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Mining helium-3 on the Moon for unlimited energy

There is enough fuel on the Moon's surface to power the fusion reactors that can advance the Earth's economy and begin industrializing space. Marsha Freeman reports.

For years, space scientists have dreamed of one day using fusion power to build cities in space, a task that would be impossible with less efficient chemical fuels or inefficient solar energy, or even with more efficient nuclear fission technology. At the same time, fusion researchers hoped that in the near future, the most advanced fusion fuels would open the age of unlimited plasma energy. Now, both of these dreams could become a reality just after the turn of the century, by implementing a new proposal to mine helium-3 from the Moon. Helium-3 will be a crucial fuel for fusion reactors on Earth and in space.

"There is enough fuel on the Moon to meet the present energy needs of the entire Earth for close to 2,000 years," Dr. Gerald Kulcinski told a lunar science conference in September 1986. This lunar fuel is an Earth-rare isotope of helium, which is abundant in much of our Solar System and on the Moon. Kulcinski and the research group at the Fusion Technology Institute at the University of Wisconsin are now working out the details of a plan to begin lunar mining of helium-3, not only for use in setting up lunar industries and powering Earth reactors, but also for advanced fusion propulsion systems to open the rest of the Solar System to man's exploration.

Using fusion energy on the Moon was the centerpiece of the lunar industrialization plan worked out by space scientist Krafft Ehricke. In an article on industrializing the Moon in 1982, Ehricke noted that Selenopolis, his name for a lunar city, "cannot be built with yesterday's technology." Fusion energy will be as fundamental on the Moon as the Sun's energy is for the Earth's biosphere, Ehricke said, for "conditions for fusion plants are more favorable in the high vacuum on the lunar surface than on Earth." Ehricke set the goal of using "clean" deuterium-helium-3 fuel to do the job. Now, based on the work of the Wisconsin team, that goal can be met much earlier than Ehricke had envisioned.

Industrial materials processing on the Moon will be significantly different than conventional Earth technologies, which require vast amounts of water, chemicals, and other volatiles that do not exist in the lunar environment. Fusion has great advantages, even over nuclear fission, for materials processing and other industries: It requires a small amount of fuel, most of the fuel is already on the Moon, it produces no waste that requires recycling, it requires virtually no radiation protection, and it can make use of direct conversion technologies such as magnetohydrodynamics (MHD)—getting rid of the steam turbine. In fact, direct plasma processing, using the high-temperature charged-particle product of the fusion reaction itself, has the potential to increase productivity by orders of magnitude over today's chemical or even electrical processing technologies.

Previously, the only obstacle Ehricke and others saw to a lunar fusion economy, was that the deuterium (D) and tritium (T) isotopes of hydrogen, which scientists planned to use as fuel, had to be transported from Earth, creating a serious economic penalty.

Fusion scientists knew that eventually they would be able to use advanced fuel cycles, such as the fusion of helium-3 and deuterium, and that this was desirable because it would greatly reduce radiation problems from tritium and highly energetic neutrons. In addition, with advanced fuel cycles, energy conversion efficiencies could be doubled or tripled. However, in the past, fusion scientists were not aware of any ready source of helium-3 that would make commercial development of this advanced fuel realistic. As Kulcinski put it, "The lack of a long-range supply of helium-3 has limited serious consideration of this fuel cycle for the past 20 years."

Even the most recent work on advanced fusion fuel cycles, such as the soon-to-be-published book, *Introduction to Fusion Energy,* has assumed that "obtaining the required helium-3 poses a serious problem, since it is not available in the quantity needed for a fusion economy based on the deuterium-helium-3 reaction." Endeavoring to find a way to open up the possibility of this superior advanced fusion fuel cycle, fusion scientsts proposed that power plants producing fusion with the more elementary D-T or D-D reactions would create tritium as a by-product, and that they would then collect the helium-3 that is produced as tritium decays. The deuterium-helium-3 fusion "satellite" plants could then produce the "clean" fusion.

Accumulating helium-3 by waiting for tritium to decay is a very slow route to the 21st century. The Wisconsin team's plan for mining helium-3 on the Moon will get us there much faster. According to the Wisconsin group, an aggressive space program that takes America back to the Moon just after the turn of the century, and an aggressive fusion research effort that demonstrates a deuterium-helium-3 reactor by about the same time, could open an era of unlimited energy on Earth and in space for millennia to come.

The helium advantage

One basic requirement for all of human economic activity is energy, and electricity is the universal form of energy available today. For 100 years, mankind has produced almost all of its electricty by burning coal, oil, gas, or uranium to produce heat, which is used to boil water and run steam turbines. One of the major advantages of using deuterium-helium-3 reactions to produce fusion energy is that most of the output is not heat, but charged particles, which can be converted directly to electricity in a variety of ways.

Compare this with other fusion reactions. If fusion energy is produced with deuterium and tritium, about 80% of the output will be in the form of high-energy neutrons. The only efficient way to extract energy from these uncharged particles is to slow them down through collisions with a material or blanket that lines the reactor wall. When they slam into the liner material, heat is produced. This means that a reaction taking place at millions of degrees will have to have its energy degraded to less than 2,000° in order to match the limit of today's steam turbine technology.

A fusion fuel cycle using D-D reactions improves the quality of the fusion energy, because about two-thirds of the total energy released is in the form of charged particles, with the rest in neutrons. But with deuterium-helium-3, the neutrons are virtually eliminated (**Table 1**).

The opportunity to use charged particles to directly convert the fusion output to electricity is a prerequisite for space propulsion systems (which certainly will not carry along steam turbines), and for power plants on the Moon, where there is no water available to turn turbines. The efficiency of conversion will be increased from today's utility steam turbine systems of 34%, at best, to potentially 100%, with no wasted energy. The high-temperature plasma, which is the product from any individual plant, could be used both to produce electricity and to directly process materials.

TABLE 1

Comparison of fusion fuel cycles

Fuel	Reaction products	% energy released as charged particles
D-T	Neutrons + helium-4	20
D-D	Neutrons + helium-3 Protons + helium-4	66
D-H^3	Protons + helium-4	93-100

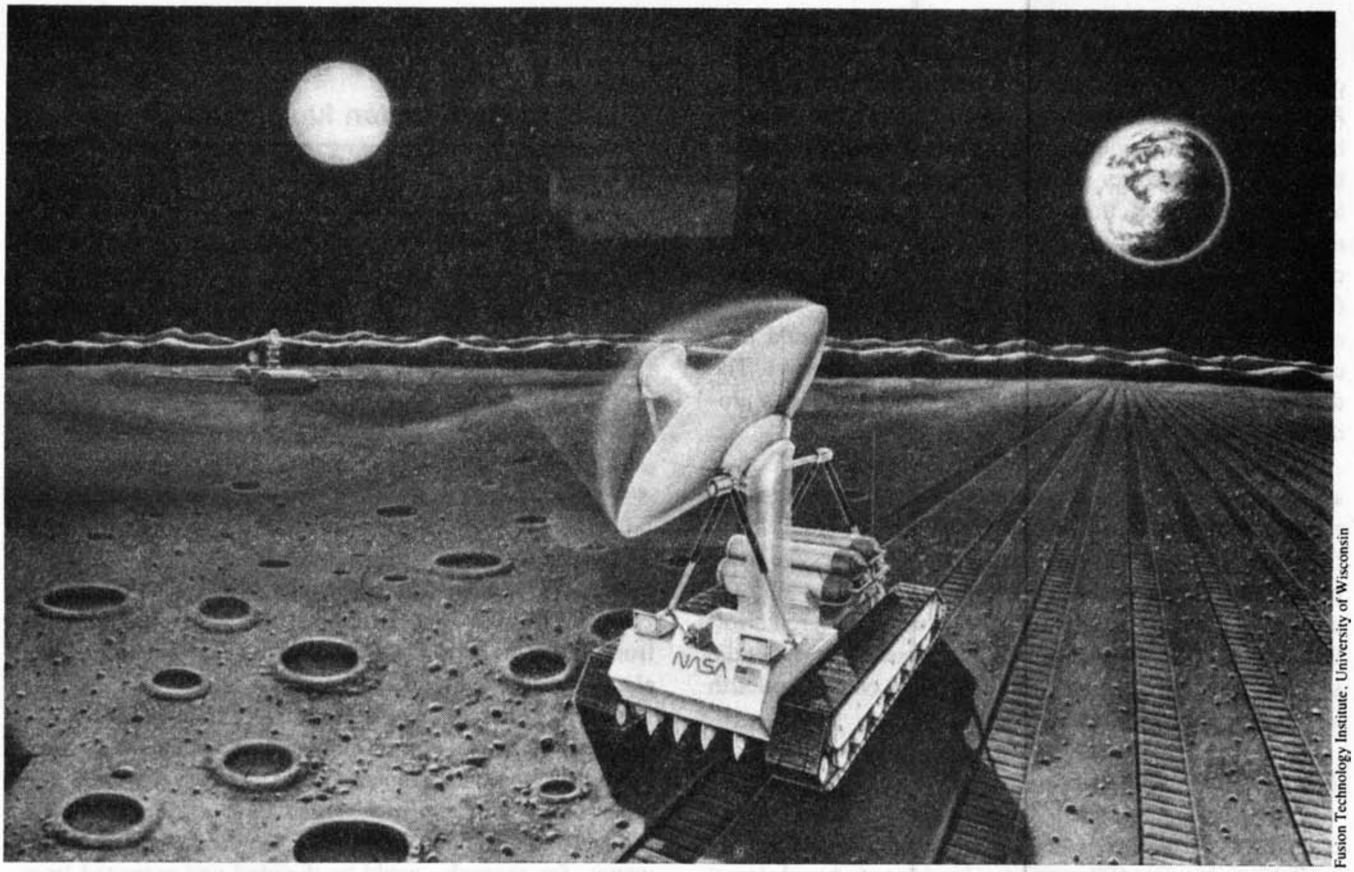
The deuterium-helium-3 fusion fuel is the most efficient, releasing nearly all of the energy produced as charged particles and permitting the direct conversion of the fusion energy to electricity.

Various direct conversion designs and technologies are currently being considered for match-up with deuterium-helium-3 fusion power plants, and for different reactor geometries. One would involve the use of the synchrotron radiation produced in the fusion process. Energy in the form of microwaves, for example, could be diverted and extracted from the reactor for direct use in materials processing and the transport of energy to remote parts of the Moon, or for conversion to electrical power. Designs are also under consideration for diverting a portion of the charged particles from the fusion reaction for either magnetohydrodynamic (MHD) conversion systems which have already been demonstrated, using low-temperature fossil fuel plasmas.

In studies carried out at the Lawrence Livermore National Laboratory, *in situ* fusion-MHD conversion designs are also being investigated, where the magnetic field already used to contain the fusion reaction would do double duty, and be used for the MHD conversion as well. The charged particles and electromagnetic radiation produced by the fusion reaction could be used to ionize a separate working fluid, right inside the wall of the reactor.

Electrostatic conversion involves diverting the protons released by the fusion reaction and organizing them into beams. The positively charged proton beams from the deuterium-helium-3 reaction are then matched to electrodes with similar voltages, where the protons are collected, producing high-voltage direct current.

A second major advantage of the deuterium-helium-3 fuel cycle is the simplification of the design of the fusion reactor itself, because radioactive tritium fuel will be eliminated and the high-energy neutrons will be much reduced. Although there is the possibility that side-reactions of D-D could take place, producing unwanted neutrons, the helium-



Fusion Technology Institute, University of Wisconsin

In a concept developed at the University of Wisconsin, a remotely operated mobile unit scoops up lunar soil, extracts the helium and stores it, and then ejects the mined soil. Illustration by John Andrews.

3 to deuterium ratio can be increased in the fuel mixture, to perhaps nine parts helium to one part deuterium, in order to lessen the D-D reactions. It is also possible that spin-polarizing the fuel will suppress side D-D reactions.

Tritium is not an abundant, naturally occurring isotope of hydrogen on Earth, because of its short half-life of 12.3 years. Therefore, for D-T fusion, the tritium will have to be bred from lithium in a blanket surrounding the reactor cavity. The deuterium-helium-3 reaction eliminates the need for this breeding blanket, because it eliminates the need for tritium.

Because there is no radioactive fuel or by-product from deuterium-helium-3, special precautions for handling the fuel and waste are unnecessary. With lower neutron flux and radiation effects, internal reactor components should last longer, with increased plant lifetime.

The paucity of natural helium-3 on Earth is not the only reason, however, that the emphasis in the fusion program has centered on using deuterium and tritium; the D-T fusion reaction is the easiest to obtain in terms of the temperatures required, the strength of the magnets, and so on. For example, producing fusion energy with deuterium-helium-3 requires plasma fuel temperatures three to five times higher than those already achieved in current fusion tokamak experiments (about 100 million degrees). Kulcinski has noted, however, that in the past 15 years, fusion scientists have increased the plasma operating temperature by a factor of 40, so another factor of 5 "should not take an unreasonably long time."

In order to contain the plasma fuel at this higher temperature, the external magnetic fields must also be increased. Instead of the 10-12 tesla magnetic fields that are now conceived as necessary for D-T tokamaks, Kulcinski notes that 16-tesla magnet systems will be needed. (A tesla is 2,000 gauss, with 0.5 gauss equal to the magnetic field of the Earth.) Again, in terms of getting from here to there, this is only a 30% increase from magnetic fields already achieved in the Mirror Fusion Test Facility-B at the Lawrence Livermore National Laboratory, and the Japanese plan to build a 16-tesla fusion magnet test facility, according to Kulcinski.

It is also possible that polarizing the fusion fuel (aligning the spin of the fuel particles) could increase the reactivity of the plasma, thereby lessening some of these constraints, in addition to suppressing the unwanted D-D reactions. Increasing the plasma reactivity by 50% could reduce the overall reactor size by two-thirds. The Fusion Technology Institute is investigating the potential advantages of spin polarization this year.

What kind of fusion reactor design will be best fitted for using deuterium-helium-3? There are advantages to the linear, or open fusion reactor designs, such as the tandem mirror, whose open ends would allow the easy extraction of plasma particles for direct conversion. Initial experiments using electrostatic direct conversion on the Tandem Mirror Experiment at Lawrence Livermore National Laboratory have demonstrated a 95% efficiency. This design would also be best suited for fusion propulsion, as an open end is needed to expel the particles out the back end of the rocket.

The donut-shaped tokamak design, which is driven by higher plasma currents, would lend itself to synchrotron radiation conversion. The microwaves would be produced in the cavity of the reactor, which would have highly polished walls to reflect them. The microwaves could then be diverted to a nearby facility, where they could be converted to electricity or used in chemical processing or even food irradiation.

The modifications required for existing D-T experiments or devices that are on the drawing board in order for them to test the advanced deuterium-helium-3 fuel would be a "very small perturbation" in the program according to Kulcinski—in other words, barely noticeable. The team is now investigating how and when this unexplored fusion fuel cycle can be tested. They are confident that when the next-step fusion Engineering Power Reactor machine is operating, perhaps by the year 2000, it will be possible to have deuterium-helium-3 fusion fuel ignited and burning in a demonstration reactor.

If fusion scientists are now optimistic that there are no insurmountable physics problems to going directly to advanced fusion fuels as soon as the engineering technology is ready, the only question is, where will they get the helium-3?

Phase 1: helium-3 on Earth

Between now and the year 2000, when the manned space station will have small vehicles parked outside that can go back and forth to the Moon, where will the helium-3 come from for the fusion reactor? The solar wind, which constantly spews high-energy particles and radiation from the Sun throughout the Solar System, has been found by spacecraft probes to contain about 20 parts per million particles of helium-3. However, these particles do not survive the Earth's atmosphere and are, therefore, not found deposited on the Earth's surface. Some helium-3 exists in the nuclear weapons program. Helium-3 is a natural decay product of radioactive tritium, which is used today principally for the production of thermonuclear weapons. Although the inventory of tritium from weapons production is classified, it has been estimated that there are currently about 300 kilograms (kg) of tritium in U.S. weapons. As 5.6% of this tritium decays each year, there should be about 15 kg of helium-3 produced per year in this manner. If this helium-3 were collected, it could reasonably provide between 200-300 kg of helium-3 for fusion experiments by the year 2000, when such amounts would be required for a demonstration reactor. In addition, there is a small amount of helium-3 that can be extracted as a by-product of natural gas production.

Researchers have estimated that this could provide, cumulatively, more than 200 kg by the turn of the century. The tritium decay from Canadian CANDU fission reactors, and other small supplies, could bring the total to between 500-600 kg (**Table 2**). This supply could power a small (100-200 MW) electric demonstration plant, for several decades, at a current cost of $700 per gram of helium-3.

Phase 2: helium from the Moon

Because the Moon has no atmosphere, the helium-3 bombarding it from the solar wind has collected there over billions of years. Samples of lunar soil returned by the Apollo astronauts and analyses from the Soviet unmanned Luna probes indicate that the lunar soil contains an estimated 1 million tons of helium-3.

The Wisconsin group states, "The characteristic of the lunar soil (regolith) that makes it an effective collector is its extremely fine grain size," which is due to the pulverization of the soil to a depth of between 5 and 15 meters, caused by the impact of meteorites.

It has also been determined that the lunar mare or dark plains, have a higher helium content than the soil in the highlands, because the solar wind particles appear to be concentrated in ilmenite granules, which comprise up to 10% of the mare soils.

How much of the helium-3 on the Moon can be economically exploited is still under study, but the technologies for extracting the helium are already under development in a variety of studies on lunar mining. Studies are ongoing, for example, to develop methods for the extraction of plentiful oxygen from the lunar soil, which will be crucial for the lunar base.

The Wisconsin team has designed a way that the recovery of helium from the lunar surface soils will involve a simple process. In the latest concept developed at Wisconsin for

TABLE 2

Potential terrestrial sources of helium-3

Source	Cumulative to the year 2000 (kg)
U.S. weapons	300
CANDU fission reactors	10
Storage at natural gas wells	29
Known reserves at gas wells	187
Department of Energy research supply	13
Total	500-600

Before the turn of the century, a total of 500-600 kg of helium-3 could be made available from Earth-based sources.

mining the lunar helium, a remotely operated mobile unit will collect and process the soil.

The rover will pick up the top 30 centimeters of lunar soil. The raw material will be scooped up at the front of the unit and will be heated by the Sun to 600° Celsius. At that temperature the helium is vaporized and extracted. The extracted helium-3 will be stored in a tank on the mobile unit, and the processed soil will be dropped back on the surface about a meter from where it was scooped up.

If the processing is done during the two-week lunar day, the ambient temperature on the lunar surface will be nearly 130°, and the remainder of the heat can be supplied by solar collectors, which are pointed toward the Sun.

It has been estimated that to produce 1 kg of helium-3, about 100,000 tons of pristine soil will have to be processed.

Once the helium is liberated, the helium-3 must be separated from the more abundant helium-4. Cryogenic distillation is a technology that has been demonstrated to produce 99.99% pure helium-3. When the helium is cooled to only 2.1° above absolute zero (2.1° Kelvin), the two isotopes of helium can be separated using fine filters. If these distillers are operated during the alternate two-week lunar night, when the ambient temperature on the surface is already down to 120° K, less energy will be needed for cooling.

If the volume of the cargo bay of one Space Shuttle orbiter were filled with helium-3 mined on the Moon and the helium were transported back to Earth, it could produce as much electricity in fusion power plants as the United States consumed throughout 1985! This would require mining an area on the lunar surface that is approximately equivalent to the size of Washington, D.C.

How much energy would be produced on Earth by using the helium on the Moon is, of course, a function of the rate of growth of energy consumption and the percentage of the lunar surface that is mined. Mining 1% of the entire lunar surface, could provide all of the Earth's energy, at a little more than today's levels of consumption, for about 100 years.

At present, the world's population consumes approximately 10 terawats (1 terawatt equals 1,000 billion watts) of total energy per year. On an average, this is about 2 kilowatts per capita for 5 billion people. Kulcinski's group assumes that the world's population will grow to about 8 billion early in the next century, and that there will be at least a modest increase, to an average of 3 kilowatts per capita, during that time. Therefore, minimally, 24 terawatts per year will be needed.

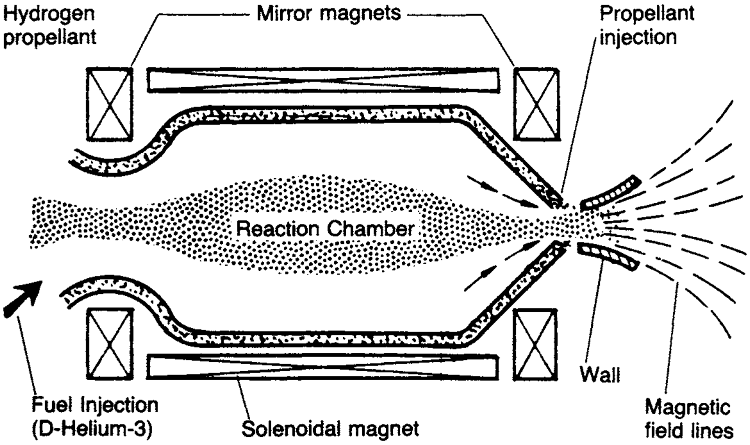
If the entire surface of the Moon were mined, and all the helium-3 recovered were used in Earth-based fusion power plants, the helium fuel could produce enough energy to meet current world demand for 1,900 years. It will not be practical, however, to mine the entire surface of the Moon, because other scientific and industrial activities will be ongoing on the lunar surface. It also will not be necessary to mine the entire Moon, because there are much larger reserves of helium-3 just a little farther away on other planets.

The lunar helium reserves will also be needed to fuel the space propulsion systems that NASA must develop over the next 20 years. John Santarius, one of the scientists at the University of Wisconsin, has estimated that a deuterium-helium-3 fusion-propelled rocket could obtain a specific impulse up to 1 million seconds. This value, which measures the efficiency of the fuel in the propulsion system, can be compared to the 800-second value for today's Space Shuttle-type chemical rocket systems.

This fantastic rocket capability would have a tremendous impact on possibilities to explore the Solar System. Although the rocket would have a low overall thrust (rate of acceleration), the constant acceleration rate would produce impressive velocities over time, and open up regions that are today beyond our reach, such as the outer planets, for human ex-

FIGURE 1

Schematic of a fusion-propelled rocket



This early design for a fusion propelled rocket uses the magnetic mirror configuration. The Wisconsin group estimates that a deuterium-helium-3 propelled rocket would reach a specific impulse of 1 million seconds, compared to the present 800 seconds achieved by chemical rocket systems like those by the Shuttle.

Source: John J. Reinmann, "Fusion Rocket Concepts," Technical Paper, Sixth Symposium on Advanced Propulsion Concepts, Air Force Office of Scientific Research, Niagara Falls, N.Y., May 4-6, 1971 (Washington, D.C., NASA Technical Memorandum TM X-67826).

TABLE 3

Potential extraterrestrial sources of helium-3

Source	Potential supply (kg)
Moon	1.1×10^9
Jupiter	7×10^{22}
Saturn	7×10^{22}
Uranus and Neptune	10^{20}

The Moon can supply us with enough helium-3 to power the Earth for 1,900 years, but even more fantastic reserves of helium-3 can be found on Jupiter, Saturn, and beyond.

ploration. Manned spacecraft today do not accelerate once they are in space but maintain ballistic trajectories, basically coasting, due to the weight penalty involved in carrying additional fuel needed for constant acceleration.

A fusion-propelled rocket could directly expel the products from the fusion reaction, rather than using the reactor to produce electricity or simple heat. "Cold" hydrogen gas or other particles could be added to the exhaust flow to increase the mass and thrust. This would create the ability to "tune" the rocket, by changing the thrust ratio and specific impulse according to which parameters were desired during any particular mission.

The helium on the Moon will not be an unlimited energy supply in itself, but it could function as a one-century bridge to the recovery of virtually limitless helium-3 from the outer planets. It will open the next millennia, providing humanity with the first biologically benign, non-polluting, efficient, and economical energy in human history. The abundance of this quality of energy will actually *create the possibility, and is itself prerequisite,* for the colonization of space, and the necessary revolution of all economic activity on the Earth. The Moon can open the fusion era.

Phase 3: Jupiter and Saturn

During the second half of the 20th century, mankind opened the space frontier by stepping on the Moon and sending his robots to planets farther away. In the next century, mankind must set up permanent scientific laboratories in Earth orbit, an industrial and scientific base on the Moon, and colonize Mars.

Robotic spacecraft not only will further explore the outer planets, but also can become fuel tankers, bringing to the space colonists and the Earth the helium-3 needed for continued growth and exploration.

While the Moon has been capturing helium from the solar wind in the grains of its surface over eons, the giant gaseous planets are actually composed mainly of hydrogen and helium. There are estimates that as much as 25% of the weight of Jupiter and Saturn is helium, which would make more than 10^{23} kg of helium-3 available in their atmospheres. This fantastic reserve of fuel is what awaits us on the other side of the one-century lunar helium bridge (**Table 3**).

Today's spacecraft use ballistic trajectories to traverse the multibillion-mile distances to the great planets. Even with the help of gravity assists from fly-bys near other planets, the Sun, or the Moon, these are arduously long trips, whether the spacecraft is manned or unmanned. The fusion propulsion that will be commonly available by the time we are looking toward Jupiter and Saturn for our helium-3, will make these round trips no more arduous than today's supertanker journeys from the Middle East or Alaska.

There is also helium below the frozen surfaces of Neptune and Uranus, and possible resources of helium-3 on Mars, Mercury, the asteroids, or the moons of various planets, which still remain to be investigated.

It is inconceivable that if deuterium-helium-3 fusion were demonstrated to be feasible on Earth near the year 2000 and became widely commercially deployed in space and on Earth during the next century, that a system for extracting and delivering helium-3 from the outer planets would not be available soon after that. Fusion will provide the quality and abundance of energy to allow mankind to explore and colonize space. Space science and technology will be key to making available the extraterrestrial resources that will bring the age of fusion power to the Earth and to its offspring centers of human civilization on other planets.