cannot readily be scaled up to provide larger amounts.

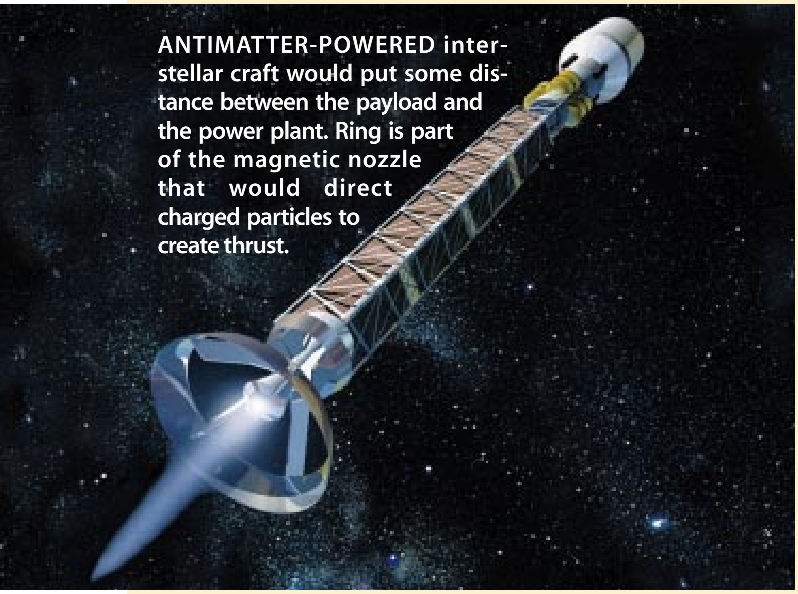
Many space buffs believe nuclear reactors designed to operate in space could be the answer. Because operating a reactor generates some radioactive waste, proponents of space nuclear power now envisage designs that would be launched on chemical rockets in an inactive state. They would be energized only after attaining a safe distance from Earth, so they would present no threat in the event of a launch accident. Some estimates indicate that a nuclear-powered journey to Mars might last just 100 days, about half the estimated trip time for a chemical rocket. A reactor could also be valuable to provide power to support a base on Mars,

Reaching for the Stars

by Stephanie D. Leifer

The notion of traveling to the stars is a concept compelling enough to recur in countless cultural artifacts, from Roman poetry to 20th-century popular music. So ingrained has the concept become that when novelists, poets or lyricists write of reaching for the stars, it is instantly understood as a kind of cultural shorthand for striving for the unattainable.

Although interstellar travel remains a glorious if futuristic dream, a small group of engineers and scientists is already exploring concepts and conducting experiments that may lead to technologies capable of propelling spacecraft to speeds high enough to travel far beyond the edge of our solar system. A propulsion system based on nuclear fusion could carry humans to the outer planets and could propel robotic spacecraft thousands of astronomical units into interstellar space (an astronomical unit, at 150 million kilometers, or 93 million miles, is the average distance from Earth to the sun). Such a system might be built in the next several decades. Eventually, even more powerful engines fueled by the mutual annihilation of matter and antimatter might carry spacecraft to nearby stars, the closest of which is Proxima Centauri, some 270,000 astronomical units distant.



ANTIMATTER-POWERED interstellar craft would put some distance between the payload and the power plant. Ring is part of the magnetic nozzle that would direct charged particles to create thrust.

BOB SAULS *John Frassanito & Associates*

The attraction of these exotic modes of propulsion lies in the fantastic amounts of energy they could release from a given mass of fuel. A fusion-based propulsion system, for example, could in theory produce about 100 trillion joules per kilogram of fuel—an energy density that is more than 10 million times greater than the corresponding figure for the chemical rockets that propel today's spacecraft. Matter-antimatter reactions would be even more difficult to exploit but would be capable of generating an astounding 20 quadrillion joules from a single kilogram of fuel—enough to supply the entire energy needs of the world for about 26 minutes.

In nuclear fusion, very light atoms are brought together at temperatures and pressures high enough, and for long enough, to fuse them into more massive atoms. The difference in mass between the reactants and the products of the reaction corresponds to the amount of energy released, according to Albert Einstein's famous formula $E = mc^2$.

The obstacles to exploiting fusion, much less antimatter, are daunting. Controlled fusion concepts, whether for rocket propulsion or terrestrial power generation, can be divided into two general classes. These categories indicate the technique used to confine the extremely hot, electrically charged gas, called a plasma, within which fusion occurs. In magnetic confinement fusion, strong magnetic fields contain the plasma. Inertial confinement fusion, on the other hand, relies on laser or ion beams to heat and compress a tiny pellet of fusion fuel.

In November 1997 researchers exploiting the magnetic confinement approach created a fusion reaction that produced 65 percent as much energy as was fed into it to initiate the reaction. This milestone was achieved in England at the Joint European Torus, a tokamak facility—a doughnut-shaped vessel in which the plasma is magnetically confined. A commercial fusion reactor would have to produce far more energy than went into it to start or maintain the reaction.

But even if commercial fusion power becomes a reality here on Earth, there will be several problems unique to developing fusion rockets. A key one will be directing the energetic charged particles created by the reaction to produce usable thrust. Other important challenges include acquiring and storing enough fusion fuel and maximizing the amount of power produced in relation to the mass of the spacecraft.

Since the late 1950s, scientists have proposed dozens of fusion rocket concepts. Although fusion produces enormous amounts of very energetic particles, the reaction will accelerate a spacecraft only if these particles can be directed so as to produce thrust. In fusion systems based on magnetic confinement, the strategy would be to feed in fuel to sustain the reaction while allowing a portion of the plasma to escape to generate thrust. Because the plasma would destroy any material vessel it touched, strong magnetic fields, generated by an assembly that researchers call a magnetic nozzle, would direct the charged particles out of the rocket.

In an engine based on the inertial confinement approach, high-power lasers or ion beams would ignite tiny fusion fuel capsules at a rate of perhaps 30 per second. A magnetic nozzle might also suffice to direct the plasma out of the engine to create thrust.

The particles created in a fusion reaction depend on the fuels used. The easiest reaction to initiate is between deuterium and tritium, two heavy isotopes of hydrogen whose atomic nuclei include one and two neutrons, respectively, besides a proton. The reaction products are neutrons and helium nuclei (also known as alpha particles). For thrust, the positively charged alpha particles are desirable, whereas the neutrons are not. Neutrons cannot be directed; they carry no charge. Their kinetic energy can be harnessed for propulsion, but not directly—to do so would involve stopping them says Samuel L. Venneri, NASA's chief technologist.

Reactors could be used for propulsion in various ways. One that generates thrust directly and operates for a short intense burst is described by James R. Powell on page 70. Such a design might make it possible to return rock samples to Earth from Pluto, Powell maintains. But there are other possibilities. A reactor could be designed to generate heat over long periods. Several different schemes then would be available to convert the heat to electricity to power ion drives, Hall thrusters or a new type of electric propulsion in early development known as a magnetoplasmodynamic thruster. "You can mix and match different reactor and thrust

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in a material and making use of the heat generated by their capture. Neutron radiation also poses a danger to a human crew and would necessitate a large amount of shielding for piloted missions.

These facts lead to a key difficulty in fusion fuel selection. Although it is easiest to initiate fusion between deuterium and tritium, for many propulsion concepts it would be more desirable to use deuterium and the isotope helium 3 (two protons, one neutron). Fusion of these nuclei produces an alpha particle and a proton, both of which can be manipulated by magnetic fields.

The problem is that helium 3 is exceedingly rare on Earth. In addition, the deuterium–helium 3 reaction is more difficult to ignite than the deuterium-tritium reaction. But regardless of the fusion fuel selected, a spacecraft of thousands of tons—much of it fuel—would be necessary to carry humans to the outer reaches of the solar system or deep into interstellar space (for comparison, the International Space Station will have a mass of about 500 tons).

Even individually, the key obstacles to fusion propulsion—getting higher levels of power out of a controlled reaction, building effective containment devices and magnetic nozzles, and finding enough fuel—seem overwhelming. Still, for each of them, there is at least a glimmer of a future solution.

In the first place, there is every reason to believe that fusion reactors will go far beyond the break-even point, at which a reactor produces as much energy as is fed into it. Inertial confinement work in the U.S. is enjoying robust funding as part of the stockpile stewardship program, in which researchers are working on methods of assuring the safety and reliability of thermonuclear weapons without actually test-firing them. The research is centered at the National Ignition Facility, now under construction at Lawrence Livermore National Laboratory. The facility is expected to start up in 2001, with full laser energy of 1.8 million joules—for four billionths of a second—available in 2003. With that kind of power, researchers anticipate liberating up to 10 times the energy required to initiate the reaction.

There are indications, too, that the tokamak, which has dominated magnetic confinement research, may someday be supplanted by more compact technologies more amenable to rocket propulsion. In 1996 the Fusion Energy Sciences Advisory Committee of the U.S. Department of Energy endorsed investigation of such promising magnetic confinement schemes as reverse-field pinches, the field-reversed configuration and the spherical tokamak.

In the meantime, workers have begun preliminary work on magnetic nozzles. The largest research effort at present is a collaboration among the National Aeronautics and Space Administration, Ohio State University and Los Alamos National Laboratory. Researchers from the three organizations are using extremely high electric currents to create a plasma, which in the experiments stands in for a fusion plasma, and to study its interactions with a magnetic field.

Even the fusion fuel problem may be tractable. Although there is very little helium 3 on Earth, there are larger quantities of it in the lunar soil and in Jupiter's atmosphere as well. Also, other elements found on Earth, such as boron, may figure in alternative fusion reactions that are difficult to ignite but that yield alpha particles.

For all the promise of fusion propulsion, there is one known physical phenomenon—matter-antimatter annihilation—that releases far more energy for a given mass of reactants. A space propulsion system based on this principle would exploit the mutual annihilation of protons and antiprotons.

This annihilation results in a succession of reactions. The first of these is the production of pions—short-lived particles, some of which may be manipulated by magnetic fields to produce thrust. The pions resulting from matter-antimatter annihilation move at speeds close to that of light.

Here again, though, one of the key problems is scarcity: the number of antiprotons produced at high-energy particle accelerators all over the world adds up to only a few tens of nanograms a year. To carry humans on a rendezvous mission to the nearest star, Proxima Centauri, a matter-antimatter drive system would need tons of antiprotons. Trapping, storing and manipulating antiprotons present other major challenges because the particles annihilate on contact with ordinary protons.

Nevertheless, it may be possible to exploit, albeit to a lesser extent, antimatter's high energy content while requiring much smaller numbers of antiprotons—amounts that are most likely to be available in the next decade. Such a system would use antiprotons to trigger inertial confinement fusion. The antiprotons would penetrate the nuclei of heavy atoms, annihilating with protons and causing the heavy nuclei to fission. The energetic fission fragments would heat the fusion fuel, initiating the fusion reaction. The first steps toward determining the feasibility of such a propulsion system are already being taken under NASA sponsorship. One research activity is the design and construction, at Pennsylvania State University, of a device in which antiprotons could be trapped and transported.

DANA BERRY (*spaceship*); ROBERT O'DELL (*Orion nebula*)

HUMAN-PILOTED interstellar spaceship would have a rotating structure in front, to simulate gravity in four compartments.

At this very early stage, the challenges to building fusion—let alone antimatter—propulsion systems may seem insurmountable. Yet humankind has achieved the seemingly impossible in the past. The Apollo program and the Manhattan Project, among other large undertakings, demonstrated what can be accomplished when focused, concerted efforts and plenty of capital are brought to bear. With fusion and antimatter propulsion, the stakes could not be higher. For these will be the technologies with which humanity will finally and truly reach for the stars.

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