THIOKOL PROPULSION

ROCKET BASICS

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A Guide to Solid Propellant Rocketry

THIOKOL PROPULSION

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Sir Isaac Newton

The Third Law of Motion

"For every action there is an equal and opposite reaction."

This booklet was first produced by Thiokol nearly thirty years ago, in the early 1970s. In that time, many changes in materials and processes have occurred. These changes have had a significant impact from initial design and testing to manufacturing the final product. New materials and processes allow Thiokol's scientists and engineers greater control - improving quality, reliability and performance.

Certain statements in this booklet are obviously dated. Less efficient designs give way to those that prove to be more efficient. Through all of these changes, the basic principles of physics remain constant and the information presented here remains valid.

Background and Applications

HISTORY

Rockets have been around in one form or another since at least the 13th century. Precisely who invented them is uncertain, although it is likely that an ancient Chinese scientist or philosopher happened upon the principle when he observed the violent exit of exhaust products from a jar or tub in which he was mixing black powder. Or, he may have accidentally caused a vessel of some sort to fly into the air by lighting powder beneath it.

And, it probably was a Chinese who developed the first rocket, because they are generally credited with the discovery of black powder and the first use of “fire arrows” in battle during the siege of Kaifung-fu (Peiping) in 1232 A.D.

In its most elementary form (the fireworks rocket used throughout the world in displays and celebrations), the rocket consists of four main components.

1. A charge of propellant to develop the propulsive force, which is termed thrust.

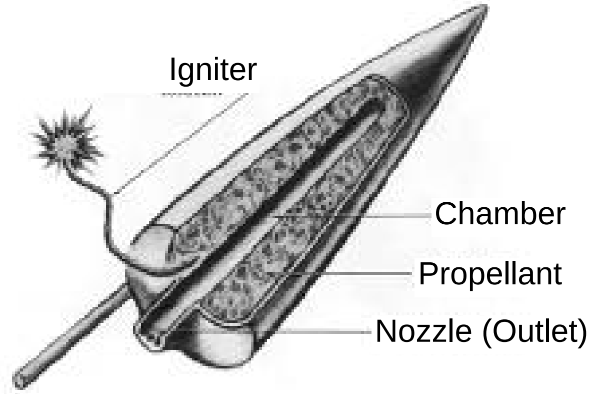
2. A hollow tube or chamber within which the propellant is burned.

3. An igniter with which to start combustion of the propellant.

4. A nozzle or outlet through which gases of combustion are exhausted.

Precisely what caused a rocket to be propelled from one place to another probably made little difference to the Chinese, Arabs, and others who produced them for use in battle through the earliest years of recorded time. Prior to about 1500 A.D., all black powder was rather slow burning and therefore suitable for use as a rocket propellant.

Improvements in recipes used to manufacture powder after the invention of the gun, however, produced a powder that burned too fast for use in rockets. After this date, lazy gun powder, i.e., gun powder whose rate of burning has been reduced by the addition of extra charcoal, was used. In 1591 the German author Johann Schmidlap described rocket manufacture in great detail.



What Causes Rocket Movement?

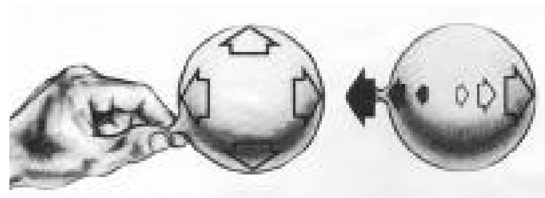
One of the first written attempts to explain what causes the rocket to be propelled through the air was published in the year 1540 by an Italian, Vanoccio Biringuccio, in his book “De La Pirotechnia.” He attributed the propulsive force to a “strong wind,” the development of which he described thus:

“One part of fire takes up as much space as ten parts of air, and one part of air takes up the space of ten parts of water, and one part of water as much as ten parts of earth. Now sulphur is earth, consisting of the four elementary principles, and when the sulphur conducts the fire into the driest part of the powder, fire, and air increase. . . the other elements also gird themselves for battle with each other and the rage of battle is changed by their heat and moisture into a strong wind.”

Biringuccio’s description of the burning, gas exhausting phenomenon was correct enough, despite its nontechnical language. But it didn’t explain why a strong wind, which was blowing downward should cause the rocket to rise upward. It was nearly a century and one-half later that Sir Isaac Newton, the English mathematician, scientist, and philosopher, developed his Third Law of Motion to explain what occurs.

The Third Law of Motion states that “for every action there is an equal and opposite reaction,” which in itself doesn’t really explain how a rocket can be propelled upward by exhaust of particles of matter through a pot pointing in the opposite direction.

This phenomenon can be best illustrated by using a balloon or other airtight vessel as an example. What compressed air or other gases are contained in a balloon press equally on all parts of the chamber, so the balloon remains at rest. If a leak should develop, however, some of the gas is allowed to escape, thus creating an action - the movement of gas particles at a velocity greater than that of the surrounding air. The remaining gas within the balloon still presses against the constraining parts of the wall equally; however, release of pressure through the leak causes a strong pressure unbalance directly opposite the leak. Consequently, the pressure opposite the leak is not counteracted, and the balloon moves away from it.



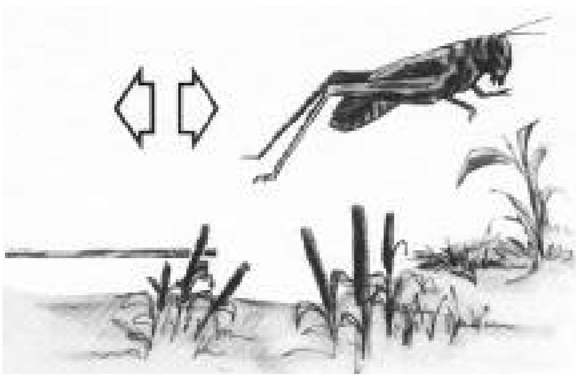
Air pressure equal to all parts of the balloon.

Air escapes, creating an equal, but opposite reaction and the balloon moves away.

A simple illustration of Newton’s law and what causes the rocket to move upward as the gases are exhausted downward can be drawn by imagining a grasshopper sitting on a piece of driftwood which is floating in a quiet lake.

Assume that the weight of both the grasshopper and his perch are precisely the same. If the grasshopper decides to “abandon ship” and jumps from the wood to the shore, a distance of four inches, discounting any drag which might be imposed on the wood, the wood will move in the opposite direction four inches. Because of their equal weight, both the grasshopper and his erstwhile perch will move at the same speed. Had both moved outward along the balance of a scale, the balance would not have moved at all because of the perfect balance of the two weights in opposite directions.

The movement of the rocket is very much like that of the piece of driftwood away from the grasshopper, the gases being exhausted through the nozzle providing the power, which in our example was provided by the grasshopper's legs, causing the driftwood (rocket) to be kicked the opposite way.



ACTION: Grasshopper jumps to shore

REACTION: Driftwood is pushed in opposite direction

APPLICATIONS: Ancient and Modern
(as of 1960s and 1970s)

From its first introduction as an artillery weapon by the Chinese, the solid propellant rocket was used primarily as a weapon of war until the post World War II era.

Introduced to the Mideast and European area by the Arabs, the war rocket was a primary instrument of both land and sea warfare at various times throughout history. It fell into disuse for nearly two centuries following the

Congreve and His Developments

invention of handguns, mortars, siege guns and cannons.

Interest in war rockets was revived during the early 1800's and they were developed and used extensively during what is known to military historians as the "Congreve Period." This interest was the direct result of the heavy damage suffered by British troops in military action against the native ruler, Hydar Ali, Prince of Mysore, India. The British suffered severe losses from bombardment with war rockets from a distance of 1 to 1 1/2 miles, especially at Seringapatam, in 1792 and 1799.

Colonel William Congreve read about the battles and began his experiments with large skyrockets in 1801 or 1802. He obtained the use of the laboratories and firing ranges at the Royal Laboratory at Woolwich for developmental work. His rocket developments were first put to use in the siege of Boulogne, in 1805 by the British Army. Their use against Fort McHenry during the War of 1812 was the event which inspired Francis Scott Key in writing the words "the rockets red glare, the bombs bursting in air. . . " in the Star Spangled Banner.

Congreve's rocket, with a long stick trailing to provide stability, gave way during the mid-19th century to a stickless variety invented by British inventor William Hale. His contribution

Other Applications and Experiments

to rocketry was the impartation of spin to stabilize the missile through insertion of three slightly inclined metal vanes in the nozzle.

The rocket principle was adopted about 1821 by Captain Scoresby of the whaling ship, Fane, for propelling harpoons, but was later replaced with the harpoon gun that provided greatly improved accuracy. In areas where extreme accuracy is not critical, however, the rocket has served seamen well for propelling lines for rigging breeches, buoys, and for hurling small anchors ashore so that lifeboat-size vessels can negotiate a heavy surf.

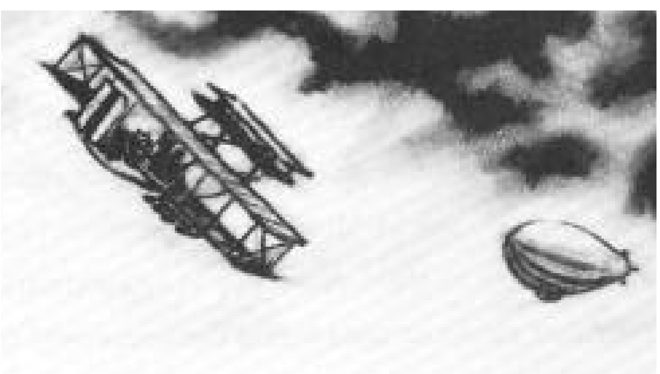
An underwater war rocket patterned after a popular fireworks projectile of the early 18th century was developed following the accidental demonstration of its explosive power in 1734. During a celebration on the Thames, an underwater fireworks rocket rose up under the hull of a barge and the strong final powder charge exploded, causing the barge to sink and its passengers to be thrown into the water.

The submarine mine, based on the underwater explosive power principle, was developed by the Russians during the Crimean War and by Confederate engineer officers during the American Civil War.

The first experiment with an underwater torpedo carrying an explosive warhead was conducted by its inventor, U.S. Army Major Hunt, near Red Hook in New York Harbor in 1862. Although never used as a naval or coastal defense weapon by any country, the rocket torpedo was the forerunner of the present-day naval torpedoes powered by electrical motors or steam turbine engines.

World War I

The French were the only combatants to use rockets operationally during World War I. Incendiary rockets were first used against a German Zeppelin (gas-filled heavier-than-air craft) during an air- raid on the Bar-le-Duc railroad yards in 1916.



Later, the French also used the first air-launched rockets, again, against zeppelins. Nieuport biplanes were outfitted with racks for four rockets on each wing strut and their use against captive balloons was credited with forcing the Germans to discontinue use of this type of observation aircraft.

World War II

All major combatants in World War II, except the Italians, developed war rockets. Some of the most widely used and best known were: the American Bazooka antitank missile, Calliope 4.5 inch battery rocket, and antisubmarine Projector Mark 10 (known as the Hedgehog); the German Nebelwerfer 15 and 21 centimeter high explosive and Schweres Wurfgerat 21 centimeter incendiary rockets; and the British 3 and 5 inch rockets.

A German development, the V-2 rocket bomb with which they bombarded London, was the model upon which much of the early postwar development of intermediate and intercontinental range ballistic missiles was based by both the American and Russian governments.

The nonstorable nature and extended fueling time of most liquid fueled rockets, however, led researchers to look for a method of manufacturing propellant for solid fueled missiles which would be storable, instantly ready for launch, and provide more constant thrust than that produced by granular “gunpowder” types of propellant which had been used to that time.

Postwar Developments

America’s first synthetic rubber, a polysulfide base material discovered by Dr. J.C. Patrick, in 1928 provided the basis for modern solid propellant development. Used as a binder in which metallic fuel and chemicals oxidizing agents are suspended, the viscous material can be cured to a firm rubbery consistency after it has been cast into the rocket motor case. Demonstration by Thiokol Chemical Corporation in 1949 of the principle of internally burning material bonded to the case proved the applicability of solid propellants in large rocket motors. This bonding principle has since been applied successfully to such operational ballistic and guided missile systems such as Minuteman, Sergeant, Falcon, Genie, Polaris and Poseidon. Smaller rockets also have been used extensively in scientific research programs aimed at uncovering the secrets of the Earth's upper atmosphere and outer space.

Unlike systems such as the modern turbojet, pulse jet and ducted aircraft engines, the solid fueled rocket carries its oxygen supply aboard as an integral part of the propellant and consequently can operate efficiently in the rarefied air or the stratosphere and beyond and in the airless vacuum of space. Because of this fact, small solid rocket motors have been used with great reliability to decelerate spacecraft returning from trips to the Moon and for other space applications.

Solid motors measuring as much as 260 inches in diameter and developing as much as 3.5 million pounds of thrust were developed for possible use as space boosters during the mid-1960's. Motors of 120 inches in diameter and approximately 125 feet long have served as zero stage boosters for the Titan IIIC and 65 inch diameter motors for the Delta launch vehicles to provide thrust augmentation needed to loft heavy payloads as such as communications and surveillance satellites into orbit.

Large solid propellant boosters up to 156 inches in diameter are being considered for use as reusable booster stages for the Space Shuttle which is to be developed in 1975. As man moves out into the farther reaches of outer space, controllable solid propellant rocket motors, which can be called upon as needed to provide thrust for mid-course corrections will play an increasing role.

Update: Thiokol has been supplying solid propellant rocket motors for NASA's space program since its inception. Thiokol static tested a 156-in, 13 feet diameter, solid rocket motor in 1964. In 1974 Thiokol was awarded the contract to develop the twin solid propellant booster motors for NASA's Space Shuttle fleet. Today, two 126 feet long, 12 feet in diameter, solid rocket motors filled with one million pounds of propellant each fly on every Space Shuttle flight.

What Makes a Rocket Operate?

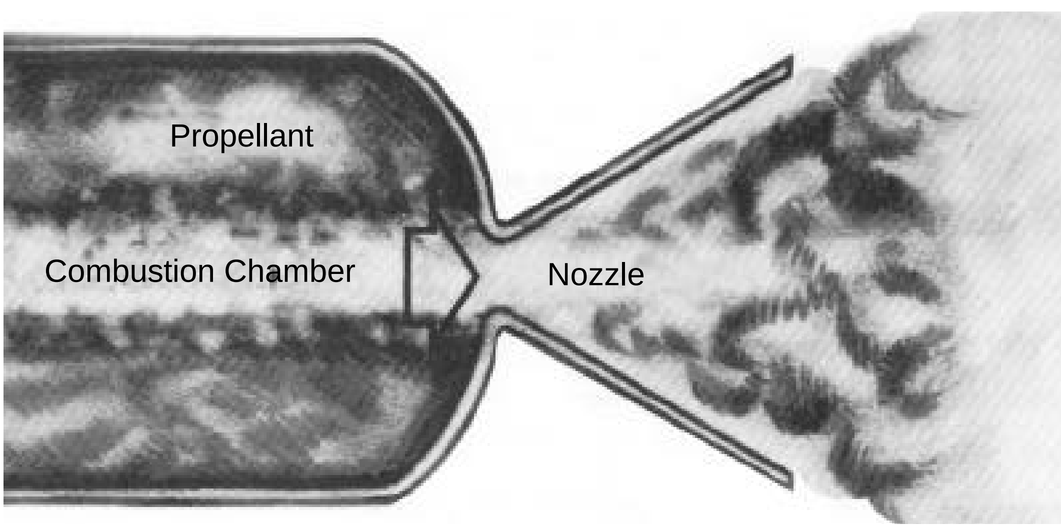
Basically, a rocket motor is the simplest form of energy conversion device. Matter in the solid or liquid state is burned, producing hot gases. The gases are then accumulated within the combustion chamber until enough pressure builds up to force a part of them out an exhaust port. The movement of gases through the exhaust port results in the conversion of heat energy into kinetic energy, or energy of motion.

In the modern solid propellant rocket motor, finely ground metals or chemicals that can serve as fuels are mixed with other chemicals, which contain oxygen (oxidizers). The proper proportions of fuel and oxidizer are then suspended in a binder material that can be cured to a solid state much like the rubber in a tire.

The most simple form of a rocket motor consists of a pressure combustion chamber containing the fuel (propellant), and a port (nozzle) through which the hot gases are exhausted. Some means of igniting the motor must be provided, either as a part of the motor or as an external ancillary device. The laws of motion developed in the 17th century by Sir Isaac Newton and the laws describing gaseous behavior developed by Robert Boyle and Jacques Charles describe the underlying principles which govern rocket motor propulsion.

Newton's first law, that of inertia states that: in the absence of contrary forces, the speed and direction of an object's movement will remain constant. Thus, if a rock could be thrown with enough force to overcome the effects of gravity and wind resistance, it would continue to move in a straight line at the same speed as it has attained at release by the thrower. Likewise, until some force is applied, the object will remain at rest where last placed or originally formed.

As applied to rocketry, the law of inertia tells us that the force generated by the thrust of the rocket motor must be great enough to lift the missile's total weight from the launch site, or it will not fly. The forces of gravity and air resistance, among others, must be taken into account in determining both the required thrust and computing its trajectory (flight path) to the ultimate target.



Energy of Heat => Movement of Gases => Energy of Motion

The second law defines acceleration as: the ratio of the applied force and the inertial (rest) mass of the object. Thus, a body that is subject to forces moves at a speed which is proportional to the amount of force applied. As an example, a golf ball moves away from the tee much faster when struck with a club than when kicked because much more force can be applied with a swinging club than with the toe of a shoe.

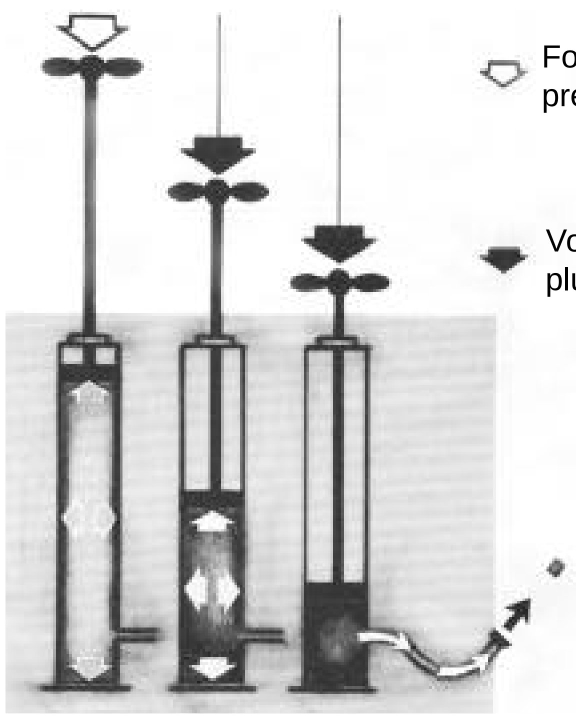
In rocketry, the greater the amount of thrust developed by the rocket motor in relation to the mass of the total vehicle, the faster the missile will move through the air. If enough thrust is developed, the speed can be built up (usually in stages) until the vehicle can escape the pull of the Earth's gravity and move into outer space.

Newton's third law, the law of action and reaction, states that: for every force exerted by one mass on another, there is an equal and opposite reaction exerted by the second mass on the first. In the rocket, the expulsion of combustion products (gases) through the nozzle produces a reactive force on the rocket in the opposite direction which causes it to be propelled.

Boyle's law states that reducing the volume of a container within which a gas is held causes its pressure to increase in direct proportion. An example is the old fashion tire pump. If air is prevented from escaping and the plunger is pushed down, as the volume of the chamber grows smaller, the pressure rises so that a plug inserted into the hole through which it normally is exhausted will eventually be forced out. An additional element of the law is that when gas is compressed, its temperature decreases.

Charles noted that if the pressure of a fixed weight of gas is kept constant while the heat is increased, the gas expands by an amount proportional to the change in temperature.

No force applied to plunger, low air pressure in chamber.



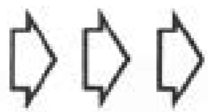
Force of plunger decreases air volume, pressure increases.

Volume of chamber decreases, plug is eventually forced out.

Defining Performance

Solid propellant motor designers employ a number of important parameters (a variable or an arbitrary constant) to define the performance of the propellants used and the motors which power rocket propelled vehicles. Since most of these terms will be used throughout the discussions which follow, brief definitions of the more common ones are presented below.

The first and most common term used in rocketry is thrust, which is a measure of the total force delivered by a rocket motor for each second of operation. Essentially, thrust is the product of mass times acceleration. In actual calculations, of course, gravity, pressure of the surrounding medium, and other considerations must be taken into account.



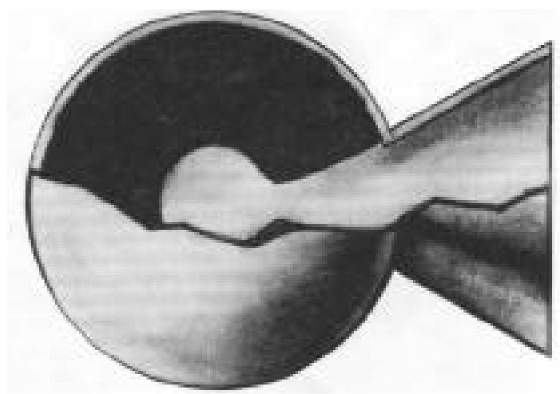
The thrust (total force) of a football player is much like that of a rocket. The force generated is a product of player's weight (mass) times player's rate of acceleration.

After the thrust developed by the rocket has been determined, this value is used to compute another important parameter, specific impulse (Isp), which provides a comparative index to measure the number of pounds of thrust each pound of propellant will produce. Expressed as pound force seconds per pound mass, Isp is referred to in the rocket engineer's shorthand language as seconds of impulse.

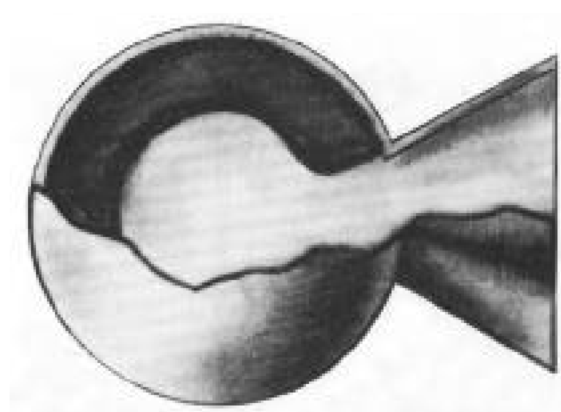
To compute specific impulse, the thrust is divided by the mass flow, or weight of the gas flowing through the nozzle throat per second.

Another important term is total impulse, which is abbreviated It. Computing this value is a simple matter of multiplying the motor's thrust by its period of operation in seconds.

Just as specific impulse is the basic chemical parameter for propellant, so is mass fraction a basic parameter for motor design. A high mass fraction indicates that more of the motor mass is propellant than is involved in the case, nozzle, and other components which do not produce thrust. A high mass fraction can be achieved by optimizing motor and structural design for minimum weight and or by using more dense propellants, which then require smaller combustion chambers. The mass fraction may be defined as the ratio of the propellant mass to the initial or total mass of the motor when completely ready for operation.



Solid fuel rocket motor with a low mass fraction.



Solid fuel rocket motor with a high mass fraction.

Modern Rocket Designs

(modern as of 1960s and 1970s)

Definition of Terms

The rocket motor in its simplest form consists of a combustion chamber which serves as a pressure vessel, a port through which the hot gases can be exhausted, and an igniter to initiate burning. The modern solid fuel rocket requires a number of specialized terms, defined below (size can vary from a few inches in diameter to more than 21 feet).

Motor Case-
Metal or fiberglass reinforced plastic vessel in which propellant is cast, and which serves as the combustion-pressure chamber.

Skirt -
A motor case wall extension provided as a point for joining motors in multistage rocket vehicles.

Insulation -
Material used to protect motor components from the extreme heat of combustion developed during the motor's operation, and from heat produced by friction on the case exterior during its movement through air.

Propellant Release Boot -
A sheet of rubber installed at the aft end of the propellant grain during casting to permit shrinkage of the cured propellant grain as it cools and thus prevent strain (deformation) with consequent cracking.

Grain -
The propellant charge. In composite solid propellants it consists of a fuel (usually metallic) and a chemical oxidizing agent (a substance which, under suitable conditions, combines with fuel elements to release the maximum possible energy) blended together and mixed into a binder, or polymer. The mixture is cast (poured) into the motor case and cured to a hard rubbery state at an elevated temperature. In double-base propellants, it consists generally of cotton (cellulose) combined with nitric acid to form nitrocellulose (guncotton), which in turn is combined with nitroglycerin, another fuel oxidizer. In the double-base propellant, the nitrocellulose serves as the binder, and the nitroglycerin causes it to gel.

Inhibitor -
A coating of noncombustible material applied or attached to specified areas of a solid propellant grain to prevent combustion taking place on that surface, to control the evolution of gases and prevent combustion in specific areas of the grain.

Gas Port Area - (gas cavity)
A cavity formed in the casting process through the center of the propellant grain to provide an increase in the surface area over which the flames can burn to produce hot gases and channel them to the nozzle. The cavities may be formed in a variety of shapes to provide larger or smaller burning areas and thus more or less hot gases as motor operation progresses, depending upon the amount of thrust which is desired at various times in the operation.

In some motors, no central perforation is formed and only the end of the grain burns. By maintaining constant burning area and thus constant thrust, this type of grain configuration provides a neutral (level) thrust-time history.

Central perforations can be designed so that the burning area, and therefore the gas evolution rate, the chamber pressure, and the thrust increase with burning time. This type of rocket motor operational history is referred to as providing progressive burning characteristics. If the grain design produced a decrease in these values, the rocket is said to have regressive burning characteristics.

Some idea of the wide variety of grain configurations, especially with regard to gas port shapes, is provided in the illustration below.

P N R

P (progressive), N (neutral) , R (regressive)

The cross sectional configurations shown generally would be expected to produce thrust-time histories of the type indicated by the letter designations below each drawing. However, many factors must be considered and such parameters as the length/diameter ratio of the motor can affect operation enough to provide a neutral trace from any of these configurations.

Nozzle -
An exhaust port in the motor case aft end shaped to control the flow of gases and to convert the chemical energy released in combustion into kinetic energy, or energy of motion.

Nozzle Throat -
The smallest internal diameter of the nozzle assembly. In the convergent-divergent DeLaval type of nozzle normally used, the inlet converges to the throat, then flares out in the nozzle expansion area.

Approach or Convergent Section -
That portion of the nozzle upstream of the throat in which the flow area is reduced and volume of the exhaust gases is reduced as they are channeled to the throat.

Throat -
The point at which exhaust gases are passed through the minimum flow area and reach the speed of sound before expanding in the exit cone to supersonic speed.

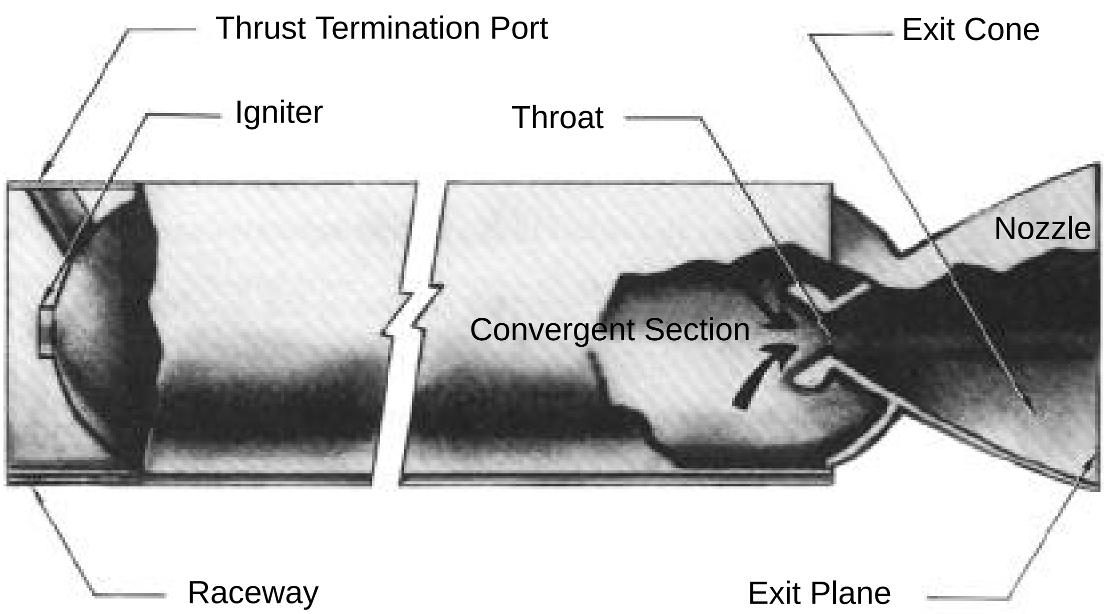
Exit Cone -
Also called the expansion section, this part of the nozzle may be contoured or conical, and is designed to provide rapid but controlled expansion of the exhaust gases passing through the throat on their way to the exit plane.

Exit Plane -
The extreme edge of the exit cone, where the static pressure of the gases should be approximately equal to the atmosphere pressure at the design operating altitude.

Raceway -
A metal or plastic covering inside of which the control and electrical system wiring or hydraulic leads are placed.

Igniter -
A device to initiate propellant burning, usually consisting of a small pyrotechnic device which produces sufficient heat and flame to cause the surface of the propellant grain to ignite.

Thrust Termination Port -
A port provided in the rocket motor case to vent combustion gases so that rocket operation can be terminated. The port usually is provided for in the head end of the motor so that gas flow is effectively diverted from the nozzle. The port is formed by firing a shaped charge of explosive placed against the outside of the forward end of the motor.
Designs of the many components that make up the modern solid propellant rocket motor require consideration of many factors, including: size and weight of the total vehicle, the mission to be accomplished, materials available, cost limitations, and the various state-of-the-art techniques to be employed.


Thrust Termination Port
Igniter
Throat
Exit Cone
Nozzle
Convergent Section
Raceway
Exit Plane

Cases

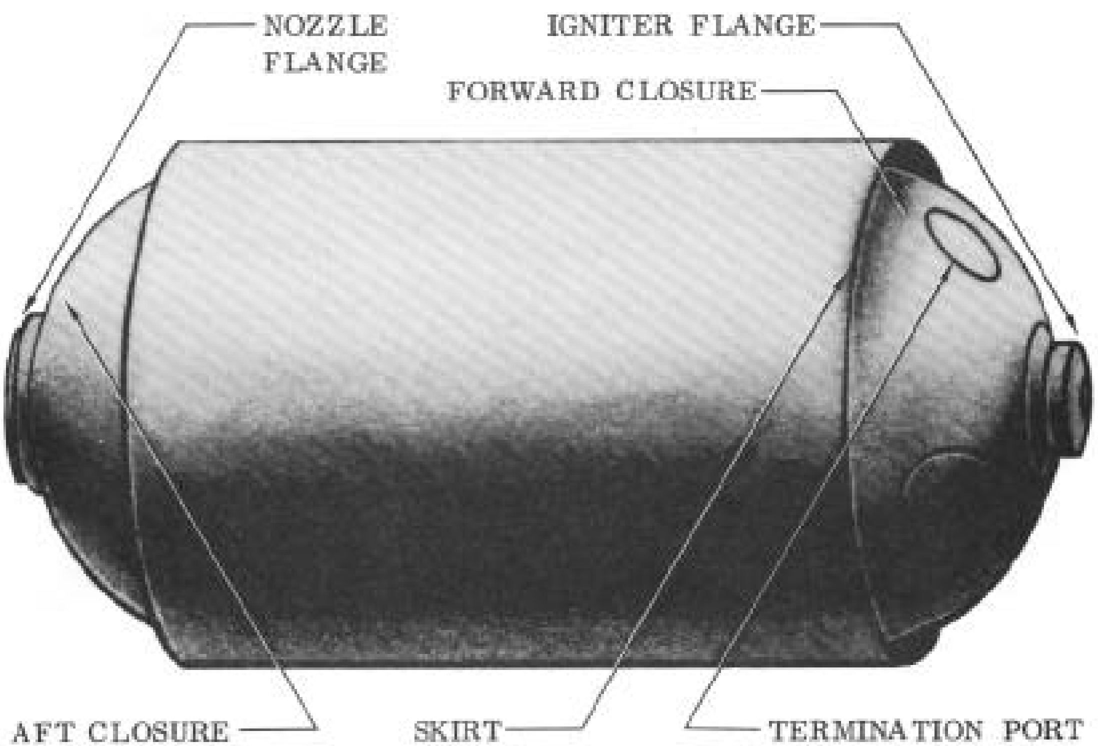
This next section discusses materials and design techniques used in developing components for propulsion systems for ballistic and guided missiles powered by solid propellant motors.

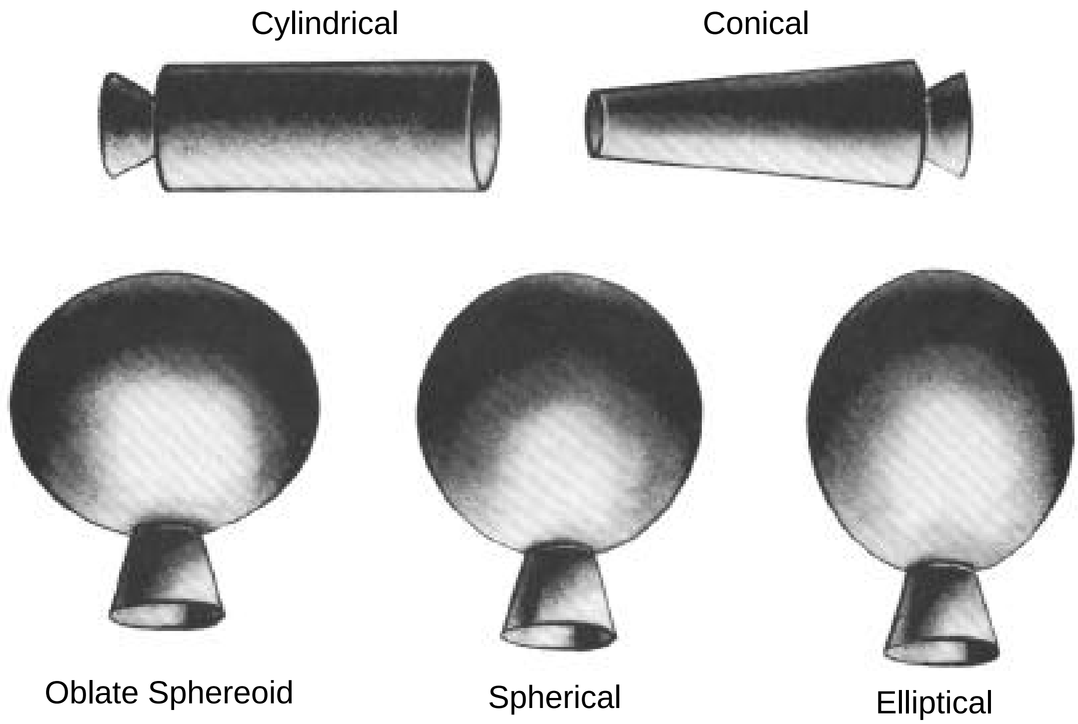
The case of a solid propellant rocket motor must serve two purposes:

1. A container for the solid propellant fuel.

2. A vented pressure chamber in which the fuel is burned to provide forward thrust when expanded into the exit cone of the nozzle.

Because of this dual role, development of an optimum case design involves providing for the interplay of the thermodynamic (chemical heat and energy) and mechanical forces (bending, pressure, etc.), which will act upon it during operation. The designer also must consider factors affecting overall performance of the vehicle, compatibility with other vehicle systems and components and cost. Depending upon the size and complexity of the vehicle for which the motor is being developed, the case may or may not incorporate all of the features illustrated.





The external configuration (shape, form) of the case usually is selected as the optimum (best) envelope for maximizing performance or minimizing cost when all independent vehicle and case design variables have been evaluated. The final case configuration may be determined, however, on the basis of: payload, limitations imposed by interstage connecting structures, available tooling, transportation size or weight limitations, handling equipment, launch facilities, use of a specified grain design, or auxiliary equipment. The size and shape constraints for small motors performing specialized functions on larger vehicles (such as retro fire duty on Apollo command modules) usually are defined by the vehicle system and imposed directly on the small motor configuration.

In selecting the materials from which the motor case will be constructed, a thorough evaluation must be conducted of the types of loads to which it will be subjected during manufacture, handling, storage, and the operation of the ballistic or guided missile, sounding rocket vehicle, spacecraft, artificial satellite, or other vehicle of which it will be a part.

Representative types of loads may include:

1. Internal pressure from hot gases produced by the motor during propellant combustion.

2. Thrust produced by the motor during operation, as well as the load produced by lower stage motors in a multiple stage missile.

3. Buckling, aerodynamic bending, and ground handling loads developed during handling, storage, and flight.

4. The effects on material strengths of heat from both inside and outside the motor, should there be an insulation failure or uneven burning.

Today's (1960s, 1970s) rocket designer has a variety of materials from which to choose in developing the optimum design to meet mission objectives. Most commonly used are the ferrous alloys, including conventional quench and temper (hardened by heating then plunging into liquid to cool suddenly) steels and nickel precipitation-hardening alloy steels, nonferrous titanium alloys, aluminum alloys, and fiberglass reinforced plastics.

The most efficient material to withstand the overall loading conditions at the highest temperature expected during the missile's useful life is selected. Critical case loading may be imposed by internal pressure or buckling forces, depending upon mission application and the location of the case in the vehicle. In single stage vehicles and the upper stages of multistage vehicles, internal pressure usually imposes the critical loading condition. Intermediate stages can be critical in internal pressure, buckling resistance, or stiffness. First stages usually are pressure critical; however, buckling and bending loads are high and may sometimes be critical.

Metal Considerations

The design engineer must consider how the welding, forming, or shaping operations to which materials will be subjected will affect their tensile strength (resistance to breaking when subjected to stretching force), fracture toughness (resistance to complete separation by cracking), and other mechanical and structural properties.

The size of the motor case may place a restriction on use of certain types of metal because heat facilities are not available to handle the extremely large sizes. Availability of odd or nonstandard sheet sizes in certain types of metal may influence the number and location of welds required to fabricate the case.

Thermal Environmental Considerations

Several sources of heat may have an effect on the motor, including: aerodynamic heating caused by air friction along the walls and attachments; conductive heating from propellant combustion; both radiant and conductive heating during handling, assembly, and checkout on the launch pad and during flight; and sterilization for planetary exploration, if part of a space vehicle.

Other Harmful Environments

All possible harmful environments and chemicals which may be encountered during the life of the motor case must be considered, beginning with production of structural materials and continuing through final service use. These may include corrosive (gradual chemical alteration at normal temperatures) influences, electromagnetic and elementary particle radiation, meteoroid impact, and other hazardous environments.

Metals Commonly Used

Conventional quench and temper steels have been used extensively as structural materials for cases, and a great deal of information is available on their properties and reaction to various fabrication processes.

Alloys containing nickel and cobalt, and other steels which harden when cold-rolled, rubbed, or struck with a hammer require special care in fabrication to prevent reduction of the ultimate strength (the strength at which destructive failure will occur), but their special properties can prove useful for special applications.

Fairly recent developments (1960s and 1970s) are the maraging (age hardening) steels containing various percentages of steel which develop extremely high strengths when aged at 850 to 950 F for a predetermined time. This aging results in formation of a molecular structure within the steel which gives it good forming and forging characteristics; good stability during heat treatment; good retention of carbon, which imparts surface hardiness.

Because of these properties, the maraging steels are the most likely candidates for use in production of large motors for space booster and Space Shuttle applications.

Titanium alloys have been used mainly because they provide extremely high strength to weight ratios, which makes possible increases in vehicle payload carrying or operational range capabilities; however, titanium alloys provide less resistance to buckling. Although not generally susceptible to corrosion (gradual chemical alteration at normal temperatures) they may develop stress corrosion (loss of strength, hardness, and other mechanical properties) under certain conditions.

Although aluminum alloys are not generally used in motor cases for space vehicles, they can be used to advantage for small cases and cases where corrosion may be a specific design problem. Stress corrosion may be a prime consideration when aluminum alloys are used as case structural material.

Reinforced Plastics

In their continuing search for ways to increase the mass fraction of the total vehicle (ratio of propellant mass to initial total mass) discussed earlier, rocket design engineers turned their attention to reinforced plastic structures in the mid-1950's. Today (1960s and 1970s), the best known missile system using motors employing this material in all stages is the Poseidon Fleet Missile. The third stage motor of the Minuteman ICBM

Design Techniques

also uses a fiberglass reinforced plastic case. Because of the importance of physical and chemical properties for determining what strength materials must be used, how they will react to atmospheric and imposed environments, etc., engineers and chemists who design rocket motors naturally would prefer to have absolutely accurate values with which to work. Experience has shown them, however, that they may use simplified assumptions which, although they do not describe conditions precisely, provide solutions which give an estimate of the motor's operational characteristics which is accurate within three percent or less.

In developing a preliminary design, the motor is divided into two sections, the chamber (combustion) and the nozzle (expansion), and conditions are assumed to have stabilized to the operating level following ignition.

The first of the assumptions is that combustion takes place within an adiabatic chamber (the rocket motor case); for example, there is neither gain nor loss of heat. In the solid propellant motor, the insulating effect of the unburned propellant in the chamber reduces the loss of heat to the chamber walls; consequently, the assumption is justifiable.

The chamber also is assumed to be isobaric; in other words, pressure is assumed to hold constant, with no changes occurring throughout operation. Under, "steady state" operating conditions, which means that all factors are in balance, very minor fluctuations in pressure are measurable, so again the assumption is justifiable.

The combustion gases in the chamber are assumed to act as "ideal gases;" that is, they behave exactly in accordance with gas laws (presented in the section on "What Makes the Rocket Operate?"), and any condensed phases (liquid portions) produced are assumed to have negligible volume.

The final chamber assumption is that the velocity of the gas stream in the chamber is negligible. Although there is some slight movement of exhaust gases in a solid propellant combustion chamber due to preliminary acceleration as the gases are forced to the nozzle entrance, they move quite slowly, the major driving force being compression resulting from the heat and continued addition of new combustion gases.

Ignition

Nearly everyone has watched television coverage of the countdown for America's Apollo Moon shots. Most of us probably have been amazed at how seemingly long it takes for the Saturn vehicle to lift off from the pad after the countdown has reached zero and the rocket engines have ignited. A ball of flame and smoke forms almost instantly after we hear the word ignition. Then time seems to stand still while we wait for the liftoff. In reality, no more than a few seconds elapse before sufficient thrust builds up to start the rocket on its flight.

To the casual observer, igniting the solid propellant motor may appear as simple as flipping a switch to turn on the electric lights at home. To the chemist, however, these are an almost limitless series of actions and interactions with which he or she must be concerned.

In general terms this is what takes place after the ignition switch is activated. The propellant is ignited using a heat or fire producing instrument; hot gases are produced; the gases are exhausted through the nozzle as pressure builds in the combustion chamber; and thrust is produced to propel the rocket. In this way, the chemical energy of combustion is converted to kinetic energy, or the energy of motion.

Most solid propellant rocket motors are initiated with a pyrotechnic device (squib) which consists of a cartridge containing combustible powders in contact with an electrical resistance wire. Initiation of burning on the squib develops extremely hot flames, which spread to the solid propellant grain or pyrotechnic charge of the main igniter. Igniters are usually identified by their shape, case type, or type of active material they contain.

The four main types of igniters are:

1. Basket
Constructed of woven wire, perforated sheet metal, or plastic in which the active material is contained.

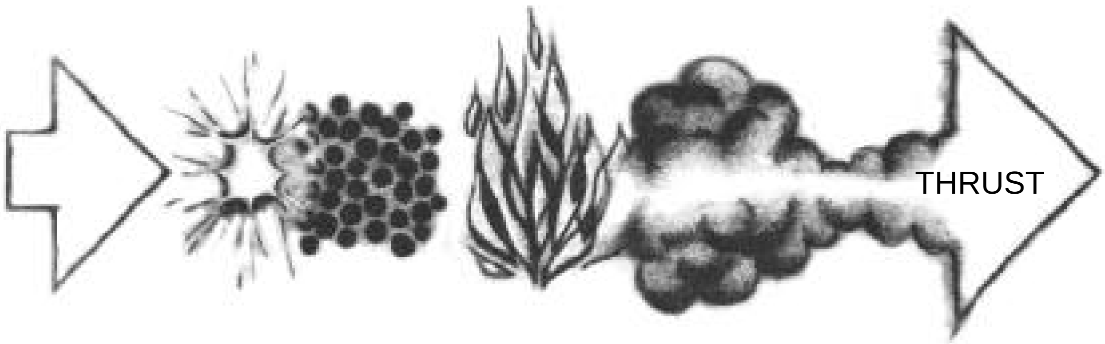
2. Jellyroll
Consisting of a pyrotechnic coating reinforced by a flexible sheet of plastic or cloth and rolled into a tube of several layers.

3. Can type
Usually consists of a metal, plastic, or paper container which is filled with an active powdered material.

4. Pyrogen
Defines an ignition device in which combustion of the igniter material takes place within a closed chamber and the combustion products are exhausted into the rocket motor. (A small rocket motor is used to ignite a large rocket motor).

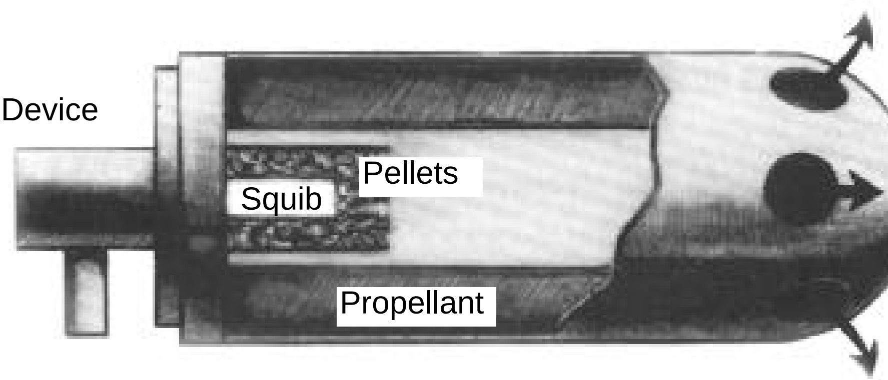
Solid propellants also can be ignited by a fluid (hypergolic) which reacts with the solid propellant ingredients to cause spontaneous combustion.

Ignition Sequence



Ignition activated | Propellant ignited | Fire | Produces hot gases | Exhausted under pressure

Typical Pyrogen Igniter



Safety and arming device activates squib ⇨ Squib then ignites explosive tablets ⇨ Flame from pellets ignites propellant ⇨ Hot exhaust from igniter discharges into motor and starts burn

NOZZLES

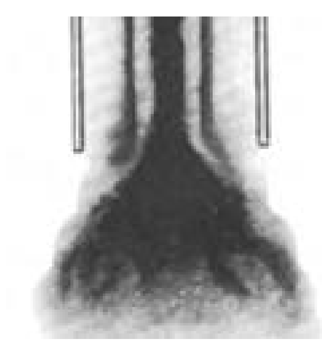
The hot, energetic gases which are released by combustion of solid rocket propellant represent a reservoir of potential energy which must be converted to kinetic (motion) energy if it is to accomplish the work of propelling the rocket from the launch pad to its intended destination. Unless the energy is efficiently applied to the work, much or all of its potential will be wasted as it dissipates into the surrounding atmosphere in the form of heat.

The nozzle is the device by which the internal energy of the exhaust gases is converted into kinetic energy, thereby producing thrust (force). For any given propellant system, the nozzle acts as a metering device to control the rate of gas flow, thus creating a predictable amount of thrust over a programmed time period. The energy conversion is accomplished by causing the gas molecules to accelerate to extremely high velocities as they leave the motor.

Solid propellant combustion produces a mass of hot gases equal to the mass of the solid material being burned. These hot gases fill the combustion chamber soon after ignition, and the pressure quickly reaches the operating (steady state) level, at which a constant amount is produced. Just how the nozzle can cause the gas particles to accelerate by apparently restricting their free flow by providing a smaller exit cross sectional area than that of the chamber is not readily apparent.

What actually happens is this: The hot gases developed by propellant combustion are partially entrapped by the motor aft closure and the convergent section of the nozzle, thus causing them to compress.   A curious fact of gas behavior is that under compression, if an escape route is provided, pressure drops as potential (pressure) energy is converted to kinetic energy (velocity).

Rocket engineers measure the speed at which gas particles move in relation to the “local speed of sound” (sonic velocity). The term “local speed of sound” does not refer to the 760 mph value at sea level that we associate with sonic velocity in aircraft. Instead, it refers to the speed at which sound travels through combustion gases under the temperature and pressure conditions existing at a specific point in the gases.   At a critical pressure, gas flow escapes through the nozzle throat at acoustic (sonic) velocity, and a balance is reached between gas propagation and exhaust.



No restriction of the exit area, gases escape at subsonic velocity

Exit area is restricted by aft closure, gases at acoustic velocity.

Exit area restricted by aft closure and nozzle, gases escape at supersonic velocity

Since the gases within the rocket motor's combustion chamber move at a speed less than the local acoustic velocity, they are said to be flowing subsonically. It is the function of the nozzle to cause them to accelerate at a controlled expansion so that the maximum possible kinetic energy is developed from the potential energy produced by combustion.

Approximately 65 to 75 percent of total vehicle thrust is developed by acceleration of the combustion products to sonic velocity at the nozzle throat; the remainder is developed by acceleration to supersonic velocities as the gases expand in the divergent (expansion cone) section.

Thus, without the divergent nozzle section to control and direct the expansion of gases already moving at sonic velocity, one-quarter to one-third of the propulsive thrust generated might be wasted as the particles dispersed into the surrounding medium.

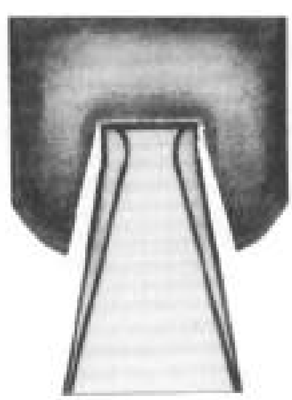
All nozzles currently used on solid propellant rocket motors are of the converging-diverging (DeLaval) type, which is made in two basic configurations, the external and submerged.

A nozzle type known as the "spike" configuration has been under development for some time, but to date has found application mainly on experimental motors as a means of controlling thrust magnitude and or chamber pressure to provide stop restart capability, and for missile applications requiring control of the amounts of thrust to be delivered at different times during the rocket's flight. The external configuration is the basic classical convergent-divergent design which is mounted entirely external to the motor. In the submerged configuration, the nozzle entry, throat, and part or all of the expansion core is cantilevered or extended into the motor chamber.

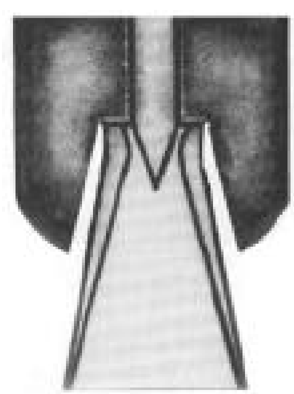
The submerged design is the more complex of the two, because: both the inner and outer surfaces of the submerged portion are exposed to the hot gases; and the submerged section must structurally withstand external pressure forces in addition to the forces developed by gas flow along its inner surfaces.

Nozzle Types

External

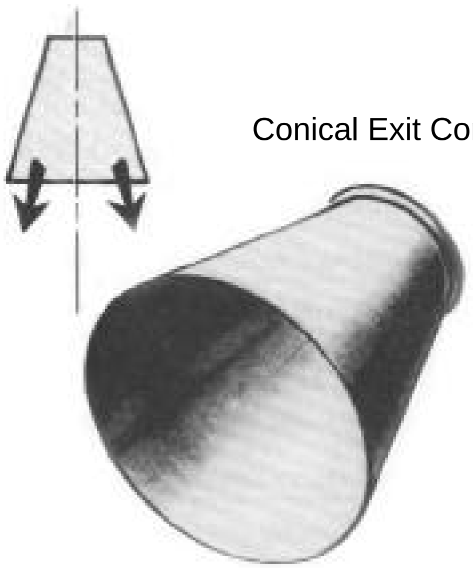


Submerged

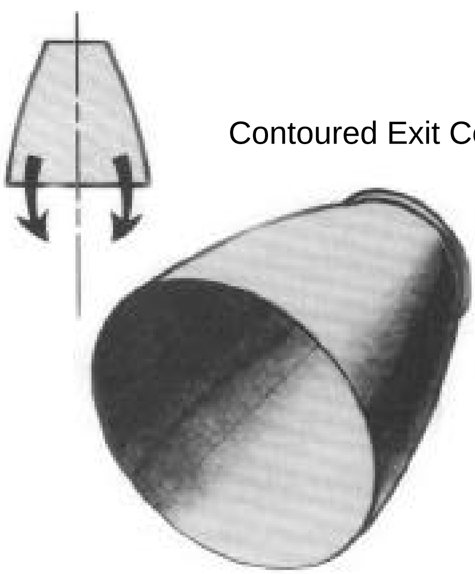


Spike

In addition, there are two basic exit cone configurations, conical and contoured. The purpose of contouring the cone is to direct the flow of the exhaust stream so that its force will be concentrated as directly as possible along the longitudinal centerline of the nozzle, thus minimizing flare or divergence of the exhaust stream and concentrating thrust as much as possible.



Conical Exit Cone



Contoured Exit Cone

Nozzle Materials

The materials used in the fabrication of solid propellant rocket motor nozzles can be divided generally into five classes: structural materials; adhesives; sealants and greases; thermal insulators; and ablative or erodible materials.

Structural materials are applied generally according to the maximum operating temperature to which they will be exposed.

Up to 500 °F, the most used materials are aluminum alloys and fiberglass-resin composites, both of which have high-strength-to-weight ratios, are light in weight, easily fabricated, have good corrosion resistance, and are reasonable in cost. High strength steels are used when major considerations are high strength in thin sections, or operation at the higher end of the temperature range.

Between 500° and 1,900 °F, the higher temperature iron, iron-nickel, nickel, cobalt, and iron-nickel-cobalt chromium base super alloys are used.

Above 1,900°F, alloys of refractory metals (capable of resisting high heat without cracking, melting or crumbling) such as molybdenum, columbium, tantalum, and tungsten provide high strength to approximately 4,500°F.

Above 4,500 °F, about the only structural materials available are graphite and pyrolytic graphite.

Adhesives play an important role in joining the various dissimilar materials of which the nozzle is made to assure the soundness of joints and for sealing spaces between materials to prevent gas leakage.

Sealants such as zinc chromate putty and silicone grease may be used to plug cracks. O-rings of rubber are used where more positive seals are required.

Thermal insulators are used between the nozzle ablative (erodible) and structural materials for protection of the latter from the high temperature exhaust gases. They may also be used externally for protection from aerodynamic heating. The most common nozzle insulating materials are composites of asbestos fibers and phenolic resins, and coatings of ceramic refractory materials, principally zirconium dioxide.

Ablative materials are used to withstand a combination of erosion, fusion, (liquefying or melting together by heat), corrosion, or decomposition, leading to progressive degradation (decomposition by stages), and or loss of material as a direct consequence of exposure to the hot propellant gas flow in the nozzle.

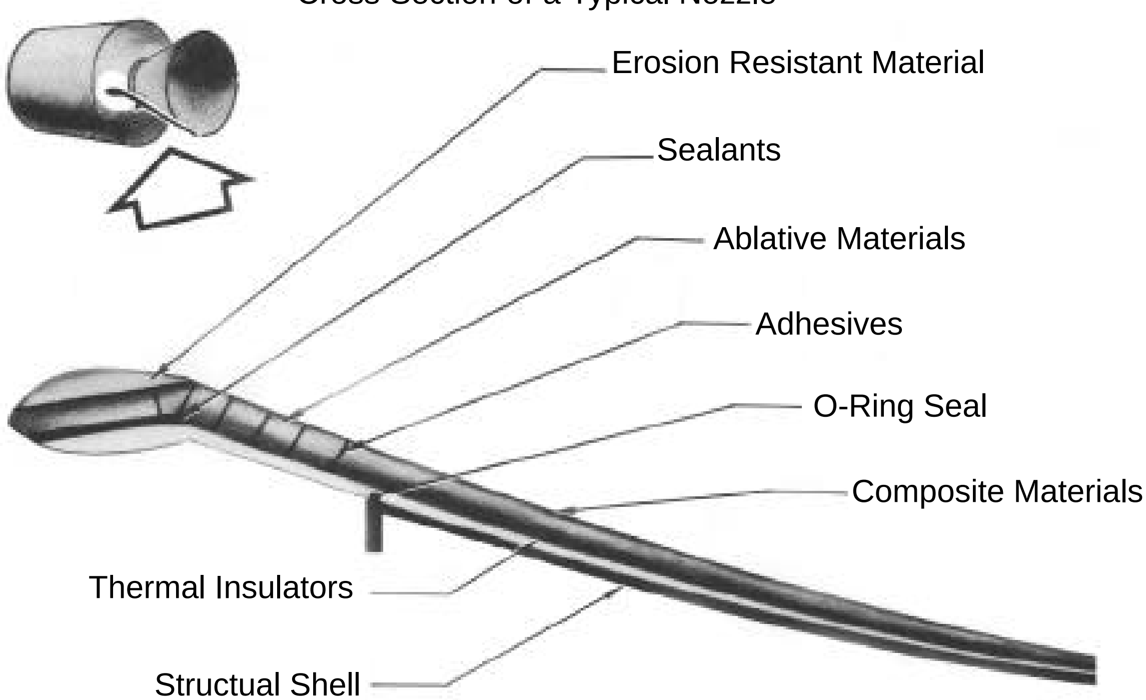
Erosion resistant materials are used in the nozzle throat, since it is subjected to the most severe environment. The most common materials are graphite and pyrolytic graphite. The stronger and more heat resistant pyrolytic graphite has high strength, high thermal conductivity (capacity to transmit heat), and low expansion.

If graphite or pyrolytic graphite cannot be used advantageously because of nozzle size or the extremely erosive nature of the exhaust products, the nozzle throat insert may be a refractory metal or an alloy, such as forged, arc cast tungsten, or tungsten-molybdenum alloy. If high erosion can be tolerated as in extremely large nozzles with large throat areas, reinforced plastics may be used, such as refractory fiber reinforced plastic composite materials.

More erosion may be tolerated in the exit cone, since it does not exercise control over gas flow, so fiberglass reinforced phenolic resins containing silica, graphite, or carbon to increase erosion resistance are used in this area.

Composite materials are under development which may be used to fabricate the whole nozzle for certain applications. Known variously as carbon-carbon composites, fibrous graphite, prepyrolyzed composites, graphite-graphite composites, graphite composites, and prechars, they will be formed primarily by pressure molding. All are characterized by two features: 1) all have been processed at a

Cross Section of a Typical Nozzle



temperature high enough so that all charable material has charred and converted to carbon or graphite; and 2) they contain a graphite or carbon fabric, fiber, filament, or felt reinforcement bonded together, with carbon or graphite as the bonding material.

Nozzle Fabrication

Several fabrication methods are employed in the manufacture of nozzles, the types and number depending primarily upon the types of reinforced plastic components that are to be used as ablative liners and ceramics or metallic components that are to be employed in those areas such as the throat where little or no erosion can be permitted to occur.

Ablative materials used in the exit cone usually are fabricated by wrapping fiberglass tape over a metal form called a mandrel, so that the grain of the finished unit is oriented to provide the required erosion resistance. Designers have found that grain directional orientation has an effect on the amount of the material that will be eroded away by the exhaust gases during rocket operation. After winding, the tape is cured, machined as necessary, and assembled with other components using adhesives and sealants as required.

Throat materials may be forged, cast, or pressure molded.

Structural shells of metal are generally machined from cast billets of aluminum or other alloys.

Flight Direction Control

Unless some means of guidance is provided, the flight of the rocket is subject to unprogrammed variations in direction that can be caused by wind currents or other natural forces. Without guidance, the rocket must follow a ballistic flight path or trajectory; i.e., its path will be similar to that of a bullet, rock, or other hurled object.

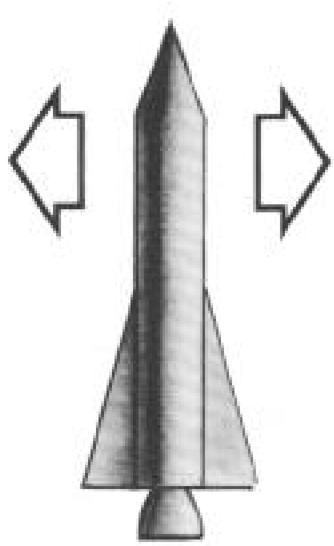
A rocket’s flight path must be planned in three dimensions, length, width, and height, so corrective maneuvers must be possible in all three planes. The simplest way of visualizing the path flown by a rocket is to think of its being propelled down the center of a tube. Each time the rocket’s flight deviates from the bounds of its allotted air space and touches the sides of the tube, a correction is made to move it back toward the tube’s center, no matter whether it must be guided up or down, left to right.

Maintaining alignment is accomplished by directional corrections in the pitch plane for up or down and in the yaw plane for left or right. Correct alignment of these axes in relation to the reference plane on which the flight path is based, is accomplished by rotating the vehicle clockwise or counterclockwise around its longitudinal (nose to tail) centerline using the roll control.

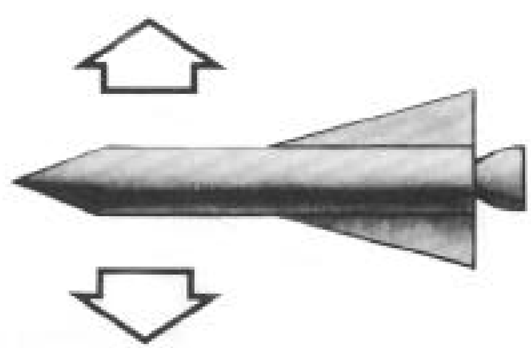
Types of Attitude Control Systems

Most air-to-air missiles, air-to-ground missiles, and ground-to-air missiles are guided through the use of movable airfoils, usually similar to the control surfaces (ailerons) on airplane wings and tails. Movable airfoils can be used for many rocket propelled vehicles because they operate within the Earth’s atmosphere and entirely, or very largely, at speeds at which such control surfaces are effective. Certain types of rocket vehicles, however, cannot depend entirely upon airfoils for control, usually because they operate in the extreme upper atmosphere or in space, where airfoils are not effective, or because their launching speed is too low for airfoils to be effective. Most ballistic missiles and space vehicles fall into this latter category.

To make directional or attitude corrections without the use of airfoils, the thrust delivered by the propulsion system must be deflected (vectored) to cause the rocket to pivot around its center of mass (center of gravity) like a lever or fulcrum around its pivot point.



Flight directional control for left of right is referred to as “yaw”

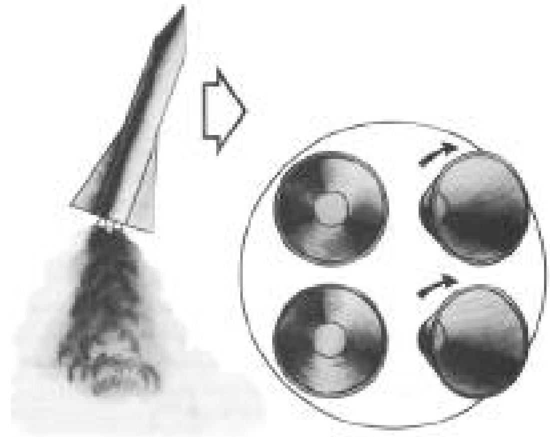


Flight directional control for up or down is referred to as “pitch”

Thrust vector control (TVC) systems can be divided generally into those which change the direction of thrust flow within the fixed nozzle and those which change it with the movable nozzle.

A primary approach to rocket motor TVC, and one of the more highly developed because of its long usage, is the diversion of exhaust gas through nozzle movement. The more common movable configurations are the single omniaxial (all directional) nozzle, multiple omniaxial nozzles, and multiple hinged nozzles.

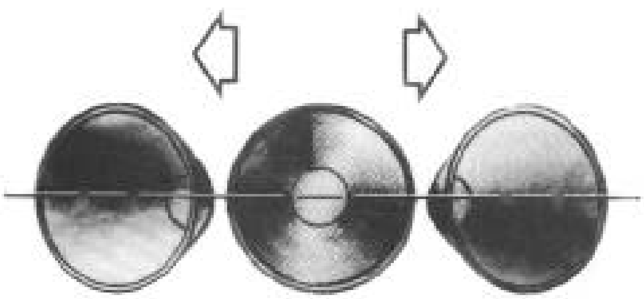
Both yaw nozzles are turned right
. . . rocket moves right



Movable Nozzles

Movable nozzles provide directional control by changing the direction of motor thrust, usually through movement of the exit cone or nozzle throat, or both. Movable nozzles move in a single plane (Stage I Minuteman) or multiple planes (Poseidon).

View from below a movable nozzle



Changing direction is affected by moving the nozzle along a single axis plane. Some nozzles move many directions (omniaxial).

Single plane nozzles usually are used in series of four so that pitch, yaw, and roll control can be achieved. When pitch or yaw motion is required, both pitch or yaw nozzles are moved in the same direction.
Roll control usually is achieved with the motion of one nozzle, or with two acting in opposite directions.

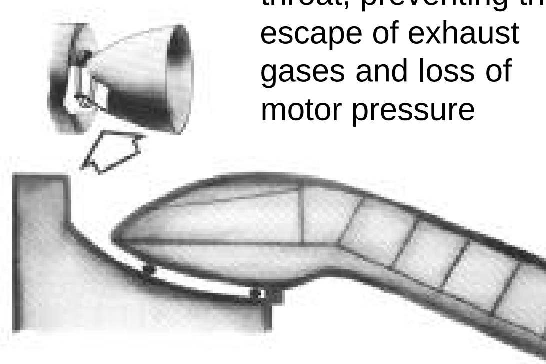
Omniaxis nozzles are capable of moving in any pitch or yaw plane with the use of special load carrying and sealing mechanisms. Since an omniaxis nozzle can provide both pitch and yaw control, only one nozzle is needed, and small secondary thrusters are used for roll control.

The two most important features of movable nozzles are the sealing and load carrying systems between the stationary and movable portions of the nozzle.

The sealing system must allow movement of the nozzle while restraining motor pressure. Sealing systems used have included rubber O-rings, bellows, diaphragms, metal reinforced elastomeric (rubber-like polymer) joints, and various combinations.

O-ring Seal System

O-rings form a positive seal around the nozzle throat, preventing the escape of exhaust gases and loss of motor pressure

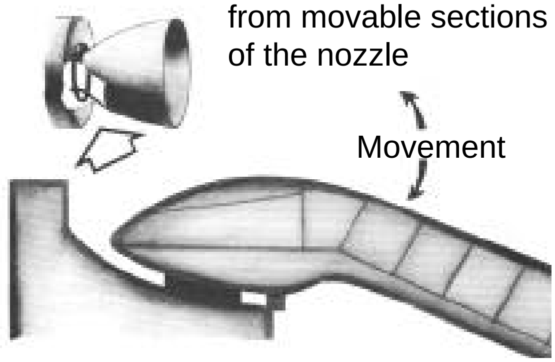


Load Carrying Systems

The load carrying system also must allow motion between the fixed and movable sections of the nozzle while preventing excessive deflections in the movable portion. The motion must be relatively free so that excessive forces are not required to obtain motion. Systems which are currently in use include the gimbal ring (universal joint type system), flexible joint (metal and elastomer laminae), and fluid type bearings. The most important function of these systems is providing mobility as well as support.

Fluid Bearing Load Carrying System

The fluid bearing separates fixed sections from movable sections of the nozzle



Jet vanes are small. Heat resistant rudders mounted near the aft end of the nozzle exit cone, which are rotated to deflect the hot exhaust gases, thereby producing a side force in the desired direction. Each of the four wedge-shaped jet vanes in the typical arrangement is securely attached to an actuator shaft. The vane in the typical arrangement is securely attached to an actuator shaft. The vanes, positioned by signals from the guidance system to the vane actuator, can be employed to obtain pitch, yaw, or roll control. Mounted to a single nozzle, the opposing pairs of vanes can be operated together to provide pitch or yaw movements; all four operated together can provide roll control.

Jet Vanes

Exhaust gases flow past vane. When activated into flow, gases are diverted by the rudder.

Fixed Nozzles

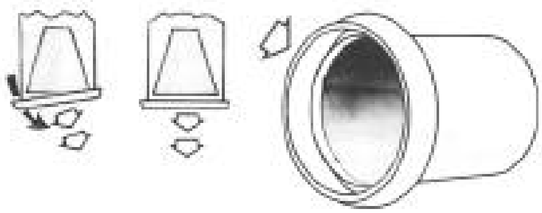
The two primary methods of producing lateral thrust with a fixed nozzle include mechanical interference (MITVC) and secondary injection (SITVC) thrust vector control.

Mechanical Interference TVC

MITVC involves changing the direction of the supersonic gases at the nozzle exit plane by inserting a heat resistant body into the exhaust stream to deflect it. Devices used in this method include jet vanes, jetavators, and jet tabs.

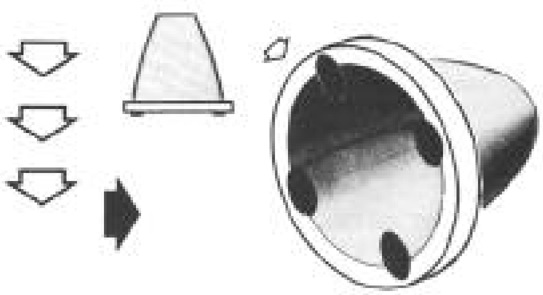
Designed to reduce drag losses associated with jet vanes, the jetavator consists of a movable surface attached to the end of the exit cone. The movable surface may be a complete spherical internally contoured ring or several segments. When actuated, it rotates into the exhaust stream, deflecting it as desired to provide the necessary thrust vector. With jetavators, pitch and yaw control can be obtained, but not roll control. Jetavators are currently used on the Bomarc booster for TVC.

Jetavator Diverting Exhaust



The jet tab system vectors the thrust by insertion of a blunt body (tab) into the supersonic exhaust stream just aft of the nozzle exit plane. Insertion of the tab induces a shock wave and a localized induced pressure area just upstream of the tab, thus producing a side force perpendicular to the axial thrust vector. The thrust vector is controlled by varying the ratio of the jet tab blockage area to the nozzle exit cross sectional area.

Jet Tab



nsertion of the tab creates increased pressure within the exit cone. The diverted force acts to vector the exhaust thrust.

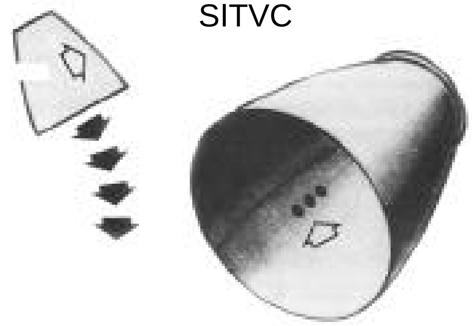
Secondary Injection TVC

Secondary injection TVC is accomplished by injecting fluid (liquid or gas) into the main exhaust stream of the rocket motor through ports in the expansion section of the nozzle.

The total side force produced by secondary injection consists generally of two parts: (1) the force caused by the momentum of the injected fluid; and (2) the imbalance of pressure induced by the injection reacting on an area of the nozzle surface perpendicular to the nozzle centerline.

Because there are several factors which influence the production of total side force during secondary injection into a supersonic nozzle, the location and angle of injection must be determined through experimentation and application of previously developed data.

SITVC



The thrust is deflected by the force of the injected fluid and by the imbalance of pressure created in the nozzle.

Types of Control Systems

Power for actuating the control systems is provided by hydraulic mechanical and electromechanical means, with electronic components especially designed for the application providing the required signals for precise positioning of components.

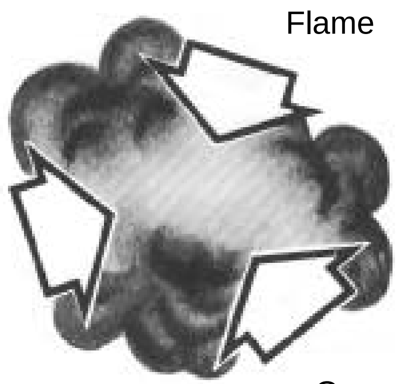
Propellants

The dictionary defines a propellant as a substance that causes an object to move or to sustain motion. Thus, rocket propellants exist for only one purpose, to produce the thrust required to cause a rocket to move from launch site to intended target.

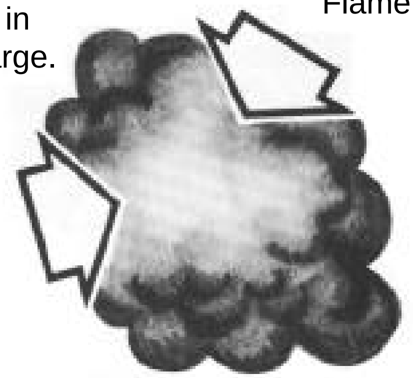
Thrust, as noted earlier, results from the production of hot gases during the combustion (burning) of the propellant and acceleration of those gases to supersonic velocity through a port or nozzle.

The internal combustion engine which powers automobiles, airplanes, and other vehicles obtains oxygen from the air, which is mixed with the fuel in the carburetor in proper proportions so that combustion can take place in the cylinders. Combustion of the propellant in a rocket motor cannot breathe air to obtain oxygen. Consequently, it must carry its own oxygen supply in addition to fuel supply. Separate fuel and oxygen supplies are carried in tanks aboard liquid rockets and these materials are mixed in the combustion chamber. In the solid rockets with which we are primarily interested, however, both fuel and oxidizer supplies must be contained within the propellent charge.

Liquid rocket:
Separate oxygen supply needed for combustion.



Solid rocket:
Both fuel and oxygen are contained in propellant charge.



To assure the release of maximum usable energy during propellant combustion, fuel and oxidizer materials are chosen carefully, and the exact proportions of each which are required for combustion are determined by analysis and experimentation.

The ideal, or best possible, solid propellant has as many of the following characteristics as possible.

1. High level chemical energy release to produce high combustion temperatures and develop maximum thrust from each pound of propellant (specific impulse) for high performance.

2. Low molecular weight of combustion products (the lower their molecular weight, the greater the acceleration that can be applied to the gases).

3. Stability (resistance to chemical and physical change) over a long period of time.

4. Maximum density so that the greatest amount of energy possible can be packed into every unit of case volume.

5. Resistance to the effects of atmospheric conditions, such as humidity, heat, cold, etc.

6. Resistance to accidental ignition from high temperature or impact.

7. Maximum possible physical strength to withstand the effects of forces imposed by heat and pressure during motor operation.

8. Very small change in volume with each degree of change in temperature, preferably matching that of the case material, to minimize stresses and strains in the two structures.

9. As nearly chemically non-reactive (inert) as possible ensuring storage and operation.

10. Easily produced and with desirable fabrication properties, such as adequate fluidity during casting; easy control of processes such as curing; and minimum volume change (shrinkage) following casting or molding.

11. Relative insensitivity of performance characteristics and fabrication techniques to impurities or small processing variations.

12. Predictable physical properties and combustion characteristics (burning rate) not affected appreciably by a wide range of storage and operating temperatures.

13. Smokeless exhaust gas to avoid deposition of smoke particles at operational locations and detection in military usage.

14. Readily bondable to metal parts, the application of inhibitors, and to different production techniques; and amenable to use of simple igniter.

15. Nonluminous, noncorrosive and nontoxic exhaust.

16. Simple method of preparation, not requiring complex chemical plant installation.

17. Grain should be opaque to radiation to prevent ignition at locations other than burning surface.

18. Able to withstand repeated extreme temperature variations prior to operation without physical or chemical deterioration.

19. Raw materials cheap, safe, and easy to handle and transport.

20. Burns at steady, predictable rate at motor operating conditions.

Solid Propellant Types

Solid propellants form mono propellant (mono = single) systems in which the oxidizer and fuel components are combined in a single mixture with a liquid material which holds them in suspension. This composition is then cast (poured) into the case, where it is cured to a solid state.

Propellant specialists divide solid propellants into two classifications - double-base and composite. These classifications refer to the physical and chemical characteristics of the propellants, as well as to the types of materials used in their manufacture.

The double-base (homogeneous) type propellants use nitrocellulose (guncotton) and an energetic plasticizer to cause it to dissolve and then harden into a solid form. Each molecule of this final material contains the fuel and oxygen required to sustain combustion (burning). The chemicals used in the manufacture of this type of propellant are unstable, usually nitrocellulose and or nitroglycerin. Each of these materials contains the necessary fuel and oxygen in its individual molecules to burn or explode without coming into contact with any other material.

Composite propellants are composed of separate fuel and oxidizer materials, neither of which will burn satisfactorily without the other. Mixed together and combined with a liquid which later is cured to solid form, they form a compound in which fuel and oxidizer are adjacent to each other in close enough contact to assure efficient combustion.

Composite propellants generally are composed of finely ground chemical oxidizers and inorganic fuels (made from noncarbon-containing material) which are suspended in a binder of rubber-like material which also serves as a fuel. Most composite propellants also may use a variety of chemicals to increase or decrease the burning rate (to control hot gas production rate), provide better physical properties than are obtainable with the basic binder, or to regulate chemical reactions for better control during the manufacturing process.

Double-Base Propellants

The nitrocellulose used in the manufacture of double-base propellants, is prepared by combining cotton (cellulose fuel) with nitric acid (an oxidizer), which produces the single chemical nitrocellulose. Addition of nitroglycerin (a shock sensitive high explosive) to the nitrocellulose causes a physical reaction which partially dissolves the latter and causes it to swell, then to gel or solidify the nitroglycerin. In the process, the nitroglycerin is made less sensitive to shock. Certain other chemicals may be added to control the speed of gelling (solidification), speed or slow the burning rate, and improve physical characteristics or other properties of the propellant.

Double-Base (Homogeneous)

Each molecule contains both fuel and oxidizers. Chemical reactions solidify the propellant and additional materials improve its physical properties.

During storage, nitrocellulose decomposes slowly but steadily by releasing oxides of nitrogen. The rate of decomposition is accelerated by the presence of these oxides. Certain materials called “stabilizers” can be combined with the oxides to remove them, thus slowing the rate of decomposition and considerably extending the useful life of the propellant.

Materials used to improve the mechanical properties and extrusion (pressure forming) characteristics of double-based propellants are known as plasticizers. They may be either explosive or nonexplosive materials.

Because of the tremendous heat developed during combustion, high temperature radiation may be transmitted deep within the propellant unless darkening agents such as carbon black or lampblack are added to make the penetration impossible. This process prevents below-surface ignition, which could cause uncontrolled burning with an undesirable increase in chamber pressure.

Other chemicals may be added to improve the burning rate of other performance characteristics of the double-base propellant. These are known as ballistic agents.

Still other additives may be used to reduce the temperature of combustion gases as a means of controlling chamber pressure, or to reduce the hygroscopicity (moisture absorbing characteristics) of the propellant. And finally, various liquid ingredients may be added to the basic materials to serve as solvents for the purpose of speeding or improving the reduction of the components to liquid form.

Composite Propellants

The separate fuel and oxidizer components used in the production of composite propellants must be mixed together in the proper proportions to assure complete combustion, since neither will sustain combustion without the other. The chemical oxidizers and inorganic fuels are ground to fine, power-like states, mixed together, then added to a liquid material (binder) which holds them in suspension while it cures to a solid state. The final composition also may include a variety of chemicals to increase or decrease the burning rate, provide better physical properties than are obtainable with the basic binder, or improve processing quantities.

Binders

Both natural and man-made materials have been used as binder-fuels for solid propellant grains, including asphalt, and synthetic liquid prepolymers. All of the organic prepolymers have rubbery properties following cure and form a strong matrix (binding structure) within which the inorganic fuels and chemical oxidizers are solidly bound.

The most commonly used liquid prepolymers cure up much like rubber. An excellent example is the curing of the white of an egg, which solidifies and becomes rubbery when heat is applied. The egg white also acts as a binder in a cake, holding the other ingredients together through development of a long, chain like molecular structure.

The prepolymers used as binders in composite propellants are initially liquid, so that the fuel and oxidizer can be blended in more easily prior to the start of polymerization (cure). The polymers cure to an irreversible solid form by cross linking (formation of long chain-like molecules linked together).

The first material used as a binder for solid propellants was asphalt, which was used in the first jet assisted take-off (JATO) units for aircraft near the end of World War II. Asphalt occurs naturally and is a by-product of the distillation of certain crude oils. It has several disadvantages for rocket applications, however, including: formation of thick black smoke combustion, a melting point near that of water (212 F), and brittleness at low temperatures unless mixed with oils.

Elastomers are the rubber-like natural and synthetic materials which have found the widest application in the modern (50’s - 70’s era) solid rocket propellants. The first material used as a binder was a liquid polysulfide prepolymer, first produced commercially as a solid elastomer in 1932 by Thiokol Chemical Corporation. Its application in “GALCIT” solid propellant by the Guggenheim Aeronautical Laboratories of the California Institute of Technology marked the beginning of the modern era in solid propellant, since it made possible production of large (up to 260 inch diameter) solid rocket motors.

Other liquid prepolymers which have been and are being used in large rocket motors include polybutadiene-acrylic and acid-acrylonitrile prepolymer, and carboxyl terminated polybutadiene. Each of these materials provides reproducible physical characteristics, and all have excellent aging and chemical resistance characteristics.

Additives

In order to obtain specific properties, several special ingredients may be added to composite propellants, including: oxidants, antioxidants, and curing and burning rate catalysts.

In other instances, an increase in the burning rate may be desirable, and this can be obtained by adding chemical agents known as burning rate catalysts which cause an increase in the combustion reactions.

Oxidizers

A number of inorganic chemicals can be used to supply the oxygen required to support the combustion of metallic and other fuels in solid propellants. The amount of oxygen provided by each oxidizer depends upon its molecular structure, and certain performance characteristics may restrict applicability to various degrees.

In general, the perchlorates: potassium, ammonium, lithium, sodium, and nitronium - have more oxygen in their structure than do the nitrates: ammonium, potassium, and sodium, although availability of oxygen is not the only consideration when choosing the oxidizer to be used.

Some of the perchlorates produce hydrogen chloride, a highly corrosive gas which forms hydrochloric acid when mixed with water, and other chlorine compounds. The exhaust gases of these oxidizers not only are toxic, but highly corrosive to many materials. With the exception of ammonium and nitronium perchlorates, all form a dense smoky exhaust because potassium perchlorate and sodium chloride are white powders. Ammonium and potassium perchlorate are only slightly soluble in water, so they can be used in propellants which are exposed to moisture.

The oxidizing potential of the perchlorates is generally high, and because of this fact they are often found in propellants of high specific impulse. All perchlorate oxidizers are potential explosives, but use of high purity material, special crystal processing techniques, and careful handling make processing of high energy propellants using these oxidizers possible. Nitronium perchlorate, the most powerful of the perchlorates, is very sensitive and can be detonated readily.

Of the three nitrates of interest, two (potassium and sodium nitrate) produce undesirable smoke because of the solids formed in the combustion products. Ammonium nitrate, widely used as a fertilizer, has the big advantage of producing a smokeless, relatively nontoxic exhaust. With the lowest oxidizing potential of all the materials used, however, ammonium nitrate is suitable mainly for low performance, low burning rate applications.

Metallic Fuels

Powdered aluminum is the metallic fuel most widely used in solid rocket propellants. The addition of approximately 15 percent aluminum powder to solid propellants seems to help in three ways: (1) by causing an increase in combustion temperature and thus an increase in thrust produced per pound of propellant (specific impulse); (2) by increasing the density of the propellant; and (3) by exerting a dampening effect on unstable burning which might develop at motor operating pressures and temperatures.

Beryllium causes not only an increased combustion temperature, but also produces lower molecular weight exhaust products; consequently, it can increase the theoretical specific weight impulse by 5 to 10 percent. The reaction products containing beryllium are extremely toxic, so special safety precautions are required.

Since metals lighter in weight than aluminum (lithium, beryllium, sodium, and magnesium) tend to be expensive, dangerous to handle in powder form, and highly active chemically, aluminum has been adopted as the workhorse metallic fuel in solid propellants.

What’s in the future?

Solid propellant technology is a continuously changing field in which even higher performance is sought and attained. Many of tomorrow’s materials have yet to be developed or tested.

Update: The last two sentences reflect the future as well as the past. Thiokol is continuously developing new materials to improve its products and meet the needs of the future.

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