AE 330/708

AEROSPACE PROPULSION

Instructor

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Solid Propellant Rocket Engines

Propellant is contained and stored directly in the combustion chamber [sometimes for long durations like 5-20 years]

Comes in variety of sizes and thrust range 2 N – 4 MN

No moving parts; Relatively simple in construction; Easy to apply; Little servicing

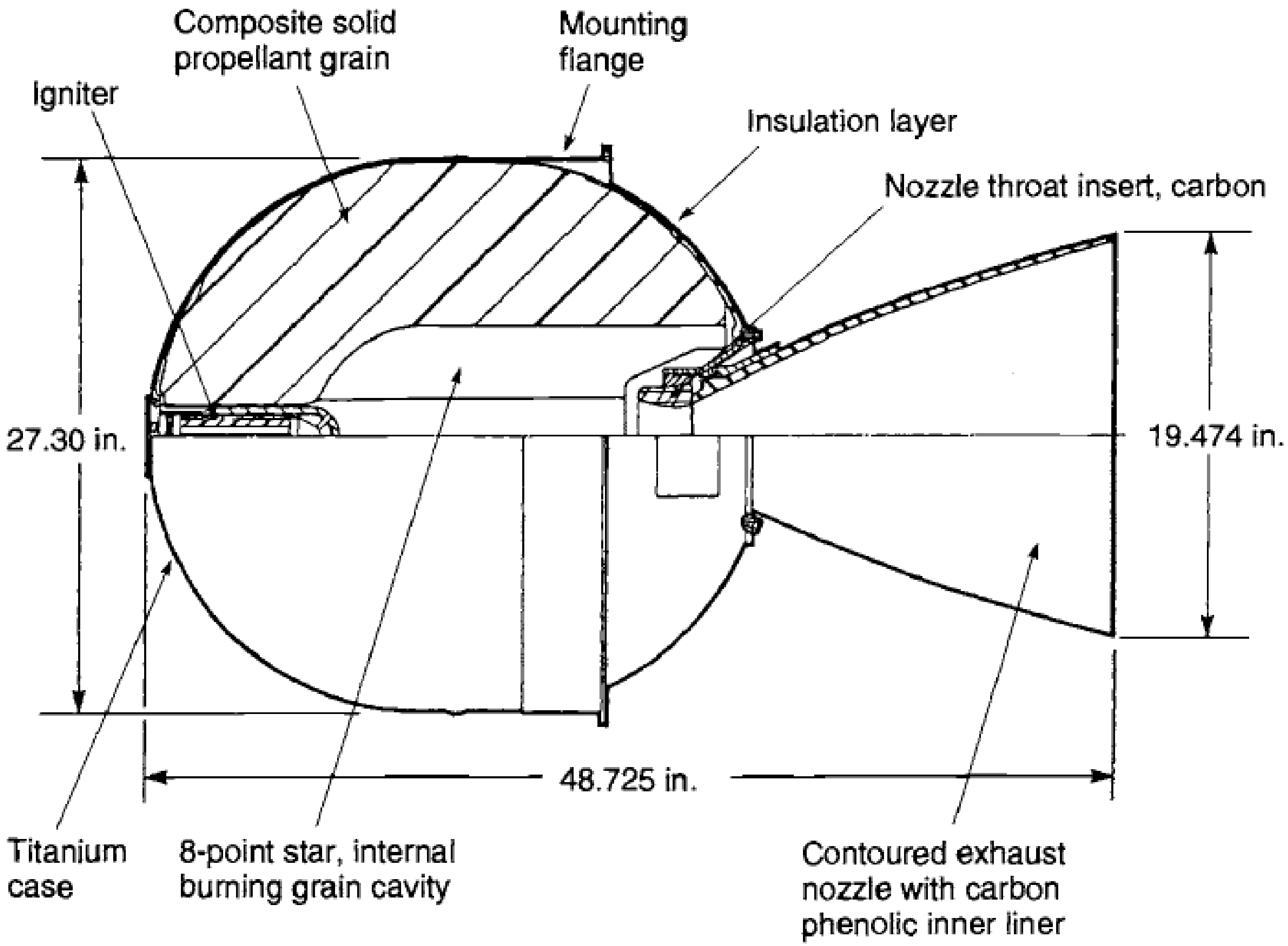
Thrust can’t be randomly varied during flight

The pretested motors cannot be used

Major Application Categories

Large boosters/ stage motors	Space launch vehicles	Large diameter, L/D~2-7, burn time ~ 60-120 sec, ε ~ 6-16
High altitude motors	Upper stages, space maneuvers	High performance propellants, ε ~ 20-200, L/D ~1-2, burn time ~ 40-120 sec
Tactical missile	Short range targets, antitank, S-A, A-A, A-S, guided missiles	L/D ~ 4-13, burn time ~ short, High acceleration, spin stabilized, booster-sustainer configuration, high thrust at launch, Low smoke/smokeless propellants
Ballistic missile defense	Boosters for ballistic missiles as well as defense against ballistic missiles	Booster rocket and a small upper maneuverable stage
Gas generator	Pilot emergence escape, actuators, valves, short term power supply	Low gas temperature (< 1300 deg. C), to create high pressure, energetic gas rather than production of thrust

Solid Propellant Rocket Construction



Major components:

Propellant grain

Igniter

Casing

Nozzle

Classification

Propellant:

Composite
Double base
Composite modified double base

Grain installation:

Case bonded
Cartridge loaded

Case design:

Steel monolithic
Fiber monolithic
Segmented

Thrust action:

Neutral
Progressive
Regressive
Pulse rocket
Step thrust

Burn rate of solid propellant

Performance of a solid rocket motor depends on

1. The type of propellant combination
2. The burn rate of the propellant
3. The burning surface area
4. The propellant grain geometry

Study of propellant burning → Internal ballistics of the motor

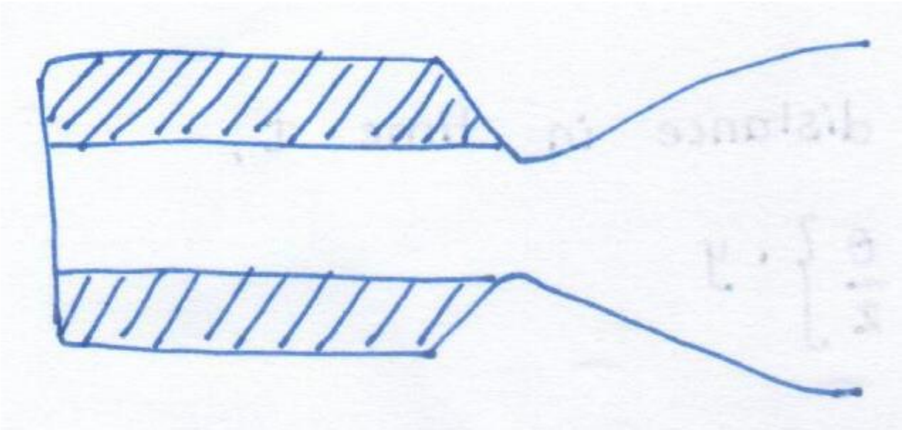
Burn rate of solid propellant

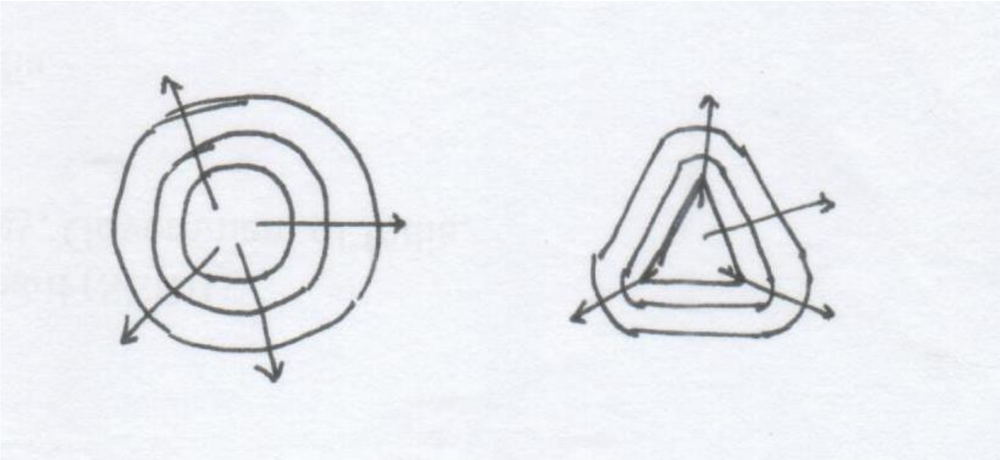
Very important parameter in the performance of the solid rocket motor

Burning of the propellant grain takes place at its surface

Burning surface recedes normal to the surface and the rate of regression of surface is called as the burn rate (mm/s cm/s)

For successful design of a rocket motor → knowledge of the burn rate behaviour of the propellant is necessary





Burn rate of solid propellant

Propellant burn rate ➔ dependent on propellant combination and may be modified in different ways

Following factors are important in affecting the burn rate of the propellant:

1. Chamber pressure
2. Initial temperature prior to the start
3. Combustion gas temperature
4. Velocity of the gas parallel to the burning surface
5. Motor motion

Burn rate of solid propellant

During the development of a new propellant or modified propellants, they are extensively tested

- Testing of burn rate at different temperatures, pressures, impurities, and other relevant conditions

- Ignitability, ageing, sensitivity to shocks, friction etc.

- Moisture absorption

Measurement of burning rate

1. Standard strand burners, often called Crawford burners

    Thin strands of propellant are burnt in controlled atmosphere

    Usually underpredicted (4-12%) as compared to full scale motor firing

    Useful in screening propellant formulations and in quality control operations.

2. Small-scale ballistic evaluation motors

    Small evaluation motors

    Gives less burning rate than the actual motors

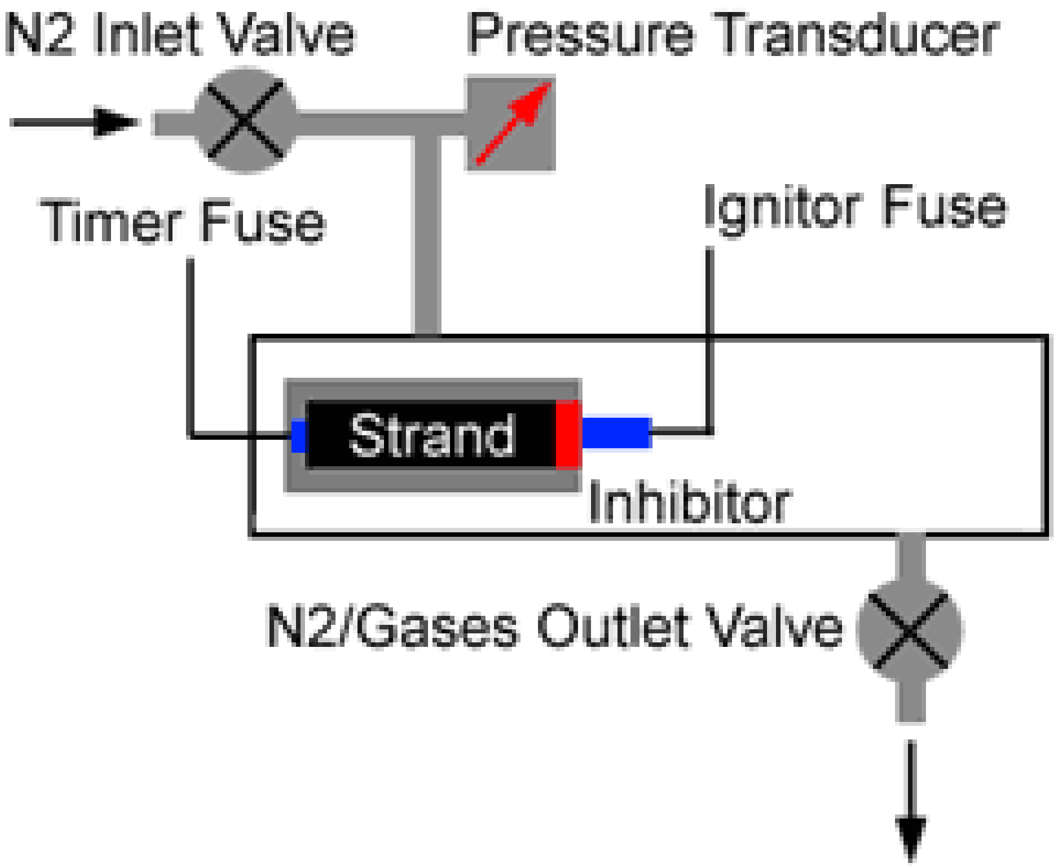
3. Full-scale motors with good instrumentation

    Gives realistic behavior of propellant burning in actual motor operation

    Usually costly and hence other methods are preferred in development phase of new propellants

    Formulation of empirical database & correlations between the burn rates obtained by different methods

Measurement of burning rate



Burn rate of solid propellant

The generation of gas mass in the combustion chamber and hence pressure build up takes place from the burning of the propellant

Rate of mass generation of the gases = $\rho_p . A_b . r$

Product of propellant density (solid phase), burning surface area and burn rate (r).

Burn rate of solid propellant

Burn rate is typically quoted at reference conditions of 294 K and 1000 psi (~70 bars)

Burn rate, $r = a \times P_1^{\,n}$

a = Temperature coefficient (empirical) and function of propellant temperature
n = Burn rate exponent or combustion index (independent of grain temperature)

This pressure dependence of the burn rate is valid for most of the propellants and hence accepted universally

Typical values of burn rate, r = 0.05 – 75 mm/s

Burn rate of solid propellant

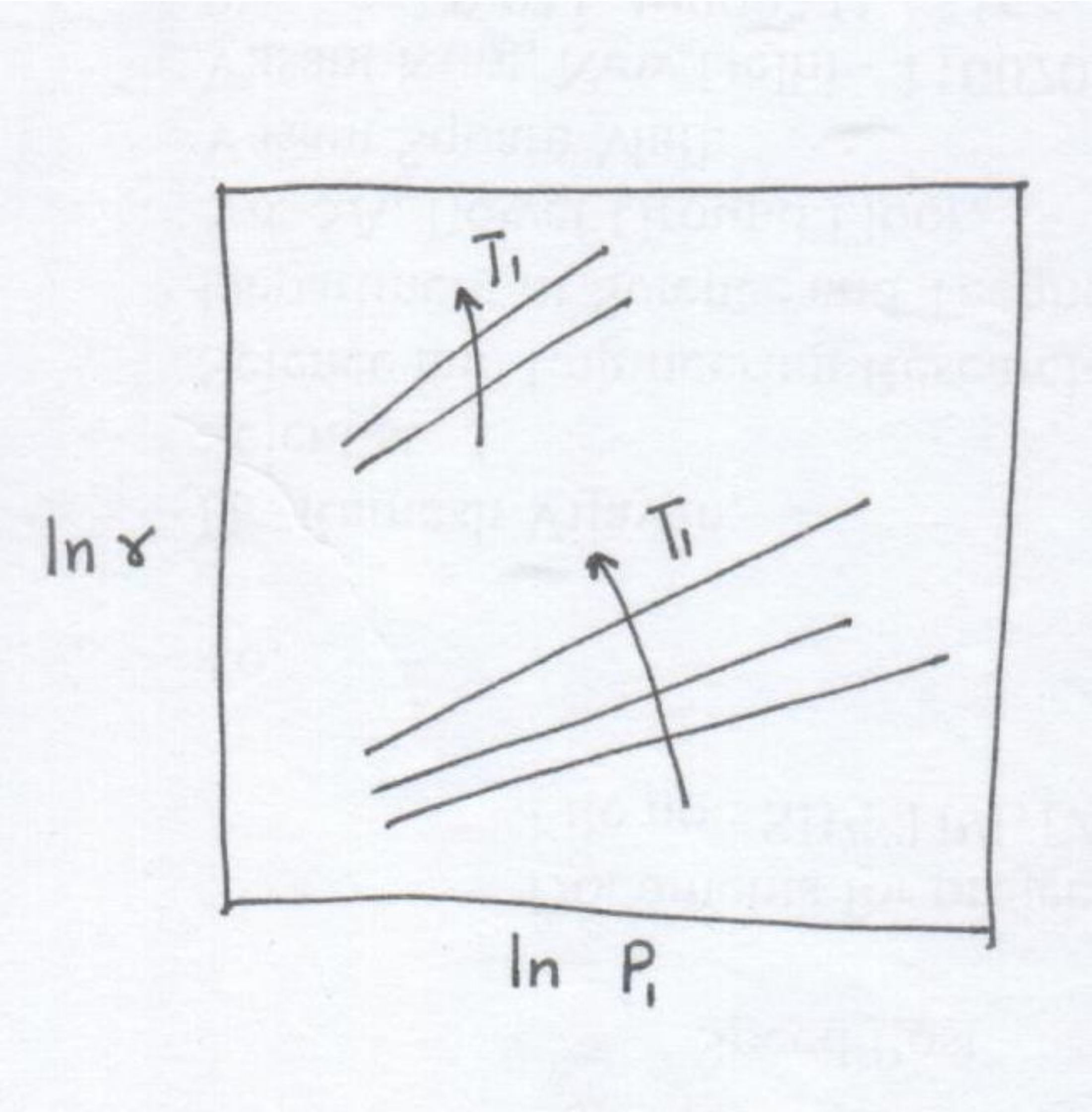
Burn rate, r → very sensitive to the value of n (0 – 1)

Typical values of n = 0.2 – 0.6

As n→1, r and P1 become very sensitive to each other leading to disastrous rise in chamber pressure in few milliseconds

As n→0, possibility of extinction of the flame

Moderate value of n ensures the stable combustion

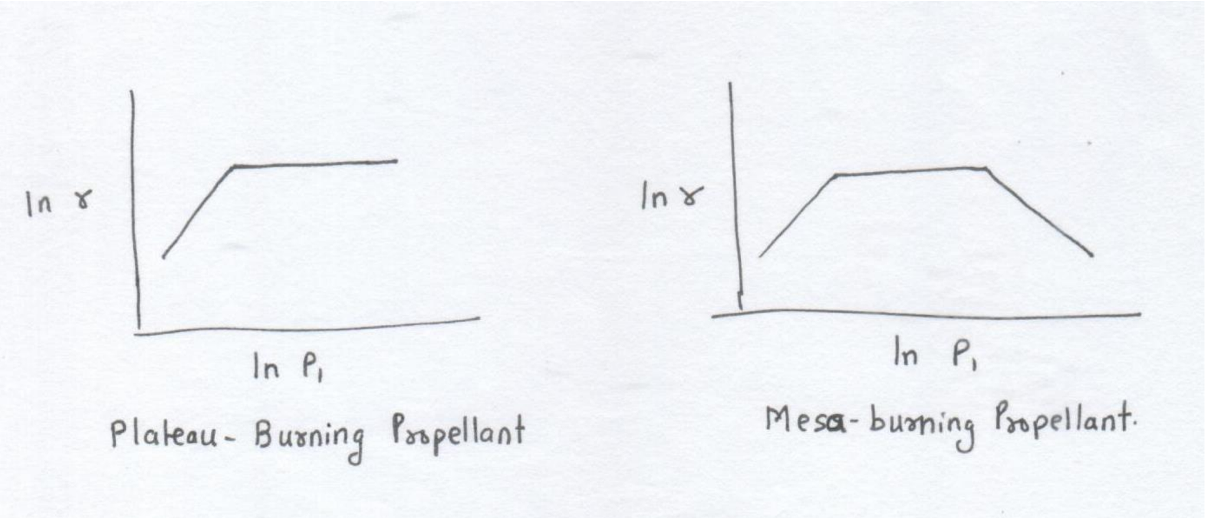


Propellant burning rate features

For a particular propellant and for wide temperature and pressure limits, the burning rate can vary by a factor of 3 or 4.

Some propellants display a negative *n* which is important for "restartable" motors or gas generators.

A propellant having a pressure exponent of zero displays essentially zero change in burning rate over a wide pressure range. *Plateau propellants* are those that exhibit a nearly constant burning rate over a limited pressure range.



Temperature effects on burning rate of propellants

Temperature increases the chemical reaction rate

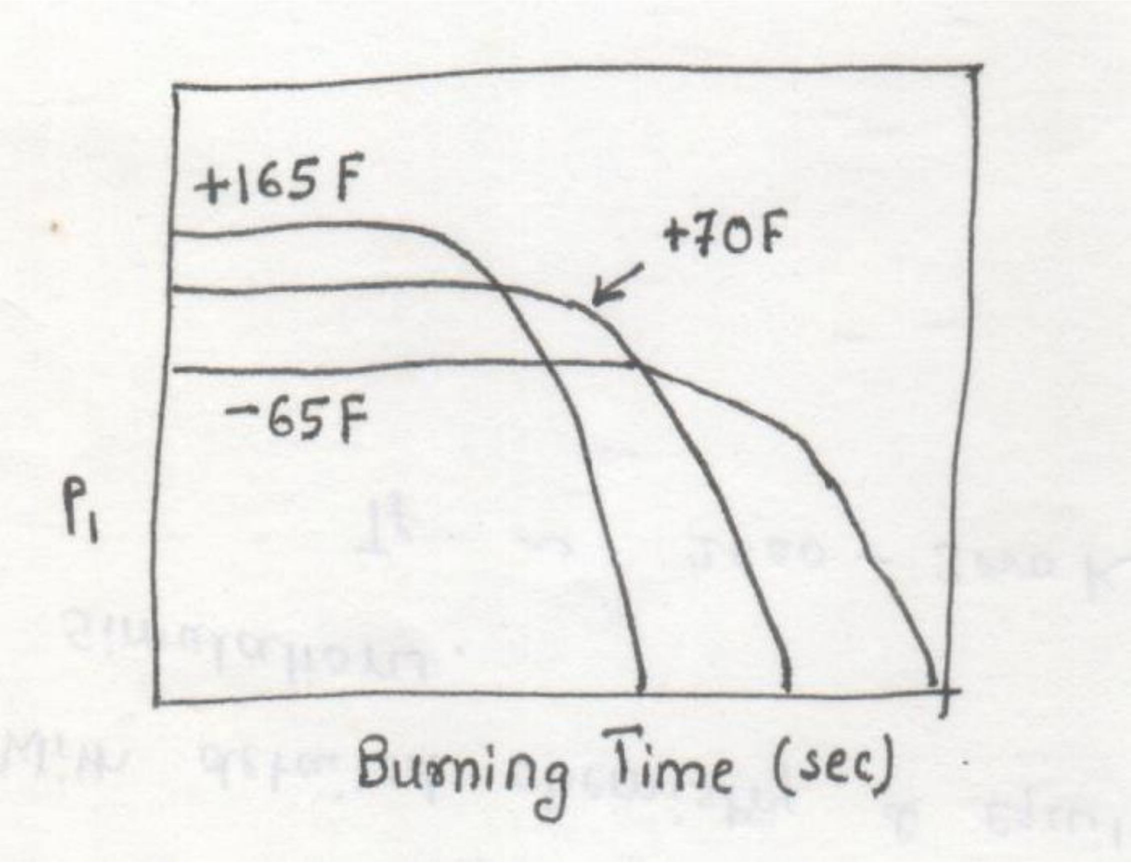
Increase in propellant grain temperature $\rightarrow$ increases in the burning rate

The propellant is consumed at a quicker rate leading to two effects:
Increase in overall chamber pressure or thrust
Reduction in the burning duration

Consequently changes in thrust, accelerations and vehicle dynamics

Important to note $\rightarrow$ Propellant temperature does not alter the amount of heat release, but changes the rate of heat release

Temperature effects on burning rate of propellants



Why the temperature effect is so important:

Air-launched missile motors – exposed to extreme temperatures like 219 K to 344 K

Consequently, solid rocket motors experience 20-35% variation in chamber pressure leading to 20-30% variation in burning time over such a range of propellant temperatures

Large rocket motors in deep space → Uneven heating of the grain (due to solar radiation on one side) creates non-uniform burning at different locations and large differences in burn rate

Common practice → Condition the motor for many hours at a particular temperature to obtain uniform propellant grain temperature before firing

Sensitivity of burning rate to propellant temperature

$$\sigma_p = \left[\frac{\partial}{\partial T}\ln r\right]_{P_1} = \frac{1}{r}\left(\frac{\partial r}{\partial T}\right)_{P_1} \approx 0.001 - 0.009\ /K$$

$$\pi_K = \left[\frac{\partial}{\partial T}\ln P_1\right] = \frac{1}{P_1}\left(\frac{\partial P_1}{\partial T}\right)_K \approx 0.067 - 0.278\ \%/K$$

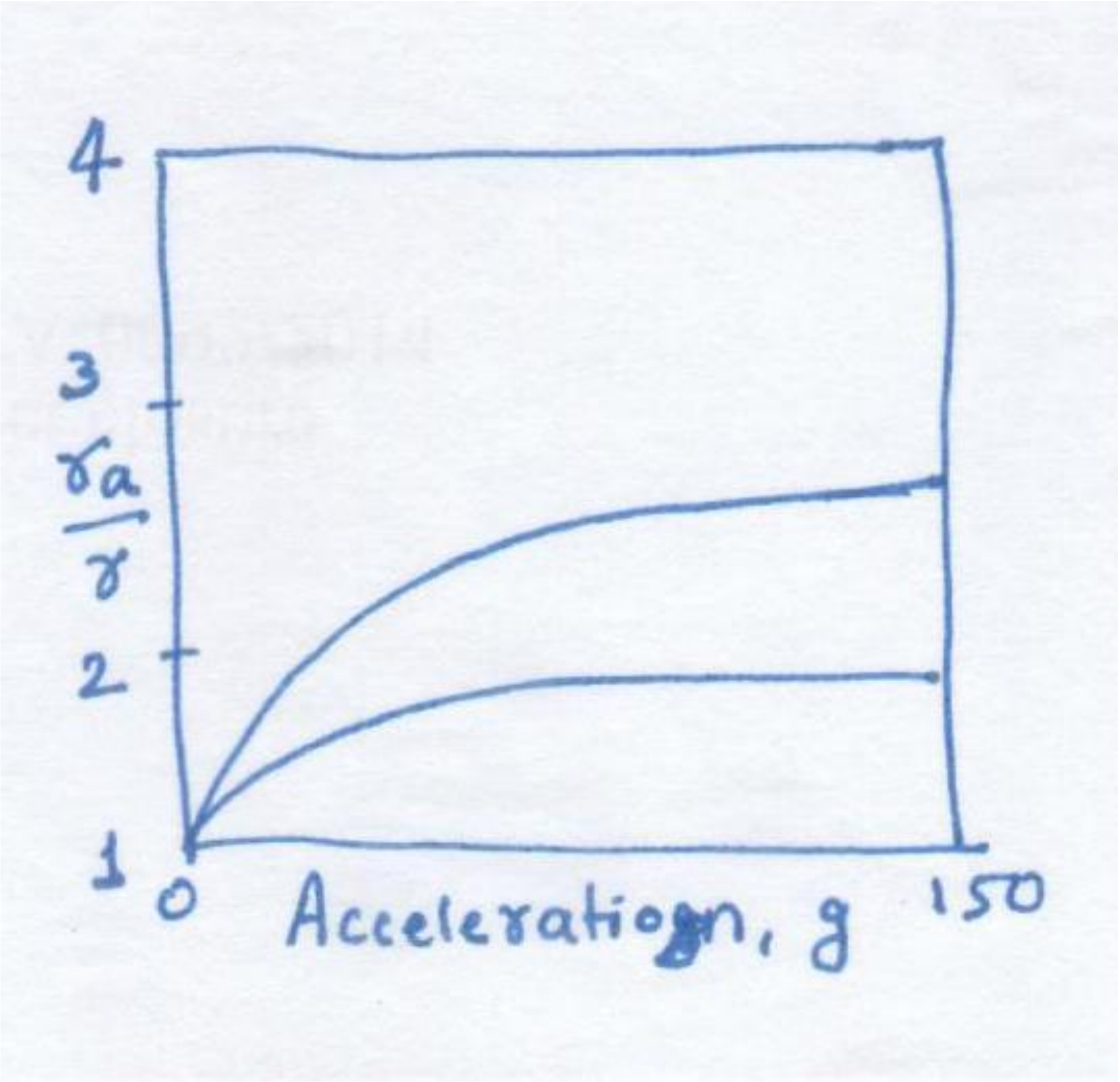
Two temperature coefficients:

σ_p → obtained from the strand burner test

π_K → from scaled or full motor test (K – Ratio of burning surface area to throat area)

Depend primarily on the nature of propellant, burning rate, composition, and combustion mechanism

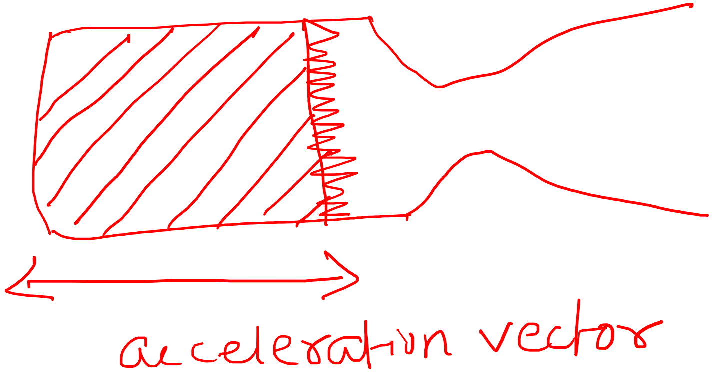
Effect of vehicle acceleration



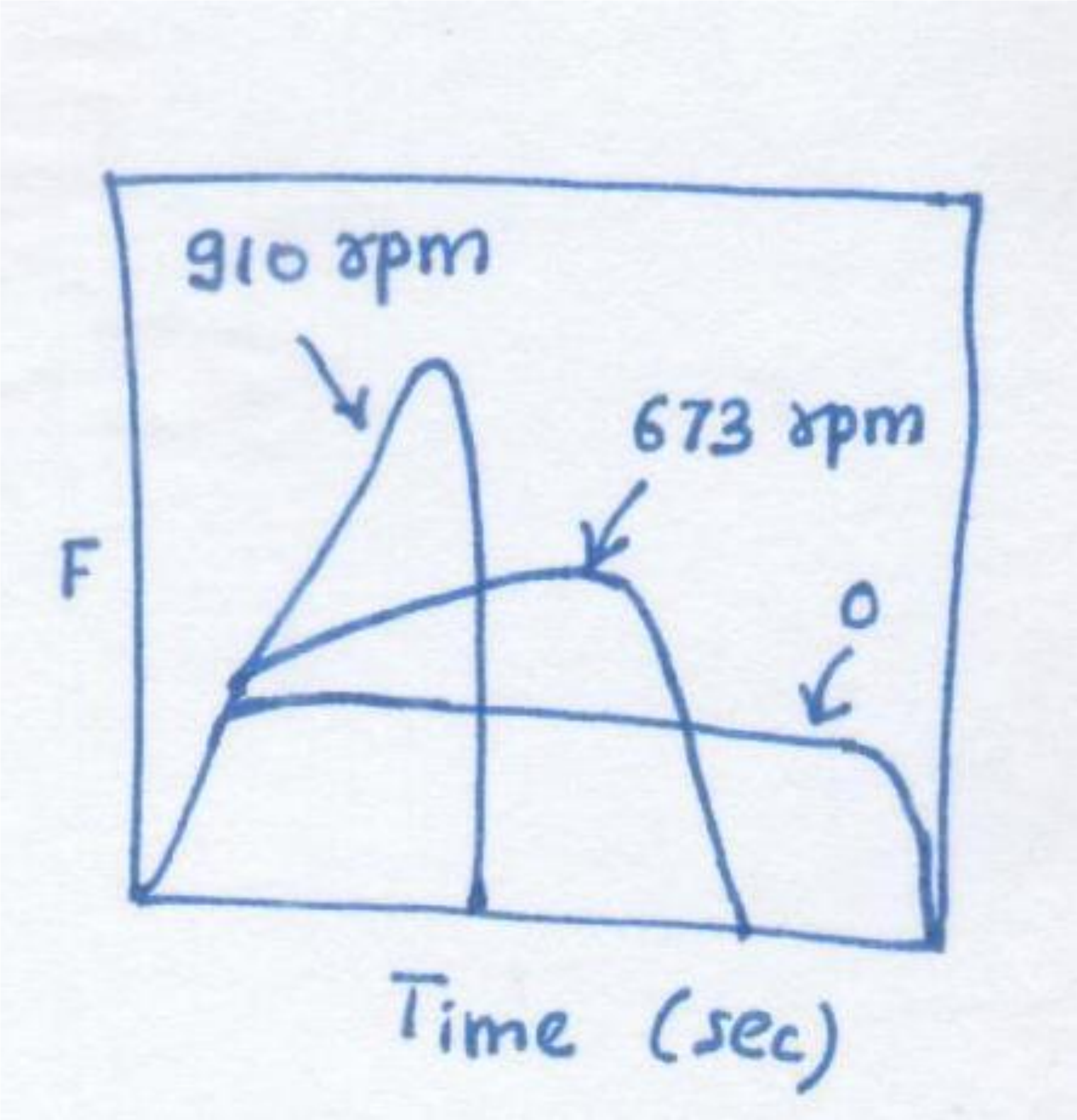
Effect of vehicle acceleration

Burning surface making angle 60-90 deg. with acceleration vector are prone to enhanced burning

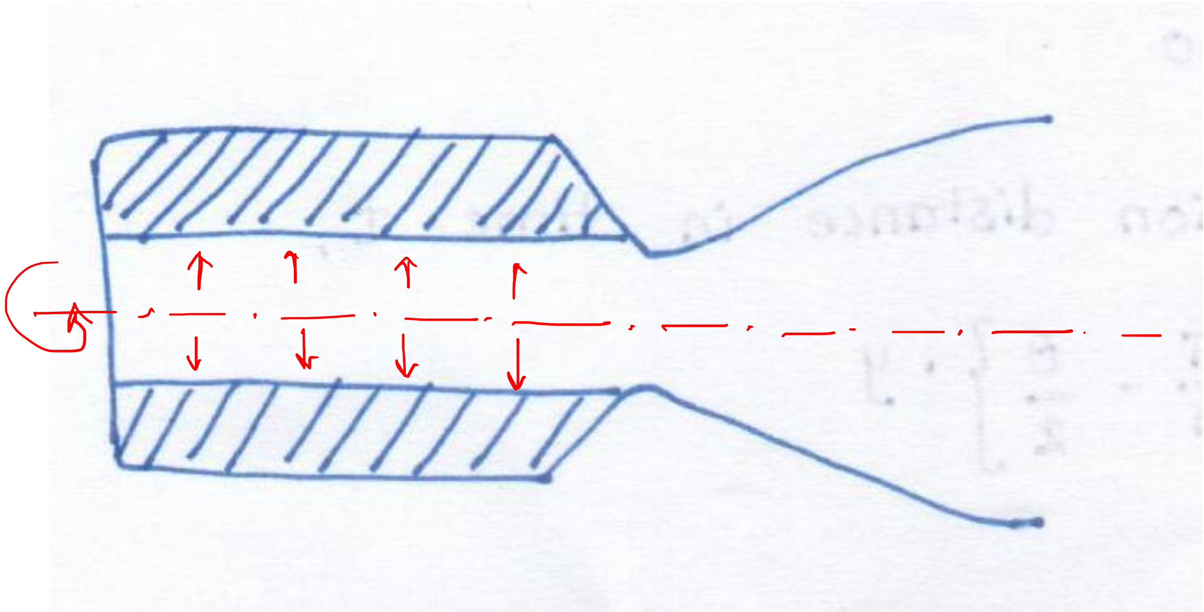
For example, end burning grain in the presence of vertical acceleration



Effect of spin



Effect of spin on thrust-time relationship



Other burning enhancements

The stresses induced by rapid acceleration or rapid chamber pressure rise – crack formations

The embedding of wires or other shapes of good metal heat conductors in the propellant grain increases the burning rate.

- Silver or aluminum is preferred
- Depending on wire size & the number of wires per cross-sectional area, the burning rate can easily be doubled.

Intense radiation emissions from the hot gases in the grain cavity

Combustion instability

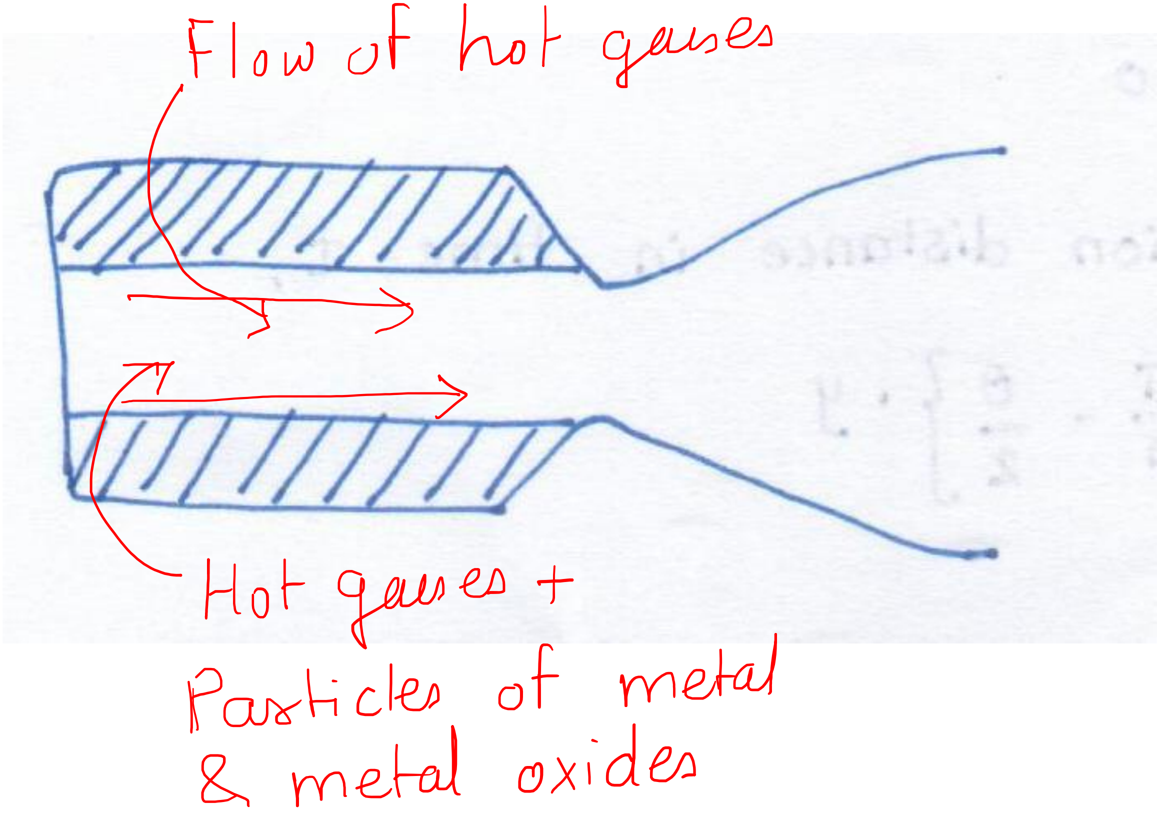
Erosive burning

Increase in propellant burning rate caused by high velocity flow of the combustion gases over the burning propellant surface

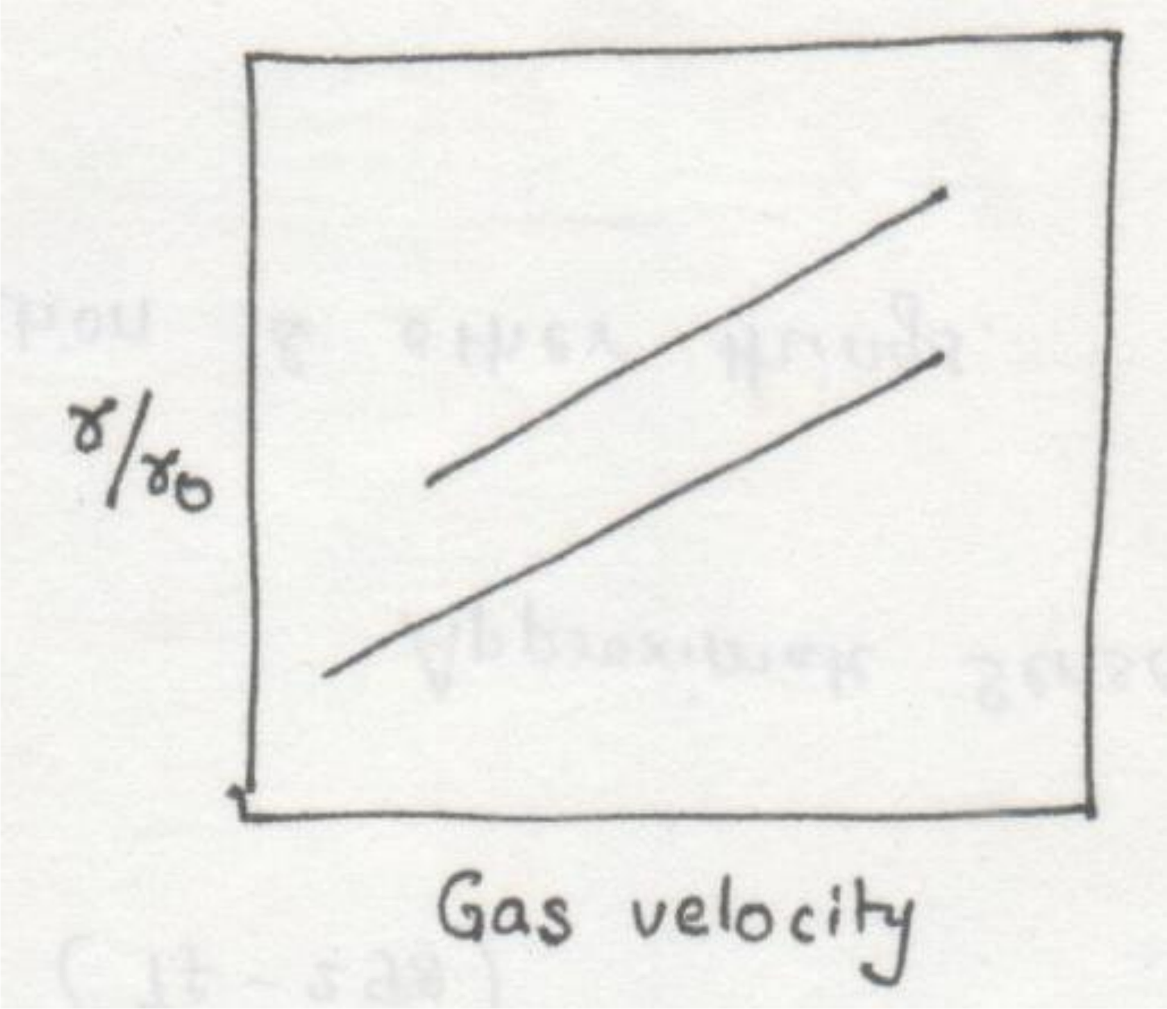
Erosive burning prominent if A/At <= 4 and hence significant in the early stages of burning

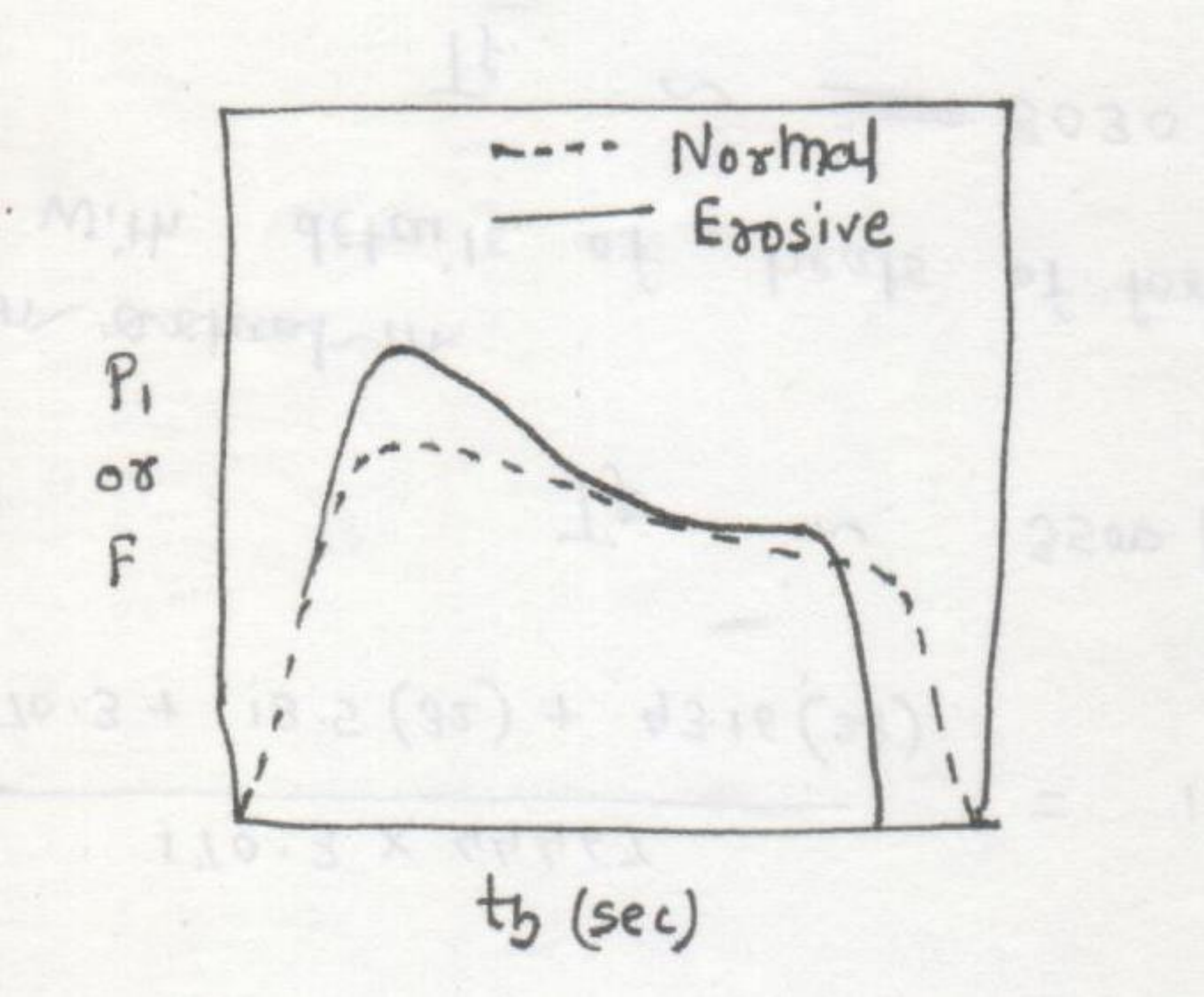
High flow velocities, action of metal/metal oxide particles, turbulent mixing in boundary layers → increase in heat transfer to the grain and enhancement of the burn rate

Effects of erosive burning → increase in mass flow rate, chamber pressure and thrust; decrease in burn time



Erosive burning





Erosive burning

$$r = r_0 + r_e$$

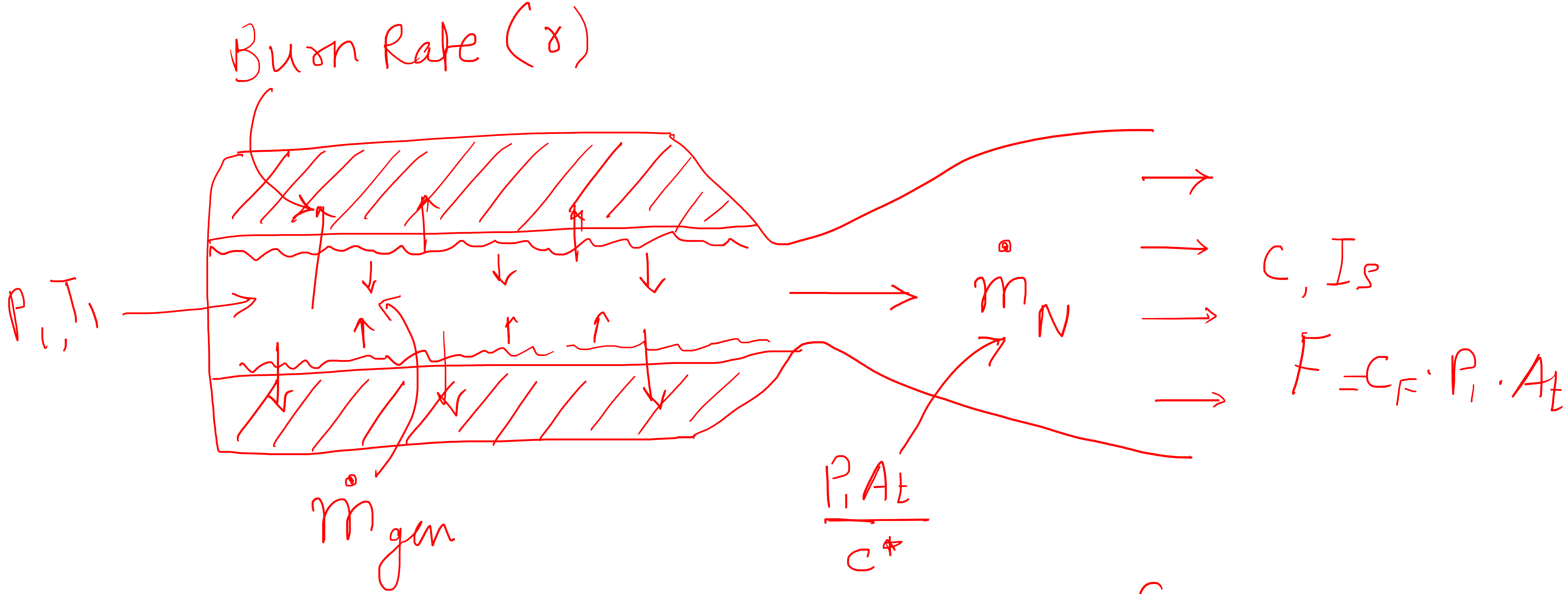
$$r = \left(a p_1^{n} + \alpha G^{0.8} D^{-0.2} \exp\left(-\beta r \rho_p / G \right) \right)$$

$$\alpha = \frac{0.0288\, C_p\, \mu^{0.2}\, P_r^{-2/3}}{\rho_p \cdot c_s} \frac{(T_1 - T_s)}{(T_2 - T_p)}$$

G – Mass flow rate per unit area
D – Characteristic diameter of the port passage (4*port area/perimeter)
α and β – Empirical constants
β is independent of propellant combination = 53
(when quantities are expressed in SI units)

Pr – Prandtl number
Cs – Heat capacity of solid propellant
T1 – Combustion gas temperature
Ts – Solid propellant surface temperature
Tp – Initial temperature of the propellant grain
T2 – Temperature inside the propellant grain during firing

Performance of solid propellant rockets



Relating ballistic parameters to performance

How P_1 depends on burning of solid prop. ?

Performance of solid propellant rockets

$$\rho_p \cdot r \cdot A_b = \frac{d}{dt}(\rho_1 V_1) + P_1 \cdot A_t \underbrace{\sqrt{\frac{k}{RT_1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}}_{1/c^*}$$

Mass generation due to propellant burning.
$A_b = f(t)$

Change in the mass of the gas (important at startup)
$V_1 = f(t)$ & change significantly with time

Mass flow from the nozzle
(A_t = assumed constant)

For steady state operation, $\frac{d}{dt} = 0$

$$\Rightarrow \quad \frac{A_b}{A_t} = \frac{P_1 \sqrt{k \left(2/k+1\right)^{k+1/k-1}}}{\rho_p \cdot \gamma \sqrt{RT_1}} = K$$

$$K = \frac{A_b}{A_t} = \frac{(P_1)^{1-n} \sqrt{k\left(2/k+1\right)^{k+1/k-1}}}{\rho_p \cdot a \cdot \sqrt{RT_1}}$$

$$\left.\begin{array}{l} \\ \end{array}\right\} \quad P_1 \sim \left(\frac{A_b}{A_t}\right)^{\frac{1}{1-n}}$$

or

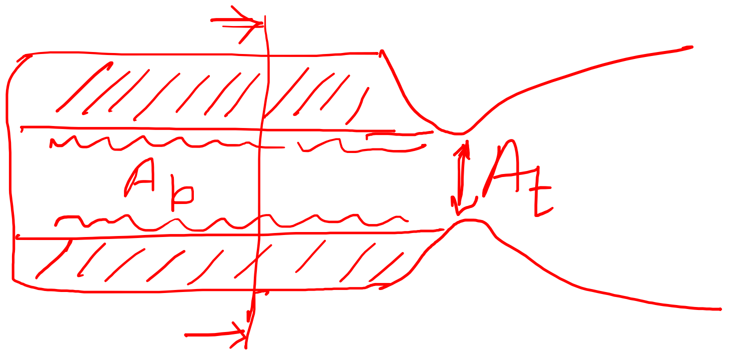
$$P_1 \sim (K)^{\frac{1}{1-n}}$$

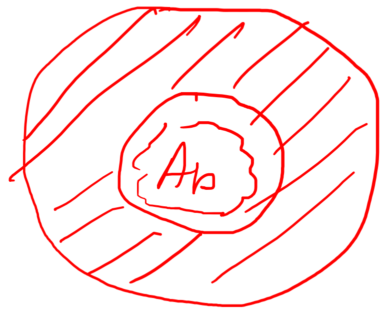
$K = \frac{A_b}{A_t}$ = Important design parameter in solid rocket motors.

For $n = 0.8 \implies P_1 \sim K^5$

In terms of characteristic velocity (c^*),

$$P_1 = \left[K a \rho_p c^*\right]^{\frac{1}{1-n}}$$





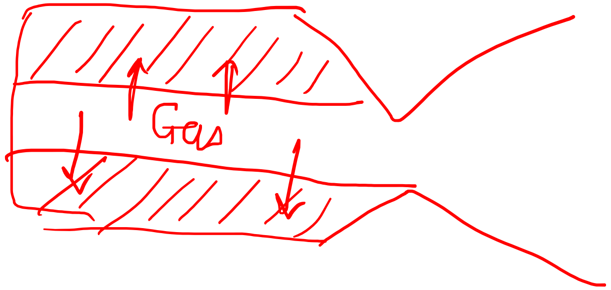
If the change in the port volume is considered …

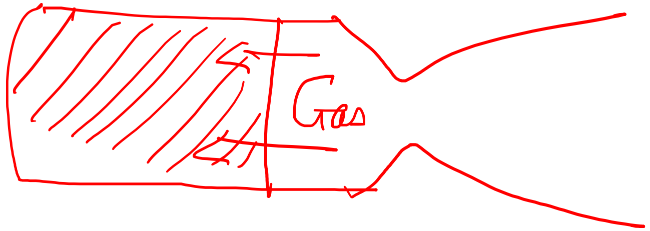
Mass of the gas in the chamber volume (V_1),

$$m = \frac{P_1 V_1}{R T_1}$$

$$\frac{d}{dt} m = \frac{d}{dt}\left(\frac{P_1 V_1}{R T_1}\right) = \underbrace{A_b \rho_p a P_1^n}_{\dot{m}_{gen}} - \underbrace{\frac{P_1 A_t}{C^*}}_{\dot{m}_n}$$

$$\frac{d}{dt}\left(\frac{P_1 V_1}{R T_1}\right) = \frac{V_1}{R T_1}\frac{d P_1}{dt} + \frac{P_1}{R T_1}\frac{d V_1}{dt}$$





But $\frac{d}{dt} V_1 = A_b \cdot r = A_b \cdot a \cdot p_1^n$

and $\frac{p_1}{RT_1} = \rho_1 =$ Density of the gas in combustion chamber

$$\frac{V_1}{RT_1} \frac{dp_1}{dt} = A_b \cdot a \cdot p_1^n (\rho_p - \rho_1) - \frac{p_1 A_t}{c^*}$$

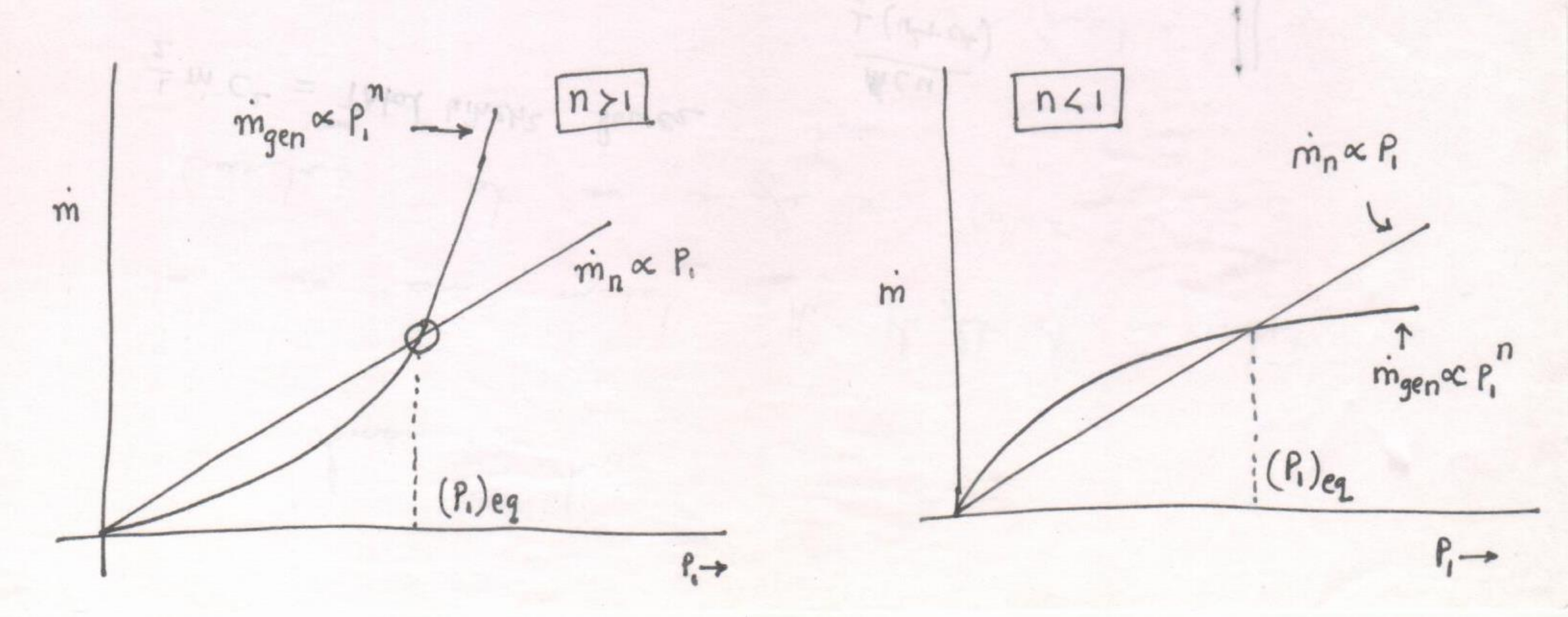
For steady state, $\frac{d}{dt} P_1 = 0$

$$(P_1)_{eq} = \left[K \cdot a \cdot (\rho_p - \rho_1) \cdot c^* \right]^{1/1-n}$$

For realistic rockets, $\rho_p >> \rho_1$ & hence

$$\frac{V_1}{RT_1} \frac{dP_1}{dt} = A_b \cdot a \cdot P_1^n \cdot \rho_p - \frac{P_1 A_t}{c^*} = \dot{m}_{gen} - \dot{m}_n$$

Stable operation of the rocket motor



Unstable

Stable

Choice of n

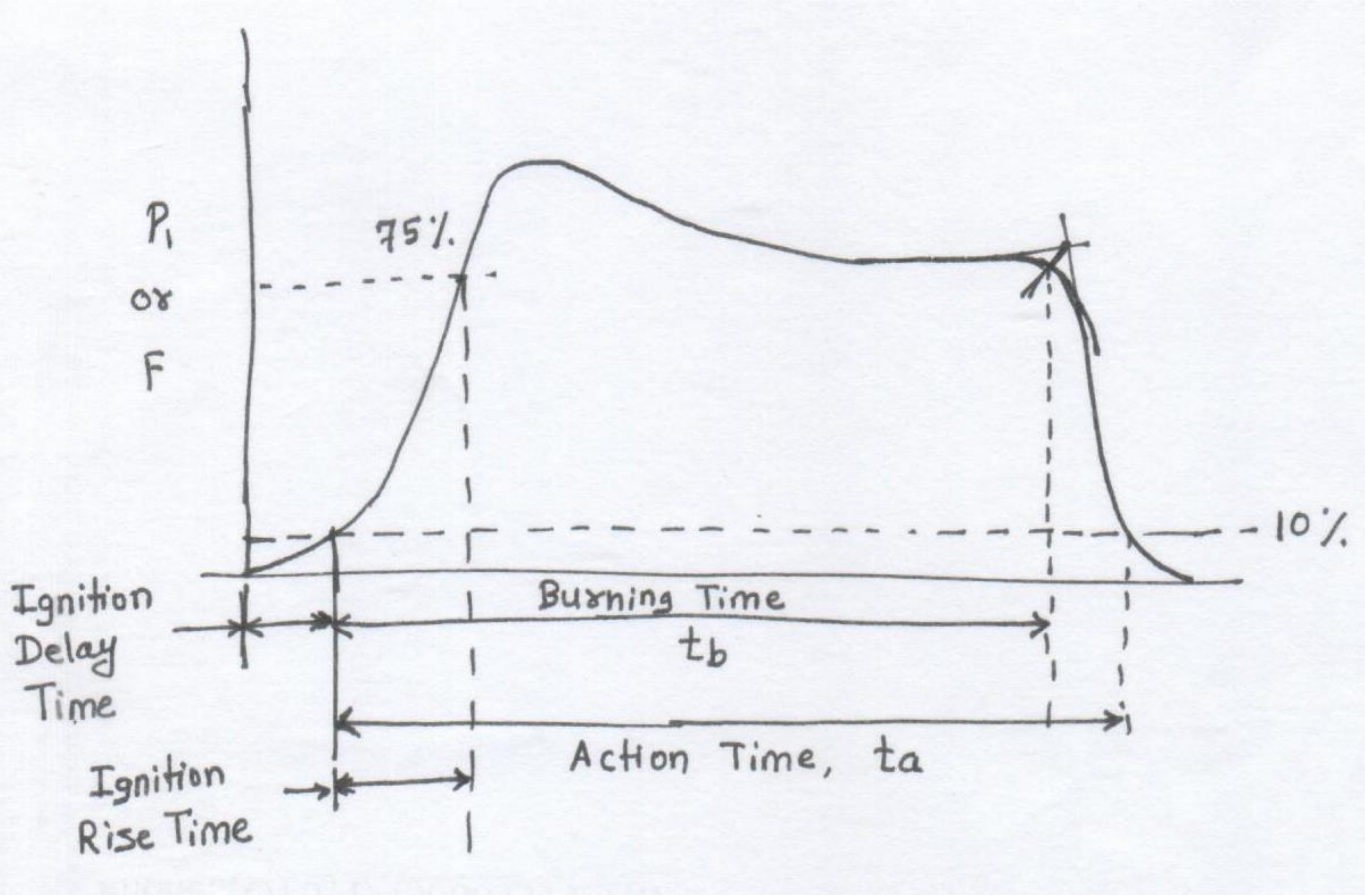
For steady state, $\frac{d}{dt} P_1 = 0$

$$(P_1)_{eq} = \left[K \cdot a \cdot (\rho_p - \rho_1) \cdot c^* \right]^{1/1-n}$$

Very large values of n make equilibrium pressure very sensitive to K and c*

For instance, for n = 0.8, the exponent becomes 5. This leads to catastrophic pressure rise due to small increases in burning surface area, or temperature etc.

Usually n = 0.2 – 0.6 is chosen for practical applications



Difficult to measure the instantaneous mass flow rate for solid rocket motors.

Hence for ground testing total impulse and total propellant mass are measured.

Average specific impulse is obtained by taking the ratio of these two parameters.

Various time scale nomenclature used for motor firing are shown.

Typical ranges of performance parameters in case of Solid rocket motors

Impulse to weight ratio : 100 – 230 sec

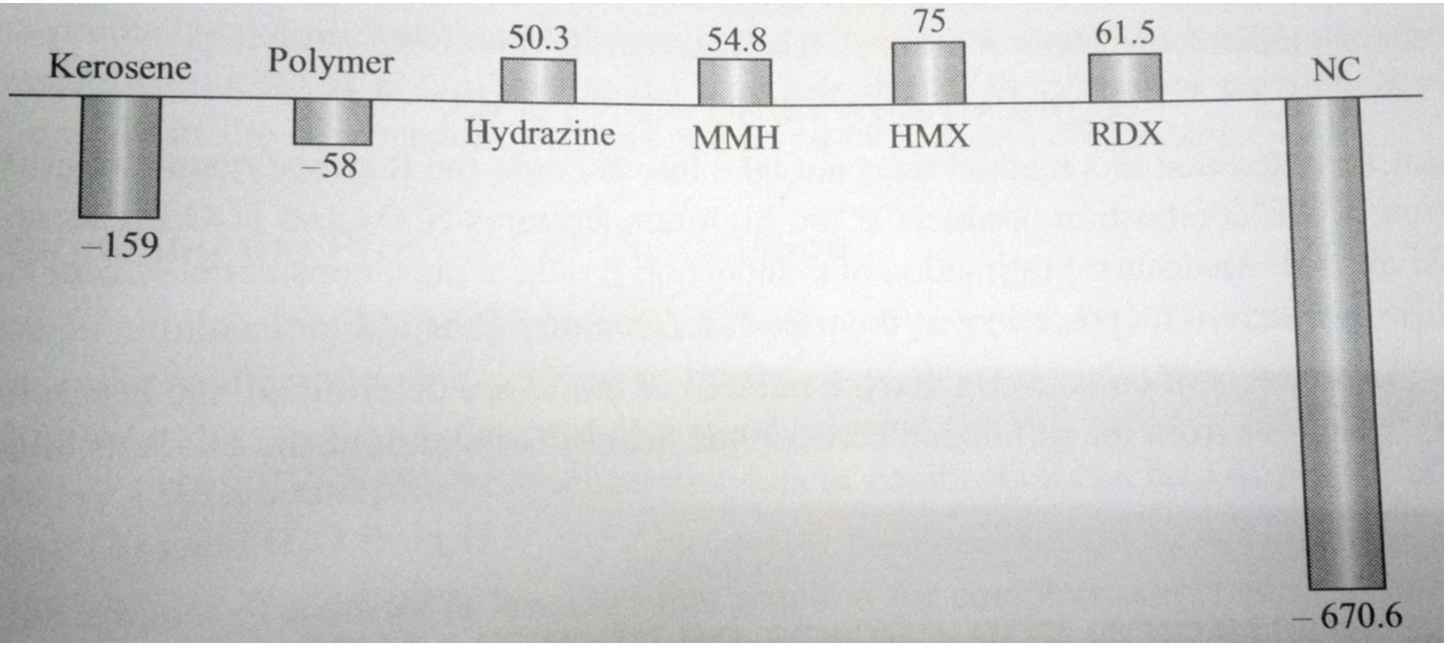
Thrust to weight ratio : 5 – 200

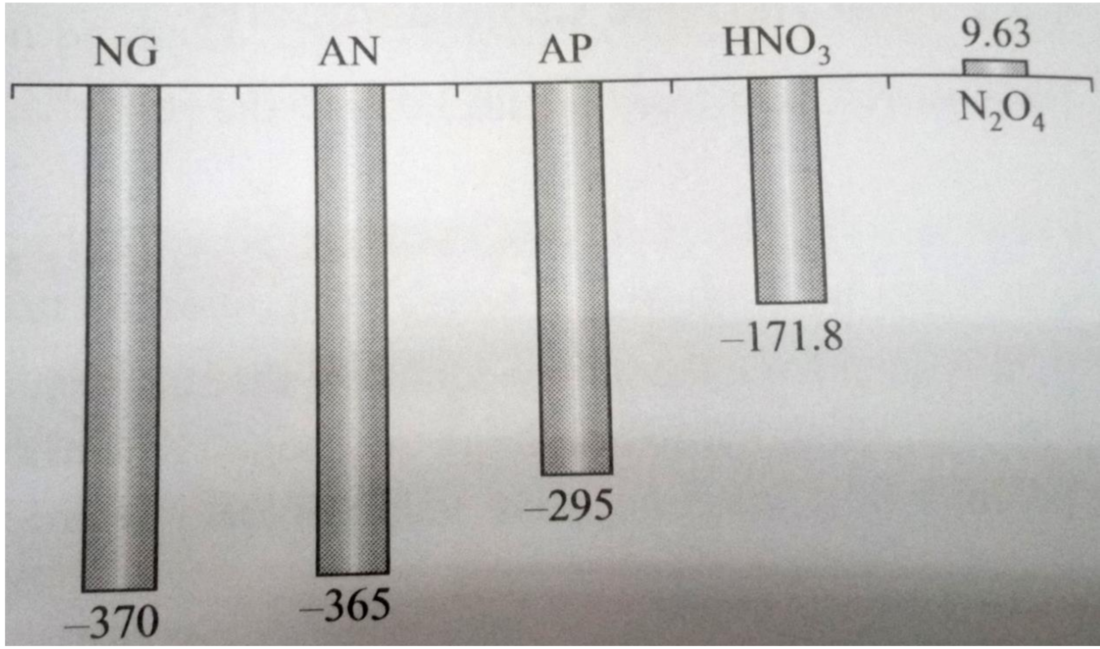
Specific impulse : 170 – 250 sec

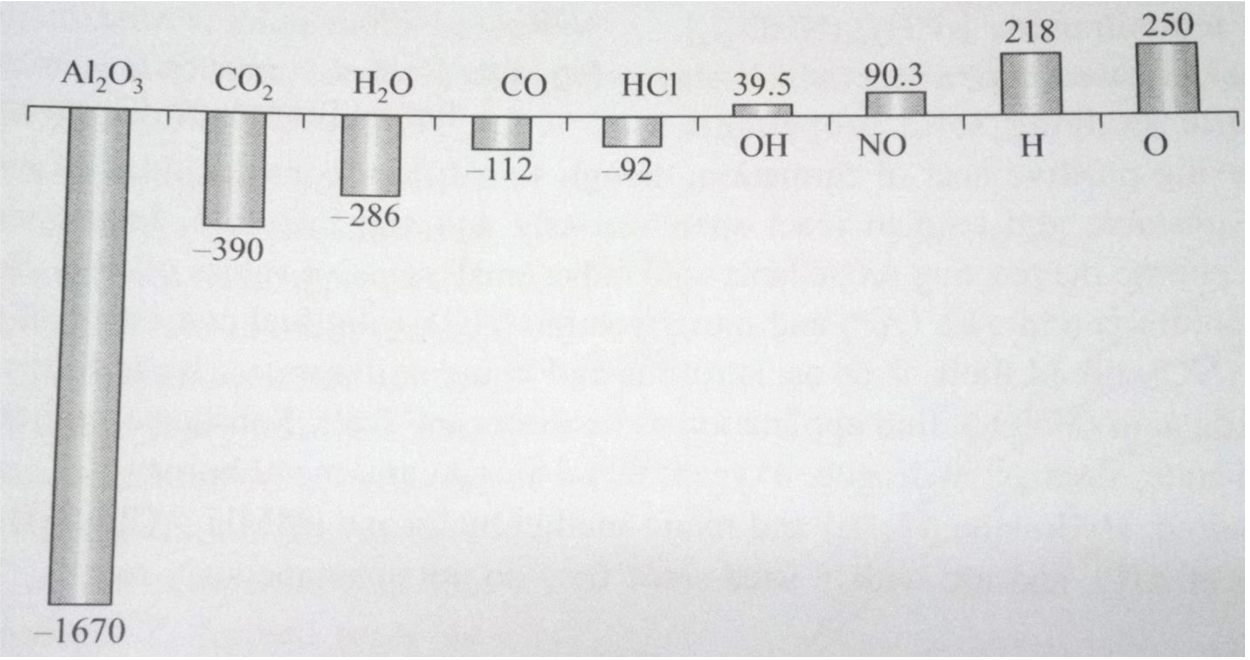
Propellant mass fraction :
For small motors ($F < 500$ N) : 0.3 - 0.75
For medium motors ($500 < F < 5000$) : 0.8 – 0.9
For large motors ($F > 5000$ N) : 0.88 – 0.945

Propellant characteristics

- High performance – high temperature and low molecular weight
- Predictable, reproducible, initially-adjustable burn rate characteristics
- Small burn rate exponent and temperature coefficient
- Adequate physical properties over the intended temperature range
- High density
- Good ignition characteristics – quick build-up of pressure
- Good ageing characteristic and long life
- Low absorption of moisture
- Low cost, easily available and low manufacturing hazard
- Non-toxic exhaust gases and low smoke exhaust







Heat of formation of products should be large negative value and that for reactants should be small negative value or even positive

Large heat of combustion

Solid Propellants

Homogeneous propellants : It is not possible to distinguish the components after the propellant is made. The components of the propellant mix into each other at molecular level.

Double base propellants are homogeneous propellants.

Heterogeneous propellant: Propellant constituents remain separated, but in close proximity with each other. It is possible to separate them.

Composite propellants fall under this category.

Composite modified double base propellants (CMDB) : Combinations of composite and double base propellant components to enhance certain characteristics of the propellants.

Double Base (DB) Propellants

Two components of double base propellant : Nitrocellulose (NC) and Nitroglycerine (NG)

Both the components contain the fuel as well as oxidizer elements and they are mixed together at molecular level

Each individual component (i.e. NC or NG) can be used as a stand-alone propellant. In that case, it is called as single base propellant

When both NC and NG are mixed, it is called as double base propellant

Double Base (DB) Propellants

Nitrocellulose (NC) : $[C_6H_{10-x}O_{5-x}(NO_3)_x]_n$ -- Solid and fuel-rich
x – depends on the amount of nitration

Nitroglycerine (NG) : $C_3H_5(NO_3)_3$ -- Liquid and oxidizer-rich

Stoichiometric mixture ➔ NG : NC = 6.5 : 1
But this will increase the liquid component significantly and the mixture will become a slurry, hard to cast into the solid propellant

Practical composition to make a solid propellant ➔ NG : NC = 0.8 : 1

Hence, double base propellant is always fuel-rich.

Composite propellants (CP)

Three main constituents: Solid oxidizer, polymeric binder and metal fuel

Oxidizer : Widely used solid oxidizer in propulsion applications is Ammonium Perchlorate (AP)

Ammonium Perchlorate (AP) – NH_4ClO_4 – solid crystalline powder
Compatible with many binders, less hygroscopic, dissociates easily, better stability

Other options for oxidizers:
Ammonium nitrate (AN) – NH4NO3 -- hygroscopic and hard to dissociate
Potassium nitrate – KNO3 – hygroscopic and hard to dissociate
Nitronium perchlorate – NO2ClO4 – poor compatibility and stability
Hydrazinium perchlorate – N2H5ClO4 – highly energetic

Composite propellants

Polymeric binder : Acts as a fuel

Compounds of C, H and O atoms (and sometimes S and N also but not preferred)

Binders are typically long chain compounds which for matrix to hold together oxidizer and metal fuel

The molecular mass of polymeric binders range from 30000 to 100000 kg/kmol

Examples:

Polybutadienes (PB)➔ --(CH2=CH-CH=CH2)n--

Polybutadiene acrylic acid acrylonitrile (PBAN)

Carboxy Terminated Poly Butadiene (CTPB)

Hydroxy Terminated Poly Butadiene (HTPB) : used widely to make high performance propellants

Composite propellants

Metal Fuel : Used in the form of metal powder to enhance the energy release from combustion since metal oxidation is highly exothermic process

Commonly used metal : Aluminium – a light metal and hence preferrable

Aluminium converts to aluminium oxide having a very large negative value of heat of formation

Typical composition of composite propellant:

Typical solid fraction ~ 87 % (AP ~ 70% and Al ~ 17%) and rest is binder
AP particle size ~ 20 – 500 microns
Al particle size ~ 20 – 50 microns

Peak performance is usually achieved with ~ 92% solid fraction (stoichiometric combination); however, large solid fraction reduces the binder component thereby reducing the binding capacity. The integrity of the solid propellant weakens

Composite Modified Double Base (CMDB) propellants

Combination of different constituents from DB and CP Propellants to achieve certain enhancements

Addition of AP crystals to DB propellants reduces its fuel-richness and improves the specific impulse

Explosives like HMX, if added to DB propellant, increase the heat release of DB propellants

Nitramine propellants: Ring shaped molecular structure with nitramine (NO2) group
HMX – Her Majesty's Explosive
RDX – R&D Explosive

Used with CP to alter the combustion process and reduce the infra-red radiation of the products

Purpose of other additives in small proportions

*improving the *rheological properties* (easier casting of viscous raw mixed propellant)

*improving the *physical properties*

*adding *opaqueness* to a transparent propellant to prevent radiation heating at places other than the burning surface

*limiting *migration of chemical species* from the propellant to the binder or vice versa

*minimizing the slow oxidation or *chemical deterioration* during storage and improving the *aging* characteristics or the moisture resistance

**Bonding agents* are additives to enhance adhesion between the solid ingredients (AP or Al) and the binder

**Stabilizers* are intended to minimize the slow chemical or physical reactions that can occur in propellants

**Catalysts* are sometimes added to the crosslinker or curing agent to slow down the curing rate.

**Lubricants* aid the extrusion process.

**Desensitizing agents* help to make a propellant more resistant to inadvertent energy stimulus

These are usually added in very small quantities.

Typical ingredients of final propellant apart from fuel and oxidizer

*Binders: provides the structural glue or matrix in which solid granular ingredients are held together in a composite propellant.

Binder materials are also really fuels for solid propellant rockets and are oxidized in the combustion process.

HTPB has been the favorite binder in recent years, because it allows a somewhat higher solids fraction (88 to 90% of AP and Al) and relatively good physical properties at the temperature limits

*Burning-Rate Modifiers:
to accelerate or decelerate the combustion at the burning surface and increases or decreases the value of the propellant burning rate.

Some, like iron oxide (Fe_2O_3) or copper chromite ($Cu_2Cr_2O_5$) lead stearate, increase the burning rate; however, others, like lithium fluoride (LiF), will reduce the burning rate of some composite propellants.

*Plasticizers:
a relatively low-viscosity liquid organic ingredient which is also a fuel. It is added to improve the elongation of the propellant at low temperatures and to improve processing properties, such as lower viscosity for casting or longer pot life of the mixed but uncured propellants.

*Curing Agents or Crosslinkers:
A curing agent or crosslinker causes the prepolymers to form longer chains of larger molecular mass and interlocks between chains. Even though these materials are present in small amounts (0.2 to 3%), a minor change in the percentage will have a major effect on the propellant physical properties

*Organic Oxidizers or Explosives:
used with high-energy propellants or smokeless propellants.

Type	Percent	Acronym	Typical Chemicals
Oxidizer (crystalline)	0–70	AP	Ammonium perchlorate
		AN	Ammonium nitrate
		KP	Potassium perchlorate
		KN	Potassium nitrate
		ADN	Ammonium dinitramine
Metal fuel (also acts as a combustion stabilizer)	0–30	Al	Aluminum
		Be	Beryllium (experimental propellant only)
		Zr	Zirconium (also acts as burn-rate modifier)
Fuel/Binder, polybutadiene type	5–18	HTPB	Hydroxyl-terminated polybutadiene
		CTPB	Carboxyl-terminated polybutadiene
		PBAN	Polybutadiene acrylonitrile acrylic acid
		PBAA	Polybutadiene acrylic acid
Fuel/Binder, polyether and polyester type	0–15	PEG	Polyethylene glycol
		PCP	Polycaprolactone polyol
		PGA	Polyglycol adipate
		PPG	Polypropylene glycol
		HTPE	Hydroxyl-terminated polyethylene
		PU	Polyurethane polyester or polyether
Curing agent or crosslinker, which reacts with polymer binder	0.2–3.5	MAPO	Methyl aziridinyl phosphine oxide
		IPDI	Isophorone diisocyanate
		TDI	Toluene-2,4-diisocyanate
		HMDI	Hexamethylene diisocyanide
		DDI	Dimeryl diisocyanate
		TMP	Trimethylol propane
		BITA	Trimesoyl-1(2-ethyl)-aziridine
Burn-rate modifier	0.2–3	FeO	Ferric oxide
		nBF	*n*-Butyl ferrocene
			Oxides of Cu, Pb, Zr, Fe
			Alkaline earth carbonates
			Alkaline earth sulfates
			Metallo-organic compounds
Explosive filler (solid)	0–40	HMX	Cyclotetramethylenetetranitramine
		RDX	Cyclotrimethylenetrinitramine
		NQ	Nitroguanadine
Plasticizer/Pot life control (organic liquid)	0–7	DOP	Dioctyl phthalate
		DOA	Dioctyl adipate
		DOS	Dioctyl sebacate
		DMP	Dimethyl phthalate
		IDP	Isodecyl pelargonate

Representative Propellant Formulations					
Double-Base		**Composite (PBAN Propellant)**		**Composite Double-Base (CMDB Propellant)**	
Ingredient	Wt%	Ingredient	Wt %	Ingredient	Wt %
Nitrocellulose	51.5	Ammonium perchlorate	70.0	Ammonium perchlorate	20.4
Nitroglycerine	43.0	Aluminum powder	16.0	Aluminum powder	21.1
Diethyl phthalate	3.2	Polybutadiene-acrylic acid-acrylonitrile	11.78	Nitrocellulose	21.9
Ethyl centralite	1.0	Epoxy curative	2.22	Nitroglycerine	29.0
Potassium sulfate	1.2			Triacetin	5.1
Carbon black	< 1%			Stabilizers	2.5
Candelilla wax	< 1%				

Characteristics of Some Operational Solid Propellants

Propellant Type	Is (sec)	Flame Temperature (°K)	Density or Spec. Gravity (sp. gr.)	Metal Content (wt %)	Burning Rate (in./sec)	Pressure Exponent n	Hazard Classification	Processing Method
DB	220-230	2550	1.61	0	0.05-1.2	0.30	1.1	Extruded
DB/AP/Al	260-265	3880	1.80	20-21	0.2-1.0	0.40	1.3	Extruded
DB/AP-HMX/Al	265-270	4000	1.80	20	0.2-1.2	0.49	1.1	Solvent cast
PU/AP/Al	260-265	3440	1.78	16-20	0.2-0.9	0.15	1.3	Cast
CTPB/AP/Al	260-265	3440	1.78	15-17	0.25-2.0	0.40	1.3	Cast
HTPB/AP/Al	260-265	3440	1.86	4-17	0.25-3.0	0.40	1.3	Cast
AN/Polymer	180-190	1550	1.47	0	0.06-0.5	0.60	1.3	Cast

Al, aluminum; AN, ammonium nitrate; AP, ammonium perchlorate; CTPB, carboxy-terminated polybutadiene; DB, double-base
HMX, cyclotetramethylene tetranitramine; HTPB, hydroxyl-terminatd polybutadiene; PVC, polyvinyl chloride; RDX, Cyclotrimethylene-trinitramine
PBAA, polybutadiene-acrylic acid polymer; PBAN, polybutadiene-acrylic acid-acrylonitrile terpolymer; PU, polyurethane;

Classification of Solid Rocket Propellants Used in Flying Vehicles

Designation	Binder	Plasticizer	Solid Oxidizer and/or Fuel	Propellant Application
Double-base, DB	Plasticized NC	NG, TA, etc	None	Minimum signature and smoke
CMDB a	Plasticized NC	NG,TMETN, TA, BTTN, etc.	Al, AP,KP	Booster, sustainer, and spacecraft
	Same	Same	HMX,RDX, AP	Reduced smoke
	Same	Same	HMX, RDX, azides	Minimum signature, gas generator
EMCDB	Plasticized NC+elastomeric polymer	Same	Like CMDBabove, but generally superior mechanical properties with elastomer added as binder	
Polybutadiene	HTPB	DOA, IDP, DOP, DOA, etc.	Al, AP,, KP, HMX, RDX	Booster, sustainer or spacecraft; used extensively in many applications
	HTPB	Same	AN,HMX, RDX, some AP	Reduced smoke, gas generator
	CTPB, PBAN, PBAA	All like HTPB above, but somewhat lower performance due to higher processing viscosity and consequent lower solids content. Still used in applications with older designs		
TPE	Thermoplastic elastomer	Similar to HTPB, but without chemical curing process. TPEs cure (crosslink) via selective crystallization of certain parts of the binder. Still are experimental propellants		
Polyether and polyesters	PEG, PPG, PCP,and PGA,mixtures	DOA, IDP, TMETN, DEGDN, etc	Al, AP, KP, HMX	Booster, sustainer, or spacecraft
Energetic binder (other than NC)	GAP, PGN, BAMO/NMMO, BAMO/AMMO	TMETN, BTTN, etc. GAP-azide,GAP-nitrate, NG	Like polyether/polyester propellants above, but with slightly higher performance. Experimental propellant.	

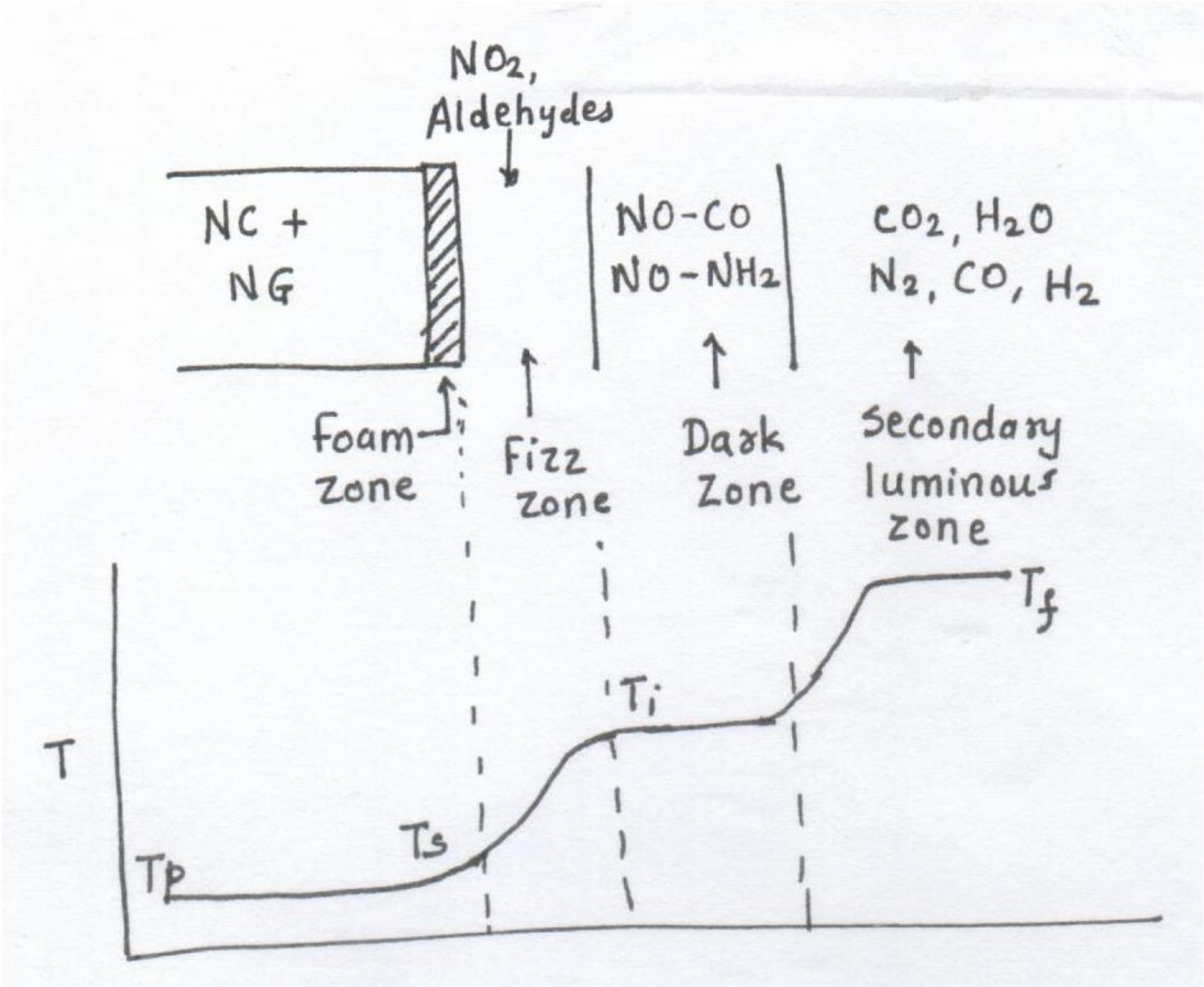
CMDB, composite-modified double-base; EMCDB, elastomer-modifiedcast double-base; TPE, thermoplastic elastomer

The combustion in a solid propellant motor involves exceedingly complex reactions taking place in the solid, liquid, and gas phases of a heterogeneous mixture.

Experimental observations of burning propellants show

- complicated three-dimensional micro-structures,
- a three-dimensional flame structure,
- intermediate products in the liquid and gaseous phase,
- spatially and temporally variant processes,
- Aluminum agglomeration,
- nonlinear response behavior,
- formation of carbon particles, and
- other complexities yet to be adequately reflected in mathematical models.

Combustion in double-base propellant



Premixed combustion

Foam zone: Exothermic degradation of propellant in solid phase liberating gases like NO2 and aldehydes

Fizz zone: Exothermic reaction to form CO, CO2 with liberation of heat. Temperature increases and this zone is luminous

Dark zone: Reactions between NO-CO and NO-NH2 take place prominently and no significant temperature rise.

Second luminous zone: Chemical reactions proceed further to give final gas mixture and temperature rises further to final flame temperature

Combustion in double-base propellant

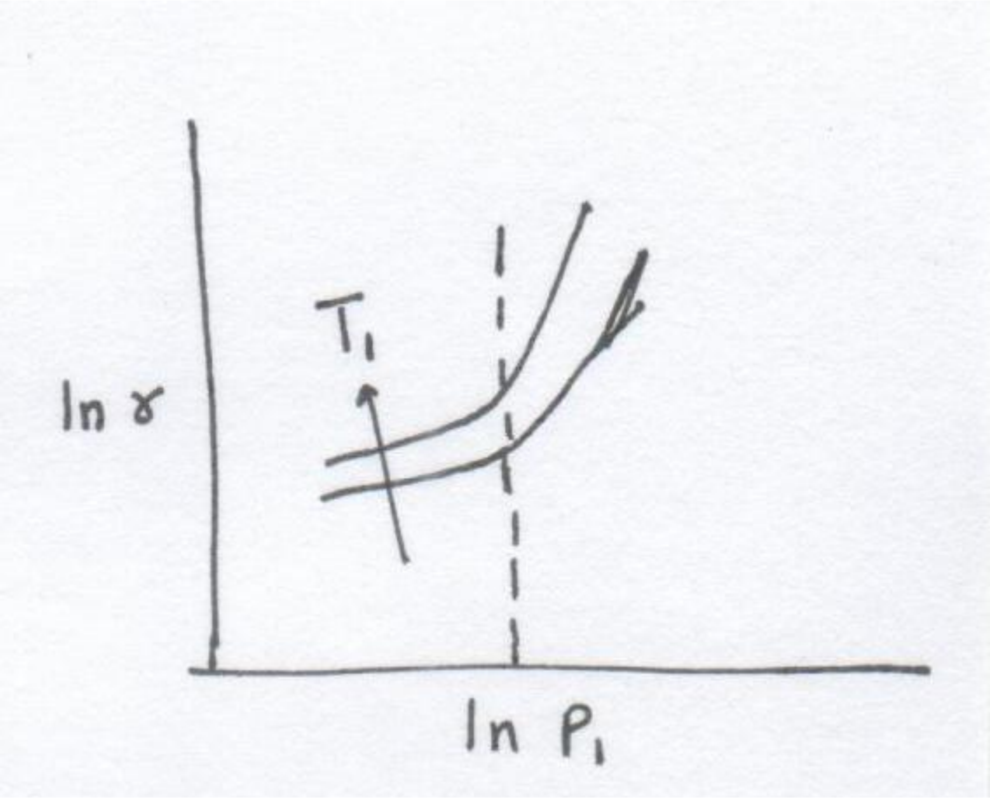
As P1 increases, the thicknesses of all the zones reduce leading to increased heat transfer to the solid surface and increasing the burn rate

The dark zone thickness decreases with increasing chamber pressure, and higher heat transfer to the burning surface causes the burning rate to increase.

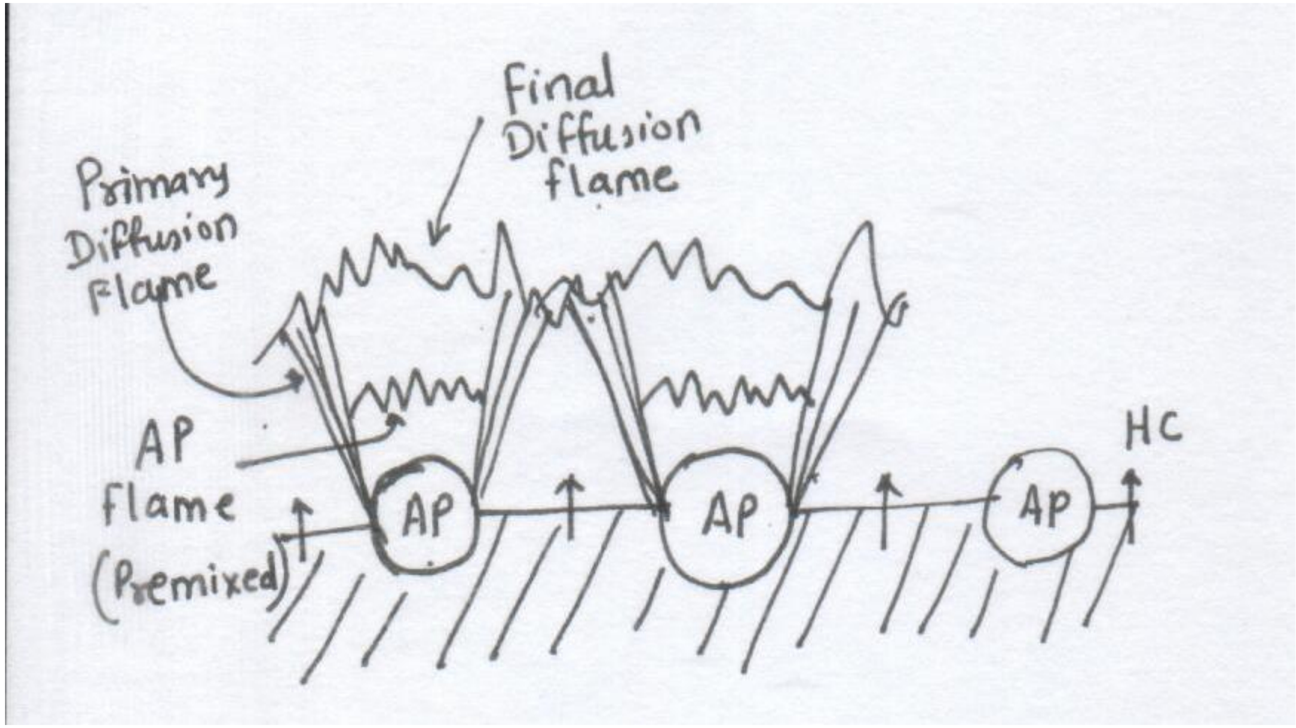
Experiments on strand burners show this dramatically: for pressures of 10, 20, and 30 atm the dark zone thickness is 12, 3.3, and 1.4 mm, respectively

At P1 <10 MPa, there exists a significant dark zone and hence DB propellants have lower burn rates than other types of propellants

At P1 >10 MPa, dark zone disappears and the burn rate increases rapidly with chamber pressure



Combustion of composite propellants



AP flame (premixed combustion):
AP (NH_4ClO_4) decomposes giving out oxidizer rich gases (NH_3+HClO_4) and raises the temperature to 1300K

Heat released causes the HC binder to evaporate and the fuel gases from binder and oxidizer rich gases from AP flame form a Primary diffusion flame

Combustion here is controlled by the mass diffusion process

The products of both the flame finally mix and burn together in Final diffusion flame to give a temperature of ~ 3200 K

The combustion zone thickness is of the order of 0.1 mm and decreases with P1

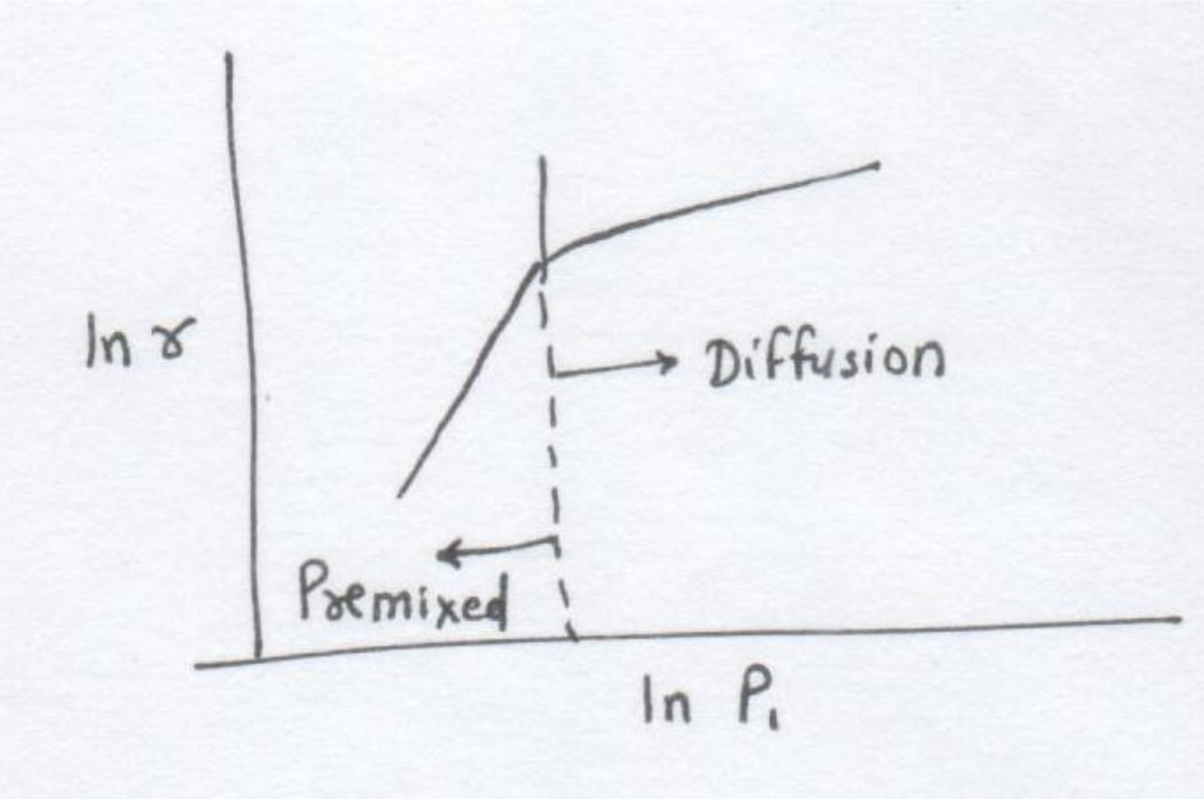
Combustion of composite propellants

At lower chamber pressure : premixed flame is the rate governing process
At higher pressure : diffusion flame is the rate governing process

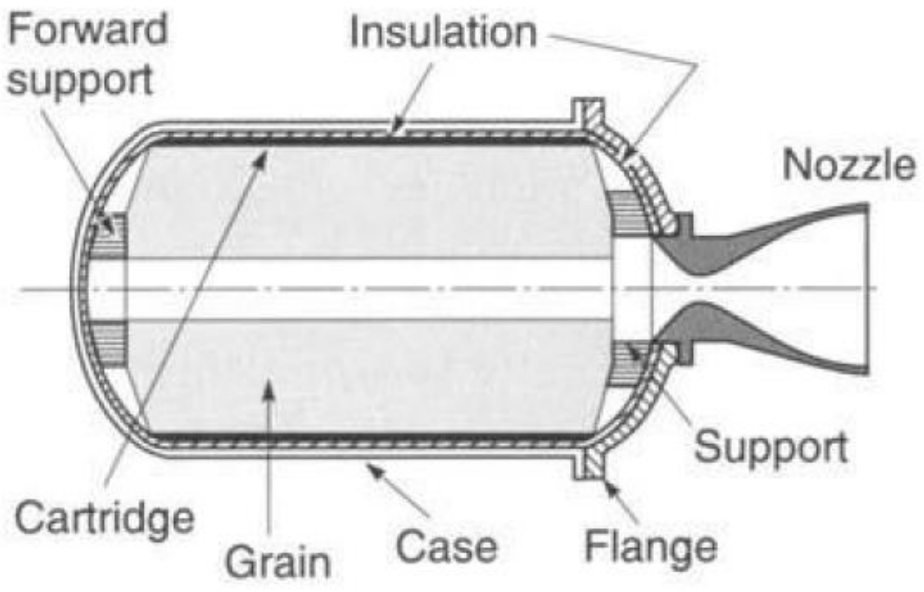
When P1 is in the range of 3 – 15 MPa, diffusion flame dominates the combustion process and n lies between 0.3-0.4

When P1 < 1 MPa, AP flame controls the combustion and n ~ 0.5

Metal fuel (Al particles) are released from evaporating binder and burn when they come into the high temperature gases. Al2O3 radiate significantly giving rise to highly visible flame



PROPELLANT GRAIN CONFIGURATION

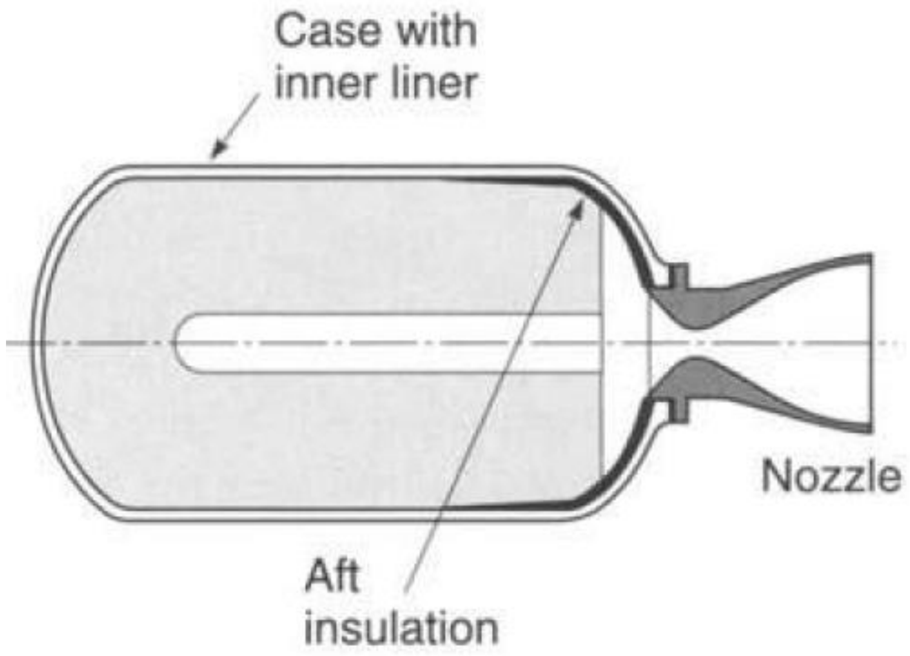


Cartridge–loaded grain
(free–standing)

Manufactured separately (by extrusion or by casting into a cylindrical mold or cartridge) and then loaded into or assembled into the case.

Easily replaceable in case of aging, low cost, easy for inspection

Small tactical missiles and a few medium-sized motors.



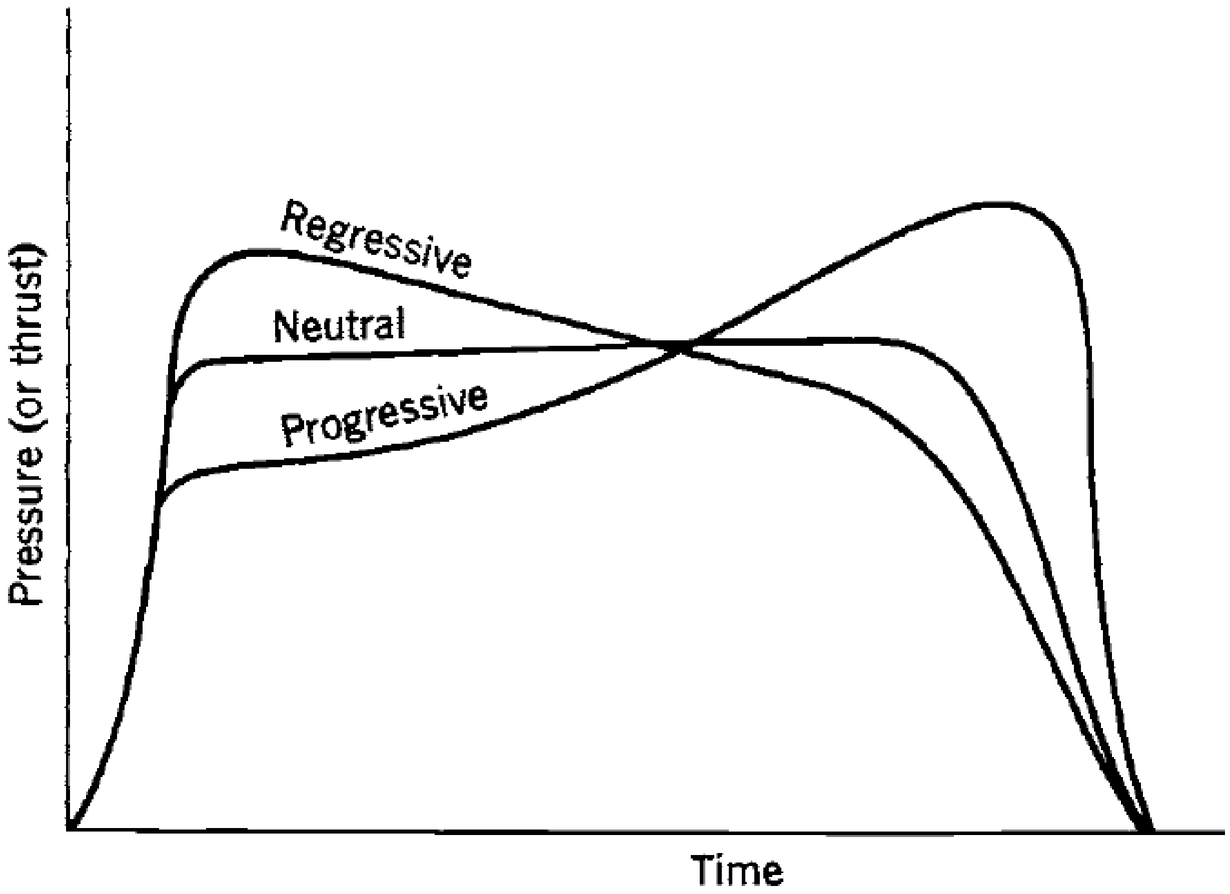
Case–bonded grain

The case is used as a mold and the propellant is cast directly into the case and bonded to the case

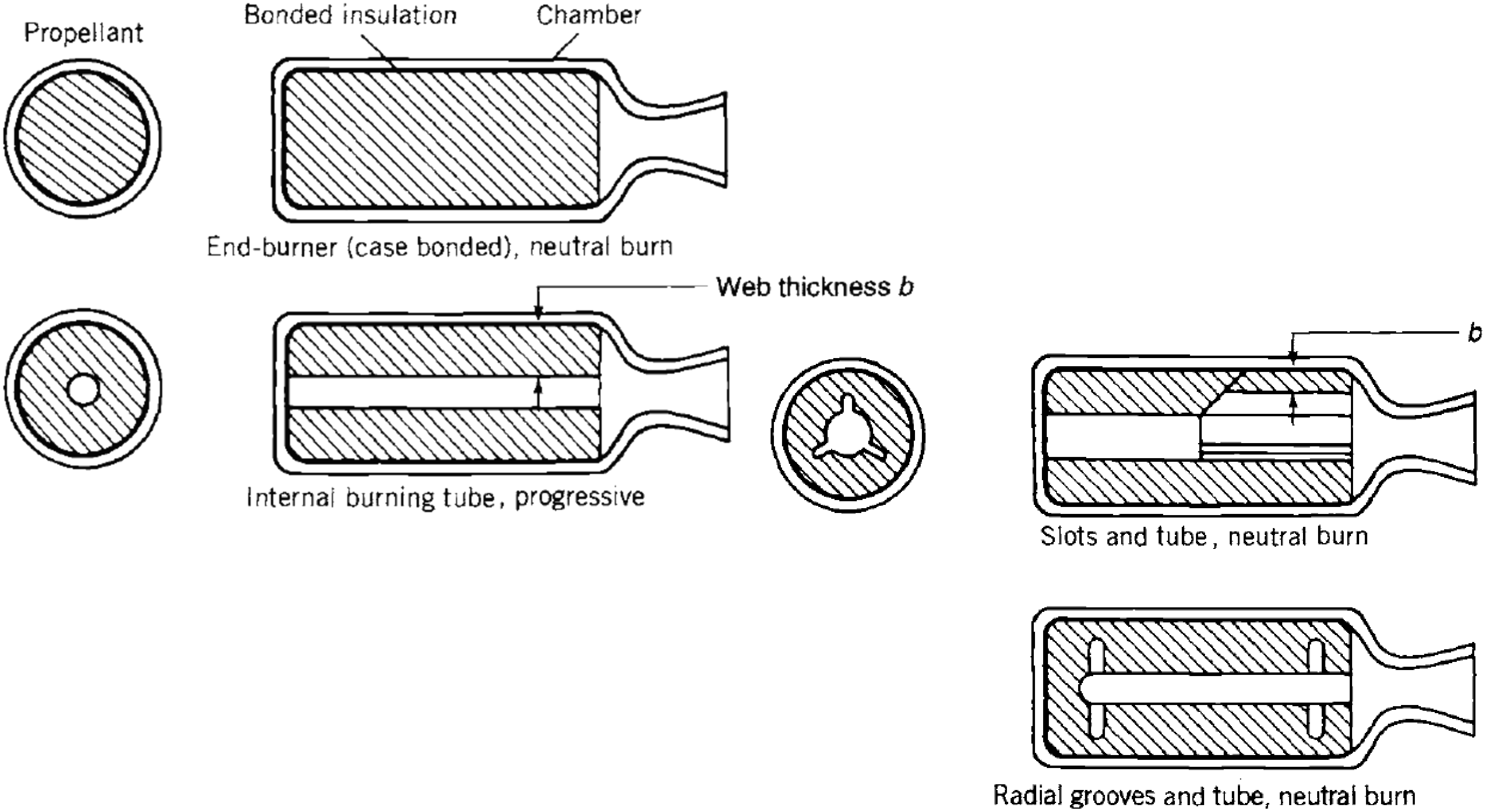
Better performance, less inert mass, better volumetric loading fraction, are more highly stressed, and often more difficult and expensive to manufacture.

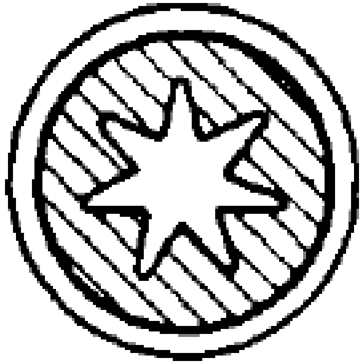
Almost all larger motors and many tactical missile motors use case bonding.

Factors affecting the solid rocket motor design

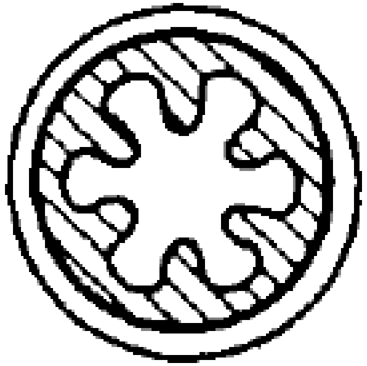


1. Flight mission
2. Grain geometry
3. Propellant
4. Structural integrity
5. Internal cavity volume
6. Propellant processing

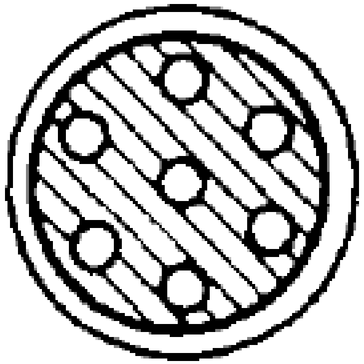

Propellant
Bonded insulation
Chamber
End-burner (case bonded), neutral burn
Web thickness b
Internal burning tube, progressive
b
Slots and tube, neutral burn
Radial grooves and tube, neutral burn



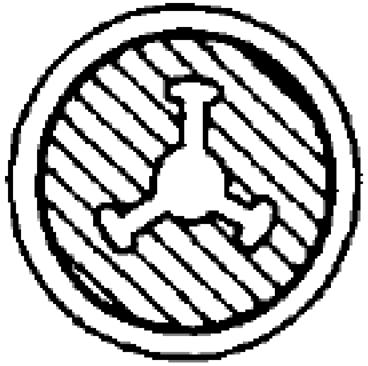
Star (neutral)



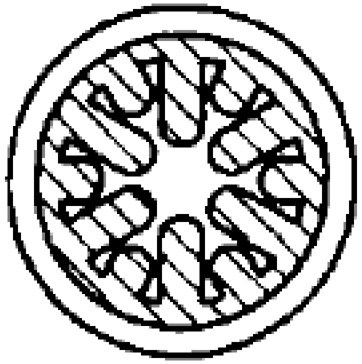
Wagon wheel
(neutral)



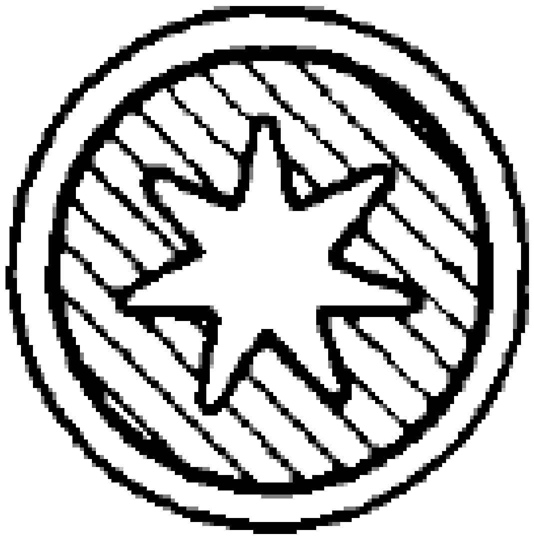
Multiperforated
(progressive-regressive)



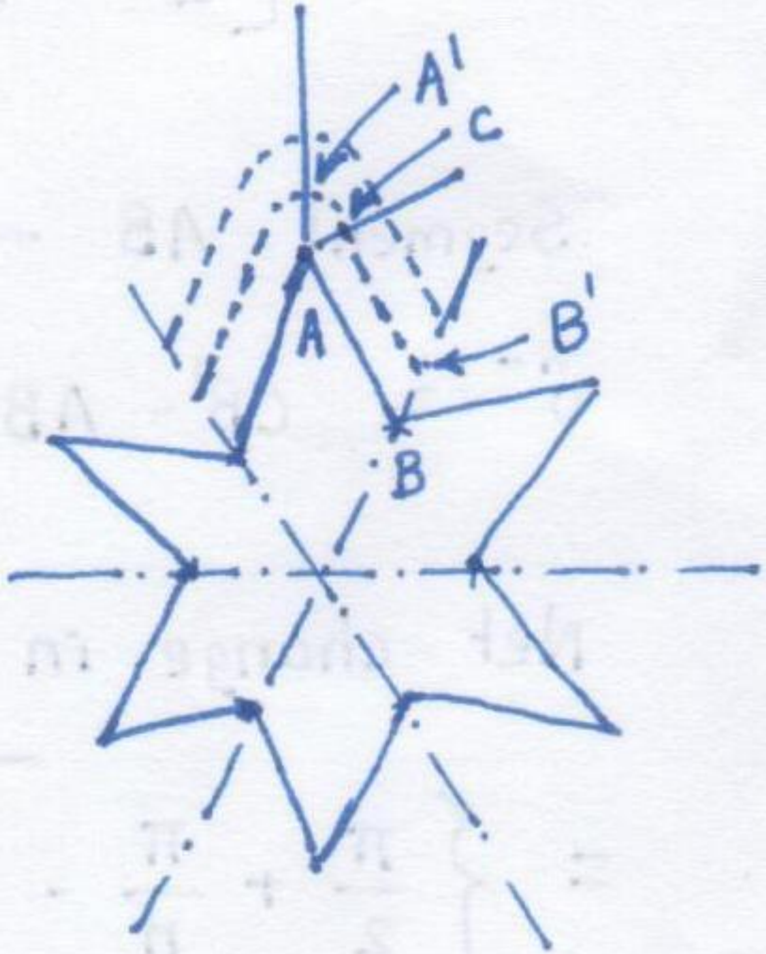
Dog bone

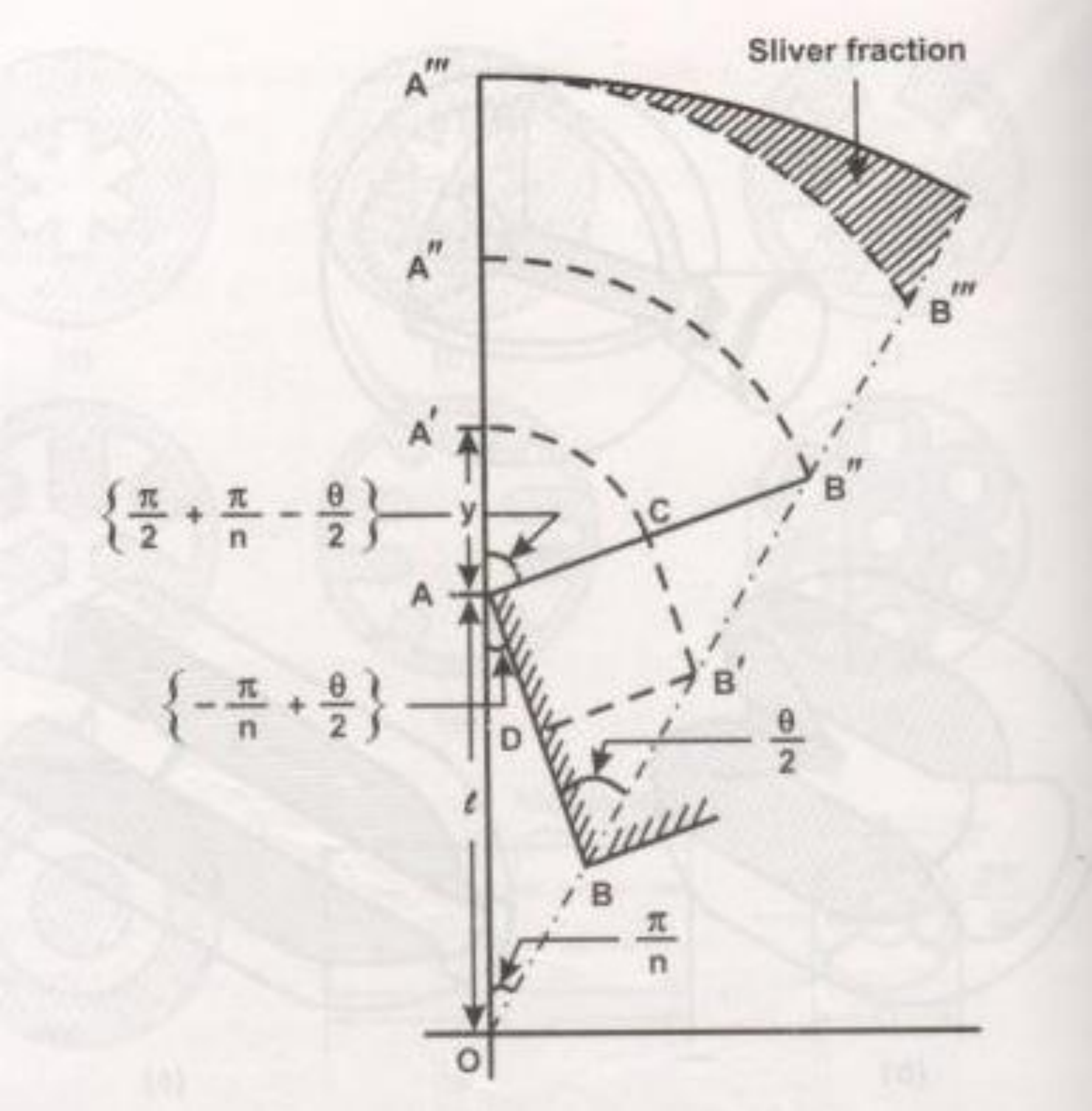


Dendrite
(case bonded)



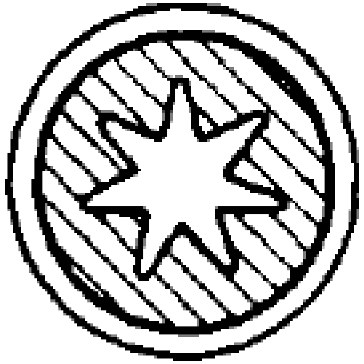
Star (neutral)





GRAIN GEOMETRY

N-pointed star configuration – capable of producing all the three types of burning characteristics



Star (neutral)

Segment $AB \longrightarrow A'CB'$ (after time ~~be~~ interval t)

Similar for all segments '$2n$' for n-pointed star.

Point $A \longrightarrow$ Arc $A'C$ $\Rightarrow$ change in length.

$$\delta^{+} = A'C - 0$$

If $y =$ Regression distance in time t,

$$\delta^{+} = \left\{ \frac{\pi}{2} + \frac{\pi}{n} - \frac{\theta}{2} \right\} \cdot y$$

Segment AB $\longrightarrow$ Segment CB' $\Rightarrow$ change in length,

$$\delta^- = CB' - AB = -BD = -y\cot\left(\frac{\theta}{2}\right)$$

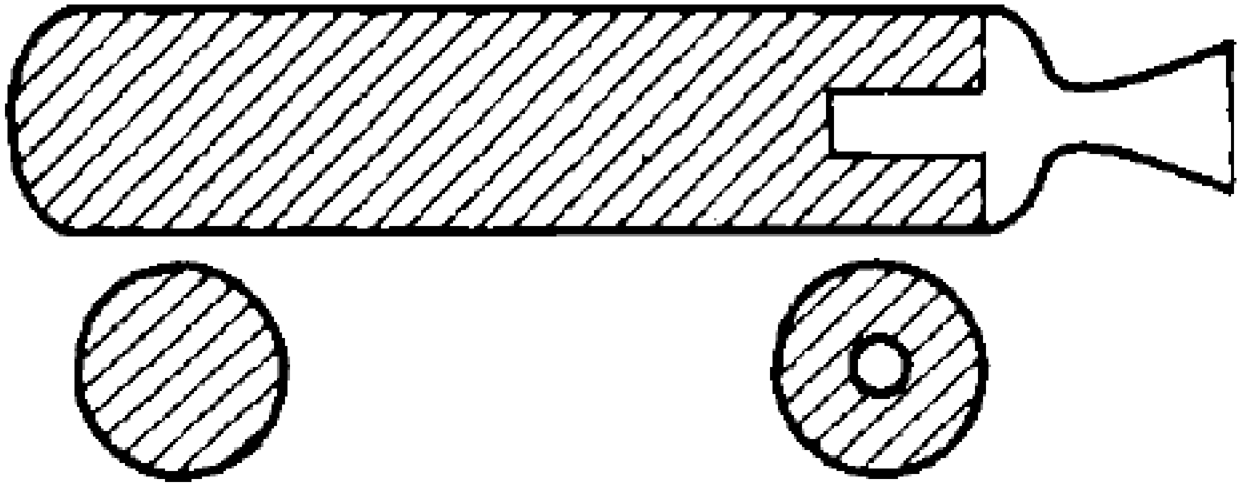
Net change in burning surface area $= \delta^+ + \delta^-$

$$= \left\{\frac{\pi}{2} + \frac{\pi}{n} - \frac{\theta}{2} - \cot\frac{\theta}{2}\right\} \cdot y$$

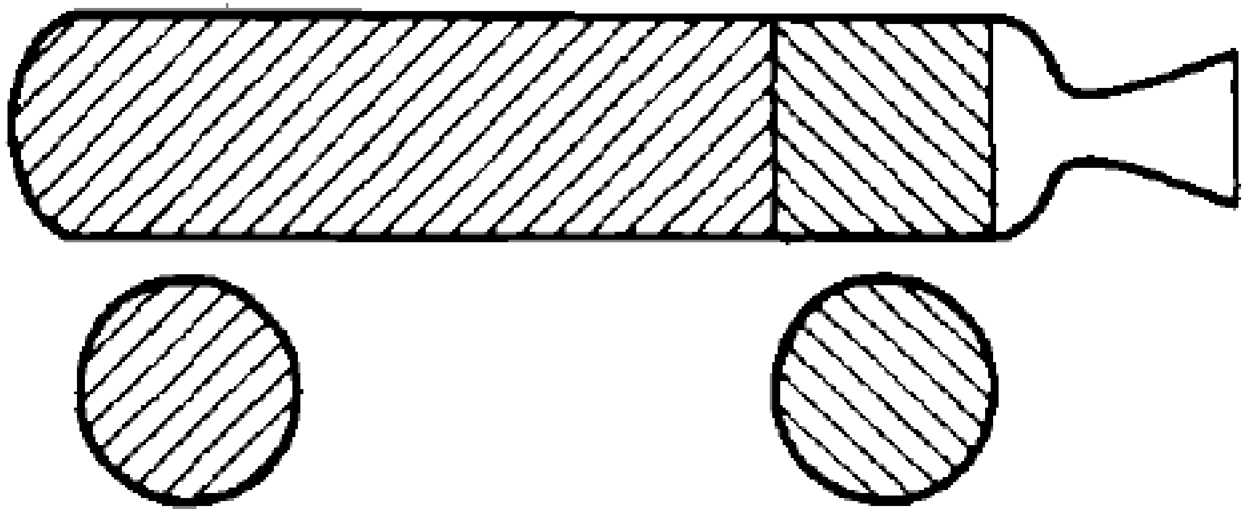
Neutral burning is possible, if $\delta^+ + \delta^- = 0$

$$\Rightarrow \boxed{\frac{\pi}{2} + \frac{\pi}{n} - \frac{\theta}{2} - \cot\frac{\theta}{2} = 0}$$

GRAIN CONFIGURATIONS FOR THRUST MODULATIONS

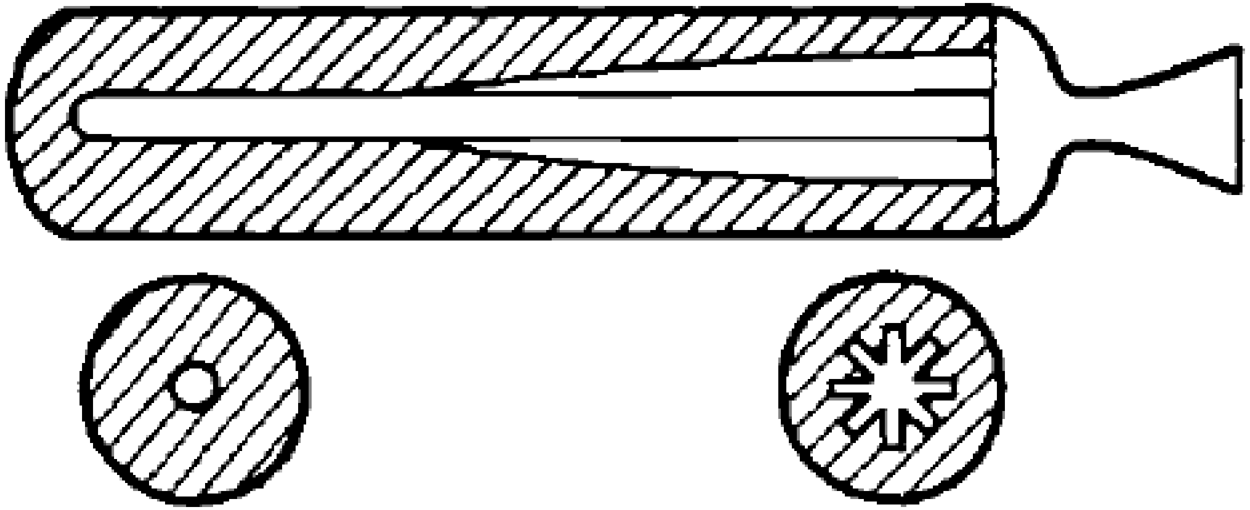


Single grain. Boost with radial burning, sustain with end burning

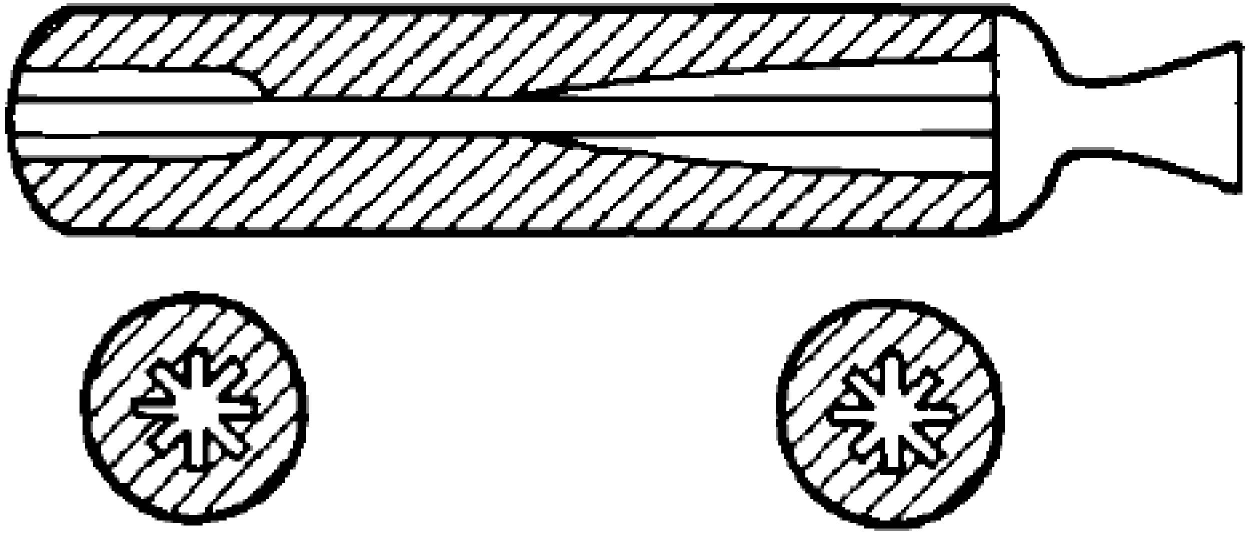


Dual end burning grains with two propellants of different burning rates. Not used today, because the manufacture is more expensive

GRAIN CONFIGURATIONS FOR THRUST MODULATIONS

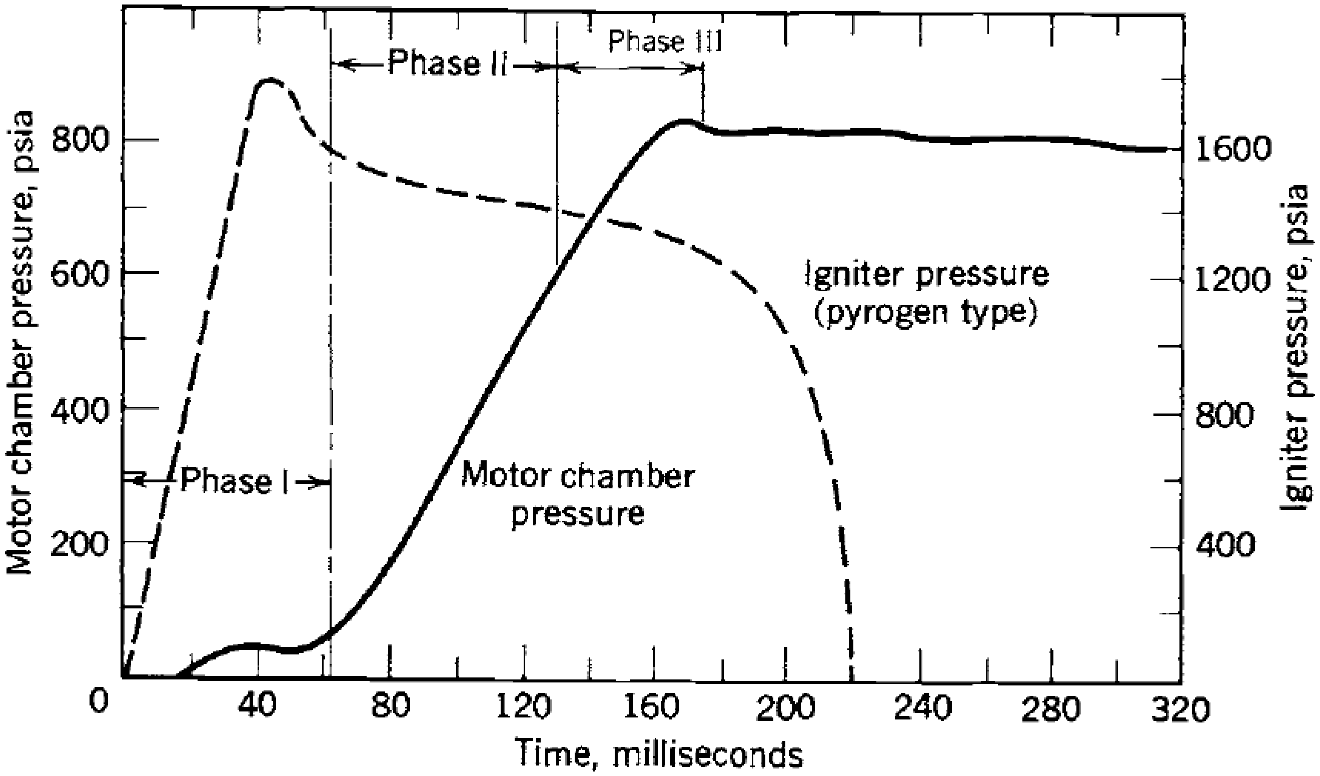


Single grain. Boost with large burning area, sustain with smaller burning area (both radial)



Single grain. Boost-sustain-boost, with different burning areas (all radial burning)

Ignition Process



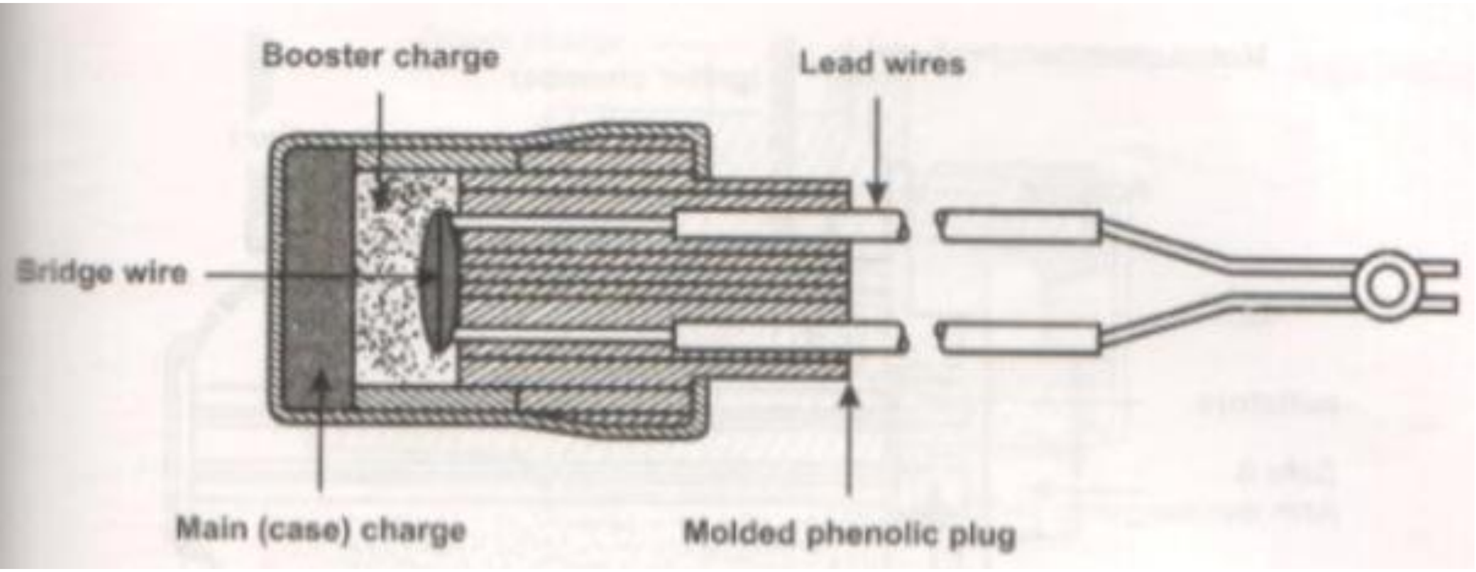
Phase I, *Ignition time lag:* the period from the moment the igniter receives a signal until the first bit of grain surface burns.

Phase II, *Flame-spreading interval:* the time from first ignition of the grain surface until the complete grain burning area has been ignited.

Phase III, *Chamber-filling interval:* the time for completing the chamber filling process and for reaching equilibrium chamber pressure and flow.

Satisfactory attainment of equilibrium chamber pressure with full gas flow is dependent on :
(1) characteristics of the igniter and the gas temperature, composition and flow issuing from the igniter,
(2) motor propellant composition and grain surface ignitability,
(3) heat transfer characteristics by radiation and convection between the igniter gas and grain surface,
(4) grain flame spreading rate,
(5) the dynamics of filling the motor free volume with hot gas

Igniters



Squib type pyrotechnic igniter:

Bridge wire of Nichrome is heated with electric current (0.5-2 A)

Primer material will explode (Mercuric Fulminate or Lead Azide in 50 mg – 1 g) < 5 ms

Energy is transferred to booster charge and main charge through transfer charge

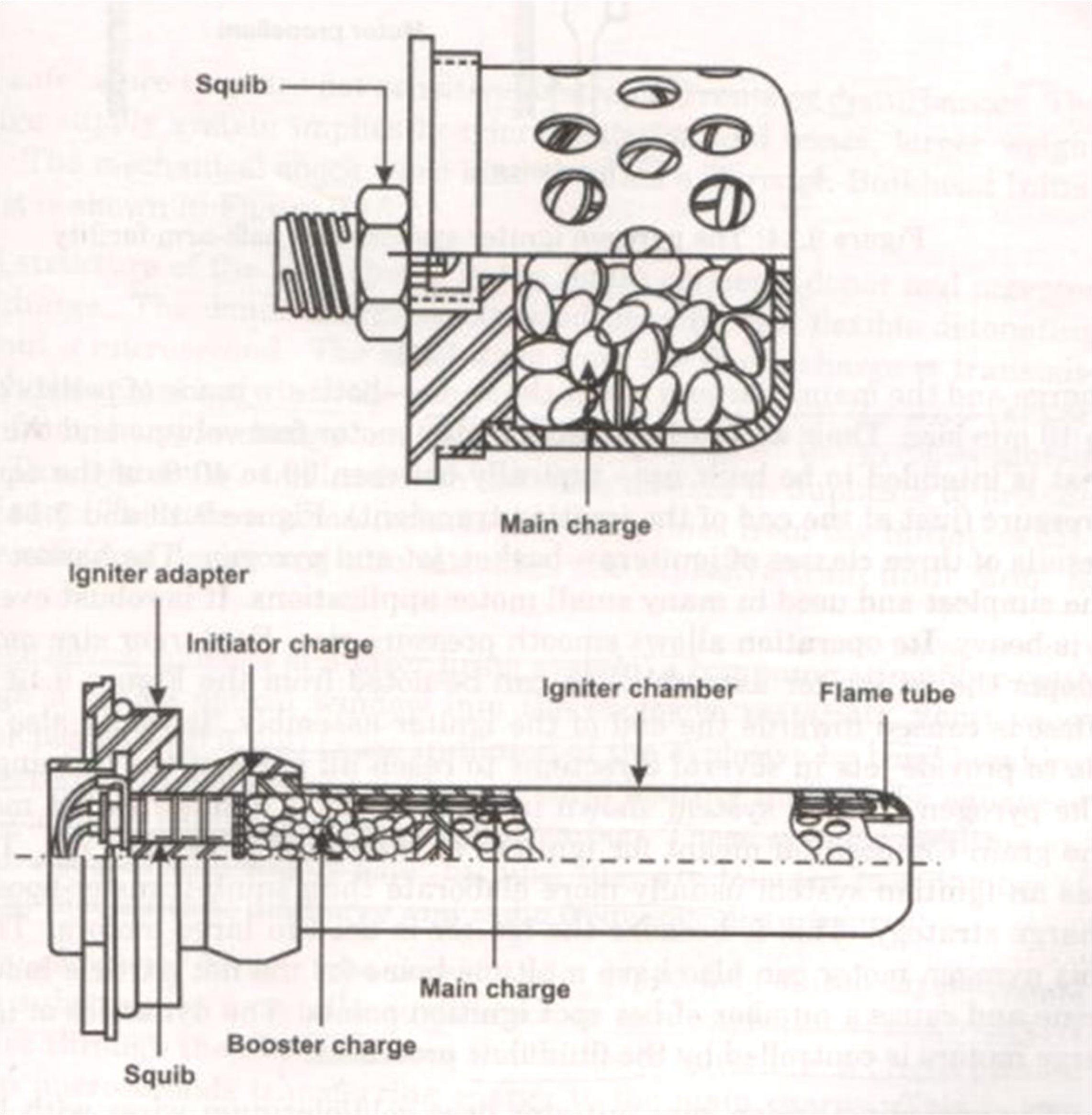
Booster and main charge – pellets of 5-10 mm size

Ignition composition:

Conventional material – Black powder (potassium nitrate 75%, charcoal 15%, Sulphur 10%), density 900-1100 kg/m^3, grain size 1-3 mm

Recent times: Binder 5-10% + metal fuel(Al, Bo, Mg) 20-40% + oxidizer(AP, KN, KP) 50-60% (fine powder) + Burn rate accelerator (1-2%)

For reliable performance – burning rate should be 15-30 mm/s



Basket and Jet type igniters

Basket: Simple, robust, small rocket motors and smooth pressure rise

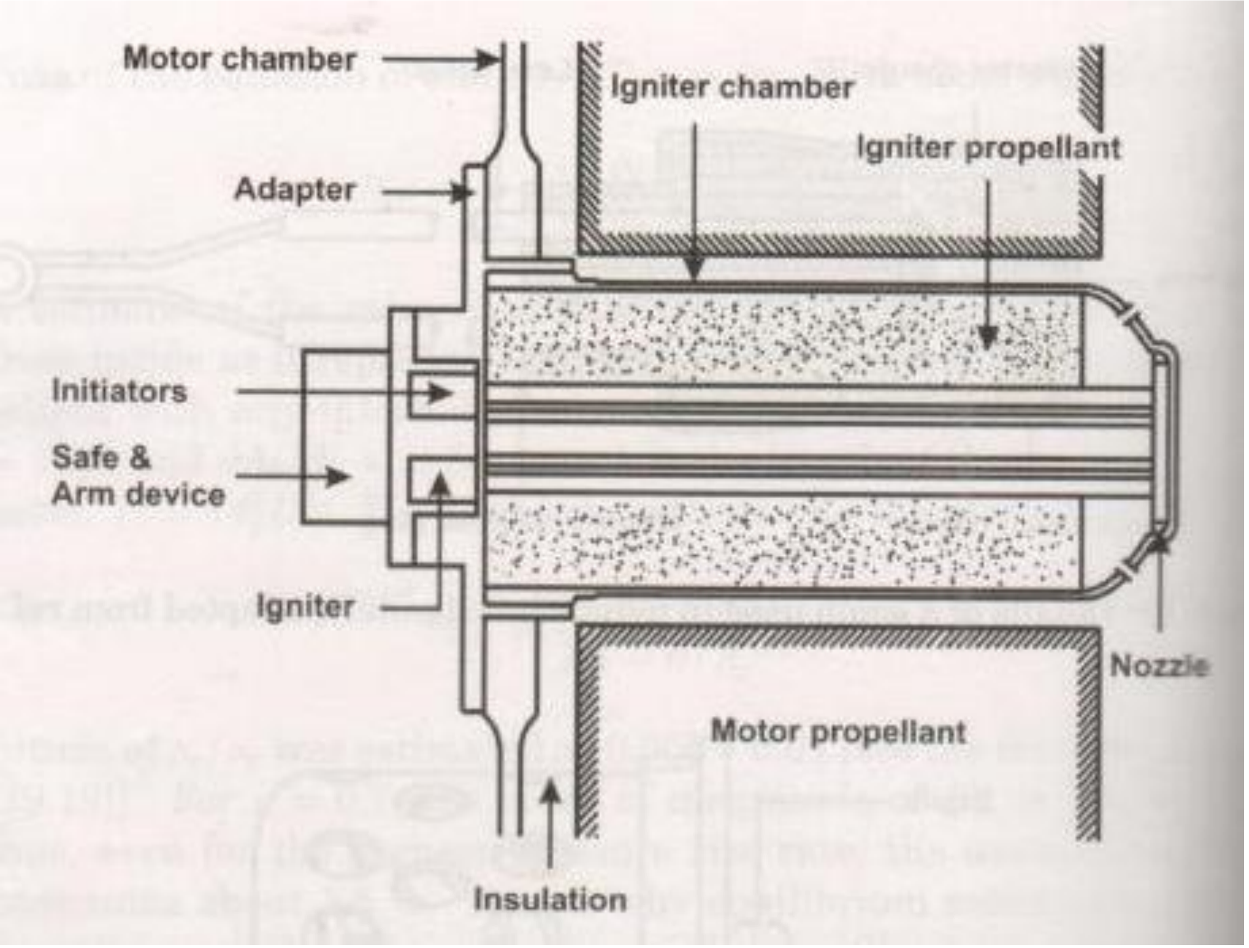
Jet type igniter:

Used for larger motors

A jet effect through the flame tube is obtained

Hot gases and solid particles are forced like jet on the propellant grain

Possible to direct the hot gas through multiple holes



Pyrogen Igniter:

A small rocket motor itself and used in large rocket motors

It has its own smaller ignition system to initiate the igniter propellant

The hot gas and particles are accelerated through single/multiple nozzles in the main combustor to generate a number of hot spots

Dynamics of ignition controlled by fluid flow processes

EXTINCTION OR THRUST TERMINATION

Sometimes it is necessary to stop or extinguish the burning of a solid motor before all the propellant has been consumed:

1. When a flight vehicle has reached the desired flight velocity (for a ballistic missile to attain a predetermined velocity or for a satellite to achieve an accurate orbit), or a precise total impulse cutoff is needed.

2. As a safety measure, when it appears that a flight test vehicle will unexpectedly fly out of the safe boundaries of a flight test range facility.

3. To avoid collisions of stages during a stage separation maneuver (requiring a thrust reversal) for multistage flight vehicles.

4. During research and development testing, when one wants to examine a partially burned motor.

EXTINCTION OR THRUST TERMINATION

$$(P_1)_{eq} = \left[K \cdot a \cdot (\rho_p - \rho_1) \cdot c^*\right]^{1/1-n}$$

Here K = Ab/At

Strategy: To increase throat area (At) suddenly

Throat is burst open by using an explosive cord around the throat area
Typical time scale ~ 0.6 – 1 millisecond

Sudden drop in pressure → increase in the flame thickness → reduction in temperature gradient → reduction in heat transfer, burn rate and gas production rate

If time taken for the pressure to drop to half its value is 3 - 4 ms, the propellant will not re-ignite. Here onwards the pressure falls exponentially
Ideal value for pressure to avoid re-ignition < 0.2 – 0.3 atm.