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EXPLORING IN AEROSPACE ROCKETRY

6. SOLID-PROPELLANT ROCKET SYSTEMS

by Joseph F. McBride
Lewis Research Center
Cleveland, Ohio

Presented to Lewis Aerospace Explorers
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1966-67

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HISTORY OF SOLID ROCKETS

The first use of rockets was historically recorded about the year 1232, when Chinese writers told of "arrows of flying fire" with propulsive power furnished by an incendiary powder. Rockets using mixtures of sulfur, charcoal, saltpeter, petroleum, and turpentine were used as weapons by the Arabs, Greeks, Italians, and Germans from 1280 to 1800.

A great variety of rockets propelled by gunpowder and similar solid-fuel combinations have been used in fireworks demonstrations and as missiles in battle for the past several centuries. The British attacked Copenhagen with 30 000 rockets in 1807, and in 1814 Francis Scott Key wrote his famous poem under "the rockets red glare" as the British bombarded Fort McHenry near Baltimore.

Interest in solid rockets of much larger size and increased performance came at the beginning or World War II, when the first jet-assisted takeoff units for aircraft were developed and used (1940-41 at Jet Propulsion Laboratory, Pasadena).

Since World War II, solid-rocket propulsion devices have been further improved in performance and greatly increased in size for use as air-to-air missiles (Sidewinder, Genie), ground-to-air missiles (Nike, Hawk), intercontinental ballistic missiles (Minuteman, Polaris), ground-to-ground tactical weapons (Sergeant, Honest John, Shillelagh), air-to-ground delivery systems (Skybolt), sounding rockets (Argo, Astrobee), space launch vehicles (Scout), and space boosters (Titan III, 156-inch and 260-inch boosters).

DESCRIPTION OF SOLID ROCKET

A solid-fueled rocket propulsion system (motor) consists of a propellant fuel-and-oxidizer charge (grain) of a certain configuration, with the following associated hardware (fig. 6-1):

(a) A case, the high-pressure gas container which encloses the grain

(b) A nozzle, the gas-expansion device through which the rocket exhaust flows

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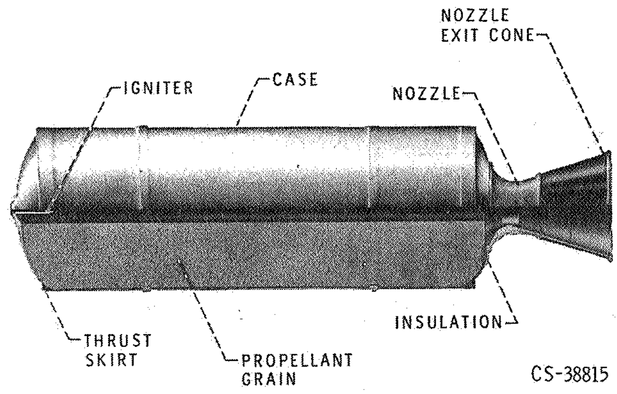


Figure 6-1. - Solid-fueled rocket motor.

(c) An igniter, the device which starts combustion of the propellant grain in a controlled manner

(d) Insulation, a temperature-resistant, low-conductivity material protecting case and nozzle from exposure to hot gases

SOLID-PROPELLANT GRAIN

A solid propellant is basically a mixture of fuel and oxidizer which burn together, with no other outside substance injected into the combustion chamber, to produce very hot gases at high pressure. Various additives may be mixed into the fuel-oxidizer combination for purposes of:

(a) Controlling the rate of burning

(b) Giving hotter-burning, more energetic, chemical mixtures

(c) Optimizing propellant grain physical properties (tensile and shear strengths, modulus of elasticity, ductility)

Grain Mixture

Most modern solid-propellant grains belong to one of two classes, double-base or composite.

The double-base propellant is a mixture of two very energetic compounds, either one of which alone would make a rocket propellant. Usually the two constituents are nitroglycerin [$C_3H_5(ONO_2)_3$] and nitrocellulose [$C_6H_7O_2(ONO_2)_3$]. As the chemical formulas indicate, both the fuel (carbon and hydrogen) and the oxidizer (oxygen) atoms are contained in each of these molecules; both substances are monopropellants which burn without any added oxidizer. The nitrocellulose provides physical strength to the grain, while nitroglycerin is a high-performance and fast-burning propellant. Double-base grains are generally formed by mixing the two constituents and additives, then pressing or extruding the puttylike mixture into the proper shape to fit the motor case.

A composite grain is so named because it is formed of a mixture of two or more unlike compounds into a composite material with the burning properties and strength characteristics desired. None of these constituent compounds would make a good propellant by itself; instead, one is usually the fuel component, another the oxidizer.

The most modern of the composite propellants use a rubbery polymer (in fact, a synthetic rubber such as polybutadiene or polysulfide) which acts as the fuel and as a binder for the crumbly oxidizer powder. The oxidizer is generally a finely ground nitrate or perchlorate crystal, as, for example, potassium nitrate (KNO_3) or ammonium perchlorate (NH_4ClO_4). The composite mixture can be mixed and poured like cake batter, cast into molds or into the motor case itself, and made to set (cure) like hard rubber or concrete. The cured propellant is rubbery and grainy with a texture similar to that of a typewriter eraser.

Composite propellants often contain an additional fuel constituent in the form of a light-metal powder. Ten to twenty percent by weight of aluminum or beryllium powder added to a polymer-based grain has the effect of smoothing the burning (combustion) process and increasing the energy release of the propellant. This added energy in the hot gases produced in combustion appears as added specific impulse I_{sp} of the rocket propulsion system.

Grain Design

Solid grains are also classed by the shapes of their exposed burning surfaces and the manner in which the propellants are burned out of the case. A great deal of engineering is devoted to the shape of the grain, the configuration of the combustion chamber, and the sizes of the parts of the grain to control stresses and the burning of the propellant.

A solid-propellant grain will burn at any point on its surface which is:

(a) Exposed to heat or hot gases of a high enough temperature to ignite the propellant mixture

(b) Far enough separated from the other case or propellant surfaces to allow gas flow past the point

Grains are classified as end-burning or internal-burning; this classification describes the propellant surface on which burning is allowed to take place. An unlimited

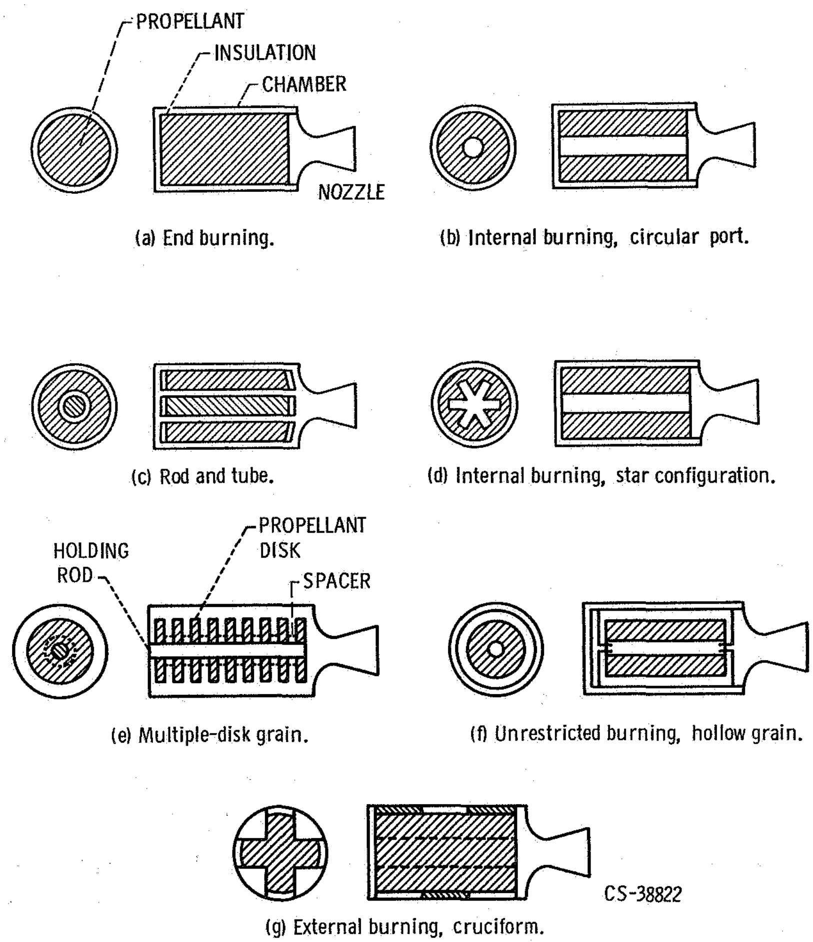


Figure 6-2. - Typical solid-propellant grain configurations. (Patterned after illustrations appearing in Rocket Propulsion Elements by George P. Sutton.)

number of combinations and variations of the basic end-burning or internal-burning grain are possible (fig. 6-2).

BURNING PROCESS

As was stated previously, a correct chemical mixture of fuel and oxidizer will support combustion when exposed to high temperature and gas flow; it will continue to burn as long as the gaseous products of combustion are allowed to escape from the burning surface.

The rate at which hot gases are produced by the burning propellant depends on the total area over which burning is occurring A_b; the rate at which burning is progressing into the propellant $\dot{r}$; and the density of the propellant being transformed into gas ρ.

(Symbols are defined in the appendix.) The flow of combustion gases off the burning surface is described by the rate equation

$$\dot{W} = A_b \dot{r} \rho \tag{1}$$

It is a characteristic of any solid propellant that its burning rate at any point on the grain surface is determined by:

(a) The composition of the propellant at that point

(b) The pressure of the gases surrounding the point

(c) The temperature of the grain at that point just as the "burning zone" approaches

These characteristics at each point on the grain are averaged for the entire grain in the general, solid-propellant, burning-rate equation

$$\dot{r} = a_B P_c^n \tag{2}$$

where $\dot{r}$ is the instantaneous burn rate (in./sec), a_B is the burn-rate constant (which varies slightly with the overall temperature of the grain), P_c is the instantaneous motor chamber pressure (psi), and n is the burn-rate exponent for the particular propellant (typical values range from 0.4 to almost 1.0).

Combining the burning-rate equation (2) with the weight-flow-of-gas-produced equation (1) yields

$$\dot{W} = A_b \left(a_B P_c^n \right) \rho \tag{3}$$

Now, for any rocket device, the thrust produced by expansion of exhaust gases through a nozzle can be expressed as

$$F = C_F A_t P_c \tag{4}$$

where F is the thrust (lb), C_F is the nozzle thrust coefficient (a constant which is a measure of the expansion efficiency of the nozzle and the properties of the propelling gases), A_t is the nozzle throat area (in.^{2}), and P_c is the rocket chamber pressure (psi).

But, thrust is also given by the equation

$$F = \dot{W} I_{sp} \tag{5}$$

where $\dot{W}$ is the gas weight flow through the nozzle (lb/sec) and I_{sp} is the engine specific impulse (a measure of propellant energy release and efficiency of gas expansion through the nozzle).

Combining equations (4) and (5) gives

$$\dot{W} = \frac{F}{I_{sp}} = \frac{C_F A_t P_c}{I_{sp}} \tag{6}$$

In the rocket, a steady-state condition is reached when the rate of gas produced equals the rate of gas flow out of the chamber

$$\dot{W}_{produced} = \dot{W}_{out}$$

or, from equations (3) and (6),

$$A_b \left(a_B P_c^n\right) \rho = \frac{C_F A_t P_c}{I_{sp}} \tag{7}$$

At any instant during the firing, everything in equation (7) is invariable except the chamber pressure. Thus, the pressure in the rocket chamber stabilizes at the instantaneous value found by solving equation (7):

$$P_c = \left(\frac{A_t C_F}{A_b I_{sp} a_B \rho}\right)^{1-n} \tag{8}$$

And so, the motor designer can control the pressure at which the rocket will operate by:

(a) Selecting the propellant, thereby fixing I_{sp}, a_B, ρ, and n

(b) Designing a nozzle size and configuration, thereby fixing A_t and C_F

(c) Designing the grain burning surface to make A_b vary as desired during the firing

THRUST-TIME HISTORY

Since the thrust of the rocket can be expressed as

$$F = C_F P_c A_t$$

We find, using equation (8), that

$$F = (C_F A_t)^{2-n}(A_b I_{sp} a_B \rho)^{n-1} \qquad (9)$$

So the thrust, like the chamber pressure, is controlled primarily by the amount of burning surface A_b exposed at each moment during the firing.

The thrust-time curve is the most important performance characteristic of a rocket motor. In space, acceleration of the vehicle propelled by this motor follows Newton's Second Law of Motion

$$a = \frac{F_{motor}}{m_{vehicle}}$$

at any instant. Therefore, the entire velocity history (mission profile) of the vehicle depends on the thrust-mass-time relationship it experiences.

Solid-motor grain design concentrates on the problem of tailoring the thrust curve by configuring the burning surface area to give the desired thrust with time (see fig. 6-3).

Thrust curves are typically progressive, regressive, neutral, or a combination of these, as shown in figure 6-4. Also noted are some of the grain port shapes which will produce these thrust variations by the manner in which their burning surfaces vary in area as burning proceeds.

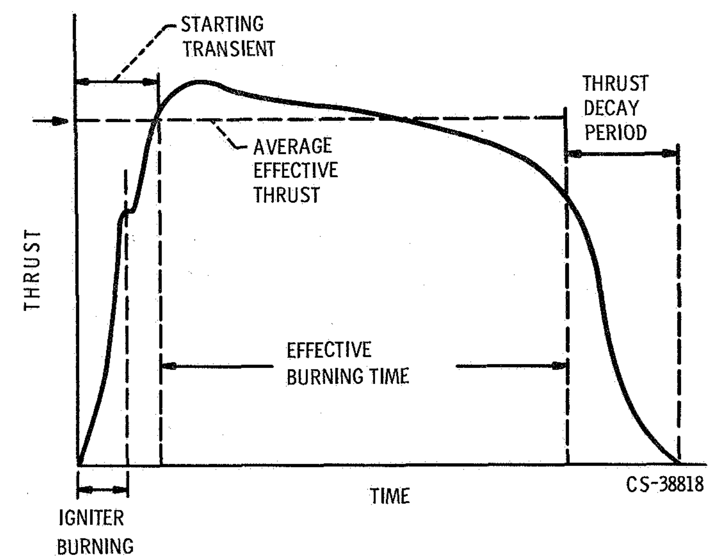


Figure 6-3. - Typical thrust-time diagram.

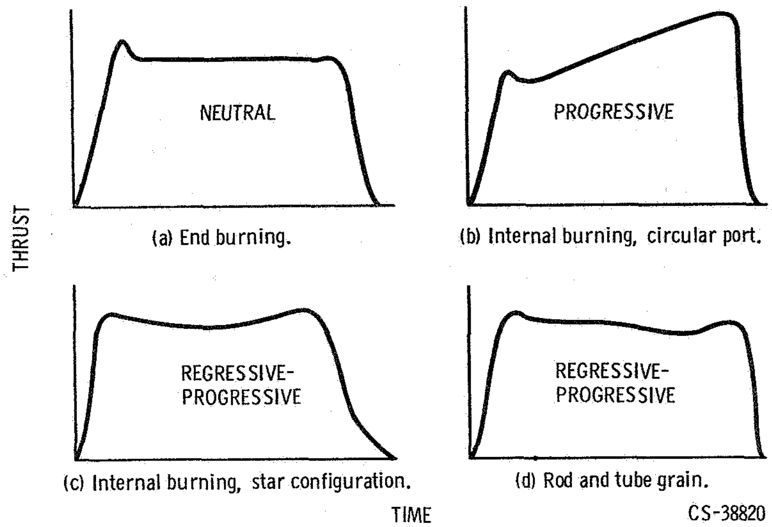


Figure 6-4. - Thrust-time histories.

Another major design problem comes in the elimination of long thrust tailoff, or decay period, at the end of rocket firing. Long tailoff time wastes propellant by burning it inefficiently at low pressure for a relatively long time. Long tailoff also endangers the motor case by exposing it to hot gases while it is no longer protected by propellant. Short, abrupt tailoff is desirable but difficult to achieve, particularly in complex star grain designs. In such grains, the nature of the burning-surface shape gives decreased burning area near the end of the firing because of residual propellant slivers.

CONTROLLABLE SOLID MOTORS

Rocket propulsion developers have done much within the past five years to correct the two great drawbacks of the solid rocket motor:

(a) Inability to shut down on command once ignited and before propellant burns out

(b) Inability to throttle chamber pressure and thrust

Developmental solid rockets have been successfully stopped by using rapid pressure decay (opening the throat or venting the case), by quenching with water or CO_2, or by using bi-grain motors (one grain fuel-rich, one grain oxidizer-rich) with the two chambers connected by a throttle valve.

Throttling has been achieved in bi-grain rockets and, of course, in liquid-solid hybrid rocket engines.

INERT COMPONENTS OF MOTOR

The propellant grain is the "live" part of the solid motor. The other parts provide no propulsive gases and do not burn, so they are "inert." The major inert components of the motor are case, nozzle, igniter, and insulation.

Case

The motor case is the pressure- and load-carrying structure enclosing the propellant grain. Cases are usually cylindrical with curved, nearly hemispherical end closures. Some motors are made with completely spherical cases.

Highest motor performance demands the lightest possible inert weight, so case design becomes a problem of obtaining the thinnest, lightest structure to contain the chamber pressure (typically 400 to 1000 psi in modern solid rockets) and to withstand the loads the vehicle encounters during its flight.

In a cylindrical pressure vessel, which most solid motor cases are, the principal stress in the wall material is given by the equation

$$S = \frac{P_c R_c}{t_w} \tag{10}$$

where S is the hoop stress (psi), R_c is the radius of the cylinder, and t_w is the thickness of the wall.

From this equation we see that the wall thickness

$$t_w = \frac{P_c R_c}{S} \tag{11}$$

can be minimized by using the highest allowable stress S, or the strongest case material, for the given chamber pressure and case size. A good case material is one with a high strength-to-weight ratio. Among today's best materials are high-strength titanium alloys, fiber-glass-and-plastic composite materials, and high-toughness steel alloys. The following examples show the uses of these materials:

(a) Steel alloys: 260-inch booster, 120-inch booster, Minuteman first stage

(b) Titanium: Minuteman second stage

(c) Filament-wound fiber-glass composite: Minuteman third stage, Polaris

Nozzle

The nozzle is the only portion of the solid motor which must withstand exposure to high-temperature, high-velocity propellant gases for the full duration of the rocket firing. The most critical location is in the nozzle throat (smallest area) section, where gas flows at Mach 1 velocity with relatively high pressure and density. In the throat, heat transfer to the nozzle wall is highest.

The greatest nozzle problem is one of finding materials suitable for high-temperature, long-duration application. A solid-rocket nozzle, of course, cannot be cooled by running fuel through its wall as in regenerative cooling of liquid rocket chambers and nozzles. Instead, the nozzle must be lined with one of the following types of material, which will withstand high temperature for long duration:

(a) A refractory substance (tungsten, graphite, etc.) which will not melt, crack, or crumble when heated to temperatures over 3000° F

(b) An ablative composite substance (plastic or rubber reinforced with refractory-type fibers or crystals) which gives off decomposition gases and erodes during firing

Ablatives are used in those applications (e. g., very large rockets) where rocket performance is not seriously degraded by change of nozzle contour or increase in throat area during firing. Refractories are mandatory in applications which cannot tolerate nozzle configuration changes.

The nozzle, too, is a pressure vessel and must be structurally designed to contain the internal pressure and aerodynamic flight loads acting upon it. The pressure within the nozzle decreases rapidly downstream of the throat, and wall thickness can be decreased sharply for a saving of inert weight.

Igniter

The solid-propellant grain burning surface must be bathed in hot gas before it will ignite and support its own combustion. The rocket igniter is a gas producer which can be started easily and dependably by a signal from the firing switch.

The most-used igniter today (fig. 6-5) is a small rocket motor itself, and it exhausts hot gas into the grain cavity of the main rocket. This igniter can be mounted at the head end or the aft end of the main rocket motor, or even outside with its hot gases directed into the main nozzle.

The igniter itself is started by yet another small charge of very fast-burning solid propellant in the form of pellets or powder. This igniter booster is started by the primary initiator, which is a hot-wire resistor or an exploding bridgewire connected to the firing switch through the ignition circuit.

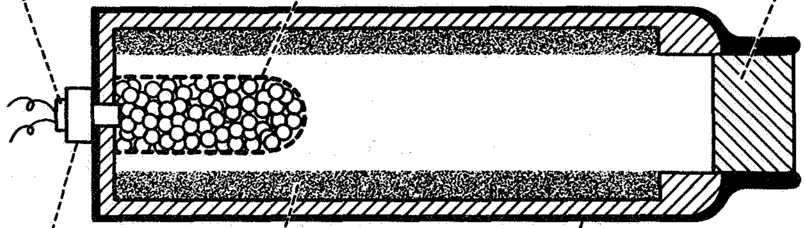


Figure 6-5. - Typical igniter.

Most of the accidents involving solid rockets have resulted from premature igniter firing, either by inadvertent application of voltage to the exploding bridgewire or by ignition of the highly sensitive igniter pellets by impact shock, stray currents, static discharge, or even radio transmissions too close to the rocket. Great effort in safety procedures has made these premature ignitions quite rare. Igniter circuits are locked open until just before firing, shunting circuits are placed across igniter input leads to eliminate stray currents, and personnel working around solid motors are required to wear conductive shoes (to prevent static electricity buildup) and use nonsparking tools.

Insulation

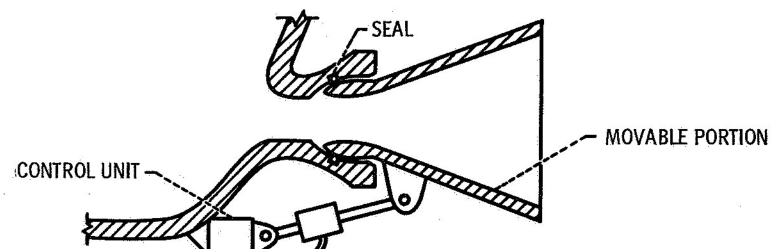
Unless it is protected by insulation, the motor case will quickly lose strength and burst or will burn through whenever hot combustion gases reach the case wall. This burning through of the case could occur near the end of the burning time in the internal-burning grain or throughout the firing time at the aft end of an end-burning grain.

Every solid motor contains a certain thickness of insulation between the propellant grain and the motor case to protect the chamber walls until all propellant has burned out and chamber pressure goes to zero. This insulation is usually an asbestos-filled rubber compound which is bonded with temperature-resistant adhesives to the case wall on one side and to the propellant grain on the other.

STEERING CONTROL

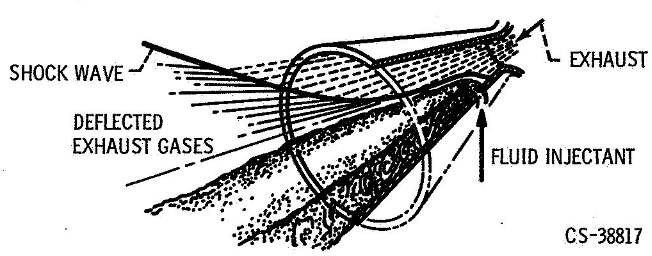
A missile or space vehicle requires a significant amount of steering control as it flies through atmospheric winds and performs the pitch, yaw, and roll maneuvers necessary in the performance of its mission. Most liquid-propelled vehicles are steered by engine gimbaling; that is, the entire chamber and nozzle assembly is moved relative to the rest of the vehicle so that the direction of thrusting is changed.

Moving a solid-rocket chamber relative to the vehicle is a large task because the chamber is a major portion of the vehicle and contains all of the rocket's propellant. The combustion chamber is not separate from the propellant tankage as it is in a liquid or nuclear rocket system. Solid rockets are therefore steered by moving the nozzle alone,



(a) Movable nozzle.

(b) Jet tabs on a rocket developed by Lockheed for the U. S. Air Force.



(c) Secondary injection.

Figure 6-6. - Thrust vector control.

by moving the exit cone of the nozzle alone, or by changing the direction of the exhaust jet coming from the nozzle. Any method of controlling the direction of thrusting in relation to the engine or the vehicle is termed "thrust vector control" or TVC.

Moving the entire nozzle or the exit cone (fig. 6-6(a)) has been done successfully in many missiles (Minuteman, Skybolt, air-to-air missiles). Deflection of the exhaust-gas jet alone has also been accomplished by placing obstacles such as vanes or tabs in the nozzle to disturb the exhaust flow pattern (fig. 6-6(b)), or by injecting a fluid (gas or liquid) through the nozzle wall at right angles to the main gas stream (fig. 6-6(c)). In this way, the jet and the thrust direction are deflected a few degrees off the vehicle centerline. This method of steering is used in such operational rocket vehicles as Minuteman II, Polaris, and the 120-inch boosters for the Titan III C.

Another method of steering for rocket vehicles involves the use of aerodynamic surfaces (vanes, fins, or canards) which give steering-control forces through lift, like an airplane wing (fig. 6-7). A vehicle with this kind of control needs no thrust vector control in

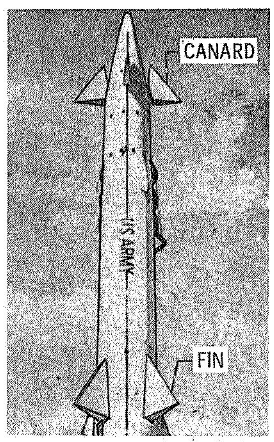


Figure 6-7. - Aerodynamic control. Nike missile with fin stabilizers and canard steering.

the propulsion system (e.g., most air-to-air and ground-to-air missiles). However, aerodynamic control can occur only in the atmosphere and while the vehicle has sufficient velocity through the air. Aerodynamic steering may be combined with TVC; the TVC provides steering control near the ground before the vehicle has built up velocity, and on the edge of the atmosphere or in space where a wing becomes useless.

SOLID-ROCKET PERFORMANCE

There are two major indicators of rocket system performance, specific impulse I_{sp} and mass fraction M. F.:

$$I_{sp} = \frac{\text{Thrust}}{\text{Rate of propellant usage}}$$

$$\text{M. F.} = \frac{(\text{Initial mass}) - (\text{Burnout mass})}{\text{Initial mass}}$$

$$= \frac{\text{Weight of propellant}}{\text{Weight of total propulsion system}}$$

Solid propellants are typically less energetic than the better liquid-propellant combinations. Modern solids have sea-level I_{sp} values in the range of 220 to 250 seconds, compared with over 350 seconds for the liquid-oxygen/liquid-hydrogen combination.

On the other hand, solid-rocket mass fractions can be quite high because there are no valves, piping, or pumps to add to the inert weight. High-performance upper-stage solid motors typically attain mass fractions nearing 0.95 through the use of filament-wound glass cases and refractory-lined nozzles. Even the large solid boosters have mass fractions exceeding 0.90, a value which liquid-fueled missiles with very thin tank walls (e.g., Atlas) can barely achieve.

The solid rocket's real advantages are its strength, since the propellant grain has considerable strength of its own and also acts as a stiffener and shock dampener, and its instant readiness, since there are no fuel tanks to be filled just prior to firing and launch.

SAFETY PRECAUTIONS

Because a solid grain consists of fuel and oxidizer in a mixture all ready for burning upon the application of heat, a solid motor can be a serious fire and explosion hazard. Double-base propellants are explosive by nature and much more hazardous than the castable composites, which are merely fire hazards. For this reason, double-base propellants are not used in large-sized motors, only in air-to-air and antiaircraft missiles and in final-stage space vehicles for which the propellant grain does not exceed several hundred pounds in weight. A high-energy double-base grain has a potential explosive yield higher than a like amount of TNT. These explosive grains can be detonated by the shock of dropping, being struck by a rifle bullet, or overheating in a fire.

The danger with a nonexplosive composite grain is that it may ignite prematurely in a fire, and the motor will become propulsive at a time and place hazardous to personnel and property.

Solid motors are processed, loaded, and stored in facilities well away from dwellings. They are surrounded by blast walls and heavy earthen bunkers to stop shrapnel and pieces of burning propellant. Motors are transported with care and with a minimum number of personnel present to reduce the chance of injury in case an accident does occur.

The same kind of care for safety is taken during the mixing of propellants, when fuel and oxidizer are first brought together in large containers and stirred by intermeshing paddles. Serious fires and explosions have occurred during mixing operations at several propellant plants. However, because of the use of remote controls, fire-control systems, and proper isolation and protection of the mixing facilities, there have been relatively few injuries and deaths in these accidents.

APPENDIX - SYMBOLS

A_b exposed grain burning area, $in.^2$

A_t nozzle throat area, $in.^2$

a acceleration, ft/sec^2

a_B propellant burn rate constant

C_F nozzle thrust coefficient

F thrust, lb

I_{sp} specific impulse, sec

M. F. rocket mass fraction

m mass, slugs

n propellant burn rate exponent

P_c combustion-chamber pressure, $lb/in.^2$

R_c radius of cylinder, in.

$\dot{r}$ propellant burning rate, in./sec

S stress, $lb/in.^2$

t_w thickness of wall, in.

$\dot{W}$ weight-flow rate, lb/sec

ρ density, $lb/in.^3$ or lb/ft^3

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