ium-tritium fusion reaction ignites at temperatures 10 times lower than the deuterium-deuterium reaction. For Mars trips, the rocket will burn hundreds of tons of deuterium and only about 10 kilograms of tritium. (Deuterium and tritium are the heavy isotopes of hydrogen.)

The conservative nature of the Livermore rocket design can be seen by the fact that it incorporates, at a large heat and weight penalty, tritium production. Ordinarily, it would be expected that terrestrial fusion reactors based on D-T would breed tons of tritium and could be readily expected to supply the kilogram requirements. But in his 1983 paper on the Livermore rocket design, Dr. Roderick Hyde notes: "One might assume that tritium will be acquired from terrestrial Inertial Confinement Fusion reactors. However, this delays the advent of rockets relative to initial Inertial Confinement Fusion success by a time-scale characteristic of the utility industry rather than that of aerospace. The Inertial Fusion Rocket discussed here will be designed to produce its own tritium; this will be seen to have important implications concerning vehicle heating."

This decision to intercept fusion neutrons with a lithium-tritium breeding blanket surrounding the magnet coil costs about 100 tons of mass—an almost 25% increase in rocket weight and a 20% decrease in power-to-mass capability. The fusion neutrons impinge on the blanket surrounding the magnetic coil and react with lithium to produce tritium. This is then captured and added to the fusion pellets.

Thus, the Hyde design is quite conservative. With a more optimal energy profile, it should be possible to significantly enhance the thrust characteristics of the Hyde rocket. Making use of more innovative concepts, in addition, could increase the overall thrust performance by an order of magnitude, as discussed in Part II of this report.

Power supply

The electrical power needed to run the lasers—about 3.3 gigawatts—is readily extracted from the expanding pellet plasma debris. Since the plasma is changing the flux of the magnetic coil, a few small induction coils placed between the ship and the main magnetic coil can readily pick up the

Nuclear reactions for rockets

The following are some nuclear reactions of interest for space rockets:

$\mathrm{D} + \mathrm{T} = \mathrm{He4}(3.5) + n\,(14.1)$

$\mathrm{D} + \mathrm{D} = \mathrm{T}(1.01) + p\,(3.03)$

$\mathrm{D} + \mathrm{D} = \mathrm{He3}(0.82) + n\,(2.45)$

$\mathrm{D} + \mathrm{He3} = \mathrm{He4}(3.67) + p\,(14.67)$

$n + \mathrm{Pu239} =$ two neutrons + fission fragments (270 +)

$n + \mathrm{U235} =$ two neutrons + fission fragments (200 +)

Here, the numbers in parentheses are the product energies in millions of electron volts (MeV). One electron volt equals 1.6^{-19} joules. Deuterium is the heavy isotope of hydrogen, whose nucleus contains one neutron and one proton and is indicated by D. Tritium, T, is the heaviest hydrogen isotope with a nucleus containing two neutrons and one proton. The heavy isotope of helium is He4 with a nucleus containing 2 neutrons and 2 protons. A free neutron is represented by *n* p; a free protron by *p*. The light isotope of helium is He3 whose nucleus contains one neutron and two protons. The fissile isotope of plutonium is Pu239. The fissile isotope of uranium is U235 which has 92 protons and 143 neutrons in its nucleus.

From these, there are three possible fusion fuels: DD, DT, and DHe3. The DT reaction ignites at the lowest temperature, and maintains the largest burn rate at all reasonable temperatures. Unfortunately, most of the energy is carried off by an energetic neutron.

The two DD reactions burn at similar rates to each other, but their sum is worse in ignition temperature and maximum burn rate than DT. While direct DD burn releases relatively little energy, it produces T and He3 which promptly burn with another D. It can be calculated that, in this case of simple reaction kinetics, the DD is more efficient than DT at energy generation per unit weight. More specifically, DD produces 1.024 times more energy than the DT per kilogram. The net result in energy per mass is essentially the same for all three fuels.

The DHe3 reaction burns roughly as well as DD; it's harder to ignite but burns faster once lit; both fuels are worse than DT. All the energy from DHe3 is in the form of charged particles, and is thus potentially useful. Of the three constituents, only D is reasonably inexpensive. It has a cost of about $0.20/gm. By contrast, the cost of T is about $7,000/gm. The standard source of He3 is currently the decay of T, leading to the same price, although this might be lowered if usefully large lodes of He4 with above natural He3 fractions could be mined. Plutonium costs upwards of $50/gm., while pure U235 costs several thousand dollars/gm. (It should be noted that hybrid fusion-fission power plants, in which fusion neutrons are utilized to breed fissile fuel—Pu239 from U238, U233 from thorium-232—in blankets surrounding the fusion plasma, will be the first types of thermonuclear reactors to be brought into operation. This hybrid technology should substantially decrease the cost of fissile fuels in general, well below the current cost levels quoted.)

required power. A short-term energy storage system is incorporated into the ship to provide the engine startup and a backup in the case of extended misfires.

The VIP and cargo modes

The 500-ton rocket could operate in one of two modes. The first would consist of a fast trip VIP mode delivering 50-ton payloads. The second would consist of a cargo mode delivering 1,500-ton payloads. The overall ship mass would be about 2,600 tons. In the VIP mode, most of the 2,000-ton mass would be for deuterium fuel. In the cargo mode, only about 650 tons of fuel would be utilized at most (**Table 3** and **Table 4**).

In terms of mission performance the rocket design was subjected to three levels of analysis of increasing sophistication. The first utilized the classical power-limited model, in which gravity and exhaust velocity limits are neglected. This case is easy to solve and gives an indication of the proper mission operating parameters. The next level of analysis takes into account the limits and tradeoffs of acceleration of exhaust velocity.

While a large exhaust velocity will eventually achieve a high velocity, faster rates of acceleration are attained by degrading the potential fusion pellet exhaust velocity of tens of thousands of kilometers per second, to levels of a few hundred kilometers per second and less. This is readily achieved with the Livermore rocket by simply adding mass to the laser fusion pellets. The pellets actually have masses up to several hundred grams. The extra mass lowers the temperature of the pellet plasma produced after the fusion microexplosion. And this reduces the pellet-debris exhaust velocity.

The results of the second level of analysis were utilized as the baseline inputs for complex computer codes. The world's most powerful computers were then used to do a full study of mission profiles, including the full effects of gravitation and planetary orbits, and requirements and optimum operating parameters derived therefrom for the third and final level of analysis.

The potential energy content per kilogram of fuel is an important parameter determining its potential performance as a rocket fuel. Chemical reactions, in general, have specific energies ranging from a few million to a few tens of millions of joules per kilogram of fuel. Nuclear fuel specific energies are 10 million times greater, ranging from several tens of trillions to hundreds of trillions of joules per kilogram of fuel.

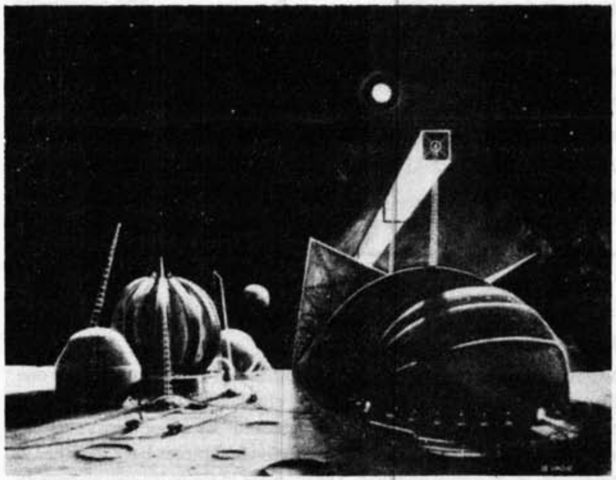
The velocity of the reaction products can be directly derived from their particle energies. The maximum reaction product velocity determines the maximum exhaust velocity that can be directly generated by a particular reaction—chemical or nuclear. The reaction product velocity is given by:

$$v = 9{,}790 \times \sqrt{(E/A)}$$

where v is the reaction product velocity in meters per second; E is the particle energy in electron volts; and A is the atomic weight of the reaction product. Chemical reaction products have energies of a few electron volts. This gives a reaction product velocity of about 540 meters per second when the product is a one electron volt water molecule. The proton generated in the D-He3 reaction has a velocity of about 35 million meters per second.

Nuclear fuels have exhaust velocities far in excess of what is generally needed for trips within the Solar System. For example, 1 g constant acceleration trips to Mars require maximum rocketship velocities in the range of hundreds of kilometers per second, while the nuclear fuel reaction products have the potential of reaching tens of thousands of kilometers per second.

FIGURE B4



Scientists at the University of Wisconsin have proposed using a fusion reaction of the hydrogen isotope deuterium combined with helium-3, a rare isotope of helium. Helium-3 is not found on Earth because Earth's atmosphere does not let the helium-3 from the solar wind reach the ground, but it is abundant on and near the surface of the Moon. This painting shows unmanned rovers, which are utilized to extract helium-3 from Moon soil, returning to base. The helium-3 is extracted in an on-board furnace, which heats the lunar soil to 600° C. The extracted helium-3 is then stored in tanks on the side, while the mined lunar soil is ejected. The helium-3 will be used as fuel to power fusion reactors to provide energy for spacecraft propulsion and industry on the Moon, as well as to meet the energy needs on Earth.