Appendix E

ROCKET THEORY

Rocketry encompasses a wide range of topics, each of which takes many years of study to master. This chapter provides an initial foundation toward the study of rocket theory by addressing the physical laws governing motion/propulsion, rocket performance parameters, rocket propulsion techniques, reaction masses (propellants), chemical rockets and advanced propulsion techniques.

PROPULSION BACKGROUND

Rockets are like other forms of propulsion in that they expend energy to produce a thrust force via an exchange of momentum with some reaction mass in accordance with Newton's Third Law of Motion. But rockets differ from all other forms of propulsion since they carry the reaction mass with them (self contained) and are, therefore, independent of their surrounding environment.

Other forms of propulsion depend on their environment to provide the reaction mass. Cars use the ground, airplanes use the air, boats use the water and sailboats use the wind. The rockets we are most familiar with are chemical rockets in which the propellants (reaction mass) are the fuel and oxidizer. With chemical rockets, the propellants are also the energy source. A conventional chemical rocket is a type of internal combustion engine burning fuel and oxidizer in a combustion chamber producing hot, high pressure gases and accelerating them through a nozzle. In electric and nuclear rockets, the propellant is essentially an inert mass.

According to Newton's Second Law, the thrust force is equal to the rate of change of momentum of the ejected matter, which depends on both how much and how fast propellants are used (mass flow rate) and the propellant's speed when it leaves the rocket (effective exhaust velocity).

Like other forms of transportation, rockets consist of the same basic elements such as a structure providing the vehicle framework, propulsion system providing the force for motion, energy source for powering the vehicle systems, guidance system for direction control and last and most important (indeed the reason for having the vehicle at all), the payload. Examples of payloads are passengers, scientific instruments or supplies. When a rocket is used as a weapon for destructive purposes, we call it a *missile*; its payload is a warhead.

Fig. 5-1. Sir Isaac Newton

ROCKET PHYSICS

Sir Isaac Newton (**Fig. 5-1**) set forth the basic laws of motion; the means by which we analyze the rocket principle. Newton's three laws of motion apply to all rocket-propelled vehicles. They apply to gas jets used for attitude control, small rockets used for stage separations or for trajectory corrections and to large rockets used to launch a vehicle from the surface of the Earth. They apply to nuclear, electric and other advanced types of rockets as well as to chemical rockets. Newton's laws of motion are stated briefly as follows:

Newton's 1st Law
(Inertia)

Every body continues in a state of uniform motion in a straight line, unless it is compelled to change that state by a force imposed upon it.

Newton's 2nd Law
(Momentum)

When a force is applied to a body, the time rate of change of momentum is proportional to, and in the direction of, the applied force.

Newton's 3rd Law
(Action—Reaction)

For every action there is a reaction that is equal in magnitude but opposite in direction to the action.

In relating these laws to rocket theory and propulsion, we can paraphrase and simplify them. For example, the first law says, in effect, that the engines must develop enough thrust force to overcome the force of gravitational attraction between the Earth and the launch vehicle. The engines must be able to start the vehicle moving and accelerate it to the desired velocity. Another way of expressing this for a vertical launch is to say that the engines must develop more pounds of thrust than the vehicle weighs.

When applying the second law, we must consider the summation of all the forces acting on the body; the accelerating force is the net force acting on the vehicle. This means if we launch a 200,000-lbf vehicle vertically from the Earth with a 250,000-lbf thrust engine, there is a net force at launch of 50,000-lbf—the difference between engine thrust and vehicle weight. Here the force of gravity is acting opposite to the direction of the thrust of the engine.

As the rocket operates, the forces acting on it change. The force of gravity decreases as the vehicle's mass decreases, and it also decreases with altitude. As the rocket passes through the atmosphere, drag increases with increasing velocity and decreases with altitude (lower atmospheric density).[1] As long as the thrust remains constant, the acceleration profile changes with the changing forces on the vehicle. The predominate effect is that the acceleration increases at an increasing rate as the vehicle's mass decreases.[2]

Figure 5-2 shows the general acceleration and velocity profiles during powered flight. The acceleration and velocity are low at launch due to the small net force and high vehicle mass at that time. Both acceleration and velocity

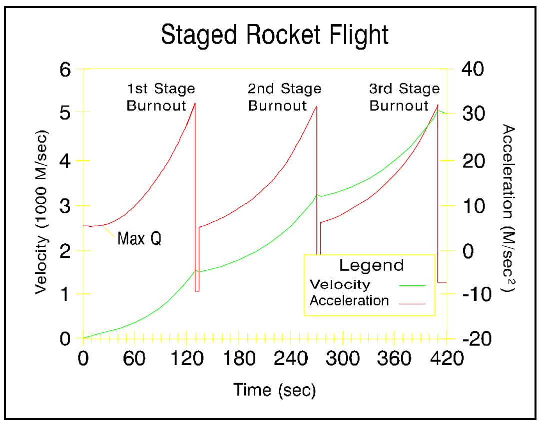


Fig. 5-2. Acceleration and Velocity

increase rapidly as the engine burns propellants (reducing vehicle mass and increasing the net force).

At first stage burnout, the acceleration drops (the acceleration at this point is due to the environment: gravity and drag) and is generally opposite the direction of

[1]The term "Max Q" refers to the highest structural pressure due to atmospheric drag.
[2]As the net force on the vehicle increases and the mass decreases, the acceleration increases at an increasing rate.

motion. With second stage ignition, acceleration and velocity will increase again. As the upper stage rocket engine(s) burn more propellants, rapid increases in acceleration and velocity occur. When the vehicle reaches the correct velocity (speed and direction) and altitude for the mission, it terminates thrust. Acceleration drops as the net force on the vehicle is due to the environment, mainly gravity, after thrust termination, or burnout, and the vehicle begins free flight. For vehicles with three, four or more stages, similar changes appear in both the acceleration and velocity each time staging occurs. Staging a vehicle increases the velocity in steps to the high values required for space missions.

Once a vehicle is in orbit, we say it is in a "weightless" condition. In fact, the vehicle is continually in free-fall, always accelerating toward the center of the Earth. The acceleration still depends on the summation of the forces acting on the vehicle (or the net force).

In a free-fall condition, we don't have to continually counter act the force of gravity, the vehicle's momentum accomplishes this task.[3] In this "weightless" condition, even a very small thrust (0.1 pound) operating over a long period of time can accelerate a vehicle to great speeds, escape velocity and more for interplanetary missions.

To relate Newton's third law, or "action-reaction law" to rocket theory and propulsion, consider what happens in the rocket motor. All rockets develop thrust by expelling particles (mass) at high velocity from their nozzles. The effect of the ejected exhaust appears as a reaction force, called thrust, acting in a direction opposite to the direction of the exhaust. The rocket is exchanging momentum with the exhaust.

[3]When the vehicle's orbit doesn't intersect the Earth's surface, we say the gravitational force is balanced by the inertial force.

It is his Third Law of Motion that explains the working principle of all propulsion systems.

A rocket engine is basically a device for expelling small particles of matter at high speeds producing thrust through the exchange of momentum. When liquid or solid chemicals are used as propellants, the exhaust consists of gas molecules. Recent scientific advances have involved experimental and theoretical work on rocket engines using *ions* (charged atomic particles), *nuclear particles* and even beams of light (photons) as "propellants."

Two items are necessary for propulsion: matter and energy. Matter is the *reaction mass* and is the source of momentum exchange. The reaction mass begins with the same momentum as the rocket vehicle, but as the rocket expels this mass, the rocket and all remaining propellants receive an equal increase in momentum in the opposite direction.

It takes energy to accelerate the reaction mass (impart momentum). The faster propellants are accelerated, the more propulsive force achieved; however, it also takes more energy.

ROCKET PERFORMANCE

There are several rocket performance parameters that, when taken together, describe a rocket's overall performance: 1) Thrust, 2) Specific Impulse, and 3) Mass Ratio.

Thrust *(T)*

The thrust is the amount of force an engine produces on the rocket (and on the exhaust stream leaving the rocket, conservation of momentum). The amount of thrust, along with the rocket mass, determines the acceleration. The mission profile will determine the required and acceptable accelerations and thus, the required thrust. Launching from the Earth typically requires a thrust to weight ratio of at least 1.5 to 1.75. Once the vehicle is in orbit and the vehicle's momentum balances the gravitational force, smaller thrust forces are usually sufficient for any maneuvering.

Specific Impulse (I_{sp})

Specific impulse is a measure of propellant efficiency, and numerically is the thrust produced divided by the weight of propellant consumed per second (ending up with units of *seconds*).

So, I_{sp} is really another measure of a rocket's exhaust velocity. Specific impulse is the common measure of propellant and propulsion system performance, and is somewhat analogous to the reciprocal of the specific fuel consumption used with conventional automobile or aircraft engines. The larger the value of specific impulse, the better a rocket's performance.

We can improve specific impulse by imparting more energy to the propellants (increasing the exhaust velocity), which means that more thrust will be obtained for each pound of propellant consumed. We can think of specific impulse as the number of seconds for which one pound of propellant will produce one pound of thrust. Or, we can think of it as the amount of thrust one pound of propellant will produce for one second.

Mass Ratio (M_R)

Since the rocket engine is continually consuming propellants, the rocket's mass is decreasing with time. If the thrust remains constant, the vehicle's acceleration increases reaching its highest value at engine cut-off; *for example,* the space shuttle reaches 3 Gs just before main engine cut-off.

The purpose of a rocket is to place a payload at specified position with a specific velocity. This position and velocity depends on the mission. We can equate the energy needed to do this to the change in velocity (or *delta-v*, Δv) the rocket imparts to the satellite. For a rocket, the ideal Δv gain depends on the I_{sp} (exhaust velocity, v_e) and the *mass ratio*.

The more propellant the vehicle can carry with respect to its "dry" weight, or weight without propellant aboard, the faster it will be able to go. Mass ratio is an expression relating the propellant mass to vehicle mass; the higher the mass ratio, the higher the final speed of the rocket. Therefore, a rocket vehicle is made to weigh as little as possible in its "dry" state. Increasing the weight of the vehicle payload results in decreasing the mass ratio, and therefore cutting down the maximum altitude or range. For example, the addition of one pound of payload to a high-altitude sounding rocket may reduce its peak altitude by as much as 10,000 feet.

PROPULSION TECHNIQUES

From our previous discussion of rocket performance parameters, we see that we would like to be as efficient as possible in developing thrust. To develop thrust, we have to exchange momentum with some reaction mass (propellant). Any way that we can do this is a valid propulsion option. We would like to choose the option that decreased the overall mission cost while still providing for mission success.

We are most familiar with chemical rocket systems, however, there are other ways we can produce rocket propulsion. The two main ways of accelerating a propellant to provide thrust are: *thermodynamic expansion and electro-static/ magnetic acceleration*. The methods for providing the thermal energy for thermodynamic expansion, or electricity for electrostatic acceleration, can come from chemical, nuclear, or solar sources.

Thermodynamic Expansion

Thermodynamic expansion is the mechanism we are most familiar with. All of our chemical systems use this method to accelerate the propellants. However, we can also use nuclear or electrical energy to heat the propellant.

In thermodynamic expansion, we heat the propellant to turn it into a high pressure, high temperature gas. We then allow that gas to expand in a controlled way to turn the thermal potential energy into directed kinetic energy, which produces thrust. The basic device used to create these large volumes of gas and to harness their heat energy is extremely simple and often contains no moving parts.

The rocket engine using thermodynamic expansion creates a pressure difference between the thrust chamber (combustion chamber) and the surrounding environment. It is this pressure difference that accelerates the gases.

A rocket engine usually operates at what the gas dynamist calls *supercritical conditions*—high chamber pressure exhausting to low external pressure. The Swedish engineer Carl G.P. De Laval showed that for supercritical conditions gases should be ducted through a nozzle that converges to a throat (section of smallest area) and then diverges to transform as much of the gases' thermal energy into kinetic energy.

Nozzles

There are a number of nozzle types; **Figure 5-3** depicts four of them. The conical nozzle is simple and easy to fabricate and provides adequate performance for most applications; however. it also has off axis exhaust velocity components which reduces the efficiency. The radial velocity components cancel and don't contribute to the overall thrust, therefore the energy going into the radial velocity is wasted. The contoured or bell-shaped nozzle provides for rapid early expansion producing shorter (less massive) nozzles, and redirects the exhaust toward the axial direction near the nozzle exit. The plug and expansion-deflection type nozzles are much shorter than a conventional conical nozzle with the same expansion ratio.

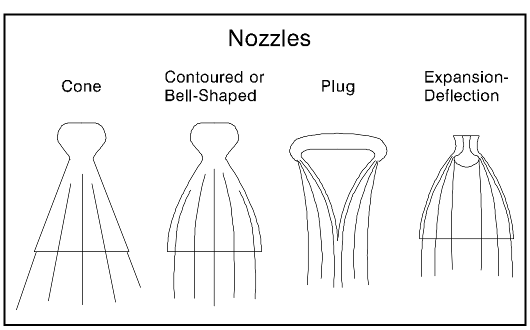


Fig. 5-3. Nozzle Types

These nozzles have a center body and an annular chamber. The plug changes the direction of the gas flow from the throat during expansion from radial to an axial direction. The expansion of exhaust gas is determined by ambient pressure. A variation of the plug nozzle is the aerospike, which uses radial auxiliary combustion chambers around the exit to the main combustion chamber. The exhaust plumes from the auxiliary chambers expand to form a "nozzle" for the gases escaping from the engine. Over expansion and under expansion can be largely compensated for by increasing or decreasing the thrust of the auxiliary chambers.

Chemical Rockets

Chemical rockets are unique in that the energy required to accelerate the propellant comes from the propellant itself, and in this sense, are considered energy limited. Thus, the attainable kinetic energy per unit mass of propellant is limited primarily by the energy released in chemical reaction; the attainment of high exhaust velocity requires the use of high-energy propellant combinations that produce low molecular weight exhaust products. Currently, propellants with the best combinations of high energy content and low molecular weight seem capable of producing specific impulses in the range of 400 to 500 seconds or exhaust velocities of 13,000 to 14,500 ft/sec.

Chemical rockets may use liquid or solid propellants or, in some schemes, combinations of both. Liquid rockets may use one (*monopropellant*), two (*bipropellant*) or more propellants. Bipropellants consist of a combination of a fuel (kerosene, alcohol, hydrogen) and an oxidizer (oxygen, nitric acid, fluorine). The liquids are held in tanks and fed into the combustion chamber where they react and then expand through the nozzle.

In contrast, solid propellants are an intimate mixture containing all the material necessary for reaction. The entire block of solid propellant, called the *grain*, is stored within the combustion chamber. Combustion proceeds from the surface of the propellant.

A chemical rocket engine is little more than a gas generator. The rapid combination (combustion) of certain chemicals results in the release of energy and large volumes of gaseous products. The gas molecules generated have considerable energy in the form of heat. In ordinary chemical rocket engines, the temperature of the resulting gases can rise higher than 5,500 degrees Fahrenheit.

For chemical systems in general, liquid propellants provide higher specific impulses than solid propellants. We call liquid Hydrogen (LH) and liquid Oxygen (LOX) high energy propellants because of the large energy release during combustion and the high transfer of thermal energy into directed kinetic energy of the exhaust stream.

An efficient LH/LOX burning engine produces around I_{sp} = 390-430 sec. on average.[4] Solid propellant motors produce around I_{sp} = 265-295 sec.

The total impulse of a rocket is the product of thrust and the effective firing duration. A typical shoulder launched short-range rocket may have an average thrust of 660 pounds for an effective duration of 0.2 seconds, giving a total impulse of 132 lbf-sec. In contrast, the Saturn rocket had a total impulse of 1.14 billion lbf-sec.

Nuclear Rockets

The nuclear rocket is an attempt to increase specific impulse by using nuclear reaction to replace chemical reaction as the energy source. The nuclear reactor generates thermal energy and heats the propellant which is then expanded through a conventional nozzle.

Compared to the chemical rocket, the nuclear rocket has some advantages. The energy released in a nuclear reaction is very much larger than that of a chemical reaction (on the order of a million times larger), and since the energy source is separate from the propellant, we have a larger latitude for propellant choice. Thus, hydrogen would be a good propellant because it has the lowest atomic weight, and would provide the highest exhaust velocities for a given chamber pressure and temperature.

We might think that the abundant energy in nuclear rockets would mean that we could employ indefinitely high chamber temperatures. This is definitely not the case, however, since the heat is transferred from a solid reactor to the propellant. Thus the structural components within the nuclear rocket, unlike those in a chemical rocket, *must be hotter than the propellant*, and the temperature cannot exceed the limiting temperature of the structure or the reactor material. The attainable temperatures in nuclear rockets to date are considerably below the temperatures attained in some chemical rockets, but the use of hydrogen as the propellant more than offsets this temperature disadvantage. Thus, as far as specific impulse is concerned, the increased performance of nuclear rockets is entirely due to the use of a propellant with a low atomic weight. The nuclear fission rocket offers roughly twice the specific impulse of the best chemical rocket (about 800-1,000 seconds), while delivering fairly high thrusts for long periods of time.

One theoretical improvement is a high-density reactor using fast neutrons. This type of reactor is expected to produce higher performance levels in a smaller

[4] The I_{sp} of any particular engine depends upon its design altitude. The Space Shuttle Main Engines (SSME) produce I_{sp} = 363.2 @ sea level, and 455.2 @ vacuum.

package than the thermal (or slow) reactors. Another improvement is a gas core reactor in which the operating temperature could be much higher. This increase in temperature would occur because of the elimination of the solid core of fuel elements used in slow and fast reactors. These structural elements are temperature limited.

NASA's Lewis Research Center is pursuing a concept for a reusable vehicle propelled by a nuclear thermal rocket (NTR) to take astronauts to the Moon and back (**Fig. 5-4**). With the addition of modular hardware elements, the lunar transit vehicle would become the core of a spacecraft to land astronauts on Mars early in the 21st century.

Specific impulse has reached about 850 seconds in nuclear engines, while the best

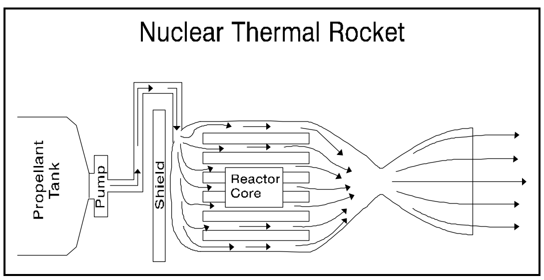


Fig. 5-4. Reusable Rocket

liquid oxygen/liquid hydrogen combustion engines only approach 475 seconds (in a vacuum). Such a system could decrease transit times to Mars from 9-15 months down to 4-6 months, leaving more time for exploration. Of course nuclear rockets have drawbacks. Nuclear reactors are not only heavy, but while in operation, produce large amounts of radiation. The mass and radiation hazard prohibit its use as a launch vehicle. However, once in space the benefits on long range missions would more than offset the extra mass.

Electrothermal Rockets

Another method using thermodynamic expansion is the *arcjet*. The arcjet is an *electrothermal* rocket because it uses electrical energy to heat a propellant. In this method, an annular arc is created in the chamber and the propellant is heated to high temperatures as it interacts with the arc. After the heating, the propellant is expanded through a conventional nozzle (**Fig. 5-5**).

This type of propulsion takes advantage of using hydrogen as a propellant, and, like nuclear rockets, experiences a similar performance gain in

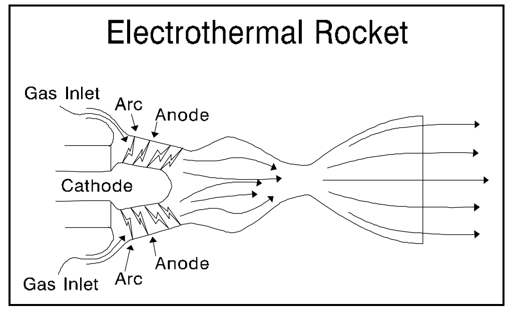


Fig. 5-5. Conventional Nozzle

specific impulse (up to 1,200 seconds). Unlike nuclear rockets, arcjets are small, producing little more than several pounds of thrust.

Electrical Propulsion

Electrical and electromagnetic rockets fundamentally differ from chemical rockets with respect to their performance limitations. Chemical rockets are *energy-limited*, since the quantity of energy is limited by the chemical behavior of the propellants. If a separate energy source is used, much higher propellant energy is possible. Further, if the temperature limitations of solid walls could be made unimportant by direct electrostatic or electromagnetic propellant acceleration without necessarily raising the fluid temperature, there would be no limit to the kinetic energy we could add to the propellant. However, the rate of conversion from nuclear or solar to electrical energy and then to propellant kinetic energy is limited by the mass of the conversion equipment. Since this mass is likely to be a large portion of the total mass of the vehicle, the electrical rocket (including electrothermal/static/magnetic) is essentially *power-limited*.

Electrostatic/magnetic rockets convert electrical energy directly to propellant kinetic energy without necessarily raising the temperature of the working fluid. For this reason the specific impulse is not limited by the temperature limitations of the wall materials, and it is possible to achieve very high exhaust velocities, although at the cost of high power consumption.

Because of the massive energy conversion equipment, electrical rockets have low thrust, perhaps only one-thousandth of vehicle weight in the Earth's gravitational field. For this reason, they are mainly restricted to space missions during which the gravitational forces are very nearly balanced by inertial forces. Low accelerations are quite acceptable, since the journeys are of long duration.

The propellant of an electrical rocket consists of either discrete charged particles accelerated by electrostatic forces, or a stream of electrically conducting fluid (plasma) accelerated by electromagnetic forces.

Electrostatic Rockets

These are commonly called *ion rockets*. Neutral propellant is converted to ions and electrons and withdrawn in separate streams. The ions pass through a strong electrostatic field produced between acceleration electrodes. The ions accelerate to high speeds, and the thrust of the rocket is in reaction to the ion acceleration (**Fig. 5-6**).

It is also necessary to expel the electrons in order to prevent the vehicle from acquiring a net negative charge. Otherwise, ions would be attracted back to the vehicle and the thrust would vanish. They remove these excess electrons by re-injecting them back into the exhaust ion beam.

Ion rockets offer very high specific impulses (a typical figure being 10,000 seconds with values ranging up to 20,000 seconds), but very low thrust, one-half pound being high. It has been estimated that an ion rocket employing cesium propellant would require over 2,000 kW of electrical power per pound of thrust.

The propellant for ion engines may be any substance that ionizes easily. Unlike thermodynamic expansion, the size of the molecules is not a primary factor. The most efficient elements are mercury, cesium or the noble gases.

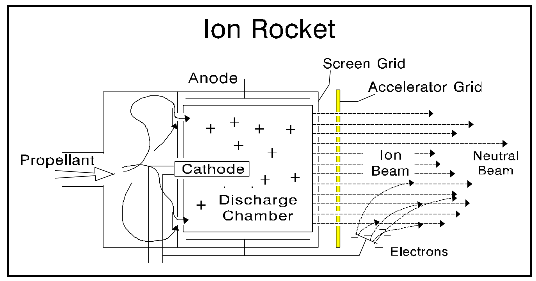


Fig. 5-6. Ion Acceleration

Electromagnetic Rockets

There are three major types of electromagnetic rockets: *magnetogas-dynamic*, *pulsed-plasma* and *traveling-wave*. All methods use a plasma with crossed electric and magnetic fields to accelerate the plasma.

A plasma is an electrically conducting gas. It consists of a collection of neutral atoms, molecules, ions, and electrons. The number of ions and the number of electrons are equal so that, on the whole, the plasma is electrically neutral. Because of its ability to conduct electrons, the plasma can be subjected to electromagnetic forces in much the same way as solid conductors in electric motors.

<u>Magneto-gas-dynamic Drive</u>.

Strong external electric and magnetic fields direct and accelerate the plasma stream, imparting high exhaust velocity. The performance is limited due to non-perpendicular currents flowing in the plasma at high field strengths. The specific impulse is lower than ion rockets but still very high (around 10,000 seconds). The mass flow rate is restricted so the thrusts remain low.

Pulsed-Plasma Accelerators.

One of the disadvantages of the steady crossed-field accelerators is that they require a substantial external field and therefore, a massive electromagnet. It is possible to make an accelerator for which an electromagnet is unnecessary by using the plasma current itself to generate the magnetic field, which gives rise to the accelerating force. Whereas the crossed-field accelerator is analogous to a shunt motor (which has separate current circuits for the electric and magnetic fields), the analog of this type of accelerator is the series motor in which the magnetic field is established by the same current which interacts to establish the crossed field force.

Traveling-Wave

A third type of plasma accelerator, sometimes called the magnetic-induction plasma motor, offers potential advantages over both the foregoing accelerators. It requires neither magnets or electrodes, and relies on currents being induced in the plasma by a traveling magnetic wave.

If the current in a conductor surrounding a tube containing a plasma increases, the magnetic field strength in the plane of the conductor will increase. Then an electromotive force will be induced in any loop in this plane. If the conductor current increases rapidly enough, the induced electric field will establish a substantial plasma current. The induced magnetic field and plasma current then interact to cause a body force normal to both, which tends to compress the plasma toward the axis of the tube and expel it axially.

A traveling-wave accelerator makes use of a number of sequentially energized external conductors along the tube. As the switches are fired in turn, the magnetic field lines move axially along the tube, interacting with induced currents and imparting axial motion to the plasma.

The inward radial force on the plasma in this accelerator appears to offer an advantage in keeping the high temperature plasma away from the solid walls of the tube. The fact that no electrodes are needed is also an attractive feature.

STAGING

Currently, the only practical method we have for launching satellites is with chemical systems. As we found out in the rocket performance section, specific impulse and mass ratio limit our chemical systems' performance.

What does this mean in terms of satellites and space probes? A rocket has to provide enough energy, essentially 25,000 ft/sec (17,500 mph), to orbit the Earth as a satellite and 36,700 ft/sec (25,000 mph) to escape the Earth's gravitational field and become a planetoid circling the Sun.

A body must attain a velocity of nearly 35,000 ft/sec to hit the Moon. No practical rocket of one stage can reach the critical velocities for satellites or space probes.

A solution to this problem is to mount one or more rockets on top of one another and to fire them in succession at the moment the previous stage burns out. For example, if each stage provides about 9,000 ft/sec in velocity when fired as above, it would take three stages to put a satellite in orbit, or four stages to reach the moon or go beyond it into space as a deep space probe orbiting the sun.

Staging reduces the launch size and weight of the vehicle required for a specific mission and aids in achieving the high velocities necessary for specific missions.

Multistage rockets allow improved payload capability for vehicles with a high Δv requirement, such as launch vehicles or interplanetary spacecraft. In a multistage rocket, propellant is stored in smaller, separate tanks rather than a larger single tank as in a single-stage rocket. Since each tank is discarded when empty, energy is not expended to accelerate the empty tanks, thereby achieving a higher total Δv. Alternatively, a larger payload mass can be accelerated to the same total Δv. The separate tanks are usually bundled with their own engines, with each discardable unit called a stage.

The same rocket equation describes multistage and single-stage rocket performance, but it must be applied on a stage-by-stage basis. It is important to realize that the payload mass for any stage consists of the mass of all subsequent stages plus the ultimate payload itself. The velocity of the multistage vehicle at the end of powered flight is the sum of velocity increases produced by each of the various stages. We add the increases because the upper stages start with velocities imparted to them by the lower stages.

A multistage vehicle with identical specific impulse, payload fraction and structure fraction for each stage is said to have *similar stages*. For such a vehicle, the payload fraction is maximized by having each stage provide the same velocity increment. For a multistage vehicle with dissimilar stages, the overall vehicle payload fraction depends on how the Δv requirement is partitioned among stages. Payload fractions will be reduced if the Δv is partitioned suboptimally.

ROCKET PROPELLANTS

The type of rocket engine determines the corresponding type of propellant storage and delivery systems. In the case of chemical rocket engines, the propellants may be either liquid or solid.

Rocket engines can operate on common fuels such as gasoline, alcohol, kerosene, asphalt or synthetic rubber, plus a suitable oxidizer. Engine designers consider fuel and oxidizer combinations having the energy release and the physical and handling properties needed for desired performance. Selecting propellants for a given mission requires a complete analysis of mission, propellant performance, density, storability, toxicity, corrosiveness, availability and cost; size and structural weight of the vehicle; and payload weight.

Liquid Propellants

The term “liquid propellant” refers to any of the liquid working fluids used in a rocket engine. Normally, they are an oxidizer and a fuel, but may include catalysts or additives that improve burning or thrust. Generally, liquid propellants permit longer burning time than solid propellants. In some cases, they permit intermittent operations. That is, combustion can be stopped and started by controlling propellant flow.

Many combinations of liquid propellants have been investigated. However, no combination has all these desirable characteristics:

- Large availability of raw materials and ease of manufacture
- High heat of combustion per unit of propellant mixture
- Low freezing point (wide range of operation)
- High density before combustion (smaller tanks)
- Low density after combustion (higher γ)
- Low toxicity and corrosiveness (easier handling and storage)
- Low vapor pressure, good chemical stability (simplified storage)

Liquid-propellant units can be classified as monopropellant, bipropellant or tripropellant in nature (**Fig. 5-7**). A monopropellant is a single liquid possessing the qualities of both an oxidizer and a fuel. It may be a single chemical compound, such as nitromethane, or a mixture of several chemical compounds, such as hydrogen peroxide and alcohol. The compounds are stable at ordinary temperatures and pressures, but decompose when heated and pressurized, or when a catalyst starts the reaction.

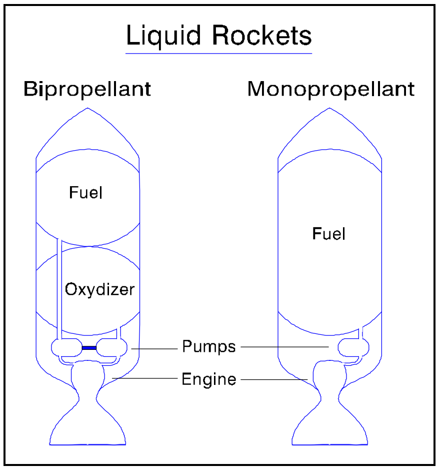


Fig. 5-7: Liquid Propellants

Monopropellant rockets are simple, since they only need one propellant tank and the associated equipment. The most common monopropellant systems use hydrazine. Bipropellant units carry fuel and oxidizer in separate tanks and bring them together in the combustion chamber. At present, most liquid rockets use bipropellants. In addition to a fuel and oxidizer, a liquid bipropellant may include a catalyst to increase the speed of reaction, or other additives to improve the physical, handling or storage properties.

A tripropellant has three compounds. The third compound improves the specific impulse of the basic propellant.

Liquid propellants are commonly classified as either cryogenic or storable propellants. A cryogenic propellant is one that has a very low boiling point and must be kept very cold. For example, liquid oxygen boils at -297° F, liquid fluorine at -306° F and liquid hydrogen at -423° F. Personnel at the launch site load these propellants into a rocket as near launch time as possible to reduce losses from vaporization and to minimize problems caused by their low temperatures.

A storable propellant is one that is liquid at normal temperatures and pressures and may be left in a rocket for days, months, or even years. For example, nitrogen tetroxide boils at 70° F, unsymmetrical dimethyldrazine (UDMH) at 146° F and hydrazine at 236° F. However, the term storage refers to storing propellants on Earth. It does not consider the problem of storage in space.

As described earlier, in order to store the liquid propellants within the rocket vehicle until such time as they are introduced into the combustion chamber of the rocket engine, large tanks are required. Once combustion starts and pressure is built up inside the combustion chamber, the propellants will not flow into the combustion chamber of their own accord. A method of forcing the propellants into the combustion chamber against the combustion pressure is required. Two methods presently used to accomplish this are shown in **Figure 5-8**. The simplest of these provides a gas pressure, usually helium, in the propellant tanks sufficient to force the propellants out of the tanks through the delivery piping and into the combustion chamber.

The pressurization method requires propellant tanks that are strong enough to withstand the pressure and this, in turn, means thick tank walls and increased tankage weight. This decreases the mass ratio. Therefore, there is a definite limit

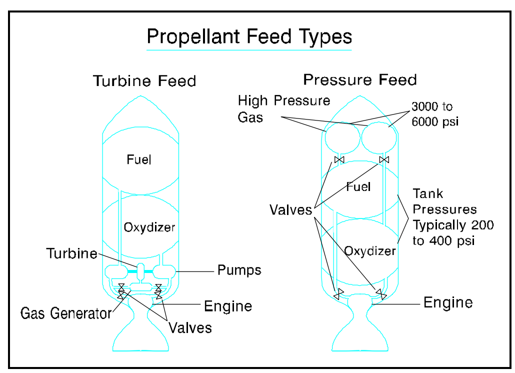


Fig. 5-8. Propellant Feed Types

to the size of the rocket vehicle that can use the pressurization method.

The second method, as previously described, utilizes pumps to drain the propellants from the tanks and force them into the combustion chamber. This requires a pump for each propellant as well as some method of driving the pumps. These pumps are usually the centrifugal type. They are generally driven by a turbine mounted on the same drive shaft. The turbine, in turn, is powered by a small gas generator that may use the decomposition of high-strength (highly concentrated) hydrogen peroxide to produce steam. Other sources of turbine power may be the two rocket propellants, burned in a small auxiliary combustion chamber, or a small solid-propellant grain burned to produce driving gas. A novel method involves bleeding some of the combustion gas from the rocket engine back to the turbine. This is a system which essentially "bootstraps" itself into operation. Pump delivery systems allow the use of extremely thin-walled propellant tanks, which increases the possible mass ratio.

With liquid propellants, the combustion process starts when the propellants are injected into the rocket engine. The propellants are driven into the combustion chamber through an "injector," which often looks like an overgrown shower head. The injector serves to break up the propellants into atomized spray, thus promoting mixing and complete combustion. Injectors are extremely difficult to design, as there are no definitive mathematical equations that analyze their operation. Modern injectors are built as a single unit that forms the forward end of the combustion chamber. They are perforated with hundreds of tiny holes, the number, size, and angle of which are critical.

Propellants may be chosen so that they react spontaneously upon contact with each other. Such propellants are known as *hypergolic* and do not require a means of ignition in order to get combustion started. Ignition for non-hypergolic propellants requires an igniter. Igniters are usually pyrotechnic in nature, although some engines have used spark plugs.

Typical non-hypergolic combinations are alcohol/LOX, gasoline/LOX, liquid hydrogen/LOX, alcohol and nitric acid, and kerosene (RP-1)/LOX. Typical hypergolic combinations are aniline and nitric acid, fluorine/hydrazine, fluorine and hydrogen, hydrazine/hydrogen peroxide, and aniline and nitrogen tetroxide.

Monopropellants are chemicals which decompose in the presence of a suitable catalyst or at a suitable temperature releasing energy in the process. Hydrogen peroxide (75 percent pure or better) is a common monopropellant used in many vehicles for small adjustment or vernier rockets. Such strong peroxide mixtures, however, must be handled with great care because they decompose with explosive suddenness in the presence of impurities. Other monopropellants are nitro-methane (CH_3NO_2), ethylene oxide (C_2H_4O) and hydrazine (N_2H_4). Many of these propellants are highly unstable, many are highly toxic and some are both.

Liquid propellant engines are extremely versatile, can be throttled, and can be used again by simply reprovisioning the propellant tanks. They provide high specific impulses, but are more complex and therefore, less reliable than a solid motor.

While it is possible to argue endlessly over the merits of both types, it is safe to say that both solid-propellant motors and liquid-propellant engines will continue to be used in the future for specific applications where their respective advantages outweigh their disadvantages.

Solid Propellants

The solid-propellant motor (**Fig. 5-9**) is the oldest of all types and is by far the simplest in construction. Since the propellants are in solid form, usually mixed together, and since a solid-propellant charge undergoes combustion only on its surface, there is no need to inject it continuously into the combustion chamber from storage tanks. Solid propellants are therefore, placed right in the combustion chamber itself. A solid propellant rocket motor combines both the combustion chamber and the propellant storage facilities in one unit. A solid-propellant charge, or "grain," is ignited and burns until it is exhausted, changing the effective size and shape during its operation.

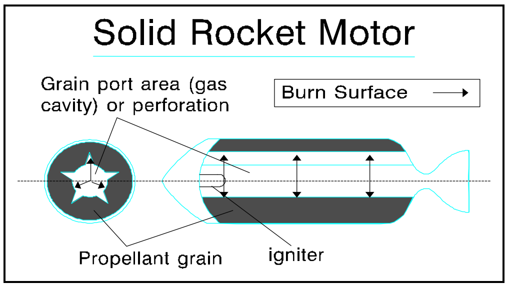


Fig. 5-9. Solid Propellant Motor

Since a solid-propellant grain burns only on its surface, the shape of the grain may be designed to regulate the amount of grain area undergoing combustion.

Since the thrust is dependent upon the mass flow rate, which is in turn dependent upon the amount of propellant being consumed per second, the thrust output of a solid-propellant rocket motor can be determined in advance, or "programmed." A grain that burns with constant area during the thrust period yields constant thrust and is known as a *restricted* or *neutral-burning* grain (It might, for example, burn from the aft end to the forward end in the manner of a cigarette) (**Fig. 5-10**).

In addition, a grain may be designed to burn with increasing area and thrust (*progressive*) or with decreasing area and thrust (*regressive*). Choice of grain style depends on the motor's use.

There are many chemical combinations that make good solid propellants. Aside from gunpowder and metal-powder mixtures (such as zinc and sulfur) which have erratic burning rates and poor physical properties, there are two classes of solid propellants which were originally developed for rockets during and after World War II and are in wide use today: *double-base* (homogeneous) and *composite* (heterogeneous) propellants. Double-based propellants consist chiefly of a blend of nitrocellulose and nitroglycerin with small quantities of salts, wax, coloring and organic compounds to control burning rates and physical properties. The double-based propellants may be regarded as complex colloids with unstable molecular structure. Homogeneous propellants have oxidizer and fuel in a single molecule. The blast from a small chemical igniter easily starts the rapid recombination of this structure in the process of burning. Aging allows a slower rearrangement of the molecules, and thus often significantly changes the burning properties of the propellant. Double-based propellants can be formed efficiently in many shapes by either casting or extrusion through dies.

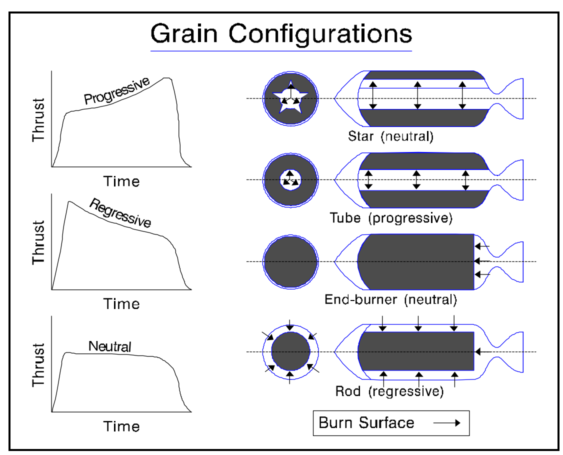


Fig. 5-10. Grain Configurations

Composite propellants, as the name implies, are mixtures of an oxidizer, usually an inorganic salt such as ammonium perchlorate, in a hydrocarbon fuel matrix, such as an asphalt like material. The fuel contains small particles of oxidizer dispersed throughout. The fuel is called a binder because the oxidizer has no mechanical strength. Usually in crystalline form, finely ground oxidizer is approximately 70 to 80 percent of the total propellant weight. Composites are usually cast to shape. Current work with composites and double-based propellants incorporates light metals (such as boron, aluminum, and lithium), which yield very high energies.

Although less energetic than good liquid propellants (lower specific impulse), solids have the advantages of fast ignition (0.025 seconds is common) and good storability in the rocket. Making them, however, is costly, complex and dangerous.

An ideal solid propellant would possess these characteristics:

- High release of chemical energy
- Low molecular weight of combustion products
- High density before combustion
- Readily manufactured from easily obtainable substances by simple processes
- Insensitive to shock and temperature changes and no chemical or physical deterioration while in storage
- Safe and easy to handle.
- Ability to ignite and burn uniformly over a wide range of operating temperatures
- Nonhygroscopic (nonabsorbent of moisture)
- Smokeless and flashless

It is improbable that any propellant will have all of these characteristics. Propellants used today possess some of these features at the expense of others, depending upon the application and the desired performance.

Propellant Tanks

The function of the propellant tanks is simply the storage of one or two propellants until needed in the combustion chamber. Depending upon the kind of propellants used, the tank may be nothing more than a low pressure envelope or it may be a pressure vessel for containing high pressure propellants. In the case of cryogenic propellants (described later), the tank has to be an exceptionally well insulated structure to keep propellants from boiling away.

As with all rocket parts, weight of the propellant tanks is an important factor in their design. Many liquid propellant tanks are made out of very thin metal or are thin metal sheaths wrapped with high-strength fibers. These tanks are stabilized by the internal pressure of their contents, much the same way balloon walls gain strength from the gas inside. Very large tanks and tanks that contain cryogenic propellants require additional strengthening or layers. Structural rings and ribs are used to strengthen tank walls, giving the tanks the appearance of an aircraft frame. With cryogenic propellants, extensive insulation is needed to keep the propellants in their liquefied form. Even with the best insulation, cryogenic propellants are difficult to keep for long periods of time and will boil away. For this reason, cryogenic propellants are usually not used with military rockets/ missiles.

The propellant tanks of the shuttle can be used as an example of the complexities involved in propellant tank design. The external tank (ET) consists of two smaller tanks and an intertank. The ET is the structural back bone of the shuttle and during launch it must bear the entire thrust produced by the solid rocket boosters and the Orbiter main engine.

The forward or nose tank contains LOX. Antislosh and antivortex baffles are installed inside the LOX tank as well as inside the other tank to prevent gas bubbles inside the tank from being pumped to the engines along with the propellants. Many rings and ribs strengthen this tank.

The second tank contains LH. This tank is two and a half times the size of the LOX tank. However, the LH tank weighs only one third as much as the LOX tank because LOX is 16 times denser than LH.

Between the two tanks is an intertank structure. The intertank is not actually a tank but a mechanical connection between the LOX and LH tanks. Its primary function is to join the two tanks together and distribute thrust loads from the solid rocket boosters. The intertank also houses a variety of instruments.

Turbopumps

Turbopumps provide the required flow of propellants from the low-pressure propellant tanks to the high-pressure rocket chamber. Power for the pumps is produced by combusting a fraction of the propellants in a preburner. Expanding gases from the burning propellants drive one or more turbines which, in turn, drive the turbopumps. After passing through the turbines, exhaust gases are either directed out of the rocket through a nozzle or are injected, along with liquid oxygen into the chamber for more complete burning.

Combustion Chamber and Nozzle

The combustion chamber of a liquid propellant rocket is a bottle-shaped container with openings at opposite ends. The openings at the top inject the propellants into the chamber. Each opening consists of a small nozzle that injects either fuel or oxidizer. The main purpose of the injectors is to mix the propellants to ensure smooth and complete combustion with no detonations. Combustion chamber injectors come in many designs.

The purpose of the nozzle is to provide for gas expansion to achieve the maximum transfer of thermal energy into directed kinetic energy.

HYBRID ROCKETS

Another rocket engine should be mentioned. Composite (hybrid) engines are combinations of solid and liquid propellant engines. In a composite engine, the fuel may be in solid form inside the combustion chamber with the oxidizer in a liquid form that is injected into the chamber.

Though not in widespread use, they do offer some advantages in rocket propulsion. **Figure 5-11** depicts a simplified structure of the hybrid system.

Theoretical work on hybrid propulsion dates back to the 1930s in both the U.S. and Germany. In the 1940s, a hybrid motor was built that burned Douglas Fir wood loaded with carbon black and wax in 10% liquid oxygen. Germany's wartime experiments tried powdered and re-formed coal fuel cores, but even clean coal contained too many impurities to be a good rocket fuel. Work continued into the 1960s with both the Navy and Air Force funding research.

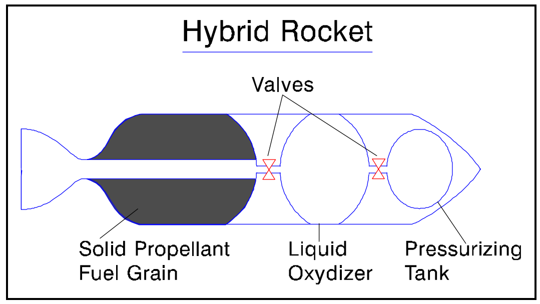


Fig. 5-11. Hybrid Rocket System

The hybrid fuel burns only on contact with the oxidizer, and cracks in the fuel grain do not admit enough oxidizer to support catastrophic failures common to solids. Also, unlike conventional solids, the flow of oxidizer makes the hybrid throttleable and restartable. Even though hybrids cannot match the density-impulse of solid rocket motors loaded with aluminum, motors with thrusts ranging from 60,000 to 75,000 pounds have been tested. Future tests expect thrusts reaching 225,000 pounds.

Safety is an inherent advantage, claim makers of hybrid systems. As noted above, cracks in the fuel, because they are not exposed to the oxidizer, do not cause an explosion. Hybrid propulsion makes launch vehicles safer in flight. Engine thrust can be verified on the pad before releasing the vehicle for flight. And, unlike solids, hybrids can be shut down on the pad if something goes wrong.

Environmental concerns are lessened using hybrid systems specially designed to minimize pollution effects. The hydrogen chloride in solid fuel exhaust has already become an environmental concern for the acid it dumps on the surface of the Earth, and the damage it does to the protective ozone. Aluminum oxide, an exhaust component of traditional solid rockets, is also environmentally suspect. A hybrid launch vehicle using polybutadiene fuel and liquid oxygen produces an exhaust of carbon dioxide, carbon monoxide and water vapor similar to that of kerosene/liquid oxygen engines.

COOLING TECHNIQUES

The very high temperatures generated in the combustion chamber transfer a great deal of heat energy to the combustion chamber and nozzle walls. This heat, if not dissipated, will cause most materials to lose strength. Without cooling the chamber and nozzle walls, the combustion chamber pressures will cause structural failure. There are many methods of cooling, all with the objective of removing heat from the highly stressed combustion chamber and nozzle.

Radiation Cooling

This is probably the simplest method of cooling a rocket engine or motor. The method is usually used for monopropellant thrusters, gas generators, and lower nozzle sections. The interior of the combustion chamber is covered with a refractory material (graphite, pyrographite, tungsten, tantalum or molybdenum) or is simply made thick enough to absorb a lot of heat. Cooling occurs by heat loss through radiation into the exhaust plume. Radiation cooling can set an upper limit on the temperature attained by the walls of the thrust chamber. The rate of heat loss varies with the fourth power of the absolute temperature and becomes more significant as the temperature rises.

Ceramic Linings

In relatively small (low temperature) rockets, the interior walls of the combustion chamber and nozzle may be lined with a heat-resistant (refractory) ceramic material. The ceramic gets hot, but because it is a poor conductor of heat, it prevents the metal walls of the motor/engine from becoming overheated during the short operating period. This method is not adequate for large rockets in which the more intense heat must be transferred rapidly from the walls of the thrust chamber. Ceramic linings are also too heavy for use in large rockets.

Ablation Cooling

As mentioned earlier, in the ablation cooling method, the interior of the thrust chamber is lined with an ablative material, usually some form of fabric reinforced plastic. This material chars, melts and vaporizes in the intense heat of the nozzle. In this type of “heat sink cooling,” the heat absorbed in the melting and burning (the energy alters the chemical form instead of raising its temperature) of the ablative material prevents the temperature from becoming excessively high. The charred material also serves as an insulator and protects the rocket case from overheating. The gas produced by burning the ablative material provides an area of “cooler” gas next to the nozzle walls. The synthetic organic plastic binder material is reinforced with glass fiber or a synthetic substance. Solid rocket motors use ablative cooling almost exclusively, as there are no other fluids to use to cool the nozzle throat.

Film Cooling

With this method of cooling, liquid propellant is forced through small holes at the periphery of the injector forming a film of liquid on the interior surface of the combustion chamber. The film has a low thermal (or heat) conductivity since it readily vaporizes and protects the wall material from the hot combustion gases. Cooling results from the vaporization of the liquid which absorbs considerable heat. Film cooling is especially useful in regions where the walls become exceptionally hot, e.g., the nozzle throat area.

Transpirational Cooling

This technique is very similar to film cooling. The combustion chamber has a double-walled construction in which the inside wall is made of a porous material. Propellant is circulated through the space between the walls and seeps continuously through inner wall pores into the combustion chamber. There it forms a film which rapidly vaporizes. The cooling action is much the same as film cooling, but has the additional advantage of allowing considerable heat to be absorbed by the propellant within the walls of the chamber. This method is also referred to as evaporative or sweat cooling. Major drawbacks to transpirational cooling are that it is difficult to manufacture this type of chamber, and also difficult to maintain a steady liquid flow through the pores.

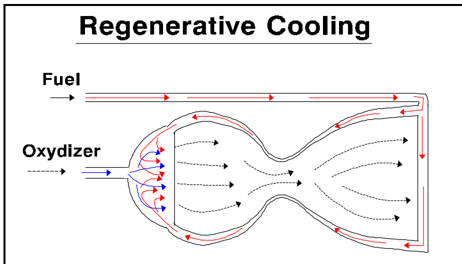
Regenerative Cooling

This is the most common method of cooling for cryogenic propellant rockets. It involves circulating one of the super-cooled propellants through a cooling jacket around the combustion chamber and nozzle before it enters the injector. The propellant removes heat from the walls, keeping temperatures at acceptable levels. At the same time, the temperature of the propellant rises, causing it to vaporize faster upon injection. This cooling method is often used with gas generator systems as a way to drive turbopumps (**Fig. 5-12**).

Solid Rocket Motor Cooling

In solid propellant motors, the nozzle serves the same purpose as in the liquid engine. Because there is no super-cooled propellant available to provide cooling, we use other methods for thermal protection. If not properly constructed, the walls of the combustion chamber will become excessively hot. This could cause case failure under the high operating pressures existing in the interior. To prevent this, the inner wall of the motor case is coated with a liner or inhibitor. This liner provides a bond between the propellant grain and the case preventing combustion from spreading along the walls, and acts as a thermal insulator, protecting the case from heat in areas where there is no propellant. The unburned propellant provides additional thermal protection as it must be vaporized before it will burn.

In solid-propellant rockets, the nozzle's form is often achieved with a shaped insert which keeps the nozzle throat cool to prevent significant damage during the operation of the motor. Common insert materials include both refractory substances, like pyrographite



The fuel flows around the nozzle and combustion chamber absorbing heat as it flows. It then enters the cumbustion chamber and reacts with the oxydizer. The reclaimed energy adds to the exhaust energy.

Fig. 5-12. Regenerative Cooling

and tungsten or ablative substances. The ablative materials are fabric reinforced high temperature plastics as previously discussed. There is usually no significant change in motor performance due to deterioration of nozzle throat ablatives.

Another method of keeping the nozzle throat cool is the use of a cooler burning propellant located near the throat area which will burn and form a thin layer of cooler gas next to the nozzle walls. This thin film of gas protects the nozzle from the high temperature gas created by the main propellant.

THRUST VECTOR CONTROL

In a rocket, the rocket engine or motor not only provides the propulsive force but also the means of controlling its flight path by redirecting the thrust vector to provide directional control for the vehicle's flight path. This is known as thrust vector control (TVC). TVC can be divided into those systems for use with liquid engines and those for solid motors.

When choosing a TVC method, we need to consider the characteristics of the engine/motor and its flight application and duration. Also, the maximum angular accelerations required or acceptable, the environment, the number of engines/motors on the rocket, available actuating power, and the weight and space limitations are all weighed against each other to produce a cost effective, yet appropriate, system of control. The effective loss of engine performance due to the use of a particular TVC method and the maximum thrust vector deflection required are major design considerations

Liquid Rocket TVC Methods

Gimbaled Engines

Some liquid propellant rockets use an engine swivel or gimbal arrangement to point the entire engine assembly. This arrangement requires flexible propellant lines, but produces negligible thrust losses for small deflection angles. This method is relatively common (**Fig. 5-13**).

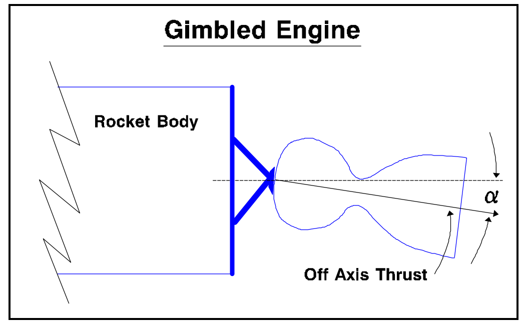


Fig. 5-13. Gimbaled Engine

Vernier Rockets

Vernier rockets are small auxiliary rocket engines. These engines can provide all attitude control, or just roll control for single engine stages during the main engine burn, and a means of controlling the rocket after the main engine has shut off (**Fig. 5-14**).

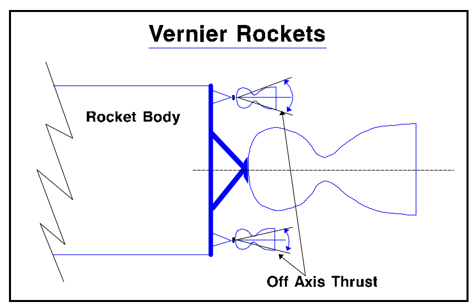


Fig. 5-14. Vernier Rocket

Jet Vanes

Jet vanes are small airfoils located in the exhaust flow behind the nozzle exit plane. They act like ailerons or elevators on an aircraft and cause the vehicle to change direction by redirecting the rocket. Jet vanes are made of heat-resistant materials like carbon-carbon and other refractory substances. Unfortunately, this control system causes a two to three percent loss of thrust, and erosion of the vanes is also a major problem (**Fig. 5-15**).

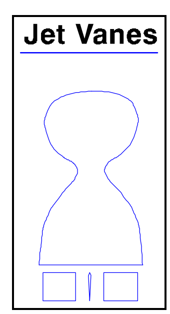


Fig. 5-15. Jet Vanes

Solid Rocket TVC Methods

Rotating Nozzle

The rotating nozzle has no throat movement. These nozzles work in pairs and are slant-cut to create an area of under expansion of exhaust gases on one side of the nozzle. This creates an unbalanced side load and the inner wall of the longer side of the nozzle. Rotation of the nozzles moves this side load to any point desired and provides roll, yaw and pitch control. This system is simple but produces slow changes in the velocity vector. Rotating nozzles are usually supplemented with some other form of TVC.

Swiveled Nozzle

The swiveled nozzle changes the direction of the throat and nozzle. It is similar to gambaling in liquid propellant engines. The main drawback in using this method is the difficulty in fabricating the seal joint of the swivel since this joint is exposed to extremely high pressures and temperatures (**Fig. 5-16**).

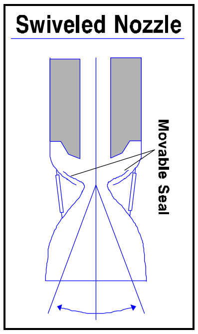


Fig. 5-16. Swiveled Nozzle

Movable Control Surfaces

Movable Control Surfaces physically deflect the exhaust or create voids in the exhaust plume to divert the thrust vector. This method includes jet vanes, jet tabs, and mechanical probes. These TVC approaches are all based on proven technology with low actuator power required. They suffer from erosion and cause thrust loss with any deflection.

A similar system is the jetavator, a slip-ring or collar at the nozzle exit which creates an under expansion region (as discussed in conjunction with rotating nozzles). The jetavator is a movable surface which allows the under expanded region to be moved 360 degrees around the rocket nozzle to produce pitch and yaw control. This system was developed for the Polaris SLBM.

Secondary Fluid Injection

A secondary fluid is injected into the exhaust stream to deflect it, thereby changing the thrust vector (**Fig. 5-17**). Fluid injection creates unbalanced shock waves in the exhaust nozzle which deflects the exhaust stream. There are two types of fluid injection systems.

The Liquid Injection TVC uses both inert (water) and reactive fluids (rocket propellants) for the TVC. Reactive fluid combustion in the exhaust plume creates the greater effect. Hydrazine, water, nitrogen tetroxide, bromine, hydrogen peroxide, and Freon have all been used.

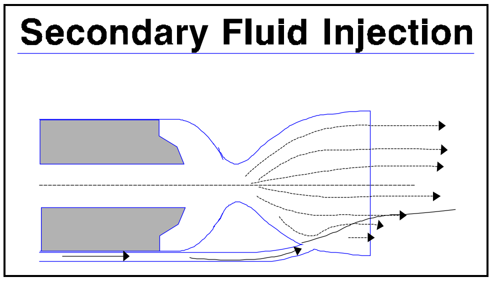


Fig. 5-17. Thrust Vectoring

The Hot Gas Injection TVC uses gas either vented from the main combustion chamber, or from an auxiliary gas generator. These gases are "dumped" into the nozzle to cause the unbalanced shock wave.

SUMMARY

Table 5-1 summarizes the capabilities of the different types of rocket engines and propellants. Each has its own advantages and disadvantages. Specific use of a particular type depends upon the mission.

Type	Thrust (1000 lbs)	I_{sp}	Missions
Chemical Liquid Solid	 1500 2000-3000	 260-455 200-300	Manned missions near Earth and Moon. Instrumented probes to Venus and Mars.
Nuclear	250	600-1000	Heavy payload manned missions to Moon, Venus and Mars.
Arc-Jet	.01	400-2500	Very heavy payloads from Earth orbit.
Plasma	.005	2000-10,000	To other planets and stationkeeping
Ion	.001	7500- 30,000	For deep space missions

Table 5-1. Rocket Engines and Propellants

TOC

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