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The space transport needs for Mars colonization

Charles B. Stevens reviews the prospects of space transport with a view to achieving a permanent colony on Mars within 40 years. Part of an ongoing series on new methods of space propulsion.

> It is the year 2015. A conical spaceship as wide as a football field hovers in orbit above Mars. Out of its blunt bow, a landing craft carries its human passengers slowly to the planet's surface.
>
> —From *Interplanetary Propulsion Using Inertial Fusion* by Charles D. Orth et al., Livermore (UCRL-95275) (1987).

The following report reviews the current and future prospects of space transport with particular emphasis on achieving a permanent, significantly self-sustaining colony on Mars by approximately 2027 A.D. through both a technologically and economically feasible crash program. To establish a colony on Mars during the next four decades will require trillions of 1987 dollars. Therefore, to be economically practical, the permanent Mars colony must not only have a high pay-back following completion, but the scientific and technological spin-offs generated during its construction must produce a net operating benefit for terrestrial economies. This requires that the specific future and existing technologies, such as controlled thermonuclear fusion, utilized for the crash Mars program not only prove feasible, but are most efficient in producing productivity increases in the civilian economy.

Effective space transport in general requires extremely high units of power, efficiently delivered at high fluxes and energy densities over a wide range of values of the total energy spectrum. Happily, these same general features also characterize the general trends of advance for tools and machines most emphatically seen since the 16th century.

Existing power plant units, weighing tens of thousands of tons, deliver on the order of 1 gigawatt of electric power with operational efficiencies of about 30%—i.e., about 70% of the throughput of the energy potential of the fuel must be removed from the power plant as waste heat. Rockets for Earth to Mars transport will require power units delivering a trillion watts of thrust at 99% operational efficiencies—i.e., the ratio of the waste heat that is absorbed by the rocket, and must be rejected, to the thrust energy must be on the order of 1 to 99.

The rocket engine achieving this level of performance would have a mass on the order of a few hundred tons; in other words, a 1,000-fold increase in gross output, a 50-fold increase in net operating efficiency, and 100,000-fold increase in overall operating power density—the power to mass ratio. The fuel utilized must be thousands of times cheaper and have thousands of times greater energy potentials per unit mass.

Obviously, the technology of the rocket engine attaining this level of performance would also make possible much more versatile, powerful, and economical terrestrial power plants. This generally means that development of such rocket engines will have to be based on advanced thermonuclear fusion energy technology.

Today, fusion energy research has been held back due to lack of funding. The Mars colonization effort will necessitate putting the fusion program back on track and gearing it up to achieve more advanced systems than those currently contemplated for terrestrial power plants.

General requirements

A key element in determining the technical performance requirements of interplanetary rockets for large-scale colonization of Mars is the fact that human physiology demands that prolonged zero-gravity environments be avoided. It would, therefore, in general be required that rockets for human transport achieve high, constant accelerations approaching about 1 g—10 meters per second squared—about the same as that produced by the Earth's gravity at its surface. Interestingly enough, in terms of technical feasibility, a rocket was designed in the 1960s using existing, off-the-shelf technology which could achieve this constant acceleration and deliver upwards of several hundreds of thousands of tons payload. But this super-supertanker-scale spaceship would require using up the entire Soviet inventory of nuclear weapons for a single, one-way trip to Mars. This single, one-way trip in rocket fuel costs would consume on the order of 5% of the existing U.S. annual national economic output, and is therefore unacceptable.

To be fair, this gargantuan hydrogen bomb-powered rocket design put together in 1968 by Freeman Dyson, a scientist who worked in the U.S. pulsed nuclear rocket Orion Project (see **Figure 1**), was actually aimed at interstellar transport taking several decades of flight time. Its scale was not only a product of the technical requirements of high-performance hydrogen bomb-powered flight, but the design indicates one of the most feasible directions for attaining 1 g acceleration reaction rockets for Mars colonization within the coming decades: inertial confinement fusion (ICF).

In this case, micro fusion explosions, with millions of times lower yield than hydrogen bombs, could be set off by lasers and propel a much smaller and exceedingly more economical spaceship. Rocket fuel costs would be reduced several thousandfold.

In general the technical feasibility of acceptable transport to Mars depends on the three following areas of the existing frontier science and technology:

1) Plasma hydroelectrodynamics. This includes the production of dense ICF and magnetic fusion energy producing plasmas; ultra-strong, ultra-high energy flux hydromagnetic plasma configurations; multicomponent plasmas for maintaining and producing high-energy relativistic particle beams and energy storage systems; and high energy flux plasma environments for more efficient processing and fabrication of superalloys and advanced materials generally.

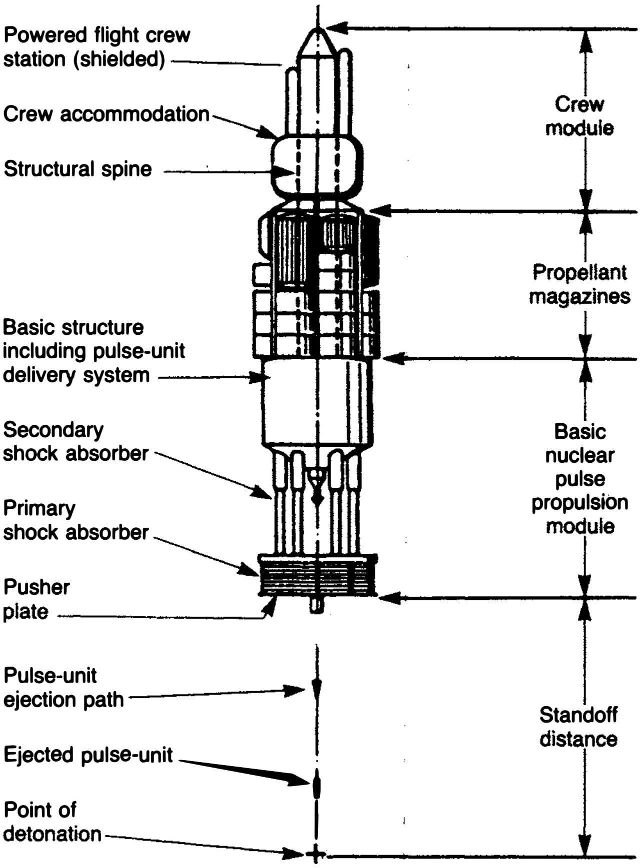
2) Coherent electromagnetic radiation. This includes pulsed, ultra-high-power lasers for ICF and continuous high output lasers for chemical and machine-tool-like processing of materials.

3) Advanced computing and control. Revolutionary in-progress developments here include: dedicated-application, "parallel processing" modules capable of terabit per second processing speeds; real-time control systems; optical analog devices for generating so-called non-linear solutions explicitly, holographically, by simulating constructive-geometric generations of Riemann surfaces and kindred functions. The development of optical/analog/digital hybrids with massive "parallel processing" capabilities, follows. These types of devices are necessary for many applications already practicable as soon as such devices are available, and will be indispensable for instrumention and diagnostics of controlled processes operating at ultra-high energy flux densities and ultra-short pulse increments.

Before proceeding to a more detailed technical review of these frontier areas and their existing and prospective future applications to Mars colonization, this report will outline the

FIGURE 1

Schematic of Orion vehicle



The above is a schematic of the declassified version of the Orion rocket developed under NASA contract NAS8-11053. Because of top secrecy, only a scaled-down version of Orion was made public. As Drs. A.R. Martin and A. Bond note in their 1979 Journal of the British Interplanetary Society *review of Nuclear Pulse Propulsion: "We may therefore conclude that this vehicle represents the lower end of the spectrum in both scale and performance for external nuclear pulse rockets and that far superior results could be achieved." The scaled down module was 10 meters in diameter, 21 meters long, and designed to be compatible with the two stage variant of Saturn V, which at that time was envisaged as the main workhorse through the 1970s and into the 1980s. The basic propulsion module mass was about 91 tons, but at the time of orbital ignition, the stage would have a total mass of up to 1,143 tons for missions to Mars, including a 20 man crew and 150 tons of payload.*

design and functioning of a recent ICF rocket design, raising important technical and scientific issues in this context, and then proceed to a brief history and review of nuclear pulsed rockets.

A laser fusion rocket for interplanetary propulsion

Before discussing the details of the Interplanetary Laser Fusion Rocket design, which was developed at Lawrence Livermore National Laboratory and presented by Roderick A. Hyde (leader of the Special Studies Group at Livermore that worked on it) to the 34th International Astronautical Federation held in October 1983, let us examine it *in operation,* in terms of a family moving to Mars in 2025.

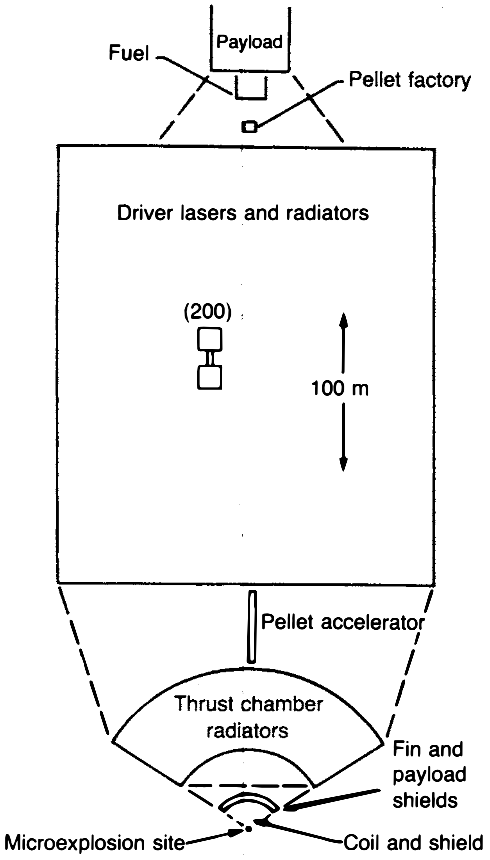
Several weeks before leaving for Mars the family would pack up their furniture and belongings and send them on ahead. These would be taken on a robot-piloted Livermore rocket flight to Mars. The robot flights take 22.2 days to travel the 100 million kilometers (60 million miles) to Mars. This is a little more than twice the time it takes for passenger flights—9.4 days. But this longer travel time permits the ship to carry a 1,500-ton payload—30 times greater than the 50-ton payload of the 9.4-day passenger mode.

On the day that the family is to leave for Mars, they go out to the municipal airport and board a transatmospheric aerospace plane. These supersonic aircraft are currently under development and are projected to become operational before the year 2000. Their primary function is that of rapid air transportation around the world. (As President Reagan's science adviser, Dr. George "Jay" Keyworth, noted when he announced the national program to develop such supersonic aircraft in 1985, these transatmospheric vehicles will be capable of achieving 6 to 10 times the speed of sound and will therefore be able to go from New York to Tokyo in less than two hours by the 1990s.)

Slightly modified versions of the transatmospheric aerospace plane can and will be utilized as the follow-on to the Space Shuttle for the delivery of material to near Earth orbit. While the Livermore rocket carries a passenger load the same size as that of a contemporary jumbo jet, the accommodations are actually more like that of an ocean liner. This is because, weight, not volume is the only impediment to travel in space. The rocket passenger quarters can be quite large. In our case, the plane would rendezvous with the Livermore rocket in Earth orbit. This transfer takes less than two hours. Shortly thereafter, the rocket engages its engine and the trip begins.

FIGURE 2

Vehicle layout of 1983 Hyde laser fusion rocket



The Livermore/Hyde rocket design utilizes a viable acceleration in order to achieve the most efficient trajectories. More advanced versions could achieve the more physiologically advantageous constant, near 1 g acceleration. At first, the acceleration of the ship is quite substantial—which is also the case at the end of the trip—almost one-tenth that experienced on Earth. At the midway point to Mars, the ship attains a maximum velocity of 165 kilometers per second—roughly 360,000 miles per hour. The ship then turns around and begins to use its engine to decelerate into an orbit around Mars. When Mars is reached after nine-and-a-half days, a transatmospheric plane makes a rendezvous in orbit with the rocket and transfers the passengers to a local Martian municipal airport.

Within a few days the family has fully recovered from the trip and begins life on Mars.

The Livermore rocket

Figure 2 and **Table 1** show a crude cross section of the Livermore rocket design. The payload is carried at the front of the ship (top of diagram) and is connected to the rocket engine by a 20-ton truss. The payload compartment contains a small megawatt fission electric power reactor to meet housekeeping requirements. Between the two is a small, automated factory for making the small hydrogen fuel pellets—weighing less than a few ounces apiece. These are consumed by the engine at a rate of 100 pellets per second. The primary fusion fuel is deuterium, which currently costs less than 20¢ a milligram and is readily obtained from seawater. Fifteen milligrams of deuterium are burned in each

TABLE 1

Fusion rocket compartments

Laser compartment	Tons
200 KrF lasers	110
Heat rejection radiators	92
Optics, structure	18
Energy handling	42
Subtotal	**262**
Thrust chamber	
Coil, shield, li-blanket	126
Heat rejection	40
Subtotal	**166**
Payload and fuel compartments (empty)	
Payload shield	17
Fuel tank	16
Housekeeping reactor	5
Support truss	20
Subtotal	**58**
TOTAL	**486**

TABLE 2

Rocket versus power plant requirements

	Rocket	Power plant
Power to mass ratio	High	Low
Total mass	Low	High
Waste heat	Low	High
Radiation containment	Low	High
Output entropy	High	Low
Neutron output	Low	High
Driver efficiency	Highest	High
Volume to mass ratio	High	Low
Surface to volume ratio	High	Low
Rep rate	Highest	High

pellet at a cost of $3 per pellet. The benign deuterium fusion fuel is carried next to the payload compartment. In fact, in the fast passenger mode, most of the large 1,500-ton cargo space would be taken up by deuterium fuel tanks and the cheap ballast material added to the fusion pellet to increase the exhaust mass of the rocket.

The rocket engine compartment begins with a 100-meter-long section containing 200 Krypton Fluoride (KrF) excimer laser modules. The lasers are spaced out over such a large area in order to enhance their radiant heat dissipation.

Heat dissipation is one of, if not the major problems of the design of a rocket engine. Not only must the rocket engine develop huge power thrust outputs with a small engine mass, but it must also do this at a high efficiency. If not, heat will build up in the rocket and cause it to melt.

Since there is no ambient material like air or water into which to dump waste heat in space, all of the waste heat must be radiated away. Effective radiation cooling calls for large surface areas, and high operating temperatures are required. If the rocket engine does develop significant amounts of waste heat, then a vicious circle develops. More mass is required in the form of heat radiators. This requires more engine power to propel the ship. The KrF laser was chosen as the "driver" for inertial confinement pellet fusion, because of its high output-to-weight potential and its high operating temperature which permits effective radiant cooling of its components.

Many of these characteristics needed for high-thrust rockets differ substantially from what is required for terrestrial electric power plants. For example, it would be difficult to efficiently utilize a trillion watt output power plant today, except in locations of extremely high population density, such as Western Europe, Japan, or the eastern United States.

Terrestrial power plants can have large masses, low power-to-mass ratios, etc., while high-thrust rockets have the opposite requirements (see **Table 2**). For example, terrestrial power plants can utilize co-generation, where the "waste" heat is actually utilized to run some industrial and/or agricultural process. But, given the requirements of high-thrust space flight, fusion rocket R&D will lead to higher power density, more efficient terrestrial power plants at a rate faster than would otherwise be the case. Recent developments in high-temperature superconductors will provide the technology for efficiently transmitting large power outputs over great distances.

Each of the 200 KrF laser modules fires a 2-million-joule laser pulse once every 2 seconds. This results in 100 pulses a second, each capable of igniting one fusion pellet. The total weight of the laser modules, their radiators, optics, energy handling, and structural components is 262 tons.

Since 1983, the KrF laser has progressed far more rapidly than expected. This is primarily due to the SDI missile defense program. The technology already exists to build megajoule KrF lasers; techniques of pulse compression, such as beam stacking and multiplexing[1] and nonlinear Raman pulse compression[2] (which are needed to achieve the high power densities required for ignition of inertial confinement thermonuclear fusion) have been demonstrated in principle. In fact even the projected laser operating efficiencies have been almost doubled beyond the 6% assumed by the Livermore design to almost 11%. This would substantially reduce the required laser mass.

The thrust chamber

The final compartment of the rocket is the thrust chamber which has a total mass of 166 tons. It is the business end of the rocket and is best described operationally. The following sequence of events occur 100 times per second.

First a deuterium fueled pellet weighing a few tens of grams is accelerated by a magnetic gun to a speed of 2 kilometers per second. (Ten-kilometer speeds have already been attained in such guns, which are currently being utilized to fuel fusion experiments.) The pellet proceeds through the thrust chamber radiators, which dissipate waste heat, through the fin and payload shields and the single-turn, 13-meter-diameter superconducting magnet coil and its shield.

Upon arriving at the appropriate point, the interactive optics,[3] like those currently being utilized in laser-target tracking and pointing experiments, direct a 2-million-joule, 200-trillion-watt peak-power KrF laser-pulse onto the pellet. This intense pulse ablates the surface of the pellet and causes the fuel containing interior to be shock compressed to super densities and temperatures like those found in the centers of stars. At the kilogram per cubic centimeter and 100 million degree Celsius temperatures thus generated, most of the fuel undergoes nuclear fusion within a few billionths of a second.

This produces about 2,000 megajoules of fusion energy—a gain of 1,000 over that of the input laser energy. Of this fusion energy output, 1,280 megajoules is contained in the plasma debris of the pellet. This plasma pellet debris will generate the thrust to propel the rocket. Most of the 380 megajoules of neutrons and 330 megajoules of output in the form of x-rays generated is lost to space. Since the plasma debris will be directed away from the ship, the waste heat contained by it—all of the energy not going into a directed thrust—will simply be left behind and not affect or heat the ship in any way.

Magnetic nozzle

This is the key to the effectiveness of laser pellet fusion for powering rockets. Only a small percentage of the total fusion energy output, other than the directed thrust, intercepts the ship. The magnetic field interacts with the spherically expanding thermonuclear plasma to generate an asymmetrical jet. It is this "jet" which produces the rocket thrust. Waste heat and entropy are thrown out the rear end with the pellet debris in the plasma jet. Of the total fusion power output of 200 gigawatts (produced by one hundred 2,000-megajoule pellets per second), only 4.2 gigawatts ends up as waste heat—about a 98% effective operating efficiency. Still, 40 tons of the 166 tons of the thrust chamber mass are taken up by heat rejection radiators.

The superconducting magnetic coil provides the means of redirecting most of the pellet plasma debris out of the rear of the rocket and magnetically transferring the resulting thrust to the material rocket structure. The 13-meter diameter coil carries a current of 22 million amperes. This produces a magnetic field with a stored energy five times greater than that of the 1,280-megajoule pellet debris plasma. The coil is made with a vanadium-gallium superconductor which operates at a temperature of 4.8° and a peak field of 158,000 gauss.

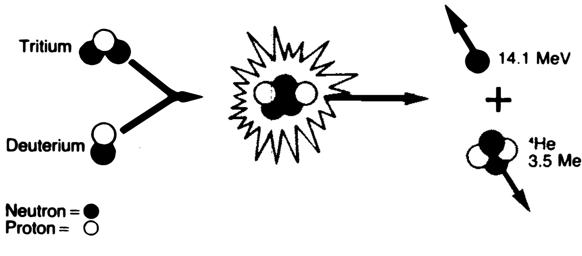
As the plasma pellet debris rapidly expands, it encounters the coil magnetic field. The dense plasma cannot penetrate the magnetic field, and thus compresses it. Given the greater stored energy of the magnetic field, the plasma is stopped before reaching the coil and redirected away from the rocket.

What is nuclear fusion?

The currently most likely form of nuclear fusion applicable to high-thrust rocket operation is inertial confinement fusion. This is the type of fusion already utilized in large, fission explosive-driven hydrogen bombs. Laboratory and power plant inertial confinement fusion (ICF) can also be achieved through substituting intense laser or particle beams as the driver. In this case, the energy is released as a microexplosion, as in a large internal combustion engine, with a total energy release millions of times less than the fission bomb-driven hydrogen bomb.

A second general approach is magnetic fusion, which would involve more continuous energy outputs and indirect rocket propulsion systems in which the fusion energy is converted into thrust through some intermediate process, such as particle beam or plasmoid accelerators. Powering electromagnetic rail-guns with magnetic fusion reactors is another possibility. The rail-gun output would produce the rocket thrust in this case. And while ICF is

FIGURE B1
The fusion process



Fusion is produced when the nuclei of elements fuse together, either under high pressure and density or confined by magnetic fields. The fusion fuel is a very hot, ionized gas (a plasma), and can be isotopes of hydrogen, helium, or potentially even heavier elements. Energy is produced as either fast-moving neutrons or as electrons and positively charged particles.

In this way, the momentum of the plasma debris is transferred to the rocket through the compressed magnetic field. The plasma thrust is shaped into a jet in the process. Thus, the coil also acts as a magnetic "nozzle" to increase the efficiency of converting plasma energy into thrust. The single-coil design achieves a nozzle efficiency of 65%—that is, 65% of the plasma momentum is transformed into thrust momentum. (A small fraction of the plasma does escape toward the ship. This small, inward jet is directed away from the ship by a small magnet deflection coil.)

Rocket fuel

The Livermore rocket utilizes fusion pellets which contain some tritium fuel to spark deuterium fusion. The deuter-

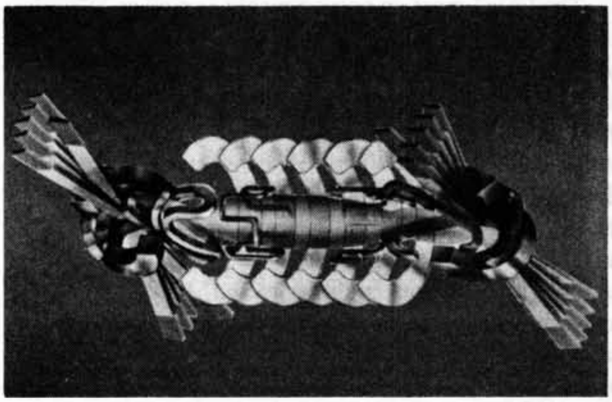
technically more advanced today for application to high-thrust rockets, the possibilities of magnetic fusion-powered rockets should not be ignored.

The laboratory ICF uses both the general approach of the hydrogen bomb design and a more direct approach. In the direct approach the intense laser or particle beams are symmetrically directed onto the surface of a small sphere of fusion fuel. These intense beams burn off a surface layer of the fuel pellet and further heat it. This ablation corona then acts like the exhaust of a rocket and implodes the remaining fuel to high densities and temperatures needed for igniting nuclear fusion. This, of course, would only occur if the beam deposition is highly symmetric since any deposition asymmetry leads to either an aspherical, incomplete compression of the remaining fuel pellet, or an entirely flawed action with no compression at all. This symmetric deposition is extremely difficult to achieve.

The hydrogen-bomb-based hohlraum design appears to be much more easily attained. In this case, the laser and/or particle beam energy is first transformed into x-rays and trapped in a cavity—the hohlraum. This transforming and trapping process "naturally" leads to a very symmetric distribution of the radiant energy in the form of x-rays. A fusion pellet within the cavity is then driven by this trapped radiation to the high densities and temperatures needed for igniting thermonuclear fusion reactions.

In both cases, the driving radiation produces a rocket action. Both the energy gain and velocity multiplication modes of rocket drive can be found in ICF pellet designs. For example, in general, the objective in ICF is to efficiently obtain high compressions of the fusion fuel. This high density produces high rho-r's and high burnups leading to high gains. (Rho-r is the product of the compressed fusion fuel pellet density and its radius. For ICF, rho-r is the same as the Lawson density-confinement time product. Gain is the ratio of the fusion energy output to the laser energy input.) This efficient compression is obtained by utilizing the energy gain rocket mode. The laser energy must be efficiently absorbed by the surface layer of the fusion pellet at a rate which matches the exhaust velocity of the ablation corona to the velocity of implosion of the pellet surface.

FIGURE B2



One of the many fusion reactor designs under development is the Tandem Mirror. The fuel undergoing fusion is contained in the cylindrical section in the center while magnets at either end of the cylinder keep the plasma from leaking out. This particular design may be appropriate for a fusion propulsion system, because one of the ends could be left open to let the exhaust particles out.

FIGURE B3

A first-generation fusion propulsion design

Fuel	**D-Helium-3**
Power	1,000 MW of fusion energy
Weight of Reactor	500 tons
Acceleration	.01 Earth gravity
Trip time to Mars	80 days

The first-generation propulsion system proposed would produce 1,000 megawatts of fusion energy using deuterium and helium-3. About half of the weight of the power plant to produce the energy, as now envisioned, would be the huge magnets. With this kind of propulsion system, the spaceship could accelerate at between one-hundredth and one-thousandth Earth's gravity, and reach Mars in about two-and-one-half months. More advanced designs should take us to Mars in less than two days, while providing an artificial gravity from the constant acceleration. This would avoid the negative effects of zero gravity and the radiation hazards of a long flight.

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:

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

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

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

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

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

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

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.

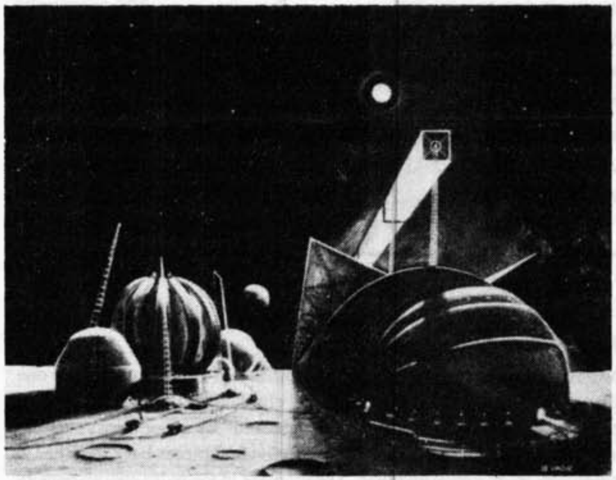
The velocity of the reaction products can be directly derived from their particle energies. The maximum reaction product velocity determines the maximum exhaust velocity that can be directly generated by a particular reaction—chemical or nuclear. The reaction product velocity is given by:

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

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.

TABLE 3

Rocket missions

	Mars	Jupiter	Pluto
VIP trips (50-ton payload)			
Distance (100,000,000 km)	8	7.8	59.25
Trip time in days	9.4	39.8	153.9
Maximum velocity (km/sec)	165	339	667
Maximum acceleration (cm/sec^2)	81.1	39.5	20.1
Cargo Trips (1,500 ton payload)			
Distance	8	7.8	59.25
Trip time in days	22.2	93.6	363
Maximum velocity	70	144	284
Maximum acceleration	14.7	7.14	3.63

TABLE 4

Fusion pellet energy spectrum

Laser ("driver") energy	2 megajoules
Laser peak power	200 terrawatts
Burned pellet plasma	1,280 megajoules
X-rays	330 megajoules
Gamma rays	39 micromoles (about 10 megajoules)
Neutrons	380 megajoules (about 1.3 millimoles)
Deuterium burned	15 milligrams
Tritium burned	0.1 milligrams

Notes

1) Beam stacking and multiplexing are utilized in combination with one another. A single laser pulse can be optically broken into several "pieces"—"multiplexed. These pieces can then be "stacked" by using mirrors whose physical separation is spaced to bring the individual pieces back together to form a single, more powerful pulse. The increase in the pulse energy density is simply given by the number of pieces into which the original pulse was broken up.

2) Nonlinear Raman pulse compression is a technique in which a laser pulse passes through a gas and as a result of an induced nonlinear change in the optical properties of the gas, the laser pulse is compressed to a much higher energy density. Usually, a second, lower-power laser pulse is used to induce the nonlinear change in the gas's optical properties. All of these technologies are being rapidly developed as part of the Strategic Defense Initiative missile defense program.

3) Interactive optics consist of reflecting surfaces whose optical properties change according to the nature of the incident light pulse—a sort of "rubber" mirror. As a result, interactive optics permits one to take out the "distortions" introduced into a laser pulse, such as the distortions produced while transiting the atmosphere.