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ABSTRACT

This book, one in the series on Aerospace Education III, includes a discussion of the essentials of propulsion, control, and guidance and the conditions of space travel. Chapter 1 provides a brief account of basic laws of celestial mechanics. Chapters 2, 3, and 4 are devoted to the chemical principles of propulsion. Included are the basics of thrust, the differences between solid and liquid propellant engines, devices for generating electrical power in space, the potentialities of nuclear and electric rockets and thrust and thrust-vector controls. Chapter 5 is entitled "Control and Guidance Systems" and deals with topics such as servomechanisms and computers, types of guidance systems, and position fixing or celestial navigation. The final chapter includes a discussion of suborbital, earth orbital, lunar, and interplanetary flight. The book is designed for the Air Force Junior ROTC program. (PS)

# SPACE TECHNOLOGY

## Propulsion, Control and Guidance of Space Vehicles



Aerospace Education III

# Space Technology:

*Propulsion, Control and Guidance of Space Vehicles*


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# Preface

TWO SPACE VEHICLES are traveling around the earth in the same orbital pathway, one a thousand miles behind the other. How can the rear vehicle catch up with the one in front to accomplish a rendezvous? Does it apply rocket thrust rearward to increase its velocity? That would seem logical. Or does it thrust forward for braking effect or "retrothrust?" That would seem completely illogical, but it happens to be the right answer.

The laws governing space flight do indeed seem peculiar, but they are the same laws that Galileo, Kepler, and Newton discovered centuries ago. In this text, we shall strive, without overwhelming the student with mathematics and other technicalities, to provide a better understanding of the interplay between natural and man-made forces by which travel beyond the earth's atmosphere—in orbit around the earth, to the moon, or to other planets—is accomplished.

Although other volumes in the Aerospace Education series have dealt with space and space vehicles, this is the first that attempts to set forth the essentials of propulsion, control, and guidance and the conditions of space travel in a systematic way.

Here are some more interesting questions: Why bother chilling liquid propellants down to $-300°$ or $-400°$ F. when there are others that work at normal temperatures? Why not propel a space vehicle by electrical rather than chemical energy? Why should such a vehicle follow a different pathway through space than that of a chemically-propelled vehicle? If sighting to the earth and a distant star establishes a vehicle's location in space somewhere on the surface of a cone, what further sightings must be made to fix its location?

These are the kinds of practical questions that study of this unit can answer.

Beginning with the basic laws of celestial mechanics, the text discusses chemical propulsion; the basics of thrust; the differences between solid and liquid propellant engines; devices for generating electrical power in space; the potentialities of nuclear and electric rockets; thrust and thrust-vector controls; servomechanisms and computers; and command, inertial, and celestial guidance. In the final chapter, the discussion returns to celestial mechanics and compares the characteristics of suborbital (missile and sounding rocket), earth orbital, lunar, and interplanetary flight.

There is much in these subjects to fire the imagination, but our purpose is to be realistic. If not "down to earth," we shall at least stay within the solar system. The story told here is not a science-fiction movie of voyages to distant galaxies but a practical view of what man has already accomplished or is likely to accomplish within the next few decades.

# Contents

**THIS CHAPTER** reviews and builds upon background you have acquired in previous units of the Aerospace Education Course. First the basic laws of planetary motion and gravitation are set forth. Then the conditions of aerodynamic flight for both aircraft and missiles are described, followed by a parallel section introducing the conditions of space flight, which will be more fully described in later chapters. Upon completion of this chapter, you should be able to do the following: (1) list Kepler's three laws of planetary motion; (2) list Newton's three general laws of motion and apply them to examples of motion on the ground, in air, and in space; (3) review the principles of reaction motors, whether of aircraft or spacecraft; and (4) compare the conditions of motion in atmosphere and in space with regard to vehicle control, friction, airfoils and streamlining, and propulsion needs for launch and flight.

IN THIS UNIT, while we consider the marvels of exploration of the moon, the planets, and outer space, we must at the same time bring our minds down to earth. There are practical concepts to consider—the ABCs of vehicle movement. Previously encountered facts and ideas must be reviewed as we move on to the new.

The title of this unit should make clear what the subject matter will be. There is the force which moves a vehicle, or **propulsion.** There are the means of regulating this propulsion and steering a vehicle, or **control.** Finally there are the means of navigating or using the vehicle's control mechanism purposefully to get from one place to another, or **guidance.** A topic closely related to control and guidance of spacecraft is **orbits and trajectories.**

To introduce these concepts and acquire a better insight into the special nature of space travel, let us devote this first chapter to two things: a review of certain fundamental physical laws that apply to all vehicles, and a comparison of vehicle behavior in air and space.

## SOME SEVENTEENTH-CENTURY LAWS

On the ground, in air, and in space, propulsion and control are achieved by obeying or applying certain physical laws discovered by Galileo (1564-1642) and Kepler (1571-1630) and set down systematically by Sir Isaac Newton (1642-1727). You may have heard that modern astronomers and theorists like Einstein have rendered these laws obsolete, but as long as we are considering vehicle motion within the solar system and at speeds much slower than the speed of light (and we do not intend to venture beyond these limits in this unit), we can continue to live with these seventeenth-century laws. In fact, man has only recently "discovered" these laws all over again—that is, found out by direct experience that they really work. Only recently has man actually experienced the weightlessness that to Newton was a mathematical formula. Only within the past decade has he actually traveled in vehicles that speeded up and slowed down in obedience to Kepler's traffic laws.

### Gravity and Gravitation

These two words refer to the same force, but in precise usage, **gravitation** is the basic term for mass attraction between two bodies in space, while **gravity** is limited to this attraction as we experience it at or near the surface of the earth. We can theorize that when a pencil falls to the floor, the earth attracts the pencil as the pencil attracts the earth; but practically speaking the attracting force in the earth overwhelms all others. It acts, so it seems, straight down. Actually, since the earth is turning on its axis, "gravity" is a combination of the rotating and the downward forces. Otherwise a dropped object would always land somewhere to the west of its release point. In this text, in referring to the complex forces interacting between sun, planets, moons, and man-made space vehicles, "gravitation" will be the preferred term.

According to legend, Galileo experimented with gravity by dropping iron shots from the Leaning Tower of Pisa, as shown in Figure 1. Newton also was inspired by the simple phenomenon of a falling object—an apple from a tree. The accomplishment of these men is not that they "discovered" the old folk truism that "Whatever goes up must come down" or explained why our feet are held to the ground, but that they charted and measured this force, and extended its principles to explain the motions of the heavenly bodies.

Newton concluded that any bodies in space are attracted toward each other with a force proportional to the product of their masses and to the inverse square of the distance between them. A body like the moon is forever drawn toward the earth by this force. What keeps it from falling into the earth with a mighty crash is that it also has a forward velocity (according to the laws of motion discussed below). Scientists are not in agreement as to how the moon acquired this velocity in the first place; let us merely settle for the fact that it exists. The moon "falls," but

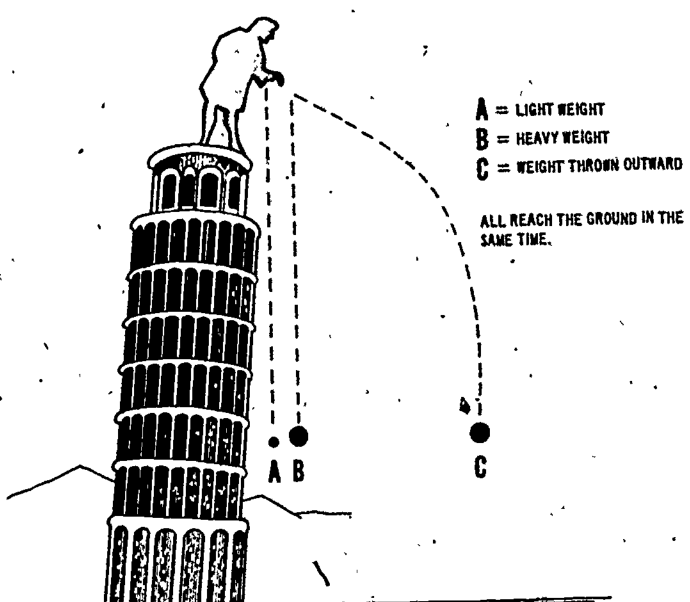


Figure 1. Galileo's legendary experiments at the Tower of Pisa explored gravity with iron balls.

along a trajectory that carries it beyond the body toward which it is falling, so it keeps circling the earth. In similar manner, man-made satellites orbit the earth and the planets orbit the sun. The attraction of gravitation weakens with distance, and the speed with which a body must move to stay in orbit also decreases with distance.

A space vehicle orbiting at an average height of 100 nautical miles* must move at an average speed of 25,567 feet per second* in order to stay aloft. At higher altitudes it can move slower. For example, a synchronous satellite can remain poised over a single spot on the surface of the earth (it must be over the equator) at an altitude of 19,351 nautical miles, as it takes exactly a day to make its orbit, moving along at 10,078 fps. Conversely, however, it takes greater boost velocities for a space ship to reach higher altitudes. As one ventures still farther into space, the influences of the moon, other planets, and the sun begin to affect an orbital path even before the grip of earth gravitation is completely escaped.

### Kepler's Laws of Planetary Motion

Johannes Kepler observed three laws of the behavior of planets upon which Newton built and which can be extended nowadays to cover spacecraft and other orbiting bodies.

1. *The orbit of each planet is an ellipse with the sun at one focus.* Kepler thus noted that planetary orbits were not quite circular. The same is true of man-made earth satellites, which travel an elliptical path with the earth at one focus. Similarly, the path of a ballistic missile is an ellipse, but one that happens to intersect the surface of the earth.
2. *Every planet revolves so that the line joining it to the center of the sun sweeps over equal areas in equal times.* While this law can easily be imagined as applied to a circular orbit, Figure 2 illustrates a way to divide an *elliptical* pie into eight equal portions. To slice out equal portions of the pie in equal time periods, the planet must obviously travel fastest around that

*Some handy conversion figures:
1. Nautical miles (6080 feet) to statute miles—multiply by 1.15 (Also use to convert velocity in knots to miles per hour)
2. Statute miles to nautical miles, or mph to knots—multiply by 0.87
3. Feet per second to miles per hour—multiply by .682 (Rounded numbers like .68 or even .7 may be satisfactory for a rough approximation, since the usual reason for converting the sum is merely to give one the "feel" of a velocity on a familiar scale.)
4. Miles per hour to feet per second, multiply by 1.467 or rounded decimal

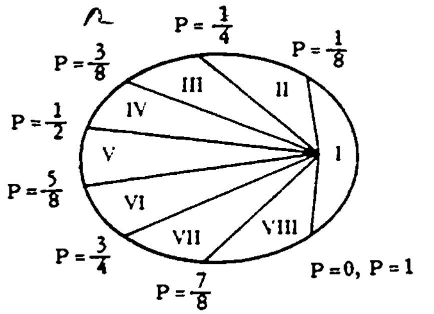


Figure 2. Elliptical orbital pie, sliced into equal parts, demonstrates Kepler's Second Law

part of its path that lies closest to the sun (rim of pie wedge I) and slowest in the portion farthest from the sun (rim of wedge V). If the pie orbit were circular, the planet would move at a uniform speed.

3. *The squares of the sidereal period* of any two planets are to each other as the cubes of their mean distances from the sun.* If one planet travels slower while farther out, it is also true that in a series of planets, the ones farther out will travel slower. Kepler's third law expresses the mathematic formula for this phenomenon. By this formula if planet B is twice as far from the sun as planet A, roughly speaking, planet B's year would be 2.8 times as long as planet A's year. (If both planets were traveling at the same speed instead of obeying Kepler's third law, planet B's year would be only twice as long as planet A's.)

Kepler did not understand *why* planets behaved in that manner; he merely observed and chartered *how* they behaved. More insight is offered, not only in the behavior of planets but into vehicle motion in general—from bicycles to spacecraft—by Sir Isaac Newton's famed three laws of motion.

## Newton's Laws of Motion

1. *With no force acting upon it, a material body at rest will remain at rest and a material body in motion will remain in motion, unchanged in direction and speed.* Actually there is no such thing in space, as far as man has been able to discover, as a body absolutely "at rest." A body is at rest only in relation to another

*The interval of time it takes a planet to complete a circuit around the sun body. A parked car is riding a spinning planet on a journey around the sun. The sun, scientists agree, is also in motion through space, but if we confine our thinking to the solar system, we can assume it to be at rest. Everything else in the solar system is in motion, and all calculations can begin by assuming a body to have an "initial velocity."

2. *A change in the motion of a body indicates the presence of a force and is proportional to and in the direction of that force.* this force can be gravity or gravitation due to the mere presence of another body, or it can be an application of energy such as results from burning fuel.
3. *For every action there is an equal-and-opposite reaction.* As applied to thrust, this law should be a familiar one to the student, who has encountered it in previous units of Aerospace Education such as *Aircraft of Today*, *Spacecraft and Their Boosters*, and *Propulsion Systems for Aircraft*. One should also be aware of it in regard to gravitational and inertial forces acting upon a vehicle in space.

### Explanation of Terms

Along with these laws, you should also know the meaning of certain terms associated with them. Here let us explain mass, inertia, momentum, friction, and acceleration

MASS.—Mass is the measure of the amount of matter in a body, which causes it to have weight under the influence of gravity. If you weigh 150 pounds on earth at sea level, you will be "weightless" in orbit but you will still have a body—with 150 mass pounds.

INERTIA.—Inertia is that state of rest or constant motion mentioned in Newton's first law. More specifically, it is the tendency of a body to resist any change in speed or direction. It presses you into the back of the seat of an accelerating car, or throws you forward if the car slows abruptly, or pulls you toward the outside of a sharp curve—or lets you sit as quietly as if in your living room as long as the vehicle is moving straight ahead at a steady velocity.

MOMENTUM.—Momentum, in regard to a moving body, is the same thing as inertia. It is the quantity that keeps it moving steadily in a given direction. More precisely, it is the measure of that quantity: momentum = mass x velocity.

FRICTION.—**Friction** may be defined as the rubbing together of two substances or bodies in contact with each other, of a body in contact with a gas or fluid, etc.; the resistance to relative motion caused by this contact. For earthbound and airborne vehicles, gravity and friction are the twin conditions which forbid them the unrestricted momentum, the free unpowered flight of planets and space vehicles. Even without brakes, a car will eventually roll to a stop because of gravity pressing down (and pavement pressing *up*) on bearings and tires and creating friction. Water and airborne vehicles must move through a resisting medium. Force must be constantly applied to overcome this resistance, whether or not there is any velocity gain or "acceleration" (see below). Friction also generates heat—ranging from the warmth felt in your hand when you rub a surface to the fiery rock- and metal-consuming heat of a meteor racing through air.

ACCELERATION.—**Acceleration** means *increase* of velocity per unit time, the result of propulsive forces applied to a vehicle according to the second law of motion. We can also speak of slowing down or "deceleration" as "negative acceleration." The essential thing either way is *change*. Mathematically, "change in velocity" is written as "$\Delta v$." Space personnel use the word **delta-V** frequently as part of their shop talk. They may be exercising some license when they speak of getting "more delta-V" out of a propellant instead of "more thrust," but the idea communicates, and the concept is important.

Now let us begin to apply these laws to vehicle motion, considering first vehicle motion in air.

## VEHICLES IN AIR

Vehicles in air must be adapted to an environment that resists, applies pressure, and produces friction. Note that we have said "vehicles in air" and not "aircraft." When we discuss space vehicles, we cannot leave the subject of aerodynamics behind us. If they are to be launched through the earth's atmosphere and brought back through the same atmosphere for a safe landing, they must obey aerodynamic laws at these times. If the vehicle really is an aircraft, designed for aerodynamic flight and nothing else, it enjoys an immense profit of advantages in exchange for its lack of ability to travel at 17,000 miles per hour or reach the moon. A helicopter can hover stationary over any spot on earth and maneuver almost as tightly as an automobile wriggling into or out of a parking space. An airplane, even a supersonic jet, can make a 180° or 360° turn, make evasive maneuvers in combat, fly due east or west, make an unscheduled landing at Paducah, Kentucky, and perform numerous other miraculous feats impossible for an orbiting spacecraft. Before its testing was discontinued by NASA, the X-15 rocket propelled airplane reached speeds in excess of 4,500 mph and altitudes of up to 60 miles mainly because its rocket engine needed no air. At extreme altitudes it found enough atmosphere for very limited aerodynamic maneuvering (Fig. 3).

## Propulsion

All aircraft engines, like rocket engines, are reaction motors. This is as true of propeller driven as of jet airplanes. All these propulsion units work by hurling a mass of gas rearward to produce the equal and opposite reaction that gives the craft its forward thrust according to Newton's third law The gas must be **accelerated**, hurled rearward faster than the speed at which the craft encounters it. The mass of gas used in this fashion by the propeller driven aircraft is the **ambient** or surrounding air itself.

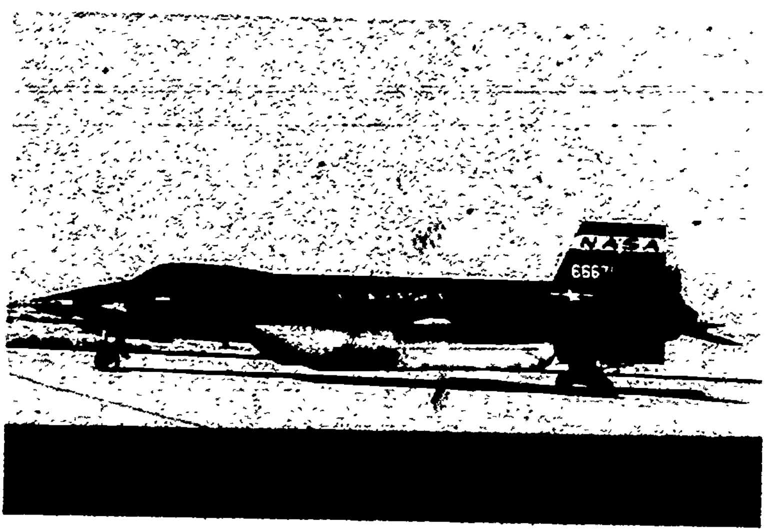


Figure 3 The X 15 rocket airplane carried its own oxygen, and so performed at extreme altitudes, but could perform limited aerodynamic maneuvers

thrust back by the propeller. No thrust is gained from that portion of the air that must pass through the engine itself for combustion or "breathing" purposes. The mass of gas used by the turbojet engine serves two purposes. feeding combustion and, as combustion exhaust, providing thrust by its all important function of rushing out the back door faster than it came in the front The turbofan or fanjet engine employs both these principles The rocket motor also hurls a mass of gas or combustion exhaust rearward. Its distinction compared with an airplane jet is that it must carry its own oxidizer as well as fuel supply. or its own mass of gas, in order to propel in space.

A rocket motor. however, is not necessarily designed purely for operation in the vaccum of space. Many military rockets and missiles are designed for use in the atmosphere. Even space launch vehicles must expend the greater amount of their energy in the atmosphere.

We must repeat what has been said so often in other Aerospace Education units, that neither rockets nor aircraft jet engines operate by pushing against either the atmosphere or the launching pad. In fact, these obstructions impair the efficiency of the reaction by slowing down the rearward rush of the propellant gas. Even airbreathing jet engines (ramjets especially) are more efficient in thin high atmosphere than in dense lower atmosphere.

The maximum altitude at which a turbojet can operate is about 20 miles, or 105,000 feet; the ramjet can operate as high as 28 miles or 150,000 feet. We shall have more to say about the ramjet later. for one must be more familiar with the problems of space propulsion to appreciate certain of its possibilities. At this point we might say that we earthlings who grumble about the price of gasoline are not sufficiently thankful for the fact that air costs nothing, takes up no space aboard our automobiles and airplanes, and adds no weight to these vehicles.

### Aircraft Control

Again for the sake of comparison, let us review the means by which aircraft flight controls operate. We must also give consideration to some of the aerodynamic features of rockets in air and space vehicles during launch and reentry within the atmosphere.

The aircraft presents various resisting surfaces or airfoils to the onrushing air. These include wings, rudders, stabilizing fins, ailerons, elevators, tabs, flaps, and spoilers. For braking effect on a fast landing, we might add a parachute or two. Pressure against some of these surfaces (and negative pressure drawing against others according to **Bernoulli's Law**)* produce changes in the attitude of the aircraft. **Attitude,** an important word in this study, means the position of a vehicle in regard to the direction it is traveling. In an aircraft, attitude control and flight control are virtually the same thing; in a spacecraft they are two different things. This fact holds for helicopters as well as conventional airplanes, but to keep our discussion simple, let us stick to conventional airplanes. These have rigidly mounted engines, positioned to propel in a forward direction only. To steer an airplane to the right of its original flight path, the pilot sets certain airfoils to make the air push and draw the tail to the left. The airplane, like a lever on its fulcrum, then swings on its center of gravity, aiming the rigidly mounted engines rightward to produce thrust in a new direction.

If some surfaces of an aircraft are designed to resist air, the opposite side of the coin is streamlining—the shaping of an aircraft and its parts so that the whole system slips through the air *in the desired direction* with minimum resistance, while opposing flight in undesired directions with maximum resistance. Both attitude and flight control depend upon these two factors.

Another element of control is regulation of propulsion. As in an automobile, we take this feature for granted. We assume that a pilot can regulate an aircraft engine's power output through such phases as takeoff, climb, cruise, descent, and landing. Within the design liimts of the aircraft, altitude, and other factors, an aircraft can also accelerate or reduce speed in level flight or without changing course just as an automobile can vary its speed and remain on the same road. A spacecraft cannot always do these things.

Thus we see that engine and airfoil controls together provide the aircraft with great flexibility and freedom of maneuver which any astronaut might envy, but for these freedoms more thanks are due to Mother Nature than to the aircraft manufacturer. The friendly atmosphere provides lift and friction, and pays more than half the propellant bill to boot.

*As the velocity of a fluid increases, its internal pressure decreases

## Missiles and Spacecraft in Air

Missiles, rockets, and even spacecraft also make use of aerodynamic controls. In fact, much in the way of sophisticated guidance of military missiles is also dependent upon aerodynamics. A heat-seeking Sidewinder or radar-homing Sparrow (both solid-propellant rockets) could not give chase to an enemy aircraft taking evasive maneuvers without making use of the same environment that makes the enemy's maneuvers possible. These are tricks these missiles can do which an ICBM, because it flies a space trajectory, cannot do. The mechanics of gravitation and orbits do not permit such acrobatics in space, just as the friction of the atmosphere and the heavy pull of near-earth gravity will not permit the tremendous velocities attainable in space. Thus certain reports of the behavior of UFOs—unidentified flying objects, sometimes called "flying saucers"—imply utter defiance of the natural laws cited in this chapter.

ESCAPE.—To facilitate escape, launch vehicles have streamlined noses. If the payload is an unaerodynamic satellite, it remains encased in that nose until it is in space. Some launch vehicles have stabilizing fins to provide better control during the boost phase of the flight, but many do not. The latter depend on deflection of thrust and other space-type controls while operating within the atmosphere. Complexities of the control problem during the launch phase will be discussed later.

RENTRY.—When you see a shooting star at night, you are witnessing an uncontrolled reentry into the atmosphere and seeing how much heat atmospheric friction can generate at high speeds. When a chunk of matter hurtling through space, called a **meteoroid,** comes under the influence of gravity, it begins to plummet toward the earth as a **meteor.** It falls toward the earth faster and faster through an environment perhaps too thin to be called atmosphere but nevertheless containing enough molecules to warm it with their friction until, at a height of about 70 miles, it is hot enough to begin to glow. As it streaks toward earth at speeds up to 40 miles per second it encounters heavier and heavier layers of atmosphere and glows brighter and brighter until it is all consumed. (If an unconsumed remnant reaches the earth, it is called a **meteorite.**)

Man-made objects in earth orbit eventually suffer this fate too. Dead satellites, discarded booster engines, ~~and other~~ items of so-called "space junk" eventually slow down in near-earth space. The friction of a thin scattering of air molecules, too thin to be called atmosphere, and of numerous tiny micrometeoroid particles, eventually produces a braking effect on the orbiting vehicle or object; and the orbit **decays**—that is, the force maintaining the object in orbit loses strength. The object is then pulled toward earth by gravity and ends its existence in a blaze of glory as a meteor. A space ship with a man aboard would suffer the same fate without proper means of bringing it to earth safely.

A flatiron-shaped **lifting body,** an aircraft currently under development for gliding on atmosphere, is one answer to this problem. At present, however, the tried-and-true method of safe reentry is one that involves maneuvering the craft's attitude just before reentry so that it presents its blunt end forward as it descends into the atmosphere. This blunt surface is coated with an **ablative* heat shield,** which absorbs the heat of atmospheric friction, heats to a bright glow, then carries the heat away from the vehicle through the simple process of wearing and flaking off. As the craft reaches the lower atmosphere, parachutes are deployed for more drag prior to a gentle splashdown. Thus reentering space vehicles make use of atmospheric drag just as aircraft do.

## VEHICLES IN SPACE

In space, the laws of Galileo, Kepler, and Newton operate in a very forthright fashion. Without the friction of atmosphere to impede it (except to the slight degree already described), a body in motion truly operates according to Newton's first and second laws; and in orbit it travels faster at **perigee** (the point on its orbit closest to earth) and slower at **apogee** (the point farthest away from earth), just as Kepler said it would.

Without atmosphere, airfoils are useless, and so is streamlining. Satellites of all sizes and shapes, be they cubes, giant balloons, or irregular objects projecting flat surfaces and antennas in various directions, regardless of attitude, sail serenely through an unresisting vacuum in unpowered flight at speeds of many

*Pronounced "a-BLATE-ive" (unlike the grammatical term, which is pronounced "AB-lative.")

thousands of miles per hour. Attitude is unrelated to line of flight, except insofar as it positions a rocket motor to deliver thrust in a given direction. A spacecraft can fly sideways or nose up or nose down. It can **roll** round and round its axis, or **yaw** from side to side, or **pitch** up and down, or even **tumble** end over end, and it will still continue in the same line of flight at the same speed. These motions may be undesirable and controlled attitude may be desirable for a number of reasons, but they have no effect on line of flight or velocity.

There is one misleading notion that should be corrected right now. Do not imagine that, because a space vehicle is "weightless," it should be easy to maneuver. If a satellite weighing 140 tons on earth can be put into orbit, consider that it carries 140 mass tons in space, and multiply this by a velocity on the order of 25,000 feet per second to calculate its tremendous inertia. To steer it from one orbit to another, or launch it precisely on a trajectory that will take it to the moon, powerful G-forces and inertial forces must be overcome. That, of course, is why the booster has so much mass in the first place. Most of it is rocket engine and propellants to accomplish this job on behalf of a much smaller payload. Let us consider propulsion a little further.

### Propulsion

In all space operations, a few minutes of thrust establishes a velocity maintained by coasting. A ride through space is mostly downhill. A coasting satellite can only stay in one orbit, but even one retaining some thrust capability must carefully conserve it for use at times when delta-V is required, the uphill part. Of all these hills, the hardest is the first, getting off the earth.

The two biggest monsters in US space programs are Titan IIIC and Saturn V. Titan IIIC, with its two strap-on solid boosters, can develop a total of more than three million pounds of thrust (Fig. 4). Early in 1965 it demonstrated its prowess by boosting a 21,000-pound dummy payload into earth orbit. This performance was topped in November 1967 by the Saturn V, with an initial stage thrust of 7,500,000 pounds and a second stage of 1,000,000 thrust pounds, which orbited a 280,000 pound payload, the third stage's 200,000 pounds of thrust in turn boosted 30,000 pounds to a higher orbit. Total thrust of that Saturn V, all stages, was 8,700,000 thrust pounds.

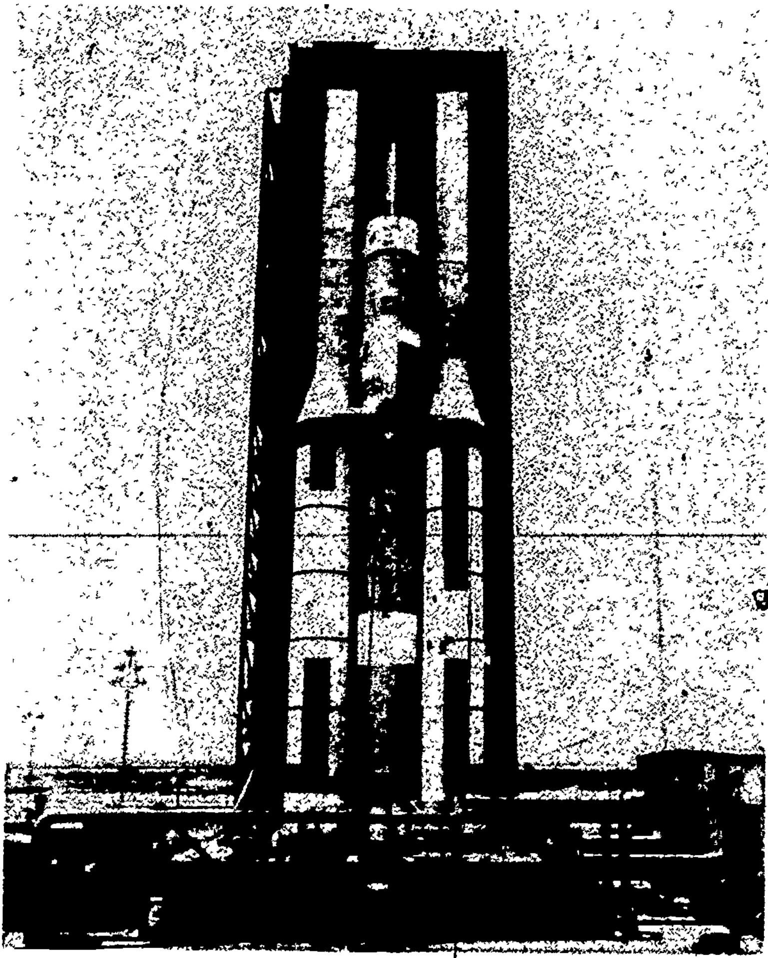

Figure 4. Titan IIIC, with two strap-on solid booster motors, can develop more than three million pounds of thrust.

As they sat on the launching pad, Titan IIIC weighed 1,400,000 pounds and Saturn V 6,100,000 pounds. The greater part of these weights was propellant.

The Saturn V booster used in the Apollo moon flight program achieved some increases in both weight and total thrust. For instance, the launch vehicle used in the flight of Apollo 11—the flight that first put men on the moon—weighed around 6.5 million pounds and developed nearly nine million pounds of total thrust. The Apollo spacecraft itself—including Command, Service, and Lunar Modules, a Spacecraft-Lunar Adapter, and a Launch Escape System—weighed 96,698 pounds. Later Apollo flights were in roughly the same range.

In the blazing, earth-shaking, ear-splitting spectacle of a space launch at Cape Kennedy, the missile is seen through immense billows of smoke and flame beginning its rise as ponderously and slowly as a freight elevator in a warehouse. But it does rise, faster and faster, each additional second of burning time adding velocity to velocity—continuous delta-V. As the fuel is consumed, the weight of the load decreases considerably, but not enough. There is still the dead weight of the engine itself adding to the burden of the launch, and eventually this engine runs out of propellant. Therefore propulsion is divided into stages. As each stage burns out, the next one—smaller and lighter—is ignited and the dead one is automatically detached and thrown away, or, to use the proper term, **jettisoned.** This lightens the burden still more until only the relatively small orbital payload remains.

A costly procedure indeed. In view of the inflexible seventeenth-century laws we have cited, must man always pay such a high price for getting into space? The experts feel that this fare can be greatly reduced. There are unbreakable limits imposed by nature, but other limits, imposed by the present "state of art" of aerospace science, in the future will be expanded greatly. Here let us suggest some of the directions which propulsion progress might take, some of these topics to be amplified in Chapters 2 to 4 of this study.

One is the recoverable booster stage engine. If the booster stage cannot be carried along for the whole trip, as an airplane or automobile carries its power plant without throwing it away to lighten its load, perhaps the discarded booster stage could make a soft landing or splashdown and be repaired for future use. Some liquid rocket engines, at least, are costly and complicated enough to make the effort worthwhile. (Solid booster motors, being little more than shaped containers for the propellants, may continue to be disposable.) The space shuttle now under development as a relatively cheap means to supply manned orbiting stations around the earth (and perhaps even to launch satellites) will be a two-stage rocket ship with an expendable booster stage that will be usable around 100 times.

Another approach, of course, is that of improving the fuel and oxidizer performance. and this effort goes on continuously. Less **propellant weight flow rate*** producing more thrust means higher specific impulse, measured in **seconds. Specific impulse** is the number of pounds of thrust delivered by one pound of propellant in one second. If the engine were throttled down to very low thrust, you could put this figure another way—the number of seconds over which one pound of propellant would continue to deliver one pound of thrust. Either way it means mileage, less propellant weight per payload. At present, a specific impulse of 400 seconds is considered good for space rocket propellants. Within the theoretical limits of chemical propulsion, as discussed in Chapters 2 and 3 there is still much room for improvement.

But there seem to be limits to chemical propulsion which can be exceeded by nuclear propulsion. There are also a number of actual and proposed means of nonchemical low thrust propulsion, no good for boosting off the earth but useful for midcourse flight and maneuvers. Various means of nonchemical propulsion are discussed in Chapter 4.

### Control and Guidance

To preview the topics of control and guidance of space vehicles, it is perhaps best to postpone discussion of the actual means of accomplishing these aims to a later chapter and discuss here some of the problems of the space environment in this regard.

Control of a vehicle out in space is a subject hard to differentiate from propulsion, for it is all accomplished by propulsion. How can an unpowered vehicle, coasting under the conditions described above be made to behave itself properly? How can it be held to a desired attitude, let alone made to change vectors? Since airfoils are useless, the only thing that will work in space is thrust—mammoth thrust, as we have seen, for boosting the vehicle into space, substantial thrust for getting the acceleration—the delta-V—for changing to a higher orbit or a trajectory to the moon or another planet. Negative delta-V or retrothrust, is the means of descending to a lower orbit or (in some cases) reentry. Steering (or **thrust vector control**) is, of course, possible, by means of deflect-

*Propellant weight flow rate is the weight of propellant consumed in a given period of time In calculating specific impulse that time is one second, and the resulting figure is expressed as "seconds of specific impulse" ing the exhaust gases.* Some of the aims one might think would be accomplished by steering are accomplished by other means. One does not zoom an orbiting spaceship by aiming it upward like an airplane. To go "higher," one usually adds thrust to straight ahead movement.

An extremely important aspect of control in space is the accuracy with which propulsion must be started, regulated, and ended. Timing must be down to split-second accuracy; thrust must be controlled to achieve a precise velocity, for velocity, we repeat, is not only a question of *how fast* but also *where* the vehicle will go. Such terms as **windows** and **corridors** indicate the precise time intervals or pathways that must be taken to accomplish a mission or bring back any human passengers alive. Guidance, as we shall learn, can be provided by several systems, but all of them must be automatic and computerized, whether the craft is manned or unmanned.

As Willy Ley once said about how to reach the moon: "You shoot into infinity, and you do it at such a time that the moon gets in the way." All voyages in space, even near-earth orbits, are like that. As in skeet shooting, it is a matter of predicting a meeting point for shot and target. There are some orbital paths and trajectories a space vehicle can follow and others which are impossible. The path of a satellite projected straight down to the earth's surface is called its **ground track.** If it is desired to make a vehicle pass directly over a given location on the face of the earth at a given time, one cannot simply "steer" the vehicle along the desired ground track. The correct procedure, rather, is to launch the vehicle with the right velocity at the right time and let the laws of Kepler and Newton provide the ground track. Accomplishing a rendezvous between two satellites in space is a similar problem. From such examples we can see the importance of orbits and trajectories.

## SUMMARY

Propulsion, control, and guidance are essential to the movement of all vehicles—on the ground, in the air, and in space. It is also true that all vehicles obey the same laws, no matter in which environment they move. Twentieth-century accomplishments in space

*This deflection changes the *thrust vector*—the line of action along which thrust operates are based on an understanding of physical laws first discovered in the seventeenth century by Galileo, Kepler, and Newton.

Galileo and Newton related the force of gravitation as we experience it on earth to the mass attraction between bodies in space. Kepler tracked the orbits of planets carefully and determined that the planets follow an elliptical rather than a circular path, with the sun as one focus of the ellipse. He also observed that planets moved faster in that part of the orbit that lay closer to the sun, and that near planets also moved at a faster average velocity than more distant planets. From the groundwork provided by Galileo and Kepler, Newton developed the three laws of motion: 1. A body will continue in the same state of rest or motion unless acted upon by another force, 2. Any change in its velocity indicates the action of another force, and 3. Action and reaction are always equal and opposite.

All bodies, whether on earth or in space, obey these laws, but if bodies on earth or in atmosphere do not *seem* to obey them it is because of the force of friction. Other terms and concepts that must be understood for purposes of this study are "mass," which a body always has regardless of "weight" (the product of mass and gravity); "inertia" and "momentum," the products of mass and velocity; and "acceleration," the change of velocity brought about by either propulsion or gravitation.

To appreciate movement in space, a review of the conditions of vehicle movement in atmosphere is useful. A point worth remembering is that not only aircraft move in atmosphere but also spacecraft during the launch and reentry phases of their flights. All aircraft engines operate on the same action-and-reaction principle as rocket motors. Jets, especially ramjets, actually function with greater efficiency in high thin atmosphere, under conditions that approach those of space travel. Although aircraft are inhibited in velocity by atmospheric pressure and friction, these same conditions permit flexibility and maneuverability denied to spacecraft by the tremendous inertia imposed by gravitational forces, and by lack of friction.

Spacecraft need a certain amount of streamlining to facilitate flight into space. Their main aerodynamic problem is that of reentry—to avoid being consumed by the heat of atmospheric friction like a shooting star or meteor. The current tried and true method of reentry is that of using a blunt surface coated with a material called an ablative heat shield to carry off heat as it disintegrates.

In space, the laws of Galileo, Kepler, and Newton operate in very forthright fashion. Lack of friction permits unpowered flight, regardless of attitude. The principal problem is to get the vehicle into this environment from the earth's surface, a task which today can be accomplished only by generating immense thrust forces and wastefully discarding booster stages as well as burning up propellants to lighten the burden. The greater part of a spacecraft's weight as it sits on the launching pad is propellant. Future developments include a nuclear rocket engine as well as other means of propulsion.

The control problem in space is based on the fact that the vehicles have tremendous inertia and lack maneuverability. It is mostly done by precise computerized regulation of propulsion to attain the exact timing and velocity that will inject the vehicle into a given orbit or trajectory where Keplerian and Newtonian laws will do the rest.

Armed with the broad insights offered by this chapter, the student can now begin to explore the subjects we have summarized in a little more detail. The next chapter will deal with chemical propulsion.

## WORDS, PHRASES, AND NAMES TO REMEMBER

| | | |
|---|---|---|
| ablative | gravitation | momentum |
| acceleration | gravity | Newton's Laws of Motion |
| ambient | ground track | orbit |
| apogee | inertia | orbital decay |
| attitude | Kepler's Laws of Planetary Motion | perigee |
| Bernoulli's Law | | pitch |
| control | jettison | propulsion |
| corridor | lifting body | roll |
| decay | mass | sidereal period |
| delta-V | meteor | specific impulse |
| flow rate | meteorite | stage |
| friction | meteoroid | thrust vector |
| | | trajectory |

## QUESTIONS

1. What is the difference between gravity and gravitation?
2. Work the example we have given with the statement of Kepler's second law. Assume simplified figures, such as 10 distance units for planet A's distance from the sun, 10 time units for its period of orbit, and 20 distance units for planet B's distance from the sun. Solve for planet B's period of orbit in time units.
3. Which of Newton's laws makes seat belts desirable in an automobile? Which of Newton's laws represents the function of the seat belts themselves?
4. Name some of the advantages which aircraft have compared to spacecraft.
5. What is the current method of solving the reentry problem for space vehicles? What is one proposed method under development?
6. Why must rocket engines be constructed in stages for a space launch? Why must they be discarded after one use?
7. What function does velocity have in regard to a space vehicle that is not generally considered in regard to land or air vehicles?

## THINGS TO DO

1. The next time you ride in a car, pay particular attention to the forces at work—acceleration, momentum, inertia—and be aware of how we use Newton's Laws of Motion in everyday practice. This should make you appreciate the fact that such laws are not just theoretical statements for laboratory use only.
2. See if you can find out how many satellites are currently in orbit around the Earth, how many of them are still performing the tasks that they were sent up for, and how many have become "space junk." Is there any danger of overcongestion of orbital space from these satellites?

## SUGGESTIONS FOR FURTHER READING

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THIS CHAPTER begins with a review of basic chemistry to provide an understanding of oxidation before focusing on propulsion. The basics of thrust are then presented in terms of combustion chamber and nozzle, mass flow, specific impulse, and other factors related to the heaviest task of propulsion—boosting a vehicle off the surface of the earth. After completing study of this chapter, you should be able to do the following: (1) cite examples of the basic chemical process of oxidation ranging from extremely slow to extremely fast; (2) compare combustion in an air-breathing engine with that in a rocket engine; (3) describe a molecule's path from combustion chamber to nozzle exit plane of a rocket motor; (4) define specific impulse, thrust-to-weight ratio, mass ratio, gross-weight-to-payload ratio, and ΔV, and (5) describe the process by which a payload is boosted from the earth's surface into orbit.

CHEMICAL propulsion is currently man's only means of escaping into space and his principal means of giving himself a choice of pathways in space. With limited exceptions, nonchemical propulsion systems, which will be described in Chapter 4, still belong to the future. Nuclear engines nowadays are already doing some of the world's work. They drive ships and submarines and supply cities with electricity. The earthshaking roar of a Saturn booster, however, is not nuclear. Man's mightiest thrust into space to date is that of thousands of tons of chemicals undergoing an old fashioned reaction known as oxidation or combustion.

In this chapter, we shall discuss both chemical propulsion and some of the basics of propulsion itself. There are important differences between the two main types of chemical propellant systems, liquid and solid, but these will be discussed in Chapter 3. Aspects of thrust so fundamental that they apply to both types of system are discussed in this chapter. Special attention will be given to the heaviest task of propulsion, the launch into space. The first topic is very fundamental indeed—a backtrack into elementary chemistry to provide an understanding of that all-important thing called oxidation.

## OXIDATION AND COMBUSTION

A chunk of iron turning rusty in moist air and a huge rocket blasting off into space have one thing in common. a chemical reaction called **oxidation.** In both of these instances. a chemical element or compound classed as a fuel. more technically a **reducer,** reacts with another chemical element or compound called an **oxidizer** or **oxidant.** These words are derived from "oxygen." which is the most common oxidizer.

### Oxidizers and Reducers

Various oxidizer-reducer combinations can produce an endless variety of reactions. all classed as oxidation. When it comes to rocketry, however, a certain few elements, occurring in a wider variety of compounds. dominate the field.

OXIDIZERS.—The element oxygen occurs in air as a molecule of two oxygen atoms, written in the shorthand of chemistry as $O_2$. To concentrate this pure form of oxygen in a tank in sufficient quantity for usefulness in a non-airbreathing engine, it must be chilled down to below its boiling point, an extremely frigid −297° F., to become a liquid. Anything kept at such extremely low temperatures is called **cryogenic.** Cryogenic oxidizers and reducers are both used widely in today's space programs. There are. however, other forms in which oxygen can be packaged for use aboard a rocket, which do not require deep cold. These are chemical compounds containing oxygen (that is, chemicals of which the smallest unit or molecule contains atoms of oxygen and other elements). Two other elements besides oxygen can be used as oxidizers in pure or compound form: fluorine and chlorine.

REDUCERS.—Any list of fuels or reducers must begin with the elements hydrogen, carbon, and nitrogen. Certain compounds of hydrogen and carbon called **hydrocarbons,** including coal and petroleum products like kerosene and gasoline, are the basic fuels of modern transportation and industry and are important in the space program as well. Nitrogen (inert as it occurs in atmosphere as $N_2$

molecules but highly reactive in other forms) figures importantly in explosive and other high-energy compounds and mixtures. It too plays a key role in rocket propulsion. Pure hydrogen, in the form of $H_2$ molecules, is an excellent rocket fuel, but it is even more cryogenic than oxygen. To be tanked in liquid form, hydrogen must be chilled to −423° F., a bare 27° above absolute zero. These are the most important rocket fuel elements. Fuel compounds and mixtures based on these and others are endless in number.

PROPELLANT COMBINATIONS.—It takes both an oxidizer and a reducer to propel a rocket. *Both* these ingredients are called **propellants,** or their combination can be referred to in the singular as *a propellant.* In this text we shall adhere to this technical usage and not refer to the total ingredients of chemical propulsion as fuel. Such an expression as "a pound of propellant" means so many ounces of fuel and so many ounces of oxidizer, whatever may be the proportions and regardless of whether these ingredients are stored in one container or two.

Ignoring for now the mechanics of liquid and solid systems, let us consider three basic ways in which propellants are stored and used (there are variations we need not consider at present):

1. Oxidizer and fuel are kept in separate containers and fed into a combustion chamber for ignition. Such a combination is called a **bi-propellant,** and is the most common form of liquid propellant (Fig. 5).
2. Oxidizer and fuel are stored together as a solid mixture or compound in a container which also serves as a combustion chamber. The mixture reacts only when properly ignited.
3. Oxidizer and fuel are stored together as a liquid mixture or compound in a container and then fed together into a combustion chamber for ignition. This mixture is called a **monopropellant.**

Chemically, even when oxidizer and reducer occur in a mixture, they are considered to be two separate ingredients, but there is such a thing as a **self-reacting compound.** In such a compound, one molecule contains atoms of both oxidizer and reducer and, upon ignition, reacts with itself, yielding energy as it breaks down or decomposes.

Let us return to fundamentals for a while.

### Nature and Effects of Oxidation

We have mentioned rusting of iron and blastoff of rocket as extreme examples of slow and fast oxidation. To understand the process a little better, let us look at a third example, a charcoal fire. Its main reaction occurs between carbon in the fuel and oxygen in the air to form molecules of carbon dioxide ($CO^2$). In this process, a solid shrinks to ashes, but $CO^2$, in the form of an invisible gas, takes its place. Nothing is gained or lost in an oxidation. The total mass of all the ingredients involved in the reaction remains the same before, during, and after, whatever the form, wherever it goes. This classic principle, called **conservation of mass,** is an important one for chemical propulsion. A chemical reaction, then, is a process neither of creating nor destroying matter but of reshuffling and recombining it. As a **physical activity,** this process can be described as that of molecules clumping together to form larger molecules or splitting apart to form smaller molecules or atoms.

A charcoal fire in a backyard grill, however, is not kindled for the sake of producing carbon dioxide. It is the *heat* of this reaction that sizzles the steak. The physical activity we mentioned is a vigorous one. *The heat of a chemical reaction is the effect of atoms and molecules being stirred into rapid vibration or motion.*

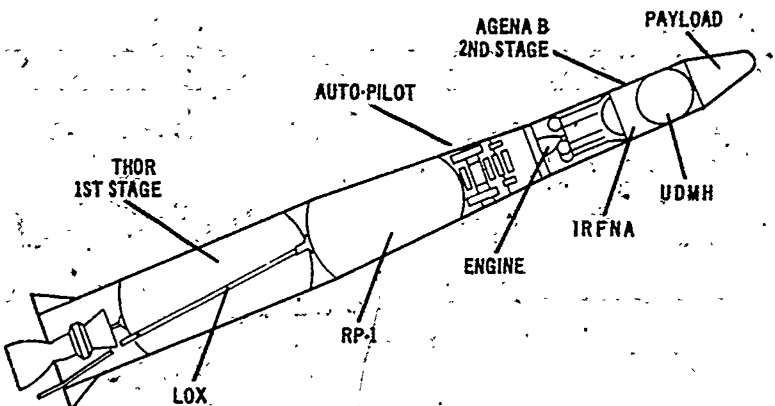



Figure 5. Cutaway model of a Thor-Agena B rocket shows how oxidants and reducers are stored in a liquid-propellant vehicle.

If the vibration becomes rapid enough (faster than $10^{11}$ cycles per second) the energy takes the form of visible light. Thus the charcoal fire has glowing coals and dancing flames.

In rusting iron, "heat" is produced. That is, molecules are stirred by the process into vibrating with slightly increased speed, but the reaction is so slight that no thermometer can record it. In a space rocket, the reaction is swift and violent, producing thousands of degrees of temperature, brilliant light, loud noise (at lower altitudes where atmosphere is present—the reaction in space is silent), and, most important of all, *force*—that which moves mass. The energy effects differ, but they are all the results of one thing: the dance of the molecules—molecules vibrating, molecules swarming in helterskelter flight, molecules rushing in headlong flight.

At this point, let us switch to a more descriptive word: **combustion** instead of oxidation. Actually they mean the same thing, with a meaning that can be stretched to include the rusting of iron or the digestion of food. In preferred usage, however, combustion means *rapid* oxidation, producing palpable heat, visible light, and usually, expansion of a liquid or solid into a gas. In short, it is fire.

There are, however, all kinds of fire. Fires vary widely in speed of reaction, from slow broil to sudden explosion. They vary in means of ignition, and, above all, in the forms and proportions of their energy output. To demonstrate this fact, let us look at a couple of fast, energetic fires. A photo flashbulb's contents can be ignited by a tiny hot wire and yield high energy in the form of sudden, brilliant light. This reaction, however, has a relatively low force output, not enough to burst the glass and plastic container. By contrast, a small quantity of TNT, a high explosive, would yield much greater force but not so bright a flash.

We might consider TNT a bit further, since it might have some possibilities as a rocket propellant, for which force is paramount. It carries its own oxidizer supply, being a self-reacting compound of carbon, hydrogen, oxygen, and nitrogen ($C_7H_5O_6N_3$). TNT, for all its violence, is a sluggish reactor. The hot wire that can trigger a flashbulb would have no effect on it; neither would a match. It requires the shock of another explosion to detonate TNT. So far, so good; these qualities tend to make it safe and sure. Its main drawback is the suddenness of its explosion. Once it is properly triggered, it blows up all at once, with equal and shattering force in all directions. Unless diluted with other ingredients, it would blow up a rocket rather than propel it.

Let us now see how the energy of combustion can be harnessed for a kind of work different from steak broiling, photography, or demolition.

## COMBUSTION FOR PROPULSION

First let us consider the essential qualities of a good propellant, without regard to whether it is of the liquid or solid type. Then let us look at how chemical energy is translated into physical force in a combustion chamber.

### Qualities of a Good Propellant

A propellant must have these four characteristics: (1) It must contain oxidizer as well as fuel; (2) it must ignite accurately and reliably; (3) it must yield energy in the form of force; and (4) the force must be controllable.

NEED FOR PACKAGED OXIDIZERS.—Aside from propulsion in space. where no free oxygen is available, there is another reason for putting oxidizer in a concentrated package—one which applies to operation in air as well as space and should be mentioned for its historical as well as present importance. *An oxidizer-reducer mixture will burn forcibly in a confined or semi-confined space in which an airbreathing fire would be smothered.* Men knew this fact for centuries without knowing the reason why, and exploited it long before airbreathing engines were ever imagined. Old-fashioned gunpowder or "black powder" needs no air to burn its carbon and sulphur fuel ingredients because it has an oxidizer built into a third ingredient, potassium nitrate or saltpeter ($KNO_3$). The ability of this mixture to propel a rocket or hurl a cannon ball out of an iron tube was known and employed in warfare centuries before Lavoisier discovered oxygen and the principle of oxidation in the eighteenth century. To this day all chemical rocket propellants, all gun munitions, and all chemical explosives, contain an oxidizer, burn in confinement, and do their work by bursting out of confinement or rushing out of semi-confinement. "Rushing out of semi-confinement" describes the essential rocket-propellant action. We repeat, however, that in a rocket propellant mixture, oxidizer outweighs fuel, perhaps on a grand average of

5:3. Because the cost of packaged oxidizer runs high, the air-breathing engine enjoys a tremendous weight and economic advantage in its proper environment.

IGNITION CHARACTERISTICS—We have already noted that a mixture's speed of combustion, once it starts, is not necessarily in proportion to its sensitivity to ignition. What should be the triggering properties of a good propellant? Since there are various kinds of propellants, triggered in various ways, again we must think of essential requirements rather than specific reactions. As we noted in Chapter 1, precise initiation of thrust is an important requirement for vehicle control; therefore the means of ignition must be accurate and reliable. Some motors are designed to be started but once and continue burning until all propellants are exhausted (**burnout**). Others are designed to be repeatedly started and stopped. Safety, of course, is paramount. This does not mean the ability of a propellant to stand up to any kind of rough or careless handling without igniting, but it does mean that its safety requirements should be known and feasible. Some propellants are ignitable the old-fashioned way, by a touch of heat on the order of a match flame or hot wire. Others require greater and more concentrated heat. Some require an explosive shock. Some are **hypergolic;** that is, under normal temperatures, the oxidant and reducer burst into flame the instant they are brought into contact with each other. This sounds touchy, but the main safety requirement in this case is to keep the ingredients separated.

ENERGY FOR FORCE.—Not light, not heat for its own sake, but force is the result desired from a propellant's release of energy—the sheer momentum of moving molecules. What is desired is **mass flow** of combustion exhaust, but this mass can be no greater or less than the mass of ingredients before combustion. However much a designer might wish to lighten the propellant load aboard a vehicle, he must provide for a certain irreducible minimum of propellant weight, and as things stand today in the present "state of the art," ~~this~~ load alone is most of the initial weight of the launch vehicle. The only way to get more force per load is to increase the speed of the mass flow; that is, to get more speed per molecule. Therefore, it is better not to increase mass flow by means of heavier molecules which are too sluggish. The ideal exhaust gas consists of plenty of lightweight molecules, which excel in energy and speed.

Although we shall consider the pros and cons of other fuel-oxidant combinations, the above facts so far add up to an argument on behalf of a fuel-rich hydrogen-oxygen mixture. You probably know that a fuel-rich mixture is bad for automobile performance because, with insufficient oxygen available to burn all the fuel, combustion is incomplete and unburned waste goes out the exhaust pipe. In jet or rocket propulsion, however, unburned molecules flying out the exhaust nozzle can be useful; if they are heated into swift motion, they actually add to the thrust. Some jet aircraft engines employ water injection for this very purpose.* A fuel-rich hydrogen-oxygen rocket propellant expels a quantity of extremely light unburned hydrogen ($H_2$) molecules along with the "burned" combustion product—water vapor ($H_2O$). Even the $H_2O$ molecules are light in comparison with a good many other combustion products; so the total exhaust is one of low average molecular weight and high specific impulse (a subject which will be discussed later in this chapter.

CONTROLLABLE FORCE.—As we have already indicated, however, the speed of the combustion should not be excessive. Fast but not too fast is the rule of thumb. If the ingredients are liquid, their flow into the combustion chamber can be regulated. If solid, the mixture should be of the type sometimes called "low explosive." Modern solid propellants are considerably more energetic than black powder, but they still must have the property of burning so that each particle ignites its neighbor in a swiftly-spreading reaction rather than all ignite at once, as in a "high explosive" like dynamite or TNT. For propulsion efficiency (not to mention safety), impulse must be steady, not provided all at once. Let us look more closely now at the dynamics of gas in confinement and escaping from confinement.

## Pressure and Mass Flow

It is characteristic of any gas, not necessarily a hot combustion gas, that its molecules fly about freely in a helter-skelter fashion. The reason for this random motion is that flying molecules are forever colliding with each other and bouncing away from these collisions. When a gas is enclosed in a container, molecules will bombard its walls on all sides with equal force, producing the effect we know as "pressure."

*See Aerospace Education II, *Propulsion Systems for Aircraft*, page 88.

Gas pressure can be increased by adding more molecules (inflating a tire), by reducing the size of a container (the compression stroke of a piston in a cylinder), or, most of all, by heat, which makes the bullet-like molecules fly faster and hit harder.

We have noted that molecules do not need to undergo combustion themselves to be invigorated by heat. In an external combustion engine such as a steam engine, water is subject to an outside source of heat until it expands to a gas. Its energized $H_2O$ molecules then hammer away at the engine's pistons in vast numbers to provide the driving force. Any liquid or gas employed in this fashion but not combusted is called a **working fluid.** In Chapter 4, we shall learn that the most promising application of nuclear energy to rocket propulsion employs the external combustion principle somewhat like a steam engine, using hydrogen as a working fluid.

But this chapter's concern is with the internal combustion motor, which employs the idea of creating a fire in a chamber and employing the expanding mass of its own combustion products directly. In the case of jet or rocket propulsion, this force is direct indeed—straight out the rear exit for direct thrust toward the front, according to Newton's third law.

If you could see the individual molecules in action, however, you might wonder how direct this force really is. Figure 6 describes what happens to one of them. It traces its adventures from the moment of its combustion to its departure past the exit plane of the exhaust nozzle. Newly created and loaded with energy, the molecule zips about within the chamber aimlessly at location A. It

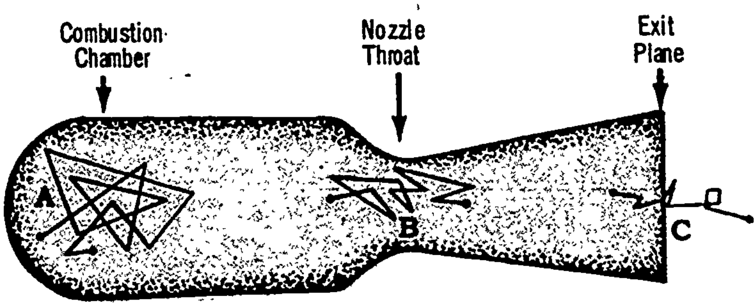



Figure 6. After combustion the individual molecules are routed toward the exit plane, their speed in the right direction increased, to provide acceleration.

beats madly at its prison walls, creating pressure. There is a way out of its prison, however, and the molecule is inevitably impelled in that direction along with a jostling crowd of its fellow molecules. We see it again at location B and again at location C. Note that its path continues to be erratic but less and less so—more zig and less zag, one might say. Finally, it escapes. The artist imagines that it executes one final "loop the loop" in farewell.

This wandering molecule would seem to be going through a great deal of wasted motion and taking much too long to make its exit. Actually, it is making excellent progress. The whole journey is accomplished in a fraction of a second. More significantly, at each stage of the journey, it is *traveling faster than before in the right direction.* Futhermore, the greater the pressure in the chamber, the greater the velocity through the nozzle. It is its speed out the nozzle that counts most. The net result, **acceleration,** is the essence of thrust. The mass of molecules is accelerating in respect to the motor, and the motor itself is moving. As long as combustion is going on inside it, and mass flow is passing out the nozzle, the motor adds velocity to velocity and accelerates.

## BASIC ROCKET MOTOR DESIGN

The vessel in which the molecular action we have described takes place is a simple container with nozzle which might be called the basic rocket motor, regardless of whether it is of the liquid or solid propellant type.*

### Overall Design

Look again at Figure 6 to consider the rocket motor's essential shape. It is that of a bottle with a flaring neck, perhaps more like a flower vase than a bottle. Motors come in a variety of sizes and shapes, but this simple drawing can serve to show us the fundamental design principles, which are as simple as ABC. A is the combustion chamber, which must contain the combustion, withstand its heat (more than 5,000°F.), and build up pressure. B is the bottleneck, the constricted throat, which allows the exhaust its

*The word *motor* is defined as a power unit that imparts motion. The word *engine* is defined (in comparison to *motor*) as a large or complicated power unit that converts energy into usable form. In our discussion, simplicity is the key. The two words often are used to mean the same thing, but it is the practice to speak of solid-propellant rocket motors and liquid-propellant engines. In our discussion, the word "motor" is used to mean only the combustion chamber and nozzle, which are common to all rockets.

one escape route but must be narrow to keep up the compression. C is the nozzle, which, by flaring outward, reduces the pressure and increases the speed of the escaping gas. In a typical rocket motor, escaping gas moves at sonic speed, about 3,000 fps at high temperature, through the throat and can reach speeds as high as 10,000 fps at the nozzle exit plane. The basic nozzle design is converging-diverging, sometimes called the **de Laval nozzle,** after Carl Gustav Patrik de Laval, a Swedish engineer (1845-1913) who developed it as a means of speeding the flow of steam in a turbine engine.

### More About the Nozzle

The **expansion ratio** of a rocket nozzle is defined as the area of the nozzle exit plane divided by the area of the nozzle throat. The greater this expansion ratio, the higher the speed of the propellant mass and the greater the thrust; but it is not quite that simple. Here as in so many other aspects of rocket design, problems are encountered and compromises must be made.

If the nozzle flares out too widely, like the bell of a trumpet, the gases are aimed out too widely for efficient reaction in the desired direction of thrust. This objection can be overcome by making the nozzle longer, thus achieving the same exit plane area, the same expansion ratio, within a narrower angle. Such a design, however, takes up too much length in the total vehicle structure, adds to dead weight and encroaches on space needed for tankage, engines, and payload. Then there is the matter of atmospheric pressure, sometimes called **ambient pressure.** This is the pressure of the air surrounding or encompassing the vehicle. In space, ambient pressure is zero, but on the launching pad, where maximum thrust is desired, it is a big item. As the propellant gas rushes out the nozzle, it loses pressure even as it gains speed, these being the twin effects of the de Laval nozzle expansion principle. The optimum expansion ration for any altitude is that which produces gas pressure equal to ambient pressure at the exit plane. If there is too much nozzle expansion, ambient pressure crowds in and blocks mass flow. Too little expansion means gas speed will not be amplified enough for maximum thrust. The design of a multistage vehicle, therefore, would call for a greater expansion ratio for each higher stage, since ambient pressure is lower where the upper stages go to work.* Since each stage operates over a considerable range of altitudes, however, each nozzle design is a compromise. Look closely at Figure 7, and you will notice how in the upper stages, the nozzle is longer (and the exit plane area greater) in relation to the nozzle throat area. This means the nozzle expansion ratio increases for upper stage.

The Laval design still holds its own in modern rocket motors, although efforts to modify and improve it are constantly going on Some of the possible variations are shown in Figure 8. The upper six drawings represent an elongated cone design and five variations. The elongated cone represents the concept of achieving a certain expansion ratio while aiming the gases in a narrow path, but with the disadvantages mentioned. Nozzle and overall length are stated as 100 percent for this design. In the variant designs, by means of setting up complicated flow paths, the same expansion ratio is achieved within a shorter overall length, with less dead weight, and with efficient aiming of thrust. The lower two

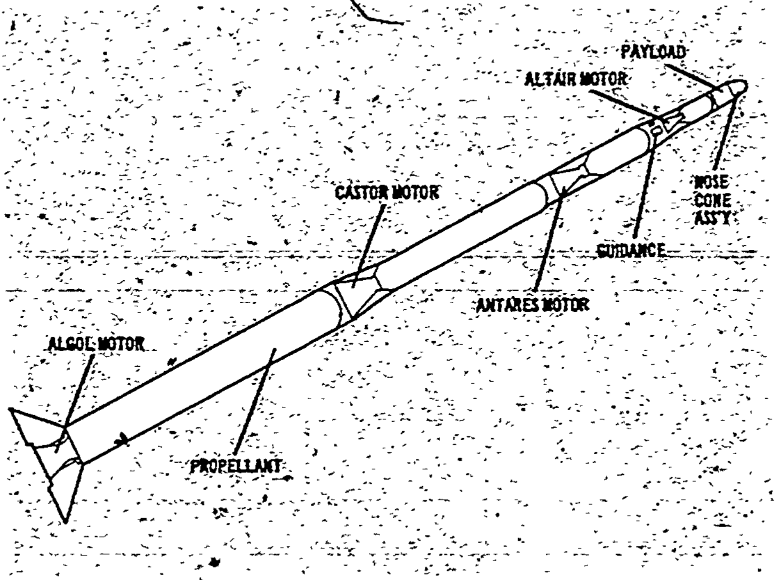



Figure 7. Scout missile cutaway shows how nozzle design can vary from lower to upper stages of a multi-stage vehicle.

*Turbojet aircraft engines have straight rather than de Laval-type nozzles because they are designed exclusively for use in atmosphere to overcome high levels of ambient pressure

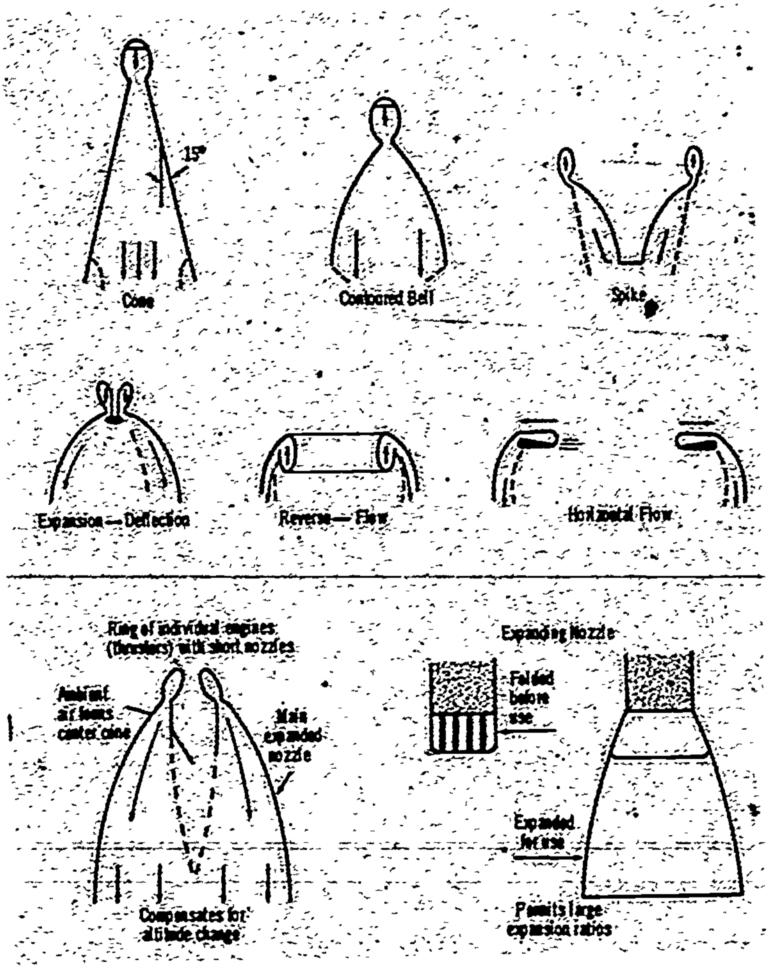



Figure 8. Schematic drawings show several different nozzle designs and how the nozzles function to control the thrusting exhaust gases.

drawings suggest ways of adjusting the expansion ratio for different altitudes.

## SOME BASICS OF THRUST

Before getting into the differences between liquid and solid propulsion, we must consider a few more aspects of thrust in general. We shall be very sparing with mathematics in this text, using only the simplest and best-known formulas.

### What is Thrust?

Thrust is stated as a sum in pounds, measuring the force delivered by a rocket stage. Here are some thrust figures relating to the smallest and largest members of the standard launch vehicle family:

*Scout*
First stage—88,000 lbs sea level
Second stage—61,000 lbs vacuum
Third stage—23,000 lbs vacuum
Fourth stage—5,800 lbs vacuum

*Saturn V*
First stage—7,650,000 lbs sea level
Second stage—1,140,000 lbs vacuum
Third stage—200,000 lbs vacuum

The figures are impressive, but what do they mean? First, we must note that 88,000 pounds means 88,000 pounds force maintained at any one instant, not over a time period. The rating can refer to an average thrust level maintained for the total burning time of the stage. but it sometimes can mean (particularly in the case of a first stage of "booster") a maximum thrust level achieved shortly after liftoff.

In calculating thrust, it is the usual practice to assume gravity at its full earth-surface value as a constant for the sake of direct comparison of motor performance of all stages, even though gravity is actually weaker at levels where the upper stages operate. On the other hand, note that atmospheric pressure is not regarded as a constant; the above figures show ratings for sea-level and vacuum conditions.

Thrust can be increased in either of two ways: by increasing the velocity of the exhaust; or by increasing its weight flow, which could be accomplished by increasing the size of the engine.

### Specific Impulse

Specific impulse (symbolized by the character $I_{sp}$) is a measure of propellant energy and is perhaps the most widely quoted figure in all of rocket technology.* We defined it in Chapter 1 as a quantity, stated in seconds, representing the pounds of thrust delivered by one pound of propellant in one second. Thus, if a booster burns 3,000 pounds of propellant per second and the $I_{sp}$ of the propellant is 300 seconds, the booster delivers 900,000 pounds of thrust. Putting it another way, specific impulse is the number of seconds during which one pound of propellant would

*An introduction to the concept of specific impulse can be found in the AE-II booklet *Propulsion Systems in Aircraft* continue to deliver one pound of thrust, assuming it could be released that slowly. It is useful to state specific impulse these two different ways because propellants have both high and low-thrust uses, and thus specific impulse can have different meanings depending on application.

In a low-thrust motor, specific impulse is comparable to automobile fuel mileage—a competition in which Volkswagens beat 400 hp sport cars. In a high-thrust motor, however, it can mean extra speed. Theoretically, and all other things being equal, a 10 percent increase in specific impulse can mean a 10 percent increase in a booster's maximum or burnout velocity. The values are directly proportional. Although it is stated as a property of the propellant, specific impulse is actually a matter of both propellant chemistry and engine design. Because it is a parameter of *both* mileage and speed, it is the most meaningful yardstick of rocket performance, but it is not the only yardstick.

Black powder has a specific impulse of about 70 to 100 seconds, inadequate for modern military or space rocketry. Modern solid propellants range in specific impulse from about 200 to 300 seconds. Modern liquid propellant combinations range up to 400 seconds and more. The *theoretical* $I_{sp}$ limit of chemical propulsion was set at about 400 seconds not too many years ago, but this ceiling has already been broken and the current theoretical limit is now estimated at 600 seconds. At present it seems safe to say that to get above 800 seconds, only nonchemical methods could be used. Nuclear engines under development may achieve 800 to 2,000 seconds. Electric engines, *in low-thrust operation,* may achieve specific impulses up to perhaps 20,000 seconds and more, but let us reserve the matter of how and under what conditions for another chapter.

Whatever is done to increase specific impulse of chemical propellants, extravagance is a basic fact of high-thrust chemical rocket propulsion. Aviation, by the specific-impulse yardstick, does much better. The $I_{sp}$ rating of jet fuel in the large turbo fan engines that power the current leading American-made transoceanic airliners is about 4,500 seconds. The comparison, of course, is unfair for two reasons: (1) aircraft engines use free air for oxidizer and are $I_{sp}$ rated on fuel weight only, and (2) airplanes do not require the intense outpouring of energy in a few minutes' time that is necessary to boost a space vehicle into orbit.

Therefore, in considering launch and other high-thrust requirements, we can recognize performance yardsticks other than specific impulse. To accomplish these tasks, it is the *volume* of energy that counts—the number of pounds of propellant that can pour out their energy at once as much as the amount of energy per pound. Some relatively low-$I_{sp}$ systems do their work simply by using up propellants faster (which, as we shall see, is an advantage in itself). Such a system, furthermore, might compensate for this extravagance by economy factors that are in its favor. Some of these are cost of the propellants, cost of the engine designed to use a given propellant mixture and difficulty of preparations for launch and countdown (a factor working against cryogenic propellants—the very ones that excel in specific impulse). Within the limits of any given equipment or situation, however, a gain in specific impulse is welcome.

In considering the factors of specific impulse, we could get into some rather complicated technology and mathematics. Instead, let us remember one aspect that tells not the whole story but, for our purposes, the most important part of it. specific impulse is dependent on the molecular weight of the products formed when the fuel burns, and on the heat of the fire that burns it.

Simply stated, the hotter the fire and the lighter the average molecular weight of the combustion products, the greater the specific impulse. Earlier we explained the desirability of a low value for molecular weight. the lighter the molecule, the faster its movement.

High temperature and light molecular weight, however, do not always occur together. Consider again the value of a fuel-rich hydrogen-oxygen mixture, cited above as ideal. Uncombusted $H_2$ molecules in a mixture are extremely light, but uncombusted molecules of *any* weight also bring down the temperature. Imperfect fires simply do not burn as hot as perfect fires. An ideal propellant mixture must be a compromise between maximum heat and minimum molecular weight that somehow balances out at maximum specific impulse for that particular combination.

## LAUNCH PROPULSION

To conclude this chapter, let us consider the problem of getting a launch vehicle off the earth and into a space orbit or trajectory. Some of the ratios and values useful for understanding this problem are thrust-to-weight ratio, mass ratio, gross-weight-to-payload ratio, and change of velocity per stage.

Imagine a tank truck with an engine so inefficient and fuel-greedy that the entire contents of the tank are used to move the truck to a destination 100 miles away. The only payload this truck can carry is the men in the cab plus a few small parcels they might squeeze in with themselves. Launch vehicles are that uneconomical. Most of their weight is in propellants (comparable to the contents of the tank); a good deal of it is in structure, tankage, engines, and so forth (comparable to the truck without its cargo); and the payload is relatively quite small. There the fairness of the analogy ends. A truck can get better mileage than that because its 100-mile destination is not 100 miles straight up, against maximum gravity. (We use 100 miles as a round number because that is roughly the minimum altitude for orbit.)

#### Thrust-to-Weight Ratio—The Liftoff Problem

Before it can begin to strive toward the required velocity for orbit or escape, the launch vehicle must first get off the ground. In regard to this first problem thrust-to-weight ratio is paramount. If Saturn V weighs 6,500,000 pounds complete as it sits in the launching pad, and has a first-stage motor that delivers 7,650,00 pounds of thrust, its thrust-to-weight ratio is 1.18 to 1. Notice that in this ratio the weight is that of the whole vehicle and the thrust is that of the first stage only, because that is the only stage that works on the liftoff problem. The first rule of propulsion is a simple one: *the thrust-to-weight ratio must be better than one-to-one: the first stage of a launch vehicle must be able to lift itself, and have, plus the load on its head, some lifting power to spare.*

But how can this 6,500,000-pound monster rise and gather speed toward orbital flight on a slim margin of 1.18 to 1, which seems barely enough to lift it off the pad? Let us look more closely at what happens.

As the booster ignites, it does not immediately deliver its full rated thrust but spends a few seconds emitting seemingly useless noise, flame, and smoke before thrust is built up to the required level. Liftoff occurs at the moment when thrust has built somewhat beyond 6,500,000 pounds. If the booster then delivered thrust at its full rating for only a second or two longer, the vehicle would rise a short distance and then drop back onto the pad with a mighty crash. The booster, however, has a suffiicent propellant supply to keep it burning and delivering a high level of thrust for several minutes, and each second of combustion after liftoff accomplishes new gains. One is the mere fact that constant application of force means not just steady velocity but acceleration. The vehicle would rise faster and faster even if its weight remained constant. But its weight does not remain constant. Propellants are consumed at the rate of about 28,000 pounds per second, so the load being lifted gets lighter and lighter, with dramatic further gain in acceleration. A minute or so after liftoff, the vehicle begins to lean from straight vertical rise toward a more horizontal flight path. As the vehicle climbs to higher altitudes, two new gains are realized. The first is a decrease in atmospheric pressure—a double dividend, since it means both decrease of air resistance to the vehicle and increase in effective exhaust flow velocity. The second is the slow relaxing of the grip of gravity itself with distance from the earth. By now the booster has probably burned out, and the second stage can now go to work, building upon gains made by the first. Thus a low thrust-to-weight ratio is built into a velocity of thousands of miles per hour.

Would a higher thrust-to-weight ratio, nevertheless, be an advantage? A higher thrust-to-weight ratio would get the vehicle off the launching pad faster, but the ultimate velocity would not necessarily be greater. One might infer that certain military missiles, used in situations where quick reaction counts, need a higher thrust-to-weight ratio than space-exploration vehicles, which need high velocities but can reach them more gradually.

In mathematical calculations related to this matter, the symbols $W_1$ and $W_2$ are used. $W_1$ is the initial weight of the missile or launch vehicle. $W_2$ is the weight of the vehicle after burnout of a stage. The difference is the weight loss due to propellant consumption. As we have noted, this is a very important index of velocity gain; but let us look a little further into this factor.

### Mass Ratio

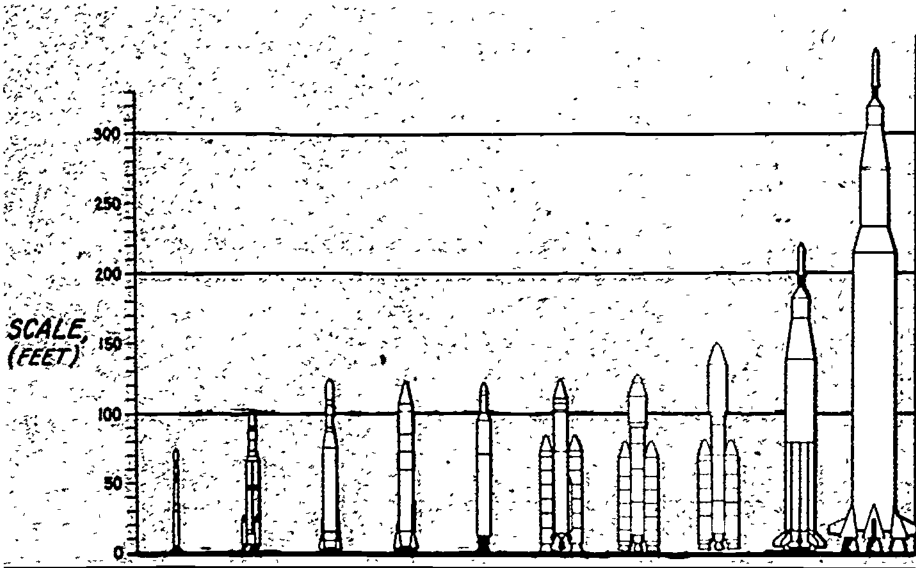
**Mass Ratio** is the ratio of initial to final weight, expressed by $\frac{W_1}{W_2}$. It can be calculated for a single stage rocket, or separately for each stage of a multistage rocket, or it can be multiplied by stages to find a **total mass ratio.** For the first stage of such a rocket, $W_2$, the burnout weight, would represent the total weight of all remaining stages, which would be payload for the first stage *plus* the burned out motors, structural members, empty tanks, and other dead weight of the first stage *before* these are jettisoned.

Mass ratio is often regarded as an index of the design engineer's problem of reducing deadweight to a minimum. A large missile, indeed, is not built for extreme ruggedness. An important reason why it must be launched straight up rather than on an incline toward its intended trajectory is that only in the upright position can it stand the stresses of launch. Several sizes of launch vehicles are used in the US space program (Fig. 9). Much progress has been made and will be made in lightening the structure, connections, piping, tanks, and motors, either by making components smaller or by finding lighter materials of adequate strength. Nevertheless, some dead weight is unavoidable. Liquid propellants need tanks, and cryogenic propellants need heavily-insulated tanks. Solid propellants need a very tough combustion chamber casing. The bigger the payload, the more propellant needed. The more propellant, the more tankage or casing. Dead weight and plenty of it is part of the cost of propulsion.

To illustrate mass ratio let us consider a hypothetical three-stage ICBM designed to fire a 200-pound payload over intercontinental distances. To simplify this imaginary missile for purposes of illustration, let us assume that each of its three stages has a mass ratio of 3.5 to 1. From Figure 10, you can see that a 227,500-pound vehicle is required to fire the 200-pound payload the required distance. Read Figure 10 from the bottom up—the order in which the missile is constructed and fired. The gross-weight-to-payload ratio of this missile is 227,500 to 200, or 1135 to 1. The total mass ratio, however, is calculated differently—by multiplying the individual mass ratios as follows:

$$\frac{3.5}{1} \times \frac{3.5}{1} \times \frac{3.5}{1} = \frac{42.88}{1}$$

Is a high mass ratio good or bad? For the time being, let us consider it as pure asset. For one thing, it might reflect reduced dead weight. For another, it could mean greater weight loss through rapid propellant consumption. This means higher and




| VEHICLE | SCOUT | LONG TANK TAT DELTA | ATLAS-AGENA D | ATLAS-CENTAUR | TITAN III B*-AGENA | TITAN III C | TITAN III D | TITAN III D-CENTAUR | SATURN IB | SATURN V |
|---|---|---|---|---|---|---|---|---|---|---|
| PAYLOAD-LB. (100 N.M.) | 410 | 2,500 | 8,400 | 11,300 | 9,000 | 27,000 | 30,000 | 35,000** | 41,000 | 260,000 |
| PAYLOAD-LB. (MAR-VENUS) | - | 500 | 700 | 1,600 | 900 | 2,800 | - | 8,500 | - | 80,000 |

Figure 9. The current family of space boosters now in use is shown in this drawing. Different space missions require different sized boosters. This "family" is adequate for all current needs.

higher acceleration because of more and more thrust behind less and less load. In the matter of high thrust versus high gravity—the launch phase—it is hard to find a more important factor than inflight weight loss due to propellant consumption.

Mass ratio, however, is a tricky figure, which only an expert can evaluate properly. A higher mass ratio can reflect profit or loss depending on what aspect of the problem is being considered. Reducing dead weight results in a desirable *increase* in mass ratio. If the profit is consumed by increased payload, however, mass ratio might remain the same or be lowered. An increase in specific impulse, as we have indicated, would similarly balance mass ratio or possibly even lower it, for more energy per pound means a lower rate of propellant consumption.

### Gross-Weight-To-Payload Ratio

Gross-weight-to-payload ratios of the earliest US satellite launch vehicles of 1957-59 were on the order of 1100 to 1 or higher. For a comparison, consider Scout. Currently the smallest member of the DOD-NASA launch vehicle family, Scout is a highly-regarded specialist in scientific research in both Government- and university-sponsored project. It is a compact, slim, all-solid, propellant vehicle 72 feet tall, 39,600 pounds, and it can put a 300 pound payload into a 300 nm orbit. The gross-weight-to-payload ratio in this case is 132 to 1, and it would be somewhat lower if calculated for a 100 nm orbit. Obviously the lowering of this ratio is an index of the great progress that has been made since 1958.

**MASS RATIOS OF A HYPOTHETICAL ICBM**

| ITEM | WEIGHT POUNDS | |
|---|---|---|
| **Third stage Operation** | | |
| Payload | 200 | = vehicle weight at engine cutoff or $W_2$ (1,000 pounds) |
| Dead weight | 800 | |
| Propellant | 2,500 | |
| Total | 3,500 | = vehicle weight at engine start or $W_1$ |
| **Second stage Operation** | | |
| Payload | 3,500 | = vehicle weight at engine cutoff or $W_2$ (10,000 lbs) |
| Dead weight | 6,500 | |
| Propellant | 25,000 | |
| Total | 35,000 | = vehicle weight at engine start or $W_1$ |
| **First stage Operation** | | |
| Payload | 35,000 | = vehicle weight at engine cutoff or $W_2$ (65,000 lbs) |
| Dead weight | 30,000 | |
| Propellant | 162,500 | |
| Total | 227,500 | = vehicle weight at engine start or $W_1$ |

Figure 10. A space booster is constructed from the bottom up in this word-and-figure picture. Notice how much of each stage is required for propellant, dead weight, and payload.

It is the policy of either a military or civil space program to use the smallest vehicle possible for a given payload. Scout gets much use, because many useful scientific observations can be made by satellites weighing 300 pounds or less. "Do not use a Saturn when Scout can do the job" is sound economic reasoning. However, when gross-weight-to-payload is the efficiency yardstick, Scout does not measure up to some of its big brothers. The 300,000-pound Atlas-Centaur vehicle (Fig. 11), for instance, can put 9,900 pounds into 300 nm orbit, a ratio of 30.3 to 1. Even for moon or interplanetary projects, Atlas Centaur can put 2,700 pounds into escape trajectory—111 to 1. The most "efficient" vehicle of the current lot according to available information, is the largest. That fascinating monster, Saturn V, all 6,500,000

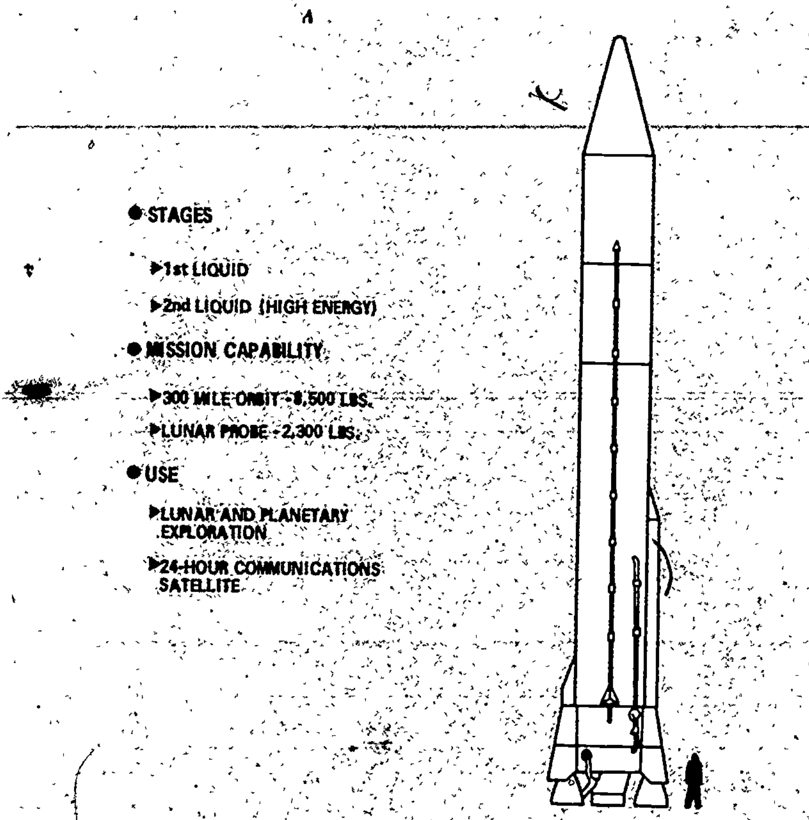
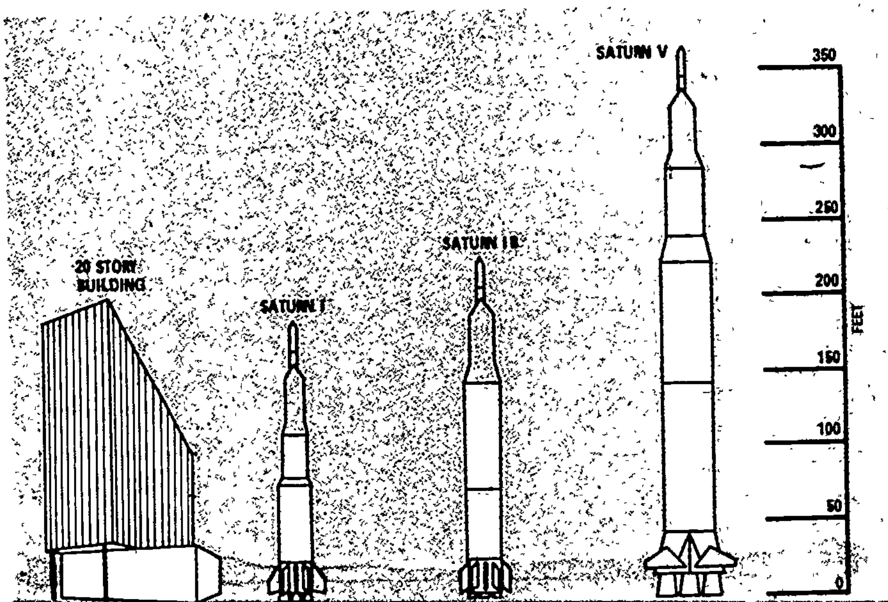



Figure 11. The versatile Atlas-Centaur vehicle has a good gross weight to payload ratio.




| PAYLOAD IN 100-MILE ORBIT | 22,000 LBS | 41,000 LBS | 260,000 LBS |
|---|---|---|---|
| APPLICATION | ORBITAL TESTS AND MISSIONS | ORBITAL TESTS AND MISSIONS ESCAPE MISSIONS WITH 3rd STAGE | ORBITAL AND ESCAPE MISSIONS LUNAR LANDING MISSIONS |

Figure 12. The Saturn launch vehicles are very large, but are quite efficient. The gross weight to payload ratio of the Saturn vehicles is impressive and their performance record outstanding.

pounds of it, looks like something designed to accomplish its task by sheer bulk rather than efficiency (Fig. 12); but its gross-weight-to-payload ratios are unbelievably low; 21.4 to 1 for 100 nm orbit (285,000 pounds) and 65 to 1 for moon trajectory (96,700 pounds).

What the above comparisons seems to indicate is that, other things being equal (which they never are), there is a certain inherent advantage in sheer mass of propellants. By other standards, however, gross-weight-to-payload may be an unfair yardstick too. Little Scout is still a remarkable performer for its size.*

*Some of the Scout's apparent disadvantage by the gross-weight-to-payload standard is accounted for by the fact that it uses solid propellants, which have lower specific impulse than the liquid propellants used in the bigger boosters. As we have indicated, however, a low-specific-impulse motor can still be capable of high thrust through the sheer rapidity with which its propellants are consumed. Scout's thrust-to-weight ratio, incidentally, is 88,000 to 35,500 pounds or 2.3 to 1—much higher than Saturn V's 1.18 to 1. The high density of solid propellants accounts for the slim profile of this missile. It weighs more than it appears to weigh.

**Velocity Gain (ΔV)**

What do all these ratios and measurements add up to? In one way or another, all add up to velocity gain—ΔV (delta V). For any stage of a launch vehicle, the difference between its initial velocity and its velocity at the burnout or cutoff of a stage is indicated by these symbols. If the first stage of a rocket reaches a velocity of 10,000 feet per second, its ΔV from zero is 10,000 fps. If the second stage, already traveling at 10,000 fps, is capable of the same ΔV, then what remains of the vehicle will be traveling at 20,000 fps by the time the second stage reaches burnout. Assuming a third stage capable of adding another ΔV of 10,000 fps, we have a vehicle capable of going into orbit at any altitude up to well over 1,000 miles with propellant to spare. (We are, of course, merely using round numbers in this example, not describing any actual vehicle's performance.) We shall not go into any particulars here about required velocities, orbits, or trajectories, which will be discussed in a later chapter. All we are doing here is describing the main task of propulsion, that of building the velocity of one stage upon that of the previous one and thus to "inject" the vehicle into a required orbit or trajectory. Mathematically, it can be stated as simply as $V_2 - V_1 = \Delta V$ (where $V_1$ = spacecraft velocity just prior to combustion of the stage in question, and $V_2$ = velocity at burnout of the stage). Translating all the weight and thrust factors we have discussed, plus others into ΔV is a very complicated procedure. Slide rules are good enough for rough estimates; precise calculation is a task for computers.

The fact remains that in actual performance, a multistage rocket is capable of coming very near to this theoretical ability to add velocity to velocity without loss. Smooth, reliable performance makes the task possible. The engines must burn out or be cut off precisely. The instant thrust is terminated, the dead weight of the exhausted stage must be detached and jettisoned without delay. Ignition of the next stage—instant thrust—must also be foolproof. If everything occurs in the proper sequence with quick timing, then old $V_2$ becomes new $V_1$ with negligible loss. When the required velocity is reached, precise cutoff again is necessary or the vehicle will go into a higher orbit than planned.

## SUMMARY

Escape into space is a miracle of the past decade, but it is accomplished by means of the most classic and commonplace of chemical reactions—that between an oxidant and a reducer or fuel, called oxidation.

Since a rocket is not an airbreathing motor, it must carry its oxidant in packaged form. One way to do this is to chill oxygen ($O_2$) to a liquid, at a temperature below −297° F. One of the best fuels in rocketry, hydrogen, is also a cryogenic gas and must be chilled to −423° F. before it can be tanked for usage. Other oxidant-reducer propellant combinations, however, can be stored and used at normal temperatures in chemical compound form. Liquids can be kept in separate tanks for feeding into a combustion chamber, or even mixed and stored together before feeding into the combustion chamber. In the case of solids, the ingredients are also mixed, and the storage container and combustion chamber are one. Usually, oxidizer and reducer are different compounds. But there is such a thing as a self-reacting compound containing both oxidizer and reducer within its own molecular structure and capable of decomposing to yield energy.

In a chemical reaction, matter is neither destroyed nor created but simply shifts around to form new combinations. The molecules involved in this shifting around may do so slowly and quietly, but often they are stirred into vigorous motion and thus produce the effects we know as heat, light, and physical force. Any oxidization rapid and energetic enough to yield heat and light is called combustion or, simply, fire. For propulsion. physical force is the desired energy yield. A propellant mixture. therefore, must have these four characteristics:

1. It must contain oxidizer as well as fuel, not only because it is to be employed in space, but also because it must be able to burn in confinement.
2. It can be ignitable in a variety of ways, but whatever the method, it must be precise, reliable, and reasonably safe.
3. It must yield energy in the form of force, achieved by volume and speed of flow of combustion exhaust, and preferably by means of a mixture of molecules of low average weight. Even unburned hydrogen molecules contribute to thrust because of their lightness.

4. It must produce controllable force. Flow of liquids into a combustion chamber can be regulated. Burning of a solid can be controlled if it is a low rather than high explosive.

In a combustion chamber, molecules are stirred by the heat of combustion into frenzied helter-skelter motion, beating at the walls of the chamber to produce the effect of pressure. The motion of a molecule becomes less erratic and more direct as it moves along its one possible avenue of escape, through the throat and exit nozzle. The essential feature of the rocket motor design is the convergent-divergent nature of the throat and nozzle. The throat must be narrow to keep up the pressure; the nozzle must flare outward to speed the exhaust gases by expansion. It is called the de Laval nozzle after the Swedish engineer who discovered the principle. Numerous design problems affect the de Laval nozzle as applied to space rocketry, especially in regard to atmospheric pressure or the lack thereof at different altitudes.

Thrust can be computed by a formula that includes flow of exhaust by weight and effective velocity against the force of gravity. The effective velocity of the exhaust flow in turn breaks down into a consideration of de Laval nozzle principles—area of nozzle at exit plane, pressure of exhaust at exit plane, and ambient atmospheric pressure, if any.

Specific impulse (pounds force per pound of propellant per second) is one of the most meaningful yardsticks in space propulsion. As a measure of propulsion energy per pound of propellant, it can be a measure of either economy or velocity, depending on how applied. Important factors in determining specific impulse are temperature of combustion chamber and lightness of average molecular weight of the combustion exhaust.

Thrust and velocity at launch can be understood in the light of one peculiar fact—that most of the gross weight of a launch vehicle as it sits on the launching pad is in propellants, and that the advantage of rapid combustion of these propellants is not only in the energy yield but also in the weight loss.

For this reason, a seemingly small thrust-to-weight ratio (first-stage pounds thrust over gross weight in pounds) such as 1.18 to 1 can give a mammoth booster like Saturn V a good head start into space because after liftoff the booster accelerates a lighter and lighter load. Mass ratio (weight of a vehicle before ignition and after burnout of a stage—the latter including deadweight plus payload) is a more direct measure of weight loss through propellant consumption, but it is a figure to be evaluated carefully by experts rather than used as a direct index of propulsion efficiency. Gross-weight-to-payload is a better index of efficiency, but it too must be regarded with caution. Space rocketry has come a long way since the 1100-to-1 and higher gross-weight-to-payload ratio of early launch vehicles. Current figures are much lower; they also seem to indicate a certain advantage for extremely large vehicles like Saturn V.

These and other parameters, all taken together in a calculation too complex for a slide rule and necessitating a computer, determine that magic figure "ΔV," change in velocity. Each stage of a launch vehicle adds its own acquired velocity to that of the preceding stage—an operation that demands smooth, reliable performance in detaching the old stage and firing the new.

## WORDS AND PHRASES TO REMEMBER

acceleration
ambient pressure
bipropellant
burnout
combustion
conservation of mass
cryogenic
de Laval nozzle
engine
expansion ratio
hypergolic
mass flow
mass ratio
monopropellant
motor
oxidant
oxidation
oxidizer
propellant
reducer
second of specific impulse
self-reacting compound
working fluid

## QUESTIONS

1. Why is it incorrect to speak of the total ingredients of a combustion for rocket propulsion as "fuel?"
2. What is meant by "conservation of mass?"
3. What are the two main reasons why a packaged oxidizer is required for space propulsion?

4. In general, what are the disadvantages of a fuel-rich mixture in any kind of internal combustion engine? What are the advantages of a fuel-rich hydrogen-oxygen mixture in rocket propulsion?
5. Explain the converging-diverging or de Laval nozzle principle.
6. Define specific impulse.
7. Why can a rather small thrust-to-weight ratio be adequate for first-stage boost?
8. What is the ratio $\frac{W_1}{W_2}$ called? Explain the meanings of $W_1$ and $W_2$.
9. Compare the gross-weight-to-payload ratios of the Vanguard I booster. Scout, and Saturn V.

## THINGS TO DO

1. See if you can find out how efficiently rocket fuel is burned before its gases exhaust. Discuss whether the rocket engines now in use would be acceptable for aircraft or surface propulsion under current environmental protection laws.
2. Research into materials is a big part of space research. Find out how this kind of research is affecting the requirements of combustion in rocket vehicles.

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Chapter 3

# Chemical Propulsion Systems

THIS CHAPTER moves from the basic features of all rocket motors to the specific characteristics of solid and liquid propellant engines. Historical backgrounds of both types of propulsion are traced. Chemical and physical properties of solid and liquid propellants most frequently used in space programs are described. Mechanical characteristics of solid and liquid engines are also described. Possibilities of engines applying the ramjet principle also are considered. After completing study of this chapter, you should be able to do the following: (1) trace the historical backgrounds of solid and liquid propulsion systems from medieval times to the present; (2) list the most common solid and liquid propellant combinations and compare their properties and capabilities; (3) explain the relationship of grain shape and thrust control in a solid-propellant motor; (4) describe the basic mechanism of a liquid-propellant engine; and (5) define double-based propellant, progressive and regressive burning, cryogenic, hypergolic, hybrid engine, Scramjet, and Scramlace.

THERE are two main categories of chemical propulsion systems: solid propellant and liquid propellant. The latter would include all internal combustion engines in the history of transportation since the inventions of the automobile and airplane. When we limit our topic to space launch vehicles, however, solid and liquid systems compete on a more equal basis. Each has its own mechanical features and propulsion capabilities.

## SOLID-PROPELLANT SYSTEMS

Solid-propellant systems are considered first for two reasons: their simplicity, and the fact that they came first historically. A brief review of the history of solid rocket propulsion is of interest.

## Historical Background

Space vehicles are not the outgrowth of air transportation. They are, rather, the offspring of weapons of war. Indeed, the history of solid-propellant rocketry is as old as that of gunpowder itself, and older than that of small firearms or artillery. Incendiary rockets were used in warfare by the Chinese back in medieval if not ancient times, and there is little doubt that the propellant used to hurl these "fire arrows" into enemy ranks was the familiar mixture of saltpeter, charcoal, and sulphur known as "black powder."* When black powder was introduced in Europe about the early fourteenth century, its first military use was the same as that of the Chinese—as a propellant for incendiary rockets. It was not long, however, before the development of firearms and artillery provided other uses for black powder and shoved rocketry into the background. For centuries, while black powder as a gun propellant served as the sole munition of warfare and changed the course of world history, rockets were virtually reduced to toy status. They were used for fireworks displays, and they were made in the familiar style. cardboard tubes filled with black powder, with wooden guide sticks attached.

A good, lively black powder mixture for artillery purposes in the eighteenth century consisted of 75 percent saltpeter, and 12 or 13 percent each of charcoal and sulphur. The principle of oxidation was not understood at that time, but it was known that the saltpeter (the oxidant source) was the ingredient to emphasize for higher burning speed and energy yield. The fireworks makers of the time prudently put a slower-burning mixture into their flimsy rockets—less saltpeter and more of the other ingredients.

A brief revival of interest in military rocketry occurred during the early nineteenth century. A British artillery officer, Col. William Congreve, developed rockets that were used in the Napoleonic Wars and against the United States in the War of 1812. Congreve made his rockets larger and stronger than any known before. His use of metal in their construction as well as in the launching tubes in turn permitted the use of a more energetic propellant mixture than the paper fireworks rockets allowed. Equipped with both incendiary and explosive warheads, Con-

*Or "gunpowder." The term "black powder" is preferred because in modern usage "gunpowder" is loosely used to describe almost any gun propellant mixture, whether powdery in consistency or not greve's rockets achieved ranges up to 3,000 yards. Their enthusiastic sponsor called them "the soul of artillery without the body." The effectiveness of Congreve's rockets, however, was questionable. Some 20,000 incendiary rockets hurled into Copenhagen by British warships in 1807 virtually burned that city to the ground. On the other hand, explosive-armed rockets used in the bombardment of Fort McHenry, Maryland, in 1814 failed to conquer the fort and provided inspiration for the lines ". . . the rockets' red glare/the bombs bursting in air" in our National Anthem.

In the nineteenth century, rocketry gradually receded into the background again. Rockets were developed as signaling devices and for the firing of lifelines in maritime rescue work, but the dramatic advances were in gun technology, both small arms and artillery. The nineteenth century indeed must even now be accounted as the century of greatest advance in these fields. It saw the introduction of rifled barrels, breech loading, stronger and lighter steels, and—before the end of the century—cannon recoil brakes, semiautomatic small arms, and machine guns. It also saw the development of high explosives and improved gun propellants, which spelled the end of the five-century era of black powder. With all these developments going on, neither military planners nor space dreamers paid much attention to rockets. The famed nineteenth century French science fiction writer, Jules Verne, could imagine only a giant cannon as a means of propelling a vehicle to the moon. As a military weapon, rockets had very limited use in World War I (1914-18), the war which awoke the world to the realities of airpower.

From the standpoint of future rocket development, the most important of the above nineteenth century advances was in the field of ammunition. First came high explosives like nitroglycerine, TNT, dynamite, and nitrocellulose (cotton soaked in nitric acid, also called "guncotton"). Early experiments with these substances as gun propellants resulted in disastrous failures; the guns blew up. Finally the ideal gun propellant was discovered to be a mixture of nitrogycerin and nitrocellulsose damped down by small amounts of other ingredients. It was much more energetic than black powder, yet was safe for use in guns; furthermore it burned much more cleanly than black powder and became known as "smokeless powder," though it was of solid semi-rigid consistency. More technically, this kind of gun propellant was known as "double based" because of the fact that it contained two explosives—each a combined oxidizer and reducer or self-reacting compound. It was also called "cordite." Ultimately the nitroglycerin-nitrocellulose or double-based ammunitions provided the means for a revival of rocketry, where they are still widely used.

Concerted efforts to develop military rockets with double-based propellants did not begin until the middle 1930s. With the outbreak of World War II came a resurgence of rocketry in the armed forces of combatant nations on both sides, all using double-based propellant systems with some variations in the chemical proportions. Multiple rocket launchers on ships were used in shore bombardment; aircraft were armed with rockets for air-to-ground and air-to-air use, and surface-launched rockets were developed as substitutes for mortars and artillery pieces. The famed bazooka, a US infantry weapon, was a light, portable rocket launcher, fired from a man's shoulder, that gave a two man team some of the firepower of a crew-served light artillery piece. There were, however, no dramatic long range uses of solid rocket propulsion in World War II such as the famed German V–2 rocket (liquid propellent).

Since World War II, development of military uses of solid-propellent rockets has continued apace, radically changing the nature of warfare at all levels and in all military services—land, sea, or air. The variety of solid-propellent missiles and rockets ranges from the 2.75-inch Mighty Mouse to the intercontinental Minuteman III and Poseidon. Improved solid propellant mixtures have also been developed. In the field of space exploration, solid propulsion has lagged behind liquid propulsion, but it is now beginning to catch up. It is still generally lower in specific impulse than liquid propulsion, but has certain practical advantages to offset this drawback.

### Solid Propellants

As used in modern missiles and space boosters, solid propellants have certain chemical and physical properties.

CHEMICAL PROPERTIES—Fuels used in solid propellants are asphalts, waxes, oils, plastics, metals, rubbers, and resins. Their oxidizers are often common nitrates and perchlorates. A look at the contents of a typical double-based propellant will tell us much about what the requirements for a modern rocket propellant are:

| *Component* | *Percentage of total* | *Function* |
|---|---|---|
| Nitrocellulose | 51.38 | Propellant |
| Nitroglycerine | 43.38 | Propellant |
| Diethyl phthalate | 3.09 | Plasticizer |
| Potassium nitrate | 1.45 | Flash depressor |
| Diphenylamine | 0.07 | Stabilizer |
| Nigrosine dye | 0.10 | Opacifier |
| Other | 0.53 | |

The first two items on the above list are the active ingredients—two propellant compounds, each containing both oxidizer and reducer. The remainder of the mixture, about 5 percent of the total, consists mostly of additives which, though small in quantity, are very important in function. The **plasticizer** helps give the propellent mixture the proper body and consistency (physical properties are discussed below). The **flash depressor** cools the exhaust gases before they escape into the atmosphere, preventing a burning tail effect and saving some wear and tear on the nozzle. The **stabilizer** reduces the tendency of the propellant mass to absorb moisture during storage. The **opacifier** is extremely important for both safety and thrust control. The opacifier makes the fuel **opaque,** which in this case means impervious to the radiant energy of heat. The opacifier keeps the heat of the burning propellant confined to the propllant's exposed edges. Without this ingredient, the heat might radiate into the interior of the propellant mass, causing it to ignite internally and blow up.

Other solid propellant combinations may not contain these particular additives in these proportions, but they must have the properties which these additives supply.

More typical of today's solid propellants are composites in which the fuel and oxidant are two different compounds. Usually the oxidant is crystalline in form and is imbedded in the fuel base. Specific impulses of a double-based and several composite propellants are as follows:

| *Fuel* | *Oxidizer* | *Specific Impulse* |
|---|---|---|
| Asphalt | Potassium perchlorate | 200 |
| Nitrocellulose and Nitroglycerine | (same as fuel) | 240 |
| Polyurethane | Ammonium perchlorate | 245 |
| Boron | Ammonium perchlorate | 270 |
| Metallic hydride | Fluoride | 300 |

Currently, the most widely used of the above in space applications is the polyurethane and ammonium perchlorate combination. The last two items on the list are still under development. Numerous other combinations are the subject of test and experiment in the search for the ideal solid propellant—one that would combine the storability and ease of handling of today's most common solids with a higher specific impulse. Certain disadvantages must be overcome. Various fluorides excel as oxidizers but are unstable and corrosive. Certain metallic fuels are high in specific impulse, and recent progress has been made in controlling the abrasive effect of their exhaust flow on rocket motor nozzles. These fuels include tetraformal trisazine (TFTA) and aluminum or boron, using red fuming nitric acid or nitrogen tetroxide as oxidizers.

PHYSICAL PROPERTIES.—In a solid rocket motor, the propellant substance is molded into its motor and casing as a single solid mass, called a grain, the shape and consistency of which determines its burning properties. Grains up to 260 inches in diameter (Fig. 13) have been manufactured and tested for use as major boosters in the space program. These large boosters are manufactured and shipped as separate cross-sectional segments, which are assembled end to end into a giant motor at the testing or launching site.

The polyurethane fuel base of the most common solid fuel mixture is a type of synthetic rubber. Despite the fact that it is outweighed by the perchlorate crystals imbedded in it, it maintains the same consistency, about that of tire rubber. Various other rocket propellants have similar plastic consistencies. It is very important that this consistency be even and free from internal bubbles or surface cracks, which might expose more burning surface than intended with resultant danger of erratic burning or explosion. The casing into which the grain is molded must, of course, be tough and heat resistant. A lining material is used as an insulator, and the case itself is made of various materials such as special steels, titanium, and fiberglass.

### Motor Design—Grain Shape and Thrust Control

Piobert's Law states that the flame front of a burning solid propellant always eats its way into the mass in a direction perpendicular to the surface. No matter how large or small this burning surface may be, furthermore, the flame eats its way into it at a fixed


Figure 13. Solid-propellant boosters with grains as big as this one have been used in the space program.

burning rate. For example, a typical double-based propellant has a burning rate of about 0.40 inch per second; a dense polyurethane composite burns at 0.22 inch per second. Therefore, the main way to increase or decrease fire intensity or thrust of a given propellant is to increase or decrease the amount of burning surface exposed.

A grain could be a solid cylinder enclosed in a motor so that its burning surface would be only the exposed end. If ignited at this exposed end, the grain would burn straight back, cigarette fashion. The grain would burn back at a fixed rate of speed, and the same amount of burning surface would continue to be exposed. Thus the burning rate would be steady, or **neutral,** and such a rocket motor would deliver a low but constant level of thrust for a predictable length of time based on the length of the grain.

Suppose that a hole is bored into this cylindrical grain for the length of the grain, and the grain ignited from within the hole. The flame would instantly spread the length of this hole, and burning would then progress from the inside toward the outer casing. The length of time from ignition to burnout would be based on the propellant grain's burning rate and its cross-sectional measurement. Thus if the grain had a total diameter of three feet and the hollow core had a diameter of one foot, the grain thickness from core to casing would be 12 inches. If the burning rate of this grain were 0.25 inch per second, the total burning time would be 48 seconds. As the fire burned, the hole would grow larger and larger; more and more burning surface would thus be exposed, and the fire and thrust would steadily increase right up to the moment of burnout. This would be an example of a **progressive burning** grain.

Typical grains do not have a smooth hollow core. Instead, they have hollow cores cast in various cross-sectional designs suggesting stars, gears, crosses, or other complex shapes (Fig. 14). In this way a large amount of burning surface is exposed at the instant of ignition. The design can be such that the core continues to keep

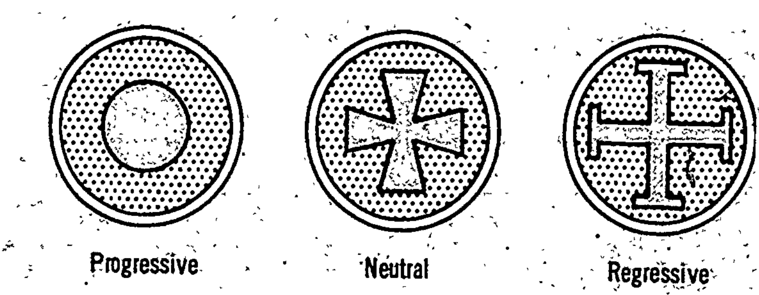


Figure 14. Cross sections of three grains show how the grain design decides the burning rate of the solid fuel.

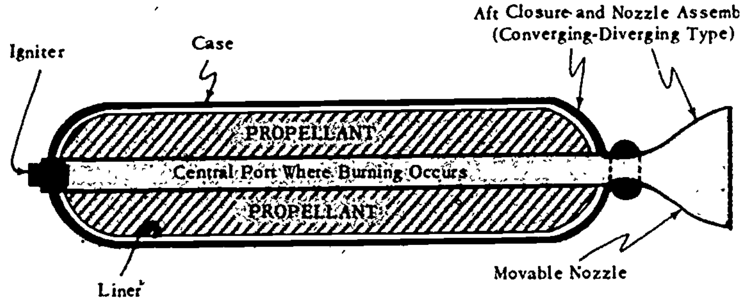


Figure 15. Lengthwise cross section of a solid-propellant motor gives a good idea of how the motor is designed.

the same amount of burning surface exposed—a neutral design yielding a high and constant amount of thrust. Variations in the design can produce either greater or lesser amounts of burning surface as the fire eats into the grain. The latter is called **regressive burning**, which can be useful when maximum thrust is needed at liftoff but a lower rate of thrust is desired thereafter. Sometimes the thrust pattern can be controlled by using layers of different propellant compositions with different burning rates and specific impulses. Painting certain surfaces of the grain with a heat resistant compound and leaving others free is another method of control.

Thus thrust control of solid-propellant rockets is accomplished by gain and motor construction. A solid-propellant motor cannot be regulated in flight by controlling propellant flow with a valve or throttle the way liquid systems from automobiles to space rockets are controlled. A solid motor's performance is programmed in advance at the factory, with a built-in **time-thrust curve** described as neutral, progressive, or regressive determined by the chemical composition and the size and shape of the grain.

The grain and its container, plus the nozzle, constitute the solid rocket motor (Fig. 15). Thus little need be said about its mechanical features. The motor, occupying the entire length of a stage, cannot be tilted or swiveled for thrust vector control; therefore, the nozzle must be made flexible or rotatable for this purpose. Figure 16 shows the nozzle of a big solid-propellant motor. Other means of steering are gas jets, deflecting vanes, or pivoted ring-shaped **jetavators** in the exhaust path (See Chapter 5). Equally important for accurate ballistic or orbital flight is precise thrust termination.

Although the grain has a known burning rate and lifetime, it does not burn out with split-second accuracy. Two means by which to achieve precise thrust termination are blowing off the nozzle to extinguish the fire by abrupt pressure drop, or suddenly valving some of the exhaust forward.

### Applications of Solid Propulsion

The solid-propellant rocket dominates the military field. Indefinite storability and instant readiness for use are its main virtues from the military point of view. A solid-propellant rocket or missile is like a loaded rifle that can rest on a rack for a year or more, yet be taken down and fired in an instant. No elaborate preparations or countdown are necessary to launch a solid-propellant Minuteman or Poseidon toward a target thousands of miles away. Numerous smaller rockets and missiles used in tactical air or ground combat are capable of much speedier reaction. In the space program, too, solid propulsion has many advantages. Motors up to 22 feet in diameter and 60 feet in length (Fig. 16) and generating 3.5 million pounds of thrust have been developed. Although solid propellants are currently lower than liquids in specific impulse, they have the advantage of simplicity, compactness, and high burning rate and can achieve high thrust through sheer volume of output.

In the current NASA family of launch vehicles, the Scout is notable for being solid-propellant in all four of its stages. Since the Scout is designed as a launcher of small scientific payloads, the fourth and smallest of its stages is of particular interest, for it demonstrates the fact that solid motors are capable of precision as well as power. Other solid motors used in NASA programs include the thrust augmentors sometimes attached to the first stages of the Thor-Delta. Each of these motors generates about 61,000 pounds of thrust, and three are generally used to augment the thrust of either launch vehicle for either larger payloads or escape velocity. The third stage of the Thor-Delta is also solid, as is the fourth stage of the Scout.

The largest solid boosters currently in use in US space programs are the two strap-on boosters of the Air Force's Titan IIIC. Each of these is made in five segments and adds more than a million pounds of thrust to the vehicle.

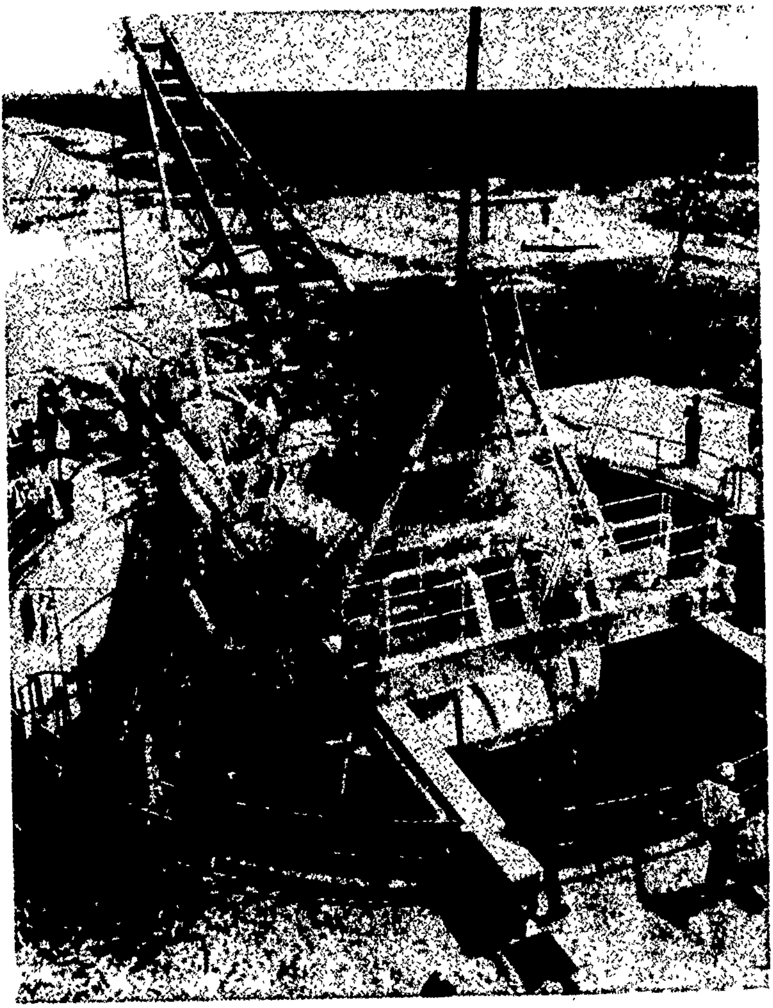

Figure 16. A giant solid-propellant motor in the test pit, its nozzle pointed skyward

## LIQUID-PROPELLANT SYSTEMS

Liquid-propellant systems currently are the prime means of propulsion into space and in space. Their two main advantages over solids are higher specific impulse and more positive thrust control. A variety of propellant combinations and engine designs are included in this category.

**Historical Background**

In 1898, five years before the Wright brothers' first airplane flight and several decades before the development of air-breathing jet propulsion for aircraft, Konstantin Tsiolkovski predicted that liquid-propellent rocketry would provide the means for man to venture into space. Tsiolkovski, an obscure mathematics teacher of Kaluga, Russia, wrote an article in that year in which he pointed out that liquid chemical propellants would provide greater exhaust velocity than any known solid rocket propellant. He further suggested that liquid oxygen and kerosene (today's propellant staples) would make a good combination. Although Tsiolkovski's article was written in 1898, it did not see print until 1903, when it was published in the Russian magazine, *Science Survey*, under the title "The Investigation of Space with Reaction Devices." Tsiolkovski never put any of his ideas into practical application, but he continued to write until his death in 1935. His articles and science fiction had a strong influence on later Soviet pioneers in rocketry and space.

Robert H. Goddard (1882-1945), the American rocket pioneer, began study and experiment in the field of rocketry while still an undergraduate and graduate student and devoted his life to this field. He theoretically determined that liquid oxygen and liquid hydrogen would be the most energetic chemical propellant and received patents in 1914 for a hybrid rocket and a multistage rocket for reaching high altitudes. He accomplished the first flight of a liquid-propellant rocket, using liquid oxygen and gasoline, on 16 March 1926. The rocket flew 184 feet in 2.5 seconds. Successful Goddard rockets ultimately came to reach 11 feet in length, 500 mph in speed, and 9,000 feet in altitude.

The most intensive development of liquid-propellant rocketry in pre World War II times occurred in Germany under the leadership of the Rumanian-born Hermann Oberth, who included Wernher von Braun among his followers. In the late 1920s and early 1930s, the emphasis of this German group was upon scientific research and dreams of future space exploration. With the advent of the Nazi regime, however, the program was killed, and later revived with a purely military emphasis. The culmination of the World War II German military rocket program is well known to history—the V-2 rocket, a single stage liquid-propellant device powered by liquid oxygen and alcohol, with auxiliary systems driven by pressurized hydrogen peroxide. With this weapon. London was bombarded from deep within Germany at ranges up to 200 miles. The V–2 weapon weighed 14 tons at launch. It reached a speed of about 3.500 mph and followed a ballistic trajectory in flight. rising completely out of the atmosphere to an altitude of 100 miles before beginning its descent to the target Its warhead weighed 1.000 pounds. In size. velocity. and range it greatly exceeded any other missile and alerted the world to both the menace and the hope of the missile and space age

Captured V–2s provided the beginnings of both the US and Soviet missile and space programs In the United States. V–2 was developed into Viking. Then came Redstone and its successors Liquid propulsion maintained its lead over solid in efforts to achieve intercontinental range. low earth orbit. and escape velocity.

### Liquid Propellants

Liquid propellants can be classified in several ways. One is according to the manner in which they are fed into combustion. Another is by means of ignition, whether hypergolic (using bipropellants that react upon contact with each other) or nonhypergolic (requiring some means of ignition). A classification commonly regarded as the most practical way of looking at propellants is that between cryogenic and storable propellants. The possible combinations are endless in number. Figure 17 is a table showing five which figure prominently in US space programs.

CRYOGENIC PROPELLANTS.—"Cryogenic," as we have noted, means "pertaining to extremely low temperatures." A rule of thumb definition of a cryogenic substance is any that has a temperature below −100° F. Cryogenic propellants. however, have temperatures far below that figure. Oxygen liquefies at −297° F.; fluorine. another oxidant. at −306° F., and hydrogen, a fuel, at −423° F. A propellant combination is considered cryogenic if either the fuel or the oxidizer. but not necessarily both, is cryogenic. An example is the widely used kerosene/liquid oxygen combination. classed as cryogenic because of the liquid oxygen

You have probably seen pictures of vehicles just prior to launch, covered with white frost and smoking with extreme cold. When the vehicle lifts off. the frost coating suddenly flakes off in a spectacular shower of ice particles. In the jargon of space personnel, the booster is said to be "shedding her skirt." The weight of this

## FIVE LIQUID PROPELLANTS USED IN DOD–NASA AND AIR FORCE SPACE PROGRAMS

| Oxidizer | Reducer | Type | Specific Impulse | Vehicle/Stage or Other Usage |
|---|---|---|---|---|
| Liquid Oxygen (LOX) | Refined Kerosene (RP–1) | Cryogenic | 300 | Thor-Agena/1st; Delta/1st; Atlas-Agena/1st; Atlas-Centaur/1st; Saturn I/1st; Uprated Saturn I/1st; Saturn V/1st. |
| IRFNA[1] | UDMH[2] | Storable | 276 | Thor-Agena/2nd; Delta/2nd; Atlas-Agena/2nd. |
| Nitrogen Tetroxide[3] | UDMH and Hydrazine | Storable Hypergolic | 288 | Gemini-Titan II; Titan III, all stages. |
| LOX | Liquid Hydrogen ($H_2$) | Cryogenic | 391 | Atlas-Centaur/2nd; Saturn I/2nd; Uprated Saturn I/2nd; Saturn V/2nd & 3rd. |
| LOX | Ammonia | Cryogenic | 296 | X–15 rocket aircraft. |

1. Inhibited red fuming nitric acid. (IRFNA)
2. Unsymmetrical dymethylhydrazine.
3. $N_2O_4$

Figure 17. The space program uses a variety of liquid propellants.

ice at launch is but one of many problems associated with the manufacture, shipping, and use of cyrogenic propellants. The effect of deep cold on engine components is another factor worth mentioning. The principal difficulty is that cyrogenics cannot be stored for any length of time in a vehicle before it is launched. To reduce losses from vaporization and minimize other problems caused by low temperatures, they are pumped into the vehicle within a few hours of launch. If any kind of problem arises to cause a delay in the countdown of a space launch, it must be remedied within a few hours. Otherwise, the vehicle must be drained of its rapidly deteriorating cryogenics and refilled prior to another attempt, at great expense and further loss of time. The delay could mean a lost opportunity for a certain mission, the passage of a window—the span of time during which the moon or another celestial target is in a desired position.

For reasons such as these, cryogenic-propellant missiles are obsolete as weapons of war. In the space program, however, all these disadvantages have been diminished with increasing countdown experience and efficiency, and are considered to be outweighed by advantages. One advantage is the relative cheapness and abundance of kerosene liquid oxygen, designated as RP-1 LOX Both components cost but a few cents per pound delivered to the launching site. The other advantage is the higher specific impulse of cryogenic propellants as a class. Even RP-1/LOX boasts 300 seconds, which is higher than that of any currently used solid or storable-liquid propellant. This is not to say that 300 seconds represents a barrier which solid or storable propellants cannot exceed, for the barrier has been broken in tests. It is, nevertheless, a convenient round number distinguishing cryogenic from storable propellants in practical use at the time of this writing. It is also true that, when chemical specific impulse ratings are boosted dramatically above this 300 level to 400 seconds and more, it is done with cryogenics. Currently ratings above 500 seconds have been achieved experimentally with liquid hydrogen and liquid fluorine (both cryogenic).

As Figure 17 reveals, RP-1/LOX is the workhorse of US space programs, the one that is most frequently called upon to perform the heavy liftoff task. It is the first-stage propellant for seven out of ten of the US standard launch vehicles (the exceptions being the all-solid Scout and the two Titan vehicles). The 7,50,000 pounds of thrust generated by the five huge F-1 engines which comprise the first stage of Saturn V are the work of the tried-and-true RP-1/LOX combination

The all-cryogenic combination of liquid hydrogen and liquid oxygen is now the favored propellant for the upper stages of the most advanced launch vehicles, the Atlas-Centaur and the Saturn family. Despite the complexities of the engines designed for this propellant and the problems associated with the tankage and flow of cryogenics in in-space use. $LH_2$/LOX is favored for its high energy output, yielding specific impulses above the 400-second mark. The use of high-energy propellants in upper stages permits carrying payloads to the moon and into interplanetary space.

STORABLE PROPELLANTS.—A storable propellant is liquid at normal temperatures and pressures and may be left loaded in a missile or space vehicle for days, months, or even years (The term "storable," however, relates to storing propellants on earth and not in space.) By means of propellants in this class, Titan II, heaviest of the US military missiles, can be launched toward its intended target at a moment's notice just as surely as any solid-propellant missile. Titan II has also been adapted to space uses, having served as the vehicle of the Gemini program. Titan III uses the same storable liquid systems plus solid-booster augmentation. Storable liquids are also used in the second stage of Delta and in the Agena–D vehicle which is the second stage of the Atlas and Thor boosters. As Figure 17 indicates, one storable-liquid propellant combination is also hypergolic. The special advantage of a hypergolic propellant in upper stage use is the relative simplicity and accuracy of thrust modulation, stopping, and restarting. It is all done by opening and closing valves, with no ignition system necessary. Advantages of storable liquids in general (not necessarily hypergolic) include lower handling costs and simplified countdown procedures, offsetting the rather high cost of the propellants themselves.

### The Liquid Rocket Engine

Compared to a solid-propellant rocket motor, a liquid-propellent rocket engine is quite a complex assembly of machinery. In one respect, however, the liquid system is simpler. Because no propellants are stored within it, the liquid-propellant combustion chamber is small and is rigidly assembled to the much larger exhaust nozzle. For thrust vector control or steering, the whole engine and nozzle usually rotate as a unit on flexible mountings called gimbals.

When several engines are grouped to form a stage, they are all of the same type and size. They do not have independent tanks but all feed from the same tanks. Therefore, part of a stage's propellant-flow system is associated with the tanks and is common to all the engines, and part is associated with the individual engines, each of which has its own complex assembly of pipes, valves, pumps and turbines, to control its own propellant (Fig. 18). Propellants are fed into the combustion chamber through a vaporizing device resembling a shower head in appearance and function (Fig. 19).

For the sake of vehicle balance and thrust control, it is essential that all engines in a stage consume equal quantities of propellants and are equal in thrust. Fuel and oxidant flows of the whole

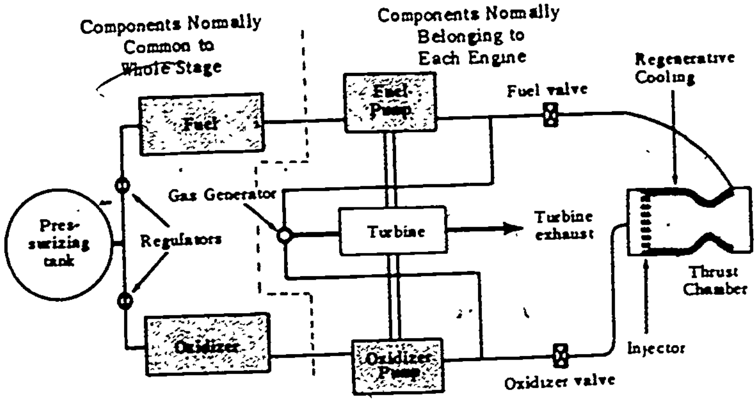


Figure 18 Schematic drawing of a liquid-propellant rocket stage shows fuel tanks common to the whole stage, but other components contained within each engine feeding from the tanks.

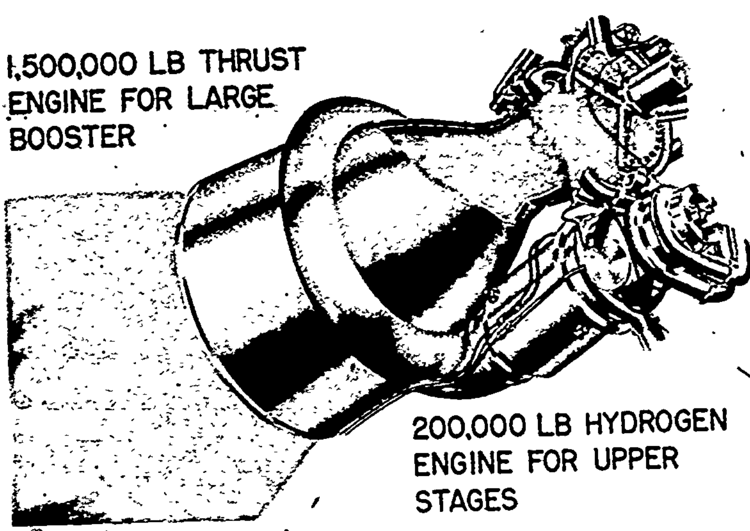


Figure 19 Cutaway of a liquid-propellant engine shows how all the plumbing fits together.

system must always be in the proper ratio and be exhausted at the same time. Propellant flow from tanks to engines is controlled in either of two main ways. One is to use a pressurized gas (nitrogen, among others, is suitable) which drives the fuel and oxidant through the plumbing into the engine. This system has the advantage of simplicity and the disadvantage of weight, for the tank that contains the pressurized driving fluid must be strong and heavy. The preferred systems, therefore, use pumps and turbines to supply propellants to the combustion chambers. Sometimes a separate gas-generation system, powered by its own small supply of propellants, is used. More often the engine has a bootstrap system either working its pumping system by the expansion of its own main propellant fluids or using a turbopump system that is driven by the engine's main exhaust gases.

Complexities of liquid-propellant engines include many sophisticated control devices. One device, for instance, senses overpressure in the thrust chamber and shuts a fuel valve until a normal combustion level is restored. Cryogenic systems usually make use of one or the other of their frigid propellant fluids in a cooling system before feeding them into the combustion chamber. The nozzle of a high-energy cryogenic engine, subject to heat damage, is surrounded by a cooling jacket through which frigid propellant gas is circulated in a process called **regenerative cooling.**

Figure 20 shows three liquid-propellant rocket engines in current DOD-NASA use. Two men in the photograph indicate the size of these engines. Five of the largest of these (the F-1, center) comprise the mammoth Saturn V booster first stage. No less than eight of the H-1 (left) are clustered to form the Saturn I booster. Both the F-1 and the H-1 burn RP-1/LOX. The J-2 (right) is designed to burn the high-energy double-cryogenic propellant $LH_2$/LOX in upper stages of Saturn vehicles.

## OTHER CHEMICAL SYSTEMS

In previous parts of this chapter we have by no means covered all the varieties of solid and liquid propellent rocket systems but have given a fair indication of what their potentialities are. In this final section. let us first consider hybrid-propellant systems (combining liquid and solid propellants). then discuss some of the potentialities of the ramjet principle.

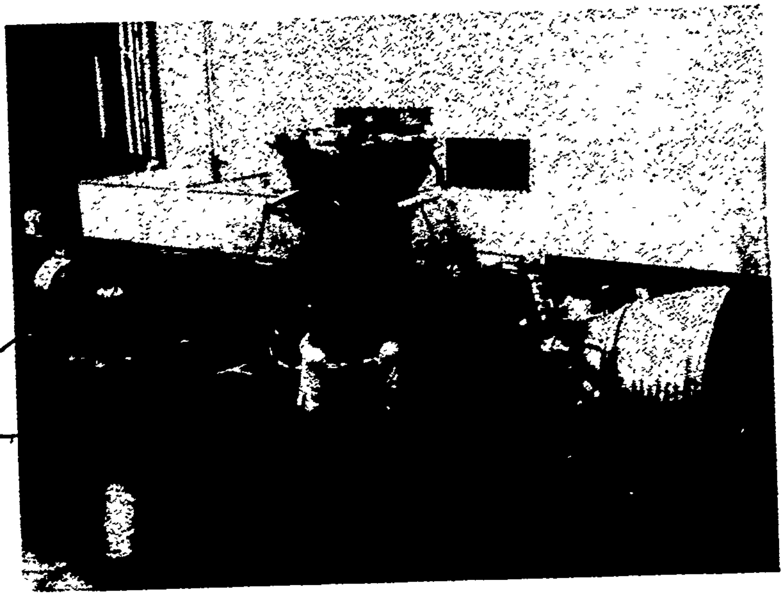

Figure 20. Three liquid engines of varying sizes, used for varying tasks. The engines are (from left) the H-1; the F-1; and the J-2. All are used in the Saturn vehicle.

### Hybrid Systems

A hybrid-propellant system combines a solid fuel with a liquid oxidizer, (or vice versa, but so far the solid fuel/liquid oxidizer system seems to be more practical). Development of hybrid engines has been going on for many years, and some experts have tended to regard such systems as obsolescent rather than advanced. Solid-propellant motors excel in compactness and simpliicty; liquid systems excel them in specific impulse. A hybrid system (Fig. 21) could combine these important virtues: the solid rocket's simplicity and readiness, and the liquid system's capability for precise thrust control. Whether the hybrid system is hypergolic or ignitable, it would excel in thrust control by its very simplicity, having one liquid feed line to control instead of two. The advantage of such a system for upper stage use requiring multiple stops and restarts is evident. Specific impulses, even though not the highest, might be on a par with those of the currently used storable liquids.

### Ramjet, Scramjet, and Scramlace

Since a ramjet is an air-breathing engine, discussion of this topic would seem to be more proper to a text on aviation rather than

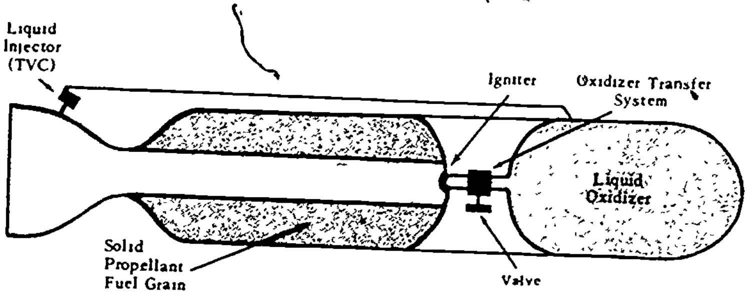


Figure 21. The hybrid rocket system could combine the solid rocket's simplicity and readiness with the liquid engine's precise control

one on space propulsion.* Nevertheless, talk of ramjet space applications is taken seriously in both NASA and Air Force research and development circles.

By way of review, let us note that the ramjet is the simplest of air-breathing jet engines. It is sometimes called an **athodyd,** a word coined from "aero-thermo-dynamic-duct"—which in turn might be very freely translated as "flying stovepipe." The ramjet has no turbo-compressor but simply takes in its air supply on the run through its wide-open intake port in front and compresses it literally by "ramming" this air into its throat through the sheer force of its velocity. Fuel is injected into its combustion chamber, mixed with this compressed air, and ignited to provide thrust. Since it requires high velocity for compression, a ramjet cannot be zero launched but must be carried to the necessary ramming velocity on board a vehicle with another motor. Even after it reaches starting speed, it burns inefficiently and is wasteful of fuel for a while, but it gains efficiency with speed and excels in economy at supersonic velocities.

One application of the ramjet was the winged Bomarc air defense missile. Now obsolete. Bomarc was launched by means of a solid-propellant rocket of 50.000 thrust pounds and could attain a range of 400 miles, an altitude of over 100.000 feet, and a speed of over 2.000 mph by means of its twin 16.000 thrust pound ramjets In October 1967, the rocket-powered X-15 experimental manned aircraft set a speed record for manned aerodynamic flight, about 4.500 mph On this flight two auxiliary ramjets added their

*In fact the ramjet is discussed in the AF-II book *Propulsion Systems for Aircraft* boost to that of the rocket engine. (Tests involving the X-15 have since been concluded.) In both speed and altitude, ramjets can exceed any turbojet. In fact, the ramjet is most efficient near the top of its altitude range. The faster it travels, the more ram compression is possible, and the more thrust is produced.

Theoretically the ramjet has no speed limit. The practical limit is currently regarded as mach 5 because of the problem of skin temperatures, but speeds of mach 9 and 10 are occasionally mentioned as possible. Recent advances have been encouraging in the area of heat control inside and outside the very high speed engines. The ceiling of a ramjet is currently regarded as about 150,000 feet, but recent estimates boost this theoretical limit higher. The nickname Scramjet (for supersonic combustion ramjet) has been applied to these hypersonic vehicles of the future.

In the thinnest layers of atmosphere along the fringes of space, the Scramjet could scoop air up fast enough to make use of it in combusting its fuel. A ramjet or Scramjet, however, cannot propel itself in space, where there is no air. One theoretical Scramjet application is that, after zero launch by rocket or other means (possibly even a turbojet aircraft), the Scramjet might acquire enough velocity in traversing the upper atmosphere to achieve orbital velocity and then "pitch up" into orbit. If the Scramjet alone cannot accomplish orbital speed, it might serve as a highly economical and weight-saving auxiliary booster to a rocket engine, which in turn could be made smaller and lighter because of this assistance.

Economy and lightness are the key to interest in Scramjet development. In today's space rockets, oxidizer outweighs fuel in ratios ranging from 3:2 upward. A Scramjet engine would need only a fuel supply and would be spared the weight, cost, and bulk of propellant, tankage, and mechanism associated with the oxidizer side of a rocket system. Furthermore, the Scramjet-powered vehicle is envisioned as a winged and fully recoverable vehicle—no jettisoned stages, no dependence on shrinkage of propellant mass, to gain the required velocity. It would not be used for deep-space probes, of course, but would be used on shuttle runs to carry men and supplies between earth and orbiting space platforms.

Beyond Scramjet is **Scramlace.** The last four letters of this word stand for "liquid air cycle engine." The Scramlace is a Scramjet equipped to scoop up even more air than required for its own propulsion. This excess would be compressed and liquefied by the Scramlace, acting as a flying liquid-air factory. When the vehicle emerged into space, the Scramlace would convert itself into a rocket engine, using the liquid air it made on its way up.

Imagine one space shuttle vehicle of the future as a winged airplane/spacecraft, capable perhaps of taking off from an airport under turbojet power just like a present day airliner, accelerating into orbit by means of Scramlace, and returning to earth with turbojet power available for an airport landing, (Fig. 22). Because it would employ chemical fuel and free oxygen, this concept still comes under the heading of "chemical propulsion." Other advanced propulsion ideas depart completely from the principle of chemical propulsion. These will be discussed in the next chapter.

## SUMMARY

Solid-propellant and liquid-propellent rockets each have an interesting history of their own. Solid-propellant rocketry goes all the way back to the middle ages, when it made its way from China into Europe. The propellant was black powder. With the development of the use of black powder as a gun propellant, however, rocketry was shoved into the background. Except for a brief period of revival during the Napoleonic Wars, rockets were used for fireworks displays and had limited military uses until World War II, when double-based propellants of much higher energy than black powder were eventually tamed for rocket applications. Liquid-propellant rockets figured more in the dreams of space-minded pioneers like the Russian Konstantin Tsiolkovski or the American Robert H. Goddard in the early twentieth century. Even in liquid propulsion, however, it was a military weapon that showed the way—the famed German V–2 rocket of World War II. With a 200 mile range and a 3,500 mph speed, the V–2 revealed the potentialities of the large rocket for global and space flight.

Solid propellants are of two main types—double based and composite. The double based type is similar to the "smokeless powder", or "cordite" that has been a standard gun propellant for many years. It consists mostly of two self-reacting explosive compounds, nitrocellulose and nitroglycerine, plus small quantities of other ingredients to control its burning properties. A composite is a mixture in which oxidizer and reducer are separate compounds.

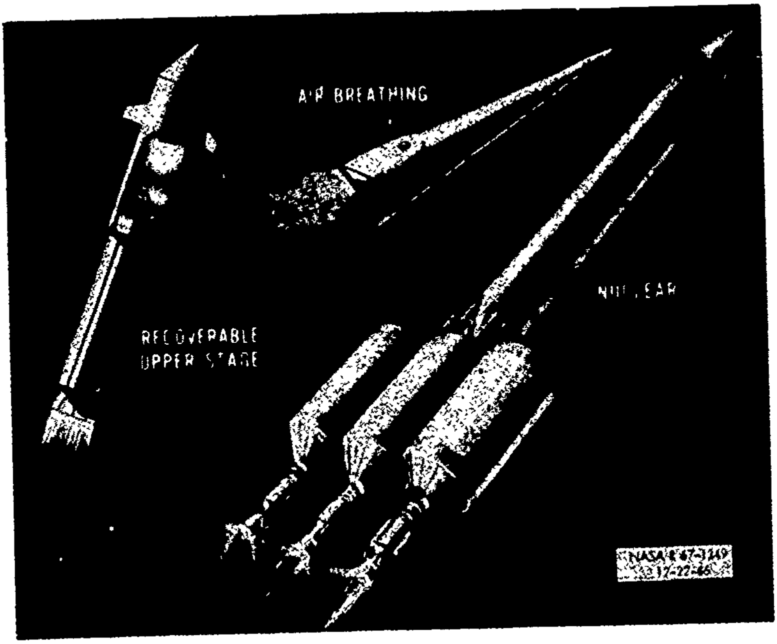


Figure 22. Three possible space ships of the future. The air-breathing ship in the center represents the Scramlace concept.

Typically, oxidant crystals are imbedded in a rubbery fuel base. Polyurethane and ammonium perchlorate form one composite widely used in the space program. Specific impulses as a rule are less than 250 seconds, but the readiness, compactness and simplicity of solid-propellant motors offset this disadvantage and make large solid boosters practical for space launches, their high thrust accomplished through sheer weight and volume of mass flow.

Thrust control of a solid motor is a matter of programming it in advance at the factory by the composition, size, and shape of the grain. The typical grain has a hole down the middle cut in the form of a star, gear or other complex shape in such a way that the amount of burning surface remains constant for constant thrust level, or it can be designed for increasing (progressive) or decreasing (regressive) thrust. One member of the DOD-NASA family, the Scout, is all solid propellent; large solid auxiliary motors are also attached to the Titan IIIC boosters, and other solid motors form part of the propulsion systems of the Thor-Delta vehicle.

Liquid-propellant systems have the advantage of higher specific impulse and more positive thrust control, the latter being accomplished by regulating the flow of propellants into the combustion chamber. Although there are many ways of classifying liquid propellants, the most practical is that distinguishing cryogenic from storable propellants. Many problems arise from the handling and use of cryogenic propellants, from the weight of ice on the vehicle at launch to the effects of their deep chill on engine components. To minimize loss through evaporation, cryogenic propellants cannot be loaded into a vehicle until within a few hours of launch. Nevertheless, cryogenics are favored in space programs because of the low cost of certain widely used cryogenic propellants (which include non-cyrogenic fuel like kerosene if used in combination with a cryogenic like liquid oxygen) as well as their high specific impulses. These range from 300 seconds for the staple kerosene/liquid oxygen combination favored for big first stage boosters above 400 seconds for the liquid hydrogen/liquid oxygen now used in upper stages of Atlas Centaur and Saturn vehicles. Storable propellants are generally within the 250-300 second range in specific impulse and have the advantage of readiness and simplicity. Titan vehicles as well as Agena upper stages have storable propellants. Some are also hypergolic and are more easily adaptable to stop-and-restart thrust control.

Liquid rocket engines are more complex than solid rocket motors. They must have pumps, compressors, turbines, and other liquid flow regulating devices.

There has been renewed interest recently in hybrid systems in which a liquid oxidant is pumped into a chamber containing solid fuel. Because only one feed line is involved, the system has the advantage of simplicity.

Within the realm of chemical propulsion is the concept of adapting the air-breathing ramjet engine to space uses. The vehicle envisioned employs an advanced ramjet concept called a Scramjet. Beyond Scramjet is the concept called Scramlace, in which the same engine could convert from Scramjet to rocket operation in space.

## WORDS AND PHRASES TO REMEMBER

athodyd
flash depressor
gimbal
hybrid-propellant
jetavator
neutral burning
nonhypergolic
opacifier
opaque
plasticizer
progressive burning
regenerative cooling
regressive burning
Scramjet
Scramlace
stabilizer
time-thrust curve

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## QUESTIONS

1. Which particular advance in gun and amunition technology in the nineteenth century led toward a modern revival of solid-propellant rockets?
2. What are some of the physical properties needed in a solid rocket propellant?
3. What would be the basic time-thrust curve (neutral, progressive, or regressive) of a solid propellant grain with a simple circular hole in its middle? A star-shaped hole?
4. Describe the contributions of Konstantin Tsiolkovski and Robert H. Goddard toward space propulsion.
5. If a grain has an eight-foot diameter and a hollow-core diameter of one foot, what is the grain thickness? If the burning rate of this grain is 0.50 inches per second, what is the total burning time?
6. How is the nozzle of a cryogenic-propellant engine cooled?
7. What is the principal advantage of a hybrid rocket engine?
8. How does a Scramlace engine obtain its oxygen suply?

## THINGS TO DO

1. Find out what new fuels or combinations of fuels are being used or experimented with for use in rockets for the space program. Note the advantages and disadvantages of these new fuels and combinations in comparison with those discussed in this chapter.
2. Check current space magazines for advances in the specific impulse ratings for solid and liquid rocket fuels. Pay attention to whether more progress seems to be in the solid or the liquid propellants.

## SUGGESTIONS FOR FURTHER READING

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**IN THIS CHAPTER** the possibilities of nonchemical propulsion are examined. ~~For the most part the engines described here are not yet in being;~~ although some are in an advanced developmental state, others lie farther ahead in the future. The engines discussed are electrical and nuclear. Preliminary topics at the beginning of the chapter include in-space propulsion and ways of generating electric power in space. When you have studied this chapter you should be able to do the following: (1) compare the problems of in-space propulsion with those of launching (as described in Chapter 2); (2) list and describe the principal methods in being and under development for providing in-space electric powers; (3) define and explain resistojet, arc jet, ion engine, radioisotope thermal generator, and plasma engine; and (4) describe current status and future prospects of nuclear and other advanced concepts of propulsion.

THE two preceding chapters were devoted to propulsion by one means only, the combustion of fuel and oxidant. Quite a variety of chemical reactions and engine designs can be included under this broad category, which we call **chemical propulsion;** and quite a variety of tasks, from launching off the earth to precise maneuvering in space, can be accomplished by this basic method.

In fact, you may wonder whether propulsion by any other means is necessary, desirable, or even possible. Not only does a chemical reaction provide heat or energy, it also produces the very substance or mass for propulsion—the rush of molecules out of an exhaust nozzle we call mass flow. But even if heat is produced by some other means, mass flow is still necessary. If the rocket need not be weighted down by fuel and oxidizer tanks, it still must have a supply of some kind of working fluid to use as a source of propellant mass. Where, then, is the improvement?

Obviously, there must be important advantages in nonchemical propulsion to warrant the intensive research and development efforts that are now being made in that direction. In this chapter, we shall consider nonchemical propulsion, how it works, and why it should be worth while. Nonchemical propulsion, for the most part, is of two classes, electric and nuclear (or a combination of the two). Some nonchemical propulsion devices have been successfully tested in space but, for the most part, nonchemical propulsion is still in its early stages of development.

Before we examine these future systems, however, we must make two digressions to consider related matters. One is propulsion in space, a different matter from the launch propulsion emphasized in previous chapters. Nonchemical propulsion is expected to be more practical over long distances. The other is electric power in space vehicles. If, for instance, electric propulsion is feasible, where does the electricity come from?

## PROPULSION IN SPACE

Without getting into the subject of orbits, trajectories, and velocity requirements—which shall be taken up later—let us consider only the thrust requirements for operating a vehicle in space. In general, these are considerably less than the booster requirements which occupied our attention in Chapter 2. The difference might be compared to the difference in effort required to roll a 16-pound bowling ball down a 60-foot alley or to toss the same bowling ball 60 feet straight up. It takes some muscle to bowl a good game, but you do not need to be a superman.

The vehicle in space, once it has been injected into a low orbital path around the earth, is weightless. If it has further uphill journeys to make—to higher earth orbit, to the moon, or to another planet—it can proceed by gradual stages—climb gentler slopes, so to speak. Its weightless state, however, is not simply due to the fact that it has achieved a certain distance from the earth. More thanks are due to the powerful force that has taken the place of gravity—the tremendous velocity the vehicle has acquired from its booster stages. The vehicle is now a Newtonian body, moving in a given direction with a given momentum and not swerving from its path or gaining or losing speed unless another force acts upon it. How great must this other force be?

Any amount at all, says Newton, will produce a change proportional to the force. Anything from a gentle nudge by a small rocket motor, such as is shown in Figure 23, to a major output of thrust by the giant propulsion motor of the Saturn V might be needed to make a particular maneuver.

When propulsion in space is employed *in harmony* with natural forces, moderate amounts of propulsive force can perform re-

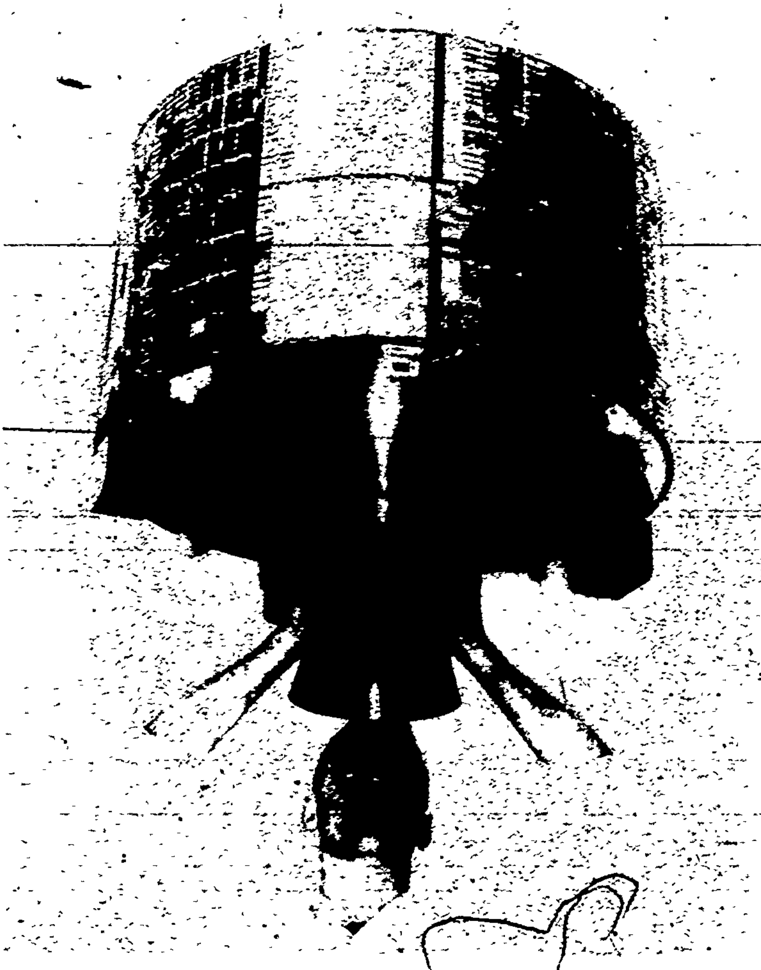


Figure 23. Small motor attached to the bottom of the Syncom satellite performs in space maneuvers Solar cells line the outside of the satellite and provide on-board power.

markable feats. If these thrusts act in the direction of a vehicle's original motion, they can produce important amounts of acceleration. Acting in other directions, they can be used for steering and braking. We shall have more to say about maneuvers in Chapter 6, but for the present, let us merely list some of the things an upper stage rocket (in some instances possibly a nonchemical one) can do in space:

1. Change the shape of an orbit from elliptical to circular or vice versa.

2. Move from a lower to a higher orbit or vice versa.

3. Change the orbital plane in respect to the earth's axis.

4. From a parking orbit around the earth, add enough velocity to escape from this orbit on a trajectory toward the moon or another planet.

5. Shorten the months-long journey to another planet by increasing velocity.

6. Apply thrust in a direction opposing flight, or **retrothrust,** for various purposes such as changing orbits (1 and 2 above), selecting a landing spot on moon, earth, or other planet; making a soft landing, or making a rendezvous with another vehicle in space.

7. Apply thrust at angles to original momentum—in other words, steer the vehicle—for various purposes.

8. Apply moderate to small amounts of thrust for minor corrections to keep the vehicle on a given orbital path, known as **station keeping.**

9. Apply very small amounts of thrust for attitude control.

Some of these tasks require more thrust than others, but all of them represent things that can be done by virtue of an original velocity—a head start. All assume a vehicle that may have *mass* by the ton but is without *weight*. Thrust-to-weight ratio as described in Chapter 2 is no factor. In space, a few pounds of thrust can move a heavy mass.

In fact, a small amount of thrust (gravity being weak and friction absent) can *accelerate* a heavy mass. Here, indeed, is the secret of low-thrust propulsion. Acceleration is measured not in *feet per second* but in *feet per second per second.* If a low-level thrust is sustained long enough. the change in velocity ($\Delta V$) can be substantial.

In the above list, items 1, 2, 4, and 5 in particular represent tasks which can be performed by sustained low-level thrust, producing gradual acceleration. Consider the largest of these tasks. item 5, interplanetary flight. Assume a moderate level of thrust that would gently accelerate a vehicle at the rate of 6 inches per second per second. This does not seem like much, but at the end of one hour, $\Delta V$ would amount to a plus 1,800 feet per second. At the end of 20 hours, the vehicle would have added 36,000 fps (or 25,000 mph) to whatever its original velocity was. Even if the motor were then cut off, the vehicle in space would continue to have the momentum of the total buildup of its velocities and months might be shaved off the travel time to another planet. This low-thrust engine would not solve the problem of getting the vehicle off another planet if it landed there, but it could be useful on long-range explorations of the solar system without landing. or as an economy engine on missions in which a high-thrust engine would be reserved for sharper velocity changes. Some space exploration concepts suggest the usefulness of even lower-thrust engines than the one suggested here—engines that would operate continuously for months if not years before reaching peak velocities. Scientists have numerous projects in mind for deep-space penetrations by unmanned vehicles and eagerly await the development of rockets and electric power sources for making these possible, even if they must wait somewhat longer for the means of manned exploration at such ranges.

Long-burning low-thrust chemical rockets do not seem practical at present. However, the development of electrical propulsion, which shows promise of engines capable of keeping up low-level thrust for days, months, or even years on end, will continue to be an important part of space programs.

Meanwhile, the desire for super engines with both high thrust and extended operating time also runs strong, and the answer to this problem seems to be nuclear propulsion. Before we consider any form of nonchemical propulsion, let us consider the problem of electric power in space vehicles.

## ELECTRIC POWER IN SPACE VEHICLES

If the subject of electric power in space vehicles were given proper emphasis in this course, it would take up at least a whole chapter if not a whole booklet. We are treating it briefly here, but it is one of the most important—and troublesome—in astronautics.

In this respect, it is interesting to compare again space vehicles with aircraft. Large military or civil aircraft, like automobiles, have main engines that are also generous dispensers of auxiliary power. They generate electricity in abundance and supply other needs through ducting of engine heat. A list of civil and military auxiliary tasks performed by airplane engine heat and electricity would include cabin heat, air conditioning, lighting, cooking, operations of weapons, cameras, radar and other surveillance gear, communications, control and guidance, and music or movies for the entertainment of passengers. Airplane engines not only provide power for a great variety of equipment but also channel an excess of electricity into storage batteries to meet certain needs that arise at times when engines are not operating. The secret of this power abundance is prolonged engine operation and the feasibility of coupling generators with machinery that must whirl at high speed anyway.

With space vehicles, the problem is scarcity instead of abundance. The motorless satellite coasting round and round the earth has no whirling turbojets to generate power, yet it is expected to operate cameras and instruments, televise pictures back to earth, or perform other tasks requiring electric power. If the spacecraft is manned, it has additional power needs for life support. Even if the vehicle still has some means of propulsion attached to it, these rockets must be saved for a few minutes of highly important maneuvering and cannot be turned on for the sake of generating electricity.

In regard to power requirements for communications, every break can be given the spaceborne equipment by making the ground equipment as powerful as possible. A powerful ground receiver can pick up a weak space signal, and a powerful ground transmitter can reach a distant and weak space receiver. In military applications, however, the vulnerability of high-powered ground installations is a drawback.

Directional antenna patterns are sometimes used to strengthen the signals from these spacecraft. Instead of broadcasting the signal in all directions (omnidirectional), a satellite can send them toward a designated receiver on earth in a sharply focused beam. This "narrowcasting" gives more **gain** (the increase of output power over input power) than an omnidirectional signal of equal power. Research and development toward the application of lasers* in communications shows many ways of improving that field.

In regard to power needs other than communications, however, the space vehicle is strictly on its own. At present, small satellites and large manned spacecraft meet their power needs with on-board sources that are limited in capacity and must be as light, compact, and efficient as science and technology can make them. Many space vehicles have power allowances smaller than 100 watts, equivalent to that of an ordinary light bulb. Even manned spacecraft have available to them only a relatively few kilowatts for maintaining communications with earth, operating life support equipment, and many other tasks.

Along with limited output comes a twin bugaboo—limited time. In general, vehicles outlast their power sources. Numerous "dead" satellites remain in orbit around the earth, their power exhausted. To keep up a program such as that of Tiros and Nimbus weather observation satellites, which televise pictures of world cloud coverage, new satellites must be launched from time to time to replace the exhausted ones. A breakthrough in developing means of either increasing or prolonging in-space power sources would be not only an important technological gain but a great money saver as well. Progress in this area has been steady. The future of interplanetary travel also depends upon increasing both the wattage and the lifetime of in-space power sources.

### Chemical and Solar Power Sources

To speak of the future of in-space high electric power is largely to turn one's attention toward nuclear engines. At the time of this writing, however, no practical nuclear means of supplying abundant power to space vehicles are available. Present nonnuclear methods are subject to the limitations described above,

*The word "laser" is an acronym derived from "light amplification by stimulated emission of radiation." Space does not permit further discussion of this important and fascinating technology in this text although research and development programs may improve them. Three are described here—batteries, fuel cells, and devices for using solar energy. Sometimes batteries and fuel cells are classed together as chemical power sources. Recent studies indicate that solar and chemical power systems will play a major role in space for at least the next 20 years.

BATTERIES.—Pre-charged on earth before launch, **batteries** can supply power to space vehicles. In fact, batteries are the oldest and still probably the most widely used power source for in-space use. The best energy storage per weight is provided by silver-zinc batteries Because of various technical problems, silver-zinc batteries are difficult to recharge in space. They are mainly used, therefore, as primary-discharge or "once through" batteries. As such they are reliable and have a high output as space power sources go, but are of short life (generally less than 2 weeks). The oneman Mercury capsule carried about 150 pounds of these batteries. More recently, silver-zinc primary batteries were used in the Apollo Lunar Module and Command Module for short-duration power needs. The nickel-cadmium battery, which has become the most commonly used space battery, has been used in numerous satellites. It can be recharged (from a solar source as described below), and can have an operational lifetime of more than two years. More research and development is needed to make these batteries more powerful and longer lived.

Research shows the potential for providing rechargeable silver-zinc batteries with long life. It appears reasonable to expect a life of several years, for example, for a synchronous satellite with silver-zinc batteries, at a power density four times that for currently used nickel-cadmium batteries.

FUEL CELLS.—The **fuel cell** is also a device for generating electricity by chemical reaction. Fuel cells, unlike batteries, use chemical fuels and oxidizers which are stored outside the cell.

In a fuel cell, two porous nickel electrodes are immersed in a solution of sodium or potassium hydroxide (Fig. 24). Pressurized hydrogen and oxygen are fed to these electrodes and diffused through them Chemical reactions between the hydrogen and the solution and the oxygen and the solution take place on the electrodes. Positive ions migrate through the solution, and negative electrons flow through the external circuit to provide power.

From a weight standpoint, fuel cells are best suited for uses requiring up to 10 kilowatts of power for operating periods be-

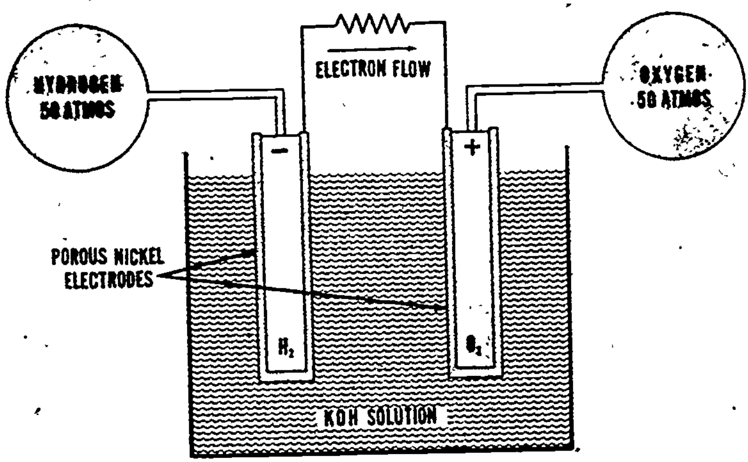



Figure 24. The fuel cell provides electrical power through a chemical reaction between fuels and oxidizer stored outside the cell.

tween a few days and several months. Another advantage of the hydrogen-oxygen fuel cell is that the chemical reaction product is potable water, useful on manned missions. The Apollo space program used the fuel cell as a primary source of in-space electrical power and drinking water.

SOLAR ENERGY.—In space, at the mean distance of the earth from the sun, the sun beams the equivalent of 130 watts of electrical energy per square foot on any surface perpendicular to its rays. Effective solar energy at a given range is called the "solar constant."

The most common solar energy conversion device for in-space power is the silicon **solar cell** (Figs. 23 and 25). Solar cells, commonly 1 x 2 or 2 x 2 centimeters in area and approximately 1/1000 to 1/500 of an inch thick, are connected together in large numbers to form a solar power trap. Unlike a battery, solar cells have no storage capacity for electrical power. The principle on which they operate is similar to that of an ordinary photographic light meter—conversion of sunlight to electricity. Solar cells are mounted either directly on the skin of a space vehicle or on broad, flat, wing-like projections called **paddles** or **arrays.**

Present silicon solar cells have an efficiency of about 10 to 12 percent if aligned perpendicular to the rays of the sun. This means that only about 10 percent of the solar rays that strike a single cell are converted to electricity. Current developmental work seeks to increase that efficiency to 20-25 percent.

Even a slightly oblique angle can result in an appreciable power loss. Therefore, body-mounted solar panels, because they face the sun at various angles or not at all, are less efficient than an array which can be oriented toward the sun. Sun-oriented arrays, however, also have their disadvantages, mainly in that they add to the mechanical complexity and power requirements of the vehicle. There is also a problem in the fact that portions of the vehicle and its solar array may throw shadows on other portions, including sensors and antennas. The design tries to minimize this factor. For such reasons, the less efficient but more reliable body-mounted solar cell panels are often used.

Another source of power (chemical or nuclear) is needed whenever a space vehicle is traversing the dark side of the earth or another celestial body. Storage batteries are often used to provide power during dark periods and are recharged when the vehicle is in sunlight.

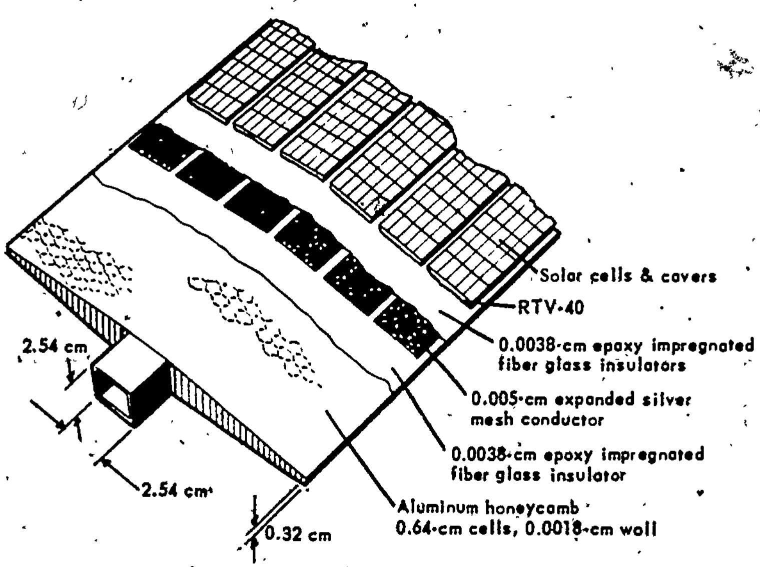



Figure 25. Solar cells convert sunlight to electrical energy for on-board power in space. Solar power has been harnessed for use on earth, too.

One drawback to the use of solar energy is that it would be of decreasing usefulness with increased distance from the sun. At the range of Mars, solar energy is about half that at Earth, and out near Saturn about a hundredth. For space travel this side of Mars, however, solar energy has shown itself to be a highly useful and economical power source, worthy of much future research and development.

A few years ago, 1-2 kilowatts seemed to be the upper limit in solar power for spacecraft. Today. 20-30Kw is deemed feasible for unmanned missions. The planned orbiting manned space station may have 25 Kw solar arrays, although researchers have not yet found what is needed to make such solar arrays **man-rated,** or capable of supporting human life.

Another method of gathering and using solar energy, under development but not yet in practical use, is that of using a mirror on some other device to focus the sun's rays on a boiler to vaporize a fluid, which in turn could turn a turbine and drive a generator. This method shows promise of being more efficient than present-day solar cells, but since solar cells themselves promise great improvement, it is hard to predict which will ultimately prove to be the superior method.

### Systems for Nuclear Auxiliary Power (SNAP)

The name SNAP applies to an overall program under the auspices of the Atomic Energy Commission (AEC), initiated in 1955, to develop nuclear electric power systems for space, sea, and land uses. AEC has worked jointly with the Department of Defense in some SNAP projects and with NASA in others.

Dozens of experimental and demonstration devices have come out of this program, but progress has been slow toward realizing the theoretical possibilities of nuclear power in space. Systems being evaluated would provide a broad range of power from 2.5 watts to 1,000 kilowatts, and beyond that lie projects for developing multi-megawatt (many thousands of kilowatts) sources.

In general, the nuclear systems under development are of two types. Those in the lower power range, using **radioisotopes,** are designated by odd numbers such as SNAP-27. Those which use nuclear **reactors** to create heat, designed to meet much larger power requirements, are given even numbers such as SNAP-8.

For the student unfamiliar with the term "radioisotope" and "reactor," we shall attempt to explain these devices briefly.

A radioisotope thermoelectric generator (RTG) (Fig. 26) works simply on decay of certain radioactive metals which yield energy as they break down and form new **isotopes** (variants of a chemical element with different atomic weights). The process provides a low but steady source of thermal power (heat). This, in turn, can be used to provide electrical power by either thermoelectric or thermodynamic means. Several small practical examples of radioisotope generators have been developed.

The RTG is light and reliable, requiring no maintenance. It is fairly expensive, but will far outlast its spacecraft's useful lifetime. RTGs are being developed for use in outer planet missions, and are already in use powering some of the instruments left on the moon by the Apollo astronauts.

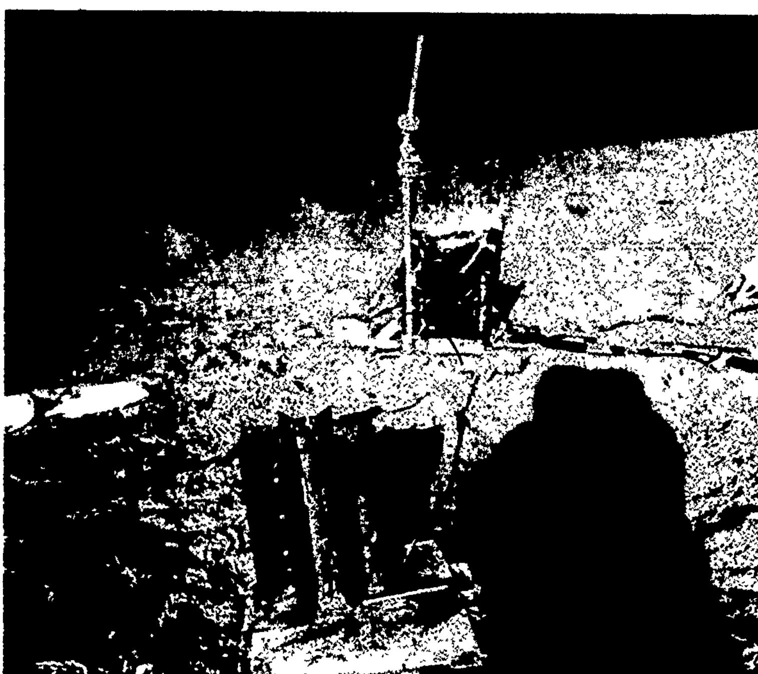


Figure 26. RTG power on the Moon This radioisotope thermoelectric generator provides long-time power for the ALSEP (Apollo Lunar Surface Experiments Package) in the background Shadow is that of the astronaut taking the picture.

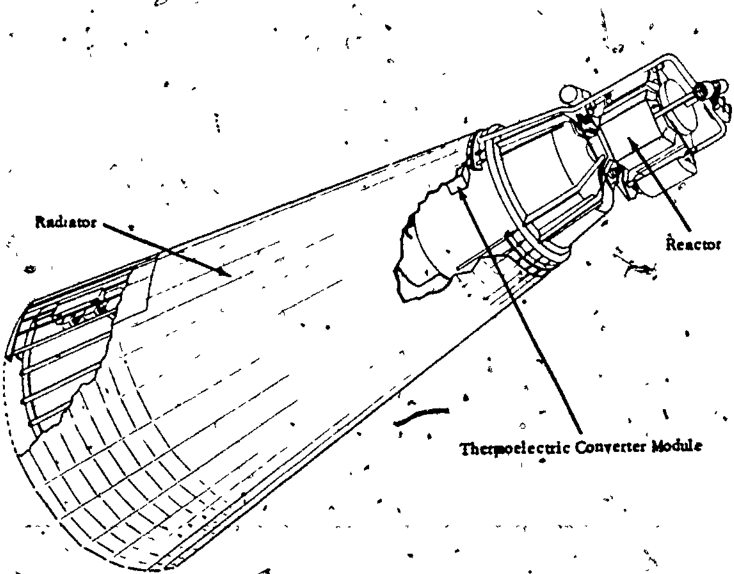



Figure 27. SNAP-10 A, the proposed nuclear reactor, could generate massive amounts of heat for rocket propulsion or other uses.

A nuclear reactor (Fig. 27) is a device which goes considerably further toward exploiting the awesome power of nuclear energy It might be called a nuclear bomb in slow motion—taming the destructive forces of **nuclear fission** (splitting of atoms) by spreading them out over a long time period. Just as in a nuclear bomb, atoms split to release nuclear energy millions of times as powerful per atomic weight as chemical energy, and these fissioning atoms shoot out neutrons, which split other atoms. In a reactor, however, a matrix of inert material keeps small masses of fissionable atoms of uranium or plutonium separated and slows down flying neutrons so that the chain reaction of atom splitting atom does not occur instantly but at a controllable rate of so many atoms at a time In this fashion, no explosion occurs, but a great amount of heat can be generated and sustained for months or perhaps years without refueling. The remainder of the process need not be explained. Once there is a heat source, there are numerous ways in which it can be put to work to generate electricity, and numerous even-numbered SNAP projects are exploring these ways.

On earth, nuclear reactors have been successfully employed as stationary power plants or to power ships and submarines. All such reactors are big and heavy, for not only are bulk and weight required for the machinery itself, but also lead or other heavy shielding material is necessary to protect human beings and many materials from deadly radioactivity. The three basic safety requirements for reactors on space vehicles are these: (1) the device should not materially increase general atmospheric background radiation. (2) At the launch pad, harmful radiation should not extend beyond the device itself or the area from which personnel are normally excluded for other safety reasons. (3) The device should not produce a local hazard upon return to earth. In addition to these requirements, the manned space vehicle must provide shielding for personnel aboard the vehicle. To sum up all these requirements—they are a weight problem. Development of reactors small and light enough to carry aboard space ships, yet powerful enough to serve these vehicles as major power sources, remains a difficult matter. Nevertheless, nuclear power sources remain the big hope of the future for astronautics, for only nuclear energy seems to promise a truly abundant and long-lasting source of *both* propulsive and other power.

SNAP reactors, we must repeat, are designed to produce only electric power and should not be confused with NERVA (Nuclear Energy for Rocket Vehicle Application) reactors, which are under development as a more direct means of propulsion. Power from a SNAP reactor might be used for electric rocket propulsion, which in fact is one of its main goals, but the principle is different from that of NERVA, which will be discussed later.

In the following discussion of electric rocket propulsion, the term **low level power source** is used to include battery, fuel cell, solar, and nuclear radioisotope (odd-numbered SNAP) power sources. These are the kinds that, in general, are available today and have limited usefulness for electric propulsion. The best promise of a prolonged high level power source conceivable at present, and the real key to the future of electrical rocket propulsion, is the nuclear reactor.

## ELECTRIC ROCKET PROPULSION

As we noted earlier, interest in electric rocket propulsion arises from its potential for prolonged operation, which greatly exceeds that of chemical propulsion, even if thrust levels are not as high In this respect, our old friend specific impulse, which figured so prominently in Chapters 2 and 3, becomes important again

### Specific Impulse in Electric Propulsion

No propulsion system, electric or otherwise, can work without a propellant mass—although in some instances of electric propulsion, the notion of mass is one that is stretched very thin indeed Nevertheless, the concept of a working fluid, a substance that is heated or otherwise energized and propelled at high velocity through an exhaust nozzle, is basic to all kinds of electric propulsion. Therefore the yardstick known as "specific impulse," more commonly thought of as a measure of chemical energy, is applicable here too.

Just as with chemical propellants, specific impulse of a working fluid is proportional to the ratio of combustion chamber temperature ($T_c$) to the average molecular weight of the combustion products (m). This ratio is stated as $T_c/m$ Subject to these conditions, a pound of working fluid will yield so many pounds of force in one second Stating the same quantity another way, a pound of working fluid will sustain one pound of force for so many seconds In space, as we have noted, *sustained* thrust is often more desirable than *intense* thrust Therefore, we are now more interested in specific impulse as an index of propellant economy or "mileage" than we are in the same value as an index of boosting power. In Chapter 3, we compared specific impulses of commonly-used chemical propellants and found that 400 seconds is a very high rating, almost the best that chemical propulsion can do nowadays, with a theoretical limit of 600 seconds set as a goal for future development. Specific impulses on this order, however, are inadequate for the kind of slow acceleration to super velocities described above which space experts would like to see made possible Electric engines are expected to yield specific impulses of 2,000 to 30,000 seconds, or more.

Before describing different types of electric propulsion, let us point out certain basic features they all have in common. Instead of heating propellant in huge volume—a great roaring fire—an electric engine would energize a very small amount of propellant The working fluid would be fed into the engine slowly in a thin stream. Thus, a relatively small tankful of working fluid might be enough for long hours, days, or even months of operation. At the same time, however, the highest possible thrust must be obtained from this thin flow if it is to have any effect at all.

Not only do certain electric engines deliver the extremely high temperatures needed, but they have a decided advantage over chemical in the matter of light molecular weight. The average chemical exhaust mass consists of a complicated mixture of light and heavy molecules. Some of these have gained weight, others have lost, in the process of combustion. As we indicated in Chapter 2, the propulsion chemist must reckon with **trade-offs**—sacrificing in one area to gain in another—of higher temperatures for lower mean molecular weight or vice versa in seeking formulas that will deliver maximum specific impulse. A chemical exhaust mass with a mean molecular weight of 20 is better than average. By contrast, uncombusted working fluid could be pure hydrogen, undergoing no chemical change, producing an exhaust gas with a molecular weight of 2—that is, nothing but $H_2$ molecules, the lightest molecules *or* atoms in nature. (Since we must consider sums proportional to square roots, the advantage of 2 over 20 is not tenfold but threefold; but it is dramatic indeed.)

In some electric rocket engines, molecular weight disappears completely as a factor as we enter the realm of electrons, ions, and plasma. In all these instances, the nozzle velocity of a very thin stream of matter would be fantastically high. Thus specific impulse ratings as high as 30,000 seconds and more might be stated as potential for some kinds of electric rocket propulsion, but these would have to be considered in terms of low rather than high thrust.

## Types of Electric Rocket Engines

A number of different types of rocket engines classed as "electric" are under development. Some have already found limited practical application with low-level power sources; others might be called more "futuristic." The future development of all engines in this class is dependent upon improvement in electric power sources.

Perhaps the simplest concept to understand is electric heating of hydrogen, examples of which are the resistojet and the arc jet. As in chemical propulsion, the energy behind the rush of particles* through the exhaust nozzle is in the form of heat Other forms of electric propulsion not only employ heat but also use electrical energy itself as a means of moving particles.

RESISTOJET.—**Resistojets** are miniature thrusters designed to deliver precisely controlled thrust for space craft attitude control and station keeping. In a resistojet engine, heat is generated by passing an electric current through a special wire or tube, which presents high resistance to the current's passage. This resistance develops heat. A stream of hydrogen or ammonia is passed over the heating element and energized to high velocity as it travels out an exhaust nozzle similar to that of a conventional chemical rocket (Fig. 28).

Resistojets in current use are about six inches long and two inches in diameter, and weigh about a half a pound. They provide about 10 milipounds (1/1000 of a pound) of thrust at specific impulses of 300-575 seconds, depending on the propellant used. An important consideration about resistojets is that they can use as propellants gases from biological waste.

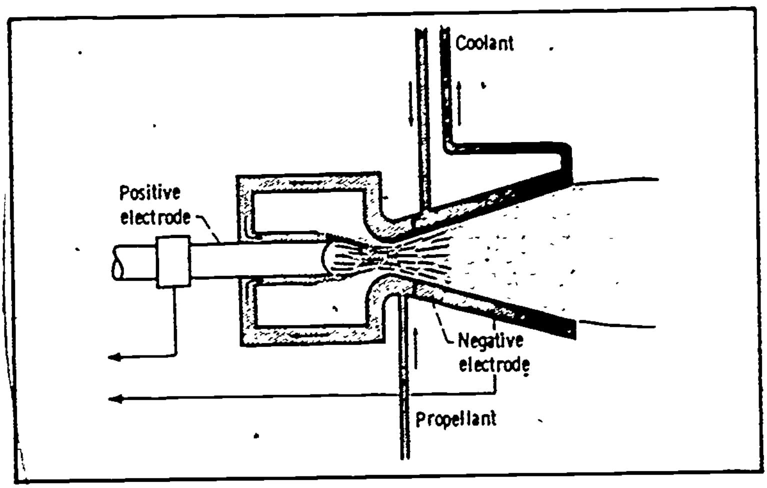



Figure 28. The resistojet, shown in this schematic drawing, applies the principles of the electric toaster, percolator, and iron to propulsion in space.

*A particle is any small piece of matter, and the rearward movement of particles through an exit nozzle, is the essence of all rocket or jet propulsion. A particle can be a molecule, as in all forms of propulsion discussed up to this point It can also be an atom or a part of an atom such as a proton, or neutron, or even an electron or photon (which are infinitely smaller than protons and neutrons)

Resistance heating is the principle on which electrical heating appliances like toasters, coffee percolators, and irons operate. The practical resistojets currently in use or under development use low-level power sources. As with all electric rockets described here, future development would depend on development of nuclear-reactor power sources. In this respect, however, the arc jet is more promising because it can deliver higher temperatures.

ARC JET.—The **arc jet** differs from the resistojet in that instead of a resisting wire or tube, there is simply a gap between electrodes. Current jumping this gap or "arcing" creates very high temperatures. Hydrogen passing through this arc is heated to thousands of degrees and expanded through a nozzle as in a resistojet or conventional chemical rocket. Theoretically, extremely high exhaust velocities and high thrust as well as long endurance, with specific impulses up to 2,000 seconds, far in excess of any known chemical or nuclear-fission system, are possible. With both the arc jet and the resistojet, the operating time is more limited by the fuel supply than by the duration of the power source. Nevertheless, these devices get the most mileage out of a supply of liquid hydrogen. Present power sources are not sufficient to realize the arc jet's possibilities to any practical degree. Teamed with a nuclear reactor, the arc jet might some day compete with more direct means of nuclear propulsion.

ION OR ELECTROSTATIC ENGINES.—**Ion engines** are in experimental use as auxiliary propulsion sources for north-south satellite station keeping and attitude control. The practical models, however, are of very low thrust and are limited to the kind of chores they are performing and to the slow, prolonged, acceleration in deep space that may be desired in some instances. Because their rate of fuel consumption is low, they can sustain thrust over long periods. Among other desirable features of ion rockets are their lightness of weight and the ease with which they can be stopped and restarted.

The ion rocket is the first example cited here of propulsion by some means other than gaseous heating. It produces thrust by **electrostatic** acceleration of charged atomic and subatomic particles (Fig. 29). A rare metal called cesium seems to be the most promising fuel element so far tested. When subjected to heat, it vaporizes and ionizes; that is, each atom gives up an electron and thus becomes positively charged and is called an ion. These ions pass through an electric grid, which accelerates their movement toward the exit nozzle at tremendous speeds. The stripped-

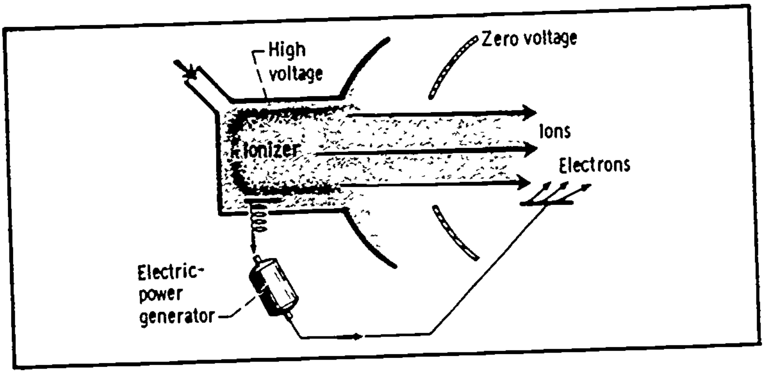



Figure 29 The ion engine gets its thrust from a tremendous acceleration of charged atomic and subatomic particles.

off electrons follow another path and are fed back into the exhaust stream to produce an electrically-neutral exhaust. (Otherwise, the motor and the whole vehicle with it would build up a dangerous electrical charge.) Although cesium ions are heavy in atomic weight, their quantity is small; the exhaust flow is thin, and its velocity many times greater than that of heated gas. Specific impulses may reach a maximum of about 16,000 seconds.

PLASMA OR ELECTROMAGNETIC ENGINES.—The **plasma engine** currently is not quite to the developmental stage of the ion engine but may some day compete with it in the field of low-thrust prolonged-operation usage. Its fuel economy and super exit velocities may add up to specific impulses of 20,000 seconds or more. Up to this point, we have dealt with three states of matter—solid, liquid, and gaseous. Some scientists now recognize plasma as a fourth state of matter. A **plasma** is not made up of molecules but of ions, free electrons, neutrons, and other subatomic particles. Some of these particles are positively charged, some neutral, and some negative so that the general mixture is electrically neutral. A plasma engine first employs electric power thermally to break a gas down into a plasma. Then it subjects the plasma to electromagnetic fields of force, which accelerates the plasma to super velocities (Fig. 30). Specific impulse is directly proportional to exhaust velocity, remember. It is the extremely high exhaust velocity of electric engines of the ion and plasma types that give them such high specific impulses.

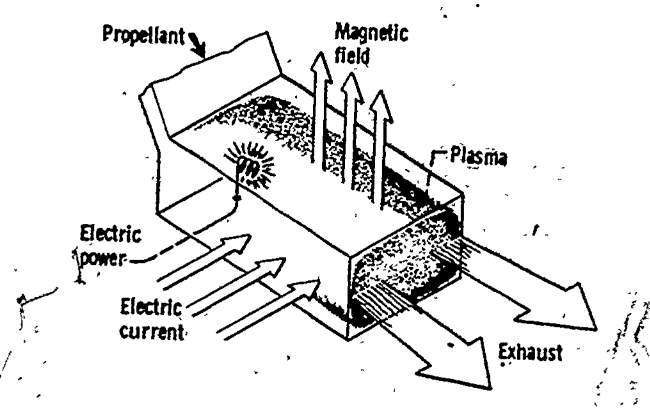



Figure 30. The plasma jet makes use of a "fourth state of matter" and electromagnetism to get its thrust.

Pulsed plasma thrusters in the thrust level range of a few tens of micropounds have a number of significant advantages in long life missions requiring precise maneuvers. This is particularly true where a large number of accurately controlled thrust pulses are needed such as on a spin-stabilized spacecraft. This plasma thruster has no valves, requires little power, and needs no warm-up time to function. Initial application of the plasma thruster is on a NASA Synchronous Meteorological Satellite (SMS), for east-west station keeping and for precession-pointing control.*

## NUCLEAR AND OTHER ADVANCED PROPULSION SYSTEMS

In this section we consider direct means of propulsion by nuclear reactor, the subject of very active research and development efforts at present. Beyond this concept lie more theoretical ideas such as the nuclear impulse and photon propulsion or "solar sail" concepts. While some of these schemes may seem futuristic day dreams, the teen-age student, if not an older person, might see them realized in his lifetime or even have a hand in their development.

*Precession can be defined as a slow change in the direction in space of the satellite's axis of rotation, resulting from the pull of competing gravitational forces. (The same effect works on the planet Earth, the result of the tendency of the gravitational attraction of the Sun and the Moon to pull the earth's equatorial bulge into line with this attraction.)

## NERVA

United States projects to develop nuclear power and propulsion have been underway for over a decade. The program, jointly sponsored by NASA and AEC, has three major parts: propulsion, power, and electrophysics. We are concerned here with the first of these. The primary propulsion effort is the development of NERVA (Nuclear Energy for Rocket Vehicle Application). The complete Nerva system passed its first ground test on February 3, 1966.

The final phase of the NERVA program—development of a flight engine—was begun in 1969, and preliminary design of the flight engine was completed in 1971. Flight testing of the engine, however, is not expected until 1978 at the earliest.

NERVA is based upon a nuclear reactor, the basic principle of which was explained above in a discussion of SNAP. In the NERVA rocket, however, the reactor will not be used to generate electricity but to apply direct heating to hydrogen for rocket propulsion. Such a system is sometimes called a **gaseous heating** or **nuclear thermal** (a term which we must be careful to distinguish from **thermonuclear,** which means an entirely different form of atomic energy) system. NERVA will deliver 75,000 pounds of thrust, and its specific impulse will be 825 seconds—double those achieved so far with chemical propulsion, but not as high as those of electrical propulsion.* In this instance, however, the objective is to combine *both* high thrust and high specific impulse to achieve a super rocket capable of carrying heavy payloads deep into space, achieving high acceleration rapidly, possibly relaunching from another planet, and doing all this with a bonus of good propellant economy. By propellant, of course, we mean the liquid hydrogen supply, which would still remain the critical factor. It would have to be conserved for use in high-thrust situations, but it would still have a great advantage over chemical propellants in this respect. The NERVA engine's capability for easy stopping, restarting, and thrust modulation plus high specific impulse will give it the means of using a propellant supply with utmost efficiency. Recoverability of the expensive NERVA system rather than its mere use and discard as a stage is another goal of the project.

*The importance and potential of nuclear research becomes obvious when we learn that theoretically, nuclear energy could produce a specific impulse of one million seconds. There are major technical problems that prohibit the attainment of the ultimate in performance.

As in the case of SNAP reactors, engine weight is still a problem. Another drawback to the present NERVA concept is radioactivity. The hydrogen working fluid, as it passes through or around the reactor and is heated, is also irradiated—loaded with radioactive particles emanating from the reactor's fissioning atoms. To shield it from this radioactivity would also mean to shield it from the very heat it is supposed to acquire and thus lower the engine's efficiency. If a NERVA engine (Fig. 31) were to be used as a first-stage launcher, the hydrogen exhaust would spew a dangerous amount of radioactivity over the launching area. Hence present concepts call for its use as an upperstage rocket, at a safe altitude. Its earlier uses could be for boosting a heavy vehicle (possibly a manned vehicle) out of a parking orbit into an interplanetary flight.

### Gas Core Nuclear Rockets

Structural limitations associated with solid fuel elements restrict the specific impulse of the NERVA-type system to around 1,000 seconds. Two concepts are under consideration in which the fuel is in the gaseous state and for which the potential specific impulse is as high as 5,000 seconds. (Actually, hydrogen and uranium plasmas are involved.) These systems, classed as **gas core nuclear rockets,** include the coaxial flow and the light bulb reactors (Fig. 32). Both cases involve difficult questions of feasibility, and probably will require many years to develop, but there has been some progress along the way.

COAXIAL FLOW REACTOR.—The coaxial flow reactor consists of a large, nearly spherical cavity surrounded by a moderator-reflector system to control and confine the radiation and the high temperatures at work. Vaporized uranium would be centered in the cavity, held there by the action of the hydrogen propellant flowing through the porous walls of the cavity. Heat generated in the fissioning uranium plasma would be transferred to the hydrogen by thermal radiation. Some of the uranium would be exhausted with the hydrogen.

NUCLEAR LIGHT BULB.—The light bulb reactor consists of several cylindrical cavities each containing a transparent wall of fused silica used to separate the gaseous uranium from the hydrogen propellant. (In contrast to the coaxial concept, no uranium would be carried away with the hydrogen stream.) Thermal radiation

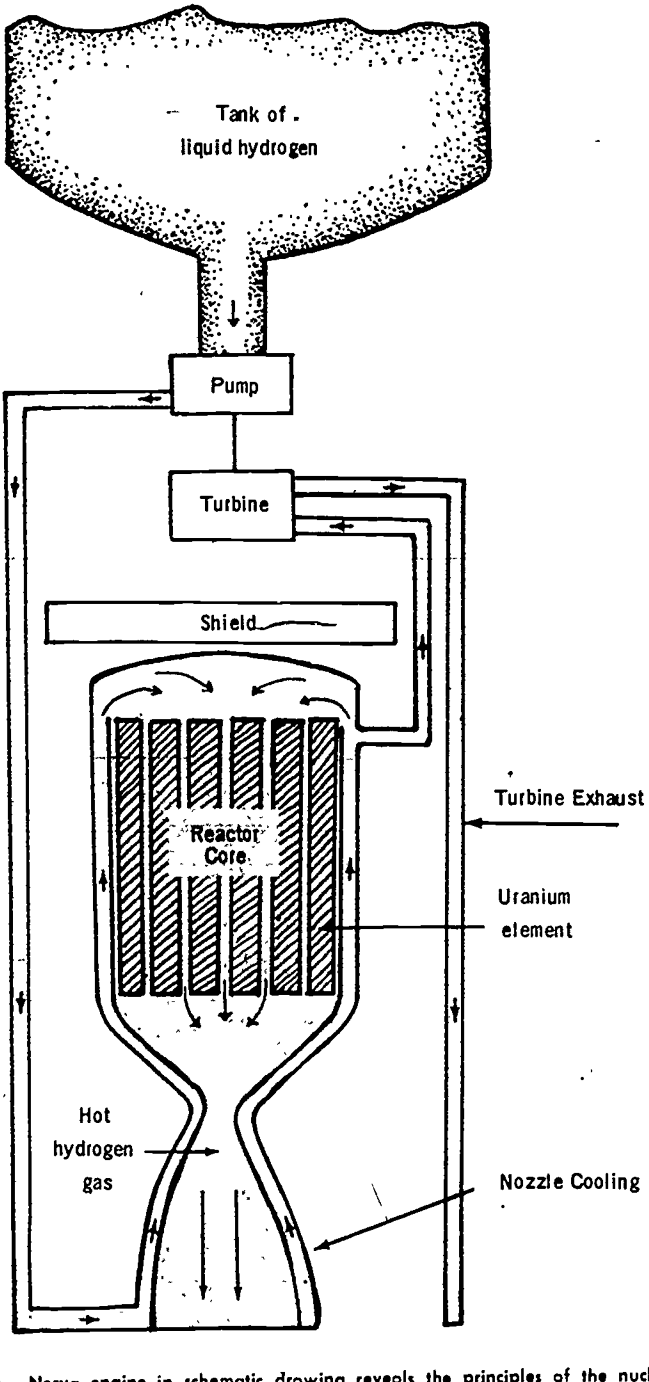
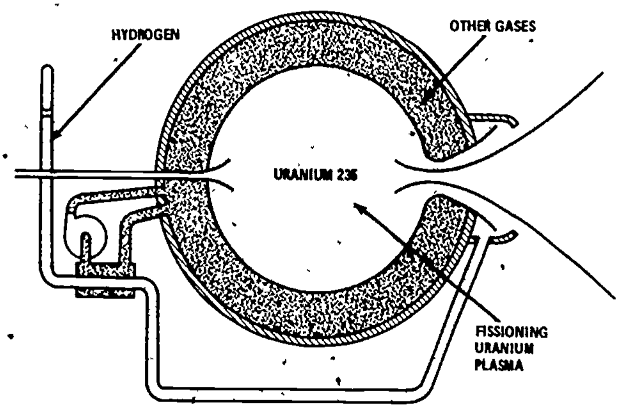



Figure 31. Nerva engine in schematic drawing reveals the principles of the nuclear rocket. Budget considerations have imperiled the future development of this concept.



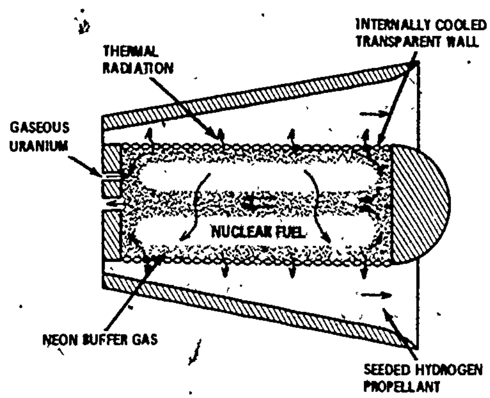




Figure 32. Two nuclear concepts employ the gas core approach. They are the coaxial flow engine and the nuclear light bulb. The exhaust of radioactive materials is a vital consideration in developing nuclear rockets.

must pass through the transparent wall in order to heat the hydrogen to desired temperatures. This construction—the transparent wall surrounding the hot reactor core—is reminiscent of a light bulb's construction and gives the engine its name. While the silica wall transmits heat to the hydrogen working fluid flowing around it, it also blocks radiation. Thus the NLB, as it is sometimes called, will be safe for first stage use in launches from earth.

The NLB-powered vehicle is envisioned as a wholly-recoverable winged combination airplane and space shape, with a single-stage power plant to carry it through all phases of aerodynamic and space flight. It would take off and land horizontally from an airport without radiation hazard. The NLB engines would have the thrust, the duration, and the ease of stopping and restarting needed for launch, prolonged or deep space flight, and aerodynamic reentry and landing.

### Deep Space Machines and Other Daydreams

Described briefly below are propulsion concepts that may lie within the realm of the possible, but so far no active research-and-development programs have been undertaken to bring them into being.

FUSION PROPULSION.—This concept goes far beyond NERVA or NLB in that it proposes use of a reactor for controlled thermonuclear energy. This is the energy of the so-called H-bomb, many times as powerful as the fission reaction employed in present-day nuclear reactors or the NERVA concept. It is based on the fusing of nuclei of the hydrogen-isotope atoms called deuterium and tritium (rather than the splitting of heavy atoms of uranium or plutonium.) Perhaps the immense heat needed to begin such a reaction could be somehow generated, and the reaction then controlled and contained by means of an electromagnetic field. Through introducing or cutting off a coolant/working fluid in the exhaust flow, specific impulse could be controlled for either extremely high thrust levels or extremely high specific impulses—up to a million seconds or more.

PHOTON PROPULSION SYSTEMS. A photon is a tiny sub-atomic unit of light from the sun. Is it pure energy, or does it have some mass? Some scientists think it has mass. At least it has been demonstrated that the sun's rays exert some physical pressure on a body in space. Photons also have a velocity, the familiar figure known as the speed of light—186,300 miles per second. The pressure of the sun's rays is slight, but on large, low-density space vehicles such as the balloon-like satellites of the Echo series, it has produced noticeable effects, **perturbations**, or variations in Echo orbital paths amounting to hundreds of kilometers. This experience suggests the idea of building huge, low-density space vehicles, either immense balloons or great extensions of the solar paddle principle now employed for electric power. These would employ the **solar sail** concept, spreading out as much area as possible to receive the sun's rays and literally be propelled by them as a sailboat is propelled by the wind.

Other even more advanced concepts include a rocket engine that would convert matter to photons—the *complete* conversion of matter to energy, compared to which present concepts of nuclear and even thermonuclear energy are merely fractional. It is only by such means that a space vehicle could approach the speed of light, and it is only by achieving such a velocity that the idea of travel beyond the solar system—to explore the sun's nearest neighbors in interstellar space—begins to show even a glimmer of feasibility.

## SUMMARY

Beyond chemical propulsion lie a number of possibilities for propulsion in space by nonchemical means. To understand how non-chemical propulsion might work, it is necessary to consider two preliminary topics. One is the nature of propulsion in space; the other is electric power sources for space vehicles.

Propulsion in space does not demand the high thrust necessary to boost a vehicle off the earth or another planet. The vehicle is weightless, and as long as it is not attempting to move in extreme opposition to its own momentum and the forces of gravitation it can accomplish a variety of tasks and maneuvers with a means of low-thrust propulsion. The vehicle can, for instance, make orbital changes, move from orbit into moon or deep-space trajectory, and even substantially reduce its travel time to another planet. With low thrust of long duration, amazing increases of velocity can be developed. For example, an acceleration of six inches per second per second, continued for 20 hours, will increase velocity by 25,000 mph Thus various means of electric propulsion become useful.

If electric propulsion is feasible, however, where does the electricity come from? The problem of developing power sources for space vehicles remains a difficult one. At present, satellites and manned vehicles are limited in size and missions are limited in duration by the electric power problem. Continuous operation of aircraft motors generates an abundance of electricity as a by-product, but coasting satellites for the present must take care of their communications and other power needs by means of storage batteries, or chemical fuel cells (which are somewhat more powerful than batteries), or photocells spread out to pick up electrical energy from the sun's rays, or combinations by which solar energy can recharge batteries or fuel cells

The SNAP projects for developing nuclear power generators suitable for carrying aboard space vehicles so far have resulted in low-level. long-duration generators of the radioisotope type, deriving electric energy from decay of radioactive metals The only kind of on-board power source that could provide a high power level and operate for a long time seems to be the nuclear reactor Achieving light weight without sacrifice of safety (shielding against radioactivity) remains a problem in SNAP projects to develop reactors.

Electric rocket propulsion is at present characterized by high specific impulse but low thrust Its high specific impulse is a result of high temperature and low molecular weight. which a resistojet or arc jet can achieve by electric heating and use of pure hydrogen as a working fluid. Extremely high specific impulses can also be achieved as a result of extremely high exhaust velocities obtained by electric rather than thermal means. Both ion (electrostatic) and plasma (electromagnetic) engines can hurl ions and electrons rearward at speeds many times greater than those obtained by heated molecules Electric engines have low thrust, however, because of the present limits of electric power and heat and the thinness of the propellant gas. whether pure hydrogen or an ionized plasma. Of electric engine concepts under current development. the arc jet. teamed with a nuclear reactor. has potentialities for higher thrust than the others Plasma and ion engines have the best potential for long operation. extending to months or possibly years

A project for developing nuclear propulsion for space vehicles has been going on for many years. and has reached a stage of development where efforts are being made to assemble a complete space-borne system called NERVA (nuclear energy for rocket vehicle application). A NERVA engine heats a hydrogen working fluid directly by means of a fission reactor, and obtains specific impulses in the 800-1,000 second range. A more advanced concept, currently in the very early stages of development, is the gas core nuclear rocket, including the coaxial flow rocket and the nuclear light bulb (NLB).

Even more advanced concepts include the thermonuclear-fusion reactor engine, the solar sail moving a vehicle by photon pressure, and photon rockets that would effect complete conversion of matter to energy. Only the last of these concepts, at present purely theoretical, suggests a way to the stars.

## WORDS AND PHRASES TO REMEMBER

arc jet
array
battery
chemical propulsion
electric propulsion
electromagnetic
electrostatic
fuel cell
gain
gas core nuclear rocket
gaseous heating
ion engine
isotope
laser
low level power source
man rated
nuclear fission
nuclear propulsion
nuclear reactor
nuclear thermal
paddle
parking orbit
perturbation
plasma
plasma engine
precession
radioisotope
resistojet
retrothrust
solar sail
station keeping
thermonuclear
trade-off

## QUESTIONS

1. **What factors make low-thrust propulsion feasible in space?**
2. **What are the shortcomings of chemical propulsion in regard to in-space use?**
3. **What are two possible methods of gathering electrical energy from the sun's rays?**

4. SNAP and NERVA represent two different concepts for use of nuclear power in space. What do the letters mean, and what is the difference between them?

5. What are the principal problems that must be solved before nuclear-reactor power in space becomes practical?

6. Explain why, in present-day nonchemical rocket engines, high specific impulse is possible only with low thrust.

7. How does an electrostatic rocket engine differ from an electromagnetic rocket engine?

8. What fluid supplies the propellant mass for each of these types of engine: resistojet, arc jet, NERVA, NLB, plasma (electromagnetic), solar sail?

## THINGS TO DO

1. Discuss the implications of nonchemical propulsion systems developed for space travel. See if you can think of any way these developments can help the millions of earthmen who will never travel in space.

2. Calculate the time required for a space vehicle to reach the speed of light (if this is possible), assuming the constant delta-V attainable with propulsion means discussed in this chapter.

## SUGGESTIONS FOR FURTHER READING

*Space Handbook*. Institute for Professional Development, Air University, Maxwell Air Force Base, Alabama, 1970.

*Space Fundamentals*. Air Force ROTC, Air University, Maxwell Air Force Base, Alabama, 1970.

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# Control and Guidance Systems

THIS CHAPTER describes in turn the physical means by which the flight of a space vehicle is controlled, the servomechanisms and computers that provide the links between these controls and human will to provide guidance, and the principal systems for guidance: command, inertial, and celestial. After completing the study of this chapter you should be able to do the following: (1) explain the differences between control, guidance, and navigation as applied to spacecraft; (2) compare the basic functions of servomechanisms in space systems and everyday things like automobiles, washing machines, and some heating plants; (3) describe the basic functions of analog and digital computers; (4) compare the problems of launch, midcourse, and terminal guidance; and (5) describe the essential features of command, inertial, and celestial guidance.

THE FLIGHT of a space vehicle is monitored and directed from start to finish by some kind of guidance and control system. Any vehicle, traveling through any medium, must be actively steered to its destination, unmanned spacecraft must get this steering through the direction of onboard electronic and mechanical devices with or without additional help from external monitors.

While control and guidance are ordinarily thought of as occurring together, the functions are actually separate and distinct. The **guidance** function may be identified as navigation—determining the relationship of the space vehicle to the planned flight path, and generating a corrective signal when a deviation occurs. The **control** function may be identified as steering—accepting the corrective signal and changing the vehicle's direction of flight so as to get it back on the right path.

In this chapter we shall consider the systems—on the ground and aboard the vehicle—by which control and guidance of space vehicles are accomplished. This could be a highly technical subject, concerning mechanisms that are for the most part electronic and extremely complex. Our discussion, however, will be limited to the broad principles on which these mechanisms operate. The next and final chapter will consider the art of guidance in harmony with the forces of gravitation or celestial mechanics.

In astronautics, however, the distinctions between control and guidance tend to be blurred. It is hard to distinguish the points in a space vehicle's electronic circuits where one function ends and another begins. For our purposes, it is better to think of these functions as being performed by one continuous system. In such a system, a command generates a signal; this signal flows through the computer to a servomechanism, which converts it into a physical action such as a slight swiveling of a rocket nozzle. The new position of the rocket nozzle then becomes an item of information that is "fed back" into the control and guidance system, just as navigation data is fed into the same system.

Despite all this automation, the astronaut faces a complex control panel (Fig. 33) and must perform tasks related to the navigation and guidance of his ship. Astronautics is one field, furthermore, in which future developments may lead to slightly less rather than more automation. Wernher von Braun, among others, has expressed the opinion that for certain maneuvers the astronaut of the future should be given more rather than less manual control over his vehicle. An astronaut's ability with mathematics, however, will never take the place of the computer.

## PHYSICAL CONTROL OF SPACE VEHICLES

As in the case of *guidance* and control, the distinction may be blurred between *propulsion* and control; for propulsion is the means by which control is accomplished. However complex the control and guidance system is, it ends at the rocket nozzle. Thrust and thrust alone can change or correct the motion of a space vehicle. Essentially, the controller can steer either by aiming the thrust in different directions or by regulating the thrust output. Remember, in space, a change in velocity brings on a change in pathways.

If thrust is necessary for control, what about satellites following certain prescribed orbital paths without the help of motors? The accuracy with which a motorless space vehicle follows an orbit or

Figure. 33. Overhead control panel of an Apollo space vehicle mockup. Note the guard lattice to prevent accidental tripping of switches during movement in the vehicle.

trajectory depends upon the accuracy with which it is first launched or injected. Various forces will, however, eventually pull the vehicle off course or produce an orbit decay to the point where a satellite will re-enter the atmosphere and be destroyed. Motorless satellites have their uses, but the simple fact is that without propulsion there is no control. Control must be exerted during the launch phase. To alter a space vehicle's course, there must be some means of rocket propulsion still attached to the vehicle.

### Main Engine Thrust Modulation and Termination

Thrust modulation, as we learned in Chapter 3, is better achieved with liquid-propellant than with solid-propellant engines. Just as an automobile or airplane engine can produce various levels of power by use of the throttle, so can the liquid-propellant engine produce varying levels of thrust by means of the valves and other controls over the flow of propellants in its feed lines. The liquid-propellant engine is also easy to start and stop. One method of velocity control that is used with liquid-propellant engines is the firing of bursts of the same intensity but different durations. This method may be combined with high-and-low thrust modulation to produce a desired velocity change. A solid-propellant motor, with its burning pattern and time curve built into its grain, has no thrust modulation capability. It has a fairly accurate means of thrust termination on command, but its restart capability is still largely experimental.

**Thrust termination,** or stopping the engine, is an aspect of control that is of particular importance. To put a vehicle into a specified orbit or escape trajectory, a certain burnout velocity must be achieved. The word burnout suggests simply exhaustion of the propellant supply of a given stage. In first stages, the rocket motors usually do burn to depletion. In upper stages, to insure accuracy of the vehicle's velocity, the engine usually must be shut off at a precise instant, whether it is approaching actual burnout or is to be restarted later.

The liquid or hybrid engine, of course, is shut off by closing of valves in feed lines. Shutting off combustion in a solid motor is a little more difficult. It is done by suddenly reducing combustion-chamber pressure below the critical pressure value for that particular motor. When this happens, the motor will, in effect, blow itself out. (Remember, there can be no smothering of a fire that carries its own oxidant as well as fuel. A destructive explosion might result if it were attempted.) As we mentioned in Chapter 3, there are various ways of suddenly depressurizing a solid rocket motor. The nozzle can be blown off, or gases can be vented forward or out the sides of the motor. A water injection technique has been tested that quenches combustion and allows restart of the motor. After shutoff of either a liquid or a solid motor, but especially in the case of the latter, combustion and thrust do not cease immediately. There is still some leftover or "residual" burning, producing low-level thrust. The amount and character of this residual burning, however, is a known quantity and can be computed in a thrust termination sequence to achieve a precise burnout velocity.

### Thrust Vector and Attitude Control

Steering or thrust vector control can be accomplished with main engines and also with auxiliary or vernier engines. Attitude control is accomplished by vernier engines or smaller devices.

THRUST VECTOR CONTROL WITH MAIN ENGINES.—As long as the main direction of thrust is on a line through a vehicle's center of gravity, the vehicle will continue to move in a straight line. If the thrust is aimed to one side of the center of gravity, the vehicle will turn like a lever on its fulcrum and change direction (Fig. 34). The powerful thrust forces of a vehicle's main stage must not be deflected too sharply or stress could destroy the vehicle. Another complication that must be computed by the vehicle's control and guidance system is the fact that, as propellants are consumed, the center of gravity itself shifts. The nature and direction of this shift depends upon a number of structural factors and the location of the main fuel tanks or solid-propellant grain.

Thrust vector control of some liquid-propellent engines can be achieved by mounting the whole engine—chamber, nozzle, and associated plumbing—on a flexible mount or gimbal and tilting the whole engine with the help of hydraulic or pneumatic devices. Other means of thrust vector control are also used, and *must* be used with solid-propellant motors. The nozzle itself can be gimballed; or a liquid or gas can be injected under pressure into the exhaust stream to deflect it; or a collar-like device called a jetavator can be placed around the nozzle exit and swiveled off center so as to encroach upon the exhaust stream and deflect it; or deflecting vanes can be placed within the nozzle.

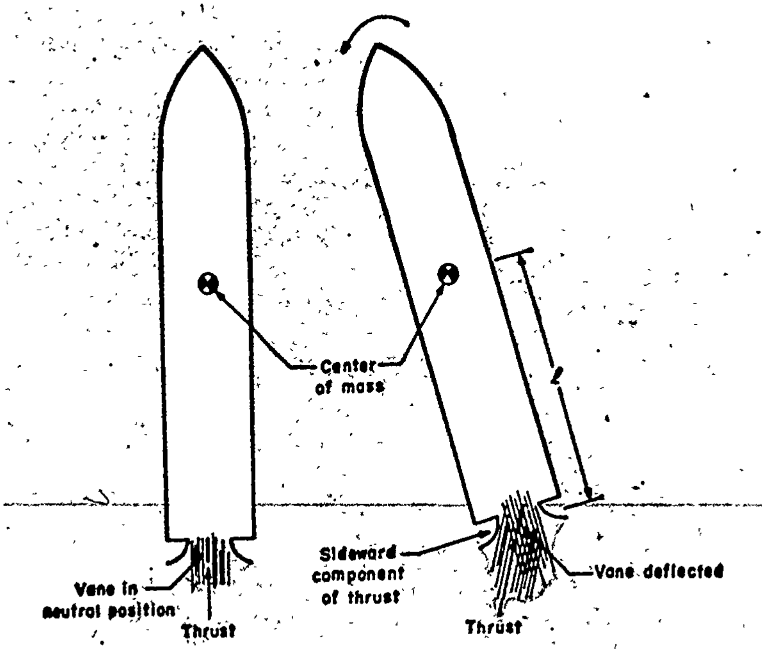


Figure 34. Steering of the rocket is accomplished, in this schematic drawing, by turning the vane (center of exhaust flow) to redirect the exhaust to obtain a new thrust vector.

Still another means of thrust vector control is to rotate the whole vehicle by means of auxiliary motors before firing the main engine in a new direction. In this fashion, the vehicle can even be turned around completely so that the main motor nozzle is aimed forward for braking or retrothrust.

AUXILIARY OR VERNIER ENGINES.—In addition to the main thrusttors of a booster or upper stage, small rocket engines can be attached to a vehicle. Such engines are called **vernier engines** after Pierre Vernier (1580-1687), a French mathematician who invented a device still widely used today to obtain a fine fractional reading on an instrument. In recent years, the name was given to rocket engines designed for making fine velocity or attitude-control adjustments in a booster or space vehicle. Vernier engines are often mounted on the vehicle in sets of three or four, spaced widely apart for better control effect.

ATTITUDE CONTROL.—Attitude control, as we mentioned in

Chapter 1, means changing the position of a vehicle in relation to its line of flight. It may be needed to position a main engine for the purpose of thrust vector control as mentioned above, or it can be used for such purposes as aiming a rigidly-mounted camera or sensing device, aligning a solar paddle for maximum energy intake, or stopping undesirable vehicle motion such as rolling or tumbling. When low levels of thrust of brief duration are thus employed, they have no effect on vehicle direction or velocity. It is not practical to use the thrust vector control of a main engine for attitude control purposes. Vernier engines, however, have that capability. Sometimes very small rockets are used for attitude control only (Fig. 35).

Some devices of even lower thrust are used for the most delicate attitude-control adjustments. These can hardly be called "motors," although technically they might be so called. Bottled gases under

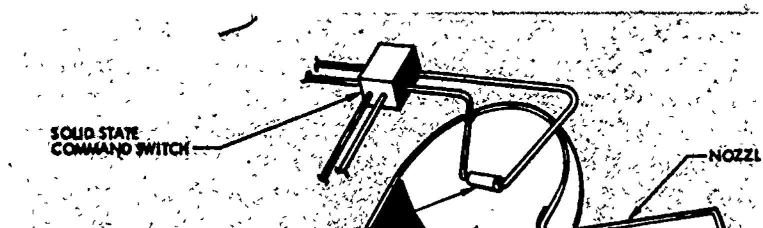


Figure 35. Small rockets are sometimes used for attitude control, as when for economic or practical reasons, it is undesirable to use the main engine for such purposes.

pressure can be vented out various exterior points on the vehicle for this purpose. A little puff here and a little puff there are enough to change attitude or steady a large but weightless vehicle. A device called a **cap pistol** features a plastic tape wound round a small cylindrical structure. In the tape are imbedded tiny pieces of solid propellant, each of which, when ignited, exerts a force said to be about equal to that of quiet human breath. The device can produce or arrest a slow rolling motion of the vehicle. Some of the low-thrust devices discussed in Chapter 4 also are used for attitude control. Such devices are much less spectacular than a 7.5 million thrust pound Saturn booster, but space progress depends upon development of means of controllable thrust at all levels.

## SERVOMECHANISMS AND COMPUTERS

Behind the rocket engine lies a system of electronic links, either through wires or radio transmission, that make it behave according to a guidance plan. The system includes **servomechanisms**—automatic devices for controlling large amounts of power by means of very small amounts of power and for automatically correcting performance of a mechanism. The word is used here broadly to mean any kind of automatic mechanism that can translate a signal into a physical action. Behind the servomechanisms lie computers, which receive, compare, and analyze information signals and relay them as command signals.

### Some Everyday Comparisons

Such systems come in great variety, and no particular one is described here. It may be helpful, rather, to consider some of the common servomechanisms or automatic control devices that surround us in our everyday lives, and compare these in a general way with space guidance mechanisms.

POWER STEERING AND FEEDBACK.—The power steering system of an automobile is an example of a servomechanism. The purpose of power steering is to reduce the human physical effort of steering. Therefore, the driver's steering wheel is not physically connected to the front wheels of a car. It is, in effect, a signal dial, like the dial of a telephone, and its function is to "tell" the steering mechanism which way to go. It does this by generating an "error" signal to indicate a mismatch between its position and that of the car wheels. Note the use of the word "error" in this description. It is not always used in the sense of "mistake" or "something wrong," but can be merely a routine or artificially-produced difference between "is" and "should be," which quickly produces its own automatic correction. As such, "error" is the essence of automatic mechanisms The signal generated by a driver's hands on the steering wheel might also be called a "command." In aerospace usage, however, **command** usually means a remote signal transmitted by radio. An automobile's power steering system also employs the principle of automatic **feedback.** The driver applies the input signal. The position of the wheels is feedback to be compared with the input to generate the error signal, and the power system redirects the wheels to "correct" the "error." Similarly in a space vehicle, electronic information flows two ways between a computer and the end mechanism such as a swiveling rocket nozzle. The feedback flow informs the computer of the change that has been made and establishes a reference for future changes. The essentials of the power steering servomechanism are shown in Fig. 36.

WASHING MACHINE AND TIMED SEQUENCE.—Another commonplace item that offers a comparison with part of an aerospace vehicle's control and guidance system is a domestic washing machine.

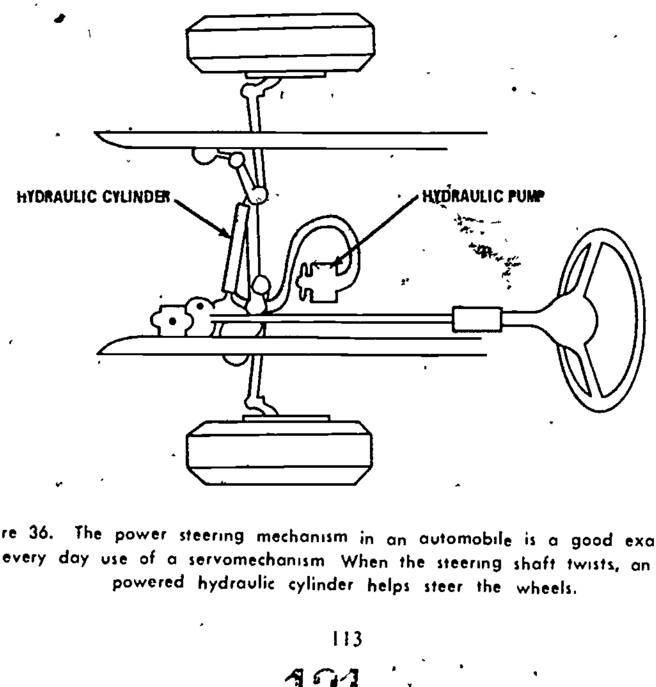


Figure 36. The power steering mechanism in an automobile is a good example of the every day use of a servomechanism When the steering shaft twists, an engine-powered hydraulic cylinder helps steer the wheels.

It follows a timed sequence of operations—so many minutes for wash, so many for rinse, and so forth. Some launch vehicle guidance systems work predominantly on this kind of timed sequence principle. With advanced knowledge of engine power and performance, vehicle weight, atmospheric density at different altitudes, and other factors, much complicated computer work is done in advance. Thus, the vehicle is programmed with a time schedule. Rate of acceleration is known; the vehicle's position in space is calculated as a matter of so many seconds of elapsed time. The sequence of commands for changing direction, engine cutoff, restart, and so forth, also occurs on a time schedule. Since the system provides for no way of correcting errors, however, it usually must be combined with inertial or other guidance systems. These systems will be discussed later.

THERMOSTAT AND ERROR SIGNALS.—One simple device, found in a great many homes, tells us much about error signals in servomechanisms—even about digital computers. A thermostat, such as governs a typical gas or oil domestic heating furnace, incorporates a thermometer. The thermostat is "programmed" by being manually set to a desired temperature. When the thermostat senses that the actual temperature has fallen below or risen above the desired temperature, it sends an error signal to the furnace. There are complex systems by which a furnace can be modulated for high and low flame, but the ordinary home system is of interest because of its simplicity. The fire has one level of intensity and responds to only two error signals: "too hot" and "too cold." By means of automatic switches, these error signals are translated respectively into "off" and "on."

Quite a few space vehicle mechanisms operate by simple "off" and "on" switching, responding to various "go" or "no go" signals. A digital computer operating on the binary number system, is really a highly complex array of "go" or "no go" circuits.

## Computers

Engineering problems more than lack of scientific knowledge delayed the beginning of the space age until the late 1950s. By the end of the '50s, two breakthroughs had been made that were to make astronautics and satellites possible. These breakthroughs were (1) the development of large booster rockets powerful enough to launch a vehicle into space, and (2) the development of highspeed electronic computers. We have already considered the importance of big boosters, and without computers, man could neither design space systems nor guide and control their operations with the needed precision.

Many types of computers are used to guide space vehicles, and some of them are quite complex. Components may be located on the ground, aboard the vehicle, or both. We shall not describe any one specific computer system here, but rather discuss the broad concepts. The principal classes of computers are analog and digital. The most useful and simple distinction for the layman to remember is that analog computers *measure* and digital computers *count*.

ANALOG COMPUTERS.—Analog computers operate from directly measurable quantities, such as voltages or electrical resistances. In some forms they might be called electronic slide rules—or a slide rule might be considered a manual analog computer. The very finest of slide rules, however, is still an estimating device which offers no fixed numerical answers. In an electronic analog computer, similar values can be represented by variable voltages, using the potentiometer principle. A simple example would be an automobile speedometer. The speed with which the car wheels turn generates a voltage comparable or *analogous* to it which registers as miles per hour on a dial. Similarly, numerical values can be represented by voltage levels on a continuous scale. For example 1 volt might represent the number 1, 12 volts the number 12, and 80 volts the number 80. In an instrument of some precision, even a value like 67½ could be represented by 67½ volts. Nevertheless, the function, like that of a slide rule, would be that of measuring or estimating rather than counting.

Two properties of the analog computer make it particularly important in support of space operations. First, the analog computer deals with continuous functions, and thus is more capable of representing physical processes than is a digital computer. Second, the analog computer can directly sense changes in physical systems without having to feed its data through an encoding device. This latter ability means the computer can be coupled directly to the output unit of an electrical sensor on a space vehicle and can perform a series of tasks based upon changes in the output voltage from the sensor.

The disadvantages of the analog computer are that its degree of accuracy is not as precise as that of a digital computer, further, the analog computer's accuracy is limited not only by the tolerances to which it can be built, but by the ability of its components to remain stable despite changes in environmental conditions and the passage of time.

Digital Computers.—Digital computers operate with distinct entities or digits rather than with continuous processes. Their accuracy depends on the size of the registers they use in performing their operations. (A computer **register** is an automatic device that keeps track of the numbers used in each computer operation.) For example, a digital computer whose registers can hold eight digits is more accurate than one whose registers only accommodate four digits.

The digital computer does not operate in a smooth, continuous process, but through a series of distinct, detailed steps. The operator must "tell" the digital computer precisely what to do in each step, no matter how trivial that instruction may seem. The list of instructions for each computer operation is called the **program**, and these programs can be very long and complex. The time it takes to prepare a long computer program can be considerable, and once written, the program is hard to change. While humans are accustomed to communicating in words, computers understand only numbers. So several "languages" have been devised to bridge the communications gap between man and machine. These languages are used to prepare the programs and are translated into digits by an intervening computer program called the **translator**. The translator also changes the machine's digital communication into program language easily understood by the human operator.

Digital computers operate under the **binary number system**, which means that they are only concerned with two digits, 1 and 0. The numbers regulate the flow of electrical current through the computer in such a way that any number of calculations may be accomplished. Depending on how the machine is programmed and for what purpose, the flow or blockage of electrical current can mean "yes" or "no," "go" or "don't go," "male" or "female," "over 21 years of age" or "under 21 years of age," or whatever else the instructions have dictated. In addition the binary number system permits almost any kind of numerical calculation, from large numbers to fine fractions.

Because they are so versatile, digital computers are used in almost every aspect of space programs, from basic design of boosters and payloads to analysis of data after the mission is completed. They monitor the status of the vehicle prior to and during launch, control the flight into orbit or deep space trajectory, and calculate de-orbit points and re-entry maneuvers.

Physical miniaturization is a very important breakthrough in computer technology, permitting finer computations in the binary system and also permitting digital computers to be carried aboard the spacecraft rather than limited to ground use. Tiny circuits can be imbedded in little pieces of plastic; transistors range downward in size to chip transistors so small that a dozen or more could be arranged on the eraser of an ordinary pencil. Numerical positions—meaning positions that will either pass or block electrical current—can be tiny conductive or nonconductive dots on magnetic tape, or on drums or disks to provide a memory bank. In a command guidance system, ground installations can house the larger and more elaborate computers, but on-board digital computers are found on all the more advanced spacecraft and launch vehicles of today. The Apollo vehicle, for instance used an onboard digital computer for flight control and navigation.

## GUIDANCE OF SPACE VEHICLES

Vehicle guidance is a process that begins with human will. In the case of an automobile or aircraft, the will is that of the driver or pilot, and can be changed at any moment. If the auto driver suddenly decides to turn left at the next intersection, or a pilot decides to change heading by 90 degrees, their manual controls allow them to implement these decisions without having the whole guidance system overhauled or reprogrammed.

In space travel as we know it today, such exercise of whim is impossible. Not only tremendous costs but the very laws of nature demand that guidance be almost completely automatic and that every journey be planned in advance to the last detail. The guidance plan is a complex mathematical problem worked out in accordance with the laws of **celestial mechanics** (as discovered by the great seventeenth-century scientists mentioned in Chapter 1 and refined by scientists of later generations). Specified orbits and trajectories must be mapped out and entrances to these chosen pathways must be exactly timed. Computers are the heart and soul of the system.

Figure 37 shows in simplified form how a computer might function during guidance of a space vehicle in flight. The sensor may monitor any number of functions or conditions of the space vehicle, such as pitch, speed, or attitude. The sensor feeds its information into the computer, where it is encoded to computer language. From the encoder, the information goes into the memory circuit, which records it for possible future reference. The information then goes into the computer's calculator/comparator, the heart of the computer, also known as the central processing unit. This unit compares the information with guidance instructions programmed into the computer earlier. If the information represents "error"—that is, if it says that what is really happening is not the same as what was supposed to happen—then the computer generates a "change" signal designed to correct the error. This change signal goes through a servocontrol, which acts on it by altering the flight controls. The process continues, with the change "feeding back" to the sensor, which monitors constantly. When the sensor gives the computer information that is no longer "in error," when the computer agrees that everything is back according to plan, the computer's "change" signals turn off.

In our discussion of guidance systems, we will relate them to the different phases of space flight, for simplicity's sake. The phases of space flight are launch, midcourse, and terminal. Each phase has its own unique problems.

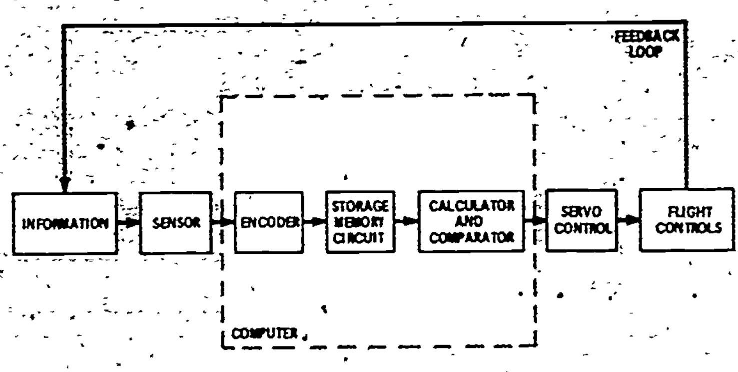


Figure 37. Greatly simplified schematic drawing shows how information flows through a computer.

### The Launch Phase

The launch phase lasts from liftoff to injection. Propulsion, and therefore acceleration, is going on constantly throughout this phase. Other factors keep changing too. Atmospheric pressure decreases with altitude, and other atmospheric effects are experienced during the early part of the ascent. Winds and turbulence force delicate corrections to maintain stability, attitude, and course. The program for an ascent into orbit begins with vertical ascent, then a roll to the desired azimuth and a slow pitchover so that the vehicle will be at the correct elevation angle for injection into orbit when the correct altitude and velocity are reached. While the booster is in the atmosphere, guidance and control commands are kept to a minimum to avoid strain on the flexible body of the booster. As a stage approaches burnout, its main engines are cut off and vernier rockets adjust the velocity to the precise burnout value desired. All of these actions create forces on which an inertial guidance system can operate.

For many purposes, launch-phase guidance may be the only guidance a vehicle receives. Just as a bullet is put on target even though it receives "guidance" only during the fraction of a second that it is still within the gun barrel, so an ICBM's ability to hit a target thousands of miles away depends entirely upon the accuracy of its launch phase guidance. Similarly, many unpowered satellites follow a prescribed orbit for a useful period of time as established by an accurate launch. *Theoretically*, it may be possible to hit within a desired target area on the moon or another planet by means of achieving the proper vectors during the launch phase. Practically speaking, however, neither deep space navigation nor precise orbital paths are possible without midcourse propulsion and guidance

### The Midcourse Phase

The midcourse phase is essentially a coasting or unpowered flight, whether it be circling the earth in an orbit or speeding toward the moon or another planet. The vehicle moves along a path established by the launch but also is affected by the laws of celestial mechanics. The vehicle is weightless and no inertial forces are acting upon it unless thrust is applied to change trajectory or orbit. If the vehicle were under continuous thrust by means of one of those electric engines described in Chapter 4, the conditions as well as the trajectory would be somewhat different, but most of the problems of midcourse guidance would be similar. In either case, some high-thrust rocket power is held in reserve for the hard pull of a correctional maneuver, if necessary.

The most basic problem of midcourse guidance is the fact that the midcourse phase is of long duration, and small injection errors increase with time. Careful navigation is therefore necessary, using tracking from earth stations or celestial guidance as a reference. One problem is that of selecting the proper time to make a correctional maneuver. The optimum time seems to be during the early part of the flight, after enough delay to determine which way the vehicle is straying and to what extent. Too much delay, however, may result in the vehicle's getting so far off course that to get it back on may require more thrust than the vehicle possesses.

### The Terminal Phase

The terminal phase is that of putting the vehicle on target or reaching a destination. It might be a landing on the moon or a planet, a rendezvous with another vehicle in orbit or deep space, or an earth reentry for a safe landing. An unmanned satellite, of course, might have no terminal phase to its flight at all. It might simply be allowed to continue orbiting after its useful life is over, until the orbit decays and the vehicle makes a fiery reentry into the earth's atmosphere. Some planetary "fly-by" vehicles continue into solar orbit or head into the sun itself. If a safe reentry or soft landing is desired, extremely accurate guidance is necessary. A guided earth reentry demands precise adjustment of velocity and attitude for entrance into a narrow **reentry corridor** only about 8 to 20 miles deep (Fig. 38) and at the proper angle so that the blunt ablative heat shield is in a position to absorb the heat of atmospheric friction and decelerate the vehicle. Overshooting this corridor means going into orbit again or bouncing off the earth's atmosphere and flying out into space. Undershooting it means too steep a descent and total destruction.

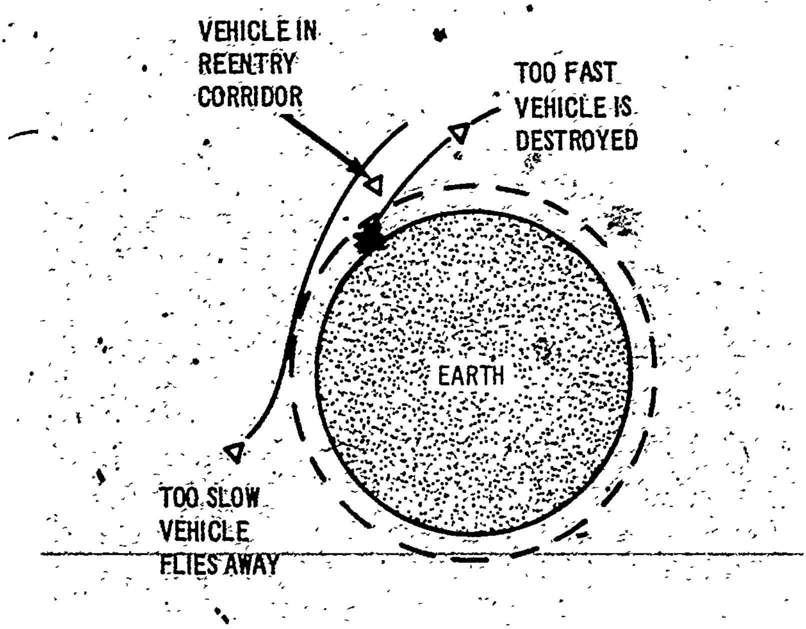


Figure 38. Manned spacecraft returning from outer space had to shoot precisely to hit the reentry corridor through the Earth's atmosphere.

## TYPES OF GUIDANCE SYSTEMS

If this discussion were to include guidance systems for all kinds of rockets and missiles as well as for launch and spacecraft, the list would be quite long and complicated. Most of these would be military weapons of varying ranges. Most would operate with aerodynamic rather than thrust vector controls, being equipped with movable airfoils (called elevons or ruddervators) and sometimes wings. Guidance systems would include infrared homing or heat seeking, radar homing, radar command, radio command, television, and even one called map matching, by which a programmed map is compared with radar signals as the missile flies along a planned route. Since we are limiting our discussion to launch and space vehicles, however, we need to consider only three basic types of guidance systems, which are used singly or in combination: command, inertial, and position fixing (celestial).

**Command Guidance**

Perhaps the type of space guidance system that seems most practical at first glance is the command guidance system. Like all the others, however, it has its advantages and disadvantages. In such a system, ground stations continuously track the vehicle by various methods, including optical telescopes, radar, radio, and other sensor beams. Ground based computers continuously compare the vehicle's actual and programmed tracks and generate correction signals when errors are detected. These are relayed to the vehicle as command signals. Command guidance can be useful in launch, midcourse, and terminal phases of space flight (Fig. 39).

Certain disadvantages of command guidance must be mentioned. One is the fact that the ground system must be very elaborate, expensive, and sometimes deployed world wide. A single ground station located at the launch site would not be able to complete the launch phase if dependence were entirely on command guidance; the vehicle, flattening its trajectory as it ascends, would be over the horizon before booster burnout. Another station, perhaps a ship at sea, must pick up the track, and still others in turn, located around the world, track the vehicle in order to determine its need for guidance. The fact that the earth rotates

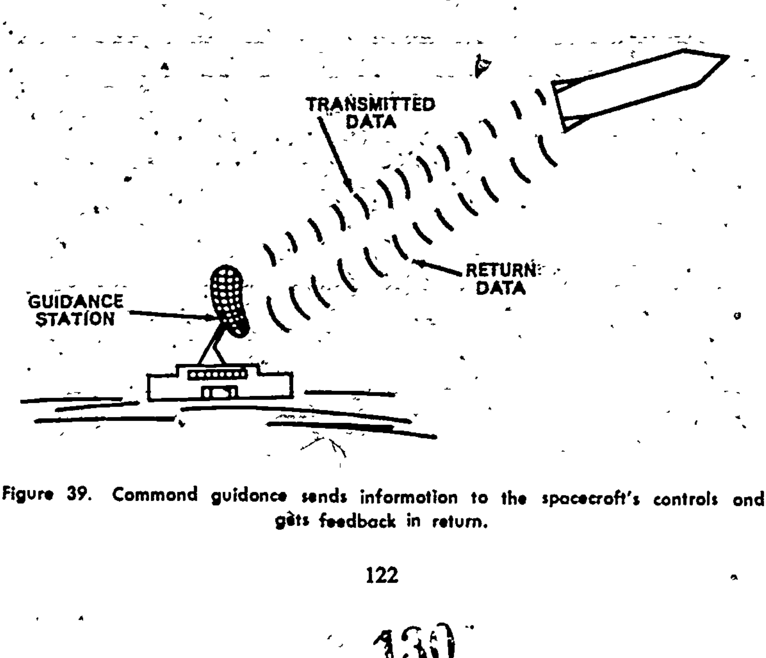


Figure 39. Command guidance sends information to the spacecraft's controls and gets feedback in return.

requires that stations be deployed around it to follow a vehicle bound for the moon or a planet as well as one in earth orbit. In peacetime, the cooperation of many friendly nations must be secured to complete a tracking and guidance network (Fig. 40). In wartime (assuming the system might be useful for military purposes), the system would not only be vulnerable to attack, but its very flow of radio and radar signals through aerospace could be easily jammed or confused by an enemy.

A constant problem of command guidance is distance. Generally, communications are reliable within **cislunar space** (literally "this-side-of-the-moon" space—out to about 250,000 miles). Signals get weaker and interference increases at interplanetary ranges. Nevertheless, unmanned flights to Mars and Venus have been accomplished with the help of command guidance.

## Inertial Guidance

Some of the disadvantages of command guidance mentioned above are overcome by an inertial guidance system. Long range military missiles use it because it is completely self-contained and broadcasts no signals for an enemy to detect or jam. In space flight, inertial guidance is especially useful during the launch phase. It is less useful in the midcourse phase except as an attitude reference device, but elements of inertial guidance can be used with other forms of guidance in all phases of space flight.

Being self-contained aboard the vehicle, an inertial guidance system uses no ground components after launch. Furthermore, it operates without knowledge of or reference to the outside environment except for initial data programmed into it before launch. In Chapter 1, we defined inertia as the phenomenon described in Newton's First Law of Motion: the tendency of a moving body to stay in its path and maintain the same speed, resisting forces that attempt to change its direction and velocity. Inertial guidance is based on this law.

A common experience of inertial force is that of a passenger in an automobile, who feels himself pressed to the seat back when the car accelerates, drawn forward when the car slows down, and pulled sideways when it rounds corners. He also experiences up-and-down sensations when the car passes over a hump in the road. Thus inertial forces in all dimensions are sensed.

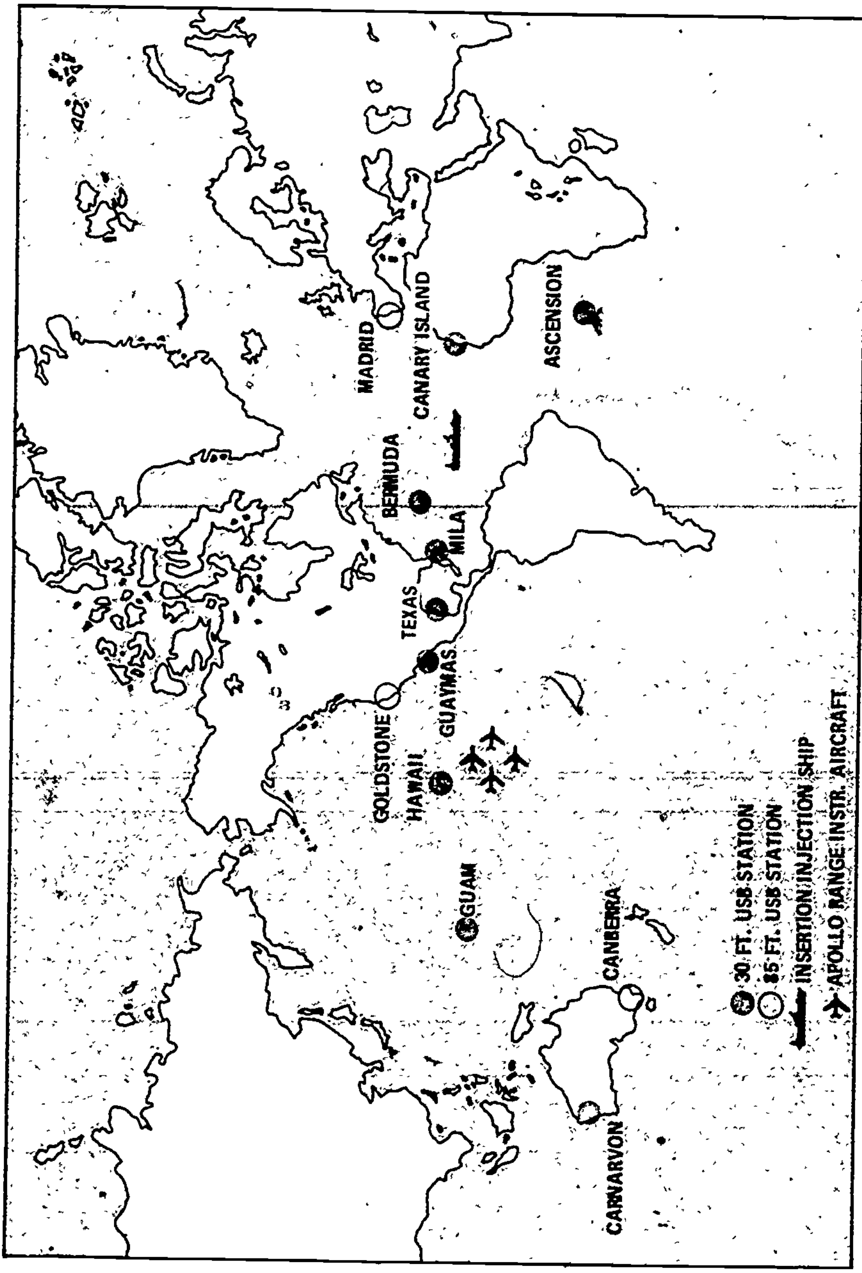


Figure 40. The National Aeronautics and Space Administration's manned space flight network

*as long as direction or velocity is changing.* If the car is traveling smooth and level on a straight road at a constant velocity, all inertial forces are zero and no sensation of movement is felt.

The writer of a TV crime or spy thriller might imagine a situation in which a blindfolded passenger in an automobile cleverly figures out where his kidnappers are taking him by making mental notes of his inertial senations as the car speeds up, slows down, and turns right or left. If this notion is too far fetched even for a TV writer, it is nevertheless true that a launch vehicle under inertial guidance is "blindfolded" and "knows where it is" by measuring the pulls and tugs of inertial forces.

Two essential components of an inertial guidance system are: (1) **accelerometers** which measure acceleration or gravitational forces that cause acceleration; and (2) **gyroscopes** to indicate the vehicle's orientation. On some vehicles, the accelerometers are mounted on a platform stabilized by means of gyroscopes. Sometimes the accelerometers themselves are gyroscopes, although other means of measuring forces may be used.

ACCELEROMETER.—The type of accelerometer called **spring mass** provides the simplest illustration of the accelerometer principle. Think of a weight or mass suspended within a box on two springs. If the box moves and accelerates, the inertia of the mass will cause it to lag behind. If the box slows down, the mass will push forward. If the box continues to move at a steady velocity, the tension of the springs will keep the mass at a neutral or zero position. Attach a pointer to the mass and a calibrated scale along one side of the box, and the device can actually measure positive and negative acceleration along the line of movement. The spring-mass principle is good for illustration but is too crude and inaccurate for space vehicle use. Another method suspends a weight in a lubricating medium and measures its movement by a magnetic coil. Still another employs the gyroscope principle, described below.

Whatever the means of measuring the acceleration, this information must be integrated by computer to provide guidance. Digital computers perform this function, in the more advanced space vehicles of today. Through servo-mechanisms, the computer actuates both attitude and thrust controls.

However complex the system behind it, an accelerometer can measure acceleration along one axis only. To measure inertial forces along another axis, another accelerometer is needed. Three accelerometers, however, are enough. When these are mounted in such a way that no two axes are parallel, they can be integrated to provide information on any force applied in any dimension. The three accelerometers, of course, must be mounted on a platform that maintains rigidity in space. Therefore, the gyroscopes that maintain proper reference for the accelerometers are as important as the accelerometers themselves.

GYROSCOPE AND THE INERTIAL PLATFORM.—A spinning top will not tip over as long as it is spinning, and a bicycle can be balanced on two wheels as long as it is in motion. It is this tendency of a whirling mass to be **spin stabilized** that is the basis of the gyroscope. When the **gyroscope,** a heavy wheel similar in principle to a spinning top, is mounted on a frame which can swing freely in one dimension on gimbals, it is called a single-degree-of-freedom gyroscope (Fig. 41). One pair of gimbals can be mounted on another to give the gyro two degrees of freedom. Spinning gyros maintain what is called **rigidity in space.** When located on earth, they do not remain spinning in an upright position but appear to lean or precess more and more over a period of hours. This is an illusion. Actually, the earth is rotating and the gyro is remaining

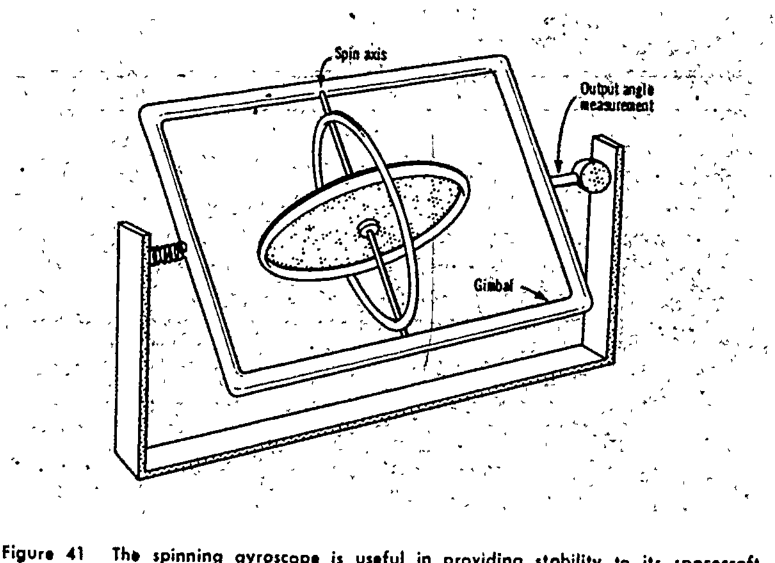


Figure 41 The spinning gyroscope is useful in providing stability to its spacecraft. This is a single-degree-of-freedom gyroscope.

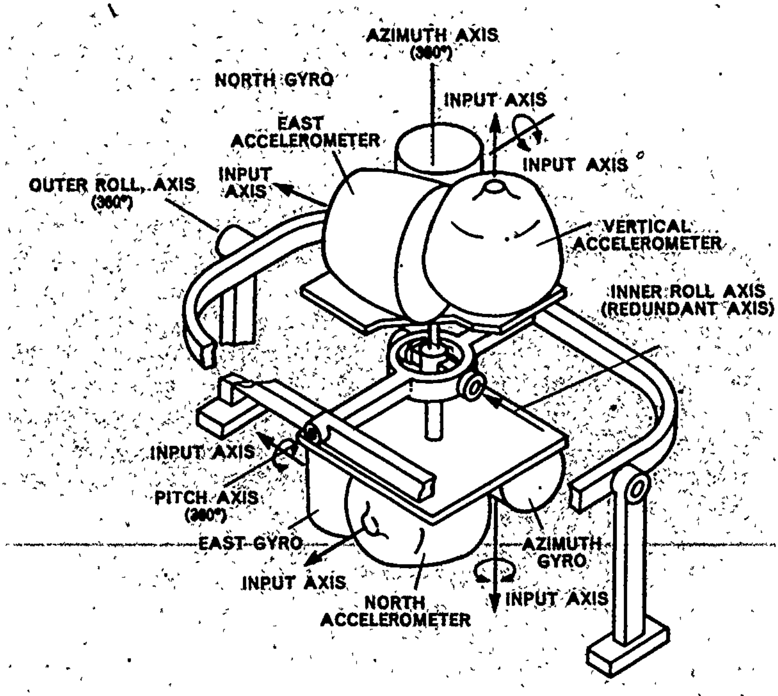


Figure 42. Gyroscopes mounted in an inertial platform help to stabilize the space vehicle.

in the same attitude *in space*. On a space vehicle, gyros can be mounted to provide signals to keep a platform mount rigid in space, and thus provide a stable reference platform for accelerometers. Besides providing a platform for accelerometers, the gyros also perform an attitude control function of their own. Small sensors mounted at the gimbals can measure the angle of precession and thus provide data to attitude control thrustors. Thus the platform not only keeps itself stable but also helps stabilize the vehicle (Fig. 42).

USES OF INERTIAL GUIDANCE.—A good many technicalities have gone unexplained in the foregoing description, and various problems have not been mentioned. Nevertheless, we have indicated that it is possible for a vehicle to "feel" its way through space and know its position. Inertial guidance is effective during the launch phase, because during that phase the vehicle is continuously accelerating. During the midcourse phase, as long as unpowered flight is maintained, an inertial guidance system cannot provide full guidance to the vehicle. When corrective maneuvers must be made, however, thrust forces come into play temporarily, and inertial guidance assists other guidance systems to accomplish the correction.

## POSITION FIXING OR CELESTIAL NAVIGATION

We have described two guidance systems, each of which provides the controllers of a vehicle in space with knowledge of that vehicle's **position in space** as a necessary prior step to directing the vehicle's further movement in space. It would seem likely that time honored methods of establishing a ship's or aircraft's location by reference to the sun and stars could also be used for guiding or navigating space vehicles.

Fixing the position of a ship at sea by celestial observation is essentially a two-dimensional problem, for the ship is located on the surface of an ocean. Even celestial aircraft navigation is still essentially a two-dimensional problem, since it is that of determining the position of the aircraft on a map. A sextant or similar sighting instrument, aimed at the sun or at a certain known star, provides information on latitude and local celestial time. Comparison of local celestial with Greenwich mean time (accomplished since old sailing vessel days by a highly accurate clock called a **chronometer**) provides the means of locating one's longitude on a rotating globe.

Celestial navigation in space is a three-dimensional problem that has interesting complications. One problem is that only one arbitrary time can be used, not a comparison between Greenwich and local time, which is a function of earth's rotation. The Apollo missions, for instance, constantly referred to "time into mission"—that is, time since launch. That was the "arbitrary time" used for all purposes requiring a time factor. Another problem of celestial navigation is that there is no gravity by which a space vehicle can establish a plane of reference called "horizontal," from which it is possible to measure the angle of elevation of a star. Another is the fact that a space vehicle's attitude need not be related to its line of travel. Still another problem is that the stars, with the single exception of the sun itself, are so distant that any kind of triangulation or reckoning by measurement of angles between them would only establish the vehicle's position as "somewhere in the solar system" but with hardly any greater degree of accuracy. Even the sun is too distant for position fixing to the desired degree of accuracy, without reference to a near body.

Accurate position fixing within the solar system, especially in cislunar space, would have to be done with the aid of *near bodies*—the earth, the moon, or the nearest planets. This requirement introduces a new difficulty, for the near bodies themselves are in motion. A complex table showing location of earth, moon and planets in three-dimensional space at different times must be programmed into the computer system of any space vehicle that intends to use celestial navigation.

Difficult as it may be, however, it is possible to locate a vehicle in space by celestial observation. Here is how it can be done.

Assume you are aboard a vehicle somewhere in cislunar space, and you wish to pinpoint your location in order to make sure you are following your programmed course. With accurate optical instruments aboard the vehicle, you take a line of sight on the center of the earth and another line of sight on a bright star and measure the angle between them. Anywhere in cislunar space, one line of sight to a given star would be—practically speaking—parallel to another. The angle of sight to earth would vary with the vehicle's position. But there are many positions, near and far from the earth, where the angle between earth, vehicle, and star would measure the same. All these possible positions would fall along the surface of an imaginary cone with its apex at the center of the earth. The apex angle of the cone is twice the supplement of the angle between earth and star. (A supplement is the amount by which an angle falls short of 180°.) The vehicle is now located somewhere on that cone, called a **cone of position** (Fig. 43). Obviously this observation is not enough.

The next step is to pick another star and establish a second cone of position, also with its apex at the center of the earth. The two cones will intersect along two lines. The vehicle is now located somewhere along either of two **lines of position** (Fig. 44). A third star and cone of position from the earth would answer the question of which one of the two lines is the correct one; but as a rule this observation would not be necessary. One of the two possible lines of position would be so far off the programmed course that it would be disregarded. You still have not

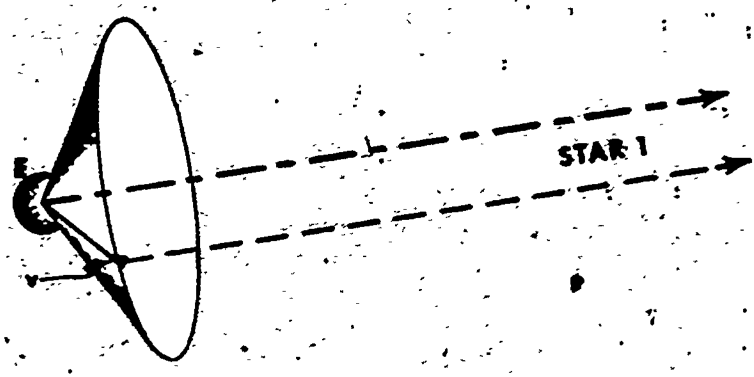


Figure 43. The cone of position, the first step in celestial space navigation, is based on sighting lines drawn from space vehicle to earth and from space vehicle to a distant star.

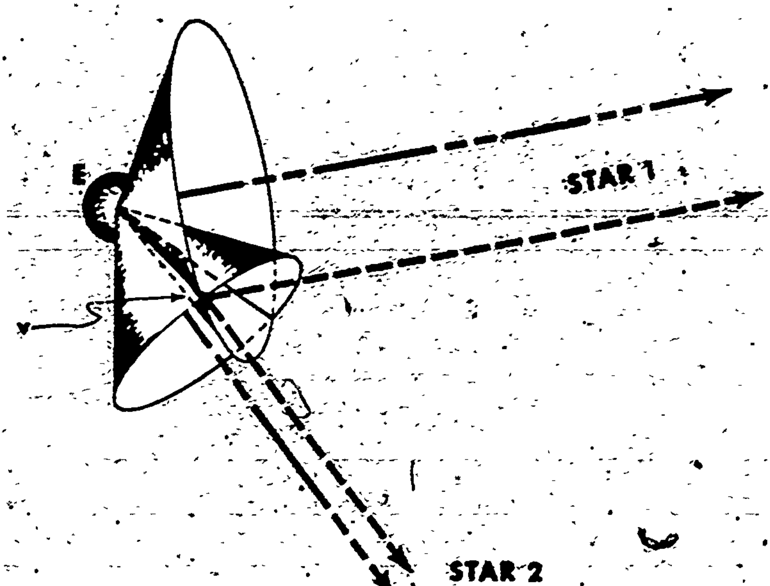


Figure 44. Constructing a second cone of position is the second step in celestial position fixing. Lines extending from the earth through the point where the cones intersect are called lines of position.

solved the problem of where you are, however. The vehicle is not located in space until it is known exactly how near or far from the earth it is along that line of position radiating from the earth.

If you now sight to the moon and a star instead of the earth and a star, and establish a cone of position with apex at the moon, the problem is solved. The point where the established line of position radiating from the earth intersects the new cone radiating from the moon is the vehicle's location in three-dimensional space (Fig. 45).

The method just described has some serious drawbacks. Since the vehicle would be moving at a high velocity, the three observations would have to be taken simultaneously. The mathematical computations, furthermore, would be a rather tough problem even for a sophisticated computer. Therefore, a more practical short-cut method is preferred. We have already mentioned the use of a programmed or pre-computed course as a shortcut for making a choice between two lines of position. It is also possible to take only one cone of position at a time and compare successive cones with a precomputed course to determine how well the vehicle is staying on course and how much correction might be needed

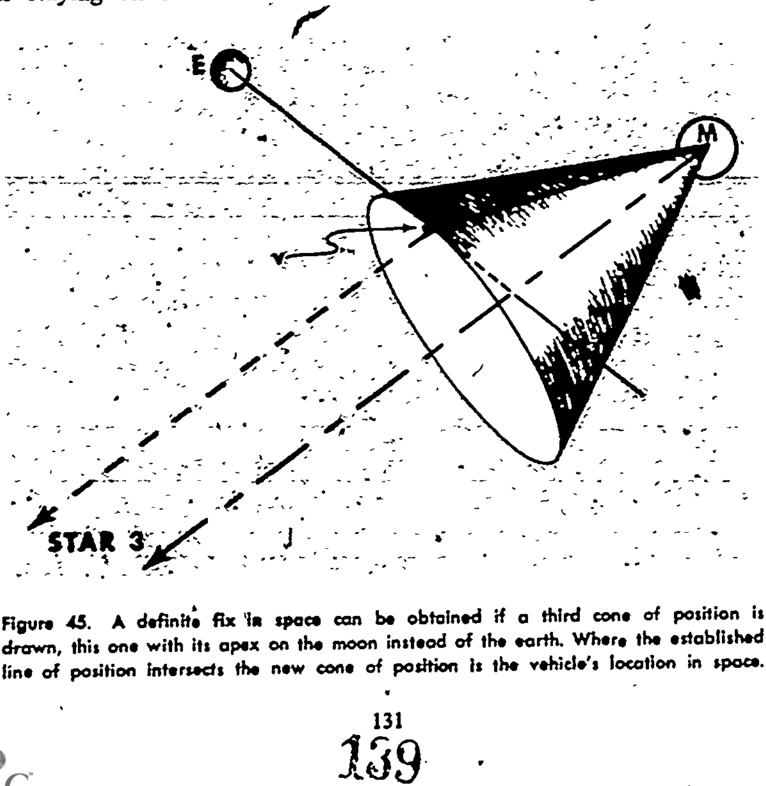


Figure 45. A definite fix in space can be obtained if a third cone of position is drawn, this one with its apex on the moon instead of the earth. Where the established line of position intersects the new cone of position is the vehicle's location in space.

To be still more practical about it, midcourse guidance of a vehicle on a lunar or interplanetary journey would not be done purely by celestial observation nor purely by comparison of actual and precomputed celestial observation. It would involve elements of inertial and command guidance as well.

## SUMMARY

Directing the movement of a vehicle in space is a matter of control—the actual physical steering of the vehicle—and guidance—the use of automatic means of making the controls respond to human will to reach a given destination. Sometimes the term navigation is used, although that is usually understood to mean position fixing as a step in guidance.

However complex a control and guidance system may be, it ends at a rocket nozzle. Thrust and thrust alone can change or correct the motion of a space vehicle, either by the way it is aimed (thrust vector control) or its output regulated.

Of particular importance is the matter of thrust termination shutting off the motor at a precise moment when a desired burnout velocity has been achieved. Liquid-propellant motors can do this more efficiently than solid-propellant motors, but an accurate sequence, taking residual burning into account, can be determined for either type of motor.

Thrust vector control is achieved either by rotating the whole engine on gimbals, the usual method with liquid-propellant engines, or by various means of deflecting the thrust that are practical for liquid or solid motors. In addition to their main engines, space vehicles are usually equipped with auxiliary or vernier engines for either thrust vector or attitude control. Finer adjustments can also be achieved with even smaller devices capable of changing attitude in vehicles that may have considerable mass but are weightless in space.

Behind the engines and devices capable of physically controlling a vehicle are servomechanisms and computers which link them with guidance systems. These are analogous to some of the common automatic devices encountered in everyday life. Power steering of an automobile works by error and feedback. A washing machine works by timed sequence. A thermostat provides an example of simple "off" and "on" response to an error signal. A space vehicle possesses numerous mechanisms that work on the same principles and in turn are regulated by computers.

The two basic types of computer are the analog and the digital. The analog can perform mathematical functions similar to those of a slide rule, measuring quantities by variable voltages. The digital deals in fixed numerical sums, operating on the binary principle, using conducting and nonconducting positions to indicate 0 and 1. Miniaturization of circuits as well as memory and storage devices permits a wide range of mathematical operations to be accomplished in a tiny fraction of a second. Computers on board a space vehicle process information picked up from a sensor and relay it to servomechanisms, which operate the actual controls and feed back information from the end mechanisms.

Different guidance systems are effective in different phases of a space flight. The three phases of space flight are the injection phase, lasting from liftoff to the point where the vehicle has achieved the desired orbital velocity and is placed in orbit; the midcourse phase, which is mostly a coasting or unpowered flight with occasional uses of propulsion to correct error; and the terminal phase, in which the vehicle closes upon its target or makes a safe reentry into the earth's atmosphere.

Command guidance is effective in any phase of space flight, since it operates by tracking the vehicle from the ground, comparing the actual with the programmed track of the vehicle, and generating error signals to bring it back on course when necessary. One of its disadvantages is costliness, since a worldwide network of tracking stations is often necessary to follow a space vehicle either in orbit or on a moon or interplanetary flight. Another disadvantage is vulnerability, either to enemy attack, enemy jamming, or natural phenomena that cause disturbances in communications.

Inertial guidance is especially effective in the injection phase, which is characterized by sustained acceleration, providing the inertial forces on which such a guidance system can operate. An inertial guidance system locates and guides a vehicle by "feel," computing velocity and position by measuring the tug of inertial force of the vehicle. The two basic components of the system are the accelerometers which measure the forces and the gyroscopes which provide a means of stabilization for the accelerometers and also help stabilize the whole vehicle. Inertial guidance is also useful in the midcourse phase for attitude control and, during those times in the midcourse phase when thrust is on, for correctional maneuvers.

Celestial or position-fixing guidance is a more difficult problem in space than it is for aircraft or ships at sea. A three-dimensional fix in cislunar or near-interplanetary space calls for reading angles between fixed stars and near bodies such as the earth, moon, or a neighboring planet. Since the near bodies are in motion, complex tables of their locations at different times must be programmed into the vehicle's computers. A program of the correct trajectory is also necessary. The fix itself is a three-step process of locating the vehicle on a cone, a line, and finally a point. A shortcut procedure is preferred by which the cone angle is compared with the programmed route in a series of observations.

## WORDS AND PHRASES TO REMEMBER

accelerometer
analog computer
binary number system
burnout
cap pistol
celestial mechanics
chronometer
cislunar space
command
cone of position
control
decay
digital computer
feedback
guidance
gyroscope
injection
line of position
navigation
near body
program
register
reentry corridor
sensor
servomechanism
spin stabilization
spring-mass principle
supplement
thrust termination
translator
vernier engine

## QUESTIONS

1. **Explain the difference in meaning between control, guidance, and navigation.**
2. **Upon what single factor does all control of a space vehicle depend?**
3. **Explain why the word "burnout," although commonly used to mean the end of the thrusting life of a rocket stage, may be inaccurate.**

4. How is thrust vector control related to a vehicle's center of gravity?

5. What are some of the reasons why precise attitude control of a vehicle may be necessary?

6. Compare a control maneuver of a spacecraft to a turn by an automobile equipped with power steering.

7. Why is timed sequence alone sometimes inadequate as a method of space vehicle guidance?

8. What is the difference between an analog and a digital computer?

9. Which form of guidance is most effective during the launch phase of a vehicle? Why is its effectiveness more limited in the midcourse phase?

10. What does the word "inertial" mean in "inertial guidance"?

11. Explain the function of gyroscopes in an inertial guidance system.

12. Why is it not possible to sight entirely on fixed stars in celestial guidance?

13. How is a cone of position reduced to a line of position?

## THINGS TO DO

1. Investigate more thoroughly the binary number system. Find out how numbers are represented and how you can "read" a number that is represented in the binary code.

2. Take a toy gyroscope and use it to study spin stabilization and precession

## SUGGESTIONS FOR FURTHER READING


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THIS FINAL CHAPTER again takes up the subject of celestial mechanics touched upon in Chapter 1 to describe the interplay between these natural forces and the man-made forces of propulsion. The basic types of space flight are described in order of increasing magnitude: suborbital trajectories, earth orbits, lunar flights, and interplanetary flights. After completing study of this chapter, you should be able to do the following: (1) explain what is meant by burnout velocity requirement and total velocity requirement; (2) explain the reasons why all space vehicles from ICBMs to interplanetary vehicles must follow limited pathways rather than navigate freely; (3) trace on a world map typical satellite ground tracks and explain the reasons why they take the form they do; (4) describe the basic maneuvers of the Apollo mission; and (5) compare the heliocentric velocities required for a vehicle to reach Mars and Venus.

NO STUDY of propulsion, control, and guidance of space vehicles would be complete without some consideration of nature's propulsion, control, and guidance. By these we mean the gravitational forces of the sun, earth, other planets, and moons which supply the main power and map out the main pathways by which man-made vehicles can move purposefully toward a destination in solar-system space. We touched upon this subject in Chapter 1, when we set forth Newton's Laws of Motion and Kepler's Laws of Planetary Motion and suggested some of the ways in which these laws of celestial mechanics affected space travel. Subsequent chapters in this text then dealt with the devices man has invented for overcoming these natural forces—engines of immense power for injection into and movement within space, and control and guidance systems of amazing sophistication for directing vehicle movement in space. Now we return to celestial mechanics to learn more about the interplay between natural and man-made forces in accomplishing space missions.

"Overcome" is perhaps the wrong word to use in describing how man can deal with gravitation. "Submit" is more accurate but the submission must be skillful. A vehicle in a gravitational field in space is like a frail canoe on a swift river. To make the analogy a little more accurate, assume that the canoe is equipped with a light outboard motor fueled with a cupful of gasoline. It lacks the power and fuel to go upstream. Even reaching a point on a bank directly across stream may be impossible. The canoe, nevertheless, can make best use of its little motor and limited fuel supply in maneuvering downstream. It can use its motor to evade rocks and snags, choose the more rapid or the safer channels, and reach a chosen destination on either bank, as long as the destination is located downstream. It must to some extent "fight" the river current but also submit to it to get where it must go.

The art of harmonizing man-made power and control with celestial mechanics is an endlessly complicated subject. In this final chapter let us merely suggest some of the problems and peculiarities of different kinds of space flight. We shall consider in turn suborbital trajectories; earth orbits, transfers, and ground tracks; moon flights; and interplanetary flights. First, however, let us consider a basic peculiarity of all space flight called velocity requirements.

## VELOCITY REQUIREMENTS

A **velocity requirement** in space terminology, means the velocity required *in order to travel a certain path.* Here on earth, the notion of such a velocity requirement may seem peculiar. On the highway, your destination may be 100 to 1,000 miles away, but you can take as much or as little time as you wish without fear of falling short of or overshooting your target. An airplane must achieve a certain velocity in order to stay aloft, but it, too, within broad limits, can vary its speed without changing course. In space, on the other hand, *how fast* you go determines *where* you go. To reach the moon in the shortest possible time demands the complicated art of plotting the best trajectory to a moving target, then applying exactly the amount of thrust needed to be injected into the chosen pathway. To circle the globe in one hour instead of the present minimum of about 90 minutes is an apparent impossibility "Pouring it on" would only take the vehicle into a higher orbit and make the trip longer. The velocity requirement in this case is the velocity required to *reach* an orbital altitude. When we recall Kepler's Laws, however, we realize that the higher the orbit, the slower the velocity in orbit. Again we can see how the laws of celestial mechanics are one set of speed laws that are strictly enforced with or without space policemen.

### Burnout Velocity Requirements

The accompanying table (Fig. 46) represents burnout velocity requirements for different types of missile and space flights. The table is considerably simplified, and perhaps we had better mention what some of the complications we have omitted are. One is that burnouts could be timed for various altitudes; here we have indicated them all as occurring at 100 nautical miles. We are ignoring for the moment the possibility that the required velocity could be more gradually acquired or some of it acquired by midcourse boost. Another complication is the factor of the rotation of the earth; here we have indicated a non-rotating earth. It would be more realistic, of course, to allow for earth rotation, but to do so would require a much longer and more complicated table. Any missile or vehicle being launched into space in a generally eastward direction will get a free boost from the spin of the globe. Just how much of a free boost would depend upon two things: the latitude of the launch site (a site near the equator, of course, moves faster than a site near one of the poles), and the exact direction (azimuth angle) of the launch.

Despite these oversimplifications, the table should be useful to provide the reader with a general notion of how much speed is required to move various distances into space. There will be further references to this table in this chapter. Meanwhile, glance over it, and ponder some of its oddities—such as why it takes more energy to "fall" into the sun than to escape the solar system.

### Total Velocity Requirements

In planning a space mission, it is necessary to calculate *total* velocity requirements. The resultant figure, in feet per second, represents the adding together of all the velocity requirements for all stages of the mission. It does *not* represent the rate of speed at

## BURNOUT VELOCITY REQUIREMENTS

(Burnout velocities at altitude of 100 nm, assuming a non-rotating earth)

| *Trajectory or orbit* | *Feet per second (nearest 100)* |
|---|---|
| BALLISTIC MISSILES: | |
| 1,000 nm range | 12,200 |
| 5,000 nm range | 22,600 |
| 10,000 nm range | 25,400 |
| SOUNDING ROCKETS: | |
| 1,000 nm altitude | 16,300 |
| 10,000 nm altitude | 31,000 |
| EARTH SATELLITES: | |
| 100 nm orbit* | 25,600 |
| 300 nm apogee** | 25,900 |
| 1,000 nm apogee | 27,000 |
| 10,000 nm apogee | 32,200 |
| 20,000 nm apogee | 33,900 |
| 100,000 nm apogee | 35,600 |
| LUNAR MISSIONS: # | 35,800–36,200 |
| EARTH ESCAPE: | 36,200 |
| INTERPLANETARY: ## | |
| Mars | 37,400–38,900 |
| Venus | 37,600–39,400 |
| Mercury | 41,000–47,900 |
| Jupiter | 45,700–46,800 |
| Escape solar system | 53,900–54,600 |
| To Sun | 99,900–105,700 |

* Approximate circular orbit.
** All apogees assume burnout, injection and perigee at 100 nm altitude.
\# Range of velocities given for transfer times from 90 to 50 hours.
\#\# Velocity ranges assume minimum energy trajectories.

Figure 46. Burnout velocity requirements for different types of missiles and space flights.

which the vehicle travels at any one moment in its journey but would be in excess of that rate. All the velocities in such a sum would not be in the same direction. Nevertheless, the sum is useful in computing the propellant requirements for a given weight and payload. The negative $\Delta V$ of retrothrust or the angular $\Delta V$ of a change of course requires energy just like the positive $\Delta V$ of acceleration. For example, the total velocity requirements for a round trip to the moon might be figured this way: injection into trajectory, 36,000 fps; braking for soft landing on moon, 8,700 fps; escape from moon (same as soft landing), 8,700 fps; return to earth, 0 fps (a free ride provided by earth gravitation); braking for soft landing on earth, 0 fps (assuming no retrothrust for aiming into reentry corridor, and the atmospheric cushion providing the free braking); total velocity requirement, 53,400 fps.

Velocity requirements, therefore, might be explained as requirements for man-made velocity needed for catching the free rides offered by celestial mechanics. Now let us consider the special problems of different types of trajectories and orbits.

## SUBORBITAL TRAJECTORIES

Two kinds of suborbital trajectories are indicated in Figure 46: ballistic missile flights, and sounding-rocket flights.

### Ballistic Missile Flights

The word "ballistic" means "bullet-like," and in some ways the flight of a ballistic missile resembles that of a bullet from a gun. As long as it is in the barrel of the gun, a bullet has energy behind it, is accelerating, and is being "guided" by the physical restraint of the metal tube surrounding it. Once it bursts from the muzzle, it is in many ways like a missile or space vehicle following a path determined by two "vectors"—the direction and speed imparted by the "launch" and the direction of the force of gravity (we can ignore wind, friction and other effects of atmosphere).

In general, any missile that has a range of several hundred miles or more, rises above the earth's atmosphere in its trajectory, and is designed to reach its target in the shortest time possible, is a long-range ballistic missile, and it must obey certain laws in its flight.* Such a missile cannot be under continuous propulsion and guidance during the entire course of its flight. Its vectors, like those

*These conditions exclude a number of long-range aerodynamic unmanned vehicles such as the Nike Hercules, Mace, and the now-obsolete Bomarc and Snark—which had intercontinental range but flew through the atmosphere at subsonic speed, really an unmanned airplane. On the other hand they include the Minuteman and Titan of the Air Force as well as the Army's Pershing and the Navy's Polaris and Poseidon.

of a bullet, are established by boost propulsion and guidance (which is probably inertial). Its burnout will occur well below the top of its trajectory. The rest of its flight, like that of an orbiting space vehicle, is unpowered and determined by the force of gravitation. It will describe a high, arching trajectory toward its target, possibly reaching a peak of several hundred miles above the surface of the earth. The path of the reentry portion of the flight will be affected by atmosphere, and the warhead must be designed to withstand the heat of atmospheric friction on reentry.

As Figure 46 reveals, the launch velocity of a ballistic missile is less than that required for any orbit, although in the case of a missile with a 10,000 nautical-mile range, it is only a little less. The missile is also injected at a higher flight path angle than the horizontal angle that is usual for orbital injection. Lacking the velocity to clear the earth, it falls back to earth along a path determined by gravity. If it could continue falling—that is, follow an imaginary path within the sphere of the earth—it would fall faster and faster to a perigee point (the point at which the orbiting vehicle is closest to earth), describe an imaginary ellipse around the center of the earth, and be carried by its own momentum right up through the earth back to the point of its injection. This trajectory is, of course, impossible, but the fact remains that the actual flight of the missile does describe the exterior portion, at apogee (point on orbit farthest from earth), of such an imaginary orbit around the center of the earth (Fig. 46). The trajectory is a section of an elliptical flight path and *the plane of this ellipse must pass through the center of the earth*. Therefore, the missile's **ground track**,—that is, the route of its trajectory projected downward and plotted on the surface of the earth—would be a part of a great circle, somewhat modified by the effect of earth rotation.* The missile could not follow a trajectory due east or due west along some parallel of latitude other than the equator (which is a great circle). Nor could it follow an eccentric or irregular path designed to fool an enemy defense system.

These facts tell us two things about ballistic missiles. One is that propulsion and guidance are available to inject a missile into a tra-

*To avoid unnecessary complications, we are assuming throughout this chapter a perfectly spherical earth with such perfectly balanced mass that its geographic center and center of gravity are one. Actually, the earth is slightly flattened at the poles, is slightly pear-shaped, and has irregularities within its mass to dislocate its center of gravity as sensed at various points. These effects are very slight, but enough to cause errors in missile and spacecraft flights. The mathematics for their correction are extremely complex.

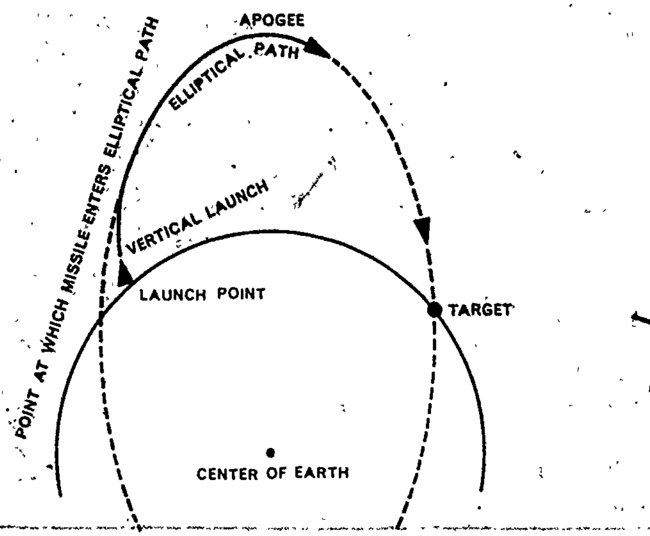


Figure 47. If it could be extended through the earth, the trajectory of a ballistic missile would complete an elliptical path.

jectory toward any target on earth with great accuracy. The second is that, since the route the missile must fly is predictable, defense measures can be taken against it.

Aside from military matters, we have also introduced two facts applying to all kinds of space flight—whether these are suborbital missile flights, earth orbits, or moon or interplanetary flights. (1) *They are either circles, ellipses, parabolas, hyperbolas, or portions thereof. (2) The plane of the flight path must pass through a center of gravity, whether of the sun, the earth, another planet, or a moon.*

## Sounding Rocket Flights

The purpose of a sounding is scientific. Instruments carried aboard a vehicle are designed to observe and measure various natural phenomena at different altitudes above the surface of the earth and transmit these data to ground observation stations by radio. After reaching its maximum altitude, the vehicle simply falls back and is allowed to make an uncontrolled reentry into the atmosphere and burn up.

The launch velocity requirements of such a vehicle are of interest, for these are requirements to reach a certain distance from the Earth *without* going into orbit. As the two examples shown in Figure 46 indicate, such a launch velocity can be either less than or more than the minimum required to put a vehicle in orbit. That for 1,000 nautical miles is definitely less. Thus, if a rising vehicle achieves a burnout velocity of 16,300 fps at a height of 100 nautical miles, it will continue to coast upward to a height of 1,000 nautical miles before its upward momentum is reduced to zero by gravity. On the other hand, the launch velocity requirement for reaching 10,000 nautical miles is quite high, 31,000 fps. An equal velocity in a different direction could put a vehicle into a high orbit, thousands of miles above the surface.

Why does this vehicle not go into orbit? The reason is that a sounding rocket is injected at a very high angle and does not have the horizontal velocity needed to put it in orbit. Like any other sounding vehicle, it eventually reaches a point where gravity overcomes its upward momentumh, and it will return to earth. Its trajectory is not necessarily straight up and down but is rather like a high, narrow arch, with a return path that would not carry it beyond the earth. If the complete path of the sounding rocket trajectory were plotted, it, too would describe an extremely narrow ellipse within the earth around the center of earth's mass.

It is also interesting to note that it does not require ten times as much velocity to reach 10,000 miles as it does to reach 1,000 miles but less than twice. The grip of earth gravity weakens with distance.

Some economic factors can also be noted. Since the sounding-rocket velocity for 1,000 miles is suborbital, it is the cheapest way of reaching such an altitude. Using a sounding rocket to reach a height of 10,000 miles, however is questionable; and for reaching still higher altitudes, it is definitely more economical to put the vehicle in orbit.

## EARTH ORBITS, TRANSFERS, AND GROUND TRACKS

A space vehicle following an orbital path around the earth is, like the moon, a satellite of the earth. Early manned satellites were considered as preliminary experiments leading toward a manned flight to the moon; but earth satellites, manned or unmanned, still have a future. They have proven their worth as a means of scientific exploration of the space surrounding the earth and of the earth itself, and their usefulness is no longer limited to pure scientific research. Communications satellites poised above the earth serve both military and commercial needs (Fig. 48); live telecasts from overseas would be impossible without them. Televised weather charting by Tiros, SMS (Synchronous Meteorological Satellite), and Nimbus satellites provides another practical application. Amazingly sharp, detailed color photographs of the earth taken with hand cameras by astronauts from altitudes of hundreds of miles suggest other useful aims served by photography. These include geological observations that might lead to oil and other mineral discoveries, and other pictures that may unlock the riches of the oceans. To achieve sharply detailed pictures requires the use of recoverable packages that allow retrieval of the film in the cameras, rather than telecast images. This retrieval would require

Figure 48. Communications satellites serve both commercial and military uses. Early Bird, shown here, was a pioneer in the communications satellite area.

precise reentry guidance techniques. (In fact, film is routinely jettisoned from reconnaissance satellites and retrieved in mid-air by Air Force teams.)

Sending satellites into earth orbit, therefore, is no mere first step into space, to be made obsolete by more spectacular voyages to the moon and the planets. At present, and for many years to come, it will remain an important activity. The major part of the science of propulsion, control, and guidance of space vehicles today is applied to launching earth satellites and steering them precisely into pathways where they will serve their purposes most effectively.

### Elliptical Orbits

The lowest earth orbit indicated in Figure 46 is an approximate circular orbit at 100 nautical miles altitude, for which an injection velocity of 25,600 fps is required. Therefore, let us use this orbit as a starting point for learning more about earth orbits. In this one instance, the injection velocity (Fig. 46), the apogee velocity, and the circular orbit velocity (Fig. 49) are all the same. At this altitude, the pull of gravity is only slightly less than it is at the surface of the earth. The velocity of 25,600 fps (or 17,400 mph, if you prefer) represents the speed at which the vehicle must "outrace the

**REPRESENTATIVE EARTH ORBITS**

| *Period of Circular Orbit* | *Altitude (nm)* | *Apogee velocity* (fps)*** | *Circular velocity (fps)*** |
|---|---|---|---|
| 90 minutes | 100 | 25,600 | 25,600 |
| 96 minutes | 300 | 24,500 | 24,900 |
| 2 hours | 900 | 21,900 | 23,100 |
| 3 hours | 2,300 | 17,600 | 20,200 |
| 6 hours | 5,600 | 12,000 | 16,000 |
| 12 hours | 10,900 | 8,000 | 12,700 |
| 1 day *** | 19,351 | 5,227 | 10,078 |
| 28 days (moon) | 208,000 | 600 | 3,300 |
| 1 year | 1,161,200 | 100 | 1,400 |

* Apogee velocity assumes injection at 100 nm altitude as in Figure 46.
** Nearest 100.
*** Synchronous satellite—precise figures shown.

Figure 49. Table of orbital velocities.

horizon" as it "falls" around the curving earth, ever maintaining the same altitude above it. It is important to note that the injection into orbit must be "horizontal" (tangent to the orbit). Any effort to extend range (as with a gun fired on earth) by giving the vehicle an upward trajectory without added thrust would only rob it of some of its vital forward velocity and bring it to earth before one orbit was completed.

For any higher orbit, we have this basic paradox. higher and higher velocities are required to *reach* successively higher altitudes (as Fig. 46 indicates), but lower and lower velocities are required to *stay in orbit* at successively higher altitudes. This phenomenon is due to the weakening of earth gravity with distance, as Kepler observed it more than 300 years ago. Representative orbital velocities are shown in Figure 49.

Let us describe what happens when a vehicle is boosted off the earth to achieve an apogee of 1,000 nautical miles. Again we must refer to two tables. According to Figure 46, a boost velocity of about 27,000 fps is needed to hurl the vehicle to that height. After burnout, the vehicle coasts outward along an elliptical path, moving slower and slower as gravitational pull gradually overcomes its launch impetus. At its planned 1,000 nm apogee it will have a speed somewhat less than 21,900 fps (the figure shown in Figure 49 for an apogee velocity at 900 nm) and will begin to lose altitude. Sliding down the far side of the ellipse, it will move faster and faster as it approaches closer and closer to earth. It will then whip around perigee at top speed. Perigee in this case will be the original point of injection, altitude 100 nm, and top speed will be the original injection velocity of 27,000 fps. The vehicle will then begin another climb toward its 1,000 nm apogee. Discounting the slow effect of faint atmospheric resistance at perigee, it will keep on swinging around this ellipse indefinitely without need for burning an ounce of propellant.

All the earth satellite figures given in Figure 46 assume the same thing. injection and perigee at 100 nm, with apogee varying according to the velocity of injection. More and more launch power, then will shoot the vehicle out to more and more distant apogees. The orbits would describe successively longer ellipses. How is it possible to achieve a circular orbit at a desired altitude?

### Circular Orbits and Coplanar Transfers

To change an elliptical into a circular orbit at apogee requires what spacemen call a "kick in the apogee." That is, when the vehicle reaches apogee, its engine is restarted to give it some additional velocity to thrust it outward and circularize its orbit. The required velocities for circular and elliptical orbits are shown in Fig. 49. Circular velocity minus apogee velocity gives the amount of "kick" needed to circularize an orbit at a given altitude (assuming 100 nm perigees as set forth in the tables).

To show how to figure the total velocity required to attain a circular orbit, let us work one little problem in simple arithmetic using sums from both Figures 46 and 49. The velocity required to boost a vehicle to an apogee of 300 nm is 25,900 fps. To this number add the difference between apogee velocity and circular velocity at 300 nm (400 fps). The sum, 26,300 fps, is the *total velocity requirement*—that required for launching a vehicle into a 300 nm circular orbit. in two steps—but the vehicle never travels that fast. The total velocity requirement is merely an engineer's figure useful in determining how much energy is needed to perform a given task, with a given payload weight.

Our round numbers do not reflect the precision with which these velocities must be calculated. If the $\Delta V$ applied at apogee is a little less than that required for circularizing the orbit, the result will be a wider ellipse with the same apogee and a higher perigee. If it is a little more, the vehicle will be boosted to a higher apogee.

Achieving a circular orbit at any height above that of launch burnout (original perigee) is done in two steps—launching into an elliptical trajectory, and applying another spurt of rocket energy at the desired altitude to circularize the orbit. It might also be done in three steps. The vehicle could be launched into a lower orbit, called a **parking orbit,** then boosted to a higher apogee, then circularized at that apogee. Moving a vehicle from one orbit to another is called a **transfer.** Such maneuvers accomplished within the same orbital plane are called **coplanar transfers.** It is possible to illustrate a coplanar transfer with a two-dimensional diagram (Fig. 50). All the movements are on the same plane, like the sheet of paper on which you see them.

THE HOHMANN TRANSFER.—Back in 1925, when space travel was only a theoretical dream, the city engineer of Essen, Germany, published a scientific paper on the most economical way to boost

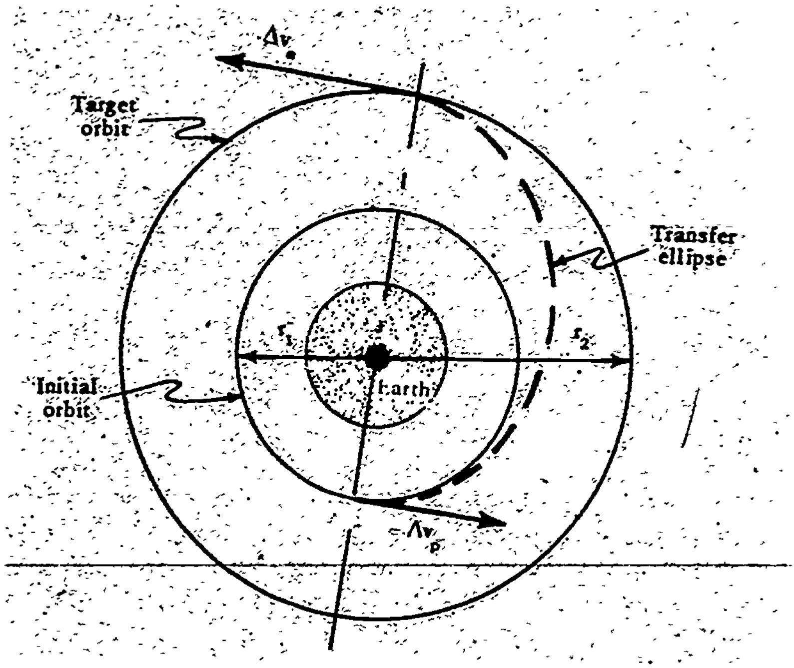


Figure 50. The Hohmann transfer is a coplanar transfer attainable by straight-ahead thrust with little energy expenditure.

a satellite into a chosen circular orbit. The method proposed by Walter Hohmann is quite similar to the one described above. It has been called the "minimum energy transfer." (Actually, it is not the minimum energy transfer in all cases, but we shall not go into the complicated technical reasons why there are exceptions to this rule.) The **Hohmann transfer,** or slight variations of it, is a practical method of space maneuver to this day. In a Hohmann transfer, the vehicle is first placed in a low elliptical, parking orbit. When the vehicle swings around to perigee, sufficient thrust is applied to push the vehicle to apogee at the desired altitude. When the vehicle reaches the high point of this **transfer ellipse,** thrust is applied again, and the vehicle moves out on a circle tangent to the transfer ellipse.

All this talk of ellipses, circles, and tangents should remind us again of the fact that all space travel is in curves. Moving in a straight line in space would require constant application of deflected thrust, a tremendous and wasteful expenditure of propellant. The curyes chosen by Hohmann are those that actually permit thrust to be applied in a straight line. A vehicle with a rigid engine or nozzle, incapable of thrust vector control, would be able to accomplish a Hohmann transfer by thrusting straight ahead at the proper transfer points. Momentarily the vehicle would move out on a straight line tangent to its former course, but almost immediately the particular new balance achieved between the forward momentum and the pull of gravity would set the vehicle on a new curved trajectory.

OTHER COPLANAR TRANSFERS.—Before we leave the subject of coplanar transfers, we might mention others ways of accomplishing transfers and maneuvers within a given plane of orbit. One is the **fast transfer** (Fig. 51) applied in modern satellite maneuvering. Instead of choosing a transfer ellipse tangent to both the lower and higher orbits, one chooses a trajectory that *intersects* the two orbits. In a direct ascent, more launch velocity would be built up than needed to reach a given apogee. At the desired altitude the kick would thus be applied lower than apogee, with deflected thrust to *aim* it into the desired circle. Because all the energy would not be working in a straight line, extra energy would be

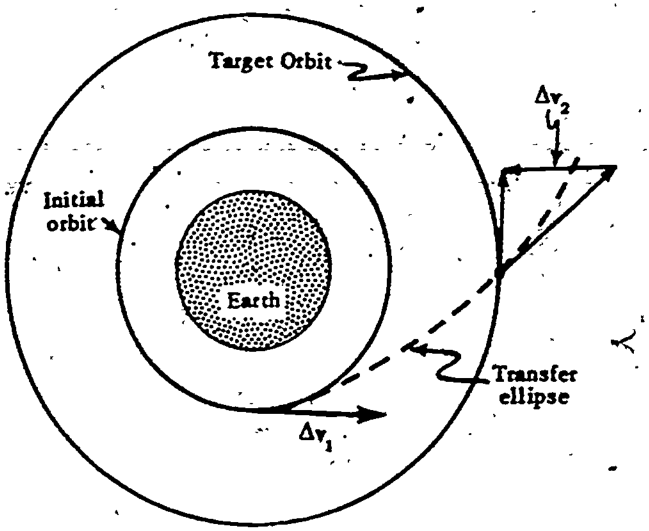


Figure 51. The fast transfer differs only slightly from the Hohmann transfer and requires more maneuverability from the vehicle.

needed to make the desired turn. The maneuver boosts the vehicle into higher orbit more speedily than a Hohmann transfer. Actually, most fast transfers ~~are~~ only slightly different from Hohmann transfers. The turn is not very sharp at either transfer point.

There is also a method of reaching a higher orbital altitude peculiar to one of the low-thrust electrical engines described in Chapter 4. Recall that when such an engine is to be used for moving a satellite into higher orbit, a conventional chemical booster engine must first be used to launch the satellite into a parking orbit. As long as the vehicle has enough velocity to stay in orbit, a low-thrust engine can be used to move it higher. The engine does not work in spurts, but is capable of *prolonged* low thrust. As long as the electric rocket keeps thrusting, the vehicle's course keeps changing toward higher and higher altitudes. In brief, it *spirals* out to the desired altitude in an ever widening orbit.

Mention should also be made of moving down from a higher to a lower orbit. To do this, *negative* $\Delta V$, or retrothrust must be applied to kill off some of the velocity that keeps the vehicle in the higher orbit. The vehicle is then drawn by gravity into an orbital path that matches its new lower velocity. As it moves lower, however, it moves faster. This is another interesting paradox: *putting on the brakes in order to go faster.* Actually it is a practical maneuver. Suppose that two vehicles are attempting to accomplish a rendezvous in the same orbit, and one is a thousand miles ahead of the other. The chase vehicle can never hope to catch up with the target vehicle while both are in the same orbit. Therefore, the chase vehicle applies retrothrust to get drawn into a downward transfer ellipse that will allow it not only to follow a short-cut route but also to be moved by gravitational pull faster along that shorter, lower route to a point where the two orbits are again tangent, and, hopefully, where the two vehicles will come within maneuvering range of a rendezvous. Needless to say, the precision of the pre-computed route selection as well as the guidance and control mechanisms used to accomplish the rendezvous itself must be extremely good.

### Non-Coplanar Transfers and Ground Tracks

All earth satellites do not orbit in the same plane, so now we must think three-dimensionally again. First, recall that any plane of orbit around the earth *must pass through the center of the earth.* If a vehicle is launched due east (azimuth 90°) from Cape Kennedy, Florida. which has a latitude of 28.5° North, it is impossible for it to keep traveling due east around the world at the same latitude. Its orbital path will bring it south across the equator to reach a latitude of 28.5° South before it swings north again. The orbital plane of such a launch is said to have an **angle of inclination** of 28.5° with respect to the plane of the equator. Aiming the satellite at launch in any direction other than due east will produce a steeper angle of inclination, causing the satellite to overfly latitudes higher than 28.5° on either side of the equator. A northward or southward injection will put the satellite in a polar orbit.

Obviously no launch from Cape Kennedy could put a vehicle *directly into* on orbit around the equator, or at any angle of inclination *less* than the latitude of Cape Kennedy itself. To put a vehicle into equatorial orbit requires a **non-coplanar transfer.** The vehicle would first be launched at its minimum angle of inclination of 28.5°. Then, on either its first or a later revolution at one of two points where it crosses the equator, thrust would be applied at the proper angle (by means of thrust vector control) to put the vehicle into an orbit coplanar with the equator. Think of this transfer maneuver as kicking the vehicle sideways instead of upward, as in the coplanar transfer. Similarly any angle of inclination can be achieved by means of non-coplanar transfer, but not necessarily in one such transfer. If the angle of change is too extreme, the vehicle may have to orbit the earth two or more times, changing its angle of inclination by a certain amount at each intersection of planes, before the desired inclination is achieved. If *both* a change of inclination and a change of orbital altitude are desired, however, the non-coplanar and altitude transfers can be achieved in one orbit by calculating the thrust angles three-dimensionally.

SYNCHRONOUS SATELLITES.—You have probably heard of Intelsat and DSCS II (Defense Satellite Communication System), satellites which are not merely used for purposes of scientific observation or experiment but earn their living by relaying radio and television signals for Government and commerical network users. To do its job properly 24 hours a day, such a satellite must remain poised in the sky, constantly above one meridian on the earth's surface. Three such synchronous satellites, spaced 120 degrees of longitude apart, can give 24-hour round-the-world service over most of the surface of the globe. Now that you have studied something about orbits and transfers, you may be able to guess how such satellites are put into position.

For a satellite to be "synchronous" with the earth—that is, keep time with the rotation of the earth so perfectly that it always remains directly above a certain meridian of longitude and never drifts east or west of it—it must have a circular orbit at one altitude only. As Figure 49 states, that altitude is 19,351 nautical miles (or 22,300 statute miles), which will give it a period of 24 hours. If such a satellite is launched from Cape Kennedy without a non-coplanar transfer, it will have an inclination of 28.5° and will not appear perfectly stationary over the earth. It can be timed to reach the right orbit at the desired meridian, but its inclination will take it above and below the equatorial plane by 28.5° in the course of its one-day orbit. Its pathway through space projected straight downward onto the surface of the earth—in other words, its ground track—would describe a narrow figure eight, crossing at the Equator, and its top and bottom touching both 28.5° parallels (Fig. 52). In order to make it hover stationary over one point on earth, it is necessary to include a non-coplanar transfer into the equatorial plane in its launch program. The one point over which it hovers must be on the equator and at no other latitude.

These are the major maneuvers for positioning a synchronous satellite. Needless to say, exact positioning requires extremely precise "station keeping" maneuvers performed with vernier engines or possibly even small jets of hydrogen peroxide.

GROUND TRACKS.—We have mentioned ground tracks several times. It is important to note that ground tracks are not merely a

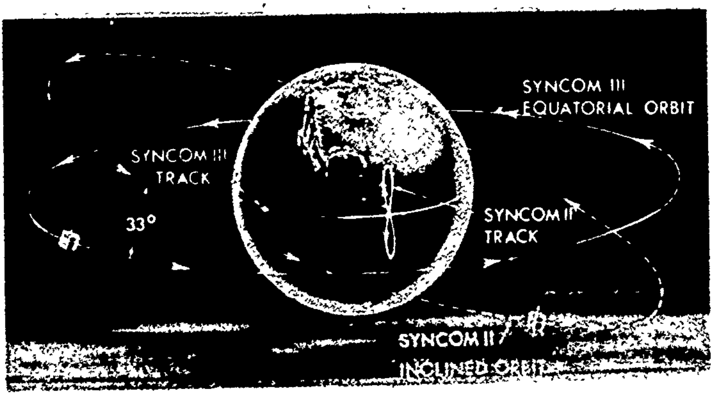


Figure 52. The ground track of a synchronous satellite launched from Cape Kennedy describes a narrow figure eight, crossing at the equator.

matter of incidental interest. Tracing a certain ground track may be the main purpose of a satellite. The business at hand may be war or espionage, in which one nation may seek to place either a weapon or a surveillance satellite over a certain part of another nation's territory. Or it may be any one of a number of peaceful pursuits already mentioned, such as weather charting, mineral prospecting, or communications relay. A study of ground tracks, combined with highly refined guidance procedures, will permit the placing of a satellite over any part of the earth's surface at any specified time. The variety of ground tracks that can be traced is great. Here let us consider a few.

First consider a typical low, circular orbit, taking about 90 minutes to circle the earth, at an inclination determined by a due east launch from Cape Kennedy. If plotted on a flat map of the Earth rather than a globe, it would describe an S-shaped curve between the 28.5° parallels north and south. If the earth did not rotate, the curve would always return to the same launch point (Fig. 53). The rotation causes the ground track to regress westward as the earth turns a certain amount eastward in the 90-minute period. Thus the ground track would trace a series of overlapping Ss as shown in Figure 54. If the orbit is higher, the amount of westward regression would increase. If the orbit is elliptical, the ground track would be irregular, making a wider sweep of a curve over the rapidly-moving perigee portion of the orbit, and a narrower hump at apogee (Fig. 55). Ground tracks made by

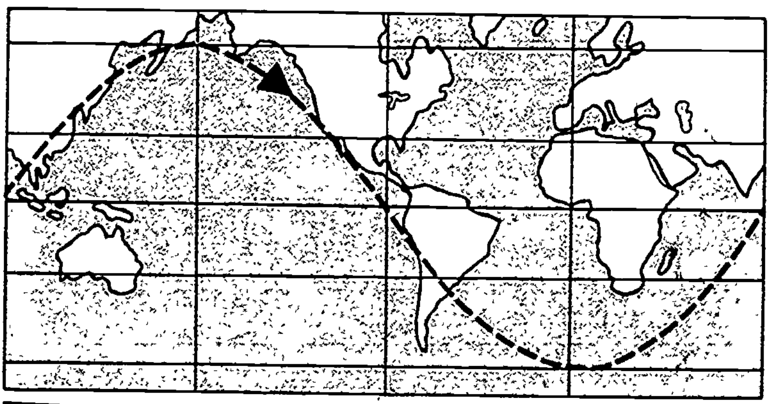

Figure 53. Ground track (sometimes called "ground trace") assuming a non-rotating earth.

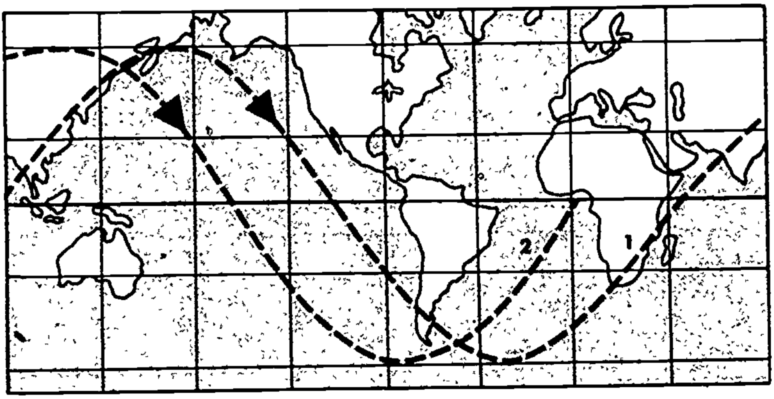


Figure 54. Rotation of the earth causes a westward regression of the ground track.

high-altitude satellites with synchronous or near-synchronous orbits are an interesting class in themselves, especially if these are of elliptical orbits. They may form irregular or eccentric figure eights with the large loop formed by perigee and the tight loop formed by apogee. When the vehicle is orbiting at a higher-than-synchronous altitude, thus taking more than a day to make the orbit, its ground track is a spiral winding around the globe (Fig. 56).

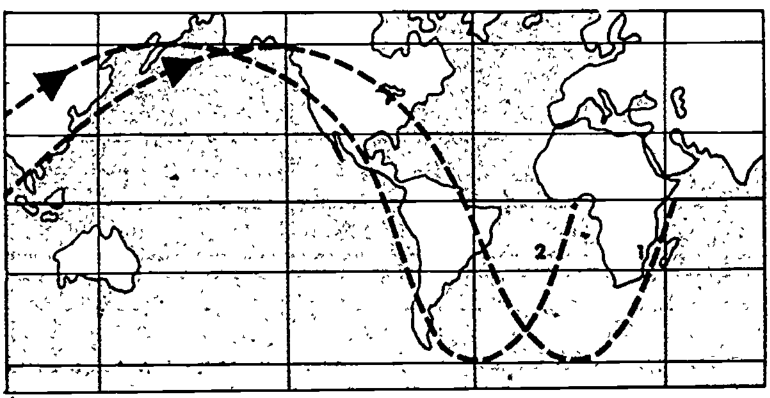


Figure 55. The ground track of a satellite in elliptical orbit is irregular, as compared to that of one in circular orbit.

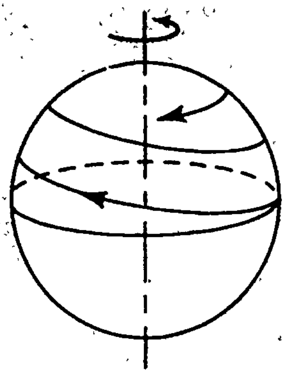

Figure 56. A higher-than-synchronous orbit takes more than a day to complete and its ground track describes a spiral winding around the globe.

## TO THE MOON AND BEYOND

Man has been to the moon and back several times, and work is progressing for eventual visits to other planets. Both the United States and the Soviet Union are expected to continue the exploration of the moon and other heavenly bodies, although perhaps on a reduced scale, with unmanned vehicles. Already, the manned and unmanned space programs of both nations have produced feats that a decade or so ago would have been considered amazing or impossible. An earth grown accustomed to the spectacular now considers them matter-of-course. In addition to manned and unmanned exploration of the moon, these feats include soft and hard landings on Venus and Mars, orbiting television satellites around Mars, and, closer to home, nuts and bolts work connected with manned orbiting space stations. More elaborate unmanned probes of Mars and Venus and the outer planets—Jupiter, Saturn, Uranus, Neptune, and Pluto—are also either in progress or near to it.

All of which demonstrates that the problems of celestial mechanics related to lunar and interplanetary travel are practical ones. The same principles that apply to earth orbits also apply to solar-system space, but the problems are complicated by extra "bodies." Up to now we have been dealing with what astronomers call the "two-body problem." The two bodies are the earth and a vehicle, and we have described various ways in which a vehicle behaves in a single gravitational field. At greater distances, we must consider the ever-diminishing influence of the earth, that powerful effect of the sun, and the various forces of the target moon or planet.

### Velocity Requirement Again

Once again, look at Figure 46 and note that range of figures from "100,000 nm apogee" to "Earth escape." A distance of 100,000 nautical miles is a little less than half way to the Moon. Thus, the difference between half way and all the way to the moon is a mere 200 fps. The range of velocities under "Lunar Missions" represents various long elliptical geocentric orbits which, if they missed the moon, would go beyond it and then return toward earth.

At the top of the range is that velocity which would carry a vehicle beyond the effective influence of the earth's gravitational field. Thinking in terms of a "two-body problem," we would say that there is a theoretical point where such a vehicle, gradually slowing down and using up its velocity as it traveled a half million or more miles away from the earth, would stop and hang motionless in space. Thinking in terms of the solar system, we would realize that the escaped vehicle would be in independent orbit around the sun.

This so-called escape velocity, in round numbers, is 36,200 fps or 25,000 mph. To be practical, it is very unlikely that an escape or moon shot would ever be attempted by massive booster power off the earth's surface with burnout at a height of 100 nautical miles. We must consider such a figure more in the nature of a total one-way velocity requirement for reaching these long distances. The route would probably include a parking orbit, and one or two midcourse boosts. At no one stage of its outward journey would the vehicle be traveling as fast as the full velocity requirement. Each increase of velocity would be partially eaten up by earth gravity, and the figure in question would be the sum of the launch boost plus all the added delta-Vs, without any subtractions. On the *return trip* from the Moon or a distant apogee, however, the *full velocity* would be reached as the vehicle reached perigee or reentry. It is the old rule of "whatever goes up must come down"—with a velocity equal to that which sent it up, as long as the velocity is any amount less than that of escape.

How far out in space lies escape? Figure 49 shows us some orbital data for a distance of more than a million nautical miles, at which distance the orbital period is one year, and the apogee velocity is a mere 100 fps (equivalent to 68 mph on the speedometer of the family car). Even at 26 million miles (equivalent to the nearest approach of Venus to earth), some effect of earth gravitation is felt. In two-body terms, the answer to "How far away is escape?" is "Infinity." However, there is a practical distance for effective escape—a distance that would put a vehicle into independent orbit around the sun with extreme unlikelihood of its ever being drawn toward the earth. That distance is about 530,000 nautical miles.

You have probably heard the expression, "A miss is as good as a mile." At velocity ranges suitable for lunar trajectories, a miss could be up to a million miles. That is, a slight change of velocity could mean hundreds of thousands of miles of difference in apogee range, up to and beyond escape. The difficulty of calculating exact velocity requirements for ranges on this order, however, is somewhat lessened by the fact that velocity can be adjusted enroute by means of the midcourse guidance techniques we have discussed.

When we look a little farther down the table in Figure 46 and note the velocity requirements for reaching different planets, we see that the differences grow larger again. The answer to this paradox is that one range of figures relates primarily to earth influence—the two-body problem—while the other reflects the immense gravitational pull of the sun. Before we consider travel among the planets, however, let us consider travel to the moon.

### Lunar Voyages

Recall Willy Ley's statement quoted in Chapter 1, on how to reach the moon: "You shoot into infinity and do it at such a time that the moon gets in the way." Thus one way of reaching the moon is to plot an escape trajectory, using an accumulated velocity of 36,200 fps. If the timing is right (which it must be, because the moon is a moving target), the vehicle will hit the moon just as a bullet will hit a target. Also like a bullet, it will travel far beyond its target in case of a miss. One of the various velocities for reaching the moon, as indicated in Figure 46, would

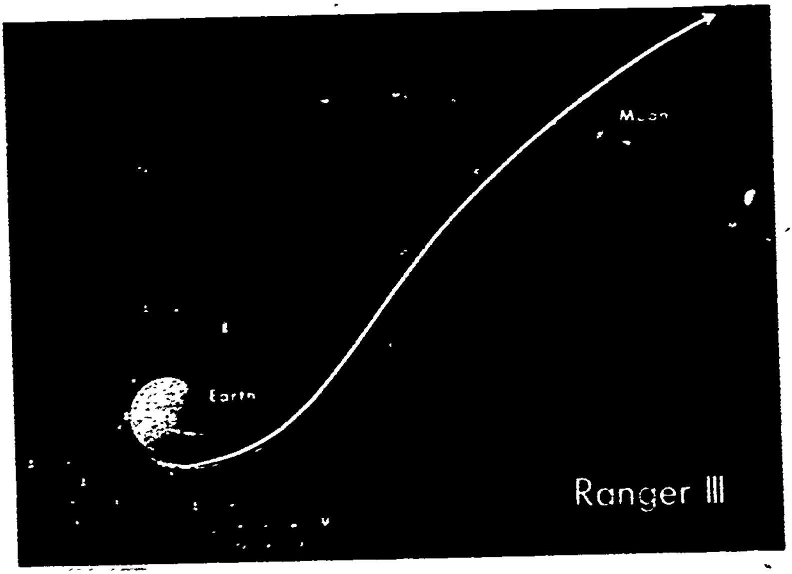


Figure 57. Ranger III suffered a near miss in its 1961 attempt to hit the moon. Techniques have since been refined so that current space shots are better controlled

be chosen purely in terms of transfer time—how long it takes to get there—the ordinary way of choosing a velocity for land or air travel. Figure 57, however, reveals how difficult it is to hit the moon. It shows how an early effort designated as Ranger III, with escape velocity behind it, went into independent sun orbit.

VARIOUS UNMANNED MISSIONS.—In the early 1960s several efforts were made to do something which, at first glance, may seem easier than hitting the moon: swinging around it and returning close to the earth. The plan was to record scientific data on a swing around the moon, store the data in the vehicle's on-board computer, then wait until the vehicle approached close to earth before transmitting them *(readout)* in a zone where reception was better. Such a mission would require sending the vehicle into a long elliptical orbit around the earth with perigee only a few hundred miles from earth and apogee beyond but not too far beyond the moon. Since the moon lies within the earth's gravitational field, such a course is possible. It is, however, a difficult one to plot. Not only is the moon a moving target, but, as we have seen, the velocity requirement for such a shot is a precise one. An error of 200 fps too little could mean falling short of the moon by as much as 100,000 nautical miles. An equivalent error on the long side could mean an infinity shot with no return at all. Thus it is understandable why several early efforts to swing around the moon were unsuccessful

Today, the moon-shot technique has been perfected and failures either to hit the moon or swing around it are unheard of. An even more difficult feat is lunar orbit, a prerequisite for a soft landing. For a lunar orbit, the vehicle must approach the moon very closely and at just the right velocity to be captured by the moon's gravitational field. The smallness and weakness of this field, and the moon's lack of atmosphere, add to the difficulty. These conditions, however, are advantages in that the amount of retrothrust needed to slow a small vehicle down for a soft landing is not very great. The vehicle need not be burdened with huge rocket motors to accomplish this task. For a small, unmanned vehicle, small vernier motors will do. A series of successful Lunar Orbiter and Surveyor (soft landing) missions was accomplished by NASA during the years 1966-68. The Viking Mars spacecraft is designed to orbit Mars and to send a soft lander module to the planet's surface. (Fig. 58).

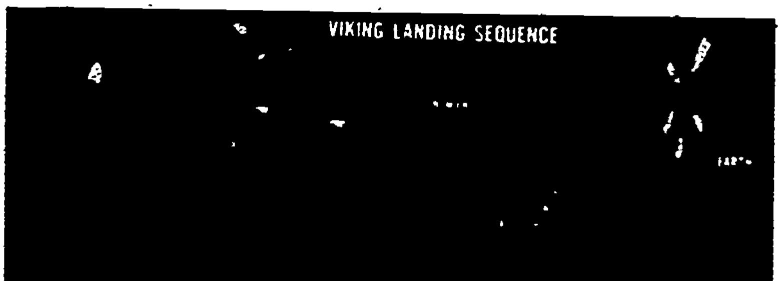


Figure 58. The unmanned Viking Mars vehicle features a separation-and-soft-landing patterned after the manned Apollo Moon landings.

THE APOLLO MISSION.—The Apollo project to land men on the moon and return them safely to earth is, of course, a vastly more complex space project than any attempted before. To describe some of the more important stages and maneuvers of the voyages is to review much of what this text has so far offered on the subject of propulsion, control, and guidance of space vehicles.

• To launch the vehicle requires a six million pound Saturn V booster. Two stages, the first burning kerosene and liquid oxygen, the second burning liquid hydrogen and liquid oxygen, boost the vehicle to a height of 100 nm, where the third stage (hydrogen-oxygen) injects it into a parking orbit. The third stage remains attached to the vehicle, so the total load orbited weighs about 300,000 pounds. Another interesting feature of the booster equipment is an interstage between the first and second stages. This consists of several small solid rockets fired for the purpose of settling the second-stage liquid propellants toward the bottoms of their tanks and counteracting weightlessness so that inertial guidance equipment will work better.

• The vehicle is launched toward the moon from its parking orbit by restarting the third stage, which burns out and is jettisoned at about 10,000 nm from the earth. The vehicle that voyages to the moon is now reduced in weight to about 97,000 pounds. This weight is not all payload. Indeed, the greater part of it consists of a sufficient amount of propellants for further maneuvers that must be made.

• Shortly after jettison of the third stage occurs an extremely delicate maneuver in space called **transposition.** The vehicle is turned around 180°. It also is separated into parts and reassembled so that crewmen can move from the command module directly into the lunar module (LM), in the rear of the ship, while the rocket nozzle of the service module is pointed forward for retrothrust on approaching the moon (Fig. 59).

• On approaching the moon, the rocket of the service module is fired to slow the vehicle down for capture in lunar orbit. (Rockets of the lunar and service modules are loaded with liquid propellants of the hypergolic type, ideal for positive restarting.)

• Again the vehicle is taken apart in space, to separate the lunar-excursion module from the command and service modules Two crewmen who are to land on the moon are in the lunar module. A third crewman stays aboard the command module,

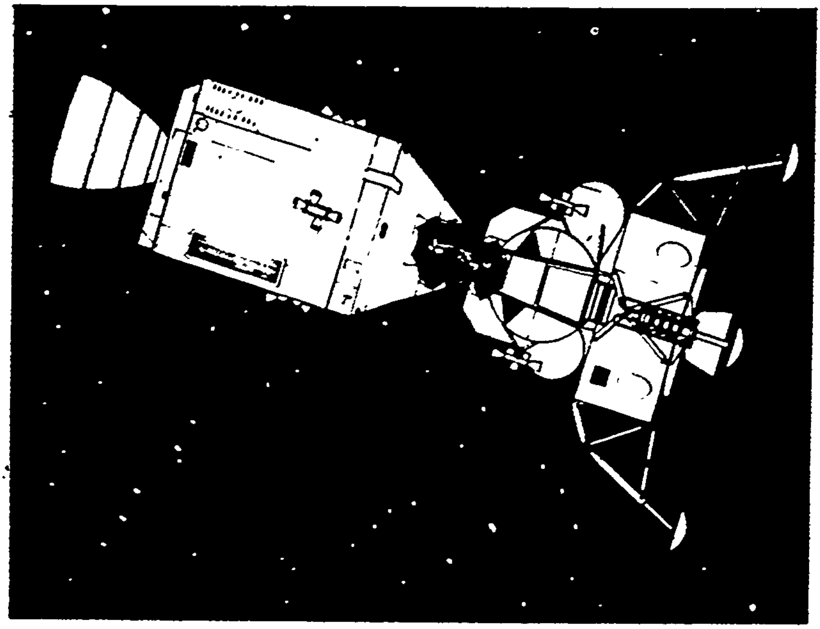

Figure 59 Artist's conception shows how crewmen on Apollo flights move between command and lunar modules as the service module rockets point forward for retrothrust.

still attached to the service module. The LM's rockets are fired for retrothrust to drop the craft out of orbit and toward the lunar surface.

- The lunar module then makes its landing on the Moon (Fig. 60), the last few thousand feet of which is accomplished by means of steady rethrothrust from its descent stage to brake the fall gradually. More than half the LM's propellant supply is used up in easing the vehicle down to a soft landing, for the vehicle that makes the landing is heavier than that which will take off. Meanwhile the command and service modules, with one man aboard, stay in orbit around the moon.

- The lunar module, its mission accomplished, fires its ascent stage rockets to make a carefully timed takeoff from the moon to rendezvous with the command and service modules.

- All three modules are again temporarily rejoined by means of an intricate rendezvous and docking in space. As soon as the modules are joined all crewmen enter the command module.

The LM is jettisoned then and either continues to orbit the moon or crashes back to the lunar surface.

• Rockets in the service module are restarted to boost the vehicle out of lunar orbit into a trajectory back to earth. On this return voyage, gravitational attraction accelerates the vehicle faster and faster toward earth so that on approach it is moving at a speed equal to the accumulated velocity requirement for reaching the moon—about 36,000 fps. The service module and its rocket are retained long enough to accomplish midcourse correction to steer the vehicle precisely toward a chosen reentry corridor rather than into orbit around earth.

• The service module is jettisoned, leaving only the tiny Apollo command module, with the entire three-man crew aboard. This capsule, weighing only a few thousand pounds, is all that remains of the mighty Saturn V launch vehicle assembly with which the

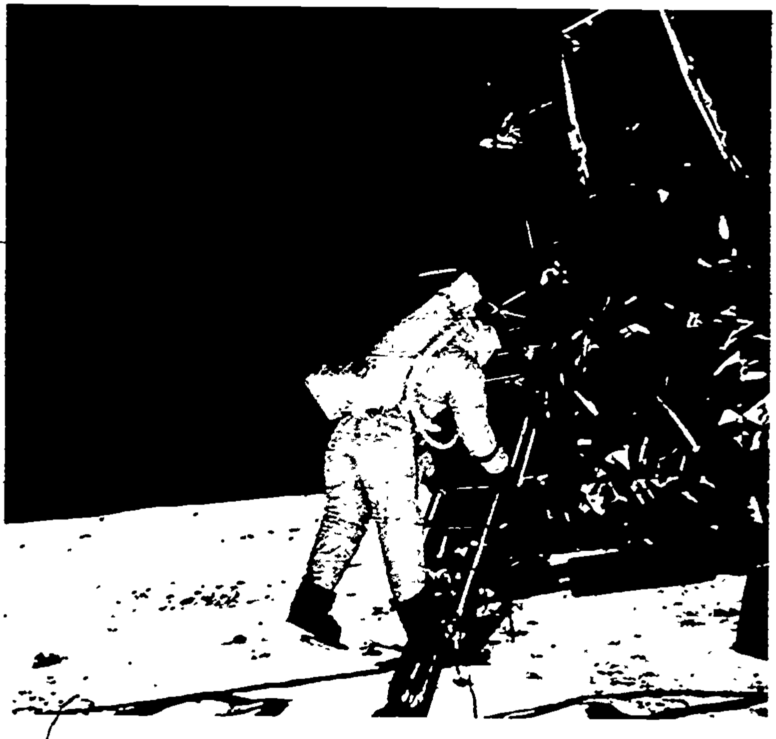

Figure 60. Astronaut alights from lunar module after soft landing on the moon.

expedition began. Most of Saturn's six million pounds was in propellants to meet a total round-trip velocity requirement of more than 55,000 fps on behalf of this tiny ultimate payload, plus an equally small lunar module. Small attitude control jets, to position the capsule for reentry with blunt end forward, are the only "propulsion" left for this essentially motorless vehicle.

- There is no retrothrust to kill off any of the vehicle's approach velocity of about 36,000 fps and ease the reentry. If there were, a rocket with a heavy propellant load would have to be added to this final stage. The blunt ablative heat shield of the Apollo command module absorbs the heat of friction, flakes off, and carries the heat away. Deployment of parachutes brings the vehicle to a safe splashdown at sea.

### Voyages to the Planets

Here let us consider briefly some of the requirements, problems and oddities of venturing into interplanetary space and visiting other planets.

## THE SOLAR SYSTEM

| | *Mean Distance from Sun (nearest 500,000 miles)* * | *Nearest Approach to Earth (nearest 500,000 miles)* | *Mass (Earth=1)* | *Escape Velocity (fps)* | Period of Orbit (Earth days or years) | *Orbital velocity (fps)* |
|---|---|---|---|---|---|---|
| THE SUN | ———— | ———— | 333,500 | 2,020,000 | ———— | ———— |
| THE PLANETS | | | | | | |
| Mercury | 36,000,000* | 50,000,000 | 0.05 | 13,700 | 88 days | 157,000 |
| Venus | 67,000,000 | 26,000,000 | 0.8 | 33,600 | 225 days | 114,800 |
| Earth | 93,000,000 | ———— | 1.0 | 36,700 | 365¼ days | 97,600 |
| Mars | 141,500,000 | 34,500,000 | 0.1 | 16,400 | 1.88 yrs | 79,100 |
| Jupiter | 484,000,000 | 367,000,000 | 318.0 | 196,000 | 11.86 yrs | 42,800 |
| Saturn | 887,000,000 | 745,000,000 | 95.2 | 116,000 | 29.5 yrs | 31,600 |
| Uranus | 1,784,000,000 | 1,609,000,000 | 14.5 | 72,400 | 84 yrs | 22,200 |
| Neptune | 2,795,500,000 | 2,678,500,000 | 17.2 | 81,600 | 165 yrs | 17,800 |
| Pluto | 3,675,500,000 | 2,668,500,000 | 0.9 | 32,700 | 248.4 yrs | 15,500 |

* Orbits of all planets are elliptical, but most are near enough to circular so that mean distance from Sun is a meaningful figure. Two planets whose orbits are rather narrow ellipses are Mercury and Pluto. Orbits of these planets are as follows:

| *Planet* | *Perihelion* | *Aphelion* |
|---|---|---|
| Mercury | 28,500,000 miles | 43,500,000 miles |
| Pluto | 2,761,500,000 miles | 4,639,000,000 miles |

Pluto is the most distant planet *most of the time.* At perihelion it is less distant than Neptune.

Figure 61. Data on Solar system shows dimensions that affect deep space travel.

THE SOLAR SYSTEM.—Figure 61 is a table which presents certain data to provide a notion of the dimensions of the solar system and some of the conditions that affect travel within it. Notice the range of sizes, including the sun itself, which has over 300,000 times the mass of the earth. Notice the range of distances, stated here for your convenience in round numbers amounting to millions or billions of miles.* Note the periods of orbit, ranging from 88 days for Mercury to almost two and a half centuries for Pluto. (Consider how long one might have to wait for one of the outer planets to get into a favorable position for a visit as well as how long a vehicle might take to get there.) Periods of orbit, we must be reminded, are a matter not only of distance traveled but also of the effects noted in Kepler's Laws, which tell us that a body moves more slowly the more remote it is from the body that controls it. The last column, orbital velocities in feet per second, reveals this fact not only in regard to the planets but also in regard to any vehicle which might be in their vicinity, and which would be constrained to obey the same celestial speed limits. The column on escape velocity reveals how much velocity is required to escape from a given planet, as well as how much *negative* velocity is required to ease down to a gentle landing there. The sum must be doubled for landing plus escape. Thus the figure is a very important one for a future astronaut to ponder.

The column headed "Nearest Approach to Earth" must be regarded with caution. We do not mean to suggest that plotting a course to intercept a planet at its nearest approach is a practical one. Consider a "Nearest Approach" figure in terms of the canoe analogy mentioned at the beginning of this chapter. It suggests, roughly, the "width" of the gravitational "river" that must be gradually crossed while traveling mainly downstream.

Many more interesting data on the solar system have been left out of Figure 61 for the sake of brevity. We might add a word on inclination. The solar system is a rather flat world—shaped somewhat like a shallow dish. The plane of the earth's orbit around the sun is called the "plane of the ecliptic." All the planets revolve in the same direction and, with two exceptions,

*The mean distance between earth and sun, 93,000,000 miles, is one "astronomical unit" (AU) a unit preferred by scientists in measuring distances in the solar system on planes inclined no more than 3.5° from the ecliptic. The exceptions are Mercury (inclined 7°) and Pluto (inclined 17°). These same two "oddball" planets also have the highest degree of "eccentricity" (most elongated ellipses) of orbits.

In terms of space travel and propellant economy, there is advantage in the general flatness of the solar system. It minimizes non-coplanar transfers, which eat up more energy than coplanar transfers. Just how the solar system got that way is a mystery science has never solved. Either the planets were originally flung out from the sun, or they entered the sun's gravitational field from the outside and were trapped. Whatever the answer, two great forces cranked this mighty machine, and keep on cranking it: (1) the original force that injected the planets into orbits proportional to velocity, and (2) the sun itself, whose very mass regardless of its heat, is the source of gravitational force that keeps the system turning.

THE HEAD START—97,600 FEET PER SECOND.—Since the earth is our home and our starting point, we may begin to consider interplanetary travel by considering our powerful head start into space—a velocity of 97,600 fps. This is the average speed of the Earth as it orbits the Sun, more technically called its **heliocentric* velocity.** Everything that is in apparent rest or motion inside the earth's gravitational field, from an orbiting satellite to a book on a table, is moving around the sun at this average heliocentric speed. Consequently any vehicle which *escapes* the earth's gravitational field is *flung* into interplanetary space at about this velocity. The vehicle leaves the earth's gravitational field like a baseball leaving the hand of a pitcher. If the vehicle is given earth-escape velocity, and no more, however, it will get nowhere in interplanetary travel. It will continue orbiting the sun at about the same distance from the sun and the same speed as the earth itself. To visit another planet, it must stray out of this orbit, and it has no power to do so. Nevertheless, its very respectable velocity of about 97,600 fps is a useful head start on which man-made rocket thrust can build for interplanetary travel.

TO MARS AND BEYOND.—Now add some rocket thrust to give the vehicle some excess velocity over escape velocity. What happens? On a larger scale, the same thing happens that we described earlier in terms of earth orbits—a boost to a higher apogee. Only this

*Literally, "sun at the center."

time we use the word **aphelion** instead of apogee, to mean that point on a **solar** orbit farthest from the sun, and say **perihelion** instead of perigee. The burnout point of this extra-velocity launch, being near the earth, establishes the earth-sun distance as perihelion of the new ellipse. How far out aphelion will be depends upon the amount of extra velocity the vehicle acquires. With sufficient boost, aphelion might be as much as 141,500,000 miles from the sun, which is in the orbital path of Mars. Mars, of course, may be on the opposite side of its orbit at the time the vehicle gets out that far—a miss of almost 280,000,000 miles, if Mars is the target. Therefore, the timing of the launch to intercept Mars is critical. It is based on the speed of Mars, the speed of the vehicle (which will be faster than that of Mars as long as its track is **inside** that of Mars, but constantly decreasing), and other factors which make for tricky mathematics and computer work.

The shortest distance between Earth and Mars, 34,500,000 miles, is of interest to those who want the nearest possible vantage point for telescope viewing, but to astronauts it is a rather academic figure. To boost a vehicle straight out to an intercept point with Mars at this *minimum distance* would require a tremendous amount of energy—enough energy to fight the forces of solar-system gravity. This is another shortcut through space of a type not feasible today. To intercept Mars by the *minimum-energy* route, taking full advantage of the earth's velocity, requires a long chase around the sun covering a distance of about 325,000,000 miles. The course is recognizable as the Hohmann transfer ellipse applied to heliocentric rather than earth orbits. A pathway of this sort was taken by a Mariner spacecraft which achieved orbit around Mars in 1971 and transmitted television pictures of the martian surface back to earth (Fig. 62). The outward journey to this photographic vantage point took about 5½ months. The pathway to Jupiter and other outer planets would be a similar swing into higher orbits depending on velocity input, with transit times measured in years rather than months.

Note once again how the main factors in interplanetary guidance are timing and velocity. Steering by means of thrust vector control—aiming the nozzle off center—is important for the sake of the corrections that must be made, but it eats up energy, and the less required the better. Boost control, to meet precise velocity requirements, is the major and most economical way of "steering" a space vehicle.

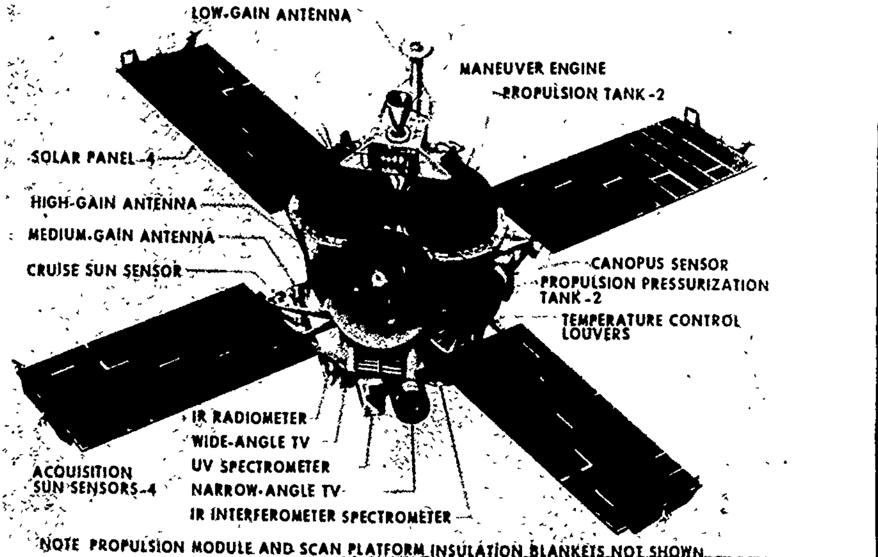


Figure 62. Artist's drawing shows components of the Mariner Mars 1971 spacecraft that has sent back some of our best pictures of the Red Planet from its Mars orbit.

TO VENUS—AND OTHER INWARD PATHWAYS.—The pathway to Venus, which orbits the sun at a distance closer than that of the earth, would seem at first glance to be easier than the pathway to Mars. One "descends" to Venus and "climbs" to Mars; not only that, but the "across-the-stream" distance to Venus is less. Why, then, does the velocity-requirement table in Figure 46 show the Venus and Mars requirements to be about the same, with those of Venus overlapping on the higher side? The answer, again, is earth velocity, 97,600 fps, which must be *reduced* to "de-orbit" an earth-launch vehicle toward Venus. Once again, it is important to point out that in space it takes as much energy to slow down as to speed up an equal amount.

The manner in which this trick is accomplished is a bit different from the manner of descending from a higher to a lower earth orbit. The latter maneuver, as we have stated, is done by retrothrust applied at the proper time. The Venus launch is accomplished more easily in terms of a three-body problem. Like the Mars launch, the Venus launch must achieve about 2,000 fps excess velocity over earth escape. The difference is that the Mars-bound vehicle is launched *in the direction of* the Earth's travel about the sun. It is launched *forward,* and its excess velocity immediately takes it farther from the sun. The Venus-bound vehicle is launched in the direction *opposite* that of the earth's travel. It is launched *rearward,* and its excess velocity, once escape has been achieved, becomes a braking velocity that pulls the vehicle closer to the sun. Which way the vehicle goes in regard to the earth's path around the sun depends only upon the time of day at the same launching site. Since the earth turns halfway around in 12 hours, "eastward" can actually be two opposite directions in relation to the Sun. A Mars flight could depart eastward at midnight; a Venus flight could depart eastward at noon. Otherwise the pathways are similar—describing the long, easy loop of the basic Hohmann transfer around the sun.

We still have not answered the question why the inward path is harder than the outward. Why does it take more energy, for instance to "fall" into the sun, a mere 93 million miles away, than to "climb" several billion miles completely out of the solar system? The answer, as briefly as possible, is that the gravitational field around a celestial body increases in intensity with closeness. Around a huge body like the sun, it is an extremely large and powerful field. To reach the sun requires killing off the entire earth velocity of 97,600 fps plus some excess. A weaker effort might, for instance, cause an earth-launched vehicle to be drawn into a close perihelion inside Mercury at a speed of perhaps 200,000 fps (Mercury's orbital speed is 157,000 fps) and flung back to the 93,000,000-mile aphelion whence the trip began.*

OTHER SOLAR SYSTEMS ODDITIES AND PROBLEMS.—Having stated the main requirements for visiting planets on either side of the earth, we may consider our topic of propulsion, control, and guidance of space vehicles—the bare essentials—virtually completed. There are numerous other oddities of celestial mechanics, however, that might be mentioned—including some that involve highly advanced mathematical concepts.

We might at this point explain why the Hohmann transfer is not necessarily the minimum energy route. Theoretically one could reach Venus with less propellant expenditure by boosting to a *higher* heliocentric orbit, then deboosting downward to take ad-

*NASA plans at this writing call for a Mariner spacecraft to be launched in 1973 to make on-the-spot reports on Venus and Mercury. In a carefully calculated trajectory Venusian gravity would be used to deflect and accelerate the Mariner toward Mercury. The craft will carry TV cameras and scientific instruments.

vantage of a faster "ski slope." (The deboost effort requires less energy at higher aphelions).

We should mention the use of a planet's atmosphere for free braking power, as well as the use of a planet's gravitational field for free propulsive energy *away* from the planet. A vehicle approaching a planet must have a sufficiently *low* velocity to be captured by that planet. If it comes in with any amount of excess velocity, it will be deflected and flung out into space on a **hyperbolic trajectory** (an open trajectory, not closed like an orbit) with increased speed—the original excess velocity plus added energy picked up from the visited planet. Mighty Jupiter, with a mass 318 times that of Earth, is an especially attractive gravitational engine for boosting a vehicle toward more distant planets. The earth-launch requirement to escape the solar system can be reduced from 54,000 to about 47,000 fps with the help of Jupiter. It can be further lowered by choosing a time when Jupiter and other planets are so lined up that a vehicle could be flung from one to another on the way out, picking up speed with each encounter.

Sometimes we hear of "two impulse" and "three impulse" maneuvers for space travel. These maneuvers assume the use of chemical rockets, with bursts of energy, each of a few minutes' duration, used at certain carefully-selected critical points in a journey to establish a major change of trajectory, such as to establish a perihelion and aphelion, or circularize an orbit, deboost to a lower orbit, etc. In between these major impulses there might be minor ones for mid-course correction.

What about *continuous* propulsion, such as might be possible with low-thrust electric rockets or nuclear rockets of the future? Continuous low-thrust propulsion would keep a rocket on a continuously changing course—a spiral. The first part of a journey may be slower than could be accomplished by chemical rockets, but on a long space journey, the gradual buildup of velocity by use of the electric rocket would make each loop of the spiral wider and faster until a velocity "crossover" point was reached at which the electric rocket would increase velocity to a value greater than possible with the chemical rocket and would reach a distant destination more quickly. It is rather like the classic race between the hare and the tortoise; the electric "tortoise" beats the chemical "hare," if the course is long enough.

Boosting off the earth, as well as landing on and taking off from other planets, however, requires an intense burst of energy which today only mammoth chemical rockets can supply. Even the high-thrust NERVA-type nuclear engines, will be rather large and heavy. A future manned round trip to another planet will no doubt take advantage of electric propulsion, but it will also have to carry along with it the means for landing and escape propulsion, with an equipment and propellant load much heavier than that of the Apollo missions. Jupiter would be an unlikely target prospect because of its powerful gravitational field and escape-velocity requirement; but Jupiter has moons about the size of the earth's moon which might be interesting to explore and would offer a spectacular platform for a close look at the largest planet.

The presence or lack of atmosphere on a planet is a factor that tends to cancel itself out in terms of landing-plus-escape velocity requirement. In short, atmosphere provides free cushioning on the way down and reduces the need for retrothrust; but to the same extent, its resistance adds to the escape velocity requirement.

All in all, Mars is the most likely prospect for manned exploration after the moon. It is Earth's next-door neighbor, not quite so close as Venus but equally easy to reach. Its atmosphere is chemically unfit for human breathing and too thin anyway. Its climate is cold and arid (although recent evidence indicates the possiblity of some water there). Nevertheless, Mars is probably no more inhospitable a place than the Moon for men clad in space suits. Furthermore, since Mars is considerably smaller and lighter than earth, its gravitational problems are smaller. Mars, however, still requires an escape velocity of 16,400 fps plus an equal braking velocity for launching—more than double the moon requirements. The total round-trip velocity requirement for an expedition to Mars would be well in excess of 70,000 fps. Realizing how much greater the payload requirements would be for such a trip, we can see that the Mars launch vehicle would have to be many times the size of the total Saturn V-Apollo assembly if chemical engines and earth launch are used.

Perhaps, instead of attempting to boost such a monster off the face of the earth, teams of astronauts could assemble the Mars vehicle in earth orbit by means of shuttle vehicles and perfected rendezvous and docking techniques. The load of propellants required to boost a space ship out of orbit is but a fraction of that required to boost it off the ground. Visits to planets other than Mars would almost certainly demand such procedures.

We could go on from here to discuss the possibilities of interstellar travel, but it is time to call a halt. The means of escape from the solar system are within man's reach. The means of getting to a destination in interstellar space, however, as we indicated in Chapter 4, are still far beyond man's capabilities. Let us conclude, then, with a "conservative" thought You now know the dimensions of some of the problems of propulsion, control, and guidance of space vehicles in terms of interplanetary travel—in a solar system man has hardly begun to explore. These are the challenges that astronauts, perhaps you among them, will face in your lifetime . .

## SUMMARY

The more one examines the operation of vehicles in space, the more one is aware of the fact that achieving a precise velocity is the greater part of guidance. Unlike ground or air travel, in which velocity determines the time taken to reach a destination but not the destination itself, velocity determines the trajectory taken by a missile, the orbital height reached by an Earth satellite, or the pathway that a vehicle in solar-system space can take to another planet. The art of space travel is that of using brief inputs of man-made velocity, provided by rockets, for the sake of catching free rides on the natural forces of gravitational attraction provided by the sun, and earth, other planets, and moons

On analysis, all pathways through space, from missile trajectories to interplanetary voyages, are orbits, parts of orbits, or hyperbolic trajectories around some center of gravity. Even a missile or sounding-rocket trajectory from one point to another on the face of the earth, if its pathway were projected into the solid earth, is revealed to be an elliptical orbit around the center of the earth. Missiles have sufficient velocity to travel through space thousands of miles before reentering the atmosphere.

Sounding rockets may rise to altitudes of a thousand miles or more at suborbital velocity. Sounding rockets of still higher altitudes have sufficient velocity for orbit but are injected at too high an angle to have the forward velocity to "outrace the horizon" and stay aloft for repeated turns around the earth.

The minimum-altitude orbit of the earth is achieved by a satellite injected *horizontally* at about 100 nm altitude at a speed of about 25,600 fps. Assuming burnout of the rocket at that point, gravity will begin to pull the vehicle downward, but the vehicle's forward velocity will carry it around the curve of the earth at the same altitude before it can return to earth. Assuming the same 100 nm burnout and injection point, greater and greater injection velocities will boost the vehicle to higher and higher apogees, but they will always return on elliptical pathways to the same 100 nm perigee.

This paradox must be noted. the higher the injection velocity, the slower the average speed. An addition of velocity in space can only boost a vehicle to a higher orbit where it will move slower. Similarly, retrothrust or braking velocity applied in space is a method of speeding up by drawing the vehicle downward into a zone where the gravitational field will move it along faster.

If a circular orbit at a higher altitude is desired, a "kick in the apogee" is applied—a second impulse of rocket energy. If it is applied exactly at the apogee point, the vehicle will move out on a line *tangent* to the former ellipse and immediately swing into the wider orbit. A change of orbits in the same orbital plane (coplanar transfer) by this use of tangent points requires the least energy. This type of transfer also requires long, gradually curving pathways rather than shortcuts. Such minimum energy transfers are called Hohmann transfers after the man who first described the principle back in 1925. Nowadays, in boosting Earth satellites to higher orbits, sometimes greater bursts of energy are applied at *intersecting* rather than tangent transfer points.

Between these coplanar maneuvers and the control of the velocity vector to achieve non-coplanar transfers, practically any objective in near-earth space can be reached. It is impossible, of course, for a vehicle to orbit the earth in any plane except one that passes through the center of the earth, but a wider variety of ground tracks can be traced, or any point on the earth's surface directly overflown, by a satellite in accordance with these principles and with the right timing and velocity inputs. Perhaps the ultimate in earth-satellite maneuvers is that which boosts a satellite to a height of

19,351 nautical miles directly over the equator, where it will circle the earth in one day and appear to hover stationary over one point on the equator. Such satellites have proven valuable as communications relays.

Flights to the moon and to other planets are accomplished by following the same principles that govern earth orbits. but the problems of such flights are no longer two body problems (that is. the Earth and a vehicle moving in the earth's gravitational field).

One difficulty of reaching or circling behind the moon lies principally in the fact that, as one aims for apogees beyond 100,-000 miles. the differences in velocity requirements grow smaller and smaller for reaching greater and greater distances. If the shot at the moving target which is the moon is given enough velocity for complete escape from the earth's gravitational field. it can be aimed with enough precision to hit the Moon, but if orbiting the satellite around the moon or capture by the moon's own gravitational field is the object. the velocity must be adjusted very precisely.

Some idea of the complexity of the Apollo manned expedition to the moon is indicated by summarizing the flight plan. Such unique steps as separating and reassembling the vehicle in parking orbit around the earth. separating the modules again so that one lands on the moon while the other orbits the moon, reassembling the modules in moon orbit. and ultimately shedding all remaining modules and leaving only a small command module for earth reentry. are included A fast reentry is used depending upon only the atmosphere to cushion the descent. Otherwise the rocket and propellants needed for braking the reentry would greatly increase the final load.

Interplanetary flights with unmanned vehicles have already been accomplished. To reach the nearby planets. Mars and Venus, the orbital speed of the earth. 97.600 fps. is used. By achieving a launch velocity on the order of 2.000 fps in excess of escape velocity. either path can be chosen. For an outward orbit around the sun to intercept Mars. the vehicle is launched ahead of the earth. and for an inward orbit to Venus. the vehicle is launched rearward so that its velocity is subtracted from rather than added to that of the earth Minimum energy or Hohmann-type routes are necessary at present. The planet in either instance is intercepted by a long orbital chase around the sun. Because of increase of gravitational field strength with closeness to the sun, the inward path is more difficult than the outward in solar-system space.

Other oddities of interplanetary travel include the possibilities of using fly-bys of planets as a means of increasing velocity, and use of low-thrust continuous propulsion in a spiral trajectory, as electric rockets become available. The largest problem to be faced in planning a manned landing on another planet is the velocity requirement for landing and escape, in addition to that required for the space journey. Assembly of vehicles in orbit may be the answer.

## WORDS AND PHRASES TO REMEMBER

angle of inclination
aphelion
coplanar transfer
fast transfer
ground track
heliocentric velocity
Hohmann transfer
hyperbolic trajectory
non-coplanar transfer
parking orbit
perihelion
readout
transfer
transposition
velocity requirements

## QUESTIONS

1. Explain the paradox of increasing velocity to slow down in terms of satellites in Earth orbit.
2. In launching a vehicle into orbit, what point of the orbit is established by burnout and what point is established by velocity at burnout?
3. What is a "total velocity requirement"?
4. What rule applies to the plane of a ballistic missile trajectory or satellite orbit?
5. What are some of th practical uses of earth satellites?
6. How is an elliptical orbit circularized?
7. What kind of transfer is accomplished by use of tangent trajectories? Intersecting trajectories?
8. In general, what kind of trajectory is characteristic of low-thrust electric rocket propulsion?
9. What is a "coplanar transfer?" A "non-coplanar transfer?"

10. What are the basic steps by which a synchronous satellite is placed in "stationary" orbit over the equator?

11. What kind of orbit has a ground track that describes a figure 8 above and below the equator?

12. How much difference in velocity requirement is there between reaching a 100,000-nm apogee and reaching the moon?

13. In the Apollo program, what is the essential difference in method between landing on the moon and landing on the earth?

14. What is the general shape of the solar system?

15. If a vehicle is launched off the earth with escape velocity and no more, what is its velocity in solar system space?

16. To reach Venus, must the heliocentric velocity of a vehicle launched from earth be increased or decreased? How is this accomplished?

17. Why does it take more energy to probe the sun than to escape from the solar systm?

18. Why might a fly-by of Jupiter be advantageous in a voyage to an outer planet?

## THINGS TO DO

1 From current reading, find out what the current emphasis is on in the American and Soviet space programs. Pay attention to information relating to cooperation in space between the two nations.

2 Find out the status of manned and unmanned exploration of the moon and the planets. Which planets are receiving the most attention, and why? Also, keep up with the status of the Grand Tour. Financial problems have jeopardized this program. See if it is still alive.

## SUGGESTIONS FOR FURTHER READING

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INDEX

The following is a list of subjects of interest to the study of space technology, including many of the terms listed in the "Words and Phrases to Remember" sections at the end of each chapter, plus other entries. Terms in this list are adequately explained in the text, usually where first mentioned. Page references locate passages where the items are defined, discussed, or explained, as necessary.

## I



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186



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