The College of Engineering
University of Wisconsin-Madison

HELIUM-3: THE SPACE CONNECTION

WCSAR-TR-AR3-9304-2

Technical Report

Wisconsin Center for
Space Automation and Robotics
•
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Humankind sought and attained galactic stature with the first explorations of the moon between 1967 and 1973. During these momentous years, our species took its first clear steps of evolution into the solar system and eventually into the galaxy. Now, as the Pueblo Indians of America relate the lesson of their ancestors, "We walk on the Earth, but we live in the sky."

Early explorers of the sky took their eyes and minds into space and became the eyes and minds of billions of other explorers on the starship Earth. They began the long process of transplanting human civilization into space. This fundamental change in the course of history occurred as humans also gained new insight about themselves and about their first planetary home. With the conclusion of the Apollo 17 mission and the Apollo Program in December 1972, humankind had reached the "end of the beginning" of its movement away from home.

The overall political backdrop against which new challenges in space will be addressed during the 1990s and early decades of the Third Millennium appears to be coalescing into three major themes: Empowerment of people, Stewardship of Earth, and, indeed, Settlement of Space.

Political debate concerning Empowerment has been part of history for thousands of years, at least since the exodus of the Israelites from Egypt, and knowing the human spirit, probably long before. Today and into the future, Empowerment of people involves finding an acceptable societal balance between individual freedom and individual responsibility.

Political concerns about Stewardship began to appear early in this century but sprang full blown into public consciousness only after World War II. Exploding populations, nuclear energy concerns, and the Apollo views of Earth thrust environmental issues onto the world political stage. Stewardship for the future embodies not only protection of Earth but improvement of the human condition.

Energy makes up the most significant component of the theme of Stewardship of Earth. The basic justification for a sense of urgency with respect to energy lies in the provision of abundant and environmentally acceptable energy resources. The need for an alternative to fossil fuels for the generation of electricity increasingly will become a global imperative.

Strong evidence now exists that the ever increasing and largely indiscriminate use of fossil fuels contributes significantly to the current rise in carbon dioxide in the atmosphere. Although the ultimate response of the Earth and its climate to this build-up remains unclear, prudence clearly demands that we find acceptable alternatives to fossil fuels as quickly as technically and economically feasible. If nothing else, the value of fossil chemicals to the feeding of more billions of people on Earth will overwhelm their value as sources of electrical power.

Finally, as access to space near Earth became relatively routine in the 1960s, the theme of Settlement of Space moved from the pages of science fiction to the speculations of futurists and the reports of strategic planners. With former President Bush's Apollo 11 Anniversary speech of July 20, 1989, Settlement moved beyond speculations and reports into national policy considerations. Settlement of Space has reached a position of national visibility not unlike that reached by Stewardship during the 1950s.

Energy resources on the moon, specifically, a light isotope of helium known as helium-3, provide the link between Stewardship and Settlement (fig. 1). Fusion power plants on Earth, fueled by lunar helium-3, have the potential to produce essentially unlimited, environmentally acceptable electrical power. By-products from the production of helium-3 on the moon would provide the hydrogen, oxygen, water, and other consumable materials critical to sustaining the early settlers of Mars.

The time has come, then, to re-evaluate what we have learned about the moon in the context of these new imperatives.

One thing we learned in 1970 from the first lunar samples (Heiken et al, 1991), and which the Wisconsin workers re-discovered in 1985 (Wittenberg et al, 1985), was that the pulverized surface materials of the moon partially retain protons (96%), He (4%), and small amounts of other ions streaming from the sun as the solar wind (fig.2). One of the solar wind volatiles is ^{3}He or just He-3 (fig. 3).

The six Apollo landings on the moon have given us a first order understanding of the systematics of He-3 distribution in the lunar regolith (see Cameron, 1988, and fig.4) as these surface materials are called. Fifty to sixty percent of the regolith down to depths of five to ten meters consists of particles less than 100 microns in average diameter, that is , it is dust. The He-3 and other volatiles have their greatest concentrations in this dust due to the large effective surface area it represents. Although we have limited data on the variations of volatile content with depth, the drill cores we have indicate no trends toward a decrease in concentration to depths of three meters.

Amounts of He-3 and other volatiles also correlate closely with the concentration of titanium in the regolith (fig. 5), due to its strong retention by the iron-titanium oxide called ilmenite. This correlation fortunately gives us one technique to measure He-3's approximate distribution over the near face of the moon. Its property as a neutron absorber with the emission of a 22 mev gamma ray promises to provide a technique for more detailed resource mapping once a spectrometer of appropriate sensitivity can be placed in orbit.

Using remote sensing techniques from Earth, the regional distribution of Ti (Johnson et al, 1992) and, thus, of He-3 has been determined to a first approximation. The area of highest potential concentration or "grade" and of probable greatest initial interest will be in the northern half of Mare Tranquillitatis.

Even though present in the regolith in amounts less than about 30 parts per billion, the total quantity of He-3 in the first three meters of lunar regolith approximates one million tonnes, including both mare and highlands (Wittenberg et al, 1986). This quantity of He-3 would provide 10 times more energy than that in all the economically recoverable fossil fuels on Earth as defined by the U.S. Department of Energy. Further, one tonne of He-3 can produce 10,000 MWe-yr of electrical energy, or approximately that required by a U.S. city with a population of 10 million, and the entire U.S. electricity consumption in 1993 could be provided by 25 tonnes.

As indicated by the NASA Lunar Energy Enterprise Case Study (1989), what really makes these numbers of economic interest is He-3's oil equivalent value on Earth today, if commercial fusion plants existed to use it, of about three billion dollars per tonne. Another way to look at this is that He-3 at one billion dollars per tonne is equivalent to seven dollar per barrel oil!

What is our energy and environmental imperative that drives the search for an alternative to fossil fuels? First, as summarized by Kulcinski and Schmitt (1990) worldwide energy use per capita has increased steadily since 1960 and is projected to reach 15 barrels of oil equivalent by 2050. For reference, the U.S. per capita energy use is currently about 60 BOE. Second, world population will approach or exceed 10 billion by 2050. Projected cumulative energy use will exceed seven trillion barrels of oil equivalent, potentially exceeding recoverable supplies.

The production of one tonne of He-3 from lunar regolith with a recoverable grade of 20 ppb requires the beneficiation of about 50 million tonnes of material and the mining of about 100 million tonnes, equivalent to an area of about 20 km^2 mined to a depth of three meters. This compares with the current annual production of coal (without overburden removal and replacement) of about 5 billion tonnes.

Simple heating to about 700^{o}C. (fig. 6) recovers over 90 percent of the He-3 and other solar wind volatiles present in the fine-grained portion of the lunar regolith (Pepin et al, 1970). If the separation of fines, their solar thermal heating, and heat recovery take place within the miner, very little mechanical energy will be required for mining and beneficiation relative to comparable large tonnage mining operations on Earth.

The conduct of actual mining operations leads to a number of possibilities, ranging from a traditional rectilinear approach (Cameron, 1990), employing a semirobotic self-contained miner and beneficiator (see Sviatoslavsky and Jacobs, 1988, and fig. 7), to a spiral mining system that includes a mobile base concept (see Schmitt, 1992, and fig.8).

Although the potential economic return on the production of He-3 should attract considerable attention, the return on the volatile by-products may be just as great (fig. 9), particularly for use in space. Hydrogen, water (a source of oxygen), nitrogen oxides, and carbon oxides all have important applications in space, not the least of which will be the support of a lunar settlement and the initial support of Mars settlements.

Mars appears to have have all the indigenous resources (Carr, 1984) necessary for permanent settlement, however, in the early start-up years, the moon may well be the low cost and necessary source of consumables supply.

The by-product volatiles have many uses (fig. 10). For example, hydrogen can be used to produce water, oxygen, and hydrocarbons as well as for propulsion and fuel cell electrical power. Water, a consequence of the reaction of hydrogen with oxides and silicates during heating, has many obvious applications for life support and agriculture. Carbon and nitrogen compounds probably will be most useful in the production of food and hydrocarbons. Helium-4 provides gas for fluid pressurization and propulsion enhancement.

Meanwhile, back on Earth, the critical question becomes how best to transition from an environmentally imprudent fossil fuel/fission energy economy to an environmentally sound economy based upon He-3 fusion.

For the purposes of comparisons, we have assumed that the penetration of fusion energy into the commercial market is somewhat faster than for fission in the U.S. and Japan but considerably slower than in France (fig, 11). If introduced in 2015, this would result in fusion capturing 50 percent of the U.S. electrical generation market in the year 2050 (fig. 12).

Based on this penetration rate, the production of He-3 would reach about 50 tonnes per year by 2050 (fig. 13), exceeding current coal production a few years prior to that. Mining an area the size of Washington, D.C. would not occur until about 2035.

At a very conservative $1 billion per tonne ($7 BOE), the cumulative market for He-3 would be over half a trillion dollars in current dollars for the first half of the 21st Century (fig 14).

The potential market value of other lunar volatiles also should not be ignored, although when there might be significant demand remains uncertain. For example, the total amount of volatiles required to support one person-year on the lunar surface exceeds 700 kg/yr (see Bula et al, 1992, and fig. 15). Once beneficiation of lunar regolith begins, the expansion of personnel at a lunar base could be tied to the rate of growth of volatile production, reaching about 150 people by 2020 under the He-3 penetration schedule assumed here (fig. 16). Eventually, the quantities of volatiles produced would be sufficient to meet the demands of a 21st Century space transportation infrastructure, including access to Mars and the Moon and return (figs. 17-20).

A near-term policy and budgetary commitment to a lunar base in support of He-3 mining appears consistent with an initial He-3 delivery date late in the first decade of the next century (fig 21). Such a commitment implies start-up costs in the range of 100 billion dollars for the base (roughly the cost of the Apollo Program in current dollars) and 30 billion for the mining infrastructure (currently a guess). These costs probably could be significantly lower if the private sector took responsibility for all or part of the enterprise.

As you can see (fig. 22), this mining schedule is consistent with the fusion development schedule suggested by

Kulcinski (1993), particularly if the Polywell™ concept proves commercially viable.

The rest of the world continues to move forward with fusion research (fig. 23), although most known programs focus on the D-T cycle, including the International Thermonuclear Experimental Reactor (ITER, 1989) effort. Only the Japanese appear to have a national eye on lunar He-3 as a future terrestrial energy possibility.

Conclusions

Clearly, enough environmental, economic, and practical potential exists for the application of lunar volatiles, He-3 in particular, that a rejuvenation of the nation's space program based on their access commands serious consideration. Lunar volatiles have broad relevance to the exploration and settlement of the solar system. Lunar He-3, He-4, hydrogen, and oxygen can be utilized in both conventional and fusion space propulsion. Lunar He-3 and lunar hydrogen and oxygen provide the option of both fusion and fuel cell electrical power generation for use in space. Most importantly, lunar He-3 offers possibly the only realistic global option for a near-term alternative to fossil fuels for the generation of terrestrial power.

It's time to take another look at the moon.

REFERENCES

Bula, R.J., Wittenberg, L.J., Tibbets, T.W., and Kulcinski, G.L. (1992) Potential of derived lunar volatiles for life support. In Lunar Bases and Space Activities in the 21st Century Second Symposium, NASA Conference Publication 3166, 2, 547.

Cameron, E.N. (1988) Helium mining on the moon. In Lunar Bases and Space Activities of the 21st Century, Second Symposium,

Cameron, E.N. (1990) Geology of Mare Tranquillitatis and its significance for the mining of Helium. In Lunar Bases and Space Activities in the 21st Century Second Symposium, NASA Conference Publication 3166.

Carr, M.H. (1984) Mars. In M.H. Carr, ed., The Geology of the Terrestrial Planets, NASA SP-469, 207-263.

Heiken, G.H., Vaniman, D.T., and French, B.M. (1991) Lunar Sourcebook. Cambridge Press, Cambridge.

ITER (1989) ITER Concept Definition. 1 and 2, IAEA, Vienna, 1989.

Johnson, J.R., Larson, S.M., and Singer, R.B. (1991) Spectral ratio methods for telescopic lunar TiO_2 mapping. Proceedings of 22nd Lunar and Planetary Science Conference, LPI, Houston.

Kulcinski, G.L. (1993) Helium-3 Fusion Reactors - A clean and safe source of energy in the 21st Century. Proceedings of the Ninth National Space Symposium, U.S. Space Foundation, (in press)

Kulcinski, G.L., and Schmitt, H.H. (1990) Fusion power from lunar resources. 41st Congress of the International Astronautical Federation, 6-12 October 1990, University of Wisconsin, UWFDM-826.

NASA (1989) Report of the NASA Lunar Energy Enterprise Case Study Task Force. NASA Technical Memorandum 101652, July 1989.

Pepin, R.O., Nyquist, L.E., Phinney, D., and Black, D.C. (1970) Rare gases in Apollo 11 material. Proceedings of the Apollo 11

Lunar Science Conference, 2, 1435-1454.
Schmitt, H.H. (1992) Spiral mining for lunar volatiles. Engineering, Construction, and Operations in Space III, Proceedings Space-92.
Sviatoslavsky, I.N., and Jacobs, M. (1988) Mobile Helium-3 mining system and its benefits toward Lunar Base self-sufficiency. Engineering, Construction, and Operations in Space III, Proceedings Space-88.
Wittenberg, L.J., Santarius, J.F., and Kulcinski, G.L. (1986) Lunar source of ^{3}He for commercial fusion power. Fusion Technology, 10, 167.

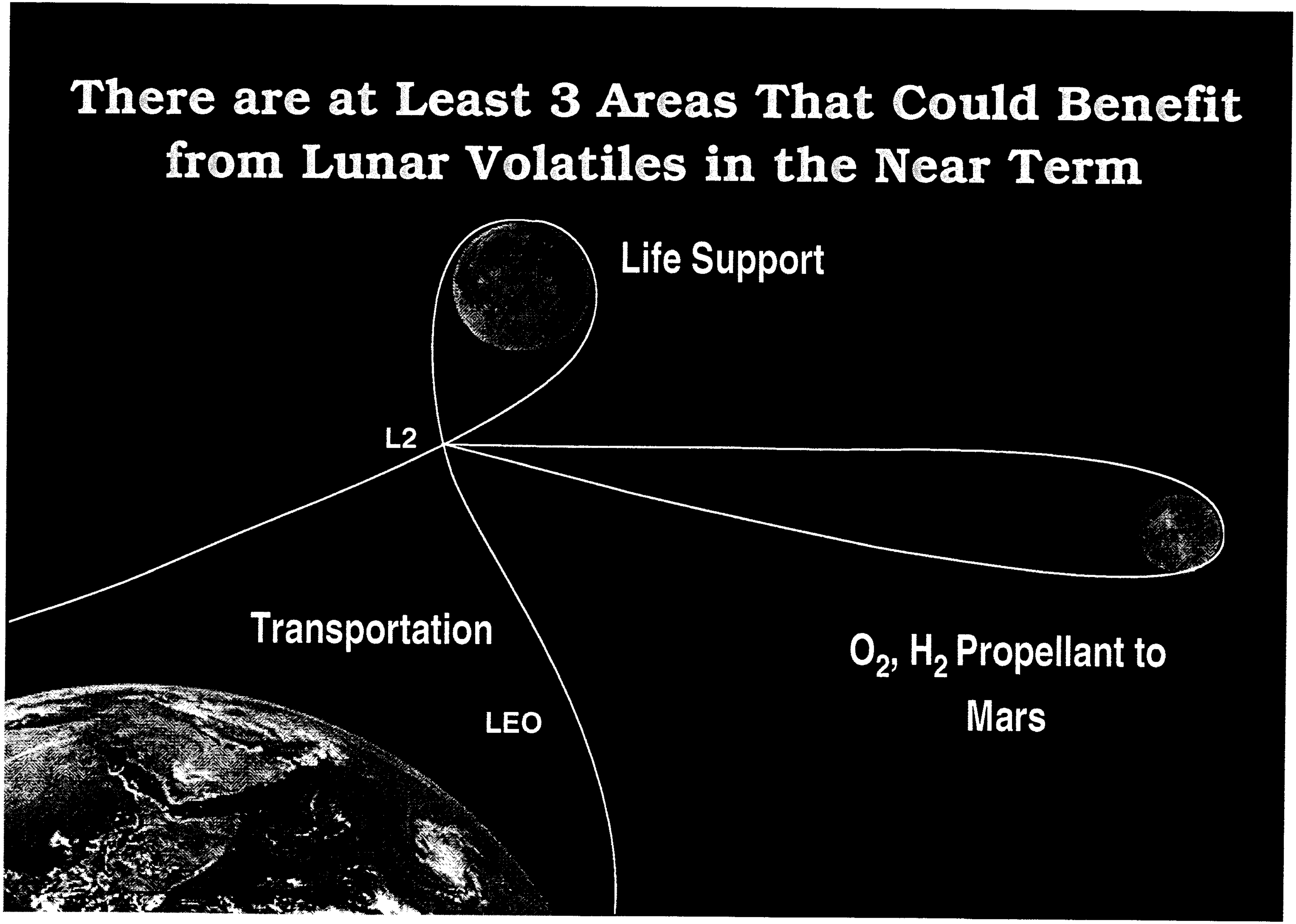
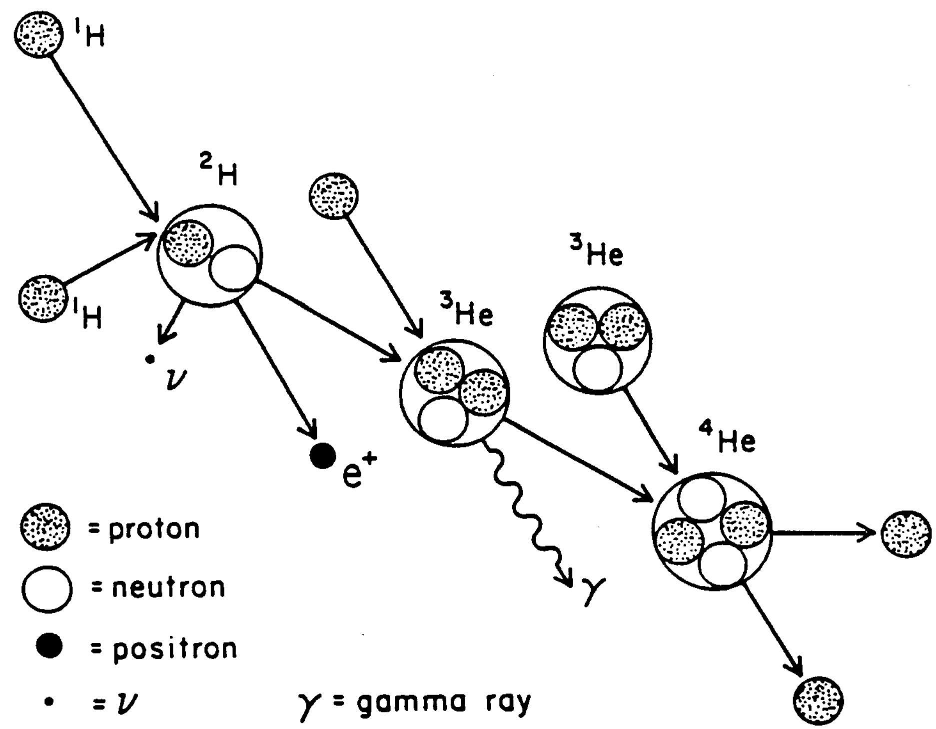

There are at Least 3 Areas That Could Benefit from Lunar Volatiles in the Near Term
Life Support
L2
Transportation
LEO
O_2, H_2 Propellant to Mars

FIGURE 1



SOLAR NUCLEAR FUSION REACTIONS VIA THE PROTON–PROTON CHAIN

FIGURE 2

Solar Wind

- 96% Protons
  4% Helium
- Energy ~3 keV
- Total ^{3}He Fluence
  500 million tonnes
  in 4 billion years

FIGURE 3

Measured Helium Content in Lunar Samples

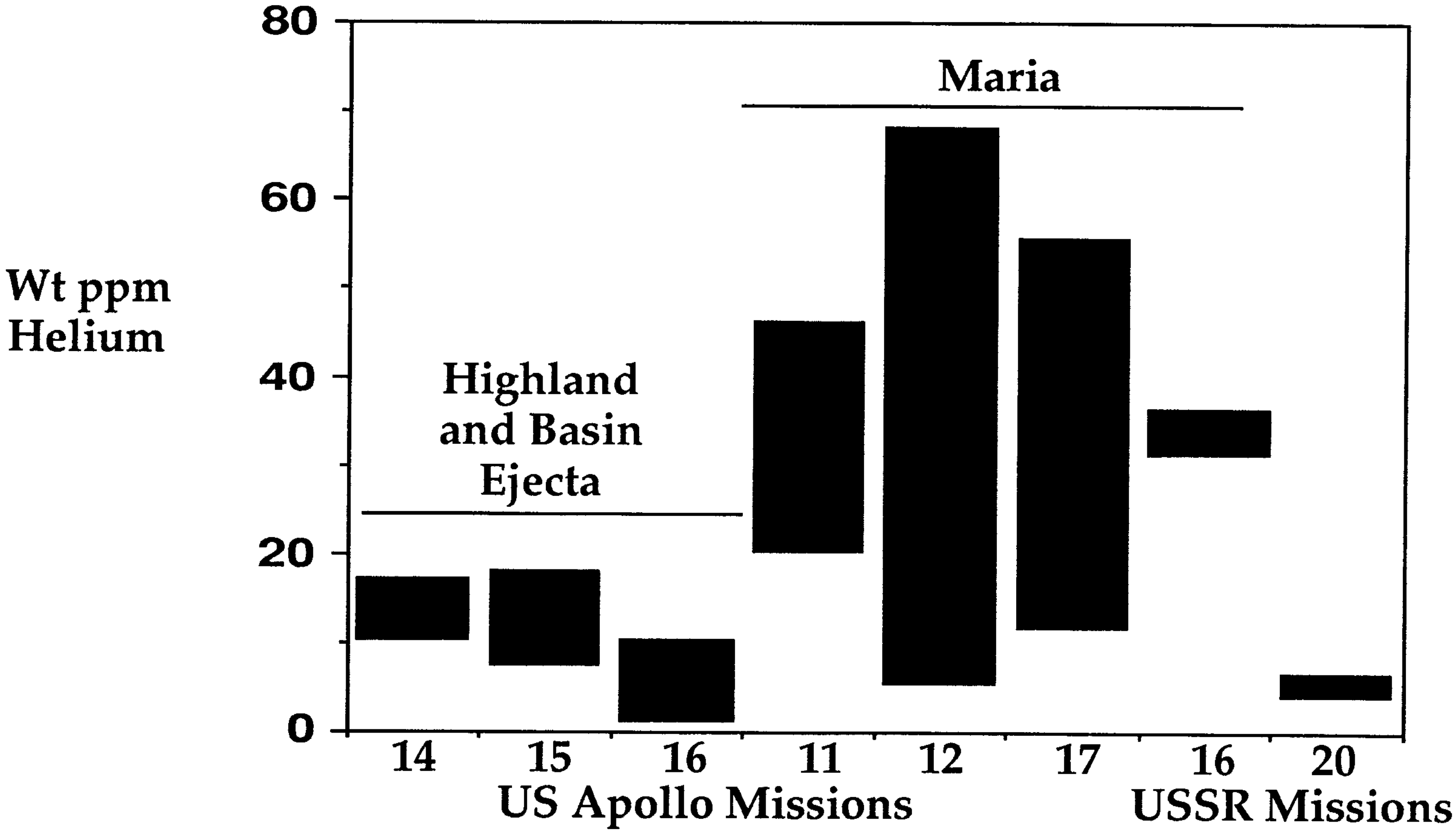


FIGURE 4

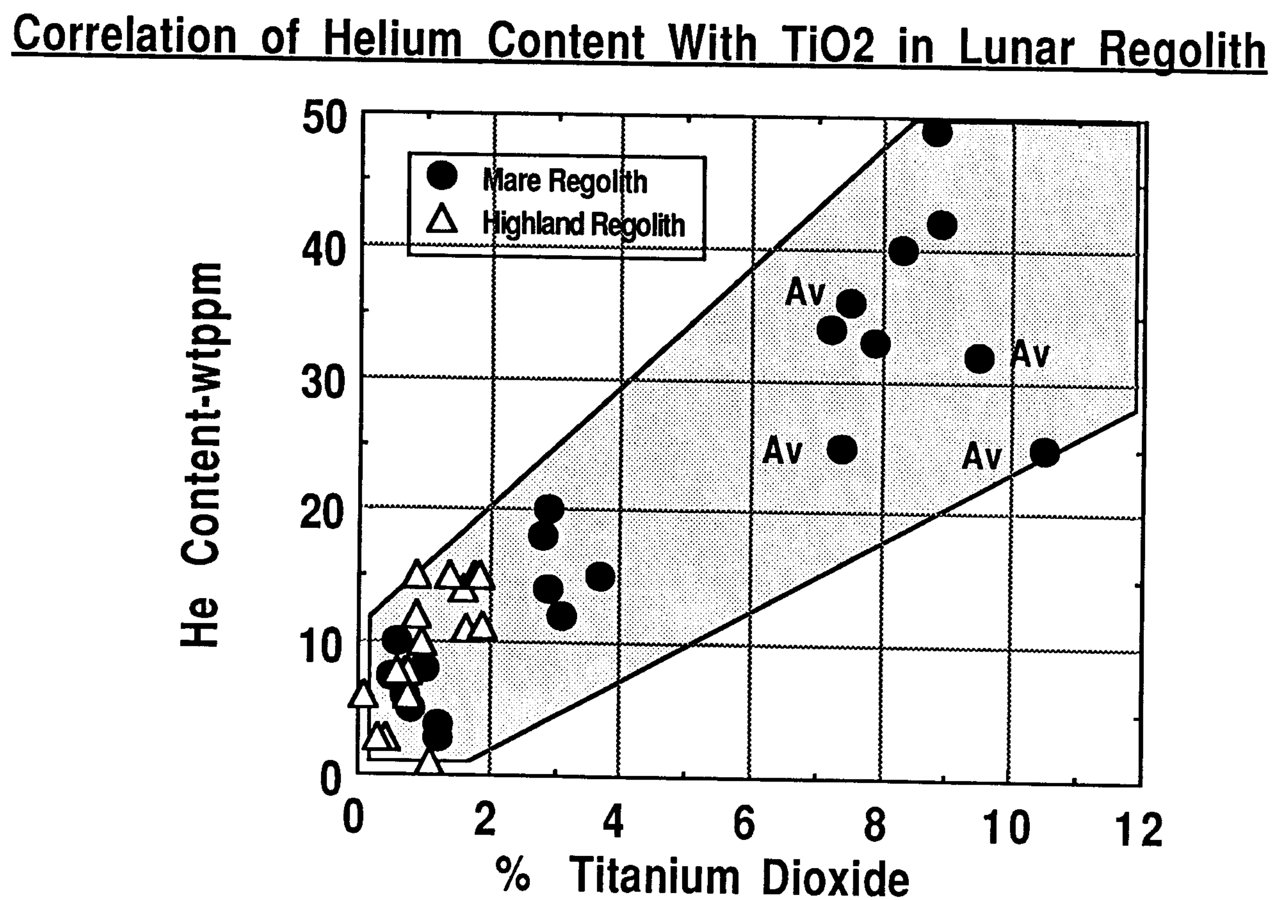
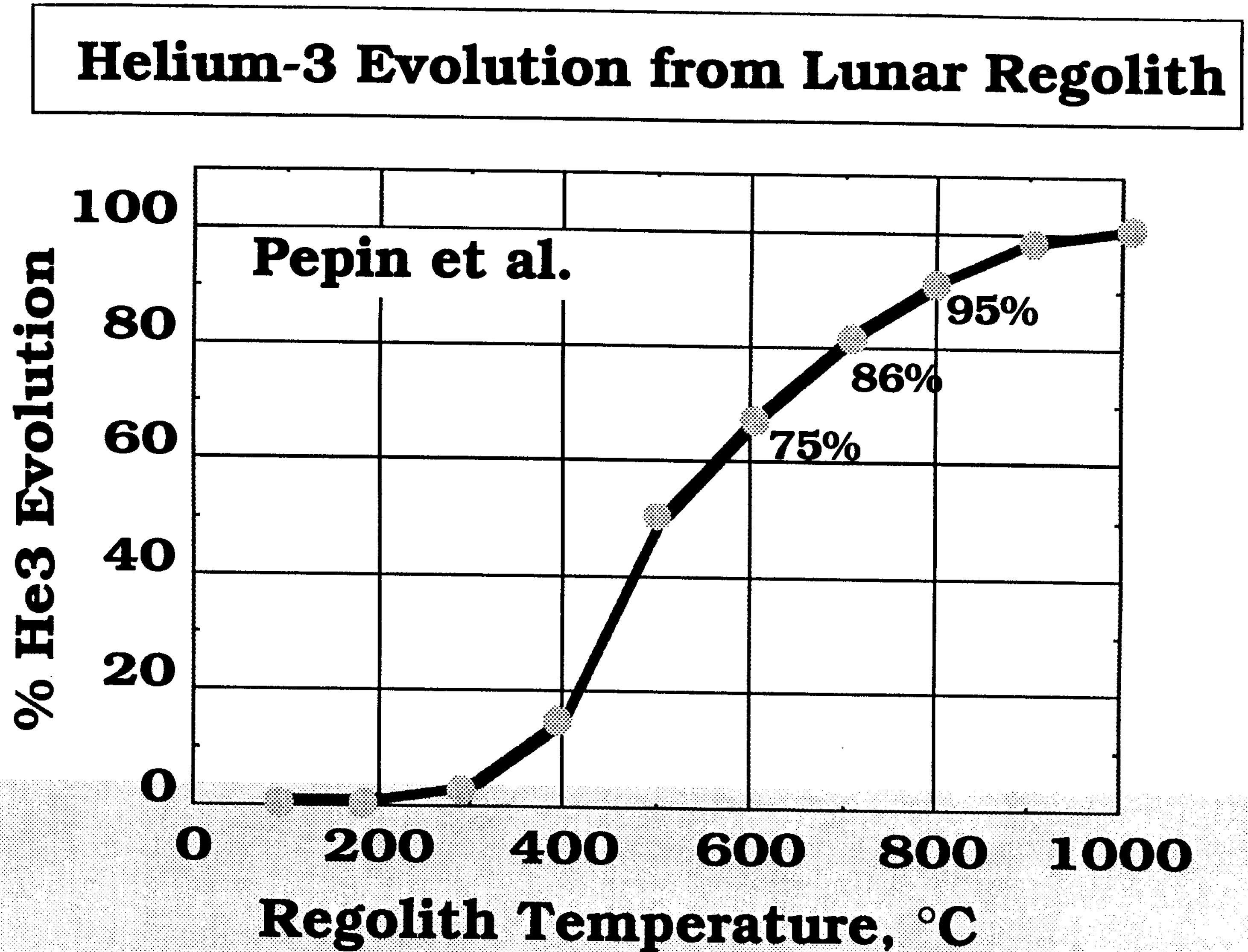

Correlation of Helium Content With TiO2 in Lunar Regolith
Mare Regolith
Highland Regolith
He Content-wtppm
% Titanium Dioxide
Av
Av
Av
Av
0
10
20
30
40
50
0
2
4
6
8
10
12

FIGURE 5



Helium-3 Evolution from Lunar Regolith
Pepin et al.
% He3 Evolution
100
80
60
40
20
0
95%
86%
75%
0
200
400
600
800
1000
Regolith Temperature, °C

FIGURE 6

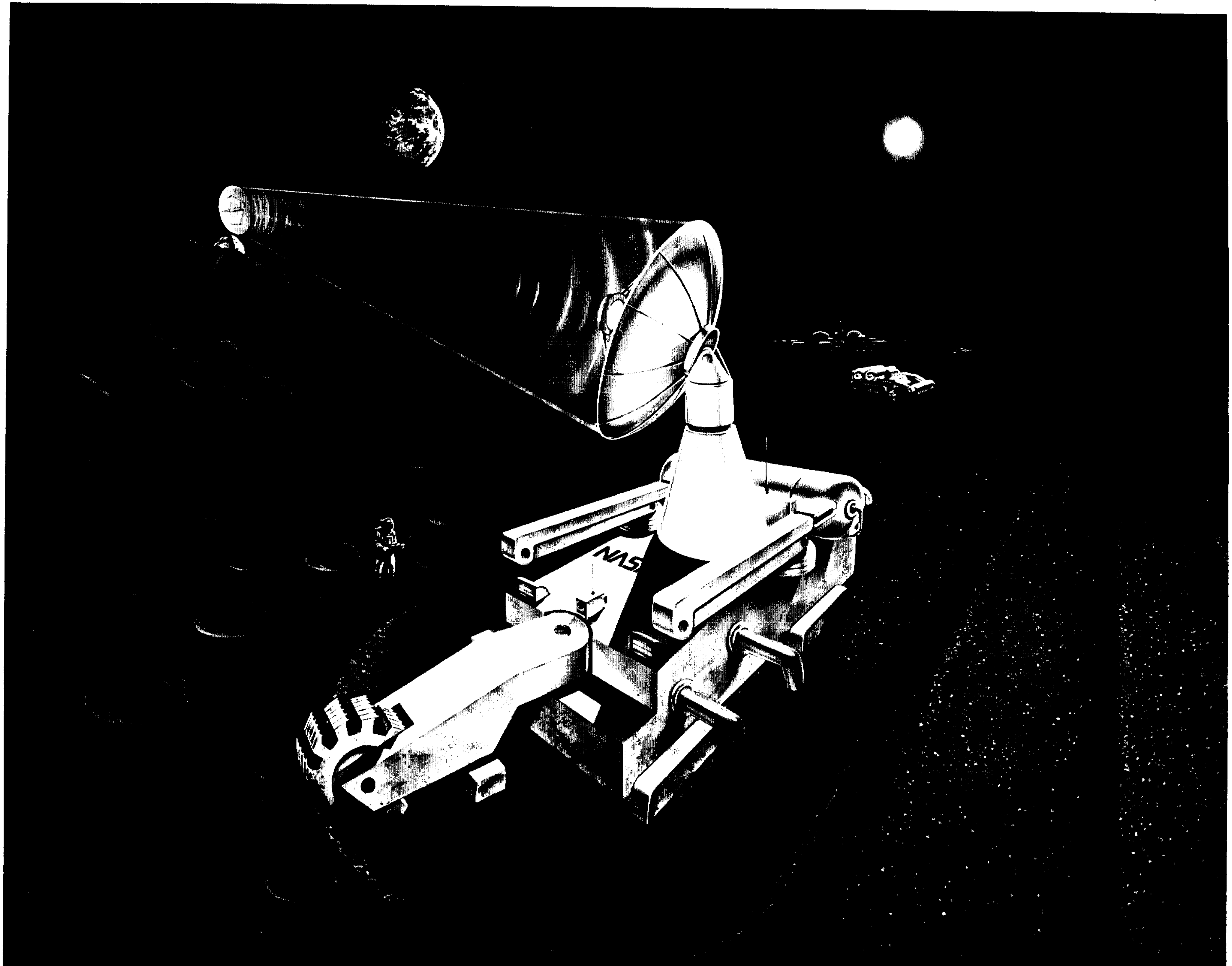


FIGURE 7

Spiral Mining System for Lunar Volatiles

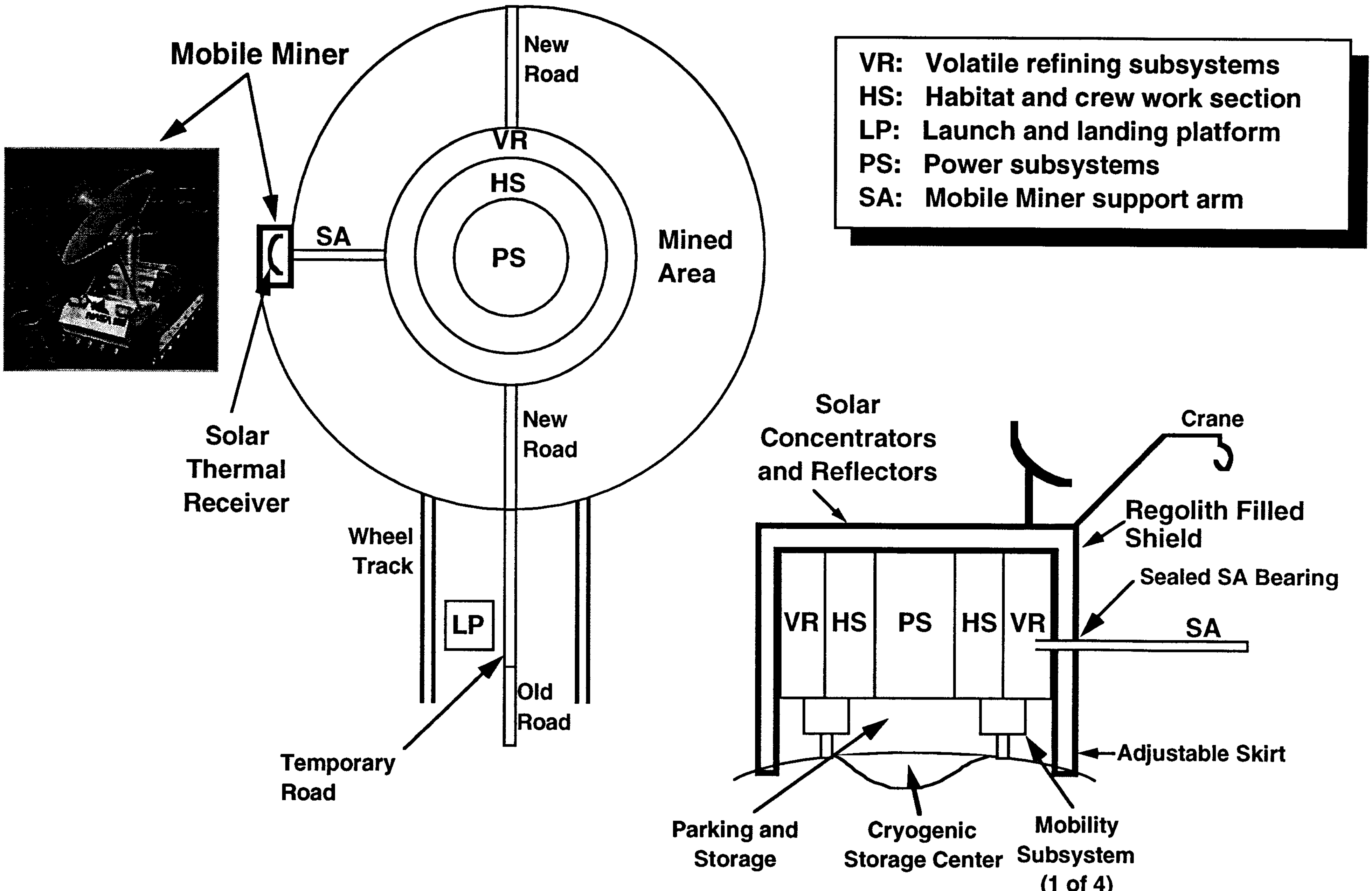


FIGURE 8

Process for Extracting Helium-3 from Lunar Regolith

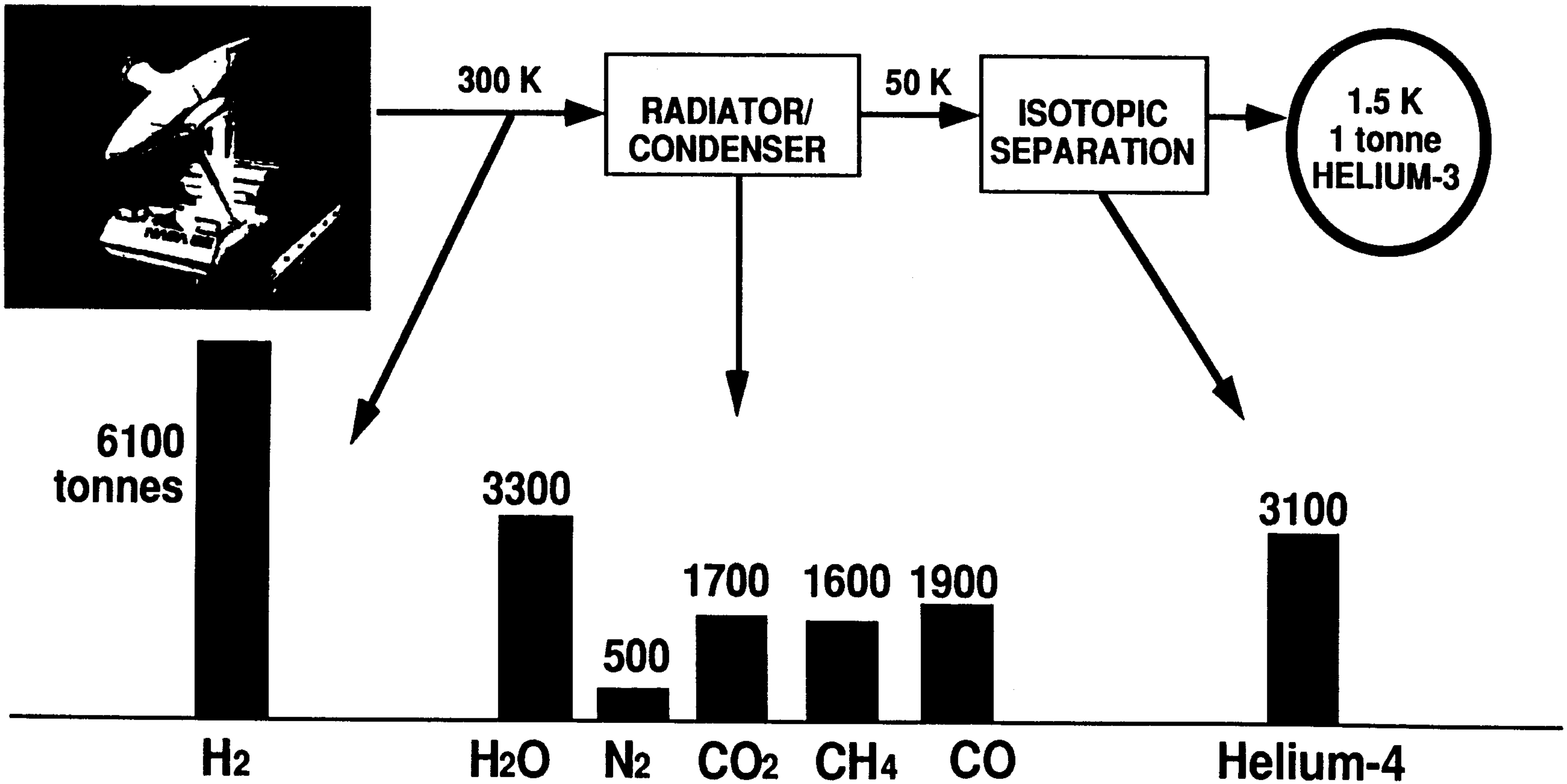


FIGURE 9

Applications of Lunar Volatiles

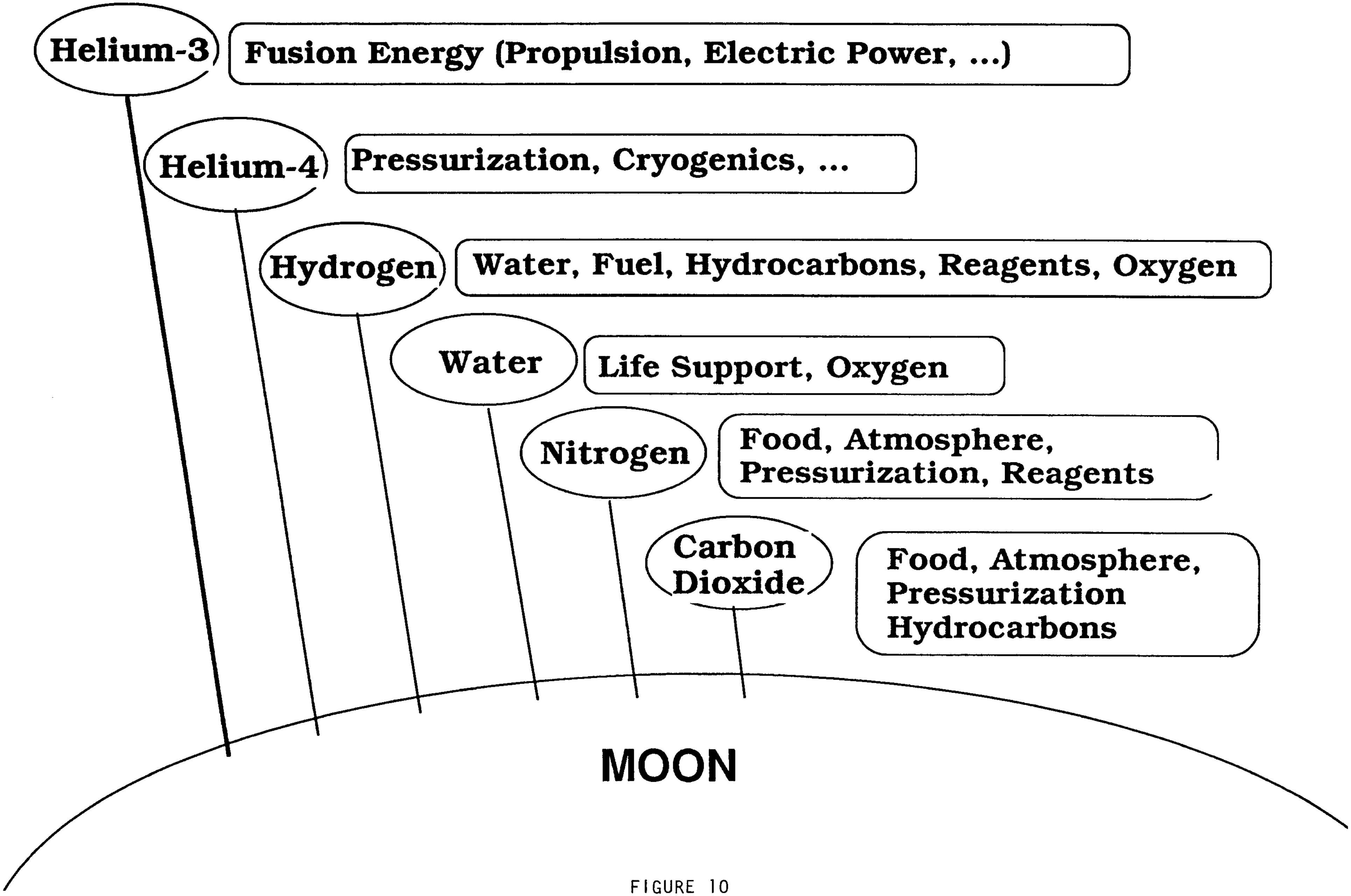


FIGURE 10

The Assumed Penetration of Fusion Energy Into the Commercial Market is Somewhat Faster Than For Fission in the U.S. and Japan But Considerably Slower Than in France

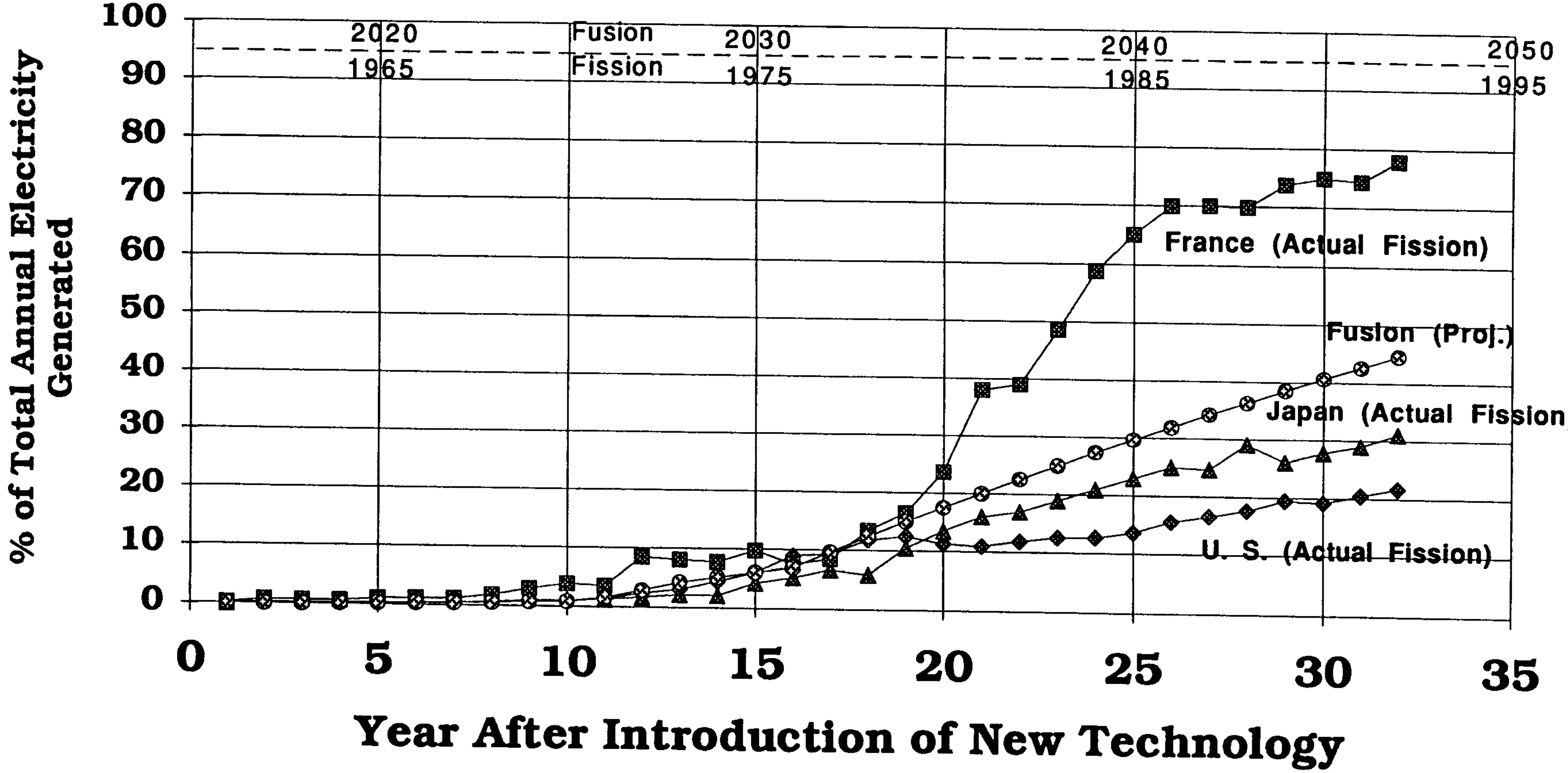
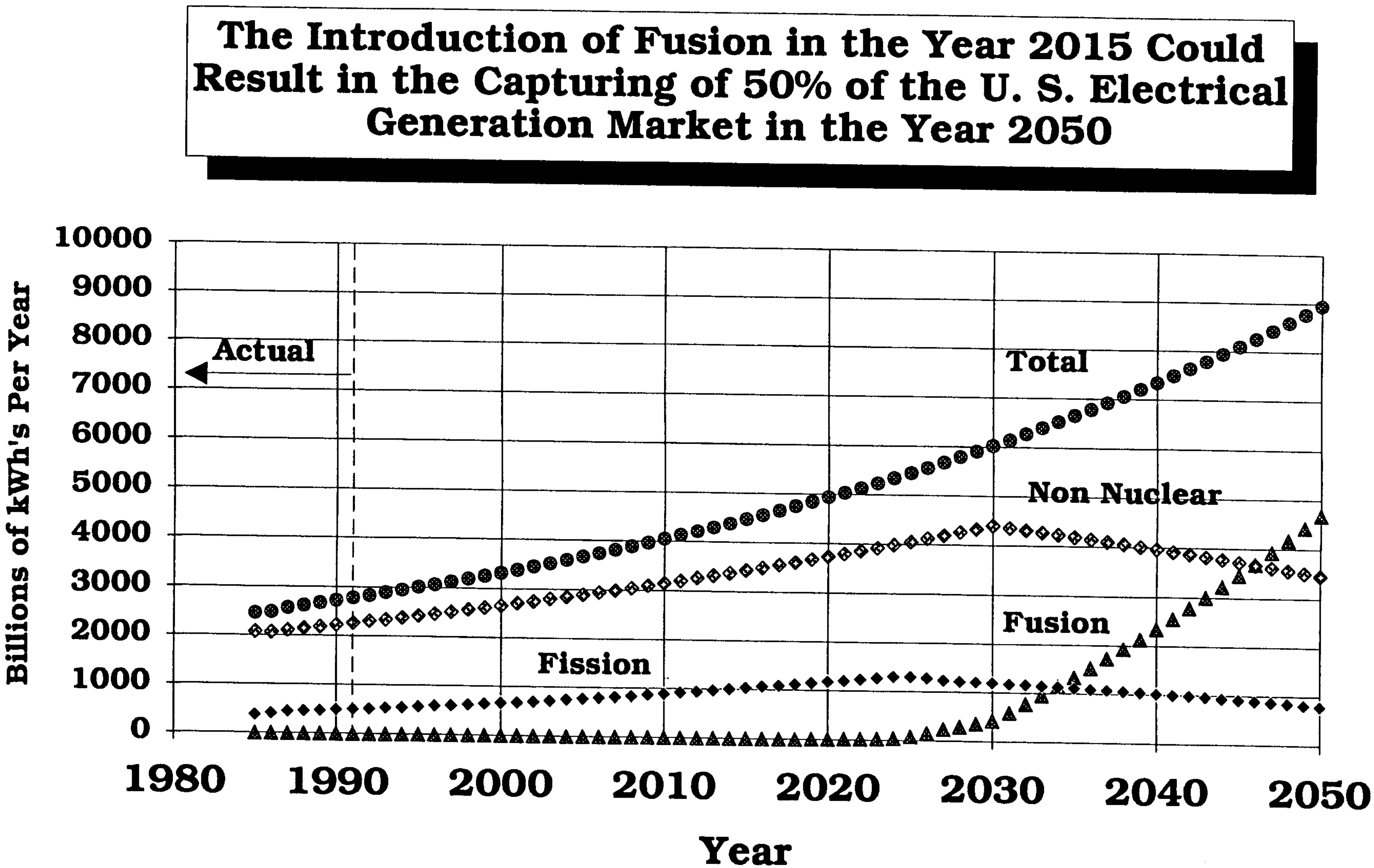


FIGURE 11



The Introduction of Fusion in the Year 2015 Could Result in the Capturing of 50% of the U. S. Electrical Generation Market in the Year 2050
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Billions of kWh's Per Year
Actual
Total
Non Nuclear
Fusion
Fission
1980
1990
2000
2010
2020
2030
2040
2050
Year

FIGURE 12

Under Conservative Penetration Scenarios, the Mining of He3 Would Not Approach 50 Tonnes per Year Until 2050

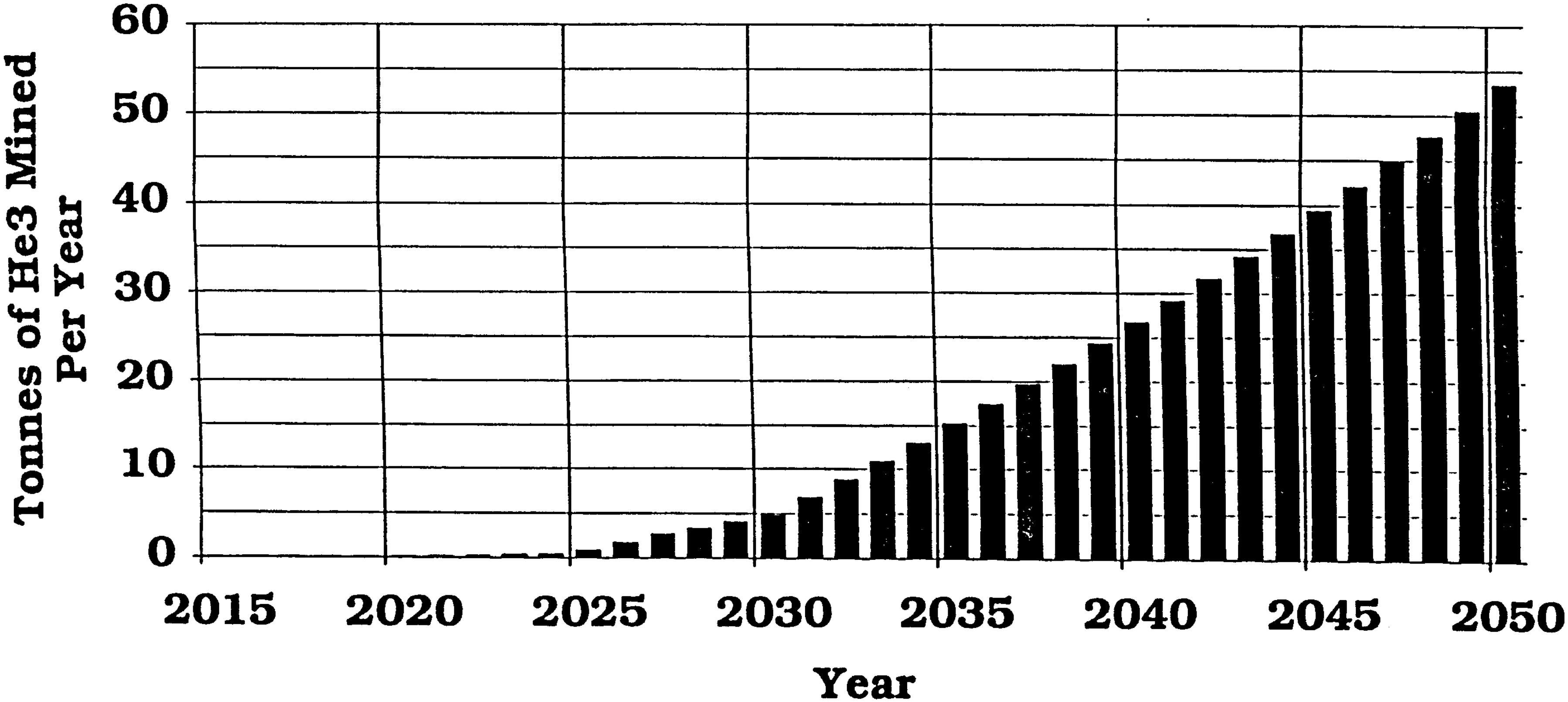
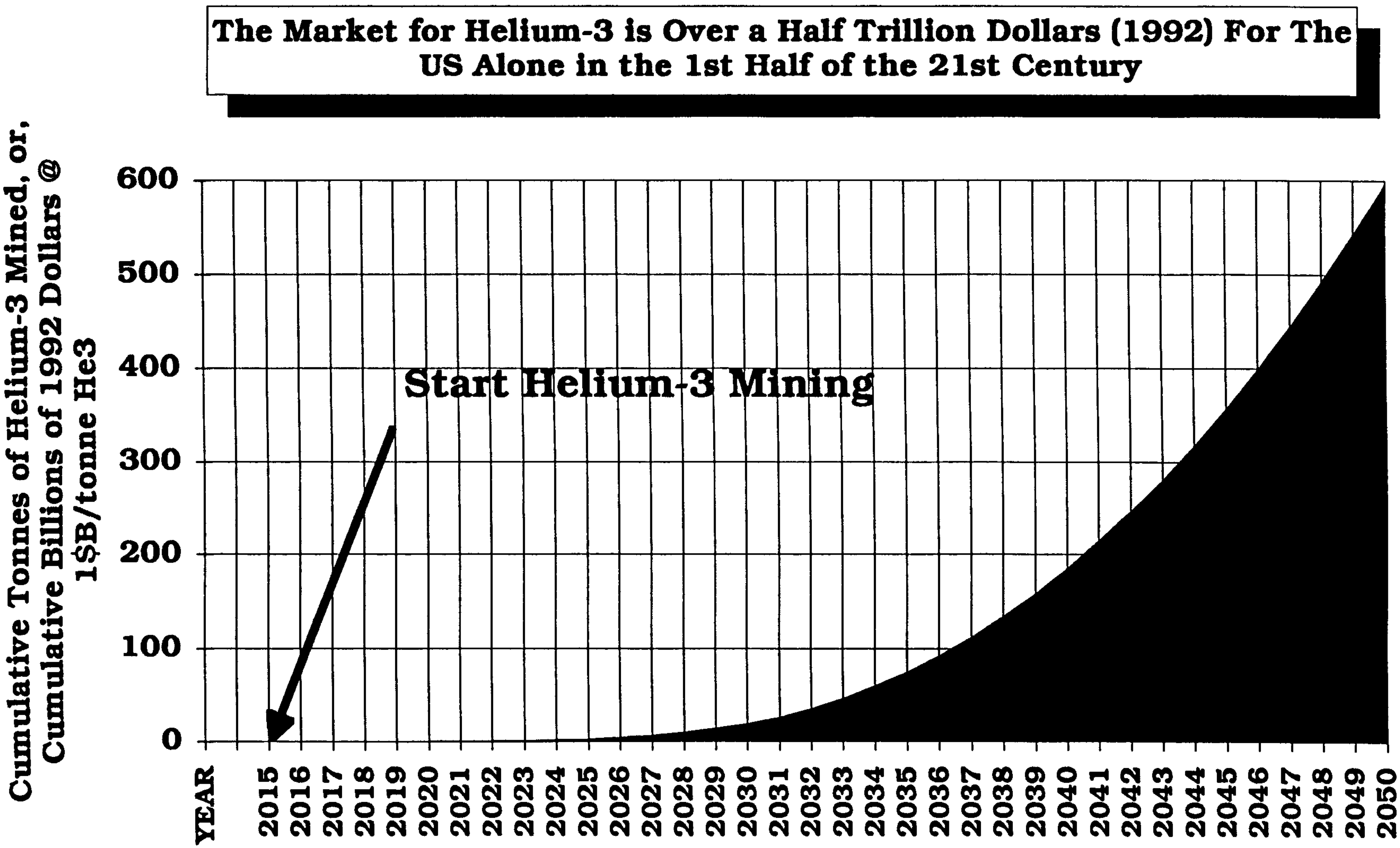
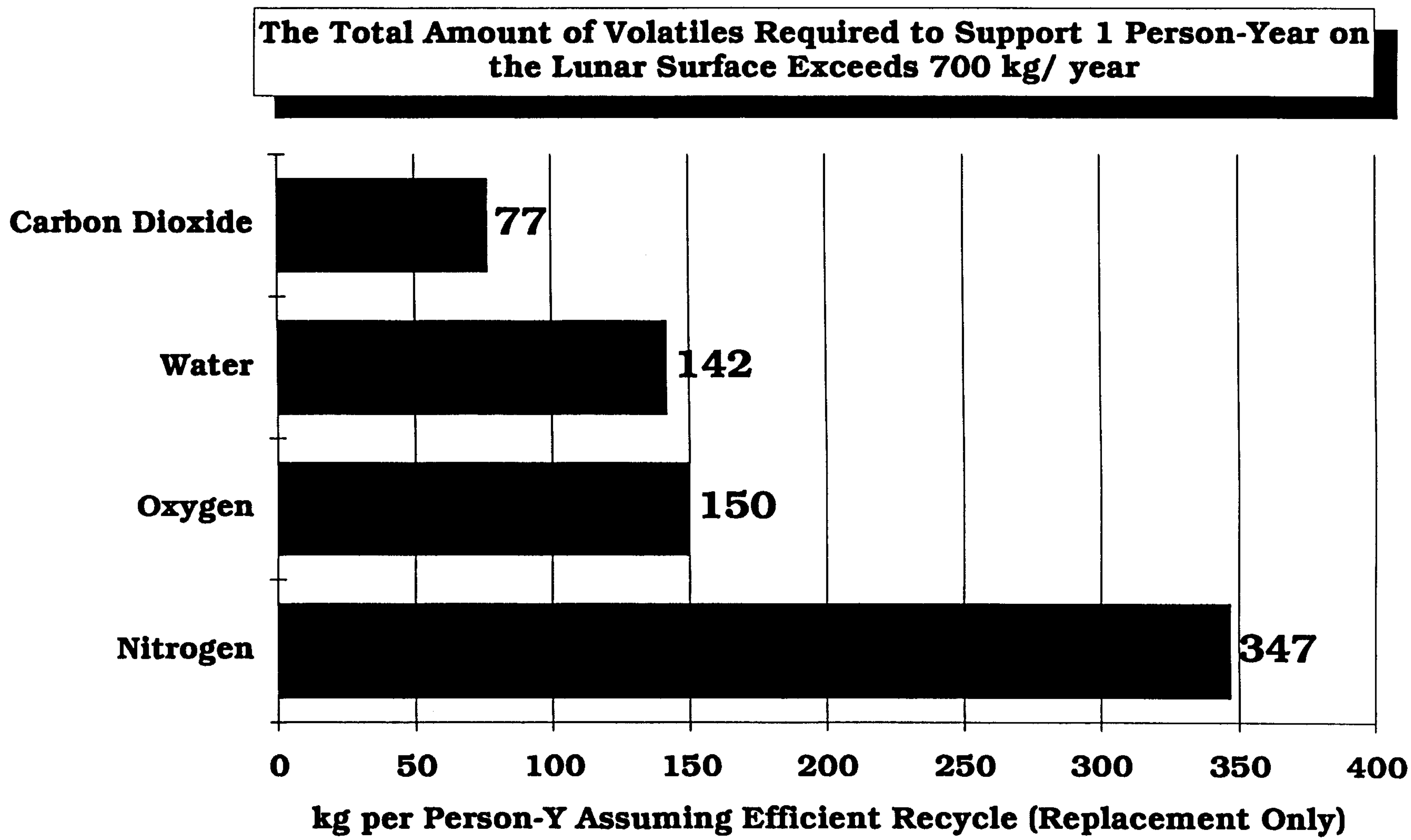


FIGURE 13



The Market for Helium-3 is Over a Half Trillion Dollars (1992) For The US Alone in the 1st Half of the 21st Century
Cumulative Tonnes of Helium-3 Mined, or, Cumulative Billions of 1992 Dollars @ 1$B/tonne He3
600
500
400
300
200
100
0
Start Helium-3 Mining
YEAR
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
2041
2042
2043
2044
2045
2046
2047
2048
2049
2050

FIGURE 14



The Total Amount of Volatiles Required to Support 1 Person-Year on the Lunar Surface Exceeds 700 kg/ year
Carbon Dioxide
77
Water
142
Oxygen
150
Nitrogen
347
0
50
100
150
200
250
300
350
400
kg per Person-Y Assuming Efficient Recycle (Replacement Only)

FIGURE 15

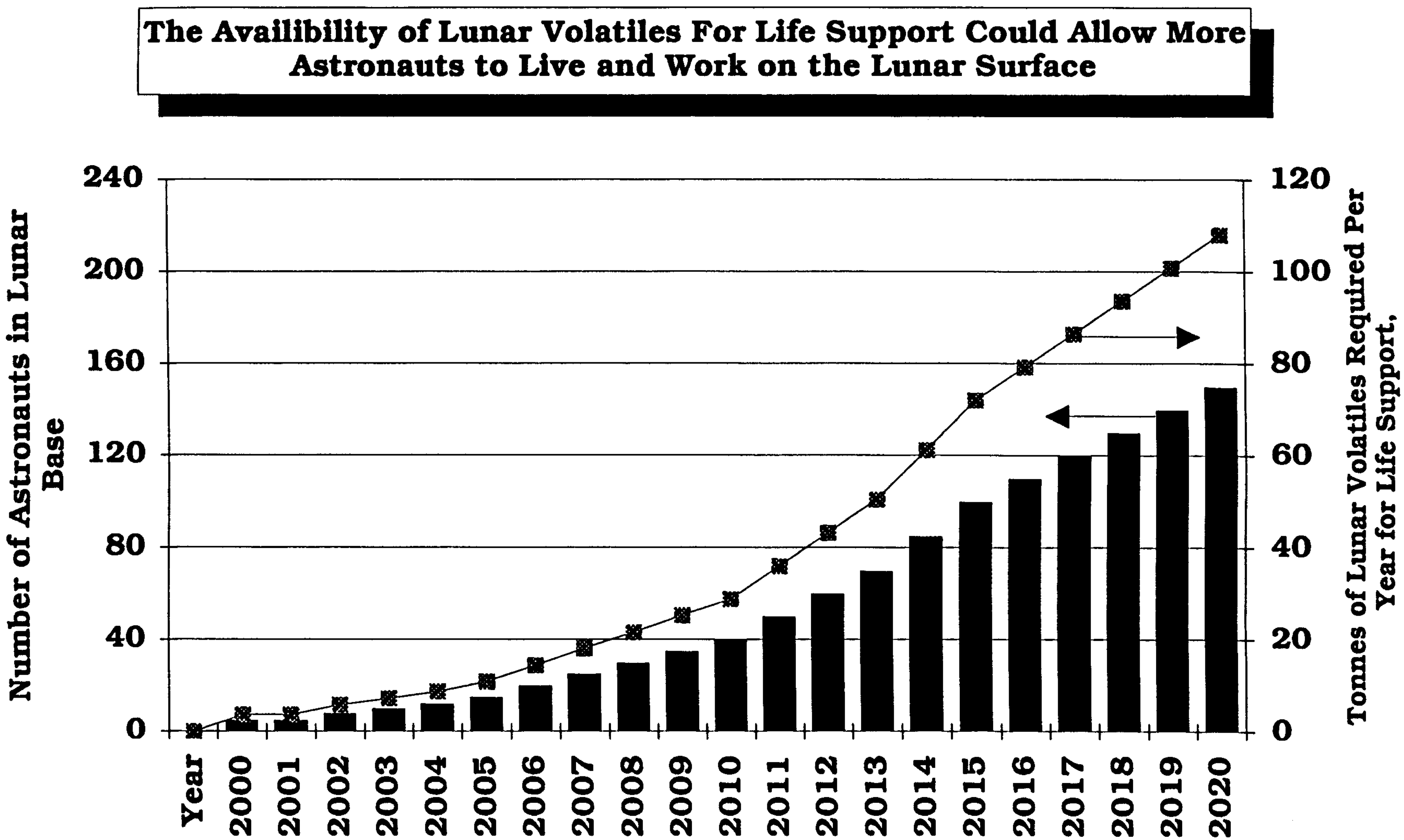

The Availibility of Lunar Volatiles For Life Support Could Allow More Astronauts to Live and Work on the Lunar Surface
Number of Astronauts in Lunar Base
Tonnes of Lunar Volatiles Required Per Year for Life Support,
240
200
160
120
80
40
0
120
100
80
60
40
20
0
Year
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

FIGURE 16

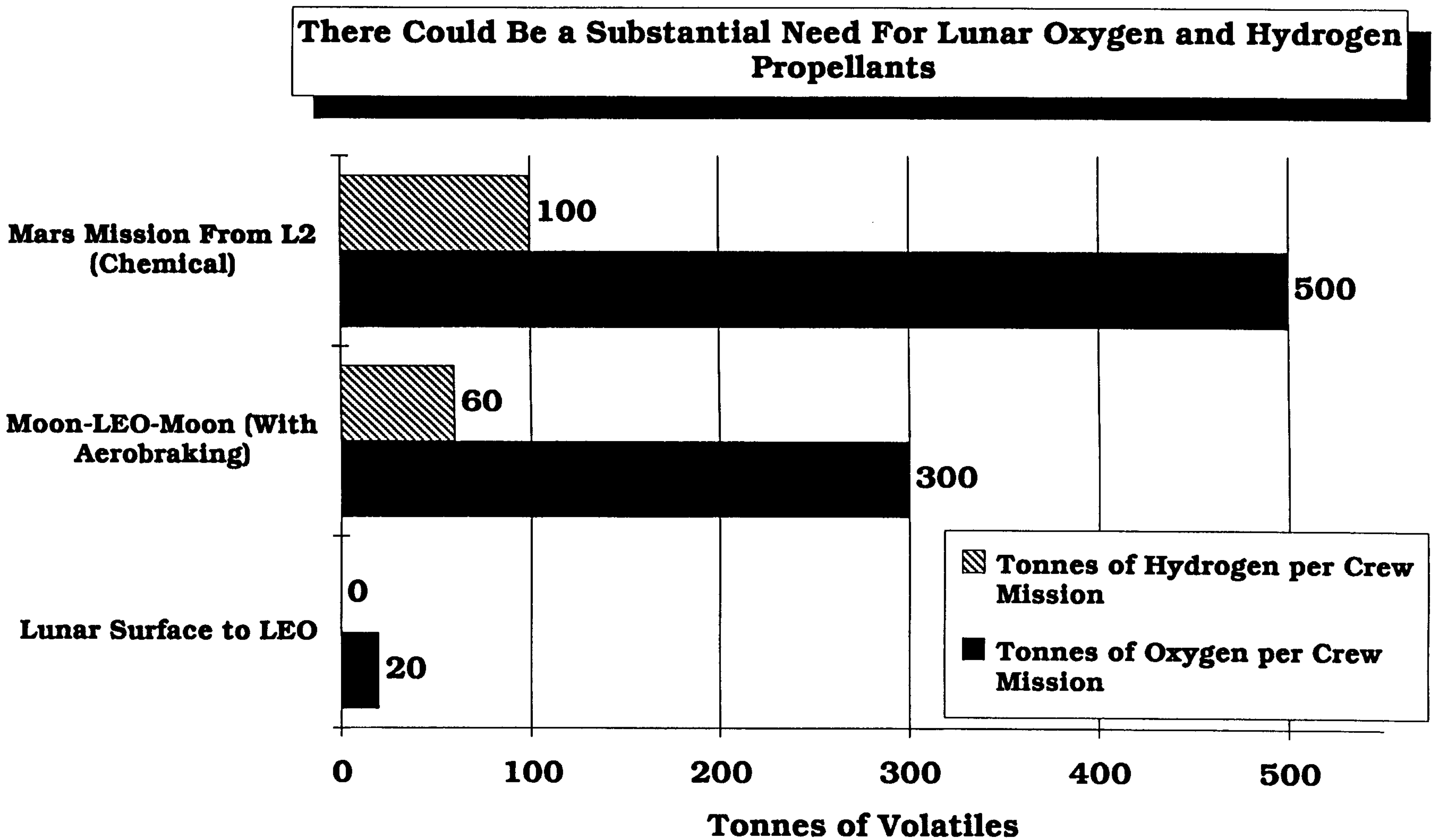

There Could Be a Substantial Need For Lunar Oxygen and Hydrogen Propellants
Mars Mission From L2 (Chemical)
Moon-LEO-Moon (With Aerobraking)
Lunar Surface to LEO
100
500
60
300
0
20
Tonnes of Hydrogen per Crew Mission
Tonnes of Oxygen per Crew Mission
0
100
200
300
400
500
Tonnes of Volatiles

FIGURE 17

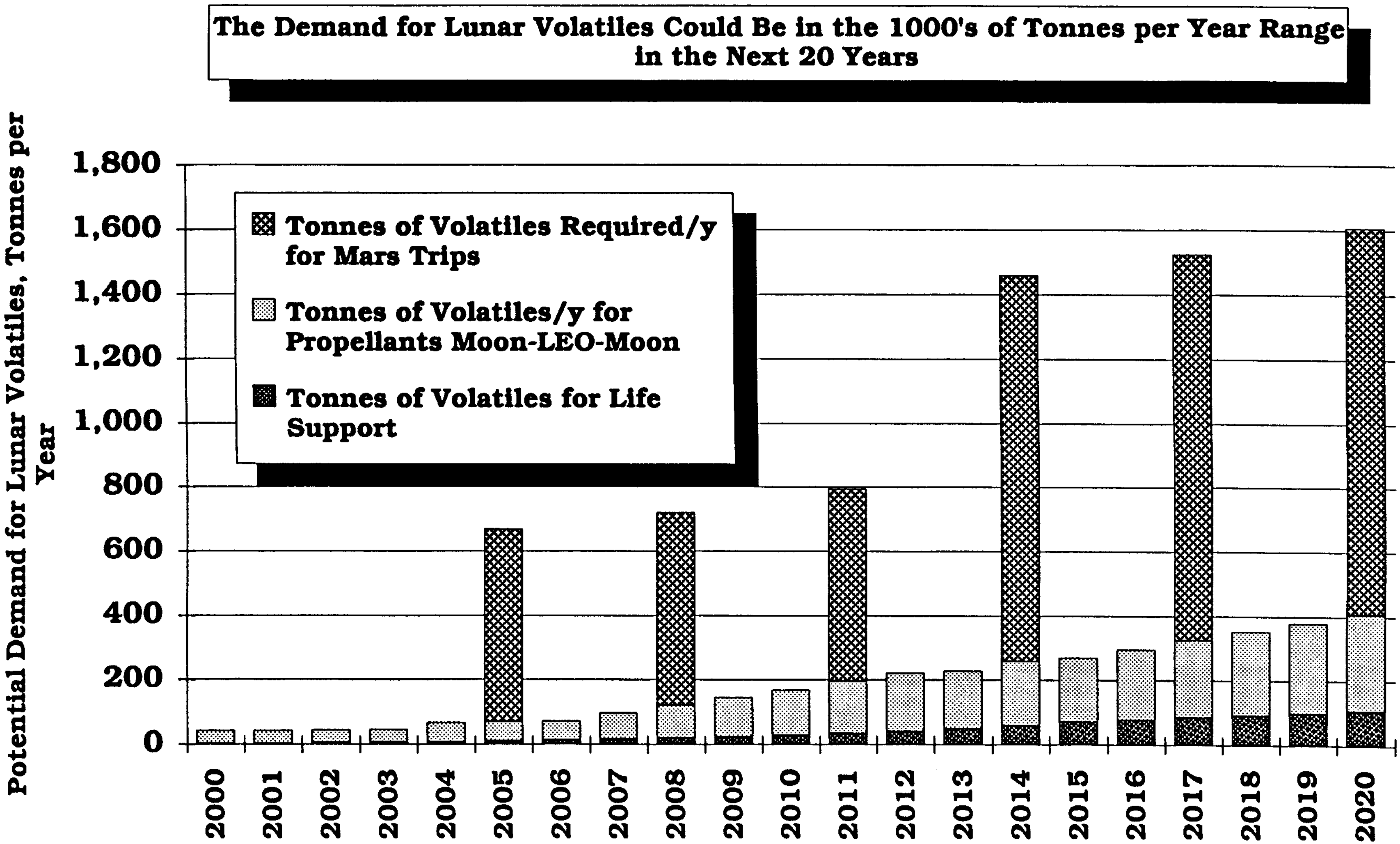

The Demand for Lunar Volatiles Could Be in the 1000's of Tonnes per Year Range in the Next 20 Years
Potential Demand for Lunar Volatiles, Tonnes per Year
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
Tonnes of Volatiles Required/y for Mars Trips
Tonnes of Volatiles/y for Propellants Moon-LEO-Moon
Tonnes of Volatiles for Life Support
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

FIGURE 18

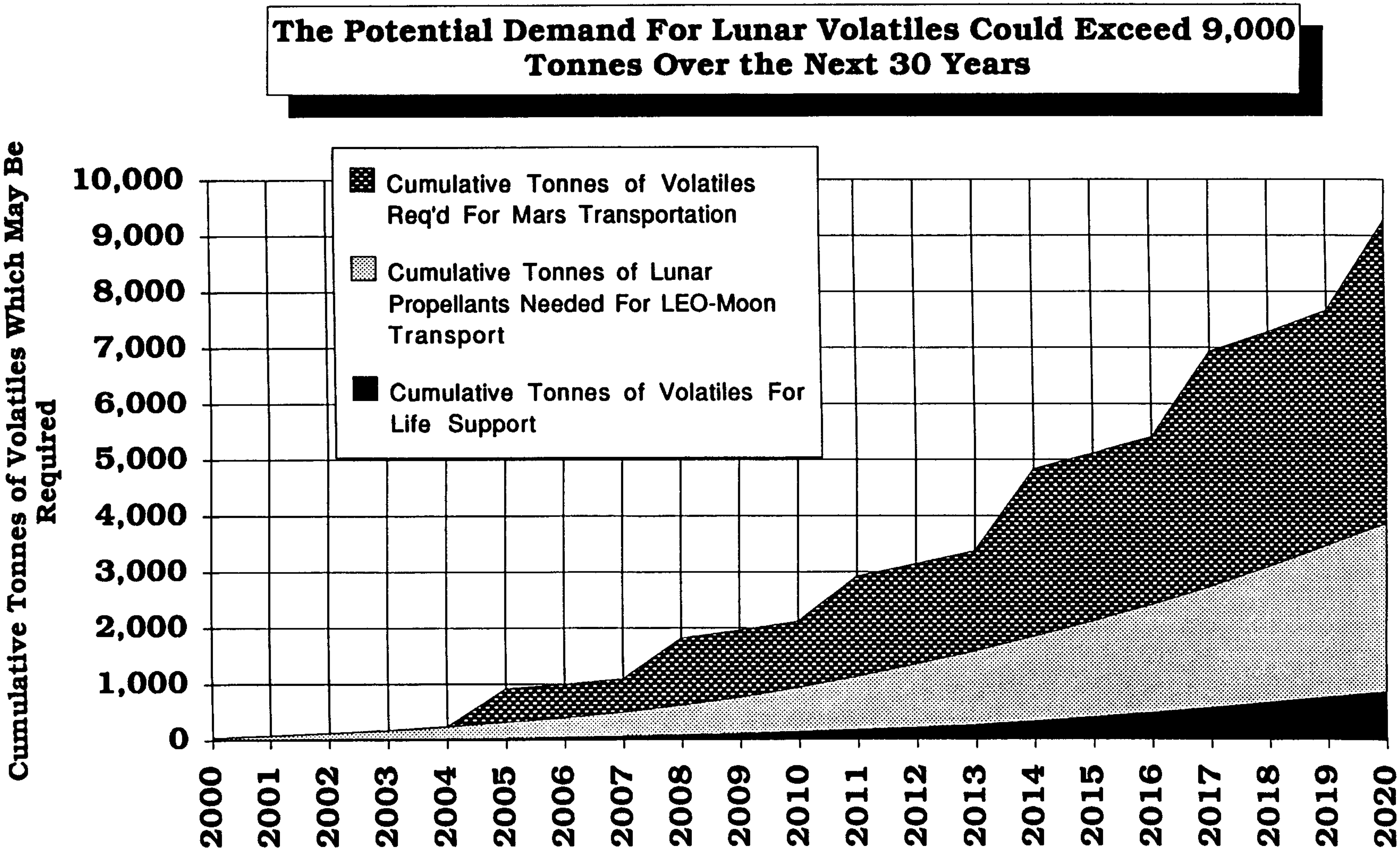
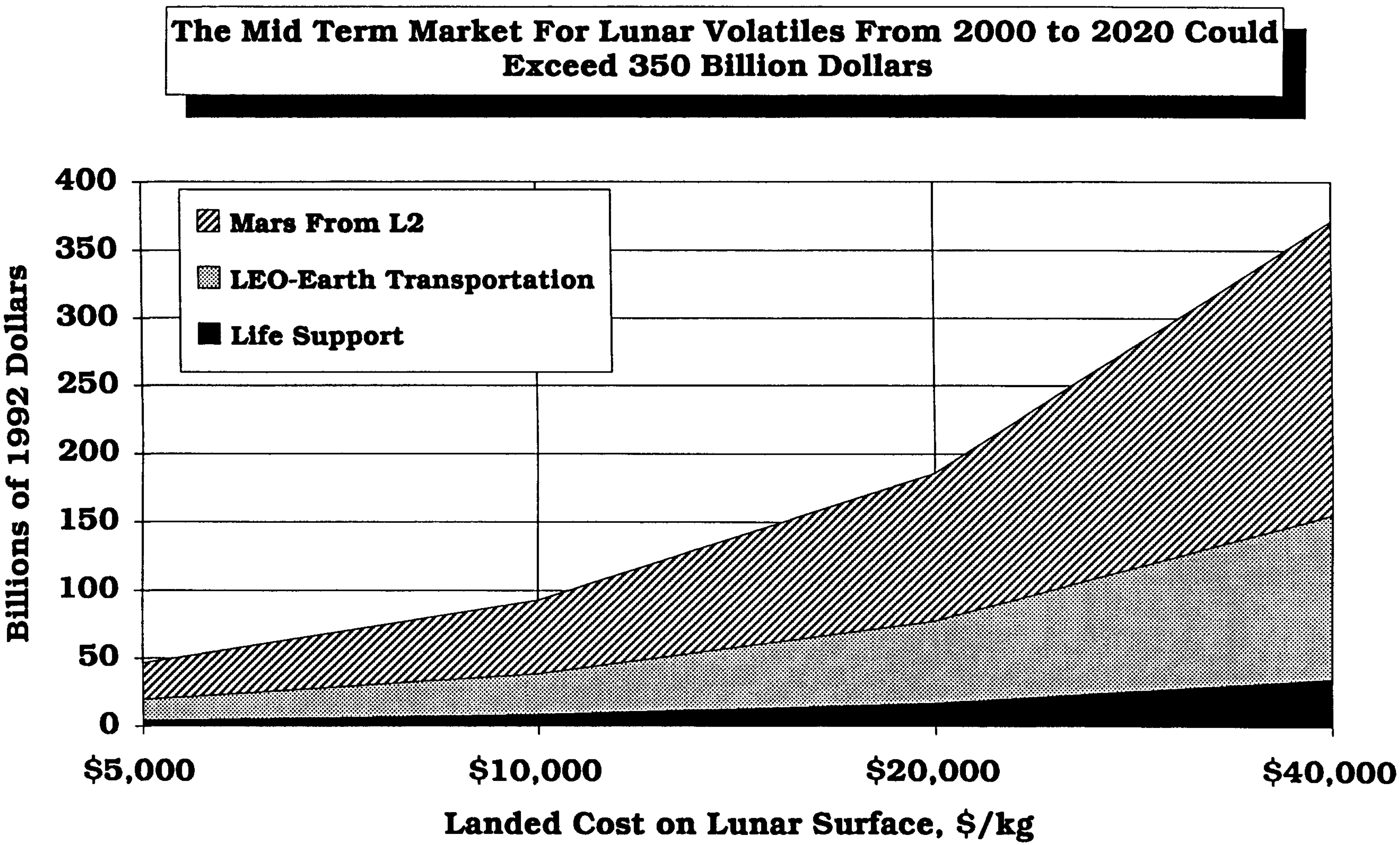

The Potential Demand For Lunar Volatiles Could Exceed 9,000 Tonnes Over the Next 30 Years
Cumulative Tonnes of Volatiles Req'd For Mars Transportation
Cumulative Tonnes of Lunar Propellants Needed For LEO-Moon Transport
Cumulative Tonnes of Volatiles For Life Support
Cumulative Tonnes of Volatiles Which May Be Required
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

FIGURE 19



The Mid Term Market For Lunar Volatiles From 2000 to 2020 Could Exceed 350 Billion Dollars
Mars From L2
LEO-Earth Transportation
Life Support
Billions of 1992 Dollars
400
350
300
250
200
150
100
50
0
$5,000
$10,000
$20,000
$40,000
Landed Cost on Lunar Surface, $/kg

FIGURE 20

Commercial DHe3 and Lunar Resource Recovery Schedules are Very Compatible

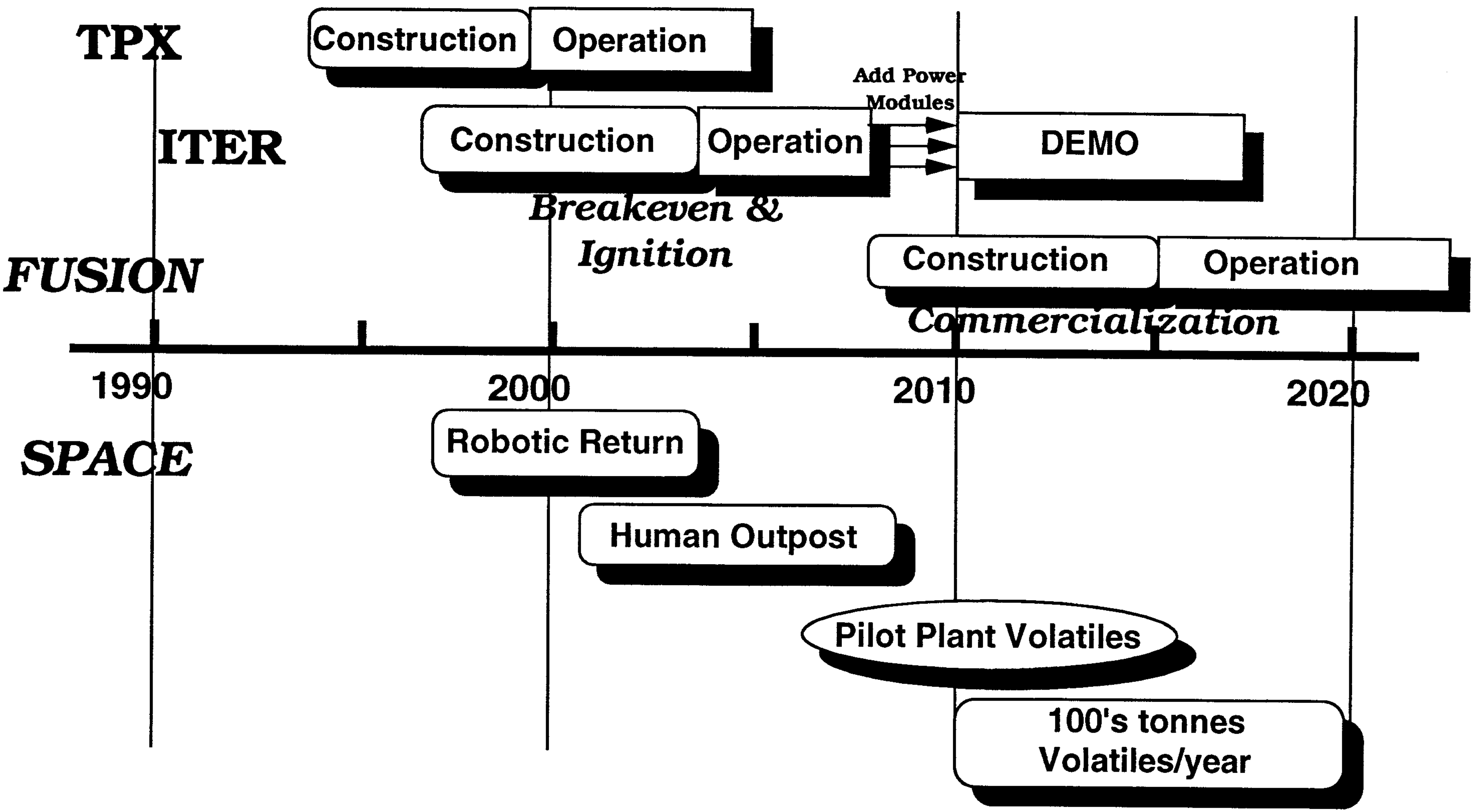


FIGURE 21

Success With the Polywell™ Concept Could Require Lunar ^3He by 2015

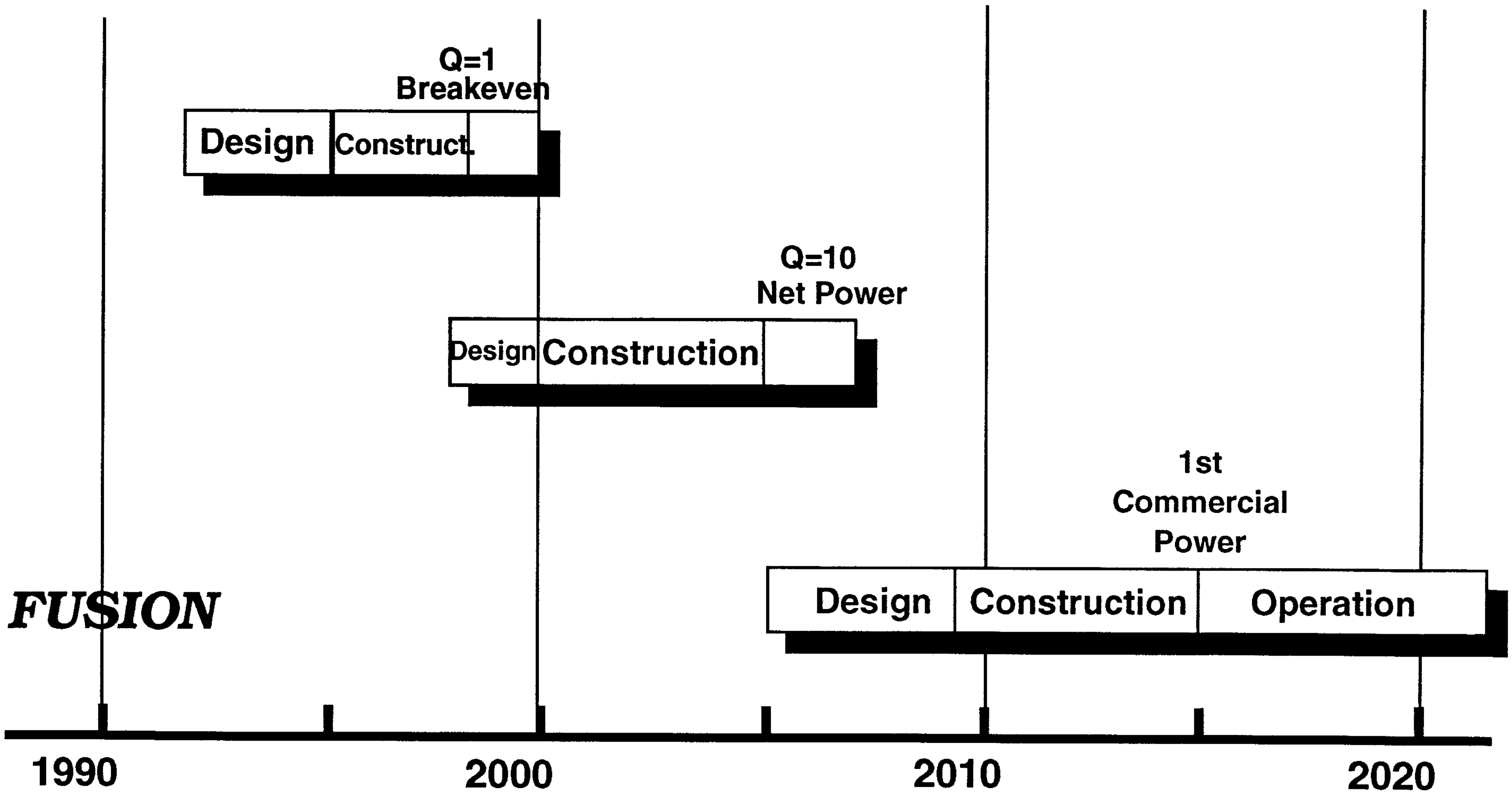


FIGURE 22

Worldwide Effort in Helium-3 Fusion and Lunar Recovery Research

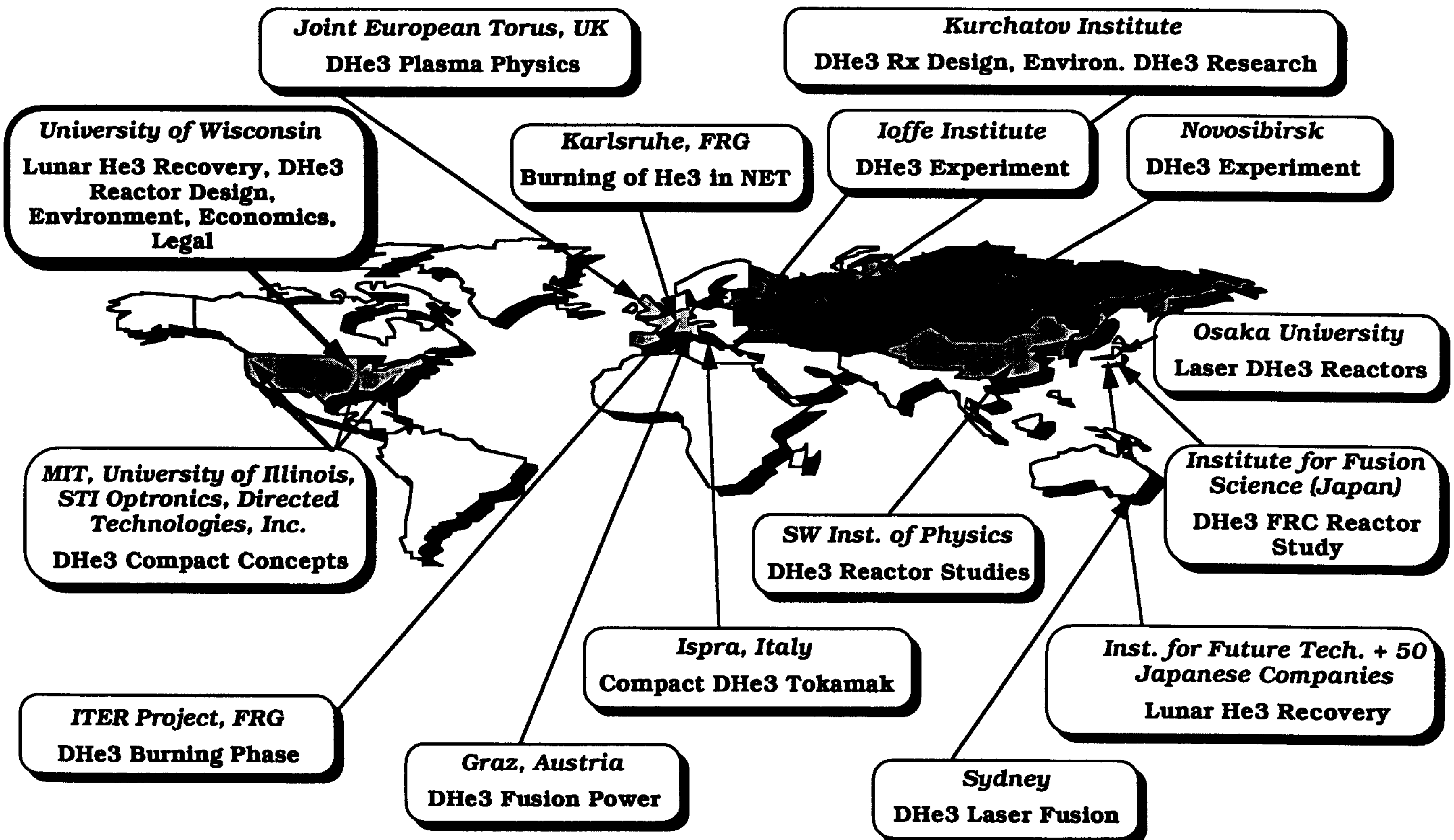


FIGURE 23