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.

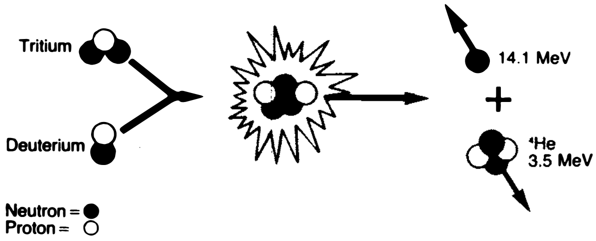
What is nuclear fusion?

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-

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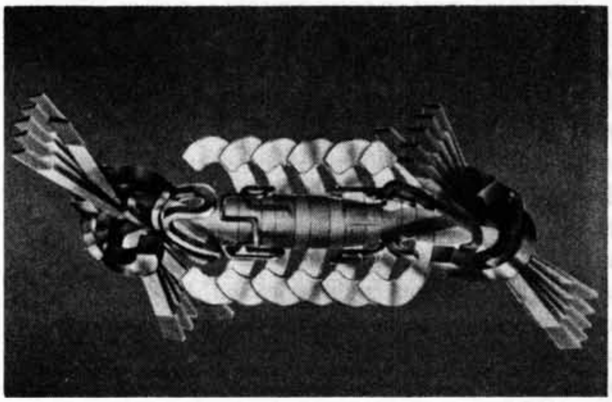
technically more advanced today for application to high-thrust rockets, the possibilities of magnetic fusion-powered rockets should not be ignored.

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.