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Towards thermonuclear rocket propulsion

If controlled thermonuclear fusion can be used to power spacecraft for interplanetary flight it will give important advantages over chemical or nuclear fission rockets. The application of superconducting magnets and a mixture of deuterium and helium-3 as fuel appears to be the most promising arrangement

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THE extreme demands being made upon flight technology for space exploration emphasize the need for drastic innovations in propulsion systems. A possible new source of energy for such application is the controlled thermonuclear reactor. Although at present this kind of reactor does not exist, its anticipated enormous energy release per weight of fuel stimulates an interest in its development for space travel.

A thermonuclear reactor is a device which heats light elements to a very high temperature (hotter than the temperature of the interior of the Sun) in order that their nuclei shall combine or "fuse" into heavier elements. Concurrent with such a nuclear reaction is a large release of energy. A hydrogen bomb explosion is an uncontrolled form of this fusion process.

The most promising reactions are between isotopes of hydrogen and helium. The nuclei of these elements have the lowest electrical charges and thus require the least amount of energy to be brought close enough together for fusion to take place. Their reactions also release a great deal of energy (shown in Figure 1). The abundance of deuterium in sea water, extractable at low cost, makes the first two reactions of interest for stationary power plants on Earth. For this type of application the other two reactions may follow as "side" reactions. As will be shown later, however, this is not the desired sequence of events for a space propulsion system.

A measure of efficiency of a propulsion system, or engine, is its specific impulse. Specific impulse can be considered as the number of seconds that the system delivers a pound of thrust for each pound of propellant consumed. The specific impulse of a conventional rocket (Figure 2a) is limited to less than 500 seconds due to the maximum energy available from a chemical reaction. Specific impulses of twice this value are predicted by use of nuclear fission rockets (Figure 2b). Finally if the energy of the fuel is converted to electricity an unlimited specific impulse is obtainable by using an electrical accelerator, as in the much-discussed "ion engine" (Figure 2c). Here the source of energy is separate from the propellant; which is ejected from the rocket at very high velocity by the accelerator.

The difficulty encountered in going to systems which utilize the propellant mass more and more efficiently is that the weight of the equipment to do the job becomes heavier and heavier. A nuclear fission electric system has a weight of the order of 10,000 pounds per pound of delivered thrust. It is thus unable to take off by itself, even from the surface of the Moon. Once placed in orbit by a chemical booster, however, the electric system could eventually spiral away from the Earth with a continuous acceleration till it reached a very high velocity. The chemical rocket, by contrast, expends its energy in a very short burst and then coasts through nearly all of its flight path. When the weight of the propellant and fuel is considered in the weight of the space vehicle, the electrical system looks more promising than the chemical rocket for interplanetary travel. The booster needed to launch a manned interplanetary vehicle is within the sizes anticipated for the near future, provided the space journey is accomplished by a high specific impulse propulsion system—even if the equipment is fairly heavy. A manned chemically powered space vehicle, however, would require too large a fuel load to permit its being placed in orbit with any reasonable booster size, and would

Fuel	*Reaction*	*Energy release (Btu/lb)*
Deuterium +deuterium	$D+D \longrightarrow He^3+n$	$3{\cdot}4\times10^{10}$
Deuterium +deuterium (equally probable)	$D+D \longrightarrow T+H$	$4{\cdot}1\times10^{10}$
Deuterium +tritium	$D+T \longrightarrow He^4+n$	$14{\cdot}5\times10^{10}$
Deuterium +helium−3	$D+He^3 \longrightarrow He^4+H$	$15{\cdot}1\times10^{10}$

KEY

H proton (hydrogen−1)	He^3 helium−3
D deuterium (hydrogen−2)	He^4 helium−4
T tritium (hydrogen−3)	n neutron

FIGURE 1. *The four most promising thermonuclear reactions. The deuterium-deuterium reactions are most attractive for stationary plants on Earth, but the deuterium-helium-3 reaction appears to have important advantages in spaceflight.*

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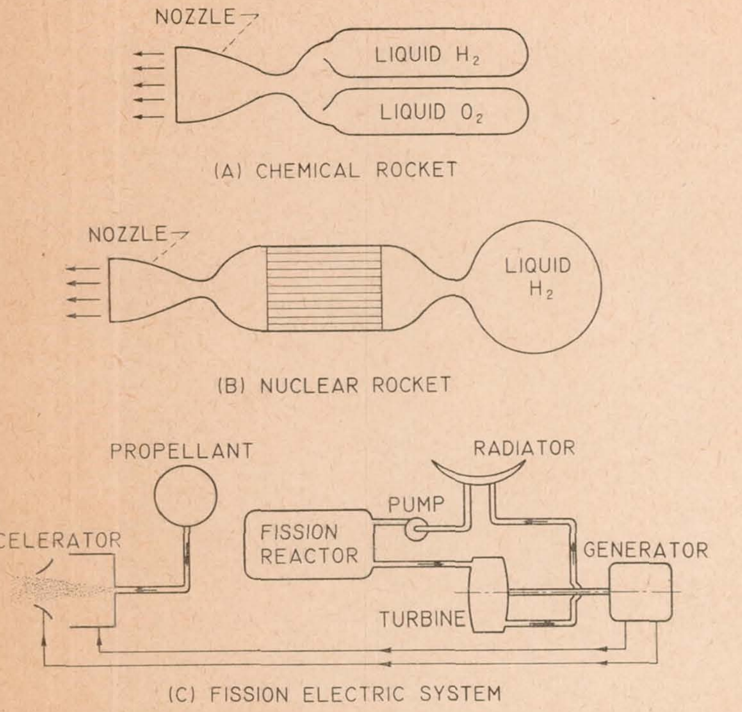

FIGURE 2. *Three types of propulsion systems.*

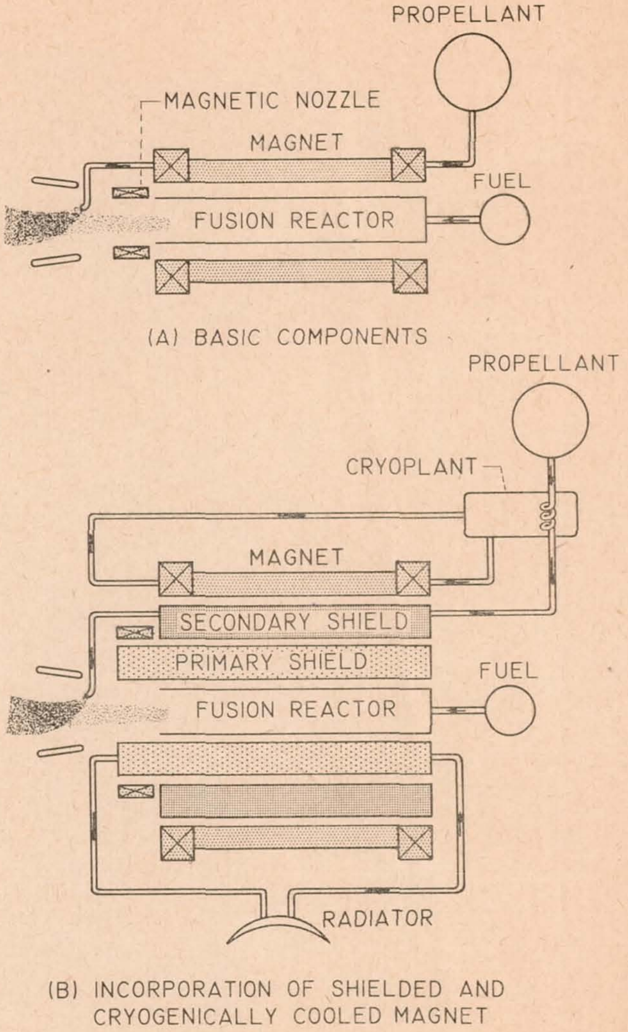

FIGURE 3. *Thermonuclear rocket.*

thus have to be launched from a space station.

The future weight of a nuclear fission electric system is predicted to be about 10 pounds per kilowatt of jet power. This large ratio of weight to power arises chiefly because of components such as the turbine, radiator, piping, and working fluid.

With these concepts and estimates in mind it is now of more interest to discuss the thermonuclear rocket. The basic components of a thermonuclear rocket are shown in Figure 3a. Little weight should be contributed by a self-sustaining fusion process. The products of the reaction have such a high energy that a specific impulse of the order of 100,000 seconds could be achieved merely by allowing them to leak from one end of the reactor. However, the thrust would then be rather small; it could be increased (with some loss of specific impulse) by mixing an additional propellant mass with the gas flowing from the reactor.

If, on the other hand, we want to use the fusion reactor to generate electricity, it is envisaged that it could be done directly, by pulsed operation of the reactor in such a way that the plasma of confined charged particles is expanded against a magnetic field. Thus it appears that the two heaviest major components (turbine and electric generator) present in a fission electric system may be absent in the thermonuclear rocket.

The release of enormous power from a thermonuclear reactor can be obtained only if the density and temperature of the plasma are kept at suitably high values. "High" in this case means number densities of the order of 10^{14} to 10^{15} ions per cubic centimetre and temperatures of the order of 10^8 and 10^9 degrees Kelvin. The corresponding pressure inside the reactor ranges from less than 100 to well over 1,000 pounds per square inch. Use of solid materials to confine this high temperature plasma would result in loss of heat into the walls so rapid that it would quench the reaction. Different types of magnetic fields have been proposed to confine the charged particles in the reactor: an example of a "magnetic bottle" is shown in Figure 4a. The magnetic pressure would then counterbalance the pressure of the plasma of charged particles, although neutrons given off in a reaction would be free to escape.

Conventional copper electromagnets used to create the magnetic bottle would weigh much more than the other components of a thermonuclear propulsion system. Moreover, the power requirements of such a magnet could well exceed the available electrical energy. The power consumption could be reduced by cooling the windings to a low temperature (10 to 100 degrees K). Part of this cooling could be effected by ducting the propellant being used through the magnet. The magnet could be further cooled, though at the expense of further weight and power consumption, using a cryoplant (refrigeration system). But the heat which the cooling system must remove from the magnet is not simply that produced by the electric current. The fact that the reactor must operate between 10^8 and 10^9 degrees K, whereas the magnet must operate between 10 and 100 degrees K, illustrates the difficulty of the heat insulation problem. Nevertheless the magnet can be quite effectively shielded from the heat radiation given off from the reactor.

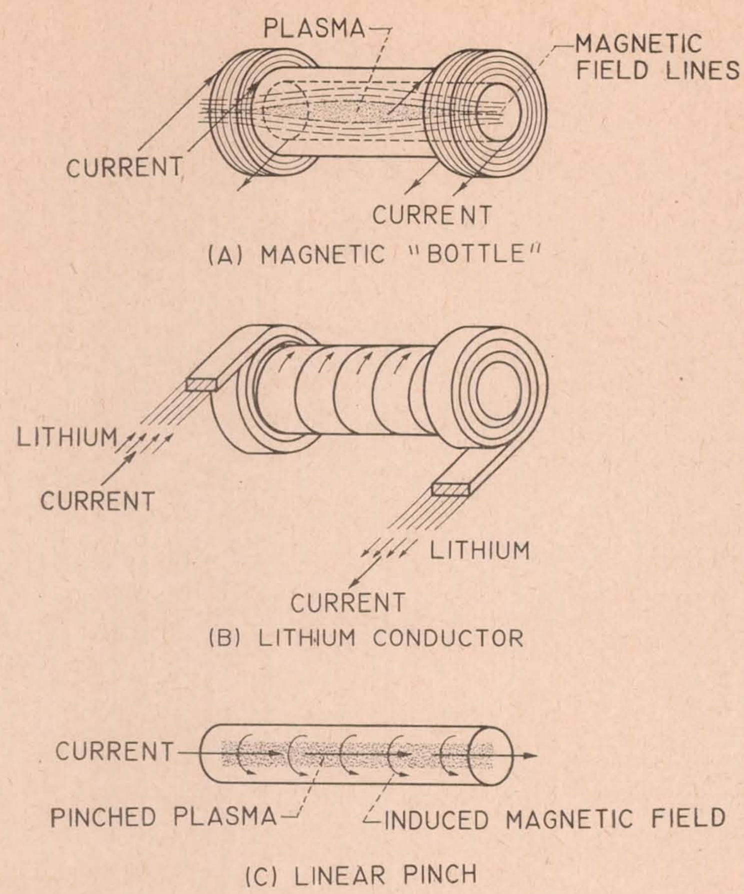

FIGURE 4. *Plasma confinement.*

The shields are, however, quite ineffective in stopping high energy neutrons, which would enter the magnet and heat it appreciably. The crew of the spacecraft would have to be heavily shielded against neutrons, at a great expense of payload. The deuterium-tritium reaction of Figure 1 liberates about 80 per cent of its power in the form of high energy neutrons. The deuterium-deuterium reactions also release neutrons in abundance, and in any case yield much less energy. These three are therefore undesirable reactions for use in the type propulsion system being considered. The deuterium-helium-3 reaction, on the other hand, liberates a large amount of energy, all of which is in the form of charged particles which can be confined. If the reactor can be kept at a high enough temperature the deuterium ions will combine with the helium ions much more readily than with other deuterium ions. With a suitably shielded system such as shown in Figure 3b and a deuterium-helium-3 reaction it is possible to keep the magnet at desirable temperatures.

Some weight reduction may be obtained if the magnet and shield are combined as proposed by J. R. Roth. In such a combination (Figure 4b) liquid lithium serves both as a conductor of electricity and as a means of ducting heat away from the reaction zone. This heat could in principle be utilized in an auxiliary turbo-electric generator, but if it were done on a worthwhile scale the weight of the system would approach the relatively heavy nuclear fission electric system described above. So it would usually be better to reject this heat directly to space by means of a radiator.

The "linear pinch" reactor (Figure 4c) was studied for thermonuclear propulsion by M. U. Clauser. In this case a discharge of electric current along the axis of the reactor induces a magnetic field that "pinches" or confines the plasma. If this device could be made to work satisfactorily the magnet could be eliminated and with it the weight and power consumption of the cryoplant. Unfortunately, experience shows that an external magnet is required for stability purposes and there is considerable scepticism about whether this particular type of reactor will ever produce thermonuclear energy.

Let us return to the two-shield system of Figure 3b. If liquid helium flows through the magnet and the heat which it absorbs is removed when it reaches the cryoplant, the magnet can be kept at such a low temperature that it reaches a "superconducting" state—provided it is made of a suitable metal or alloy. In this state there is essentially no resistance to current flow and once the current is started, it will flow indefinitely around the circuit with no power expenditure. The superconducting state can be destroyed by too large a current flow or by too large a magnetic field in the environment. Recent advances in superconductivity (using niobium-tin alloy Nb_3Sn) have led to the accomplishment of current densities of the order of 10^5 amperes per square centimetre at magnetic field strengths of the order of 100 kilogauss. By this means the magnet weight may be reduced to an almost negligible value and the only power consumption is in the cooling plant.

The overall performance of such a thermonuclear propulsion system has been estimated. The thrust in pounds per pound of engine weight may be as large as 0.01, corresponding to about 1 kilowatt of jet power per pound engine weight, while the specific impulse is of the order of 10,000 seconds. This performance is an order of magnitude better than that predicted for the nuclear fission electric system. A weight breakdown of a thermonuclear system is shown in Figure 5. An engine having 100 megawatts of jet power (large enough for manned interplanetary travel) would consume fuel at the rate of 2 pounds per month and propellant at the rate of 17 pounds per hour. Provided, therefore, that controlled thermonuclear fusion can be obtained, the high efficiency and relatively low weight should make the thermonuclear rocket, utilizing superconducting magnets and a deuterium-helium-3 reaction, a strong contender for future space travel.

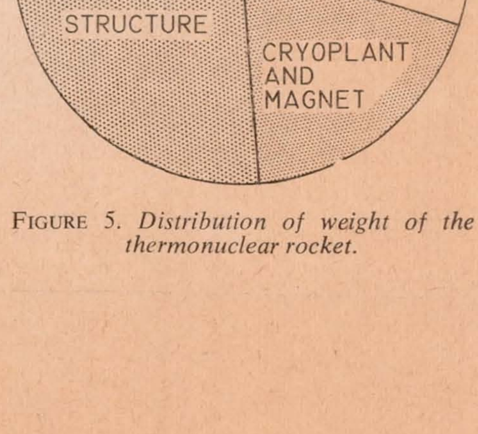

FIGURE 5. *Distribution of weight of the thermonuclear rocket.*