

CHEMICAL ROCKETS:

Chemical rockets are essentially energy-limited devices. Chemical rockets are distinguished from other kinds of rockets in that all of the energy required to accelerate the propellant comes from the propellant itself, and specifically from combustion of a fuel-oxidizer combination. Heat energy developed during combustion is used to propel the rockets. In chemical rocket propulsion, the chemical energy contained is converted into thermal energy by way of combustion in the combustion chamber. In the solid propellant rocket motor the solid propellant burns produces heat. In the liquid propellant rocket motor liquid propellants combined and produces heat, so the thermal energy is released. During the release of thermal energy, the working fluid also released, namely the propellant gases also released. Now the thermal energy that means high temperature gases produced by the propellant burning is expanded through the nozzle (i.e. thermal energy is converted into kinetic energy). The energy from a high-pressure combustion reaction of a propellant chemical, usually a fuel and an oxidizing chemical, permits the heating of reaction product to very high temperature (2500 to 4100°C). These gases subsequently are expanding in a nozzle and accelerated to high velocity (1800 to 4300 m/sec or 5900 to 14100 ft/sec).

Classification:

Chemical rockets are classified in two types

1. Solid propellant rocket motor
2. Liquid propellant rocket engine
3. Hybrid Rocket

SOLID PROPELLANT ROCKET MOTORS:

Rocket engines in which Solid fuels and oxidizers are used are known as Solid propellant rocket motors. Solid fuel (Plastic, or resin material) and oxidizer (per chlorates, nitrates) are mixed in a single propellant and is packed inside the shell.

In a solid propellant rocket motor the propellant is stored directly in the combustion chamber. The block of solid propellant is known as 'grain'. This is the name used for solid propellant. There are no moving parts, such as pumps, valves or other controls, and therefore little servicing is required and they are easy to use. The main components of this type of rocket motor are propellant, thrust chamber and igniter.

In this type of rocket, a solid 'grain' of propellant is cast into the combustion chamber and no feed system is necessary. The grain is the solid body of the hardened propellant and typically accounts for 82 to 94% of the total motor mass. To initiate combustion there is an igniter. The igniter (usually pyrotechnic, mixture triggered by an electrical signal) provides the energy to start the combustion. The grain starts to burn on its exposed inner surfaces.

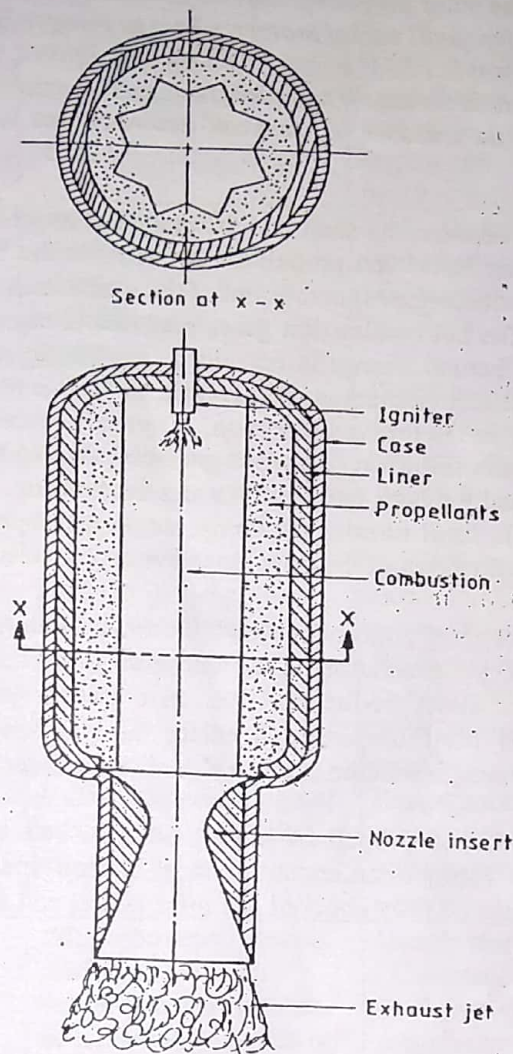


Fig. 13.2. A solid propellant rocket

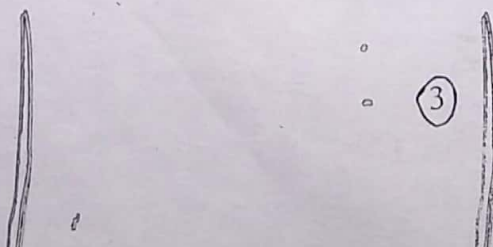
The basic layout of solid propellant rocket motor is shown in fig. The inner surfaces of the case (really a pressure vessel), which are exposed directly to hot gas, have a thermal protection or insulation layer to keep the case from becoming too hot. The case is either made of metal (such as steel, aluminum or titanium) or a composite fiber-reinforced plastic material. The propellant is housed in the combustion chamber. To initiate combustion there is an igniter. Igniter can be two different types. One is *pyrotechnic igniter* and other is *pyrogen igniter*. *Pyrogen can be imagine as other small rocket inside a rocket*. It is something similar to the rocket, that is initiated and that produces hot combustion gases, which impinge on the propellant surface (grain surface) to initiate combustion. The other igniter, which is *pyrotechnic igniter*, just a packet of some powders on ignition just it like a , "Puff" it comes and produces hot combustion

gases, which impinge on this solid propellant surface to initiate combustion. Generally *pyrotechnic igniter is used for small rocket motors, where as pyrogen igniter is used for large rocket motor. For example PSLV booster as a pyrogen igniter*, it is a rocket in a rocket, that igniter itself a small rocket. When the igniter ignites, combustion starts from the center of the combustion chamber to its outer periphery due to the star shaped combustion chamber.

A *liner* is provided between the shell and the propellant to protect the shell from high temperature developing inside the propellant layers. After the fuel is completely burned, the combustion products (gases) comes out of the nozzle with very high velocity of 1500 to 2400 m/sec. The hot combustion gases produced is expanding through the nozzle, which means the thermal energy is converted into kinetic energy, so the exit velocity is very high, so the exit momentum rate is high, so there is production of thrust. Hence it propels the rocker in the forward direction. The nozzle accelerates the hot gas; it is made of high temperature materials (usually a graphite and/or an ablative material to absorb the heat) to withstand the high temperatures and the erosion. The majority of all solid rockets have a simple fixed nozzle, but some nozzles have provision to rotate it slightly so as to control the direction of the thrust to allow vehicle steering.

The area of the propellant grain over which the combustion takes determines the magnitude of the exhaust-gas-generation. The thickness of the grain determines the burning time or duration of thrust production. An active cooling system is not required since the propellant grain itself frequently insulates the structural case through the combustion process. However, insulation is often placed on the inner surface of the case.

If comparison to Liquid propellant rocket, Solid rockets is usually relatively simple, are easy to apply. (They often constitute most of the vehicle structures require little servicing; they can not be fully checked out prior to use; and thrust cannot usually be randomly varied in flight)



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MAJOR APPLICATION CATEGORIES FOR SOLID ROCKET MOTORS:

S.NO	CATEGORY	APPLICATION	TYPICAL CHARACTERISTICS
1.	Large booster and second stage motors	Space launch vehicles; lower stages of long-range ballistic missiles	Large diameter (above 45 in); L/D of case = 2 to 7; burn time $t = 60$ to 120 sec; low altitude operations with low nozzle area ratios (6 to 16)
2.	High- altitude motors	Upper stages of multistage ballistic missiles, space launch vehicles; space maneuvers	High - Performance propellant; large nozzle area ratio (20 to 200); L/D of case = 1 to 2; burn time $t = 40$ to 120 sec
3.	Tactical missiles	1. High acceleration: short-range bombardment, antitank missile 2. Modest acceleration: air- to-surface, surface-to-air, short- range guided surface-to-surface and air-to-air missiles	Tube launched/D = 4 to 13; very short burn time (0.25 to 1 sec), small diameter (.75 to 18 in), some are spin stabilized Small diameter (5 to 18 in); L/D of case = 5 to 10; usually has fins and/or wings; thrust is high at launch and then is reduced (boost-sustain); usually high acceleration; often low- smoke or smokeless propellant
4.	Ballistic missile defense	Defense against long- and medium-range ballistic missile	Booster rocket and a small upper maneuverable stage with multiple attitude control nozzles and one or more side divert nozzles
5.	Gas generator	Pilot emergency escape; push missiles from submarine launch tubes or land mobile canisters; actuators and valves; short term power supply; jet engine starter; rocket turbine driver starter; automotive air bags	Usually low gas temperature (< 1300 °C); many different configurations, designs, and propellants; purpose is to create high-pressure, energetic gas rather than thrust

CLASSIFICATION OF SOLID ROCKET MOTORS:

S.NO	BASIS OF CLASSIFICATION	EXAMPLES OF CLASSIFICATION
1.	Application	Refer above table
2.	Diameter/Length	0.05 – 6.6 m or 0.2 – 260 in; 0.025 to 45 m or 1 to 1800 in
3.	Propellant	<p>Composite: Heterogeneous (physical) mixture of powdered metal (fuel), crystalline oxidizer and polymer binder</p> <p>Double-base: Homogeneous mixture (colloidal) of two explosives (usually nitroglycerin in nitrocellulose)</p> <p>Composite-modified double-base: Combines composite and double-base ingredients</p> <p>Gas generator and others</p>
4.	Case design	<p>Steel monolithic: One-piece steel case</p> <p>Fiber monolithic: Filament wound (high-strength fibers) with a plastic matrix</p> <p>Segmented: Case (usually steel) and grain are in segments which are transported separately and fastened together at launch site</p>
5.	Grain Configuration	<p>Cylindrical: Cylindrically shaped, usually hollow</p> <p>End-burning: Solid cylinder propellant grain</p> <p>Other configurations: refer notes</p>
6.	Grain installation	<p>Case-bonded: Adhesion exists between grain and case or between grain and insulation and case; propellant is usually cast into the case</p> <p>Cartridge-loaded: Grain is formed separately from the motor case and then assembled into case</p>
7.	Explosive hazard	<p>Class 1.3: Catastrophic failure shows evidence of burning and explosion, not detonation</p> <p>Class 1.1: Catastrophic failure shows evidence of detonation</p>
8.	Thrust action	<p>Neutral grain: Thrust remains essentially constant during the burn period</p> <p>Progressive grain: Thrust increases with time</p> <p>Regressive grain: Thrust decreases with time</p> <p>Pulse rocket: Two or more independent thrust pulses or burning periods</p> <p>Step-thrust rocket: Usually, two distinct levels of thrust</p>
9.	Toxicity	Toxic and nontoxic exhaust gases

Advantages:

1. Solid propellant rockets are *simple in design* and construction, therefore a large number of small size rockets for military use can be mass produced in short notice.
2. They *do not require feed system*; therefore they are free from the problems of moving parts such as pumps, turbines, valves, etc.
3. They are comparatively lighter for short range and small size.
4. On account of high density much larger quantity of propellants can be packed into a small space. The specific gravity of solid propellant grains ranges from approximately 1.5 to 2.
5. Solid propellant rockets have much fewer and less frequent servicing problems.
6. Problems arising from sudden emptying of propellant tanks are absent.
7. Vibration problems originating from turbo pump and liquid flow system.

Disadvantages:

1. Incase of emergency it is *difficult or almost impossible to turn off the operation midway*.
2. Minor malfunctioning or accident generally leads to wreckage or abonding the mission.
3. It is comparatively more difficult to control combustion and regulate thrust.
4. Solid propellant rockets have comparatively *lower values of the specific impulse*.
5. At the end of an operation the burnt up debries cannot be reused; this renders large operations uneconomical.

6. Nozzle cooling is not possible.
7. Long range large size solid propellant rockets are comparatively heavier.
8. Transportation and handling of these rockets before firing require greater care because of the presence of propellants throughout.
9. Refueling in long duration mission is not possible.
10. On account of the presence of solid particles in the high temperature and high speed gases exhaust nozzle suffers corrosion.

Propellant:

Propellant is the chemical mixture burned to produce thrust in rockets and consists of a fuel and an oxidizer. The propellant, which are the working substance of rocket engine. A fuel is a substance, which burns when combines with oxygen producing gas for propulsion. An oxidizer is an agent that releases oxygen for combustion of a fuel. Propellants are classified according to their state as liquid, solid or hybrid.

SOLID PROPELLANTS:

The term solid propellant has several annotations, including

1. The rubbery or plastic-like mixture of oxidizer, fuel, and other ingredients that have been processed and constitute the finished grain
2. The processed but uncured product
3. A single ingredient, such as the fuel or the oxidizer

Classification of Propellants

1. Propellants are classified by *specific applications*, such as space launch booster propellants or tactical missile propellants; each has somewhat specific chemical ingredients, different burning rates, different physical properties, and different performance. Historically, the early rocket motor propellants used to be grouped into two classes; Double-based (DB) propellants were used as the first production propellants; and then the development of polymers as binders made the composite propellants.
2. *Double-Base (DB)* propellants from a *homogeneous* propellant grain usually a nitrocellulose (NC), a solid ingredient which absorbs liquid nitroglycerine (NG) plus minor percentage of additives. Both the major ingredients are explosives and function as a combined fuel and oxidizer. Both *extruded double base (EDB)* and *cast double-base (CDB)* propellant have found

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applications in small tactical missiles of older design. By adding crystalline nitramines (HMX or RDX) the performance and density can be improved. This is called *cast-modified double-base propellant*. A further improvement is to add an electrometric binder (rubberlike such as cross linked polybutadiene), which improves the physical properties and allows more nitromethane and thus improves the performance slightly. The resulting propellant is called *elastomeric-modified cast double-base*

These four classes of double base have nearly smokeless exhausts. Adding some solid ammonium perchlorate (AP) and aluminum (Al) increases the density and specific impulse slightly, but the exhaust gas is smoky. The propellant is called *Composite-modified double-base propellant* or *CMDB*.

3. *Composite propellants* form a *heterogeneous propellant* grain with the oxidizer crystals and a powdered fuel (Usually aluminium) held together in a matrix of synthetic rubber (or plastic) binder, such as polybutadiene. Composite propellants are cast from a mix of solid (Ammonium perchlorate (AP), Aluminium powder) and liquid (Hydroxyl terminated polybutadiene (HTPB, Polypropylene glycol (PPG)) ingredients. They can be further subdivided

- (a) Conventional *Composite propellants* usually contain between 60 and 72% ammonium perchlorate (AP) as crystalline oxidizer up to 22% aluminium powder (Al) as a metal fuel, and 8 to 16% of elastomeric binder (organic Polymer) including its plasticizer.
- (b) Modified composite propellant where an *energetic nitramine* (HMX or RDX) is added for obtaining a little more performance and higher density.
- (c) Modified composite propellant where an *energetic plasticizer* such as nitroglycerine (used in double base propellant) is added to give little more performance. Some times HMX (which is solid explosive filler, its chemical name is cyclotetramethylene tetranitramine)
- (d) A *high-energy composite solid propellant* (with some Aluminium) where the organic elastomeric binder and plasticizer are largely replaced by energetic materials (such as certain explosives, some of these are called elastomer-modified cast double-base propellants (EMCDB)
- (e) A *lower-energy composite propellant*, where ammonium nitrate (AN) is the crystalline oxidizer (no AP). It is used for gas generator propellant

4. Propellants can be classified by the density of the smoke in the exhaust plume as smoky, reduced smoke, or minimum smoke (essentially smokeless). Aluminium powder, a desirable fuel ingredient is oxidized to aluminium oxide, which forms visible small solid smoke particles in the exhaust gas. Most composite propellants are smoky. By

reducing the aluminium content in composite propellant, the amount of smoke is also reduced.

4. The *safety rating* for detonation can distinguish propellants as a potentially *detonable material* or as a *nondetonable material*
5. Propellants can be classified by some of the principal manufacturing process that are used. Cast propellant is made by mechanical mixing of solid and liquid ingredients followed by casting and curing, makes cast propellant. It is the most common process for composite propellants. Curing of many cast propellants is by chemical reaction between binder and curing agent at elevated temperature (45 to 150°C), however there are some that can be cured at ambient temperatures (20 to 25°C) or hardened by a non-mechanical process such as crystallization. A solvation process (dissolving a plasticizer in a solid pelletized matrix whose volume is expanded) can also make propellant. Extruded propellant is made by mechanical mixing (rolling into sheets) followed by extrusion (pushing through a die at high pressure). Solvation and extrusion process apply primarily to double-base propellants.
6. Propellants have also been classified by their principal ingredient, such as the principal oxidizer (ammonium perchlorate propellants) or their principal binder or fuel ingredient, such as polybutadiene propellants or aluminized propellants.

Propellant ingredients:

- Inorganic oxidizer
- Fuel
- Binders
- Burning rate modifiers
- Plasticizers
- Curing agents or cross linkages
- Energetic binders and plasticizer
- Explosives
- Additives

Other propellant categories:

Gas generator propellant, Smokeless or low smoke propellant, igniter propellants



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Selection criteria of Solid propellants :(or) Propellant Characteristics:

Properties:

1. A high release of chemical energy promotes a high performance and therefore a high value of combustion temperature and specific impulse.
2. A low molecular weight of the combustion products is desirable to increase the value of the specific impulse
3. High density of the solid propellant permits the use of a small chamber volume and therefore a small chamber weight.
4. It should be possible to produce from abundantly available raw materials, which are cheap and safe to handle
5. The propellant grain must have high mechanical strength
6. The exhaust should be non-luminous (to avoid detection of direction in military applications) and non-toxic
7. The exhaust gas should be smokeless to avoid deposition of smoke particles at operational locations and to avoid direction in military a/c.
8. For minimum variation in thrust or chamber pressure, the pressure or burning rate exponent and the temperature coefficient should be small.
9. The propellant should resist erosion
10. The solid propellants conductivity and specific heat should be such as to control heat transfer to the grain
11. Physical and chemical properties should not change considerable during processing
12. Should be low technical risk, such as favorable history of prior applications.

COMBUSTION

The hardware and methods employed for the combustion of solid propellants in the thrust chamber of a rocket are quite different from those of the liquid propellants. Well-mixed fuel and oxidizer (known as propellant grain) are already present in the thrust chamber; they don't need injection and mixing during the combustion. Regenerative heating of the propellant and cooling of the thrust chamber and the nozzle walls are not practicable.

The burning rate of the propellant grain depends on the initial temperature of the grain before combustion, equilibrium combustion pressure, and the ratio of the grain surface area and the exhaust nozzle throat area. The cross sectional areas in rocket thrust chambers are generally large. Therefore, the flow of combustion gases upstream of the exhaust nozzle is at low Mach number and the equilibrium combustion pressure can be assumed to be identical with the stagnation pressure.

IMPORTANT HARDWARE COMPONENTS OF SOLID ROCKETS:

② The solid propellant is confined in a combustion chamber and the reaction gases are exhausted through an exhaust nozzle. Combustion chambers are usually cylindrical in shape with elliptical and spherical ends. (In addition the hardware portion of the solid propellant rocket often includes some or all the following provisions for assembly or disassembly of the unit, mounting gas burst diaphragms or other safety provisions to prevent over pressurization of the chamber, and means for holding the propellant grain in place. These hardware components usually uncooled and have to withstand reverse heating.

1. SOLID PROPELLANT ROCKET MOTORS IGNITERS

Igniter hardware:

The inhibition of the combustion of the propellant grain is accomplished by means of a igniter, which is usually started by means of electrical current. The igniter propellant mass is small (often less than 1% of the motor propellant) and burns mostly at low chamber pressure.

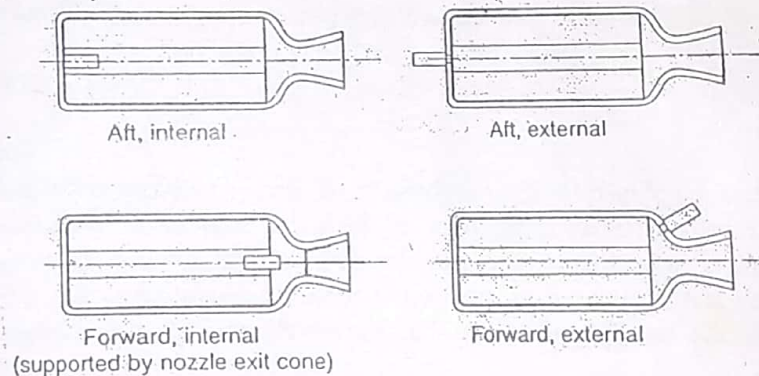


FIGURE 14-13. Simple diagrams of mounting options for igniters. Grain configurations are not shown.

Figure shows several alternate locations for igniter installations. (When mounted on the forward end, the gas flow over the propellant surface helps to achieve ignition. With aft mounting there is little gas motion, particularly near the forward end; here ignition must rely on the temperature, pressure, and heat transfer from the igniter gas. If mounted on the nozzle, the igniter hardware and its support is discarded shortly after the igniter has used all its propellants and there is no inert mass penalty for the igniter case.



Functions of the igniter:

1. Should have a very small ignition delay
2. Should raise the temperature of the grain above its ignition temperature by releasing sufficient energy
3. Should generate enough volume of gas to build up sufficient pressure for smooth burning of the grain
4. Should be stable over long periods
5. Should produce minimum combustion debris.

There are two basic types

1. Pyrotechnic type igniter
2. Pyrogen type igniter

1. Pyrotechnic type igniter:

In industrial practice pyrotechnic igniters are defined as igniters using solid explosives or energetic propellant like chemical formulations (usually small pellets of propellant that give a large burning surface and a short burning time) as the heat producing material.

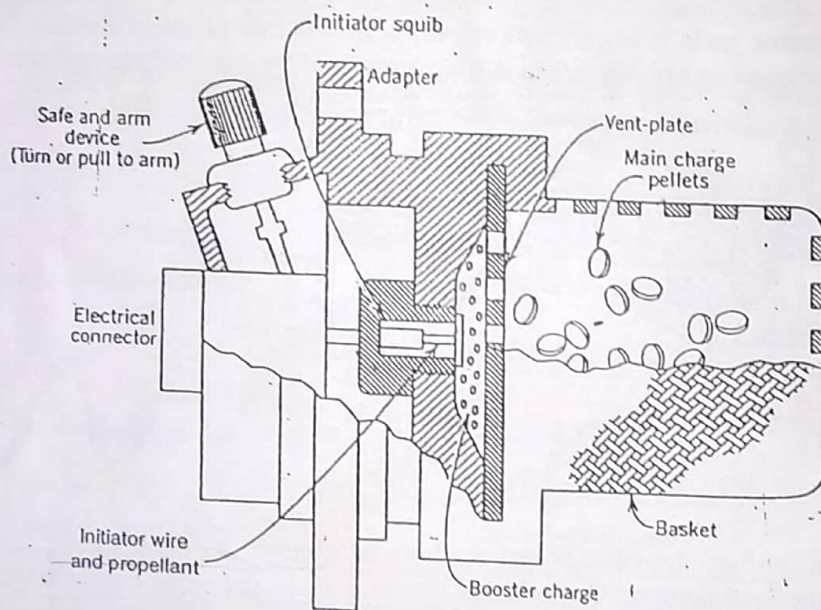


FIGURE 14-14. Typical pyrotechnic igniter with three different propellant charges that ignite in sequence.

The fig shows typical pyrotechnic igniter (pellet-basket design). The ignition is accomplished by the following stages

Stage 1:

On receipt of an electric signal the initiator releases the energy of a small amount of sensitive powered pyrotechnic housed within the initiator. This is commonly called the Squib. It generally contains 74% KN_3 , 15.6% Charcoal and 10.4% sulphur. (Gunpowder)

Stage 2:

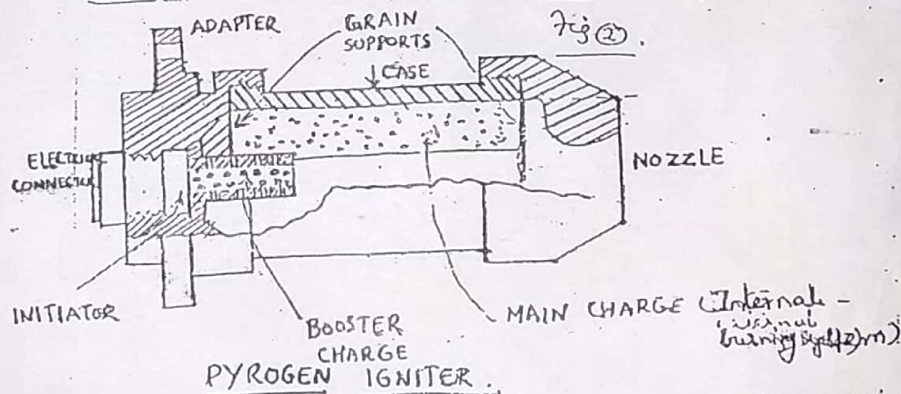
The heat released from the squib ignites the booster charge.

Stage 3:

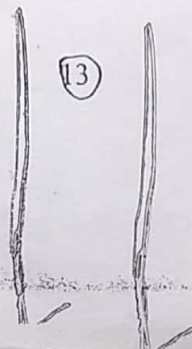
Finally the main charge is ignited. The main charge consists of pellets containing 5% binder, 24% Boron, 71% potassium. Typical binders are epoxy resins, graphite, vegetable oils, nitrocellulose and poly isobutadene. The initiators and the booster charges are such as they are easy to ignite and are self-sustaining at low pressure. In pyrotechnic igniters the heat transfer to the grain is by radiation.

2. Pyrogen type igniter:

A Pyrogen igniter is basically a small rocket motor, which is used to ignite a larger rocket motor. The Pyrogen is not designed to produce thrust. Heat transfer from the Pyrogen to the motor grain is largely convective, with the hot gases contacting the grain surface as constrained to a highly radiative energy emitted by pyrotechnic igniters.



For Pyrogen igniters the initiator and the booster charge are very similar to the design used in pyrotechnic igniters. The reaction products from the main charge impinge of the surface of the rocket motor grain, producing motor ignition. Common practice on the very large motors is to mount externally; with the Pyrogen igniter becomes a piece of ground-support equipment. J ①



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PROPELLANT GRAIN DESIGN CONSIDERATIONS:

(The grain is shaped mass of processed solid propellant inside the rocket motor. The propellant material and geometrical configuration of the grain determine the motor performance characteristics.)

The propellant grain is a cast, molded or extruded body and its appearance and feel is similar to that of hard rubber or plastic. Once ignited, it will burn on all its exposed surfaces to form hot gases are then exhausted through a nozzle. A few rocket motors have more than one grain inside a single case of chamber and very few grains have segments made of different propellant composition (eg to allow different burning rates). However, most rockets have a single grain.

There are two methods of holding the grain in the case. ^{start} Cartridge loaded or freestanding grains are manufactured separately from the case (by extrusion or by casting into a cylindrical mold or cartridge) and then loaded into or assembled into the case.

In case-bonded grains the case is used as a mold and the propellant is cast directly into the case and is bonded to the case or case insulation. Free standing grains can more easily be replaced if the propellant grain has aged excessively. In the case bonded grain, the propellant grain and casing act as a composite cylinder. Major portion of the time the propellant not only releases the energy but also act as protector for this casing.

Cartridge loaded grains are used in some small tactical missiles and a few medium sized motors. They often have a lower cost and are easier to inspect.

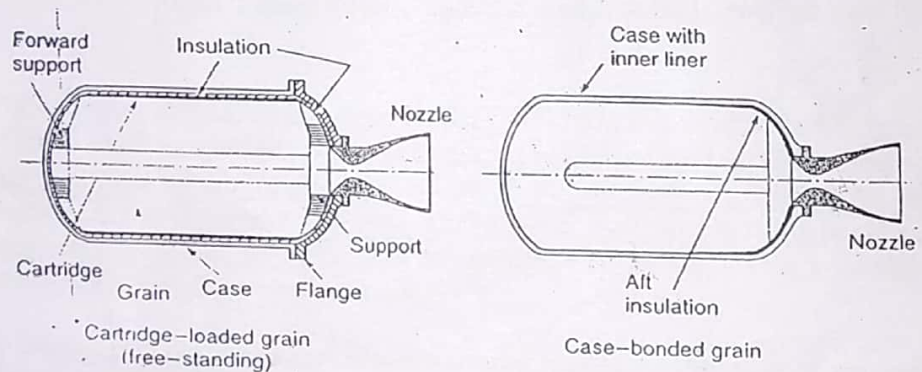
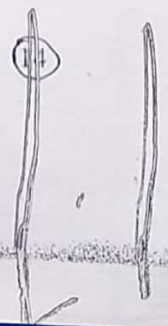


FIGURE 11-14. Simplified schematic diagrams of a free-standing (or cartridge-loaded) and a case-bonded grain.

The case-bonded grains give a somewhat better performance, a little less inert mass (no holding device, support pads, and less insulation), a better volumetric loading fraction, are more highly stressed and somewhat difficult to manufacture. Today almost all layer motors and many tactical missile motors use case bonding.



Definitions and terminology important to grain include:

Configuration:

The shape or geometry of the initial burning surfaces of a grain as it is intended to operate in a motor.

Cylindrical grain:

A grain in which the internal cross section is constant along the axis regardless of perforation shape.

Neutral burning:

Motor burn time during which thrust, pressure and burning surface area remain approximately constant, typically within about $\pm 15\%$ (i.e.) when burning takes place over a constant area of charge, the configuration of the charge is said to be neutral. Many grains are neutral burning.

Progressive Burning:

Burn time during which thrust, pressure and burning surface area increases.
(i.e. Thrust increasing with time)

Regressive Burning:

Burn time during which thrust, pressure and burning surface area decreases.
(i.e. Thrust decreasing with time)

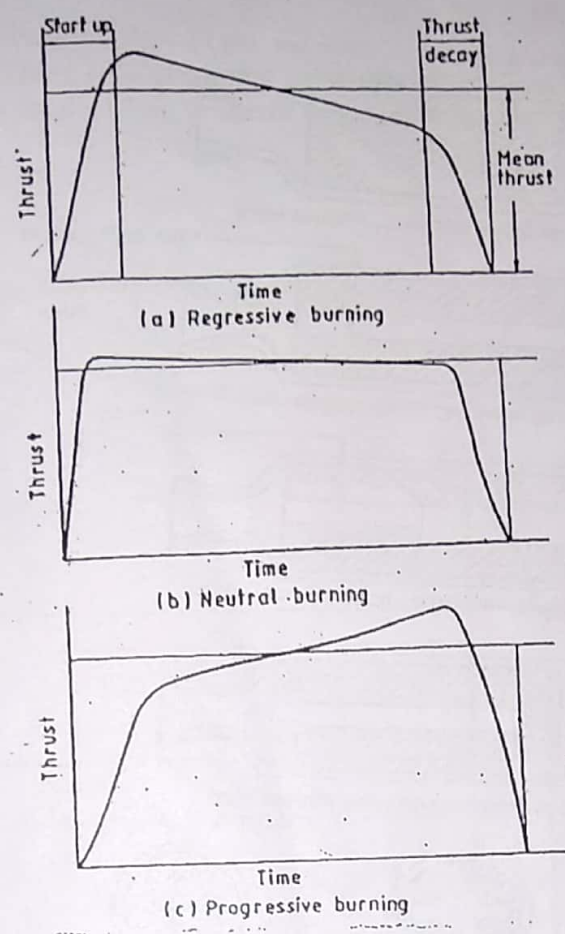


Fig A Typical thrust – time curves for solid propellant rockets

Fig A depicts typical thrust – time profiles for regressive, neutral and progressive burning of the solid propellant grain. For given values of the grain temperature and the combustion pressure burning rate and the propellant flow rate through the exhaust nozzle depend on the propellant area ratio. Therefore a regressive burning is obtained when the area ratio decreases with time (this can be obtained by employing a suitable geometrical configuration of the propellant grain).

If the burning surface is kept constant during rocket operation an approximately constant thrust profile can obtain through natural burning. If the grain configuration employed is such that its burning surface increases with time a progressive burning profile is obtained

Perforation:

The central cavity port of flow passage of a propellant grain, its cross section may be a cylinder, a star shape, wagon wheel, the slotted radial, etc.



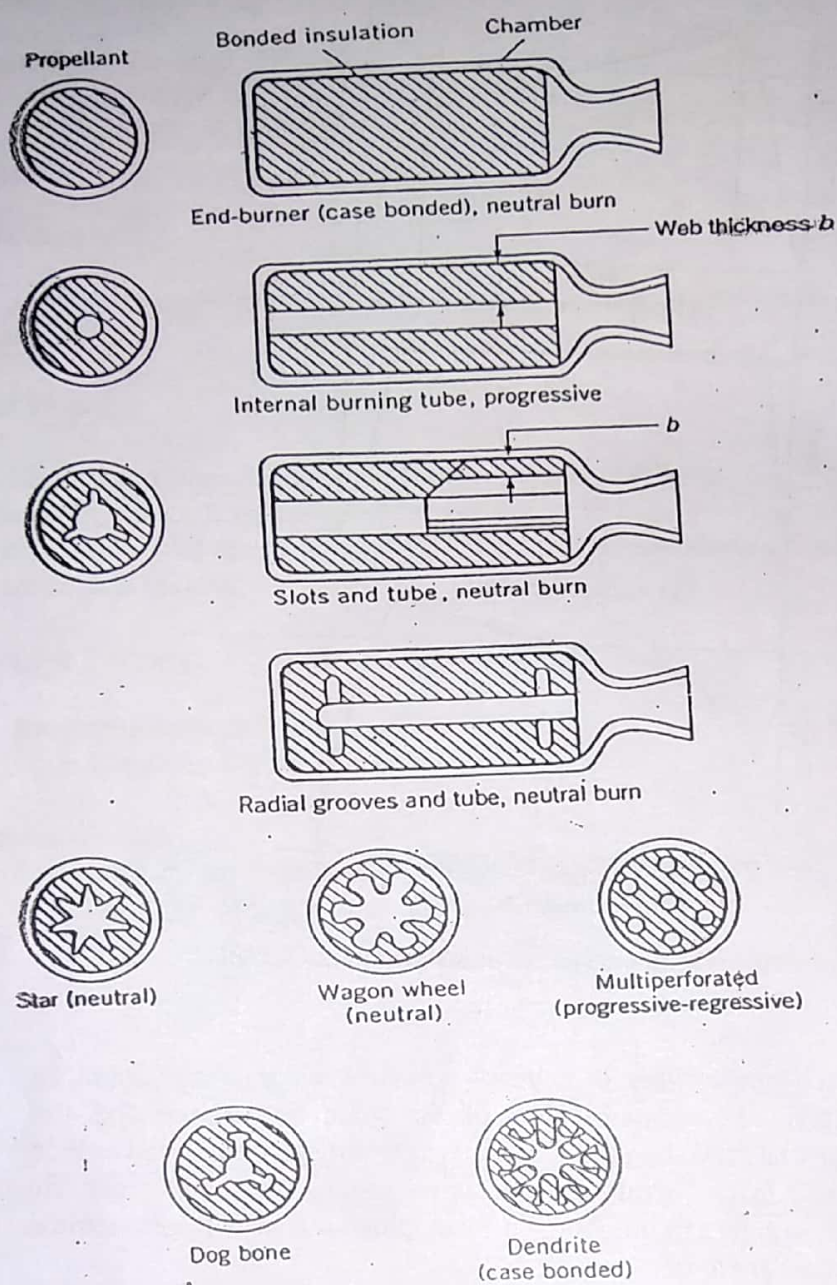


FIGURE 11-16. Simplified diagrams of several grain configurations

(The fig 11.6 shows the effect of propellant burning in surface area for geometric shape such as rods, tubes, wedges and slots)

~~Silver:~~

Any remaining unburnt propellant (or lost-that is expelled through the nozzle) is known as silvers.

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Burning time of effective burning time (T_p):

Usually the interval from 10% maximum initial pressure (or thrust) to web burnout, with web burnout usually taken as the aft tangent-bisector point on the pressure-time trace.

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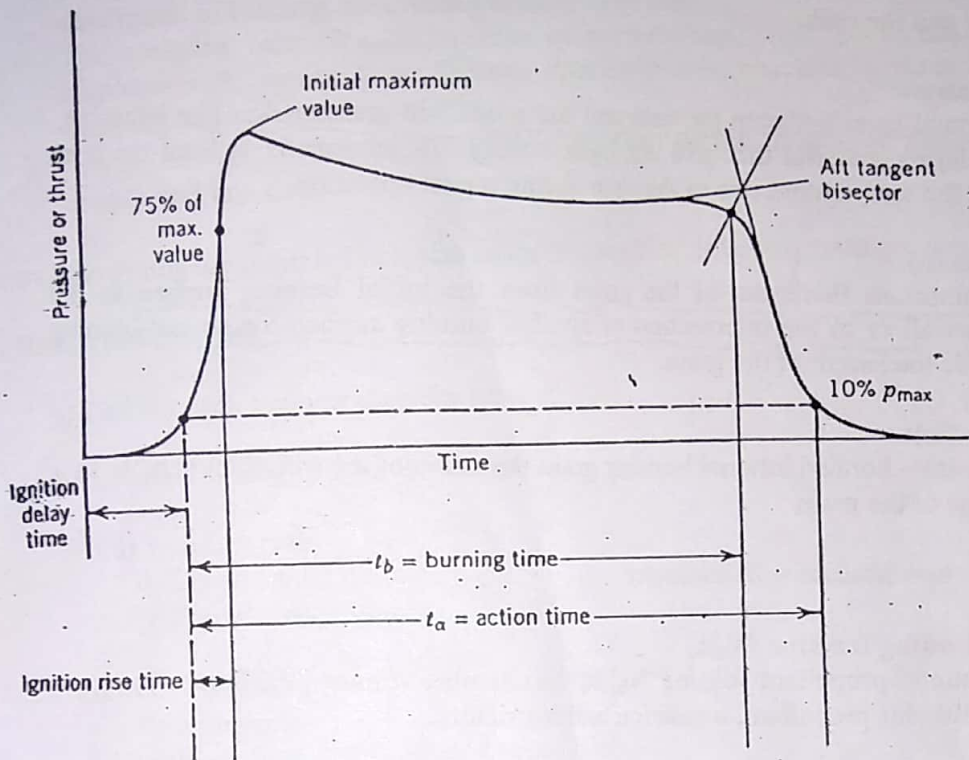


FIGURE 11-13. Definitions of burning time and action time.

Action time (T_a):

The burning time plus most of the time to burn silvers; typically, the interval between the initial and final 10% pressure (or thrust) points on the pressure time trace.

Deflagration limit:

The minimum pressure at which combustion can still be barely self-sustained and maintained without adding energy. Below this pressure the combustion ceases together or may be erratic and unsteady with the plume appearing and disappearing periodically.

Inhibitor:

A layer or coating of slow or nonburning material (usually a polymeric rubber with filler materials) applied (glued, painted, dipped or sprayed) to a part of the grains propellant surface to prevent burning on that surface. By preventing burning on inhibited surfaces the initial burning area can be controlled and reduced. It is also called restrictor.

Liner:

A sticky non-self burning thin layer of polymer type material that is applied to the cases prior to casting the propellant in order to promote good bonding between the propellant and the case or the insulator. It also allows some axial motion between the grain periphery and the case.

Internal insulation:

An internal layer between the case and the propellant grain made of an adhesive, thermally insulating material that will not burn readily. Its purpose is to limit the heat transfer to and the temperature rise of the case during rocket operation.

Web thickness (b):

The minimum thickness of the grain from the initial burning surface to the insulated case wall or to the intersection of another burning surface for an end-burning grain, 'b' equals the length of the grain.

Web fraction (b_r):

For a case - bonded internal burning grain the ratio of the web thickness 'b' to the outer radius of the grain

$$b_r = b/\text{radius} = 2b/\text{diameter}$$

Volumetric loading fraction (V_f):

The ratio of propellant volume ' V_b ' to the chamber volume ' V_c ' (excluding nozzle) available for propellant, insulation and restrictors.

$$V_f = (V_b / V_c) = I_t / (I_s \rho_b g_0 V_c)$$

Where I_t = Total impulse

I_s = Specific impulse

ρ_b = Propellant density

A grain has to satisfy several interrelated requirements,

1. From the flight missions one can determine the rocket motor requirements. This can include total impulse, a desired thrust-time curve and a tolerance thereon, motor mass, ambient temperature limits during storage and operation; available vehicle volume, and vehicle accelerations caused by vehicle forces. (Vibration, bending, aerodynamic loads, etc.)
2. The grain geometry is selected to fit these requirements. It should be compact and use the available volume efficiently have an appropriate burn surface versus time profile to match the desired thrust-time curve. The remaining unburned propellant silvers also the shift of the center of gravity during burning, should be minimized.

3. The propellant is usually selected on the basis of its performance capability (eg characteristic velocity), mechanical properties (eg strength), ballistic properties (eg burning rate), manufacturing characteristics, exhaust plume characteristics and aging property.
4. The structural integrity of the grain, including its liner and/or insulator, must be analyzed to assure that the grain will not fail in stress or strain under all conditions of loading, acceleration or thermal stress.
5. The complex internal cavity volume of perforations, slots, ports and fins increases with burning time. These cavities need to be checked for resonance, damping and combustion stability.
6. The processing of the grain and the fabrication of the propellant should be simple and low cost.

In the way the grains are mounted in rocket motor is classified into two main groups.

1. Restricted Burning

- a) End Burning grain or cigarette burning
- b) Internal burning or Radial burning:
- c) Side burning grain
 - i) Case bonded grain
 - ii) Free standing grain

2. Unrestricted Burning

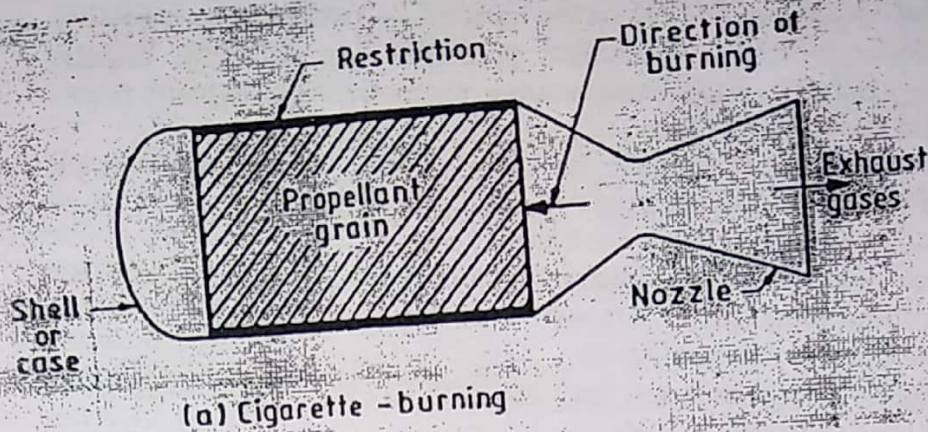
- Tubular grain
- Multiple hole grain
- Rod and Tube type grain

1. Restricted Burning

Several grain configurations are employed to obtain restricted burning of the solid fuel-oxidizer mixture at the desired rate. The inhibiting material or restrictions prevent the propellant grain from burning in all directions. Very often the restrictions assume the form of a liner between the propellant grain and the thrust chamber case or shell. The inhibiting material should not start burning along with the grain of before.

(a) End burning or cigarette burning:

In older practices employs this type of burning. In the end burning or cigarette burning (burning like cigarette) burning is initiated at one end and the surface area of burning remains constant until the propellant is consumed. Thus a "cigarette" configuration is perfectly neutral.

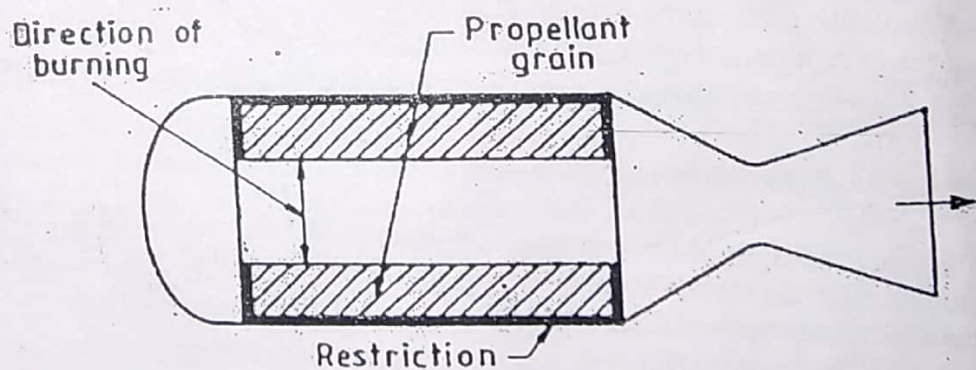


Here the grain is ignited at one end upstream of the nozzle from where the combustion starts and proceeds in the direction shown in the figure. The burning surface progressively recedes leftward. In this pattern of burning the entire thrust chamber is heated to a high temperature throughout the operation. This causes high temperature material and strength problems. Since the burning surface area remains constant a constant thrust profile is obtained.

It burns solely in the axial direction and minimizes the amount of propellant can be replaced in a given cylindrical motor case. In large motors cover 0.6m diameter these end burners shows a progressive thrust curve. Other problems are that the case is not insulated and so overheats rapidly, and the center of gravity of the motor shifts during burning. Because of these problems end-burning grains are rarely used. The fig shows that the burning surface soon forms a conical shape, causing a rise in pressure and thrust.

(b) Internal burning or Radial burning:

An improvement over end burning method is the internal burning pattern. Combustion of the propellant takes place on the surface of the internal passage or perforations provided along the whole length of the propellant grain. Different geometrical shapes of the internal passages offer different surface areas or propellant area ratio (A_e/A^*)



✓

In this configuration, burning is initiated along the whole surface of an internal hollow part. Because the burning area is large, high thrust can be obtained with short burning times. Case over-heating does not occur because the case is insulated by the propellant itself. Furthermore the center of gravity remains static throughout burning. However the simple radial burning grain is strongly progressive (i.e.) burning area and therefore the thrust increase with time.

The internal star:

The burning surface is the internal star configuration remains constant throughout burning, and the mechanical properties of the grain are not imparted.

The Waggon Wheel:

The waggon wheel is another neutral burning configuration whose very large burning surface gives high thrust, making it a suitable shape for use in boosters.

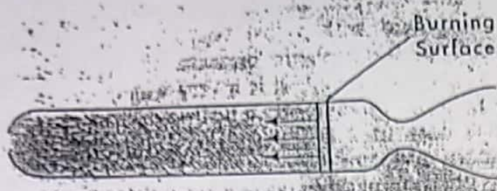


Fig 1 End-Burning Grains

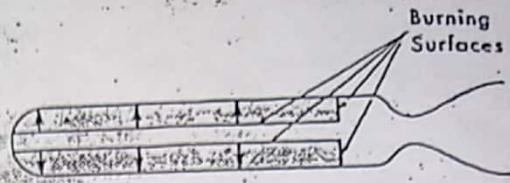


Fig 2 Radial Burning



Fig 3 Internal Star



Fig 4 Wagon Wheel

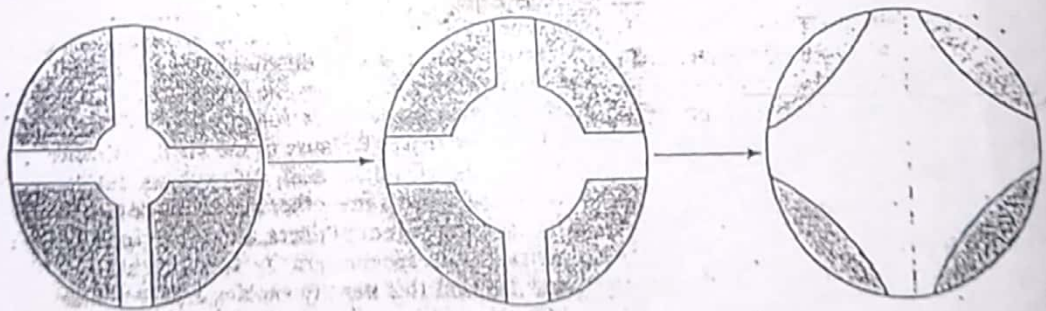


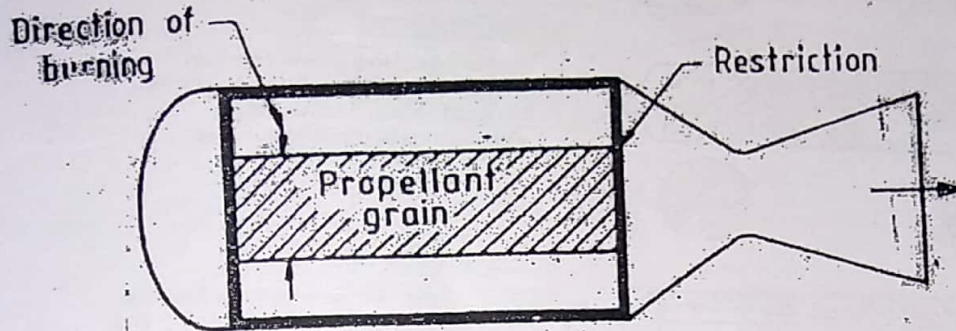
Fig 5 Slotted Radial

(AL 4, Apr 73)

B

Neutral burning:

A propellant grain with the configuration of a cross in the middle of the annular void space is shown Fig 9(c). Here the burning takes place only at the cylindrical surface of the grain. The gas pressure is same all around the grain. This can also give neutral burning.

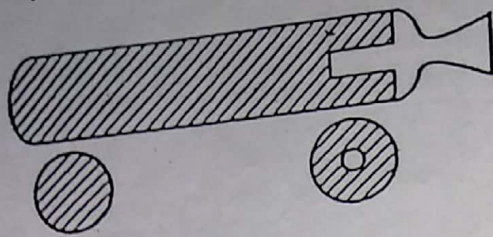


(c) Neutral burning

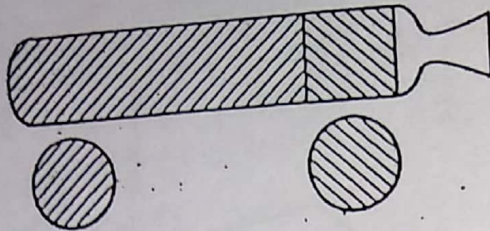
In restricted burning rockets, particularly in cigarette burning pattern a larger quantity of propellants can be packed into a given volume of the combustion chamber. This offers better utilization of the available space.

Fig 11.19 shows grains which give two or more discrete thrust periods in a single burn operation.

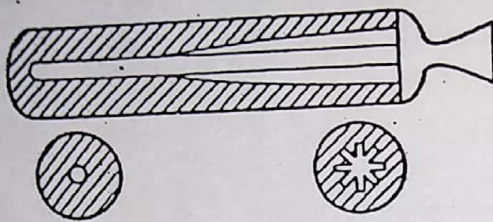
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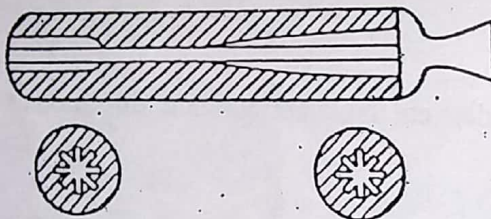
Single grain. Boost with radial burning, sustain with end burning



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



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)

2. Unrestricted Burning

If the propellant grain surface is not restricted from burning and all surfaces except those with supports are exposed to the flame or hot gases the mode of combustion is known as "unrestricted burning". This requires perforations and hollow spaces running along the length of the propellant grain as shown in Fig (10). This arrangement requires larger volume of empty spaces to permit the flow of combustion gases and provision of supports. Therefore, the quantity of propellant that can be packed into a given volume of the combustion chamber is considerably reduced; however, large values of the propellant burning surface area can be obtained by employing a number of grain configurations.

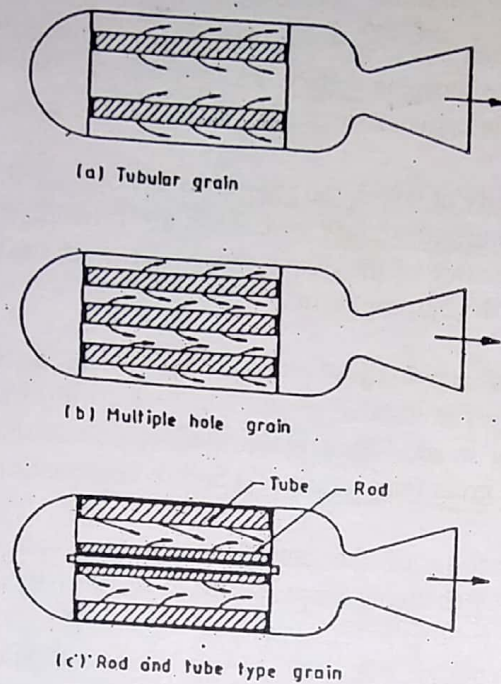


Fig 10. Solid propellant grain configurations for unrestricted burning

Fig 10 (a) shows a tubular grain shape; the hollow cylindrical grain is supported within the shell on three or more sufficiently strong webs. During combustion the outer cylindrical surface area of the grain decreases while the area of the inner surface increases. Neutral burning can be obtained if the overall area of the burning surfaces remains constant.

Fig 10 (b) shows a multiple hole grain. Burning takes place at both the outer and inner surfaces of the grain. In this configuration also burning surface area can be kept constant to obtain constant thrust.

The aforementioned configurations suffer from a serious problem of differential combustion pressure. The combustion pressure and hence the burning rate on the outer and inner surfaces are different. If the pressure difference is large the grain may crack or break. In order to avoid this the pressure on different surfaces is equalized by providing holes through the grain thickness.

The rod and tube type grain shown in Fig 10(c) ever comes this problem. Burning takes place at the inner surface of the tube and outer surface of the rod. The combustion pressure in the annular space is same. The combusting pressure in the annular space is same. Thus the burning rate is same. Since the surface area of the tube increases and that

of the rod decreases during burning any desired thrust profile is obtained by choosing different sizes and the propellants for the tube and the rod.

PROPELLANT BURNING RATE:

The rocket motors operation and design depend on the combustion characteristics of the propellant, its burning rate, burning surface, and grain geometry. The branch of applied science describing these is known as internal ballistics.

Burning rate is the velocity at which the propellant is consumed. At any instant the thrust is proportional to the burning surface area. Thus the thrust can be pre-arranged to a large extent by a suitable choice of the charge shape. In most cases the ideal is to obtain a constant thrust through the burning period.

The burning surface of a propellant grain recedes in a direction essentially perpendicular to the surface. The rate of regression or burning rate (\dot{r}), usually expressed in cm/sec, mm/sec or in sec. Burning rate mainly depend on the combustion pressure (P_c) and the propellant grain temperature (T_p) before combustion.

Burning rate is a function of the propellant composition. For composite propellants it can be increased by changing the propellant characteristics.

1. Add a burning rate catalyst, often called burning rate modifier (0.1 to 3.0 % of propellant) or increase percentage of existing catalyst.
2. Decrease the oxidizer particle size.
3. Increase oxidizer percentage
4. Increase the heat of combustion of the binder and/or the plasticizer.
5. Imbed wires of metal staples in the propellant.

Aside from the propellant formulation and propellant manufacturing process, the following can increase burning rate in a fuel-scale motor

1. Combustion pressure
2. Initial temperature of the solid propellant prior to start
3. Combustion gas temperature
4. Velocity of the gas flow parallel to the burning surface
5. Motor motion (acceleration and spin-induced grain stress)

Burning rate data are usually obtained in three ways-namely, from testing by

1. Standard strand burners often called Crawford burners.
2. Small-scale ballistic evaluation motor.
3. Full-scale motors with good instrumentation.

The burning rate of propellant in a motor is a function of many parameters and at any instant governs the mass flow rate (\dot{m}) of hot gas generated and flowing from the motor (stable combustion),

$$\dot{m} = A_b \gamma \rho_b \text{ ----- ①}$$

Here A_b is the burning area of the propellant grain, γ is the burning rate and ρ_b is the solid propellant density to motor start. The total mass m_1 of effective propellant burned can be determined by integrating the eqn ①

$$m_1 = \int \dot{m} dt = \int A_b \gamma \rho_b dt \text{ ----- ②}$$

$$m_1 = \rho_b \int A_b \gamma dt \text{ where } A_b \text{ \& } \gamma \text{ vary with time and pressure}$$

$$M = A_b^n P_b$$

Burning rate relation with pressure:

(With many propellants it is possible to approximate the burning rate as a function of chamber pressure, at least over a limited range of chamber pressures. For most production type propellants the empirical eqn is

$$\gamma = a p_1^n \text{ ----- ③}$$

where γ is burning rate is usually in cm/sec or in/sec and the chamber pressure p_1 is in Mpa or psia; a is an empirical constant (or temperature coefficient) and n is the burning rate exponent, sometimes called the combustion index, is independent of the initial grain temperature dependant on the chemical composition and the pressure range.

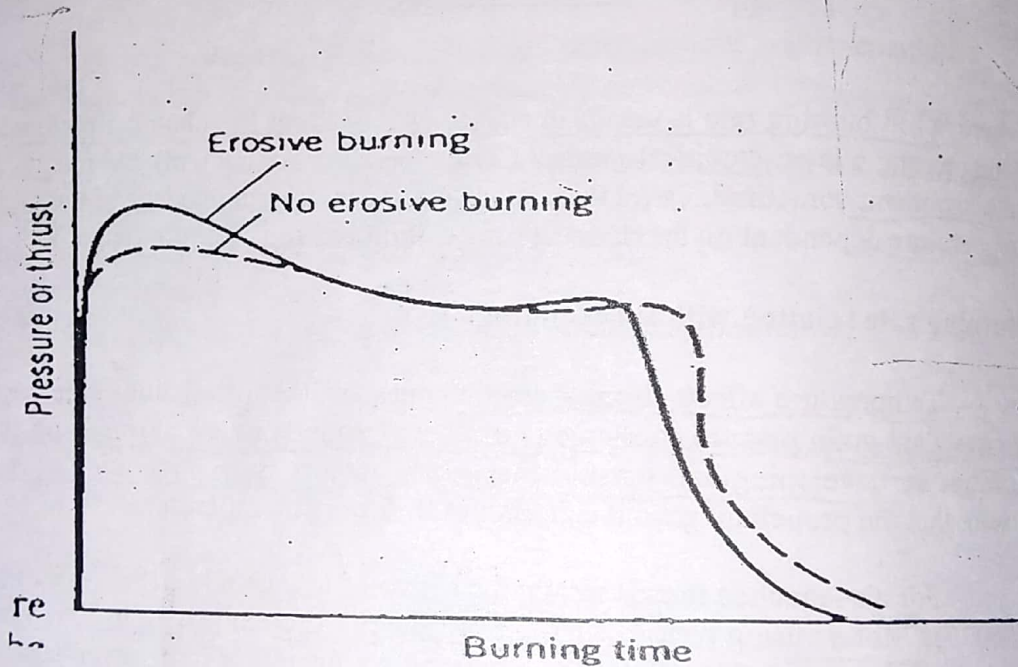
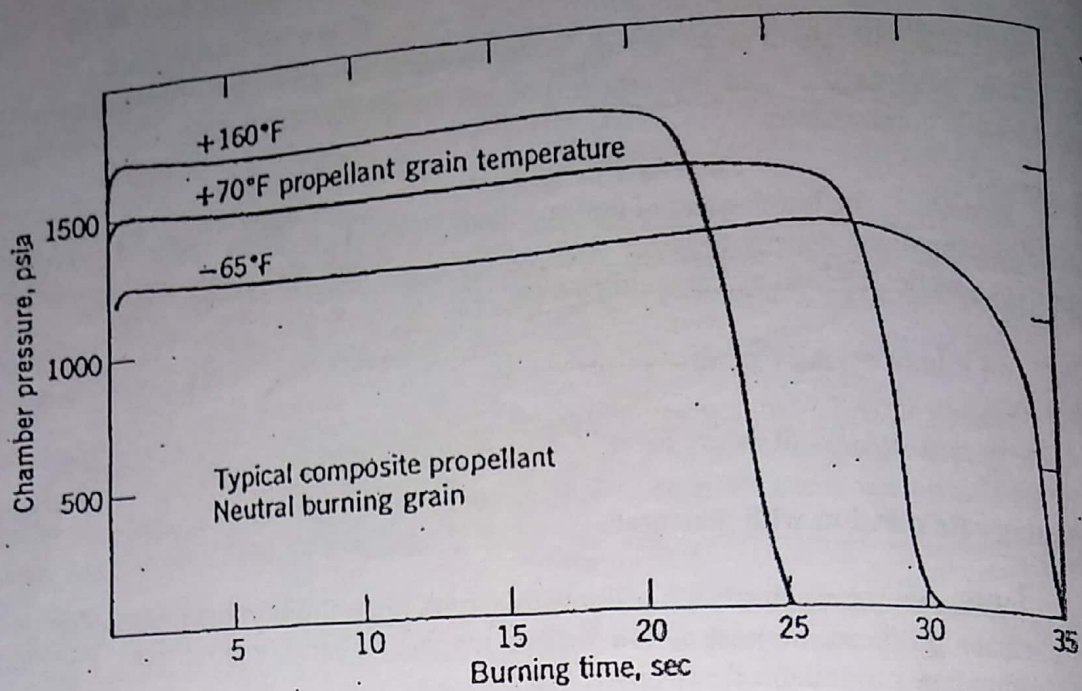
Burning rate relation with temperature:

Temperature affects chemical reaction rates and the initial ambient temperature of a propellant grain prior to combustion influences burning rate as shown in fig. Common practice in developing and testing larger rocket motors is to "condition" the firing to insure that the propellant grain is uniformly at the desired temperature.

For air-launched missile motors the extremes are usually 219K (-65°F) and 344K (160°F) Motors using typical composite propellant experience a 20 to 35% variations in chamber pressure and a 20 to 30% variation in operating time over such range of propellant temperatures.

$$m_1 = \int \dot{m} dt = \int A_b \gamma \rho_b dt$$

$$m_1 = \rho_b \int A_b \gamma dt$$



The sensitivity of burning rate to propellant temperature can be expressed in the form of temperature coefficients, the two most common being

$$\sigma_p = (\delta l_r / \delta T)_p = (1/r) (\delta r / \delta T)_p \quad \text{--- ④}$$

$$\Pi_k = (\delta l_p / \delta T)_k = (1/p_1) (\delta p / \delta T)_k \quad \text{--- ⑤}$$

Where σ_p is known as temperature sensitivity of burning rate, expressed as percent change of burning rate per degree change in propellant temperature at a particular value of chamber pressure, Π_k as the temperature sensitivity of pressure expressed as

$$\sigma_p = \left(\frac{\delta l_r}{\delta T_p} \right) = \left(\frac{1}{r} \right) \left(\frac{\delta r}{\delta T} \right)_p \quad \text{②⑨}$$

$$\Pi_k = \left(\frac{\delta l_p}{\delta T} \right)_k = \left(\frac{1}{p_1} \right)$$

36

percent change of chamber pressure for degree change in propellant temperature at a particular value of k , here k is a geometric function namely the ratio of the burning surface A_b to nozzle throat area A_t .

Burning enhancement by erosion:

Erosive burning refers to the increase in the propellant-burning rate caused by the high velocity flow of combustion gases over the burning propellant surface. It can seriously affect the performance of solid propellant rocket motors. The high velocity near the burning surface and the turbulent mining in the boundary layers increases the heat transfer to the solid propellant and thus increases the burning rate.

Erosive burning increases the mass flow and thus also the chamber pressure and thrust during the early portion of the burning as shown in the fig for a particular motor. As soon as burning enlarges the flow passage (without a major increase in burning area), the port area flow velocity is reduced and erosive burning diminishes until normal burning will again occur. Since propellant is consumed more rapidly during the early erosive burning, there usually is also a reduction of flow and thrust at the end of burning. Erosive burning also causes early burn out of the web, usually at the nozzle end, and exposes the insulation.)

Nozzleless Propulsion

①

Introduction

The concept of nozzleless rocket motors stems from the possibility of obtaining the required booster configuration in an integrated rocket ramjet type of vehicle. Despite the fact that expansion of the chamber gases cannot be effected in nozzleless system as efficiently as in nozzled rockets, an overall gain is still possible because of higher propellant loading in the given volume. Typically a performance gain of upto 15% has been projected by ISRO. In addition the system becomes much simpler leading to higher reliability.

The most critical aspects of a nozzleless system are the choice of propellant and geometric configuration supplemented with a detailed understanding of erosive burning at lateral velocities extending into supersonic flow regime. The theoretical modeling of such systems has not yet come to a proven state.

Earlier studies about the properties of a propellant suitable for nozzleless configuration have shown stringent demands on the burning rate characteristics, mechanical strength and strain capacity.

Nozzleless propulsion system, the most advanced concept was successfully demonstrated by AFRPL, USA in 1979. It was expected that such a system will reduce the cost of production in view of the elimination of the nozzle assembly, the reduction of the case insulation requirements etc., and also will improve the reliability on account of the system simplicity.

The properties required for an ideal propellant for a nozzleless configuration shows that:-

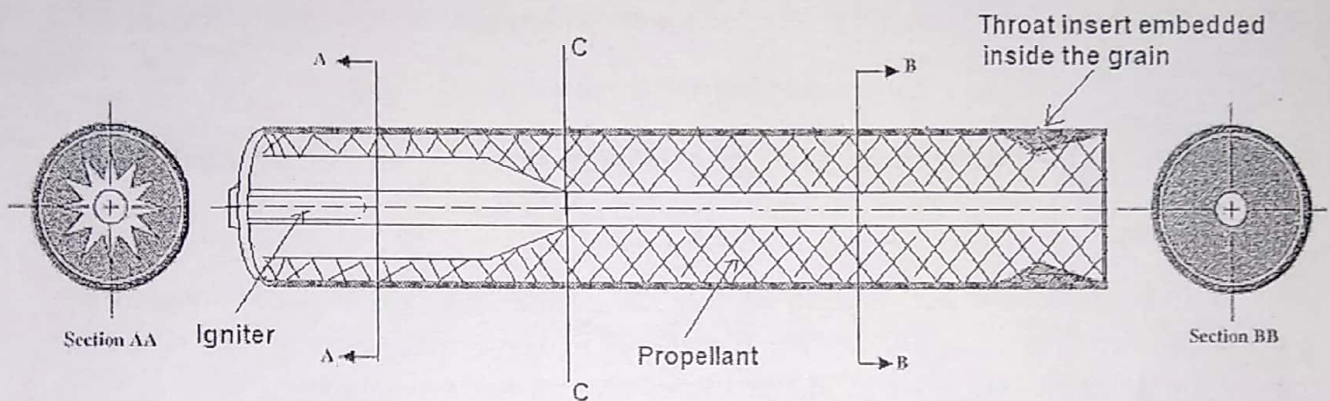
1. The burning rate of the propellant must be higher in order to prevent a long and inefficient tail off.
2. A superior strain capacity at low temperature in order to allow optimum web fraction, propellant loading and total performance is required and,
3. A higher stress capacity at high temperature so that the grain structure can survive the shear loads produced by the large axial pressure differential between the head end and aft-end of a burning nozzleless grain is also required.

The above requirements reported by the ISRO shows that the cost of development and propellant ingredient are typically higher for nozzleless motor. However, it is reported that inspite of these factors, a straight forward nozzleless booster can be designed to yield comparable performance at a price reduction of about 10% and a performance gain of upto 15% if the propellant strength and burning-rate/pressure exponent can be optimized.

Nozzleless Propulsion System

In the conventional solid rocket motor, the propellant is burnt inside a rocket chamber and the hot gases thus generated are accelerated to supersonic condition through a convergent-divergent type nozzle. The heat energy of the gases is converted into kinetic energy inside the nozzle.

Nozzleless propulsion system attempts to perform the main task of the nozzle inside the grain port itself, thereby saving the weight of the nozzle which can be replaced by additional propellant. The basic configuration of such system is shown below.



Nozzleless Solid Rocket Motor

On ignition of the grain, high volume of gas will be generated in the star portion of the grain (section AA) because of large surface area available. This gas will converge at the section CC and will flow through the tubular portion of the grain at section BB.

The gas is expected to reach sonic condition at the interface of the conical and cylindrical section and accelerate to supersonic condition inside the tubular portion.

Simultaneously, small amount of mass addition will take place inside the tubular portion due to the burning, which will progressively increase as a function of time.

Due to the existence of long tubular portion, erosive burning of the grain in the tubular portion is expected. This will be further accelerated due to attainment of supersonic condition of the gas.

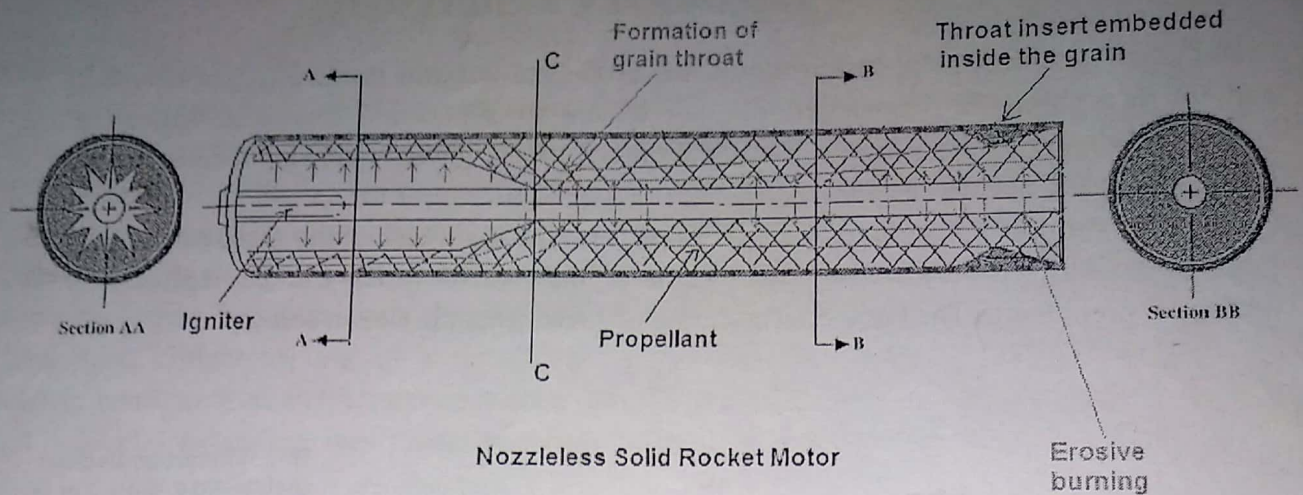


Fig.2 Formation of grain throat due to erosive burning.

Figure 2 shows the different phases of grain burning and the formation of nozzle shape due to the erosive burning inside the grain as described above.

After the completion of the burning of the star portion, the gas will continue to be generated (much lesser quantity) by the conical portion of the grain, more or less as an end burning system. However, mass addition at the tubular portion will continue.

This is expected to function till the propellant burns completely at the aft end section due to erosive burning.

Beyond this time, a nozzle hardware system will be necessary. This will be provided with a silica phenolic throat insert embedded inside the grain as shown in the figure.

Additional Reading:

- Sutton, G.P., "Rocket Propulsion Elements", John Wiley & Sons Inc., New York, 7th Edn., 2001.