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EXPLORING IN AEROSPACE ROCKETRY
20. ELECTRIC PROPULSION

by Harold Kaufman
Lewis Research Center
Cleveland, Ohio

Presented to Lewis Aerospace Explorers
Cleveland, Ohio
1966-67

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20. ELECTRIC PROPULSION

Harold Kaufman*

The chemical rocket has a high propellant consumption because it has a low exhaust velocity. Because the relation between propellant consumption and exhaust velocity is not easily seen, some explanation is required. An important quantity in rocket space flight is the total impulse. This quantity is simply the rocket thrust multiplied by the thrusting time:

$$\text{Total impulse} = (\text{Thrust})(\text{Thrusting time})$$

In general, the longer the distance a rocket must travel or the faster must be its trip, the higher the total impulse must be. Thrusting time can be measured directly, but thrust itself can be calculated from

$$\text{Thrust} = (\text{Propellant flow rate})(\text{Exhaust velocity})$$

which may be introduced into the first equation as follows:

$$\text{Total impulse} = (\text{Propellant flow rate})(\text{Exhaust velocity})(\text{Thrusting time})$$

But, since propellant flow rate multiplied by thrusting time equals propellant mass, the first equation can now be simplified to describe total impulse as

$$\text{Total impulse} = (\text{Propellant mass})(\text{Exhaust velocity})$$

For a particular space flight, a certain total impulse is required. If the exhaust velocity is low, the propellant mass must be high. The chemical rocket has a low exhaust velocity and, therefore, needs a great amount of propellant.

The reason why chemical rockets have a limited exhaust velocity is because all chemical propellants have a fixed energy per pound (i.e., heat of combustion). Since the chemical combustion process can release only so much energy per pound, the exhaust velocity is limited to about 4000 meters per second. Fortunately, several other concepts of rocket propulsion systems promise much higher exhaust velocities. If these concepts can

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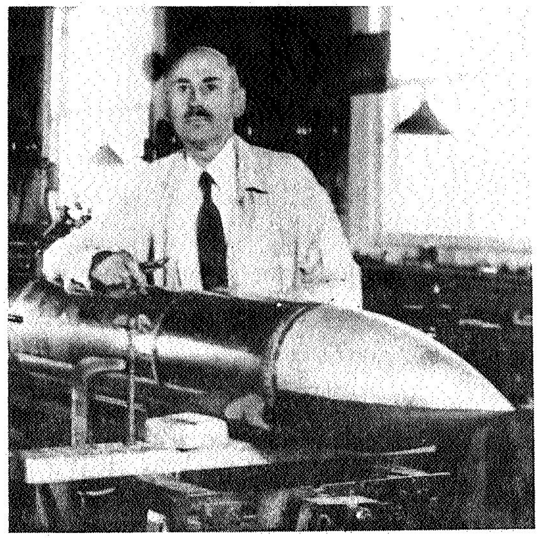

Figure 20-1. - Dr. Robert H. Goddard, American rocket pioneer.

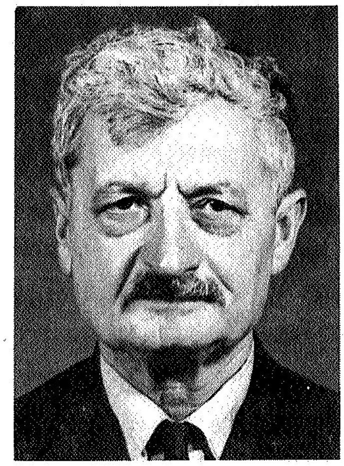

Figure 20-2. - Professor Hermann Oberth, German rocket pioneer.

be made practical, high propellant mass would be unnecessary and heavy payloads could be carried on long-distance, fast, space flights.

Dr. Robert H. Goddard (fig. 20-1), the famous American rocket pioneer, realized that chemical rockets were limited in exhaust velocity. In 1906 he wrote that this limitation in rocket exhaust velocity might be overcome if electrically charged particles could be used instead of burnt gases. Dr. Goddard's idea of using electrically charged particles as a rocket exhaust was in essence the birth of electric propulsion.

The idea of electric propulsion was explored further by Professor Hermann Oberth (fig. 20-2), a German rocket pioneer. In 1929, Professor Oberth described a possible electric rocket design which used high-voltage electric fields to accelerate charged particles to high exhaust velocities.

The acceleration of electrically charged particles requires a large quantity of electric power. In terms of propellant flow rate, the amount of electric power required is

$$\text{Power} = \frac{(\text{Propellant flow rate})(\text{Exhaust velocity})^2}{2}$$

In terms of rocket thrust,

$$\text{Power} = \frac{(\text{Thrust})(\text{Exhaust velocity})}{2}$$

Both of these equations show that electric power requirements increase as the exhaust velocity is increased. Suppose an electric rocket with a 1-pound thrust were to be built. For flights to the nearer planets, an exhaust velocity of 50 000 meters per second (about 100 000 mph) would be best for some electric rockets. More than 100 000 watts of electric power[1] are needed to accelerate enough charged particles to 50 000 meters per second in order to produce 4.45 newtons (1 lb) of thrust. That is enough electric power to light a thousand electric light bulbs or run a hundred electric washing machines.

In the time of Dr. Goddard and Professor Oberth, electric powerplants were very heavy, and conventional powerplants are still too heavy for use in electric rocket spacecraft. Moreover, they require large amounts of heavy fuel: coal, oil, or gas. Such powerplants are so heavy that very little payload could be carried.

The advent of practical atomic power improved the future of electric propulsion for space flight. As early as 1948, two British scientists, Dr. L. R. Shepherd and Mr. A. V. Cleaver (fig. 20-3), suggested that controlled nuclear fission could provide the lightweight power source needed for electric rockets. They described an electric generating system in which a nuclear reactor would heat a fluid to a high temperature. This fluid would drive a turbine, which would then drive an electric generator to provide the electricity required to accelerate charged particles to a high exhaust velocity. Although reactor structures and shields were quite heavy when Shepherd and Cleaver first proposed their plan, nuclear-energy technology has advanced rapidly, and their idea appears more practical today. The development of lightweight nuclear turboelectric systems for space propulsion power is one of today's most challenging problems. The solution of this problem may be one of the keys to practical interplanetary travel.

Once the theoretical feasibility of electric powerplants for space flight had been established, serious thought began to include another essential part of an electric spacecraft, the electric rocket engine or thruster. The first detailed discussion of the electric rocket engine appeared in 1954 when Dr. Ernst Stuhlinger (fig. 20-4) proposed designs for a cesium-ion engine, one of the types of electric rocket engine being tested today.

1

$$\text{Power} = \frac{(\text{Thrust})(\text{Exhaust velocity})}{2}$$

and 1 pound of thrust = 4.45 newtons; therefore,

$$\text{Power} = \frac{(4.45 \text{ newtons})(50\,000 \text{ meters per second})}{2}$$

Since 1 watt = 1 joule per second = (1 newton)(meters per second), power = 111 250 watts.

Dr. L. R. Shepherd

Mr. A. V. Cleaver

Figure 20-3. - Two British scientists who, as early as 1948, foresaw the use of controlled nuclear fission as a lightweight power source for electric rockets.

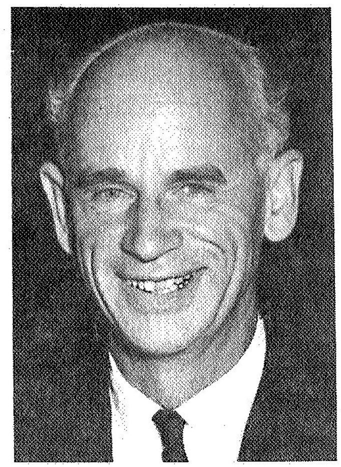

Figure 20-4. - Dr. Ernst Stuhlinger, who in 1954 presented the first detailed discussion on the electric rocket engine.

Many scientists and engineers have been working on electric propulsion for space flight since 1957. Research on electric propulsion has progressed to the point where electric rocket engines have actually been tested during short space flights. Much more research and development remains, particularly on advanced propulsion systems that convert nuclear to electric energy in new ways.

ELECTRIC THRUSTERS

The electric thruster is a device that converts electric power and propellant into a forward-directed force, or thrust. The general principle of operation is illustrated in figure 20-5. Electric power is used to accelerate propellant material to a high exhaust velocity. This velocity produces thrust. There are three general types of electric thrusters: electrothermal, electromagnetic, and electrostatic.

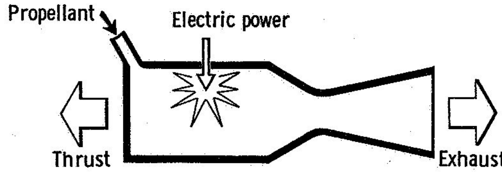

Figure 20-5. - Electric rocket engine.

Electrothermal Thrusters

The electrothermal thruster is similar in some respects to the chemical rocket. Although there is no combustion, the propellant gas is heated to high temperatures and expanded through a nozzle to produce thrust. This rocket can achieve exhaust velocities higher than those of chemical rockets because the energy added to the gas may be larger than the energy of combustion. Breakup or dissociation of the propellant gas molecules, which then absorb energy without raising gas temperature very much, places an upper practical limit on the amount of energy that can be added to the propellant. Other factors, such as material failure at high temperature, also limit the exhaust velocity.

The arcjet (fig. 20-6), in which an electric arc is used to heat the propellant, is one type of electrothermal thruster. The arcjet does not appear too promising as a thruster,

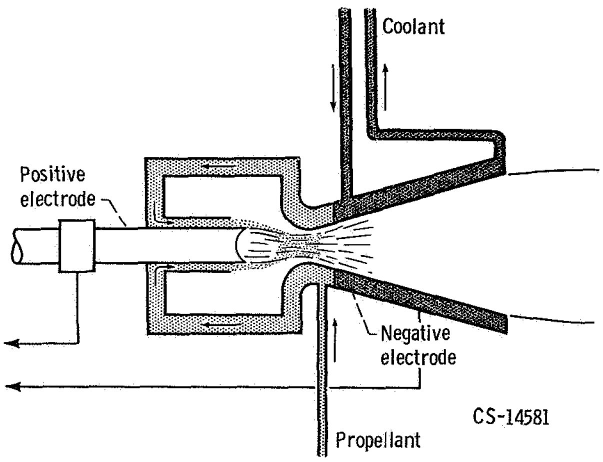

Figure 20-6. - Arcjet electric thruster.

but the technology gained in studying the arcjet has been useful for designing hypersonic wind tunnels and has led to the development of the MPD thruster, which will be described later. The second type of electrothermal thruster is the resistojet (fig. 20-7). In this thruster, a resistance heating element or hot wire is used to heat the propellant. The resistojet is simple, efficient, and reliable. The research effort on this thruster has been completed, and it is the one electric thruster that has already been used in a practical application - the station keeping of a satellite. Future missions will probably use one of the two types of electric thrusters to be discussed next, since they can produce even higher exhaust velocities than electrothermal thrusters.

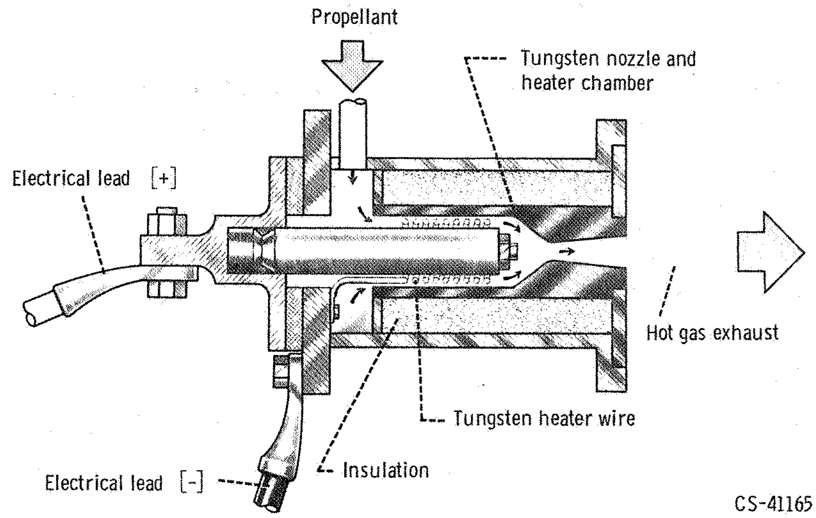

Figure 20-7. - Resistojet electric thruster.

Electromagnetic Thruster

The electromagnetic thruster is often called the plasma engine (fig. 20-8). In this thruster, the propellant gas is ionized to form a plasma, which is then accelerated rearward by electric and magnetic fields.

A plasma is merely an ionized gas, that is, a gas in which electrons have been removed from many of the atoms. In a neutral atom, such as those comprising the propellant gas, there are as many electrons around the nucleus of each atom as there are protons in the nucleus. Neutrons have no electric charge, protons have one positive charge each, and electrons have one negative charge each. With an equal number of positive and negative charges, the atoms are electrically neutral. This is the normal state for atoms

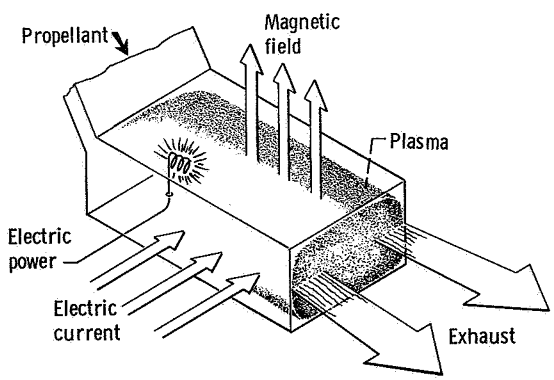

Figure 20-8. - Plasma engine.

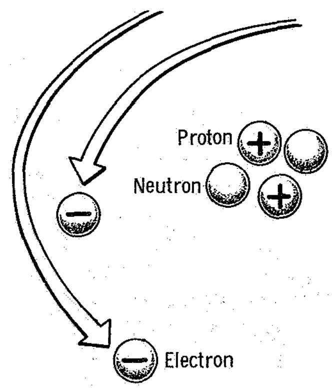

Figure 20-9. - Helium atom.

in a gas at ordinary temperatures. In figure 20-9, if one electron were knocked loose and away from the atom, the atom would have two protons and only one electron. Thus, a net value of one positive electric charge is left. The charged atom is called an ion.

The atom shown in figure 20-9 is a helium atom. It has a simple electronic structure. Other atoms have many more protons, neutrons, and electrons, but the principle of ionization is the same. An atom may be multiply ionized by the loss of several electrons. One of the significant properties of a plasma is that it can conduct electric current just as a copper wire can conduct current. It is this conductivity that makes it possible to accelerate the plasma as shown in figure 20-8. When an electric current is made to pass through the plasma in the presence of a magnetic field, a force is exerted on the plasma. Because of this force, the plasma is accelerated rearward to a high exhaust velocity. Thus, a plasma thruster is quite similar to an electric motor with the plasma taking the place of the moving rotor. This general acceleration principle has been used in many types of electromagnetic (or plasma) thrusters. Some of these have developed into potentially useful thrusters. Most are being used in various plasma physics experiments.

An even more promising electromagnetic thruster is the MPD or magnetoplasmadynamic arc type (fig. 20-10). It resembles an arcjet in general construction with the current passing between an anode and a cathode. It operates at a much lower propellant pressure than an arcjet, though, so that electromagnetic forces provide the dominant thrust-producing mechanism. The magnetic field either can be due to the current between the two electrodes, or it can be produced by a separate field coil as shown in figure 20-10. The advantages of the MPD thruster are its reasonable efficiency and the simplicity of associated electrical circuitry. It does not require much more than a source of low-voltage electric power. Considerable development remains, however, before the MPD thruster will be ready for use in space.

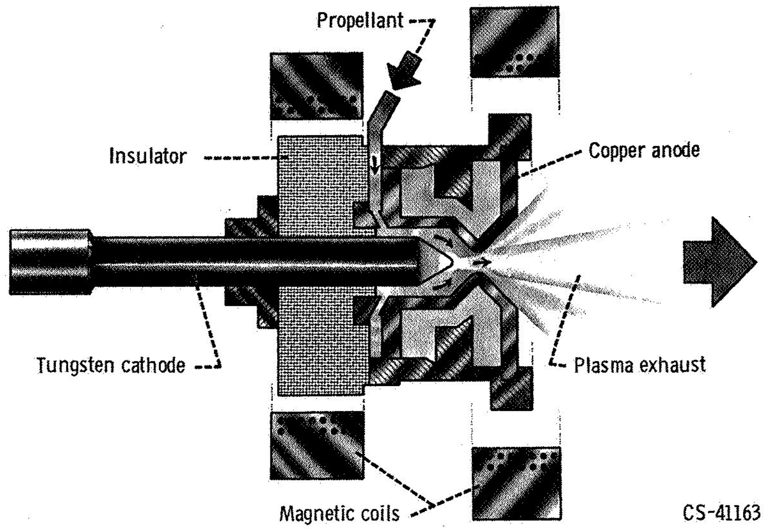

Figure 20-10. - Magnetoplasmadynamic (MPD) arc.

Electrostatic Thruster

The last general type of electric thruster, the electrostatic, is almost as well developed as the resistojet. It also uses ionized propellant, but the ions are accelerated without mixing in the electrons with them. After the ions are accelerated, the electrons must also be ejected. Otherwise the charge accumulation on the space vehicle would interfere with thruster operation. The mixing of the ejected electrons with the ion beam is called neutralization.

Simply stated, the operating principle of the electrostatic thruster is that like charges repel and unlike charges attract. The ion source has many like-charged ions which repel each other. The accelerator grid is charged with unlike charges, or electrons. This combination of repulsion and attraction serves to eject the ions with a high exhaust velocity.

There are different ways of producing ions. One is the contact ionization method (fig. 20-11) where a cesium propellant atom loses an electron (and thus becomes an ion) by passing through porous tungsten. The tungsten has to be hot enough to boil off the ions. The power needed to heat the tungsten is the largest loss in the contact-ionization thruster.

Contact-ionization thrusters appear best suited for low-thrust applications, such as station-keeping duty on a satellite. For larger sizes of electrostatic thrusters, electron bombardment appears to be a more efficient means of producing ions (fig. 20-12). Ions are produced in this type of thruster by striking propellant atoms with energetic electrons

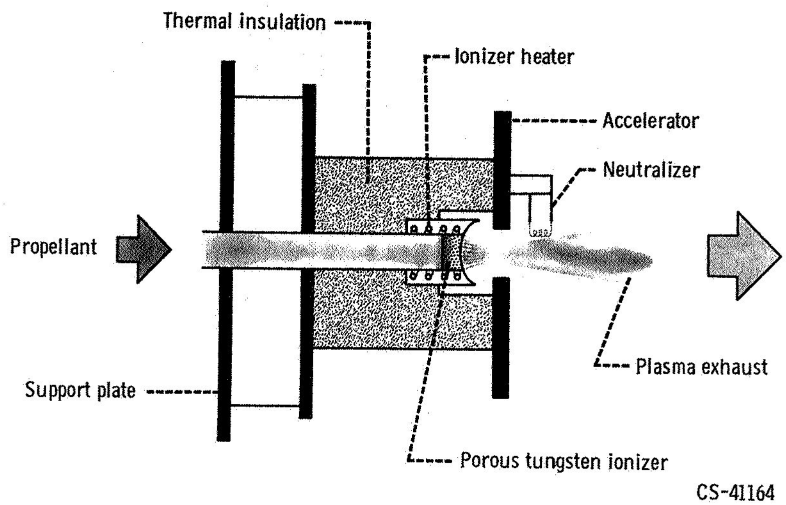

Figure 20-11. - Contact ionization thruster.

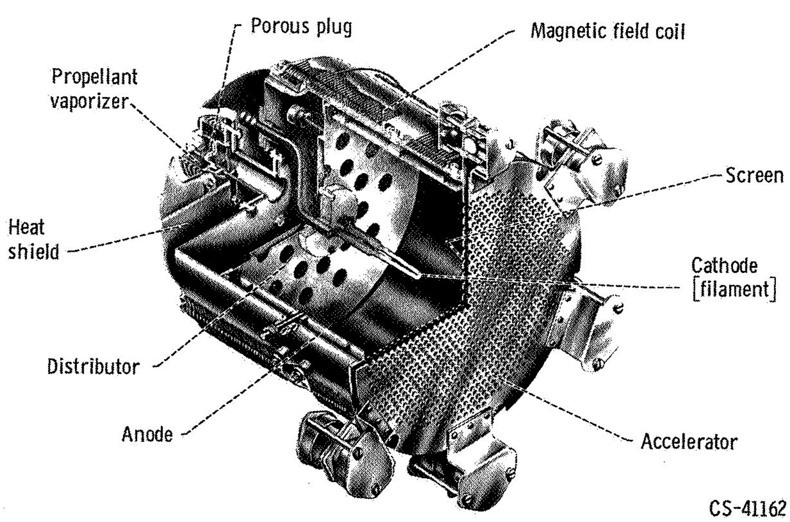

Figure 20-12. - Electron-bombardment thruster.

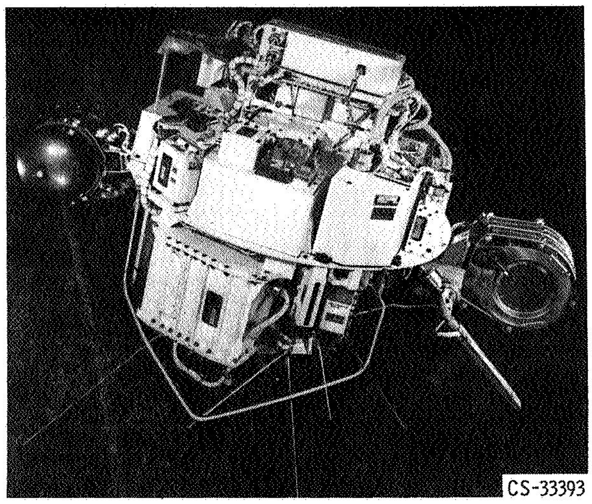

Figure 20-13. - SERT I spacecraft.

which are emitted from the hot cathode. The electron-bombardment thruster has already been tested in space for a short time on the SERT I payload (fig. 20-13). The letters SERT stand for Space Electric Rocket Test. SERT I was launched July 20, 1964, by NASA on a ballistic trajectory over the Atlantic Ocean. It was the first time that an ion engine of any type had been successfully operated in space. Measurements made during the flight conclusively proved that neutralization was not a problem and that an ion engine can generate thrust in space.

ELECTRIC POWERPLANTS

In the total electric propulsion system, the electric powerplant appears to be the heaviest component. For this reason, the specific mass of the powerplant is of major importance.

Space missions require very high total impulse, and the associated energy must be carried in a very lightweight form. Solar and nuclear energy sources appear to be the only forms of energy having sufficiently light weight. Solar energy itself is "free," but collection devices have an appreciable mass. Nuclear fission, radioisotope decay, and nuclear fusion all require onboard nuclear fuel, but the energy content is so high that fuel mass is a small part of the total mass for nuclear-electric powerplant schemes conceived so far.

A part of the solar spectrum is converted directly into electric power in solar cells by a photoelectric effect. Conventional solar cells are made of two thin layers of silicon, each of the two sheets having small amounts of artificially introduced impurity atoms.

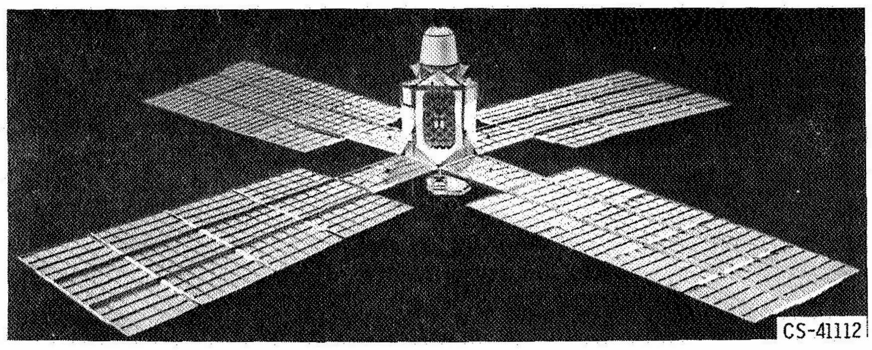

Figure 20-14. - Interplanetary probe with solar panels.

Collisions of solar photons with electrons in the top layer produce a current to the bottom layer, and hence electric power. Recent investigations with cadmium sulfide indicate that this material may be better than silicon for lightweight solar-cell arrays.

Studies of solar-cell panels based on present knowledge indicate that specific masses may be reduced to 25 to 50 kilograms per kilowatt for power levels in the range from 10 to 100 kilowatts operated in the vicinity of Earth. Such solar-cell panels would have an area of about 10 square meters for each kilowatt of electric power. The solar radiation varies inversely with the square of the distance from the Sun, so that solar-cell panels will produce less power for outward-bound missions. This effect is not severe for Earth-Mars missions, but is large for missions to planets beyond Mars. Future developments, such as the use of cadmium sulfide cells may permit the specific masses of solar-cell panels to be reduced to 10 to 25 kilograms per kilowatt. A design of a possible solar-powered interplanetary probe is shown in figure 20-14. The large solar-cell panels dwarf the rest of the vehicle.

Of the various powerplants being investigated for electric propulsion, the nuclear turboelectric is the most conventional in the sense that it has been used extensively for ground-based electric-power generation. The heat released in a nuclear reactor during fission is absorbed by a fluid passing through the reactor (fig. 20-15). The fluid carries

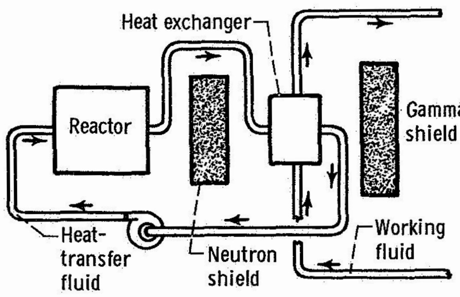

Figure 20-15. - Vapor-generating system of nuclear turboelectric powerplant.

this heat to a heat exchanger. There the heat of fusion is transferred from the heat-transfer fluid to the working fluid. The working fluid turns into vapor at a high pressure and drives a turbine. The turbine powers an electric generator to produce the electricity used to run the electric rocket engines.

Vapor being exhausted from the turbine must be cooled and condensed before it flows back to the heat exchanger, where it is heated and vaporized again. Because space is a vacuum, this cooling must be accomplished with a large radiator (fig. 20-16). There is

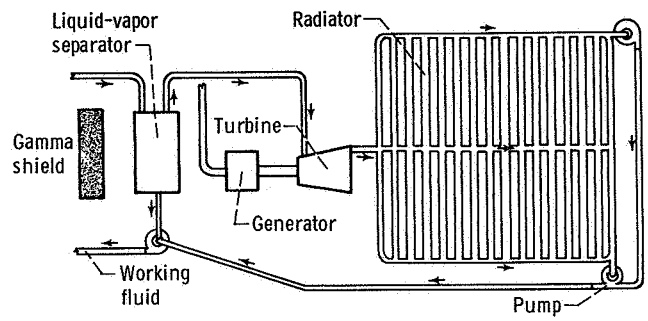

Figure 20-16. - Vapor-condensing system of nuclear turboelectric powerplant.

a greater probability of a micrometeoroid hitting a large area than a small one, and, therefore, the giant radiator must have tube walls thick enough to prevent punctures by micrometeoroids. Punctures would allow the working fluid to leak out. If this occurred, the spacecraft would stop thrusting and go into orbit around the Sun forever. Thick tube walls make the radiator heavy. Since very lightweight powerplants are needed for space flight, scientists are trying hard to design better, lighter radiators.

Analytical studies of nuclear-electric power sources for space use indicate that specific masses of 10 to 15 kilograms per kilowatt might be obtained. These low specific masses, though, require a powerplant which produces at least several hundred kilowatts. A powerplant with this capability is heavy, partly because a nuclear reactor must be large in order to function at all. This requirement for large size, together with the number of complicated components that are needed, means that such a nuclear-electric power source will be much more difficult to develop than a lightweight solar-cell power source. A nuclear-electric power source would, of course, have the advantage of being independent of solar radiation.

A design for an electrically propelled spacecraft using a nuclear-electric power source is shown in figure 20-17. Because a nuclear-electric powerplant has a low specific mass (kilograms per kilowatt) only in large sizes, the spacecraft of figure 20-17 is designed for a manned mission. To lighten the mass of the radiation shielding required,

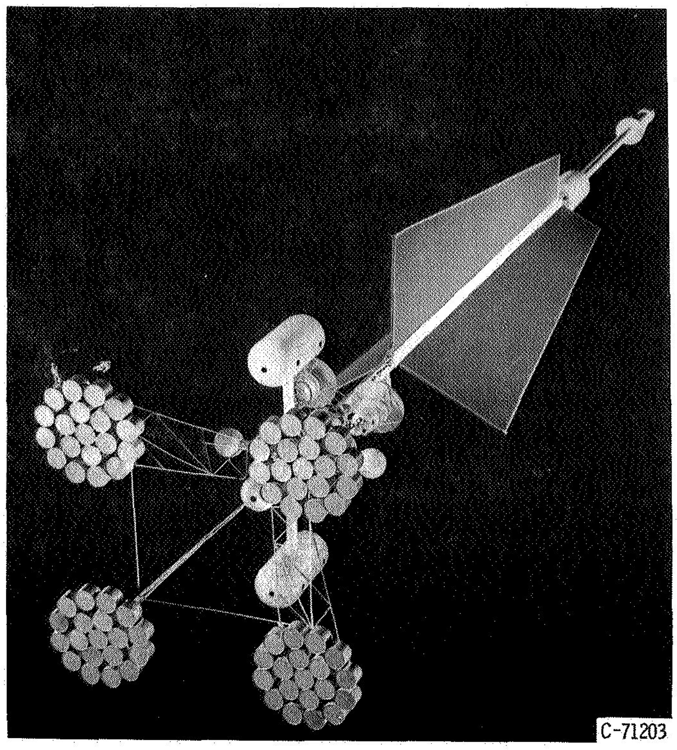

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Figure 20-17. - Nuclear electric spacecraft.

the nuclear reactor is at the opposite end of the spacecraft from the crew cabins. The large panels in the middle of the spacecraft are the radiators, and the electric thrusters are in the four clusters next to the crew cabins.

There are several variations of nuclear-electric powerplants that have been proposed for electric propulsion. These variations use thermionic converters or MHD (magnetohydrodynamic) ducts to replace the turbine and generator. Although even less developed than the turbine-generator approach, these alternatives would have the advantage of fewer moving parts.

MISSIONS

As mentioned earlier, the chemical rocket has an upper limit to its exhaust velocity; for this reason, a large propellant mass must be used for long-distance flights that require a large total impulse. The electric rocket has a much higher exhaust velocity, with the result that much less propellant is needed.

The propellant mass required for a particular space flight (i. e., a particular total impulse) can be shown on a graph (fig. 20-18). The electric power requirement, how-

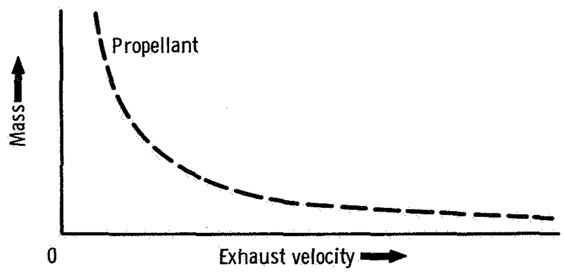

Figure 20-18. - Effect of changing exhaust velocity on propellant mass required for a specific flight.

ever, increases as the exhaust velocity increases. If the electric powerplant mass is directly proportional to its power output, the powerplant mass can also be shown on the graph as in figure 20-19. The sum of the propellant and the powerplant masses can now be shown with respect to the total spacecraft mass (fig. 20-20). The available payload mass is the shaded portion. There is a lower limit for the exhaust velocity; if the exhaust velocity is less than this lower limit, the propellant required would exceed the total mass of the vehicle. If the exhaust velocity is too high, the electric powerplant will have too much mass. In either case, the spacecraft cannot be built. It is evident that the best exhaust velocity to use is that which will allow the most payload to be carried (the lowest

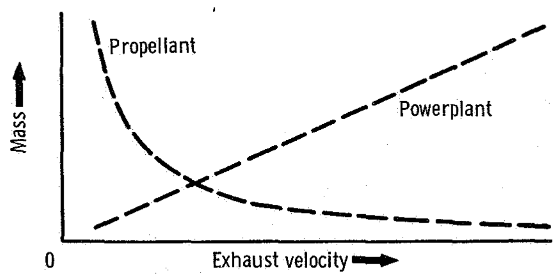

Figure 20-19. - Relation between powerplant mass and propellant mass for different exhaust velocities.

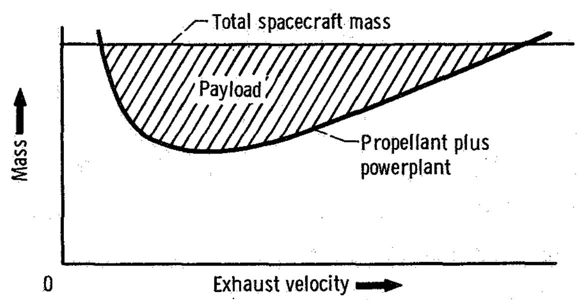

Figure 20-20. - Optimum mass and exhaust velocity for fixed total mass.

point on the shaded area of fig. 20-20). For trips to the nearest planets, the optimum exhaust velocity of electric rockets is almost always between 20 000 and 100 000 meters per second.

If a spacecraft is to take off from the Earth's surface, its thrust must be greater than its weight. For such a flight, the electric-rocket thrust would have to be much greater than the weight of the powerplant. The principles described so far can be used to show that extremely lightweight powerplants (of the order of 0.0001 kg/W) would be required. Thus, a powerplant with an output of 1000 watts could weigh only a few ounces. Space electric powerplants currently under development are hundreds of times heavier than this. Consequently, electric spacecraft currently being studied cannot be expected to take off from Earth. They must be boosted into orbit about Earth by chemical rockets.

Once in Earth orbit, electric spacecraft could fly very well with a small thrust. The electric rocket engine of an interplanetary vehicle would be started in orbit and the spacecraft would continue around the Earth in an ever-widening spiral until it effectively left the Earth's gravitational field (fig. 20-21). More precisely, it would enter a region in space where the gravity pull of the Earth is slight compared with the gravity of the Sun.

In this description of flight paths not much has been said of the actual speed of the spacecraft. Speed can be a misleading idea in the complex gravitational field of the solar system. Satellites decrease in speed as they move away from Earth. A low-level satellite moving at 7.7 kilometers per second (17 300 mph) takes about $1\frac{1}{2}$ hours to orbit the Earth. The Moon is a satellite of the Earth, too. It takes about 27 days to orbit the Earth, moving at a speed of about 1 kilometer per second (2300 mph). Thus, the Moon travels almost eight times slower with respect to the Earth than does the low-level satellite.

The electric rocket is also affected by this principle. It would move more slowly farther away from Earth. The work being done by the powerplant and the engine would be

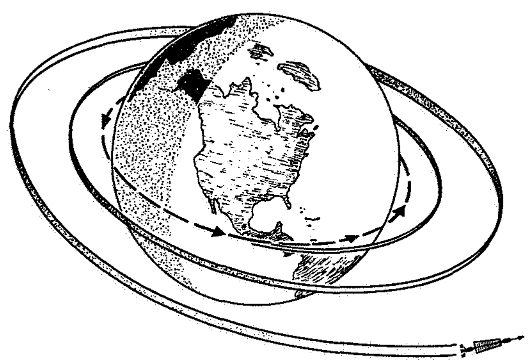

Figure 20-21. - Spacecraft departure path from Earth.

used in raising the ship up and out of the Earth's gravitational field. This work would not increase the ship's speed. The chemical rocket booster would provide the initial spurt in speed required to place the electric spacecraft in orbit. From there on, the electric rocket could provide the rest of the propulsion.

When the interplanetary electric spacecraft is hundreds of thousands of miles from Earth, the gravitational field of Earth becomes weaker than the gravitational field of the Sun. During the transition from dominance of Earth's field to dominance of the Sun's, the ship is attracted to both Earth and the Sun. This situation is so complicated that the ship's path must be calculated on a digital computer even when the rocket is coasting. When free from Earth, the ship still has the speed of Earth in addition to its speed with respect to Earth (fig. 20-22). For a mission to Mars, the electric spacecraft continues

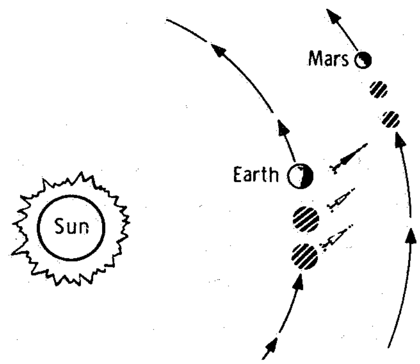

Figure 20-22. - Relative positions during spaceflight.

to thrust in the direction shown. Because it still has the speed impetus from Earth, it tends to move on around the Sun. The energy provided by the continued thrusting causes the ship to move farther away from the Sun, but because it is farther away from the Sun, it falls behind Earth in the race around the Sun. The initial speed provided by the Earth is important to any spacecraft. Without it the ship would fall into the Sun.

When the ship is about halfway to Mars, it is orbiting the Sun faster than Mars because it is closer to the Sun. In order to orbit Mars the ship must be swung around (fig. 20-23) to apply the reverse thrust necessary to slow it down to the speed of Mars. When the ship reaches the gravitational field of Mars, it must spiral down to a satellite orbit around Mars (fig. 20-24). The ship continues to thrust backward as it spirals down.

The low thrust of the electric rocket will not permit a direct landing on Mars. If the ship is manned, the crew may descend to the surface of Mars in a chemical rocket while the electric spacecraft continues to swing around Mars in its satellite orbit (fig. 20-25).

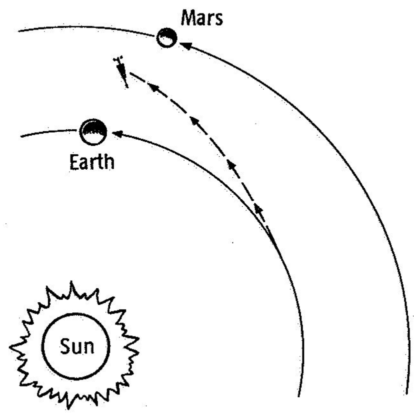

Figure 20-23. - Spacecraft assumes braking position.

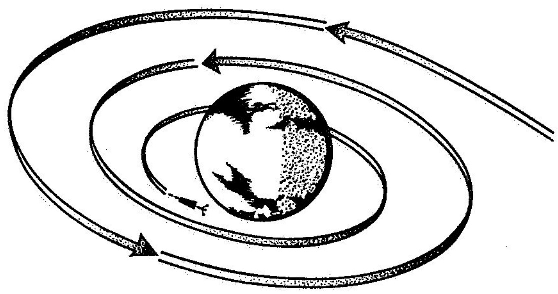

Figure 20-24. - Mars arrival path.

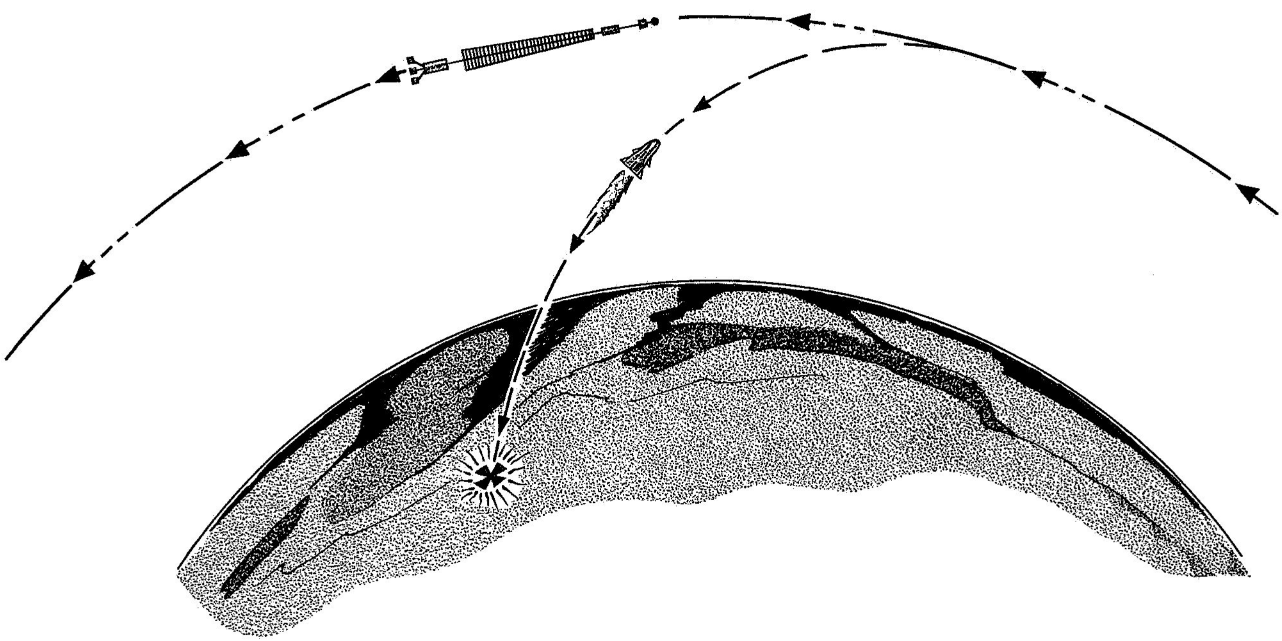

Figure 20-25. - Mars orbit and chemical rocket shuttle.

It is typical of interplanetary electric-propulsion missions that the thrustors are operated most of the time. This nearly continuous operation is necessary to make the best use of the limited power available for propulsion.

Figure 20-26 illustrates the theoretical performance of electric propulsion in orbiting a payload around Mars. The 25-kilograms-per-kilowatt curve is for power sources

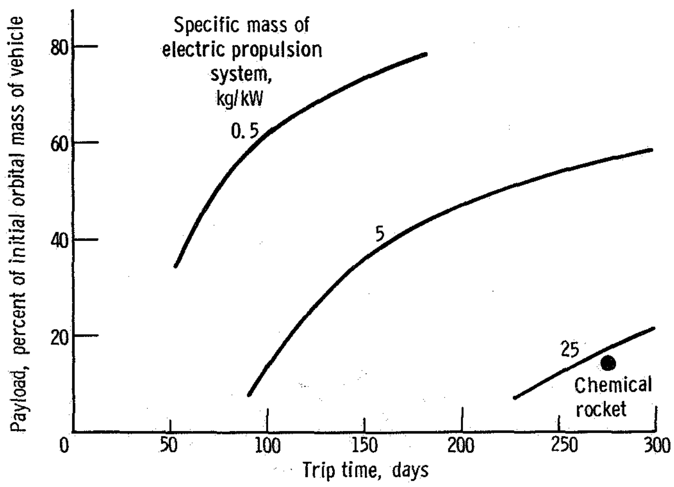

Figure 20-26. - Theoretical performance of electric propulsion system for Mars orbiter mission.

(either solar cell or nuclear electric) presently under development. The 5-kilograms-per-kilowatt curve is perhaps the best that might be hoped for with future development of these systems. Completely new approaches, though, may result in even lighter power sources, as indicated by the 0.5 kilogram per kilowatt curve. A word of caution must be included about these weights. The power source is the heaviest component of an electric propulsion system. Other components also have mass, as well as power losses, that must be included. Thus, the mass of the power source must be less than 25 kilograms per kilowatt if the complete system is to reach that value.

There are also various ways of conducting missions. Figure 20-26 is for a vehicle that uses electric propulsion starting from a low Earth orbit and ending in an orbit around Mars. If the space vehicle is first boosted to escape velocity from Earth (about 25 000 mi/hr) with a chemical rocket, the spiraling portion of the mission (fig. 20-21) can be omitted. The electric propulsion can then be confined to the portion of the mission that is in the Sun's gravitational field (figs. 20-22 and 20-23). This approach, called thrust augmentation, offers less gains for very light power sources, but substantially improves the performance of systems with 25 to 50 kilograms per kilowatt.

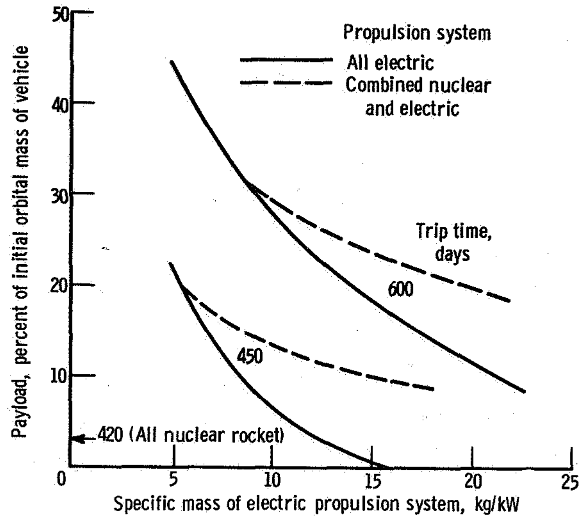

Figure 20-27. - Comparison of theoretical performance of nuclear and electric propulsion systems for Mars roundtrip mission.

The theoretical performance of nuclear and electric propulsion systems are compared in figure 20-27 for a Mars roundtrip mission. The percent payload was calculated on the basis of the starting mass in Earth orbit, as was also done for figure 20-26. Also, some atmospheric braking (11 km/sec) was assumed on return to Earth. Only one trip time is included for the nuclear rocket (420 days), inasmuch as additional time does not give payload advantages for the nuclear rocket in the same way as for electric propulsion. Two trip times are shown for electric propulsion. The 450-day trip time roughly matches the trip time of the nuclear rocket, and the 600-day trip time shows the effect of a substantial increase in this time. To approximate both the trip time and payload of the nuclear rocket, the electric propulsion system must weigh less than about 13 kilograms per kilowatt. If longer trip times are acceptable, though, the electric propulsion system can carry bigger payloads with even relatively heavy system weights. Also shown in figure 20-27 is the performance of a combined system. Roughly speaking, the nuclear rocket is used near planets (except for Earth atmospheric braking) and the electric propulsion system is used in interplanetary portions of the mission. For most of the range of interest, the combined approach shows advantages over either approach used alone.

Large interplanetary vehicles that use electric propulsion are many years away. The first practical applications of electric thrustors will be the control of satellites. In fact, as mentioned earlier, a resistojet has already been used in this application. Some satellites must be held in specific attitudes so that their instruments, antennas, or solar cells will work correctly. Other satellites must also be held in particular positions relative to Earth. For example, "synchronous" satellites must be held directly over a single spot on Earth. These are also called "24-hour satellites" because they orbit at such an altitude over the equator that the satellite revolves around the center of the Earth once every 24 hours. Since the Earth also rotates once in a 24-hour period, the orbiting satellite is stationary in relation to Earth.

Forces tending to disturb the attitude or position of a satellite are many; they are due to the oblateness of Earth and the gravitational attractions of the Sun, the Moon, and other celestial bodies. These forces are small, but over a period of days or weeks they can appreciably affect the satellite. Ion rocket engines may be well suited to overcoming these perturbing forces on satellites. The ion rocket thrust is small, but so are the perturbing forces.

Ion engines have a low propellant consumption because of their high exhaust velocities. Solar cells can provide enough electric power to run the ion engines. For these reasons, ion engines can be satisfactorily used for attitude control and position keeping of long-life satellites.

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