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FUSION POWER FROM LUNAR RESOURCES

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FUSION POWER FROM LUNAR RESOURCES

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The moon contains an enormous energy source in ³He deposited by the solar wind. Fusion of only 100 kg of ³He with deuterium in thermonuclear fusion power plants can produce >1000 MW(electric) of electrical energy, and the lunar resource base is estimated at 1 × 10⁹ kg of ³He. This fuel can supply >1000 yr of terrestrial electrical energy demand. The methods for extracting this fuel and the other solar wind volatiles are described. Alternate uses of D-³He fusion in direct thrust rockets will enable more ambitious deep-space missions to be conducted. The capability of extracting hydrogen, water, nitrogen, and other carbon-containing molecules will open up the moon to a much greater level of human settlement than previously thought.

I. INTRODUCTION

One of the most important resources for the next century will be a safe, reliable, and clean supply of energy. Without it, the earth cannot support its present population of 5 billion people and certainly not the 10 to 12 billion people likely to inhabit the planet in the 21st century. This energy is necessary to feed, protect, and clothe the world's population as well as to keep it healthy in the face of an environment under increasing stress. Indeed, both the developed and undeveloped nations of the world are already highly dependent on a steady flow of energy to maintain their very existence.

Since the 1930s, fossil fuels such as coal, oil, and natural gas have been the major energy resources driving the economy of the world. As the year 2000 approaches, two factors limit our continued reliance on these fuels for the 21st century:

1. There is a limit to fossil fuels, and they are being rapidly depleted. Based on the present rate of world per capita energy consumption (Fig. 1) and accounting for a population growth to the 10 billion levels (Fig. 2), practically all of the currently *economically* recoverable fossil fuels will be exhausted by the middle of the 21st century if no new energy resources are discovered (Fig. 3).

2. The massive burning of fossil fuels is damaging the quality of the environment worldwide. Energy use in developed and underdeveloped nations of the world is currently responsible for the emission of >5 billion tonnes of carbon [in the form of carbon dioxide (CO_2)] into the atmosphere each year. This increasing CO_2 concentration may eventually cause global warming via
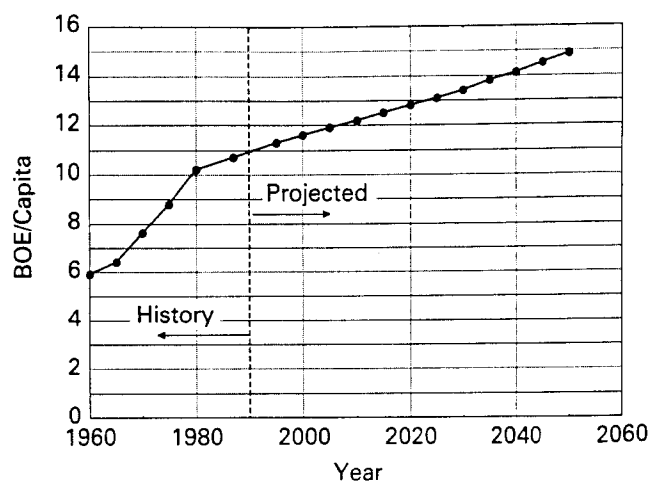

Fig. 1. Worldwide energy use per capita since 1960. Energy use per capita is expected to increase by 50% over the next 60 yr. In 1990, the United States per capita energy use was ≈60 barrels of oil equivalent (BOE)/yr.
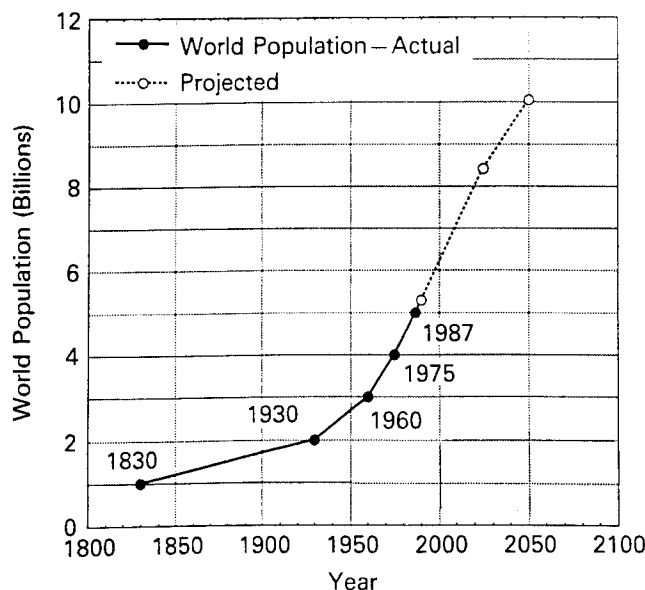
Fig. 2. World population growth—past and future. With reduced birth rates, it may be possible to limit the world population to only twice its present value of 5.2 billion people, but world population is expected to reach 10 billion by the middle of the 21st century.[1]
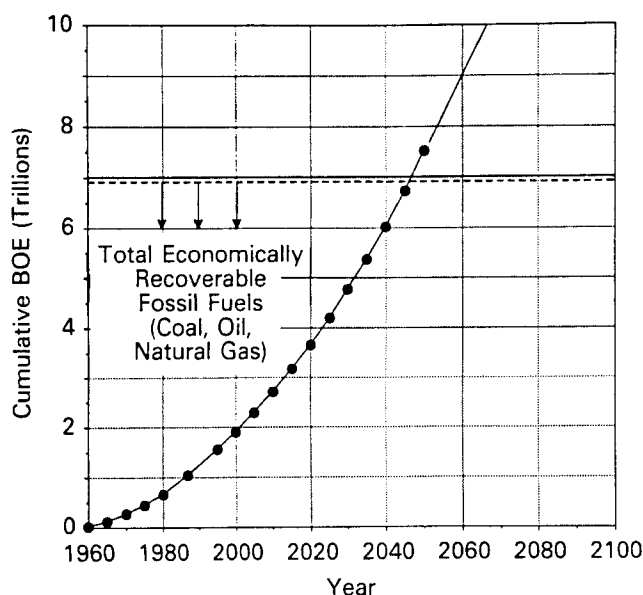

Fig. 3. Projected cumulative energy use (population times energy use per capita) may exceed currently known reserves of economically recoverable fossil fuels by the middle of the 21st century.

the "greenhouse effect." If this occurs, the warming could result in widespread resettlement of the world's population to accommodate rising seas and shifting rainfall patterns. The ancillary effects of fossil fuel uti-

lization, such as acid rain and land despoilment, will also shorten the future of these fuels as major energy resources.

Nuclear energy in the form of fission technology has been proposed to replace fossil fuels as the primary energy resource for the future. After an optimistic start (1950 through 1980), nuclear fission now faces increased public resistance to the long-term storage of radioactive wastes and to the siting of nuclear facilities. Safety concerns associated with the Three Mile Island and Chernobyl accidents have caused a reassessment of the contribution that fission will make to the energy mix of the 21st century. The breeder reactor option, popular in Europe for a long time, also appears to be losing favor around the world. It is becoming apparent that only a small fraction ($\approx 10\%$) of total energy needs will be met by current nuclear fission or breeder technologies in the early 21st century.

II. FUSION ENERGY FOR THE NEXT CENTURY

Fusion, another nuclear energy process, is safer and cleaner than fission and has been studied for >35 yr. The major fusion fuel cycle that has been examined is the reaction between deuterium and tritium:

$$D + T \rightarrow n \ (14.1 \ \text{MeV}) + {}^4\text{He} \ (3.5 \ \text{MeV}) \ .$$

Unfortunately, 80% of the energy from the D-T reaction is released as neutrons that can cause considerable damage to reactor vessel wall materials and induce substantial levels of long-lived radioactivity in the structural components of the reactor, albeit at levels far below (100 to 1000 times) those found in fission reactors.[2]

For many years, it has been recognized that an even more attractive fusion fuel exists that does not exhibit the more serious problems associated with the D-T reaction. This fuel is a combination of deuterium and ${}^3\text{He}$, a rare form of helium not found in great quantities anywhere on the earth; the products are nonradioactive protons and normal ${}^4\text{He}$:

$$D + {}^3\text{He} \rightarrow p \ (14.7 \ \text{MeV}) + {}^4\text{He} \ (3.7 \ \text{MeV}).$$

The advantages of the D-^{3}He reaction are that it releases far fewer neutrons (on the order of a few percent) than the D-T reaction, and its energy output can be converted to electricity at efficiencies twice as high as in current fission or fossil plants.[3-6] The low levels of radioactivity in the D-^{3}He reactor mean that there can be no meltdown accidents and that the low-level radioactive waste does not require a deep geological burial facility. Many other technological advantages, such as a lower cost of electricity and shorter development time, have also been identified.[6]

There are, however, two disadvantages to the D-^{3}He reaction compared with the D-T fuel cycle:

1. It requires higher plasma temperature and more stringent confinement conditions.

2. A major source of ^{3}He is required.

Because of these two disadvantages, this fuel cycle has been ignored relative to the D-T cycle in both U.S. and worldwide fusion research programs. However, progress in plasma physics during the last 5 to 10 yr has dramatically increased the power levels produced in fusion devices (see Fig. 4). The power level has increased from <1 W in 1975 to >100 000 W in 1990. Devices to increase this by another factor of 10 000 are already on the drawing board. In addition, with the temperatures that have been achieved (a value of 35 keV was recently reported),[8] we are now a factor of <2 away from those temperatures needed to successfully operate a D-^{3}He fusion power reactor at average ion temperatures of 60 keV. In addition, recent analyses of the International Thermonuclear Experimental Reactor[9] (ITER) fusion facility design indicate that a successful demonstration of the D-^{3}He cycle could occur by the year 2005. Taken in concert, these advancements mean that many of the previous feasibility questions about the plasma physics of the D-^{3}He reaction have been either reduced substantially or eliminated entirely.

III. FUEL SUPPLY FOR ADVANCED FUSION POWER PLANTS

The problem of fuel supply for the D-^{3}He reaction has been a very real barrier to its further development until fairly recently when scientists at the University of Wisconsin reanalyzed work reported by U.S. and Soviet space scientists in the 1970s (Ref. 3). Analyses of the lunar samples brought back by both U.S. and Soviet space programs revealed that there is a large supply of ^{3}He (at least 1 000 000 tonnes) on the moon.[3,4,10-13] The technical details of this discovery have been reviewed by space scientists and engineers, and now there is general agreement on the order of magnitude of this resource.[14,15]

Cameron[10,11,16] has found a relationship between the ^{3}He content of the lunar regolith and the TiO_2 concentration displayed in Fig. 5. This information, coupled with the fact that the mare of the moon contain large amounts of TiO_2-containing ilmenite, strongly suggests that the first mining sites on the moon will be in the mare.[13,16] Experiments by Pepin et al.[17] in 1970 showed that heating the regolith to $\approx 700°C$ would be sufficient to evolve the ^{3}He from the regolith. These observations are important because the loose regolith is easily processed to obtain the ^{3}He isotope.

Equipment has been designed to collect, heat, and return large amounts of regolith to the lunar surface
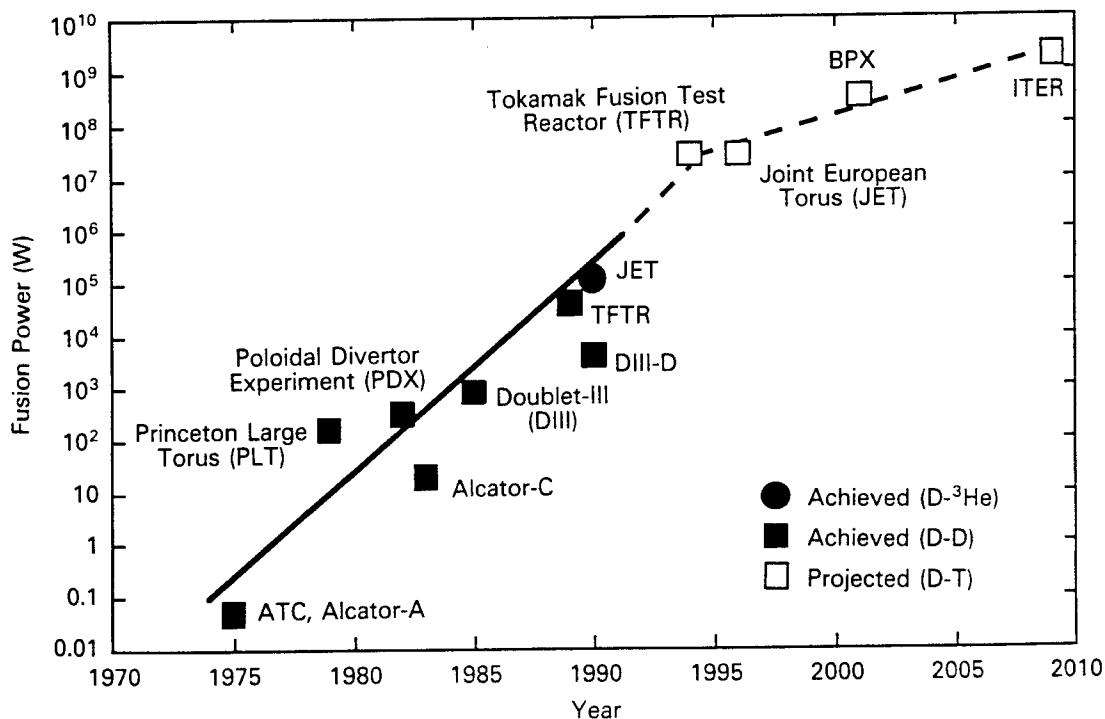

Fig. 4. Magnetic fusion power generation progress. The level of fusion power will increase substantially in the next 10 to 15 yr (Ref. 7).
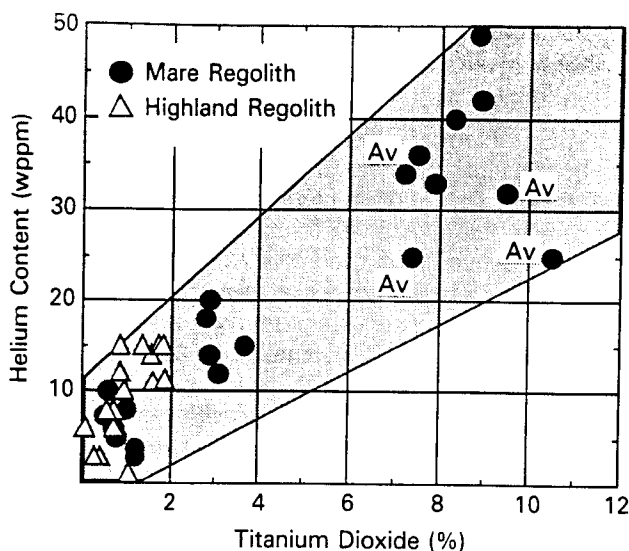
Fig. 5. The concentration of ^{3}He compared with TiO_2 content in lunar regolith.[10,11]

with a minimum of effort. Figure 6 represents the latest in a series of lunar miner designs at the University of Wisconsin. The principle of the miner operation is simple; sunlight relayed from stationary mirrors to the slowly moving miners is used to heat the regolith and power the miner during the lunar day (14 earth days). The gases (see Table I for the composition of lunar volatiles evolved at 700°C) are collected in tanks, which are then transported to radiators back at the mining base camp. During the lunar night, the gaseous mixture is exposed to the "coldness" of space (≈ 5 K), and all the components except ^{4}He and ^{3}He are condensed. The ^{3}He is separated from the ^{4}He by superleak techniques, which are well known on earth. Energy and operational analyses of lunar ^{3}He miners have been reported in Refs. 18 through 21.

The importance of the by-products of ^{3}He mining has been studied by Bula et al.[22] They found that the needs of thousands of lunar settlers (or space travelers)

could be met with the water, nitrogen, and carbon/oxygen compounds (see Table I) derived with just 1 tonne of ^{3}He. In fact, the first applications of this kind of mining equipment may supply life-supporting elements to the early lunar bases, well before the need for ^{3}He arises (≈ 2015).

The enormity of the discovery of ^{3}He on the moon can be best illustrated by the following brief observations:

1. Twenty-five tonnes of ^{3}He could supply the entire U.S. electrical demand in 1991. (This amount, liquefied, could fit into one spacecraft the size of a U.S. space shuttle.)

2. The by-products from 25 tonnes of ^{3}He could provide the needs of more than a half million people on the moon for water and air to breathe as well as the needs of >25 000 lunar inhabitants for food.

3. There is ten times more energy in the lunar ^{3}He than there ever was in all the economically recoverable fossil fuels on earth.

The legal and institutional aspects of mining ^{3}He resources have also been investigated and showed that an international company patterned after INTELSAT could function within the existing laws, treaties, and precedents to benefit both the nonspacefaring nations and investors.[23] The financial incentives for such a mining operation were recently analyzed[24,25] and indicated that a respectable return on investment (ROI) could be realized even if the cost to mine the ^{3}He was $1 billion/tonne. At that cost, the ROI is in excess of 20% *without* taking credit for the sale of the volatile by-products. It is worthwhile noting that at $1 billion/tonne, the energy content in ^{3}He is equal to oil at $7 barrel; i.e., if oil costs more than $7/barrel, it is cheaper to buy ^{3}He at $1 billion/tonne. At today's price of oil (approximately $20/barrel in 1991), that makes ^{3}He worth (in terms of equivalent energy) $3 billion/tonne. One 25-tonne shuttle load would then be worth about $75 billion or roughly twice the entire cost of the Apollo program.

TABLE I

Collection of Lunar Volatiles from ^{3}He Mining and Their Impact on Life Support on the Lunar Surface

| Element	Mass Recovery at 700°C/tonne ^{3}He·yr^{-1}	Number of Humans Supported per Year	Main Support Area
^{3}He	1	10 000 000	Terrestrial electricity
^{4}He	3100	?	Pressurization, atmosphere
N_2	400	1 150	Food, atmosphere, pressurization
CO_2	1700	22 000	Food, atmosphere, pressurization
CH_4	1600	?	Hydrocarbons, microbial synthesis
H_2O	3300	23 000	Potable needs, oxygen
H_2	6100	?	Water, oxygen, hydrocarbons, rocket fuel
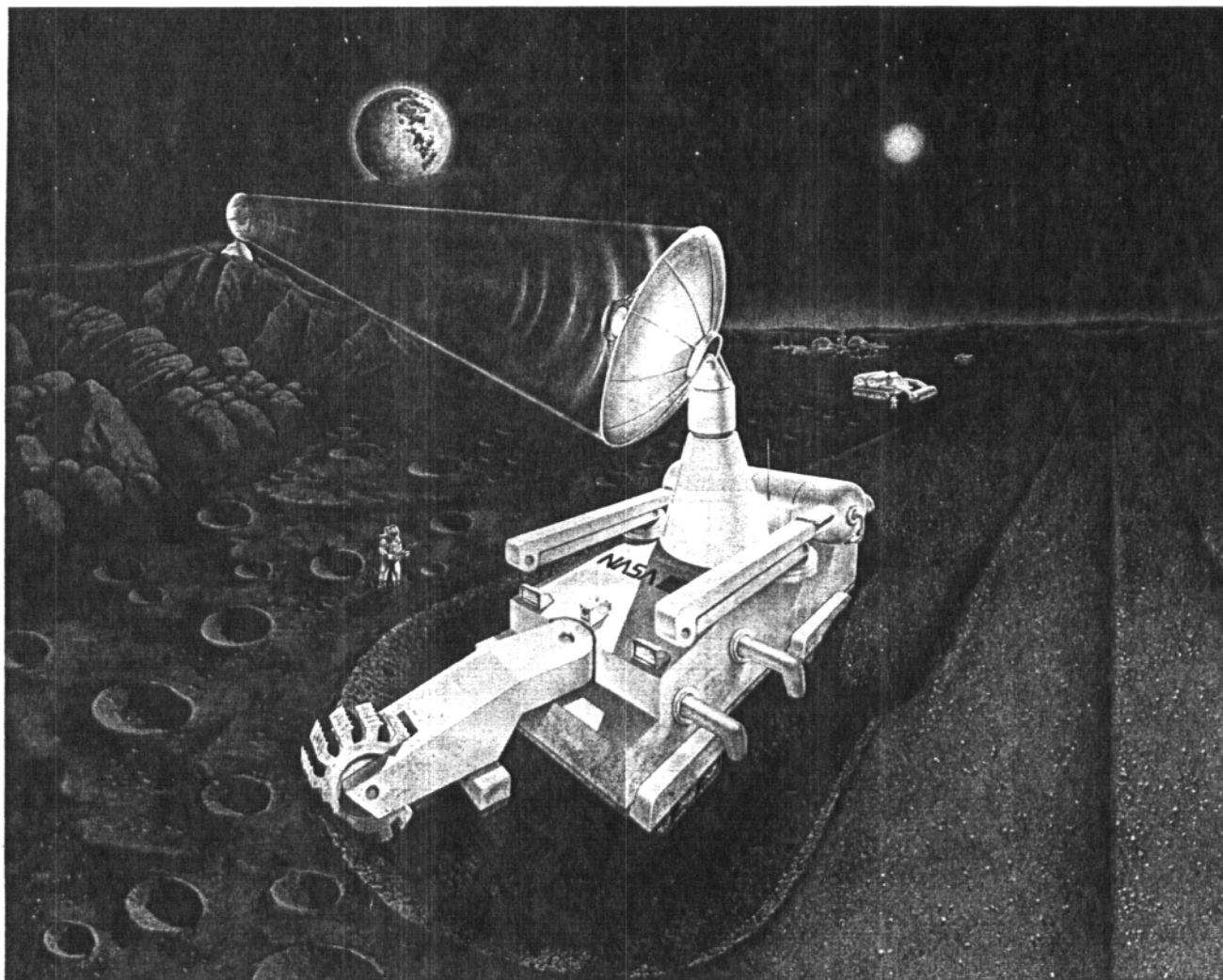
Fig. 6. Artist's conception of a lunar miner at work on the Sea of Tranquillity. Note the solar relay mirrors that beam energy to the slowly moving miner for heating the regolith. This unit could supply the ^{3}He fuel for a city of 500 000 people in the United States.

An examination of a possible timetable for ^{3}He mining reveals that lunar ^{3}He could start making an impact on world energy supplies starting between about 2015 and 2020 (see Fig. 7). This figure relates a potential development schedule for fusion to what may be loosely construed as the U.S. policy for return to the moon as outlined in Ref. 26 or 27.

The fusion program in the United States is considering[28] a high magnetic field device, the Compact Ignition Tokamak [recently renamed the Burning Plasma Experiment (BPX)], for operation at the turn of the century. This device could demonstrate the breakeven point, i.e., the conditions where the energy invested in the plasma just equals the thermonuclear energy released. The next device, ITER (Ref. 29), is a cooperative effort among the United States, USSR, Japan, and the European Community and will produce ≈1000 MW and begin operation around 2005. Slight

modifications of that device could demonstrate the ignition of a D-^{3}He plasma.[9] Since no further materials test facilities are required because of the low neutron production in D-^{3}He systems, the ITER device could be further modified to produce electricity by 2010. Assuming successful operation of a D-^{3}He ITER demonstration reactor, it is conceivable that the first commercial fusion power plant could be on-line 5 to 10 yr later. It is important to note that there is 200 to 300 kg of ^{3}He [100 kg ^{3}He burned with deuterium will release 1000 MW(electric)-yr of electrical energy] available from the decay of tritium in the U.S. thermonuclear weapons.[3] This amount of ^{3}He would be sufficient to carry out the entire development program from now through the first commercial reactor, *without* having to go to the moon.

On the space side, the first return of humans to the lunar surface could occur around the turn of the
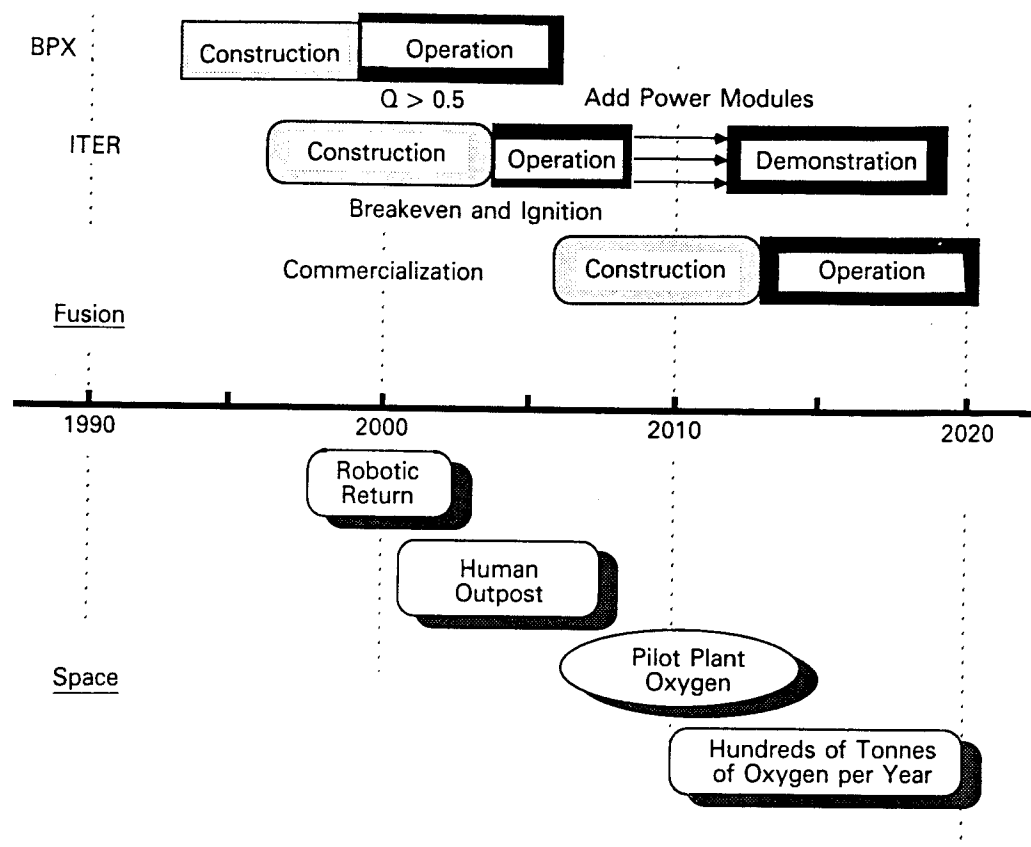
Fig. 7. Proposed schedules for developing D-^{3}He fusion and for a return to the lunar surface. There are sufficient ^{3}He resources on earth to fuel the program up through the first commercial power plant.

century.[27] After early scientific and base-building activities, commercial entities might be prepared for investment in lunar resources by 2010. Launching lunar miners to the moon in that time frame means that the first substantial amounts of ^{3}He could be returned to the earth by 2015, just in time for the start of construction of the second D-^{3}He commercial power plant. The coincidence of the two schedules — fusion needing lunar ^{3}He by 2015 to 2020 and the space program being ready for commercial operations on the moon by 2015 to 2020 — is very fortunate. Slippage or acceleration in either program's plans can now be analyzed with respect to their impact on the other programs.

Since the connection between lunar ^{3}He and fusion in 1986 (Ref. 3), many programs around the world have been initiated. Figure 8 displays those programs conducted in the United States, USSR, Europe, and Japan in 1990.

IV. SPACE PROPULSION USING D-^{3}He ROCKETS

One unique aspect of the D-^{3}He reaction is the release of a highly energetic 14.7-MeV proton. If the fusion reactor is configured in a lunar system, this proton

can be used to develop extremely high specific impulses. Santarius and coworkers have analyzed the use of D-^{3}He fusion for propulsion[30,31] and for power in space.[32-34] Their conclusions are the following:

1. The D-^{3}He tandem minor rocket can be configured in a variable-thrust/variable-specific-impulse I_{sp} mode.

2. The maximum I_{sp} developed is $\approx 1\,000\,000$ s (at low thrust).

3. Trip times from earth to the moon are not significantly affected by the high I_{sp}, but the trip time to Mars can be cut to one-third the time required with chemical rockets (see Fig. 9).

4. The advantages of high-I_{sp} rocket engines are magnified as one travels farther out into space, making trips out to Pluto and back feasible in the active lifetime of a crew (e.g., <10 yr compared with 90 yr with chemical systems).

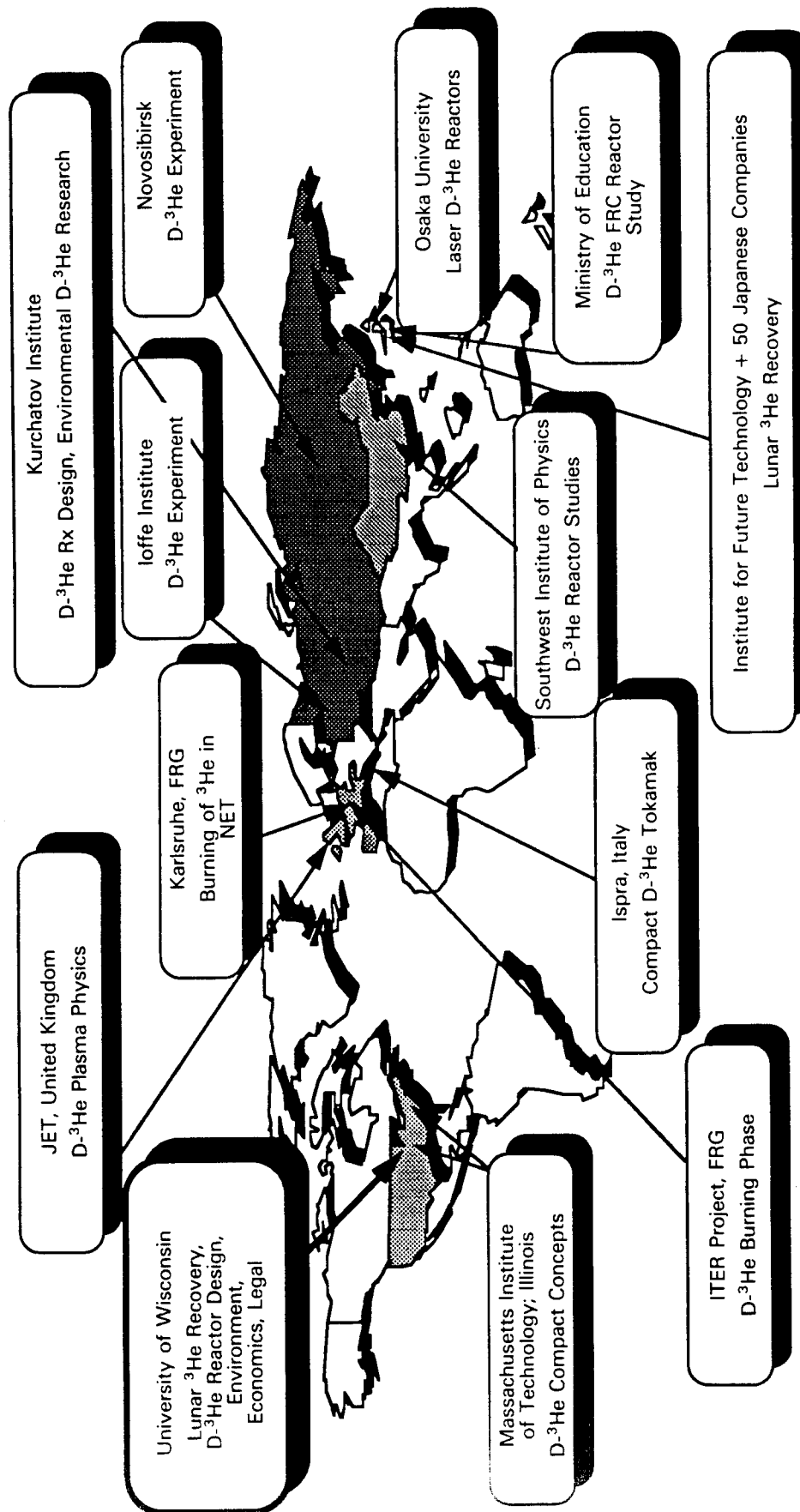5. Very high power densities in space can be developed from direct conversion of the D-^{3}He reaction

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Fig. 8. Worldwide research in ^{3}He fusion and lunar ^{3}He research (1990).

Kurchatov Institute
D-^{3}He Rx Design, Environmental D-^{3}He Research

Novosibirsk
D-^{3}He Experiment

Osaka University
Laser D-^{3}He Reactors

Ministry of Education
D-^{3}He FRC Reactor Study

Institute for Future Technology + 50 Japanese Companies
Lunar ^{3}He Recovery

Ioffe Institute
D-^{3}He Experiment

Southwest Institute of Physics
D-^{3}He Reactor Studies

Karlsruhe, FRG
Burning of ^{3}He in NET

JET, United Kingdom
D-^{3}He Plasma Physics

Ispra, Italy
Compact D-^{3}He Tokamak

University of Wisconsin
Lunar ^{3}He Recovery,
D-^{3}He Reactor Design,
Environment,
Economics, Legal

Massachusetts Institute
of Technology; Illinois
D-^{3}He Compact Concepts
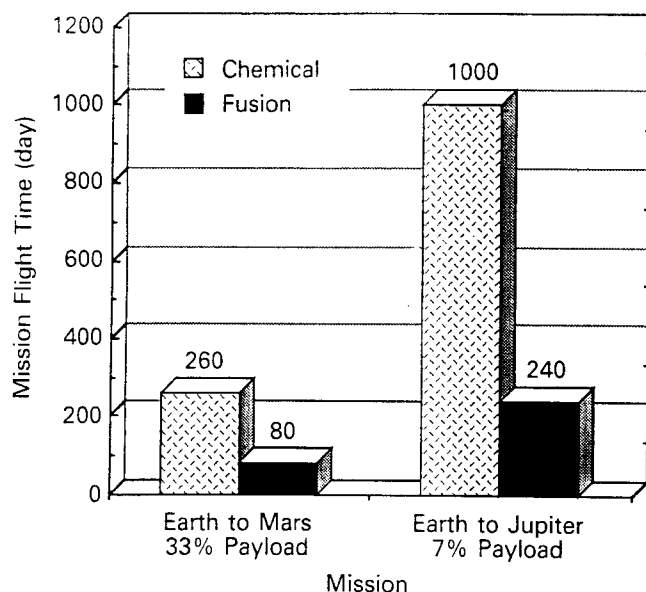
ITER Project, FRG
D-^{3}He Burning Phase

Fig. 9. The use of fusion rockets can substantially reduce the trip time to planets in the solar system.[30]

products. Power densities of 2 to 10 W/g appear possible by design of linear magnetic field configurations.[32,33]

Finally, it has been noted that fusion may be to space travel what fission reactors were to the submarine.[31] The potential of this technology may not only enable future long-distance space missions, it may be the only way we can accomplish them.

V. CONCLUSIONS

The use of lunar ^{3}He can have an enormous impact on the future energy and environmental prospects for the earth as well as on the exploration of space. Even utilizing a fraction of the 1 million tonnes of ^{3}He identified on the moon could provide for the world's electricity needs for centuries to come. The thermonuclear fuel could also be used in direct thrust rockets to develop specific impulses of more than a million seconds that will enable explorers to reach the outer limits of the solar system in time periods that are ten or more times shorter than with chemical fuels. In addition, the use of the volatile by-products from ^{3}He mining (H_2, H_2O, N_2, CO, CH_4, CO_2) can greatly expand the number of settlers that could be supported on the lunar surface and open up the possibility for making the moon the "filling station" in the sky for which we have been searching.

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