The Moon: An Abundant Source of Clean and Safe Fusion Fuel for the 21st Century

G.L. Kulcinski and H.H. Schmitt

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UWFDM-730

. Presented at the 11th International Scientific Forum on Fueling the 21st Century, 29 Sept.–6 October 1987, Moscow, USSR.

FUSION TECHNOLOGY INSTITUTE

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by

G.L. Kulcinski[a]
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I) INTRODUCTION

Modern societies depend on energy for their very existence. Without it, the earth cannot support its present population of 5 billion people let alone even dream about supporting the 8 to 10 billion people that are likely to inhabit the earth under the so called "equilibrium" conditions[1] in the 21st century. We have long passed the time when most humans can "live off the land". At the present time, the average primary energy consumption is slightly over 2 kW per capita,[2,3] but over 70% of the world's population is well below that average and is desperately trying to improve its standard of living. Therefore, copious amounts of energy will be needed over the next century to feed, clothe, warm, cool, protect and keep the earth's citizens healthy in the face of an environment under increasing stress.

Ever since the world population passed the 1 billion mark in 1830, fossil fuels such as coal, oil and natural gas have been used to sustain life on this planet. Up through 1986, we have used approximately 300 TW-years of that energy (1 TW-y = 10^{12} watts for one year). Our present world population of 5 billion people (up from 2 billion in 1930, 3 billion in 1960, and 4 billion in 1975) and a usage rate of ~2 kW/capita, means that we are currently using primary energy at a rate of ~10 TW-y/y. As we move toward the "equilibrium" world population of 8 to 10 billion people, and allowing for some modest increase in the standard of living for the underdeveloped nations, our future worldwide primary energy consumption rate will be between 20 and 30 TW-y/y. Since we have only 1000-1500 TW-years of fossil fuel energy left that is economically recoverable,[2,3] it is easy to see that somewhere in the mid 21st century we will exhaust our fossil fuel resources. It is also possible that environmental problems such as acid rain, the CO_2 "greenhouse" effect, or wars over the last remaining deposits of fossil fuels will limit the useful lifetime to even less than that determined by resources alone. It is also important to note that fossil fuels will also be of increasingly greater value as chemical feedstocks for non-fuel products to sustain the quality of life. In any case, for much of the 21st century, inhabitants of the earth will have to rely on renewable energy sources (solar, wind, hydro, geothermal, and biomass) and nuclear energy sources to survive.

The use of nuclear energy in the form of fission reactors is already widespread with some 370 reactors located in 26 countries which provide approximately 1/6 of the world's electricity. By the year 2000, this fraction will increase to approximately 1/5. However, this source of energy is not without its problems which currently range from public resistance to the storage of long lived fuel cycle wastes to reactor safety questions.

Fortunately, there is another form of nuclear energy which could provide an even more environmentally acceptable and safer solution to our long range energy problems. The fusion of certain light elements into heavier ones at high temperatures can release enormous amounts of energy. This is evident every day as we observe the fusion energy released by our sun, and every night as we observe the billions upon billions of stars which themselves are powered by fusion reactions.

Scientists have been trying to reproduce a controlled fusion reaction here on earth since 1951. After 36 years of research and the expenditure of over 20 billion dollars in a worldwide program, we are now within a year or two of the first "breakeven" experiments, historically similar in some ways to the Chicago Stagg Field fission reactor experiment conducted by Enrico Fermi and his colleagues in 1941.[4] Before the end of this decade, magnetically confined plasmas in the TFTR device at Princeton, USA[5] and/or the JET device in Culham, UK[6] will release more thermonuclear energy than required to initiate the fusion reaction.

Scientists have already anticipated success in these devices and have designed the next generation of fusion devices which will produce 100's of megawatts of thermonuclear power in the 1990's.[7] Work has even begun on commercial fusion power plants[8,9] and for fusion power sources in space.[10]

Currently, the worldwide effort in fusion is concentrating on the deuterium (D) and tritium (T) reaction because it is the easiest to initiate. However, 80% of the energy released in this reaction is in the form of neutrons and these particles not only cause severe damage to the surrounding reactor components, but they also induce very large amounts of radioactivity in the reactor structure.

It is fortunate that there is another fusion reaction, involving the isotopes of deuterium and helium-3 (He^3) which, in theory, involves no neutrons or radioactive species, i.e.,

$$D + He^3 \rightarrow p(14.7\ MeV) + He^4\ (3.6\ MeV) + 18.3\ MeV.$$

Unfortunately, some side DD reactions do produce neutrons and roughly 1% of the energy released in this reaction is released in the form of neutrons. However, such a low neutron production (compared to the DT cycle) greatly simplifies the safety related design features of the reactor and induces such low levels of radioactivity that the wastes do not require the extensive radioactive waste facilities that are so unpopular with the public today. Furthermore, since over 99% of the energy can be released in the form of charged particles, this energy can be converted directly to electricity via

electrostatic means (similar to running a charged particle accelerator backwards) with efficiencies of 70-80%.

If this reaction is so advantageous, why haven't we been pursuing it more vigorously in the past? The simple answer to that is that there is no large terrestrial supply of He^3! The amount of primordial He^3 left in the earth is on the order of a few 100 kg's[11] and the He^3 which results from the decay of manmade tritium ($t_{1/2}$ = 12.3 years) is also only being produced at a rate of 10-20 kg/year. Since the energy equivalent of He^3 is 19 MW-y per kg, one can see that to provide a significant fraction of the world's energy needs would require 100's of tonnes of He^3 per year, not 100's of kg's per year.

What is the solution? In 1986, it was pointed out by scientists at the University of Wisconsin[11] that over the 4 billion year history of the moon, some 500 million metric tonnes of He^3 hit the surface of the moon from the solar wind. The analysis of Apollo and Luna retrieved samples showed that over 1,000,000 tonnes of He^3 still remain loosely-imbedded in the surface of the moon. The object of this paper is to show how that He^3 can be obtained from the moon and how its use in fusion reactors can benefit the inhabitants of this planet. We will begin, in reverse order, by addressing the physics and technology issues associated with the use of He^3 and finish with a description of its distribution on the moon and of methods which could be used to retrieve it.

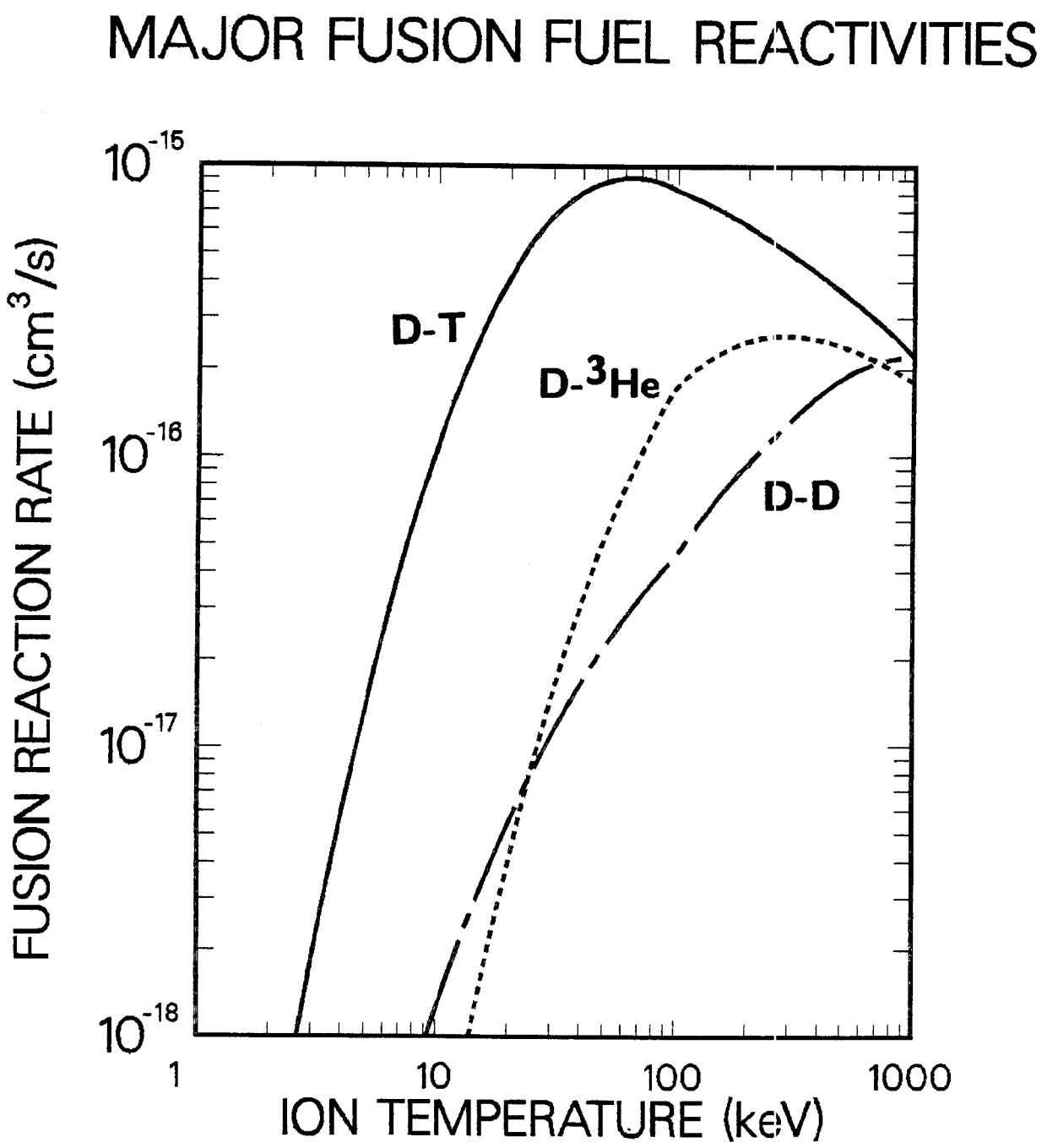
II) THE PHYSICS OF THE D-He^3 FUSION REACTION

When certain light isotopes are heated to extremely high temperature and confined to a small region of space, they can react with each other producing a heavier atom which weighs less than the reactants. The missing mass is converted into energy. The reaction rate of selected fusion fuels is plotted in Figure II-1 and reveals that the DT reaction occurs at the lowest temperatures. Figure II-1 also shows that as the temperatures are increased above 10 keV (1 keV is roughly equivalent to 10,000,000°K) the DD, then the D-He^3 reactions, become significant. For various physics reasons, the optimum temperature at which to run these reactions ranges from 10-20 keV for the DT reaction to 50-60 keV for the D-He^3 plasmas.

It was pointed out earlier that the presence of deuterium atoms in a D-He^3 plasma can result in DD reactions as well as D-He^3 fusions. These reactions are listed below (each occurs with roughly equal probability)

$$D + D \rightarrow p + T + 4.0\ MeV$$
$$D + D \rightarrow He^3 + n + 3.2\ MeV.$$

Figure II-1


MAJOR FUSION FUEL REACTIVITIES
FUSION REACTION RATE (cm³/s)
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
D-T
D-³He
D-D
1
10
100
1000
ION TEMPERATURE (keV)

Not only does one of the DD branches produce a neutron but some of the tritium produced by the other branch can also burn with deuterium by the following reaction

$$D + T \rightarrow n + He^4 + 17.6 \text{ MeV}.$$

The ratio of power released in the form of neutrons compared to that released in the D-He^3 fusion is then given as

$$\frac{P_n}{P_{D\text{-}He^3}} = (\text{Constant})\left(\frac{n_d}{n_{He}}\right)\left(\frac{\langle\sigma v\rangle_{dd}}{\langle\sigma v\rangle_{dHe}}\right)$$

where

n_d, n_{He} = number densities of deuterium and He^3, respectively

$\langle\sigma v\rangle_{dd}$ = fusion reaction rate of deuterium ions

$\langle\sigma v\rangle_{dHe}$ = fusion reaction rate of deuterium ions and He^3 ions

Constant ~ 0.03 if none of T_2 is burned and ~0.18 if all the T_2 is burned (at 60 keV).

It can be seen that there are two main factors which can cause the power in neutrons to be reduced; operation at temperatures where the ratio of the reaction cross sections is minimized and increasing the helium-3 to deuterium ratio. This latter parameter cannot be pushed too far because eventually there would not be enough deuterium atoms available for fusion and the fusion power density would be too low.

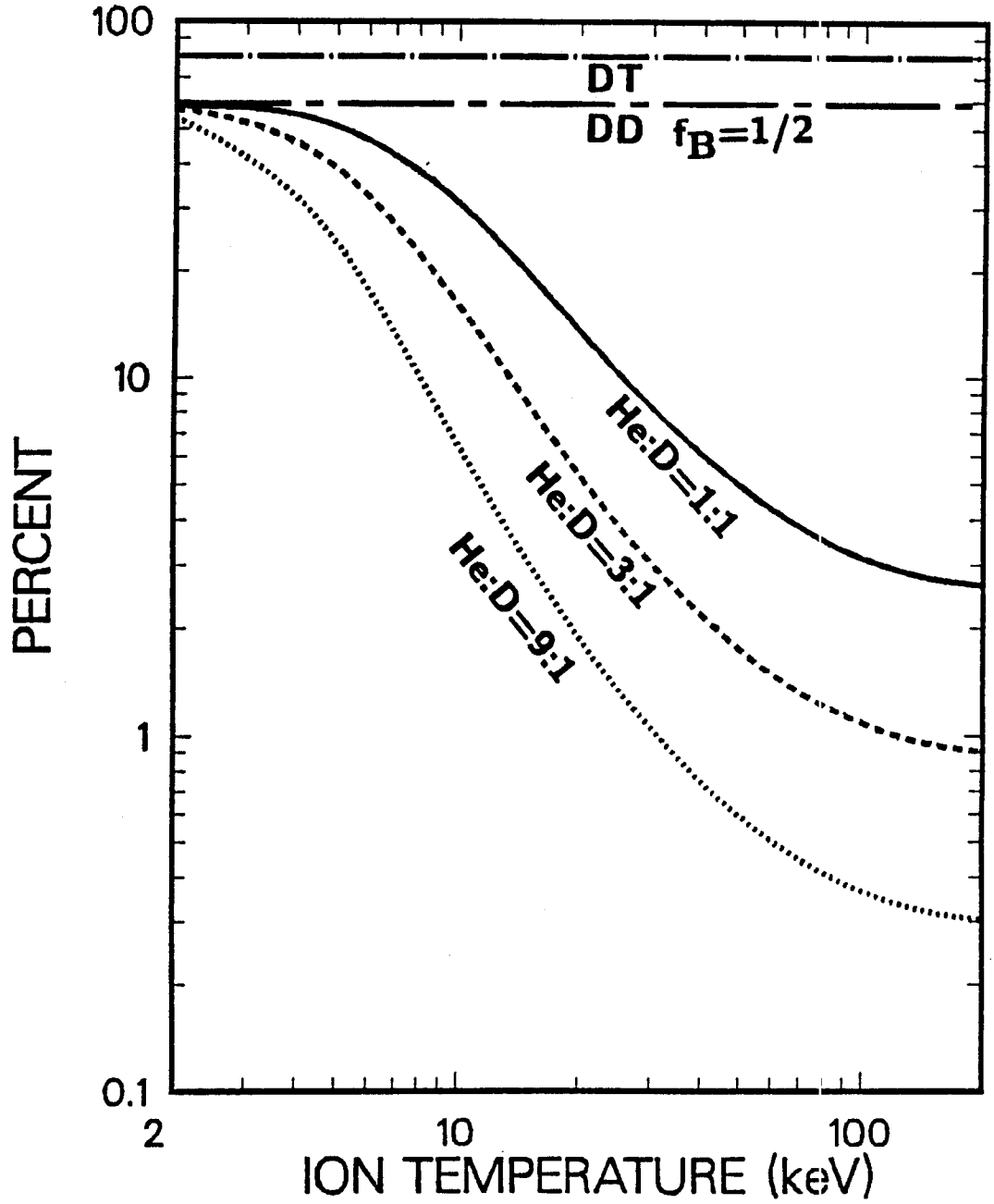
One example of how these two parameters can affect the power released in neutrons is shown in Figure II-2. Here it is shown that 80% of the fusion power released in the DT reaction is in the form of neutrons. The neutron fraction is 50% for the DD reaction and, depending on the temperature and He^3 to D ratio, as little as 1% of the energy could be released in neutrons from D-He^3 plasmas.

Aside from the advantages of low neutron production, which will be covered later, the fact that 99% or so of the energy from this reaction is released in energetic charged particles also is of major significance. These particles can be converted to electricity via direct electrostatic means. Workers at LLNL in the U.S. have shown that this can be accomplished with 70-80% efficiency at lower energies.[12] There is no reason to expect the higher energy (MeV) ions will substantially change those results.

Another advantage of this reaction is that it can be tailored to release large amounts of synchrotron radiation. Logan[13] has shown over half the energy from a D-He^3 plasma in a tokamak can be released in microwaves at 3000 GHz (~0.1 mm wavelength). Such energy could be removed from the plasma chambers via waveguides and directed to useful areas outside the reactor. Direct conversion of the microwaves to

Figure II-2

PERCENT OF FUSION POWER IN NEUTRONS (50% Tritium Burnup)



electricity via rectenna could also improve the performance of the power plant. Other uses of the microwaves such as propagating energy over long distances in space or for local uses in the vacuum of space are also being investigated.

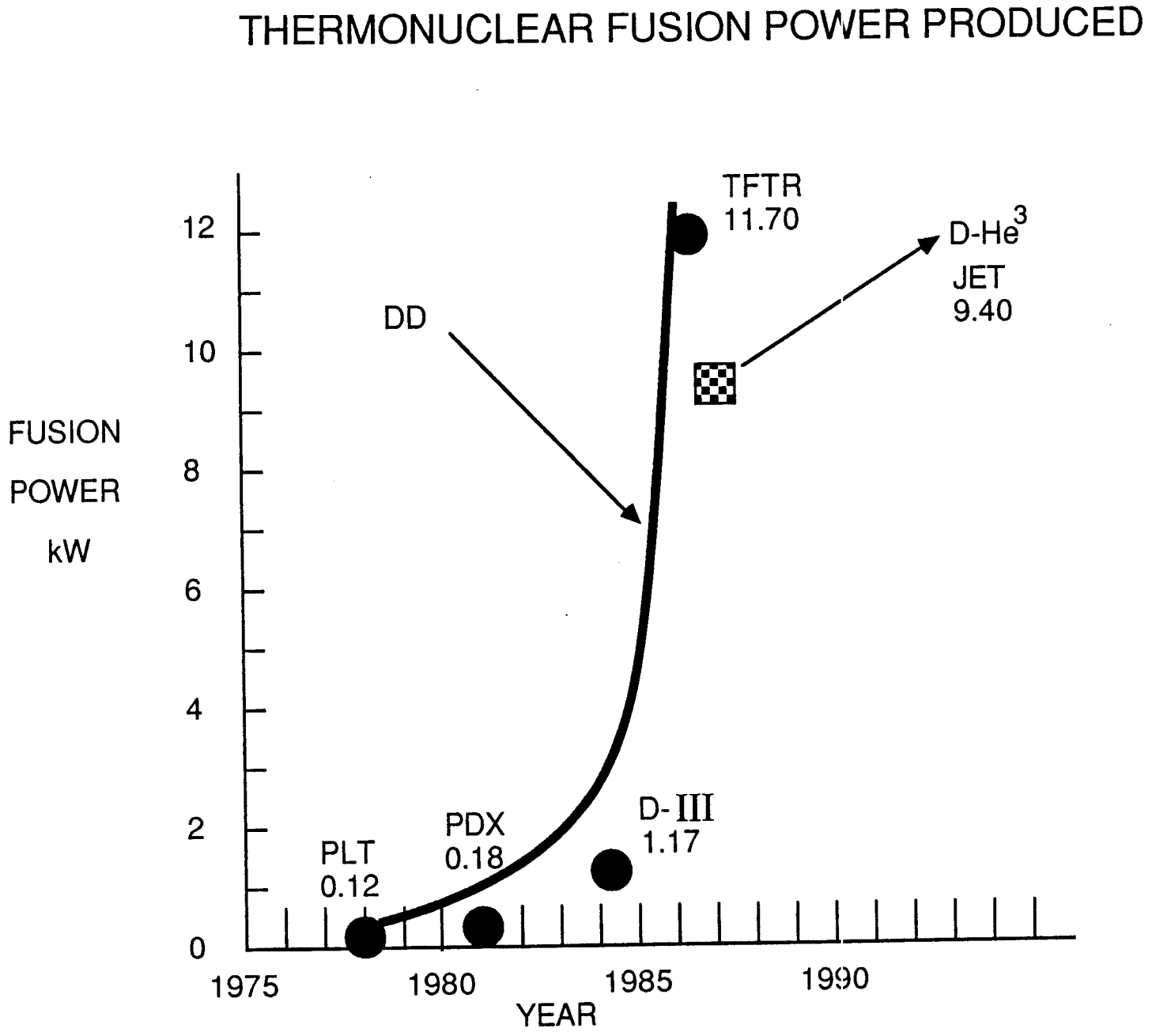
Coming back to Figures II-1 and II-2, it is evident that D-He^3 plasmas will have to be operated at temperatures about 3 times higher than DT power plants. Experiments at TFTR[14] have already achieved temperatures equivalent to ~20 keV and methods to get to 60 keV ion temperatures in tokamaks have already been discussed for NET, the Next European Torus.[15] Considering that in the past 2 decades, we have increased the plasma temperatures in tokamaks by over a factor of 100 from 0.1 keV to 20 keV, it is not unreasonable to expect another factor of 3 increase in the next decade.

It is also of interest to note that when we examine the actual amount of thermonuclear power that has been produced in the laboratory, we find that the situation is quite favorable for D-He^3. Figure II-3 shows the power released from DD plasmas in magnetically confined devices (no DT plasmas of any significance have been operated to date). It can be seen that starting with PLT in 1981 and progressing to TFTR in 1986 the fusion power released in the laboratory has increased to the level of 12 kW for a few seconds.[16] Recent experiments by Jacquinot[17] at JET in 1987 have released over 9 kW from D-He^3 reactions. It is anticipated that this energy release will approach 1 MW when all of the heating is installed on JET in 1988.

How will the breakeven and ignition experiments for D-He^3 be conducted? Emmert et al.[15,18] have shown that for the present European design of NET, simply inserting a D-He^3 plasma in place of the reference DT plasma will produce breakeven conditions. In fact, the energy multiplication can actually approach 2.5 if the inboard DT neutron shield is replaced with a thinner D-He^3 neutron shield (because of the lower neutron production less material is needed to shield the magnets from radiation damage). Such a modification is easily done when the machine is constructed and then the shield can be replaced before DT operation commences.

An even more interesting result was obtained by Emmert et al. when they examined a combination of thinner inboard shields and a 20% higher magnetic field on TF coils. It was found that NET could actually ignite a D-He^3 plasma in this case and that significant power production (100 MW) could be achieved. Such modifications could be made for less than a 10% cost impact on the design and would allow scientists to study ignited D-He^3 plasmas in the 1998-2000 time period (assuming the current 1992 construction date is maintained). This is less than 5 years after we expect to reach ignited conditions in a

Figure II-3


THERMONUCLEAR FUSION POWER PRODUCED
FUSION
POWER
kW
12
10
8
6
4
2
0
1975
1980
1985
1990
YEAR
TFTR
11.70
D-He3
JET
9.40
DD
PLT
0.12
PDX
0.18
D-III
1.17

DT plasma in CIT.[19] It is therefore quite possible that we could enter the 21st century with ignited plasmas containing both D-He^3 and DT fuel!

In summary, the physics of the D-He^3 reaction is well established and in fact, it is being studied in the major tokamaks of the world today. One of the current reasons to study this reaction is to learn about the slowing down of fast ions in hot plasmas without activating the machine significantly with neutrons. This latter point is also one of the main reasons we are interested in this fuel cycle from a commercial standpoint.

III) TECHNOLOGICAL ADVANTAGES OF THE D-He^3 FUEL CYCLE

Assuming that we can produce a well-controlled, sustainable D-He^3 fusion plasma, what technological advantages does it have over the DT cycle? We can identify at least 6 major features, most of which stem from the much lower neutron production:

1) Reduced radioactivity
2) Reduced radiation damage
3) Increased safety
4) Increased efficiency
5) Lower cost of electricity
6) Potentially shorter path to commercialization

Let us briefly examine each of these points.

III.A) Reduced Radioactivity

It stands to reason that if we produce less neutrons per unit of power, then the amount of radioactive structural material will be reduced. Attaya et al.[20] have examined the activation induced in materials that might be used in the Ra[21] D-He^3 reactor design and compared it to the activation that would be in the same materials used in the DT powered MiniMars reactor [22]. A summary of their results is given in Table III-1. It was found that not only were the radioactivity levels reduced, but that the material could qualify as class A waste burial material when the plant was torn down. This means that instead of having to bury the reactor components in a deep geologic repository (perhaps as much as a mile below the surface), they could be disposed of in trenches near (within 1 meter) the surface. The shorter half life and stability of the D-He^3 produced wastes should greatly reduce decommissioning costs and alleviate the fears of the public about sequestering the wastes for thousands of years, as is currently the case for fission wastes. Furthermore, the volume of wastes is greatly reduced because of the reduced radiation damage; the amount of "high level" wastes produced by a D-He^3 fusion plant per 1000 MWe-y (enough electricity for a city of a million people for one year) would fit within a single oil barrel. This is in contrast to a volume of over

Table III-1

A Comparison of the Waste Disposal Characteristics of Similar Structural Materials Used in DT and D-He^3 Fusion Reactor Designs

	Component Lifetime	DT Fuel Cycle Γ=2.55 MW/m^2	D-He^3 Fuel Cycle Γ=0.05 MW/m^2
PCA (An Austenic Stainless Steel)	Blanket 2 y	Class C	Class A
	Shield 30 y	Deep Geologic Waste Repository	Class C
HT-9 (A Ferritic Stainless Steel)	Blanket 2 y	Class C	Class A
	Shield 30 y	Class C	Class A

Form of Waste

Class A - Can be buried in shallow trench and no special requirements on stability of container. Waste may be unstable.

Class C - Buried at least 5 meters from surface and in chemically and structurally stable container for 300 years.

Deep Geologic Waste Repository - Must be sequestered from public and the environment, at least 200 meters below surface, usually for periods exceeding several 1000 years and continuously monitored. Details considered on case by case.

60 barrels for a similarly powered DT plant and orders of magnitude less than from a fission power plant and its reprocessing facility.

III-B) Reduced Radiation Damage

If we again use the Ra[21] and MiniMars[22] reactor designs as reference points we find that after 30 FPY's (full power years), the total DT damage to the first wall is over 1100 dpa (displacements per atom). One dpa means that every atom is displaced once during the component's lifetime and 1100 dpa means that every atom is displaced 1100 times! We do not yet know how to make materials last for much over 100 dpa in fission reactors so the entire inner structure of the MiniMars reactor must be replaced at least 10 times during the reactor lifetime. This causes loss of availability (higher electricity costs) as well as a larger volume of radioactive waste.

On the other hand, we find that in order to produce the same amount of electrical power, the components of the D-He^3 Ra[21] reactor only suffer less than 50 dpa. Furthermore, since there is no need to run the blanket at very high temperatures to produce electricity efficiently, the operating temperature can be lower, thus expanding our choice of materials and confidence that they will last the life of the plant. Figure III-1 displays the dpa/temperature parameter space for Ra and MiniMars along with an indication of the current data available on radiation damage to stainless steels. It is clear that the radiation damage from the DT reaction is much larger than anything we have experienced in fission reactors. Contrary to that situation is the fact that both the radiation damage and temperature conditions are much lower for the D-He^3 power plant and it is easy to see why we expect that we can construct a reactor which will last the lifetime of the plant. The much more benign reactor environment should also help in reducing the risk of failures in the reactor and increase our confidence in its safety.

III-C) Increased Safety

There are at least two different ways to look at this area; from a potential after-heat or meltdown phenomena and from the release of volatile radioactive elements. Sviatoslavsky[23] has calculated the consequences of an instantaneous loss of the coolant in the Ra (D-He^3) reactor on the temperature increase in the surrounding structure. A summary of his results is shown in Figure III-2. It was found that in the absolute worst case of no heat loss during the accident (i.e., as if a perfect thermal insulator was placed around the blanket immediately after losing all cooling water) the maximum temperature increase after one day is ~10° C for a D/He^3 ratio of 1:3. After a week it was 50° C and after one month it could have increased by 200° C. It is obvious that a meltdown is

Figure III-1

RADIATION DAMAGE IN DHe3 FUSION REACTORS IS MUCH LESS THAN IN DT SYSTEMS

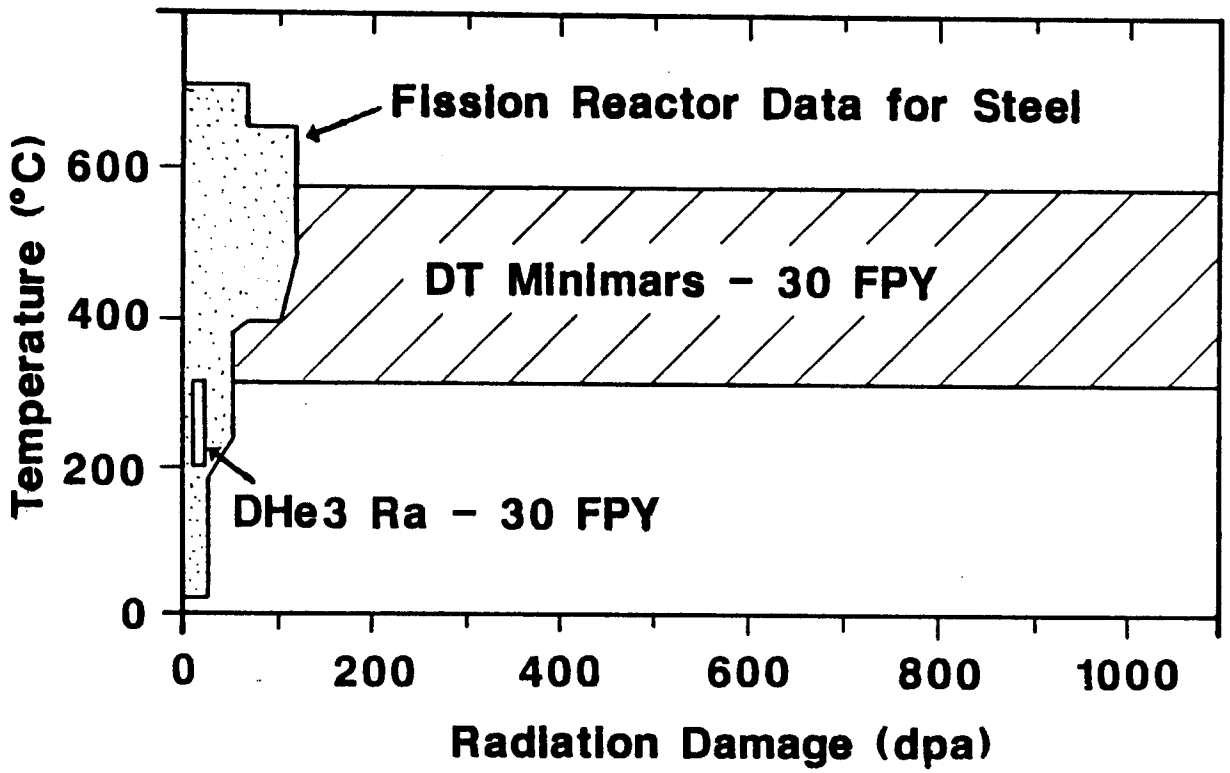
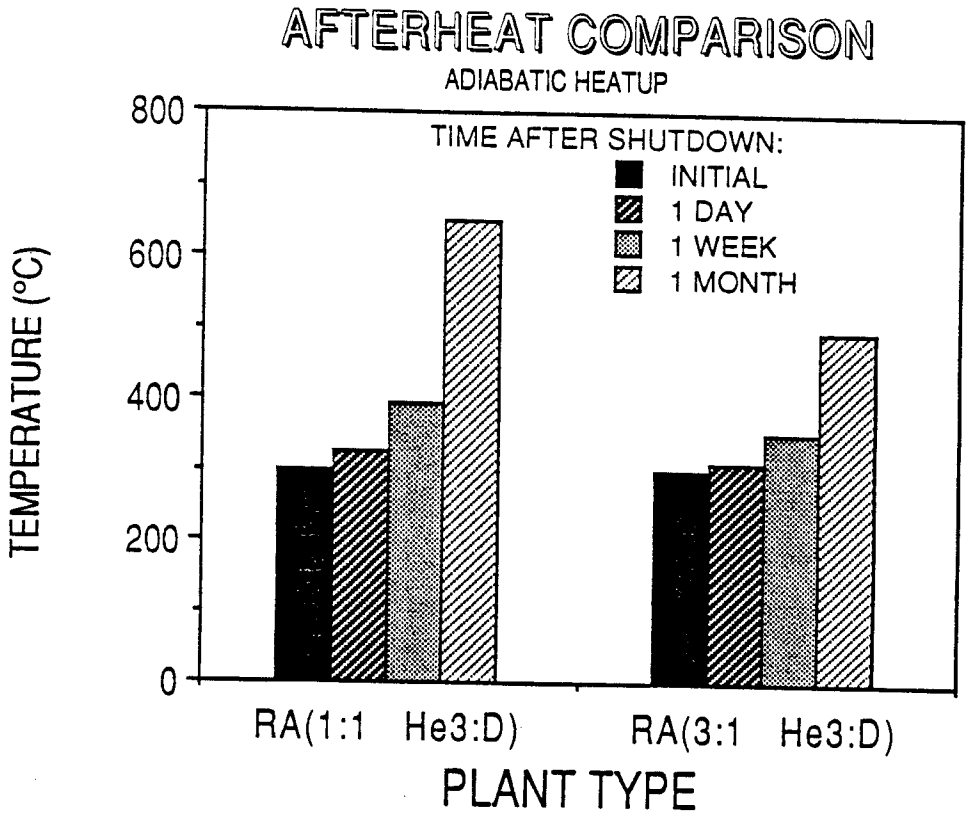


Figure III-2


AFTERHEAT COMPARISON
ADIABATIC HEATUP
TIME AFTER SHUTDOWN:
INITIAL
1 DAY
1 WEEK
1 MONTH
TEMPERATURE (°C)
800
600
400
200
0
RA(1:1 He3:D)
RA(3:1 He3:D)
PLANT TYPE

practically impossible because of the low afterheat levels generated and because there always would be some heat leakage by conduction or convection. Without the possibility of a major thermal excursion in the event of a highly unlikely, but theoretically feasible accident, the safety regulations on such a plant should be eased with a corresponding reduction in construction costs.

The other area of interest is the loss of tritium from a fusion reactor in the event of an accident that could somehow destroy all containment. The worst case, of course, is to release all the tritium in the reactor in the form of tritiated water (HTO) and having the accident occur during the worst meteorological conditions. Assessing such an event for the MiniMars[22] plant, Wittenberg[24] found that the maximum exposure to a member of the public who lives at the plant boundary would be 24 Rem (coincidentally not far from the exposure that would have been experienced at a similar position to the Chernobyl plant during its accident). Because of the much lower T_2 content in Ra (the tritium comes from one of the DD reactions discussed in section II) the corresponding exposure to the public would be only 0.1 Rem, or roughly equivalent to the annual exposure to the natural background (see Figure III-3). Again, the lack of catastrophic consequences should be reflected in lower costs of construction and hence, lower costs of electricity.

III-D) Increased Efficiency

Because the charged particles can be directly converted to electricity with 80% or higher efficiencies, we can generate electricity from D-He^3 fusion reactors at roughly twice the efficiency from fossil or fission power plants (see Figure III-4). The DT and DD systems have only 20 and 50% of their energies released in charged particles and therefore have lower overall efficiencies than for the D-He^3 case but still higher than the thermodynamically limited Light Water Fission Reactors (LWR's) and fossil plants. The higher efficiency can greatly decrease the cost of electricity and have an additional benefit of reducing the size of the heat transport system, the turbine buildings and the waste heat facilities.

III-E) Lower Cost of Electricity

It is too early to be able to calculate with any confidence the absolute cost of electricity from any fusion power plant. However, we can compare relative costs of different fusion cycles with some confidence. Using the same costing algorithms from the MiniMars[22] study as well as others derived for the U.S. tokamak program, we have compared the Ra device to MiniMars. The results are summarized in Table III-2. We find

Figure III-3

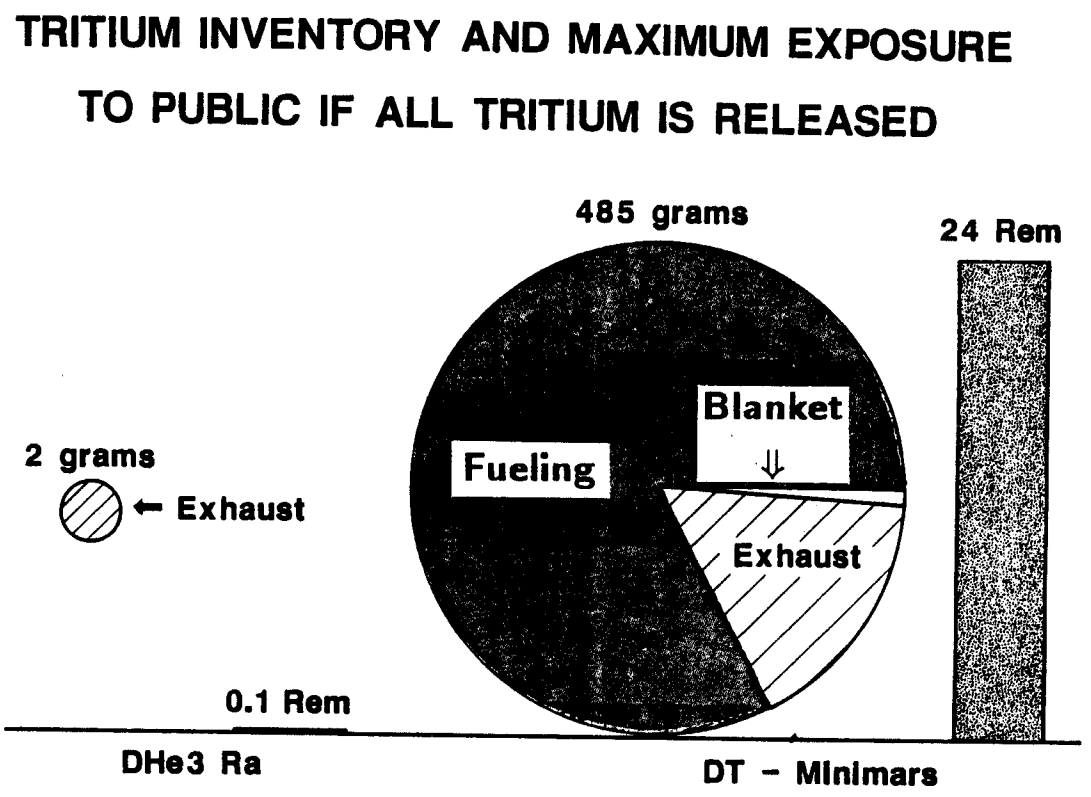

TRITIUM INVENTORY AND MAXIMUM EXPOSURE
TO PUBLIC IF ALL TRITIUM IS RELEASED
485 grams
24 Rem
Blanket
Fueling
Exhaust
2 grams
Exhaust
0.1 Rem
DHe3 Ra
DT - Minimars

Figure III-4

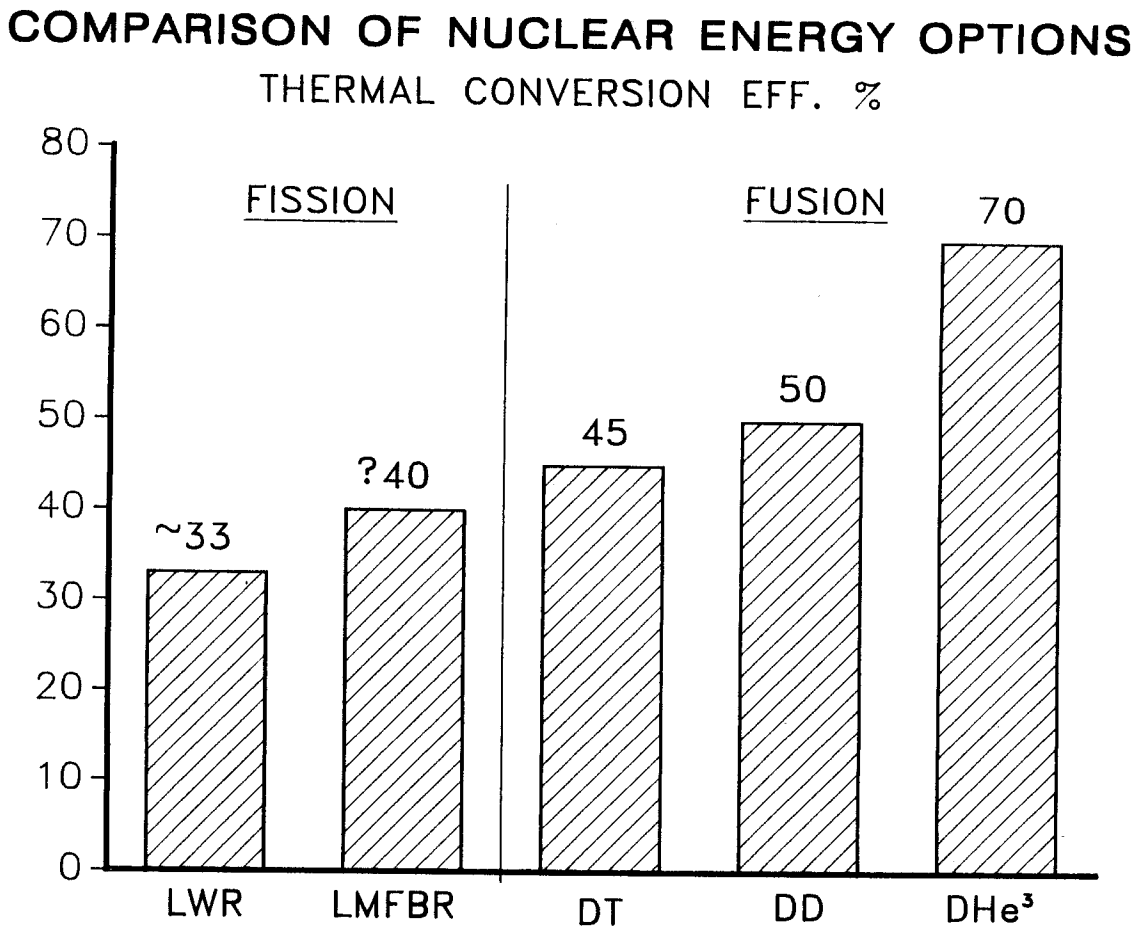

COMPARISON OF NUCLEAR ENERGY OPTIONS
THERMAL CONVERSION EFF. %
80
70
60
50
40
30
20
10
0
FISSION
FUSION
~33
?40
45
50
70
LWR
LMFBR
DT
DD
DHe³

Table III-2

$D\text{-}He^3$ Fusion Reactors Will Have a Considerable Cost Advantage over DT Fusion Systems

	DT MiniMars	$D\text{-}He^3$ Ra
Net Power - MW_e	600	600
Direct Capital Cost $/$kW_e$	1800	1250
Cost of Electricity mills per kWh	42	29*

*Note - He^3 fuel costs would add 1 mill/kWh per 100$/g.

a D-He^3 power plant could be as much as 1/3 less than a similar DT plant. The impact of such a lower electricity cost applied to the U.S. alone for 1987 would mean roughly a 30 billion dollars savings to consumers. While the exact numbers can be questioned, that the impact is in the 10's of billions of dollars can not.

It is also worthwhile to note that at 100 $/g of He^3 fuel, the cost of electricity would increase by 0.001 $/kWh. It is felt that one could pay up to 0.01 $/kWh for the fuel without unduly reducing the attractiveness of the D-He^3 fuel cycle. At 1 billion dollars a tonne, this provides a valuable incentive to study the procurement of this valuable fuel.

III-F) Potentially Shorter Path to Commercialization

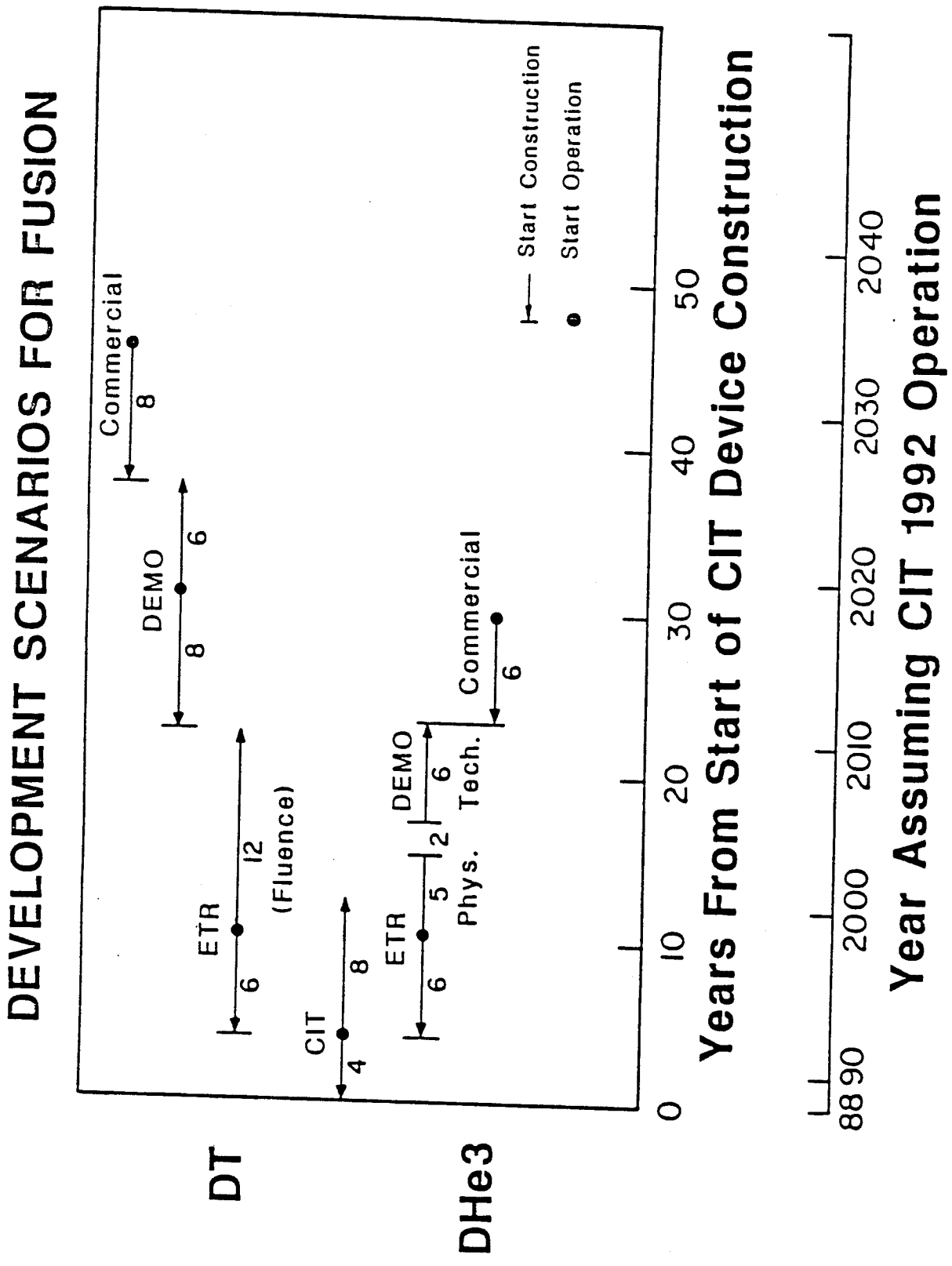
One of the great advantages of the D-He^3 fuel cycle is the fact that once it can be ignited, the development path to a commercial unit should be much easier than for the DT system. After ignition of a DT plasma is achieved and the understanding of how to control such plasmas is in hand, there remains the long and expensive process of testing materials and breeding concepts for commercial units. Along the way, demonstration power plants would have to be built to integrate the plasma physics and materials physics aspects. The current U.S. approach to that process is shown in Figure III-5.

On the DT side it begins with the CIT[19] device scheduled for operation in the early 1990's. The main objective of this device is to demonstrate ignition of DT plasmas, presumably about the middle of the 1990's.

Plans to build a engineering test facility which would follow the CIT project are already underway in several countries.[7] Using the generic name of an Engineering Test Reactor (ETR) for this device, we see that current plans call for construction in 1992 and operation in the late 1990's. This test facility would expand upon the DT ignition physics learned from CIT and do a limited amount of materials and blanket component testing. Presently, it is anticipated that the testing phase would last about 12 years. No electricity would be produced by this device (except possibly from small test blankets that could be inserted into the side of the reactor).

The ETR would be followed by a Demonstration plant which would integrate the plasma, materials, and full tritium breeding blankets into one power producing facility. This Demo is expected to produce electricity, but not on a regular and certainly not on an economical, basis.

Figure III-5


DEVELOPMENT SCENARIOS FOR FUSION
DT
DHe3
Commercial
8
DEMO
6
8
ETR
6
12
(Fluence)
CIT
4
8
ETR
6
5
2
Phys. Tech.
DEMO
6
6
Commercial
6
Start Construction
Start Operation
0
10
20
30
40
50
Years From Start of CIT Device Construction
88 90
2000
2010
2020
2030
2040
Year Assuming CIT 1992 Operation

Finally, if all went well, another commercial facility would be built sequentially to the Demo, hopefully to be ordered by an electric utility. The total time from now to the first operation of this DT commercial unit could be 50 years or more.

On the other hand, if the experiments with the D-He^3 cycle in the ETR facility were to be successful, then an alternate schedule could be pursued. Since the D-He^3 fuel cycle causes much less induced radioactivity it should be possible to convert the ETR unit directly into a power producing Demo. This is possible because, with the low neutron damage level associated with the D-He^3 cycle, we do not need a long testing program for materials and because we do not need to breed tritium, we do not need to test blanket concepts. Moving directly to a Demo on the same site by adding direct conversion equipment saves both time and capital investment. If the Demo can be successfully operated in an electrical producing mode for 4-5 years, we would then be ready to move to a commercial unit. The overall time savings should be between 10 and 20 years compared to the DT case and it is possibly the only way to have commercial fusion power reactors by the year 2020. This time period is important as we shall see later because it determines when we would begin to require helium-3 from nonterrestrial sources.

IV) WHAT ABOUT HELIUM-3 RESOURCES FOR NEAR TERM RESEARCH?

Thus far, we have not said how we would fuel the near term test reactors until we could obtain a larger external source of He^3 fuel. The answer lies with the terrestrial resources of He^3. They lie in two categories as shown in Table IV-1.[11] The first has to do with the primordial He^3 present in the earth at its creation. Unfortunately, most of that He^3 has long since diffused from the earth and been lost through the atmosphere to outer space. What is left in any retrievable form is contained in the underground natural gas reserves. Table IV-1 shows that in the underground strategic helium storage caverns, there is some 30 kg. If we were to process the entire U.S. resource of natural gas, we might obtain another 200 kg but the cost and side effects of such a project make it very unlikely that we could do such a thing.

Another source of He^3 on earth is from the decay of tritium ($t_{1/2}$ = 12.3 years). When T_2 decays, it produces a He^3 atom and a beta particle. Simple calculations of the inventory of T_2 in U.S. thermonuclear weapons shows that if the He^3 were collected, some 300 kg would be available by the year 2000. Presumably about the same amount of He^3 would be available from the weapons stockpile of the USSR. The equilibrium production of He^3 (assuming no future change in weapons stockpiles) is around 15 kg per

Table IV-1

Reasonably Assured Reserves of ^3He That Could Be Available in the Year 2000

Source	Cumulative Amount (kg)	Production Rate Post 2000 (kg/y)
TRITIUM DECAY		
● U.S. Weapons	300	15
● CANDU Reactors	10	2
PRIMORDIAL		
● He Storage	29	—
● Natural Gas	187	—
	>550	~ 17

One could also get much smaller amounts of He^3 from the T_2 produced in the heavy water coolants of Canadian CANDU reactors. This could amount to 10 kg of He^3 by the year 2000 and He^3 will continue to be generated at a rate of 2 kg per year thereafter.

We note again that 1 kg of He^3, when burned with 0.67 kg of D, produces approximately 19 MW-y of energy. This means that by the turn of the century, we could have several hundred kg's of He^3 at our disposal which could provide for several thousand MW-y of power production. The equilibrium generation rate from T_2 resources could fuel a 500 MWe plant continuously if it were run 50% of the time.

Clearly, there is enough He^3 to build an ETR (few hundred MW running 10-20% of a year) and a Demonstration power plant of hundreds of MWe run for several years. This could be done without ever having to leave the earth for fuel. The real problem would come when the first large (GWe) commercial plants could be built, around 2020. The next major question is can we get the He^3 fuel from the moon on a time scale consistent with our development path?

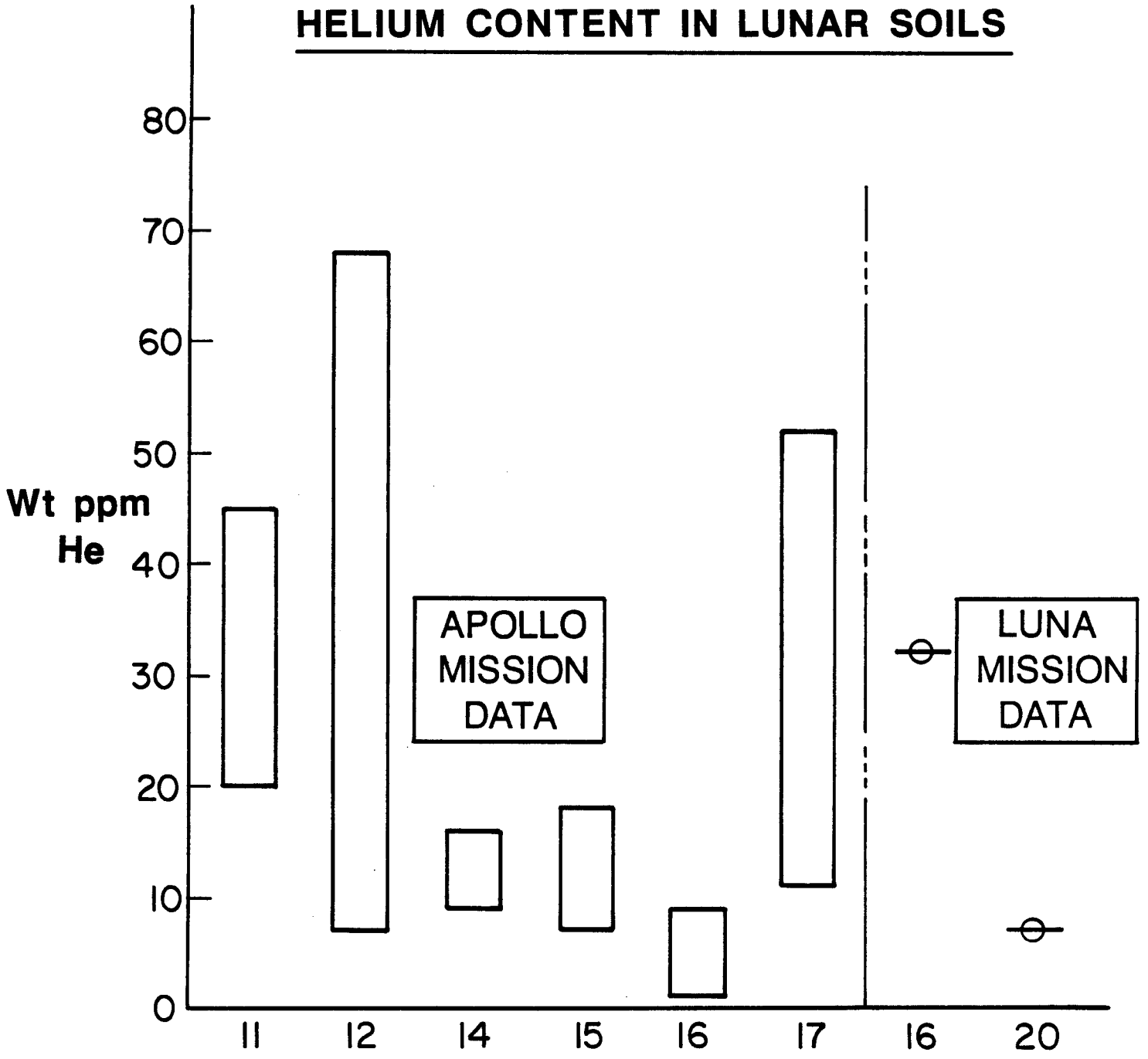
V) WHAT AND WHERE ARE THE He^3 RESOURCES ON THE MOON?

Wittenberg et al. first published their discovery of He^3 in the regoliths on the moon in September 1986.[11] Since that time, work by the Wisconsin group has elaborated on the original idea. A few highlights will be summarized here.

The origin of the main source of lunar He^3 is from the solar wind. Using data which showed that the solar wind contains ~4% helium atoms and that the He^3/He^4 ratio is ~ 480 appm, it was calculated that the surface of the moon was bombarded with over 250 million metric tonnes in 4 billion years. Furthermore, because the energy of the solar wind is low (~3 keV for the He^3 ions) the ions did not penetrate very far into the surfaces of the regolith particles (< 0.1 micron). The fact that the surface of the moon is periodically stirred as the result of frequent meteorite impacts results in the helium being trapped in soil particles to depths of several meters.

Analysis of Apollo and Luna regolith samples revealed that the total helium content in the moon minerals ranges from a few to 70 wtppm (see Figure V-1[25]). The higher concentrations are associated with the regolith on basaltic Maria of the moon and the lower contents associated with the Highland rocks and Basin Ejecta. Clearly the higher concentrations are in the most accessible and minable material. Using the data available, it is calculated that roughly a million metric tonnes of He^3 are still trapped in the surface of the moon.[11]

Figure V-1


HELIUM CONTENT IN LUNAR SOILS
Wt ppm He
80
70
60
50
40
30
20
10
0
APOLLO MISSION DATA
LUNA MISSION DATA
11
12
14
15
16
17
16
20

The next step is to determine the most favorable location for extracting this fuel. Cameron[25] has shown (Figure V-2) that there is an apparent association between the He and TiO_2 content in the samples. Assuming that this is generally true, he then examined the data on spectral reflectance and spectroscopy of the moon which showed that the Sea of Tranquility (confirmed by Apollo 11 samples) and certain parts of the Oceanus Procellarium were particularly rich in TiO_2. It was then determined, on the basis of the large area (190,000 km^2) and past U.S. experience, that the Sea of Tranquility would be the prime target for initial investigations of lunar mining sites. This one area alone appears to contain more than 8,000 tonnes of He^3 to a depth of 2 meters. A backup target is the TiO_2 rich basalt regolith in the vicinity of Mare Serenetatis sampled during Apollo 17[26].

VI) HOW WOULD THE He^3 BE EXTRACTED?

Since the solar wind gases are weakly bound in the lunar regolith it should be relatively easy to extract them. Pepin[27] found (Figure VI-1) that heating lunar regolith caused the He^3 to be evolved above 200° C and by 600° C, 75% of the fuel could be removed.

There are several methods by which the He^3 could be extracted and a schematic of one approach is shown in Figure VI-2. In this unit, the loose regolith, to a depth of 60 cm, is scooped into the front of the robotic unit. It is then sized to particles less than 100 microns in diameter because there seems to be a higher concentration of solar gases in the smaller particles (presumably because of the high surface to volume ratio).[28] After beneficiation, the concentrate is preheated (Figure VI-3) by heat pipes[29] and then fed into a solar heated retort. At this point we anticipate only heating to 600 or 700° C and collecting the volatiles emitted at that temperature (H_2, He^4, He^3, C compounds, N_2). The gases are collected and the spent concentrate is discharged through heat pipes to recover 90% of its heat. The concentrate is finally dropped off the back of the moving miner. Note that in the 1/6 gravity environment relatively little energy is expended lifting material!

Of course, this scheme would only work during the lunar day but orbiting mirrors, nuclear reactor heat from a mobile power plant, or indirect heating from microwaves generated at a central power plant on the moon could extend the operating time. Alternative schemes are being examined through parametric analyses of such variables as particle size vs. temperature vs. yield, mining depth vs. He^3 concentration vs. particle

Figure V-2

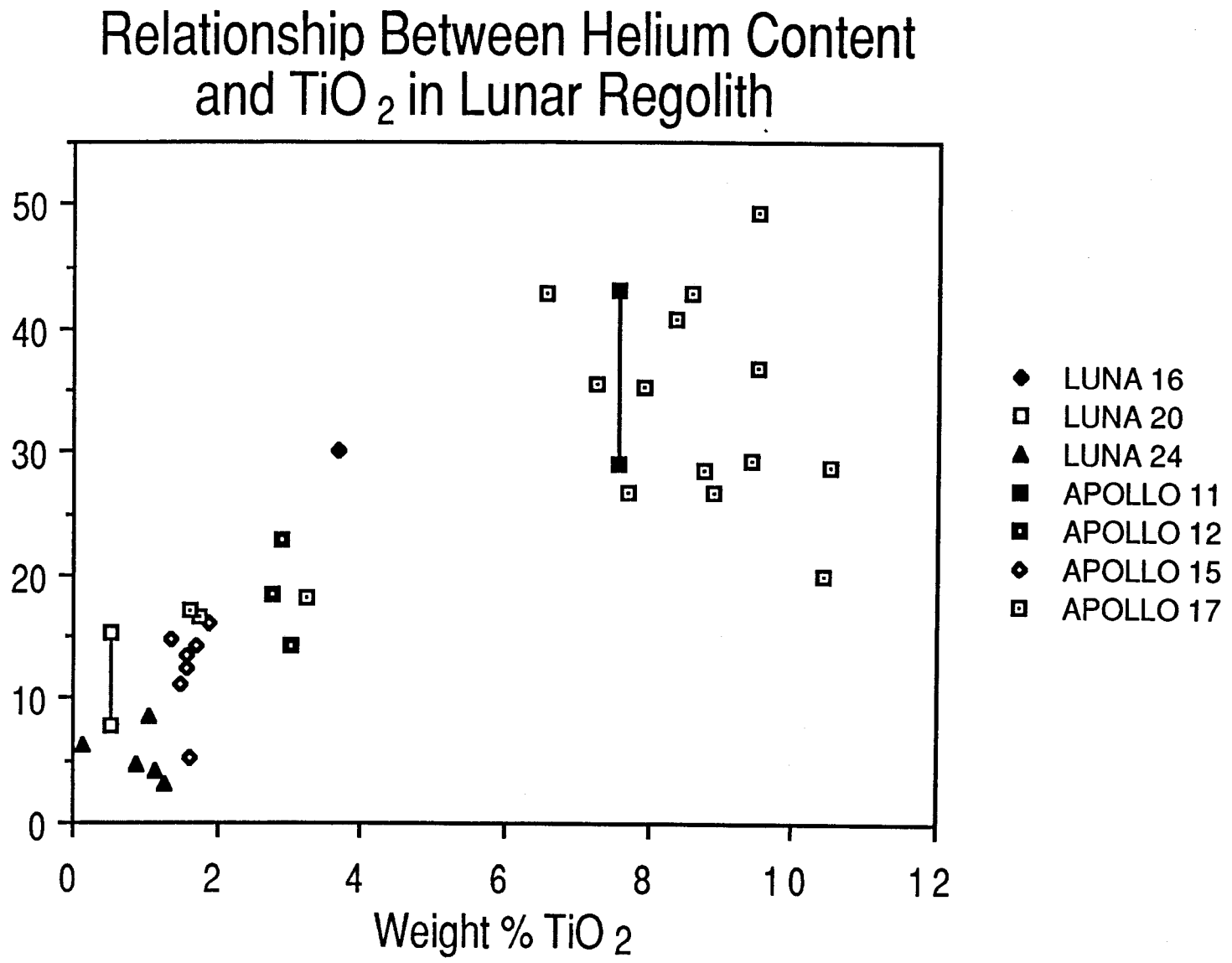

Relationship Between Helium Content and TiO 2 in Lunar Regolith
4 He wppm
50
40
30
20
10
0
0
2
4
6
8
10
12
Weight % TiO 2
LUNA 16
LUNA 20
LUNA 24
APOLLO 11
APOLLO 12
APOLLO 15
APOLLO 17

Figure VI-1

HELIUM-3 EVOLUTION FROM LUNAR SOIL

Data from Pepin et al., 1970

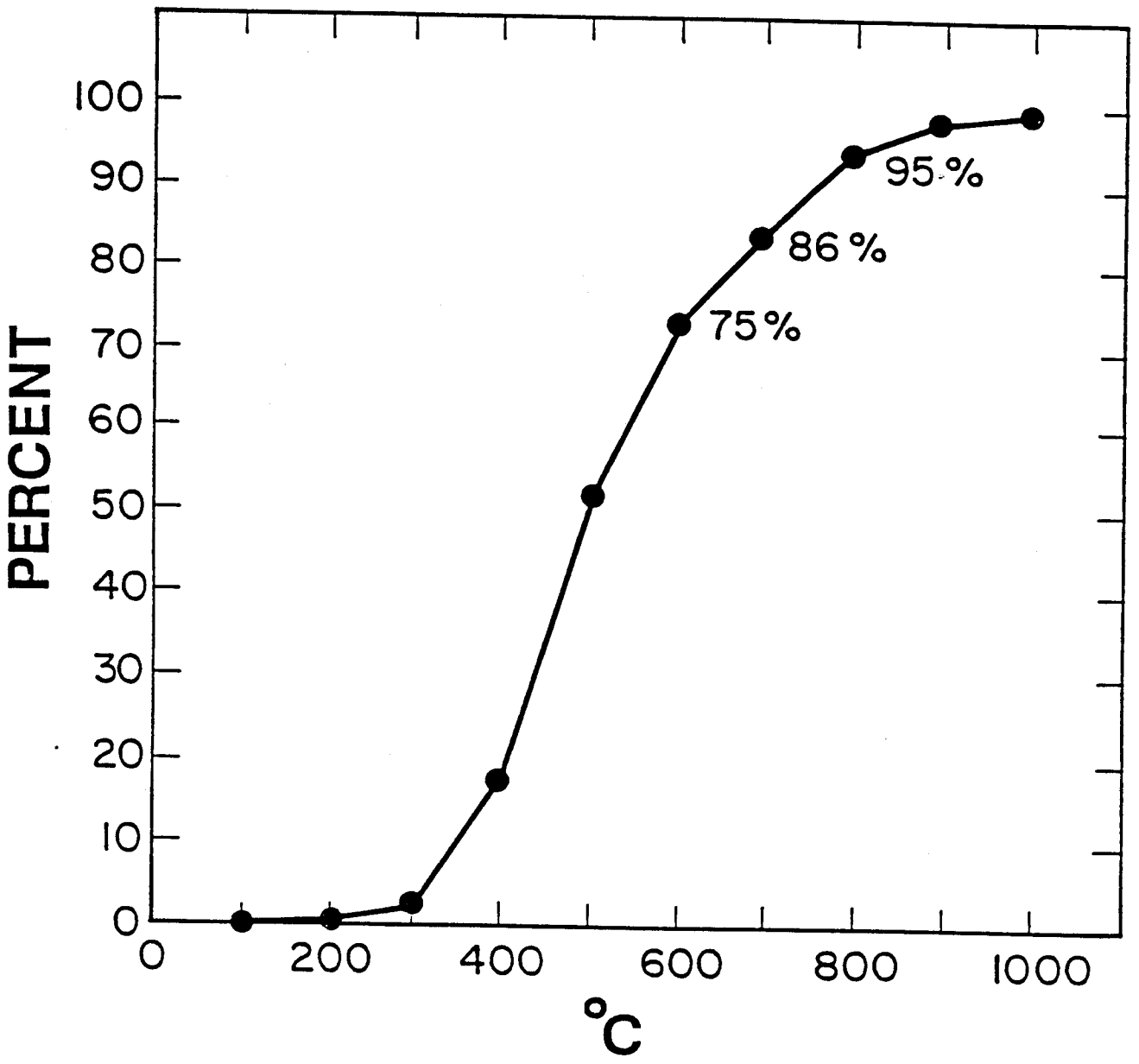
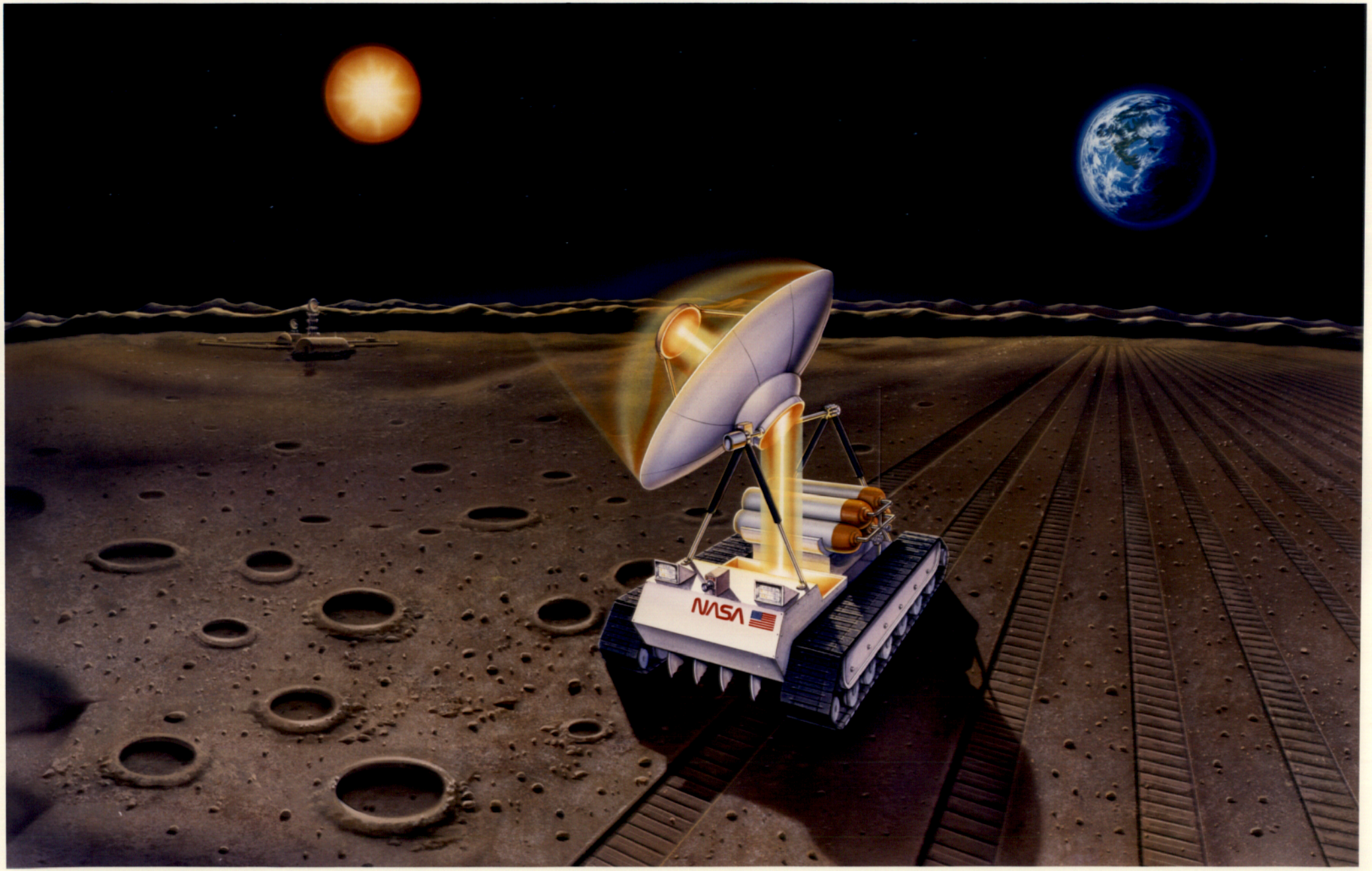
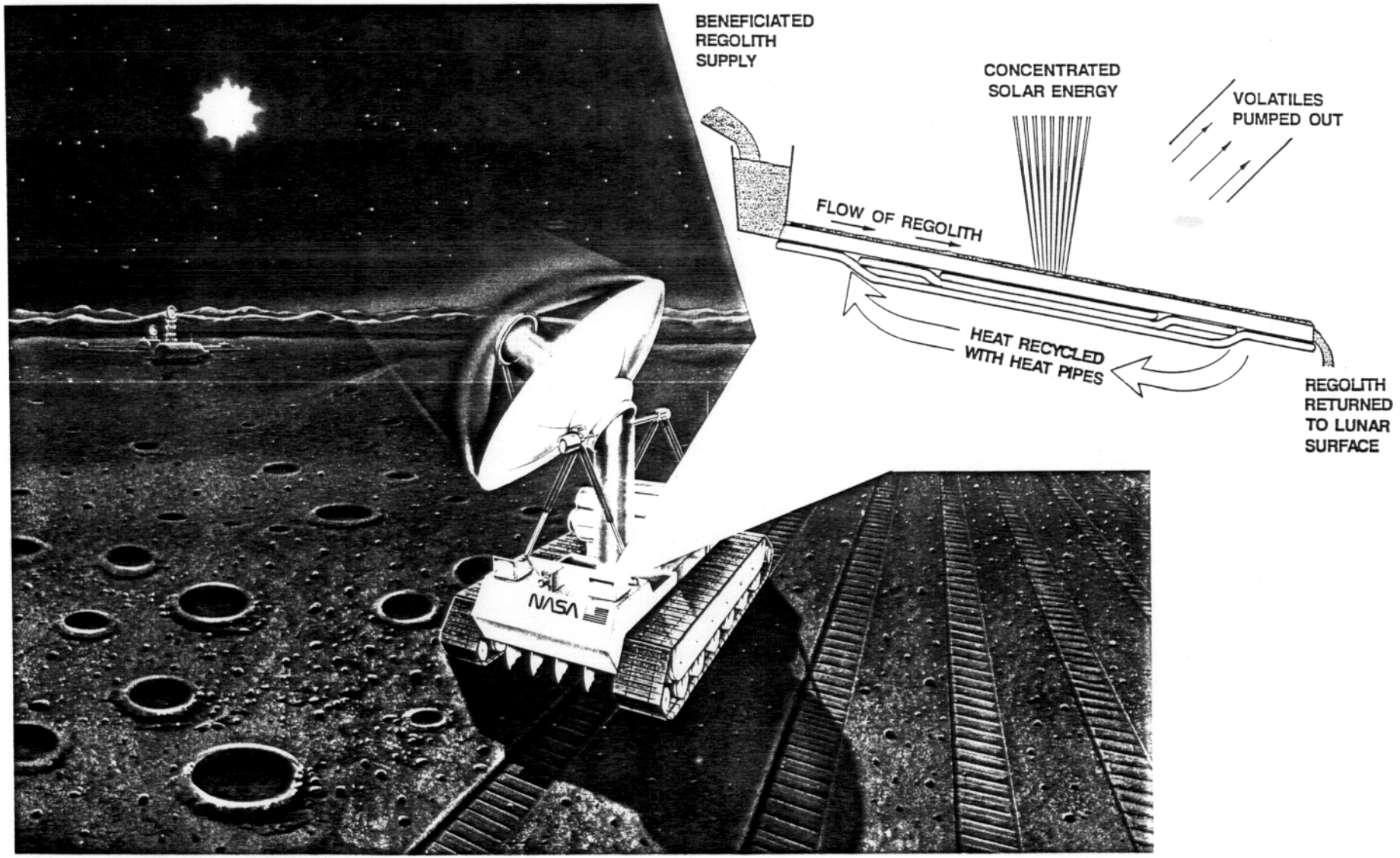


Figure VI-2. Design of lunar vehicle to extract He-3 from regolith using direct solar radiation.





SCHEMATIC OF ONE POSSIBLE TECHNIQUE FOR THE EXTRACTION OF VOLATILES FROM LUNAR REGOLITH

size distribution, manned operation vs. robotic operations vs. maintenance costs, mechanical particle separation vs. gaseous particle separation vs. yield, solar vs. nuclear power, etc.

Once the volatiles are extracted, they can be separated from the helium by isolation from the lunar surface and exposure to outer space (< 5° K) during the lunar night. Everything except the He will condense and the He^3 can be later separated from the He^4 by superleak techniques well established in industry.(30)

For every tonne of He^3 produced, some 3300 tonnes of He^4, 500 tonnes of nitrogen, over 3000 tonnes of CO and CO_2 and 6100 tonnes of H_2 gas are produced. The H_2 will be extremely beneficial on the moon for lunar inhabitants to make water and for propellents. Transportation of that much H_2 to the moon, even at 200 $/per kg, would cost ~1 billion dollars (for every tonne of He^3 produced). As previously noted, the He^3 itself could be worth as much as ~1 billion dollars per tonne. Of the other volatiles, the N_2 could also be used for plant growing, the carbon for manufacturing or atmosphere control, and the He^4 for pressurization and as a power plant working fluid.

VII) HOW MUCH IS THE He^3 WORTH?

While it is hard to anticipate the cost of energy in the future, we can base our calculations on today's experience. First of all, it is worthwhile to get a feeling for how much energy is contained in the He^3 on the moon. If the resource is 1 million metric tonnes, then there is some 20,000 TW-y of potential thermal energy on the moon. This is over 10 times more energy than that contained in economically recoverable fossil fuels on earth.

The second point to note is that only 20 tonnes of He^3, burned with D_2, would have provided the entire U.S. electrical consumption in 1986 (some 285 GWe-y). The 20 tonnes of condensed He^3 could fit in the cargo bay of just one US shuttle craft.

In 1986, the U.S. spent 40 billion dollars for fuel (coal, oil, gas, uranium) to generate electricity. This does not include plant or distribution costs, just the expenditure for fuel. If the 20 tonnes of He^3 just replaced that fuel cost (and the plant costs and distribution costs stayed the same) then the He^3 would be worth approximately 2 billion dollars per tonne. At that rate it is the only thing we know of on the moon which is economically worth bringing back to earth assuming that, early in the 21st century, the incremental cost for a He^3 mining operation could be less than ~50 billion dollars. (In fact, it is the only element that the moon has in relatively large quantity that we do not have on earth.)

It is our opinion at this time, that a realistic figure for the worth of He^3 on the earth is ~1 billion dollars per tonne. This is because the cost of the fusion power plants themselves are probably as expensive as fission plants which in turn, are more expensive than coal plants.

We have not factored in the credit for the other solar wind gases that would be extracted but it is possible that the cost of operating the mining base might be offset by the auxiliary products produced leaving the value of He^3 to be applied against capital costs and profit. Further economic studies are underway as are other options for the mining, beneficiation and extraction of this fusion fuel.

VIII) IS THE TIME TABLE REALISTIC?

It was shown in section III that no He^3 would probably be required from the moon before 2015. A recent study by Sviatoslavsky,[31] using conservative U.S. energy growth rates (2%) and conservative penetration rates of fusion beginning with the first plant in 2015, produced the He^3 demand curve shown in Figure VIII-1. This demand results in the cumulative He^3 requirements shown in Figure VII-2. It can be seen that the demand reaches the ~1 tonne per year level in 2030, 10 tonnes per year in 2035 and by 2050, nearly 200 tonnes of He^3 could be required.

This schedule should be compared to future activities in space proposed by the recent National Commission on Space (NCOS) report[32] shown in Figure VIII-3. This plan envisions the first lunar base to be established by 2005 with the first pilot plant production of oxygen by 2010. By 2015 it is anticipated that some 500 tonnes of oxygen per year could be exported from the moon to the space station (compare this to 1 tonne of He^3 per year required a decade later). Furthermore the extraction of oxygen has to be done at 1300° C, a much more difficult job that working at 700° C for He^3.

Therefore, it seems that the schedule and technology requirements required to extract He^3 from the moon are consistent with current proposals to procure oxygen for the space station or to place a colony on Mars.

IX) CONCLUSIONS

Two major consequences can evolve from this work. First, there is a reasonable possibility that we could have a clean and inherently safe nuclear power source in the 21st century which will insure the survival of life and society as we know it on earth. Secondly, the discovery that there is a large source of energy on our nearest neighbor in

Figure VIII-1

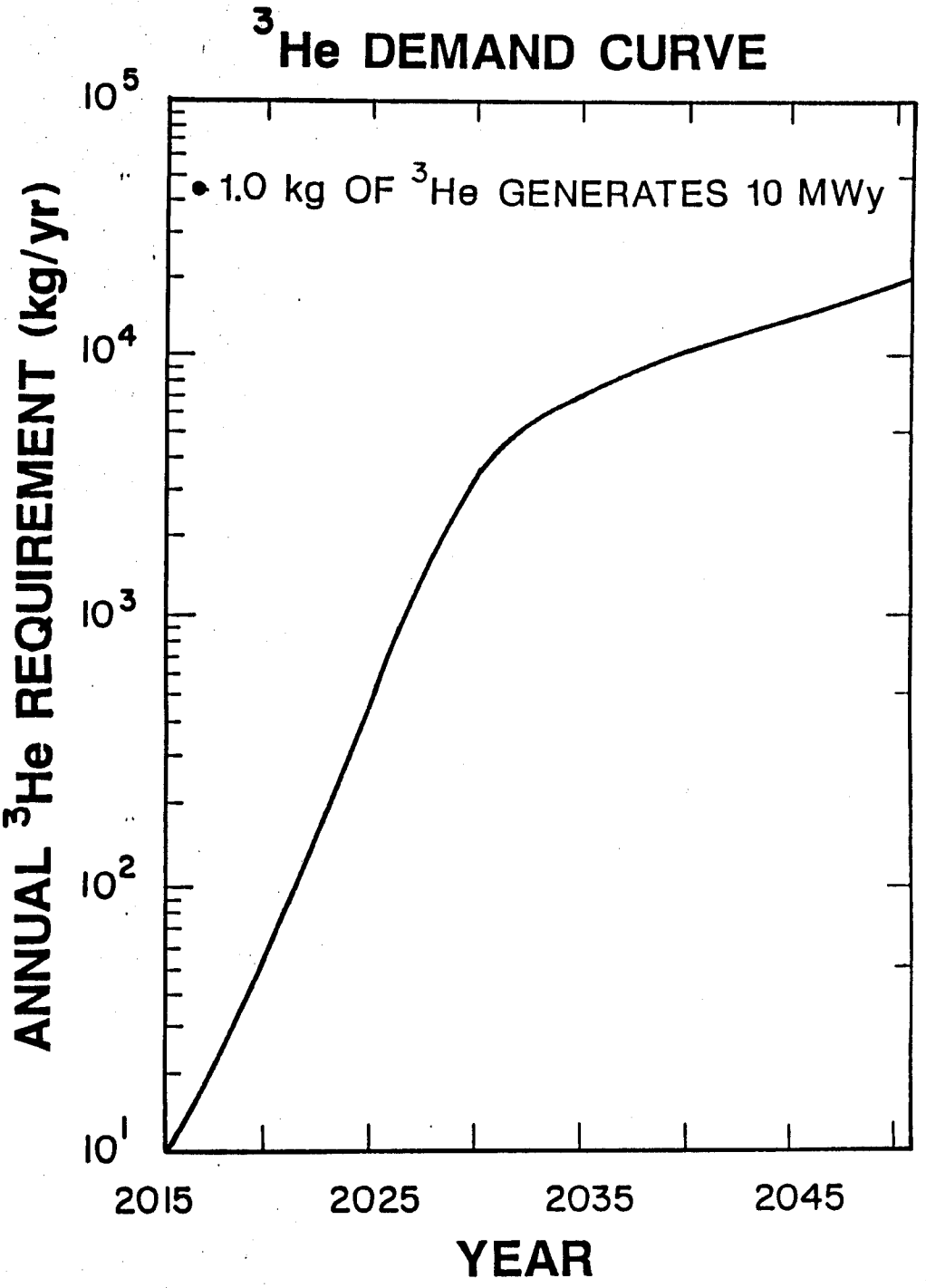
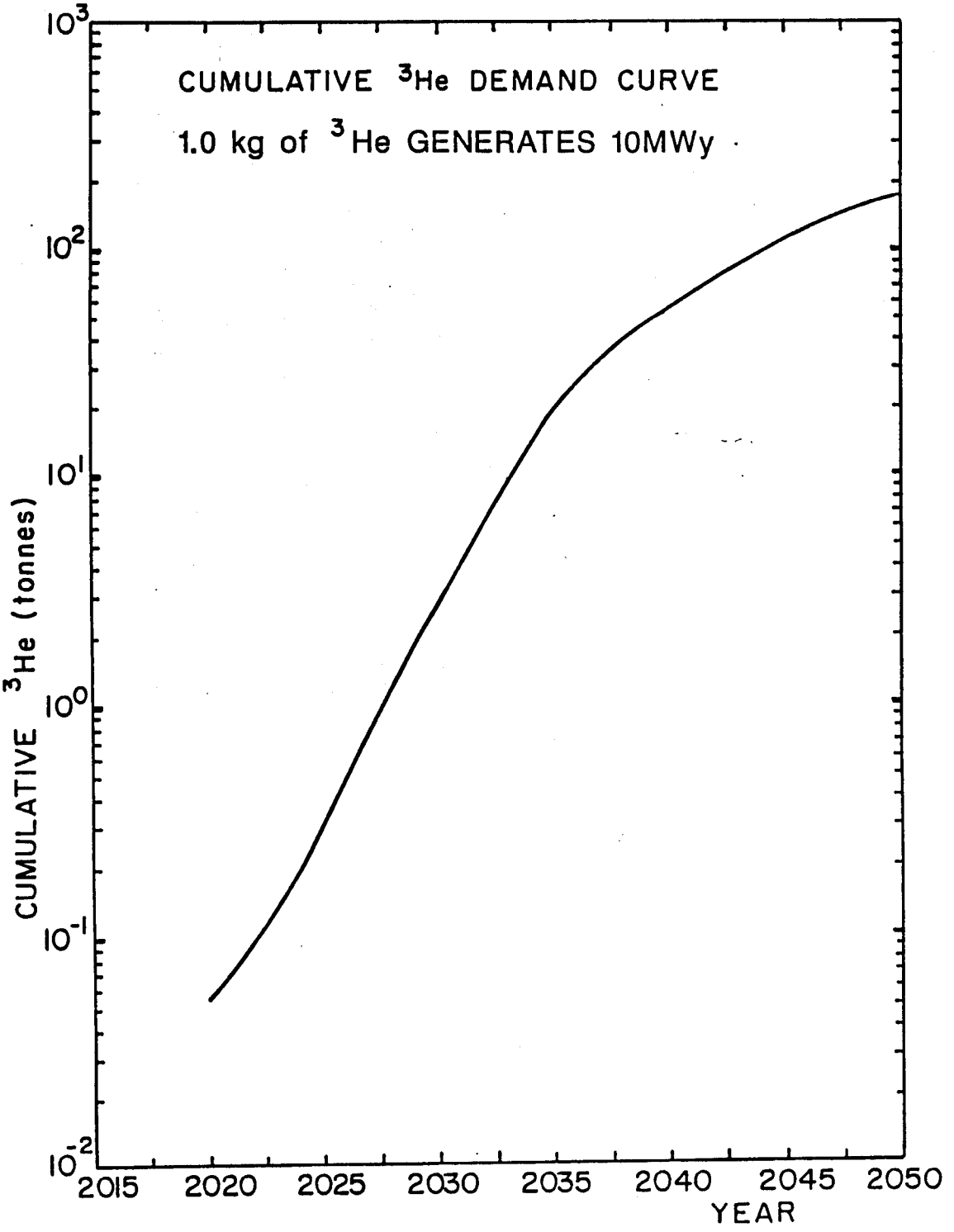


Figure VIII-2



Present Plans for Access to the Inner Solar System

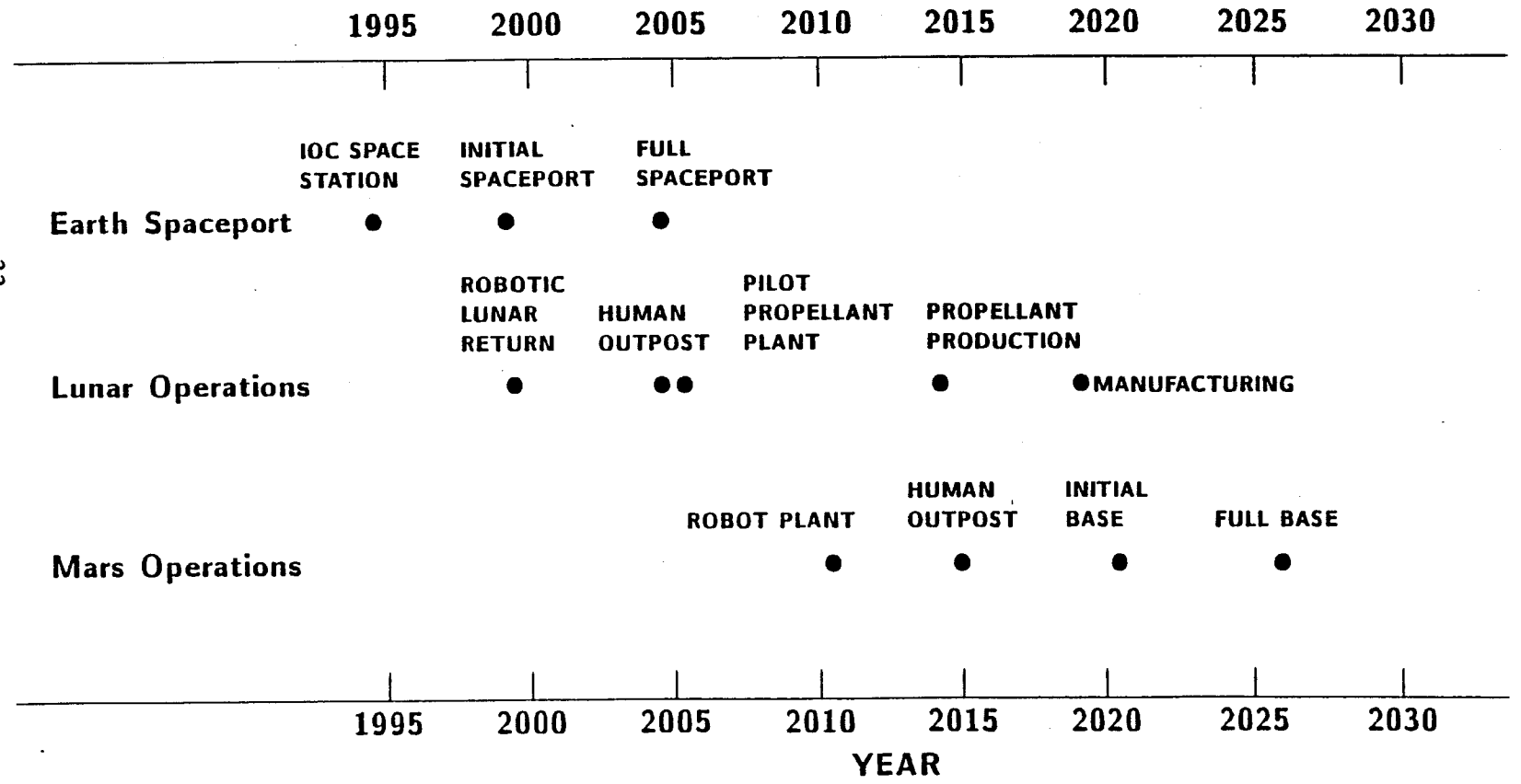


Figure VIII-3

the solar system opens up the exploration of outer space. This not only provides us with an economic incentive to return to the moon, but it can also make the settlement of space much more economically feasible than previously thought. Therefore, the successful demonstration of burning He^3 with D takes on added importance in the near term and the successful establishment of lunar bases becomes critical for the long term. Our grandchildren will be greatly affected by the outcome of these two noble endeavors.

X) ACKNOWLEDGEMENT

This work was supported in part by NASA, the University of Wisconsin, the Grainger Foundation, the Electric Power Research Institute, and the Wisconsin Electric Utilities Research Foundation. The authors also wish to acknowledge the help of scientists in the Fusion Technology Institute and the Wisconsin Center for Space Automation and Robotics. Special thanks is given to Drs. Attaya, Cameron, Emmert, Santarius, Sawan, Sviatoslavsky, and Wittenberg for permission to quote unpublished results.

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