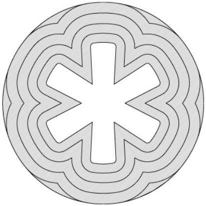
Propellant	Density [lbm/in^3]	Flame Temperature [°F]	Burning rate [in/s]	Pressure exponent, n
PVC/AP/Al	0.064	6260	0.45	0.35
PS/AP/Al	0.062	5460	0.31	0.33
PBAN/AP/Al	0.064	6260	0.32	0.35
CTPB/AP/Al	0.064	6160	0.45	0.40
HTPB/AP/Al	0.065	6160	0.28	0.30
PBAA/AP/Al	0.064	6260	0.35	0.35

Propellant burning rate, r

Internal ballistics: combustion characteristics of the propellant – burn-rate, burn-surface & grain geometry

Burn-rate: rate of regression of propellant surface. Depends on

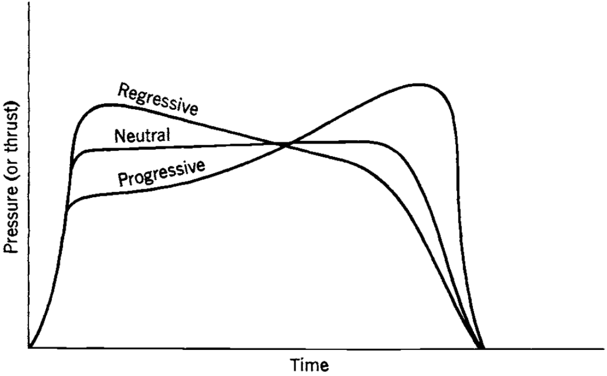
- p_c, T_c
- Initial temperature of solid propellant
- Gas flow velocity flow parallel to the burning surface
- Stresses due to motor acceleration

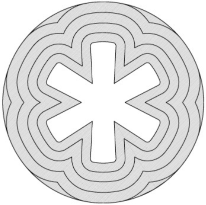


$$\mathcal{T} = \dot{m} c^* c_{\mathcal{T}}$$

$$\dot{m} = \rho_p A_b \, r$$

Propellant burn profiles

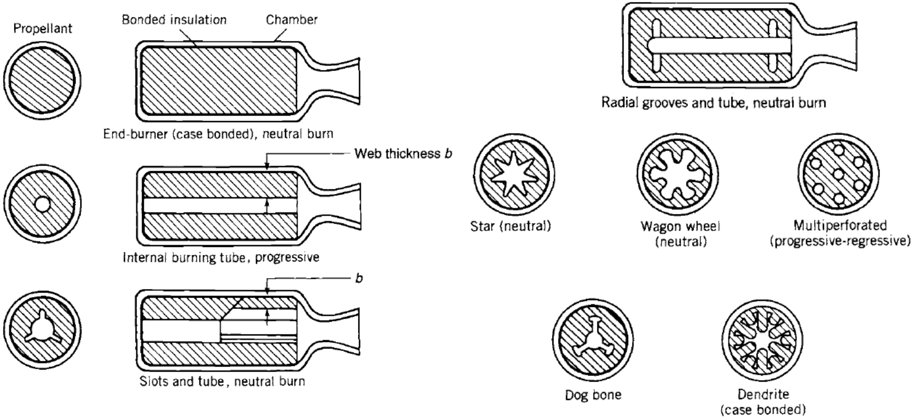




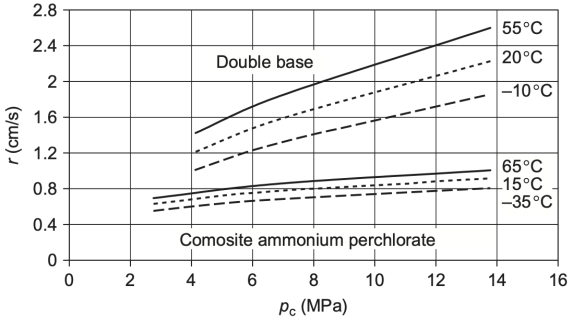
$$\mathcal{T} = \dot{m} c^* c_{\mathcal{T}}$$

$$\dot{m} = \rho_p \, A_b \, r$$

Propellant Grain & Grain Configuration



Propellant burning rate – Effect of p_c & T_c



Burning rate

$$r = a\, p_c^n$$

a, n are empirical constants, `curve-fit from data`.

Temperature coefficient, a: influenced by grain initial temperature

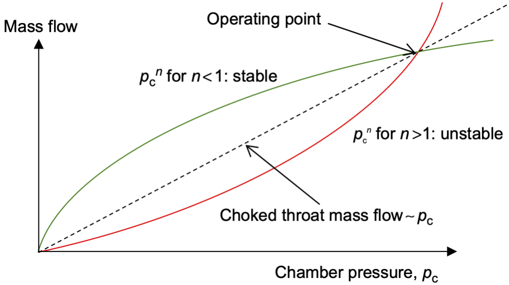
Combustion index, n: independent of the grain initial temperature

Propellant burning rate – Effect of p_c & T_c

$r = a\, p_c^n$

$n \sim 0.2 - 0.6$

$r \sim 0.05 - 75$ mm/s



Stable Operation $\rightarrow 0 < n < 1$

Heuristic Argument

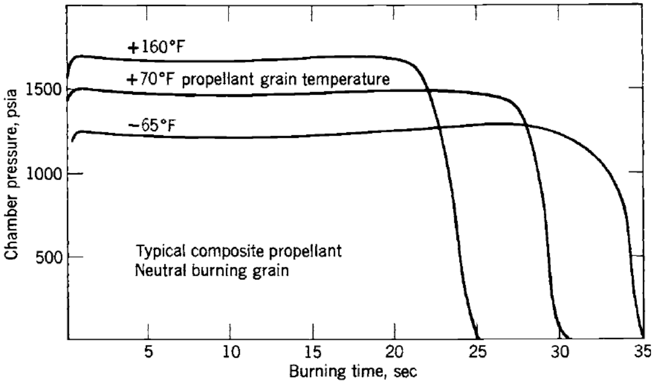
$\dot{m} \sim p_c$ – leaves the chamber

$\dot{m}_0 \sim p_c^n$ – added to chamber (burning, $\dot{m} = \rho_p A r$)

Propellant burning rate – Effect of Initial Temperature, T_p

Total impulse = integrated area under the curves

$$M_p = \int_{T_c}^{t_b} \dot{m}\,dt = \left(\int_{T_c}^{t_b} p_c\,dt\right) / c^* A_t$$



Propellant burning rate – Erosive burning

$$r = ap_c^n$$

Flow past the grain

$\rightarrow$ convection + turbulence

$\rightarrow$ increased heating of propellant

$\rightarrow$ velocity increases towards nozzle

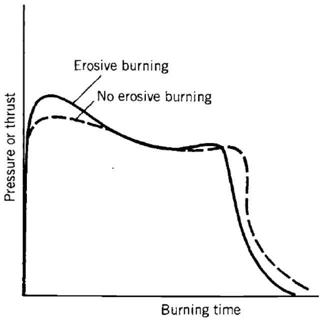
$\rightarrow$ r increases towards nozzle

$\rightarrow$ $A/A_t < 4 \rightarrow$ significant effect

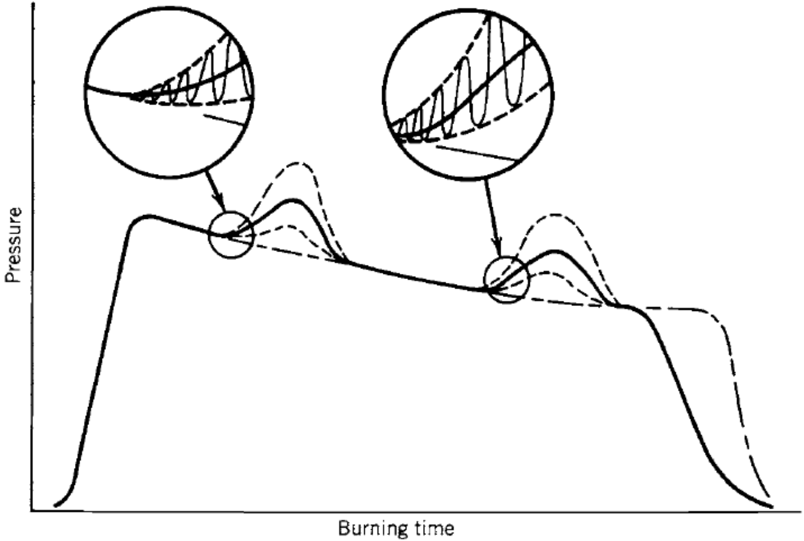
$\rightarrow$ Port Area smallest at start-up

$\rightarrow$ faster burning at start-up

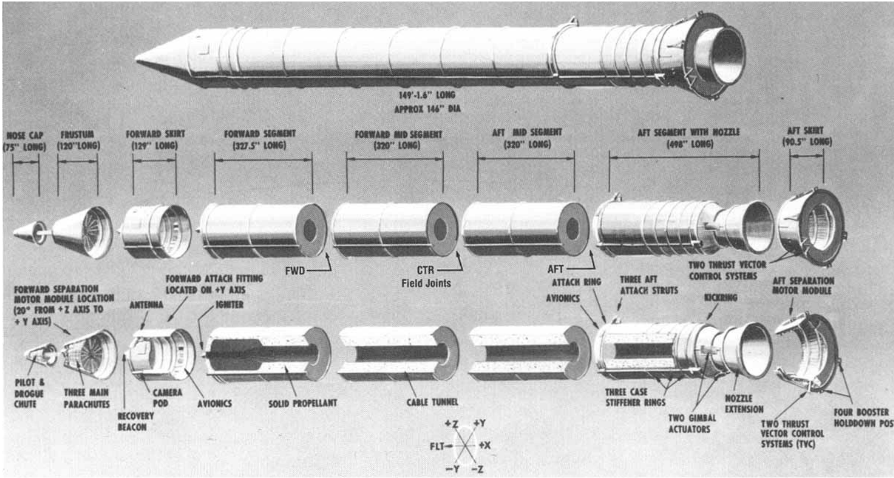
$\rightarrow$ lower thrust at end of burning



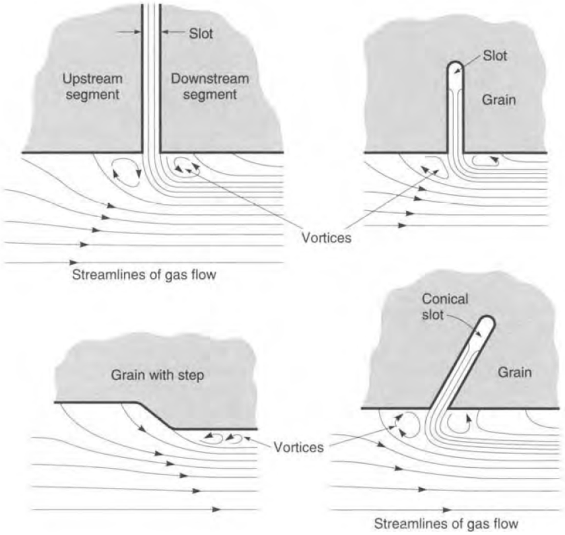
Combustion Instability – Acoustic



Assembling Space Shuttle Solid Rocket Booster



Combustion Instability – Vortex-Shedding



References & sources of images

- Textbooks by Lee, Mukunda, Sutton, Sforza & Turner
- Webpages of ISRO, Pratt & Whitney
- Images from Wikipedia, Purdue, SPG, Stanford, TuDelft (Aerospace) webpages