



Fusion Power from Lunar Resources

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FUSION POWER FROM LUNAR RESOURCES

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Abstract

It is shown that the Moon contains an enormous energy source in ^3He deposited by the solar wind. Fusion of only 100 kg of ^3He with deuterium (D) in thermonuclear fusion power plants can produce more than 1000 MW_e years of electrical energy and the lunar resource base is estimated at 1 billion kg of ^3He . This fuel can supply more than 1000 years of terrestrial electrical energy demand. The methods for extracting this fuel and the other solar wind volatiles are described. Alternate uses of D-He3 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 could not support its present population of five 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 them healthy in the face of an environment under increasing stress. Indeed, 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 are limiting our continued reliance on these fuels for the 21st century. The first is the fact that there is a finite 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 level (Fig. 2), practically all of the presently *economically* recoverable fossil fuels will be exhausted by the middle of the 21st century if no new energy resources are discovered (Fig. 3).

Secondly, 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 presently responsible for the emission of more than five billion tonnes of carbon, in the form of carbon dioxide (CO₂), into the atmosphere each year. This increasing CO₂ concentration may eventually cause global warming via 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 utilization, 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 during the period 1950-1980, 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

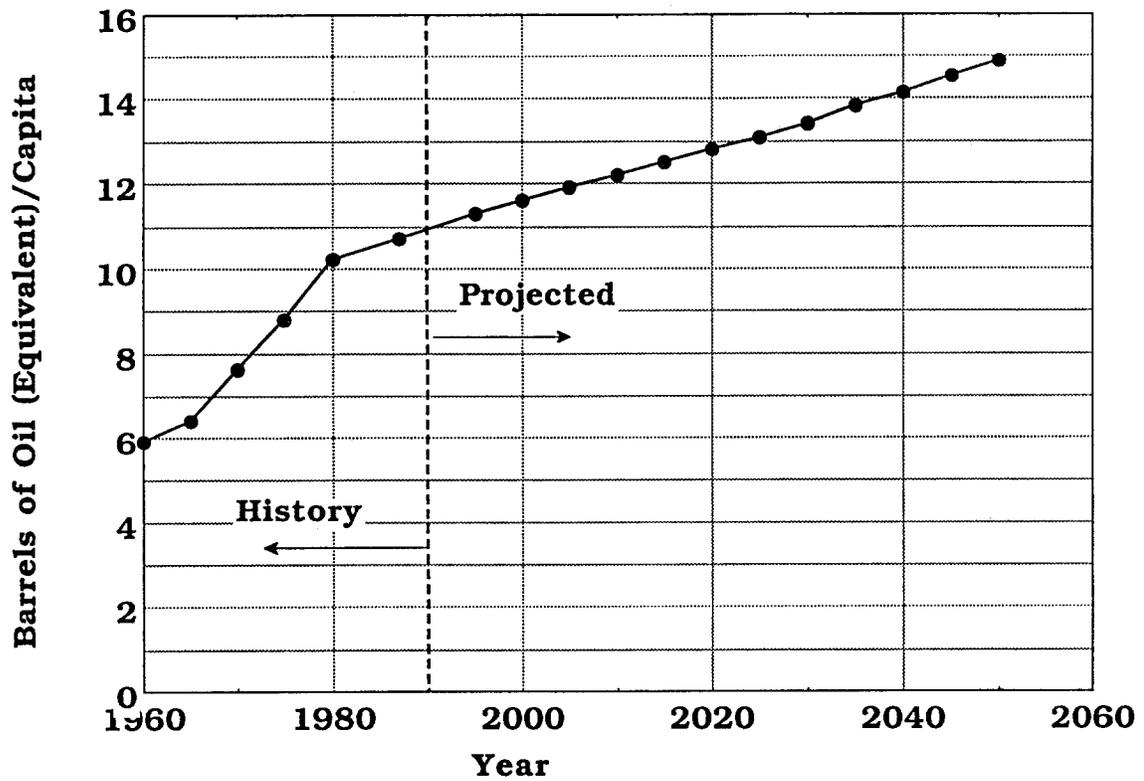


Fig. 1. Worldwide energy use per capita has increased steadily since 1960 and is projected to reach 15 barrels of oil equivalent in the middle of the 21st century. The United States per capita energy use is ≈ 60 BOE per year in 1990.

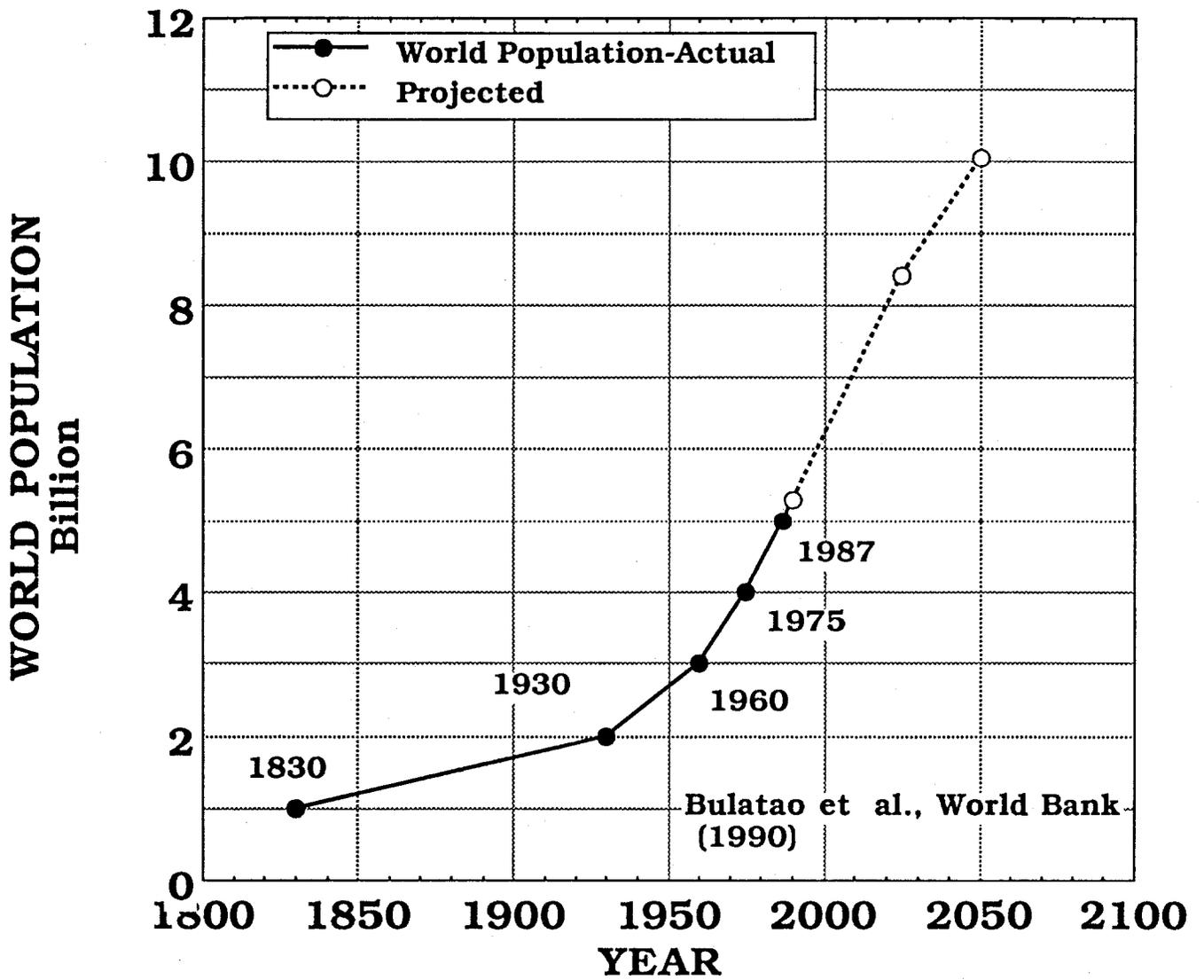


Fig. 2. World population growth - past and future. With reduced birth rates it may be possible to limit the world population to only 2 times its present value of 5.2 billion people.

Cumulative Trillion Barrels of Oil Equivalent

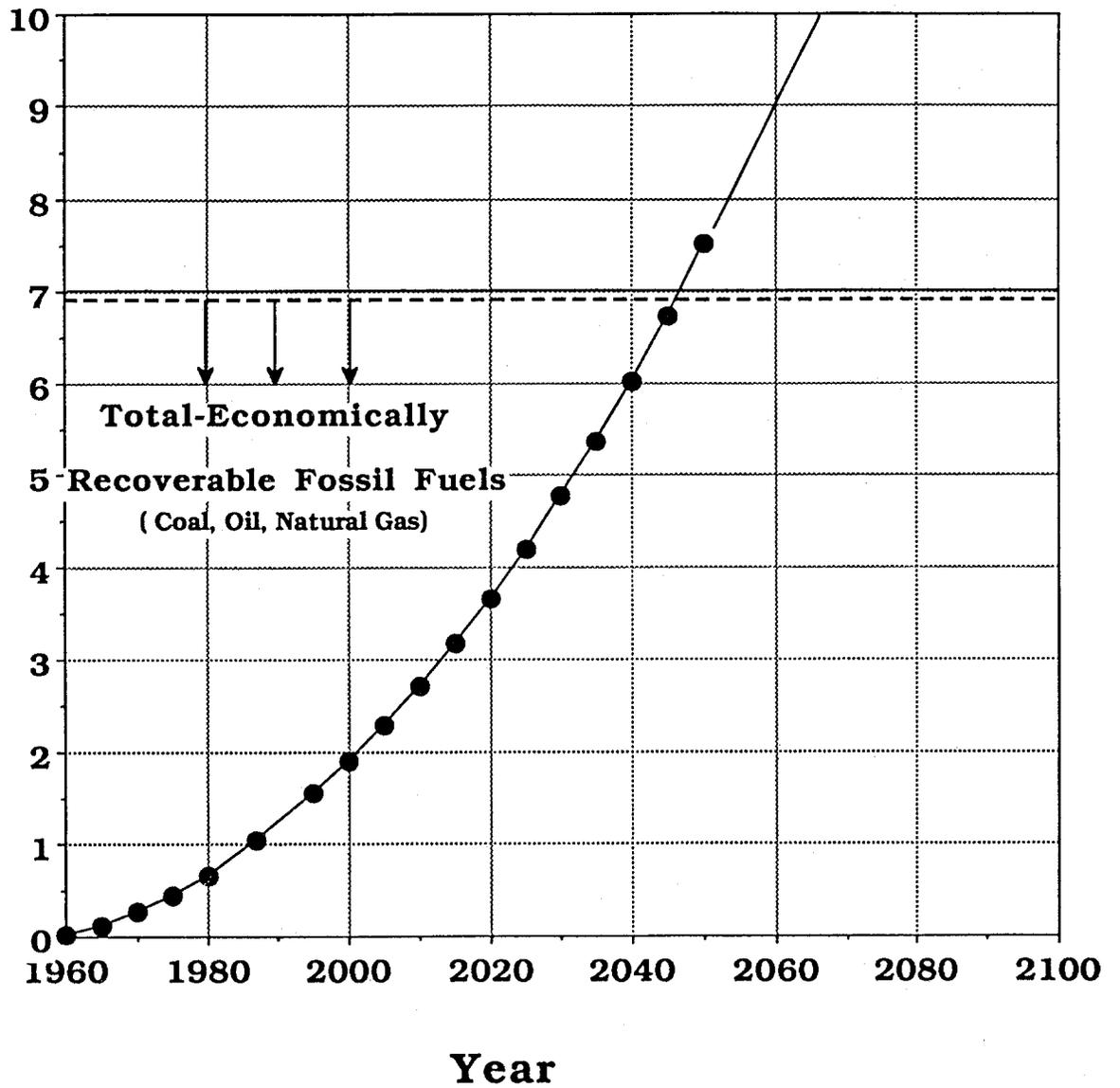


Fig. 3. Projected cumulative energy use (population times energy use per capita) will exceed the presently known reserves of economically recoverable fossil fuels by the middle of the next century.

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 utilizing 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 over 35 years. The major fusion fuel cycle that has been examined is the reaction between deuterium (D) and tritium (T)



Unfortunately, 80% of the energy from the D-T reaction is released as neutrons which 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.¹

It has been recognized for many years 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 (D) and helium-3 (${}^3\text{He}$), a rare form of helium not found in great quantities anywhere on the Earth, and the products are non radioactive protons and normal ${}^4\text{He}$.



The advantages of the D- ${}^3\text{He}$ reaction are that it releases far fewer neutrons (on the order of a few %) 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.²⁻⁵ The low levels of radioactivity in the D- ${}^3\text{He}$ reactor means 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 the lower cost of electricity, and shorter development time have also been identified.⁵

There are, however, two disadvantages to the D-³He reaction compared to the D-T fuel cycle: (1) it requires higher plasma temperature and more stringent confinement conditions; and (2) a major source of ³He is required.

Due to these two disadvantages, this fuel cycle has been ignored relative to the D-T cycle both in the U.S. and worldwide fusion research programs. However, progress in plasma physics during the last five to ten years has dramatically increased the power levels produced in fusion devices (see Fig. 4). The power level has increased from less than 1 watt in 1975 to over 100,000 watts 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 has been recently reported),⁷ we are now less than a factor of 2 away from those temperatures needed to successfully operate a D-He3 fusion power reactor at average ion temperatures of 60 keV. In addition, recent analyses of the ITER⁸ fusion facility design indicate that a successful demonstration of the D-³He 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-³He 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-³He 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 the U.S. and Soviet space scientists in the 1970's.² Analyses of the lunar samples brought back by both U.S. and Soviet space programs revealed that there is a large supply of ³He (at least 1,000,000 metric tonnes) on the Moon.^{2,3,9-12} The technical details of this discovery have been reviewed by space scientists and engineers and there now is general agreement on the order of magnitude of this resource.^{13,14}

Cameron^{9,10,15} has found a relationship between the ³He content of the lunar regolith and the TiO₂ concentration displayed in Fig. 5. This information, coupled with the fact that the Mare of the Moon contains large amounts of TiO₂ containing ilmenite strongly suggests that the first

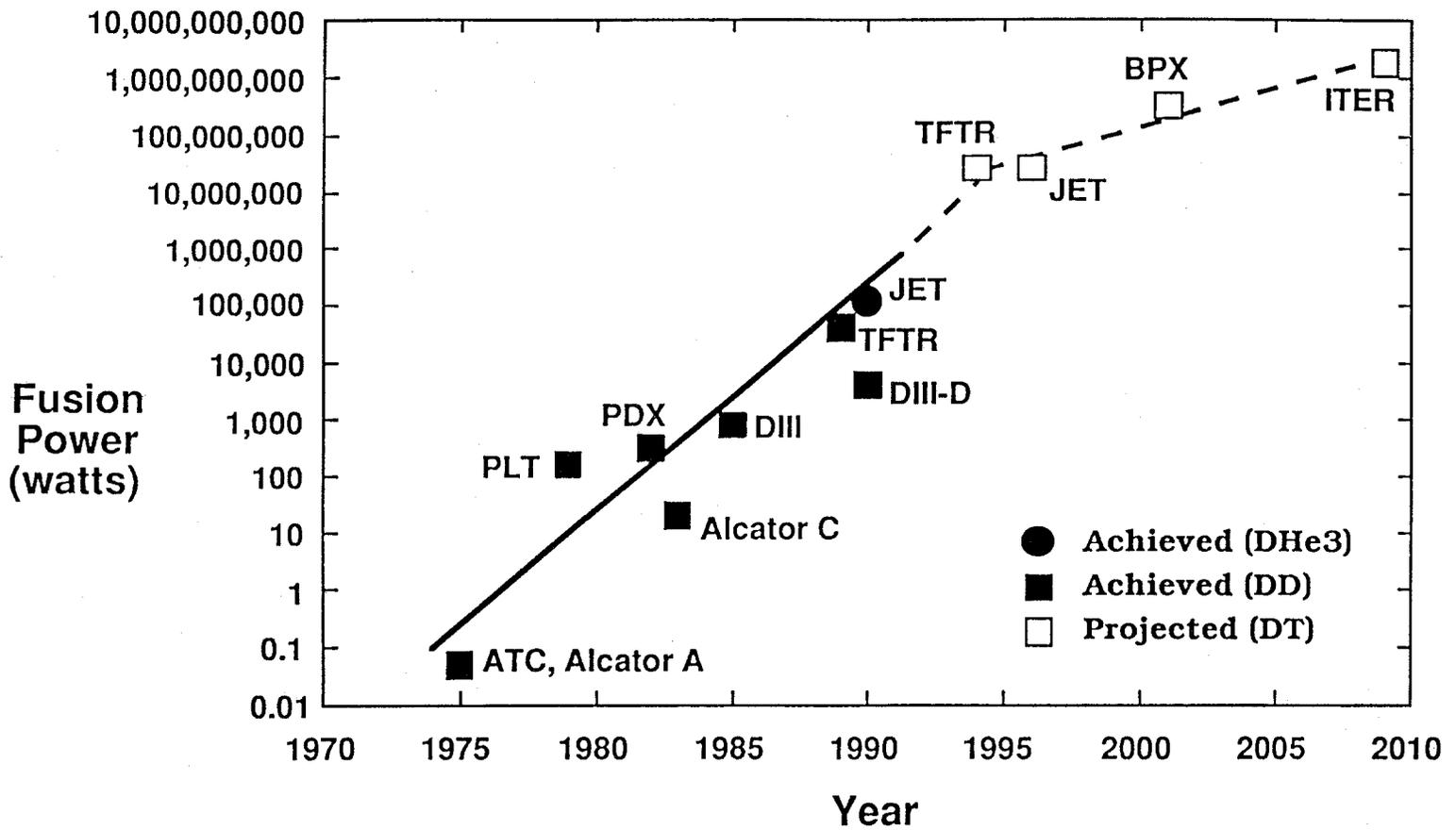


Fig. 4. The progress in magnetic fusion power generation is on a fast track and the level of fusion power will increase substantially in the next 10 to 15 years.⁶

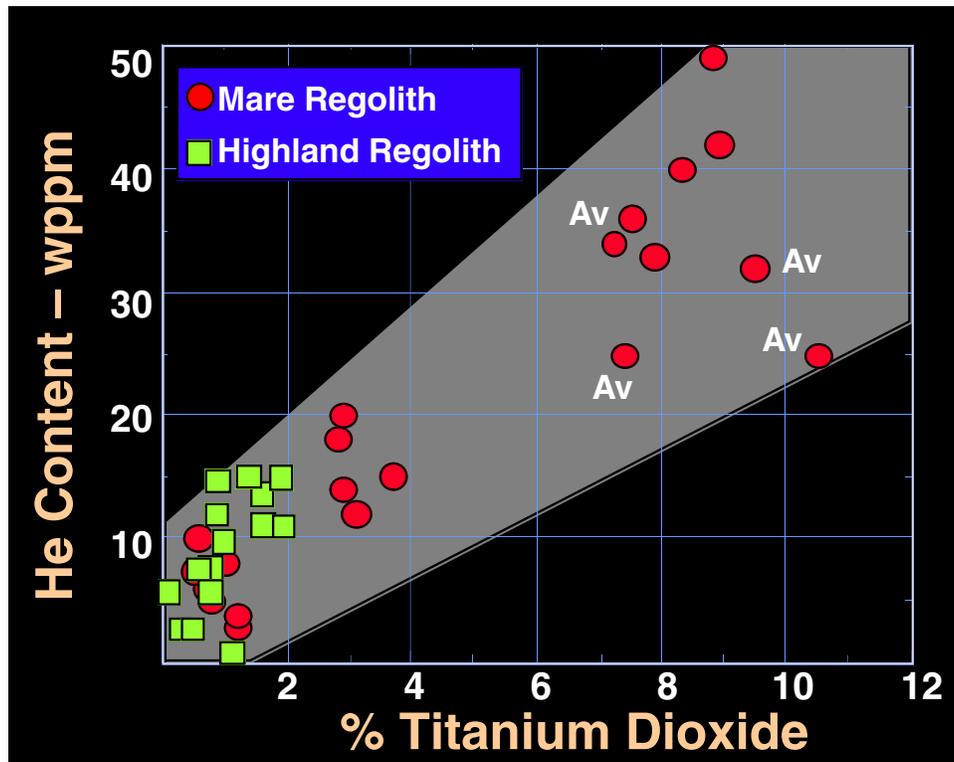


Fig. 5. The concentration of ^3He closely follows the TiO_2 content in lunar regolith.^{9,10}

mining sites on the Moon will be in the Mare.^{12,15} Experiments by Pepin¹⁶ in 1970 showed that heating the regolith to $\approx 700^{\circ}\text{C}$ would be sufficient to evolve the ^3He from the regolith. These observations are important because the loose regolith is easily processed to obtain the ^3He isotope.

Equipment has been designed to collect, heat, and return large amounts of regolith to the lunar surface 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; the sun, relayed from stationary mirrors to the slowly moving miners, is used to heat the regolith and power the miner during the (14 Earth days) lunar day. The gases (see Table 1 for the composition of lunar volatiles evolved at 700°C) are collected in tanks which are transported to radiators back at the mining base camp. During the lunar night, the gaseous mixture is exposed to the "coldness" of space ($\approx 5^{\circ}\text{K}$) and all the components except the ^4He and ^3He are condensed. The ^3He is separated from the ^4He by superleak techniques, well known on Earth. Energy and operational analyses of lunar ^3He miners have been conducted by Sviatoslavsky et al.¹⁷⁻²⁰

The importance of the by-products of ^3He mining have been studied by Bula et al.,²¹ and it was found that the needs of thousands of lunar settlers (or space travellers) could be met with the water, nitrogen, and carbon/oxygen compounds (see Table 1) derived with just 1 tonne of ^3He . 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 ^3He arises (≈ 2015).

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

- 25 tonnes of ^3He could supply the entire U.S. electrical demand in 1991. (This amount, liquefied, could fit into one spacecraft the size of a U.S. shuttle.)
- The byproducts from 25 tonnes of ^3He could provide the needs of over a half million people on the Moon for water and air to breathe as well as over the needs of 25,000 lunar inhabitants for food.



Fig. 6. An artist's conception of a lunar miner at work on the Sea of Tranquillity. Note the solar relay mirror which beam energy to the slowly moving miner for heating the regolith. This unit could supply the ^3He fuel for a city of 500,000 people in the U.S.

Table 1
**Collection of Lunar Volatiles From ^3He Mining and
 Their Impact on Life Support on the Lunar Surface**

Element	Mass Recovery @700°C Per Tonne $^3\text{He}/\text{y}$	Number of Humans Supported/y	Main Support Area
^3He	1	10,000,000	<ul style="list-style-type: none"> • Terrestrial Electricity
^4He	3100	?	<ul style="list-style-type: none"> • Pressurization • Atmosphere
N_2	400	1,150	<ul style="list-style-type: none"> • Food • Atmosphere • Pressurization
CO_2	1700	22,000	<ul style="list-style-type: none"> • Food • Atmosphere • Pressurization
CH_4	1600	?	<ul style="list-style-type: none"> • Hydrocarbons • Microbial Synthesis
H_2O	3300	23,000	<ul style="list-style-type: none"> • Potable Needs • Oxygen
H_2	6100	?	<ul style="list-style-type: none"> • Water • Oxygen • Hydrocarbons • Rocket Fuel

- There is 10 times more energy in the lunar ^3He than there ever was in all the economically recoverable fossil fuels on Earth.

The legal and institutional aspects of mining ^3He resources have also been investigated and it is shown that an international company patterned after INTELSAT could function within the existing laws, treaties, and precedents to benefit both the non-spacefaring nations and investors.²² The financial incentives for such a mining operation were recently analyzed^{23,24} and it was shown that respectable returns on investment (ROI) could be realized even if the cost to mine the ^3He was 1 billion dollars a tonne. At that cost, the ROI is in excess of 20% without taking credit for the sale of the volatile byproducts. It is worthwhile noting that at 1 billion dollars a tonne, the energy content in ^3He is equal to oil at 7\$/barrel. That is, if oil costs more than 7\$/barrel, it is cheaper to buy ^3He at 1 billion \$/tonne. At today's price of oil (≈ 20 \$/barrel in 1991) that makes ^3He worth (in terms of equivalent energy) 3 billion dollars per tonne. One 25 tonne shuttle load would then be worth ≈ 75 billion dollars or roughly twice the entire cost of the Apollo program.

An examination of a possible timetable for ^3He mining reveals that lunar ^3He could start making an impact on world energy supplies starting in ≈ 2015 -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 the 1986 National Commission on Space report, "Pioneering the Space Frontier," or the 1991 report to the Space Council, "America at the Threshold."²⁵

The fusion program in the United States is considering²⁶ a high magnetic field device originally called the Compact Ignition Tokamak (recently renamed the Burning Plasma Experiment, or 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 is a cooperative effort between the U.S., U.S.S.R., Japan, and the European Community. This device is called ITER for the International Thermonuclear Experimental Reactor. It will produce ≈ 1000 MW and operate around 2005. Slight modifications of that device could demonstrate the ignition of a D- ^3He plasma.⁸ Since no further materials test

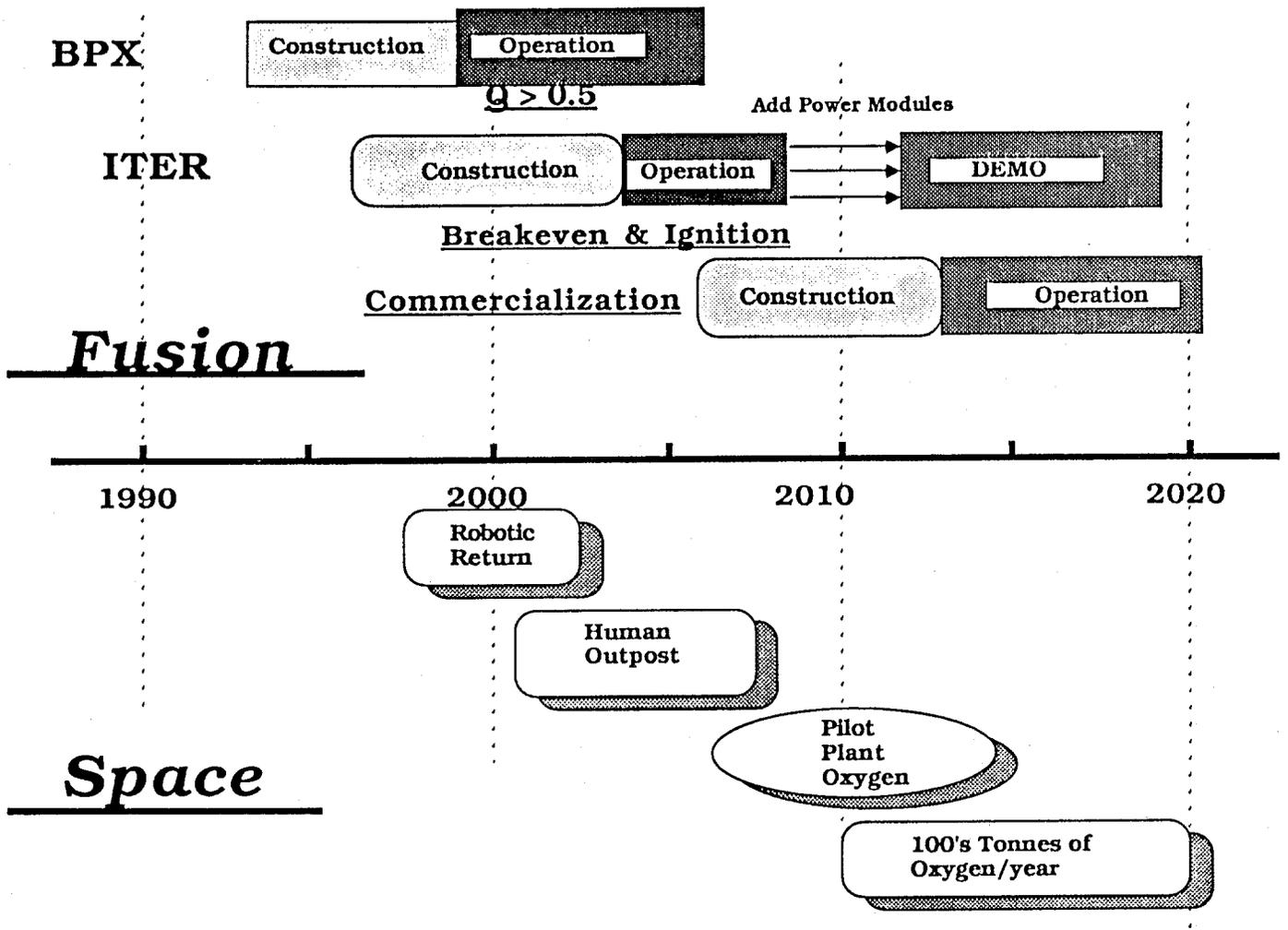


Fig. 7. The proposed schedules for developing D-³He fusion and for return to the lunar surface are compatible. There are sufficient ³He resources on Earth to fuel the program up through the first commercial power plant.

facilities are required because of the low neutron production in D-³He systems, the ITER device could be further modified to produce electricity by 2010. Assuming successful operation of a D-³He ITER demonstration reactor, it is conceivable that the first commercial fusion power plant could be on-line 5 to 10 years later. It is important to note that there is 200-300 kg of ³He (100 kg ³He burned with D will release 1,000 MW_e-y of electrical energy) available from the decay of tritium in the U.S. thermonuclear weapons.² This amount of ³He 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 century.²⁵ After early scientific and base building activities, commercial entities might be prepared for investment in lunar resources by the year 2010. Launching lunar miners to the moon in that time frame means that the first substantial amounts of ³He could be returned to the Earth by 2015, just in time for the start of construction of the second D-³He commercial power plant. The coincidence of the two schedules, fusion needing lunar ³He by the years 2015-2020 and the space program being ready for commercial operations by 2015-2020 on the moon 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 ³He and fusion in 1986² many programs around the world have been initiated. Figure 8 displays those programs which were being conducted in the U.S., U.S.S.R., Europe and Japan in 1990.

IV. Space Propulsion Using D-³He Rockets

One unique aspect of the D-³He 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-³He fusion for propulsion^{28,29} and for power in space.³⁰⁻³² Their conclusions are:

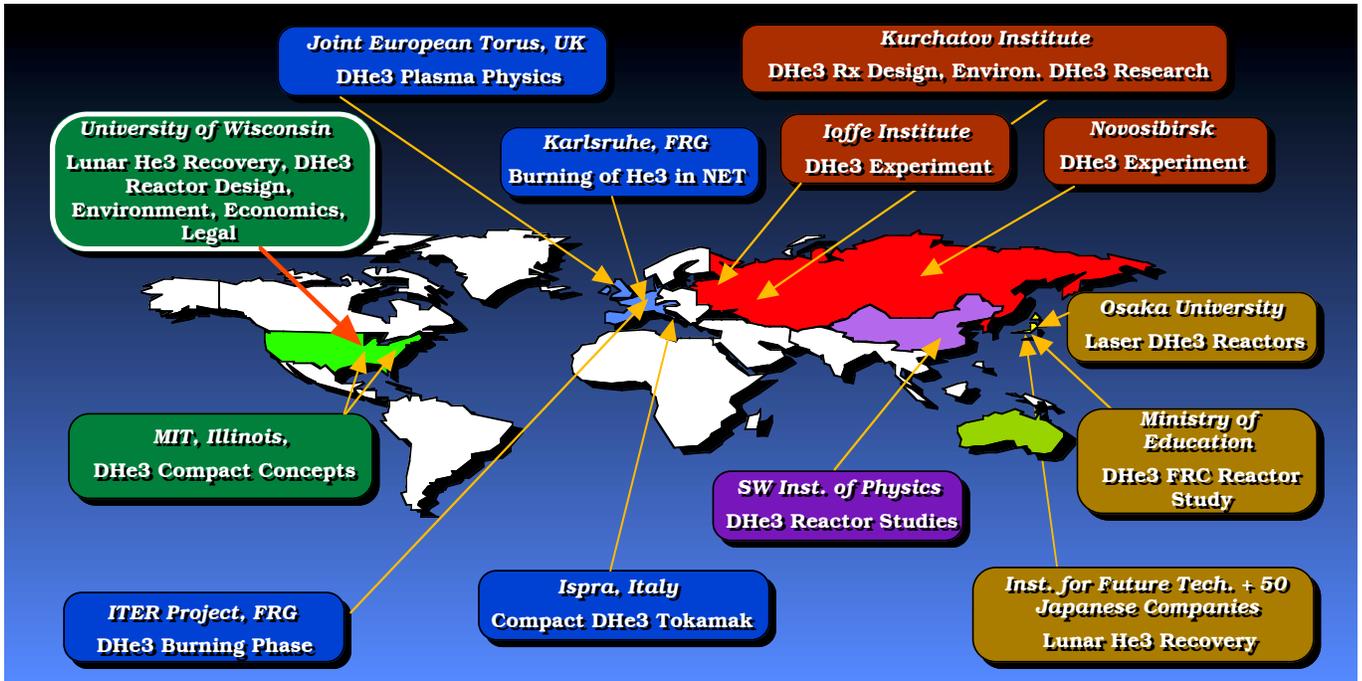


Fig. 8. Worldwide research in helium-3 fusion and lunar helium-3 research (1990).

1. The D-³He 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 1/3 the time required with chemical rockets (see Fig. 9).
4. The advantages of high I_{sp} rocket engines is 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., less than 10 years vs. 90 years with chemical systems).
5. Very high power densities in space can be developed from direct conversion of the D-³He reaction products. Power densities of 2-10 watts/g appear possible by design of linear magnetic field configurations.^{30,31}

Finally, it has been noted that fusion may be to space travel what fission reactors were to the submarine.²⁹ The potential of this technology is not only enabling for future long distance space missions, it may be the only way we can accomplish them.

V. Conclusions

The use of lunar ³He 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 ³He 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 over a million seconds that will enable explorers to reach the outer limits of the solar system in times which are 10 or more times shorter than with chemical fuels. In addition, the use of the volatile by-products from ³He mining (H₂, H₂O, N₂, CO, CH₄, CO₂) 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.

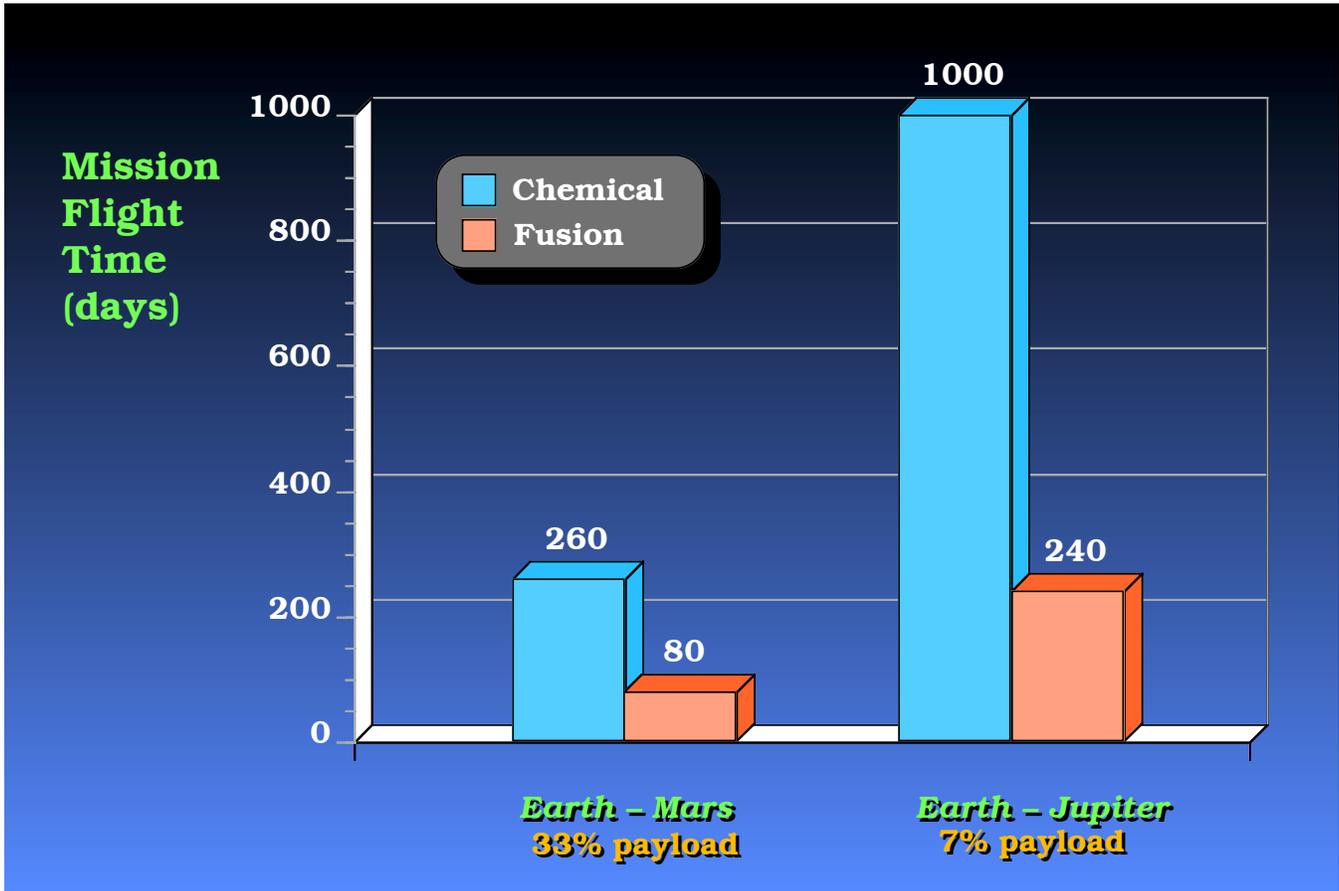


Fig. 9. The use of fusion rockets can substantially reduce the trip time to planets in the solar system.²⁸

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