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Propulsion for space vehicles

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8.1 THE CENTRAL IMPORTANCE OF PROPULSION

8.1.1 Introduction

Propulsion is the key to space travel. The future economy and logistics of space will depend upon the variety and efficiency of space propulsion engines in much the same way that terrestrial, surface, and air commerce and transport depend on the locomotive, the internal-combustion engine, and the turbojet. Rocket thrust has increased fivefold in every decade, from the V-2 engine (60,000 pounds in 1945) and the Atlas ICBM engine (300,000 pounds in 1955) to the F-1 and Saturn engines (1,500,000 pounds by 1965). Adequate propulsion magnitude and efficiency render the problems of structures, guidance, rendezvous, and landing much less difficult.

A propulsion system must have certain obvious virtues to be considered "adequate." It must be very reliable, free from hazard to humans, controllable with precision, not too expensive, and have a margin of surplus performance both in magnitude and in duration of thrust. Although the first adventures into deep space are interesting and important, they will be awkward and of little transport utility. Space travel will not have come of age until *efficient* propulsion is available. Lindbergh's single-engine flight was a great adventure, but it is a fleet of prosaic, reliable, four-engine transports that turn the Atlantic into a mill pond and make possible the current heavy traffic.

The absolutely fundamental performance limits to any reaction propulsion device imparting momentum to a payload according to Newton's second law are set by the availability of both matter and energy, and the ingenuity and efficiency with which maximum energy can be

transferred to the payload under the constraint of minimum expenditure of mass.

8.1.2 Varieties of Rocket Engines

Newton's second law may be embodied in a practical propulsion device in many ways. Setting aside, because of space limitations, the important class of engines which either consume air or are supported by it, and which play an important role when spacecraft fly within twenty miles or so of the earth's surface, there yet remain a number of basically different rocket engines which will function in a vacuum.

Liquid Propellant. An oxidizer and a fuel, for example liquid oxygen and hydrazine or liquid hydrogen, are sprayed into a pressure chamber and burned at pressures of 300 to 1000 psia and temperatures of 4000°F to 7000°F. These gases expand through a nozzle to velocities of the order of 2 miles per sec, producing a space thrust of about 300 lb for every unit weight flow (lb per sec) expelled.

Solid Propellant. An oxygen-bearing crystal in fine powder form, such as ammonium nitrate or ammonium perchlorate, is carried in a matrix (about 20% of the total weight) of rubber-like hydrocarbon polymer. Often powdered metals such as aluminum are added to increase the energy release per pound. This solid mass is ignited and burns at temperatures and pressures similar to liquid propellants to produce a typical space thrust of 275 lb per unit weight flow rate. The shape of the solid charge or "grain" must be carefully adjusted so that a more or less uniform thrust level is maintained as burning proceeds.

Hybrid Propellant. A typical "hybrid" engine utilizes a solid-fuel charge, over the surface of which a liquid oxidizer is sprayed. This has the characteristic advantage of liquids, that thrust can be started, stopped, or throttled, and it also retains the simplicity of a one-fluid plumbing system and the safety and reliability of a system in which fuel and oxidizer are not intimately mixed. Hybrid rockets are in an early stage of development, and the fundamental processes of combustion at a liquid-solid interface are not yet fully understood.

Nuclear Propulsion (Thermal). The core of a nuclear reactor is perforated, and hydrogen or ammonia is passed through and heated to the maximum temperature (about 5000°F) at which the core structure will retain its mechanical integrity and then expanded through a nozzle. This requires a power release in the core of about 100 megawatts per cu ft; it produces a space thrust of 600 to 1000 lb per unit weight flow of expellant, thus yielding double the performance of the chemical engines. The principal limit to the performance of this engine is the melting point of solid refractory metals.

Nuclear Propulsion (Unconventional). A number of "exotic" fission devices have been proposed to circumvent the material temperature limits just described. For example, a critical mass of *liquid* fissionable material is to be whirled in a cylindrical, porous, refractory basket and hydrogen then forced radially inward, cooling the basket and attaining the melting temperature of the nuclear fuel before escaping axially through the nozzle. In another system, critical masses of uranium and hydrogen are intermingled in a vortex flow, which retains the heavy uranium vapor and permits the hot hydrogen to escape. An even bolder scheme, adaptable only to large-scale devices, envisages propulsion by a series of small nuclear explosions—perhaps several hundred—set off beneath a massive base plate on which the payload rests. This idea, known as Project Orion, is in the study stage.

Electric Propulsion (Arc Jet). An electric propulsor can be defined as any system in which electromagnetic energy can be used to produce reaction thrust. One such system, simple in principle, is the thermal arc jet, in which a working substance or expellant is heated to a high temperature (10,000°F, or twice the temperature of chemical reactions is typical) by passing it through an arc and then allowing it to expand through a nozzle. This permits specific thrusts of 1000 to 2000 lb per unit weight flow of expellant, or twice the performance of the nuclear heat exchanger engine described in our mention of thermal nuclear propulsion.

There are two major problems to be solved with the arc jet. First, in any effort to raise the temperature (i.e., random translational velocity) of molecules above 5000°F, a large part of the energy supplied is lost in radiation, dissociation of the molecule, and convective heat losses to the chamber walls, so that the efficient production of translational molecular motion convertible to momentum is low; 40% is typical. Second, as will be explained in detail in Sec. 8.2, high specific thrusts require enormous power; the weight of the necessary large electric power plant is a handicap common to all electric propulsion systems.

Electric Plasma Propulsion (Ion Accelerators). The low efficiency of the thermal arc may be improved on by a system which generates charged particles such as Cesium ions and accelerates them in an ion gun similar to the gun used in television picture tubes to accelerate electrons. Such a device will yield 85% efficiency or more, and it will produce a specific thrust of 5000 to 10,000 lb per unit weight flow of expellant. However, the energy demands and other technical difficulties of this system are so great that in practice only a few millipounds of thrust have been produced in the laboratory. It is being developed (1961) with great vigor nevertheless.

Electric Plasma Propulsion (Magnetogasdynamic). In an ion accelerator engine the particles of the expellant carry a net charge and are acted on by a DC electrostatic field. Another means of exerting a body force on the elements of a plasma or an ionized gas exists that permits the plasma to be electrically neutral, i.e., to have a uniform mixture of positive and negative charges. In this technique the plasma is acted on by a *magnetic* rather than an electrostatic field. The appropriate conditions are transient and can be maintained only for microseconds, hence such an engine works in pulses, analogous to behavior of the internal combustion engine. Although the pulsed-plasma propulsor is the least well developed of all the electric engines, it has the greatest potential performance, since it will be able to produce "pinch" gas temperatures of millions of degrees in which nuclear fusion may occur, thus releasing energies even larger than those of the fission reactor.

Radiation Propulsion (Solar Sail). If the sun is used as a source of energy, the necessity for expulsion of mass can be eliminated completely. Sunlight at the earth's orbit exerts a pressure on a reflecting surface due to radiation alone of 10^{-4} dynes per cm^2. Such a force exerted on the thinnest possible plastic film produces finite accelerations of the order of 0.1 cm per sec^2. Surprisingly enough, this acceleration when continued for several months, as in a Mars voyage, produces terminal velocities comparable to those of both the electric and chemical systems. It has the logistic advantage that no mass is consumed, and if the navigator makes an error, he has a chance to correct it; the solar "wind" is not used up. In this system the astronaut's situation is quite analogous to that of an earthbound sailor.

Radiation Propulsion (Solar Collector). A rather elegant propulsion technique of somewhat limited performance is the technique in which a large mirror concentrates solar radiation on a heat exchanger that heats hydrogen for subsequent expulsion through a nozzle. The hydrogen temperature is limited by the laws of optics to something less than the sun's surface temperature, and a working fluid is required. However, problems of combustion and nucleonics are avoided.

Radiation Propulsion (Microwave). A system similar to the solar collector, but limited in application to high-altitude terrestrial satellites, is one in which a large, steerable, antenna disk on earth with an aperture of several hundred feet sends a high-power microwave beam to the satellite it is tracking. The satellite carries a medium-sized antenna of, say, 50-foot diameter, which is attitude-controlled to aim at the earth source. Such a link could transmit enough energy to operate a small but efficient ion engine, which could be used to correct errors and decay in the satellite trajectory. Probably a system for energy storage aboard the satellite, or a chain of ground stations to keep the satellite in view, would be required.

***Radiation Propulsion* (*Conversion of Matter*).** In the fission and fusion reactions a quantity of matter m is converted to energy E according to the Einstein equation

$$E = mc^2$$

where c is the velocity of light, 3×10^{10} cm per sec. Since radiant energy exerts a pressure, it is possible in principle to imagine a propulsor in which 100% conversion of matter to energy occurs. There is no known way under the present laws of physics for this to happen. However, if it did, the ultimate frugality of mass consumption would have been achieved, with a specific thrust of 10 million lb per unit weight rate of consumption of matter.

8.1.3 Conclusion

The gamut of propulsors just described ranges from the immediately available to the wildly improbable. However, the temper of the times is so unpredictable that it would be foolish to exclude any one of them. Today's radical is tomorrow's conservative, and the speed of technical development is apt to have made conservatives of us all before another half-decade has elapsed. In the sections to follow, we state certain ballistic facts of life, which will probably govern even the most exotic engines for some decades to come.

8.2 ENERGY AND MASS CONSUMPTION OF ROCKETS

8.2.1 The Trade-Off Between Energy and Mass

It can be demonstrated that, if the thrust of a jet is constant, the more frugally we spend mass the more prodigally we must squander energy. Assuming for simplicity a parallel jet of fluid which exhausts into a vacuum, the jet produces a thrust F of magnitude

$$F = \frac{\dot{w}}{g} c \tag{8.1}$$

TABLE 8.1
Power Consumed for One Pound of Thrust

Device	Mass Flow, lb/sec	Jet Speed, ft/sec	Jet Power, hp	Thrust, lb
Garden hose	1.00	32.0	0.03	1.00
Chemical rocket	0.005	6,400.0	6.0	1.00
Nuclear heater	0.001	32,000.0	30.0	1.00
Ion accelerator	0.0001	320,000.0	300.0	1.00

where $\dot{w}$ is the weight flow rate and c the velocity of the jet. The power in mechanical units required to create the jet is

$$P = \frac{1}{2} \cdot \frac{\dot{w}}{g} c^2 \tag{8.2}$$

hence

$$P = \tfrac{1}{2}Fc = \frac{1}{2} \cdot \frac{F^2}{\dot{w}/g} \tag{8.3}$$

or

$$\frac{\dot{w}}{g} = \frac{1}{2} \cdot \frac{F^2}{P} \tag{8.4}$$

Of the four variables power P, thrust F, mass flow $\dot{w}/g$, and exhaust velocity c only two are independent. It can be seen from equation 8.4 that, as mass flow rate is decreased and thrust is held constant, jet power P increases inversely. This is the major challenge and source of grief in rocket development. The data in Table 8.1 indicate the power requirements for one pound of thrust from various sample reaction propulsors.

We see from Table 8.1 that the required to produce one mass flow pound of thrust ranges from one pint of water per second to a mass per second comparable to the head of a pin while the power flow goes from what would light a 20-watt bulb to the full output of a Cadillac engine.

8.2.2 Charts for Power and Mass Flow

The equations 8.1–8.4 have been cross-plotted in Fig. 8.1 to indicate through several orders of magnitude the values of P, F, w, and specific impulse I_s. Note that hybrid units are used, since power and mass flow are metric and thrust is in pounds. It will be shown later that I_s, the specific impulse, is expressed in seconds, and that the exhaust

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