FUSION ENERGY FROM THE MOON FOR THE TWENTY-FIRST CENTURY

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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 (*Kefitz,* 1977) in the twenty-first century. Society has 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 (*Hafele,* 1981; *U.S. Department of Energy,* 1987), 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 one 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-yr of that energy (1 TW-yr = 10^{12} W 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-yr/yr. As the world moves toward the "equilibrium" 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-yr/yr. Since there is only 1000-1500 TW-yr of fossil fuel energy left that is economically recoverable (*Hafele,* 1981; *U.S. Department of Energy,* 1987), it is easy to see that somewhere in the mid-twenty-first century our economically recoverable fossil fuel resources will be exhausted. 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 nonfuel products to sustain the quality of life. In any case, for much of the twenty-first 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 nearly 400 reactors located in 26 countries that provide approximately one-sixth of the world's electricity. By the year 2000, this fraction will increase to approximately one-fifth. 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.

There is another form of nuclear energy that 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 form of energy release can be observed every day from the sun, and every night from the billions upon billions of stars that themselves are powered by fusion reactions.

Scientists have been trying to reproduce a controlled fusion reaction here on Earth since 1951. After 40 years of research and the expenditure of over 20 billion dollars in a worldwide program, the fusion community is now within a few years of the first "breakeven" fusion experiments (*Haurylak et al.* 1986), historically similar in some ways to the Chicago Stagg Field fission reactor experiment conducted by Enrico Fermi and his colleagues in 1941 (*Fermi and Szilard,* 1944). Early in the 1990s, magnetically confined plasmas in either the TFTR device at Princeton, USA (*Haurylak et al.,* 1986) or the JET device in Culham, UK (*JET Team,* 1986) are expected to 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 that will produce hundreds of megawatts of thermonuclear power in the 1990s (*Abdou et al.,* 1986). Work has even begun on the design of conceptual commercial fusion power plants (*Kulcinski,* 1985; *Hogan and Kulcinski,* 1985) and for fusion power sources in space (*Santarius et al.,* 1987).

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 D and helium-3 (He^3) that, in theory, involves *no* neutrons or radioactive species, i.e.

$$D + He^3 \rightarrow p(14.7)\ MeV) + He^4\ (3.7\ MeV) + 18.4\ MeV$$

However, some side DD reactions do produce neutrons and as little as 1% of the energy released in this reaction could be released in the form of neutrons. Such a low neutron production

(compared to the DT cycle) greatly simplifies the safety-related design features of the reactor and reduces the levels of induced radioactivity such that extensive radioactive waste facilities are not required. Furthermore, since approximately 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 has it not been pursued more vigorously in the past? The simple answer 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 hundred kilograms (*Wittenberg et al.*, 1986) and the He^3 that results from the decay of man-made tritium ($t_{1/2} = 12.3$ yr) is also only being produced at a rate of 10-20 kg/yr. Since the energy equivalent of He^3 is 19 MW-yr per kg, one can see that to provide a significant fraction of the world's energy needs would require hundreds of *tonnes* of He^3 per year, not hundreds of kilograms per year.

What is the solution? In 1986, it was pointed out by scientists at the University of Wisconsin (*Wittenberg et al.*, 1986) that over the four-billion-year history of the Moon, several hundred million metric tonnes of He^3 have impacted 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. It will be shown later in this report that even a small fraction of this He^3 could provide the world's electricity needs for centuries to come.

The main object of this paper is to show how commercial D-He^3 fusion reactors can impact the twenty-first century. After an initial discussion of the physics of this fusion cycle, a brief description of current experiments dealing with D-He^3 will be given. The technology issues of safety, availability, reliability, maintainability, radioactive wastes, and costs will then be addressed. The cost of electricity and development pathway for this fusion cycle will then be discussed. Finally, the question of fuel supply will be examined.

THE PHYSICS OF THE D-He^3 FUSION REACTION

When certain light isotopes are heated to an extremely high temperature and confined in a small region of space, they can react with each other, producing particles that weigh less than the reactants. The missing mass is converted into energy. The reaction rate of selected fusion fuels is plotted in Fig. 1 and reveals that the DT reaction occurs at the lowest temperatures. Figure 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 and engineering reasons, the optimum temperature at which to run these reactions ranges from 20 keV for the DT reaction to 60 keV for the D-He^3 plasmas.

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

$$D + D \rightarrow p + T = 4.0 \text{ MeV}$$

$$D + D \rightarrow He^3 + n + 3.3 \text{ MeV}$$

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

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

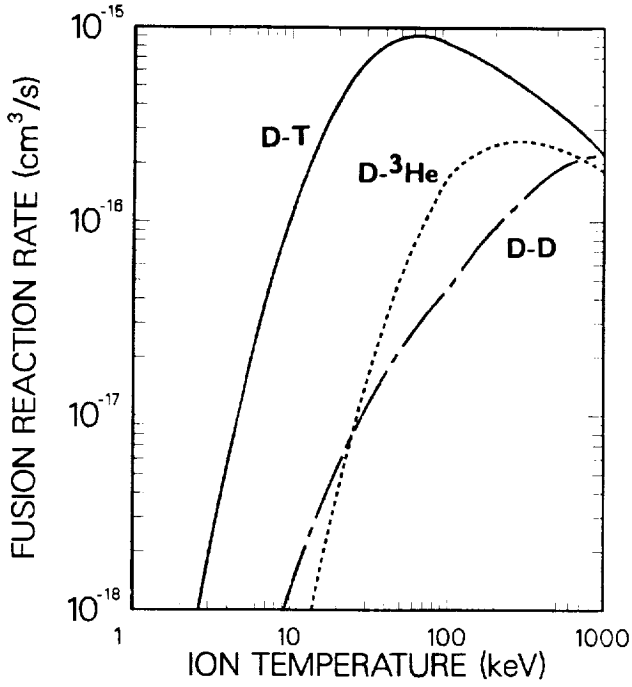

Fig. 1. Major fusion fuel reactivities.

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 D and He^3, respectively; $\langle\sigma v\rangle_{DD}$ = fusion reaction rate of D ions; $\langle\sigma v\rangle_{DHe}$ = fusion reaction rate of D ions and He^3 ions; and Constant (at 60 keV) ~0.03 if none of the T_2 is burned and ~0.18 if all the T_2 is burned.

It can be seen that there are two main factors that can cause the fractional power in neutrons to be reduced: (1) operation at temperatures where the ratio of the reaction cross sections is minimized and (2) increasing the He^3-to-D ratio. This latter parameter cannot be pushed too far because eventually there would not be enough D atoms available for fusion with the He^3 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 Fig. 2. Here is it shown that, independent of temperature, approximately 80% of the fusion power released in the DT reaction is in the form of neutrons. The neutron power fraction is ~50% for the DD reaction and, depending on the temperature and He^3-to-D ratio, as little as 1% of the power 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

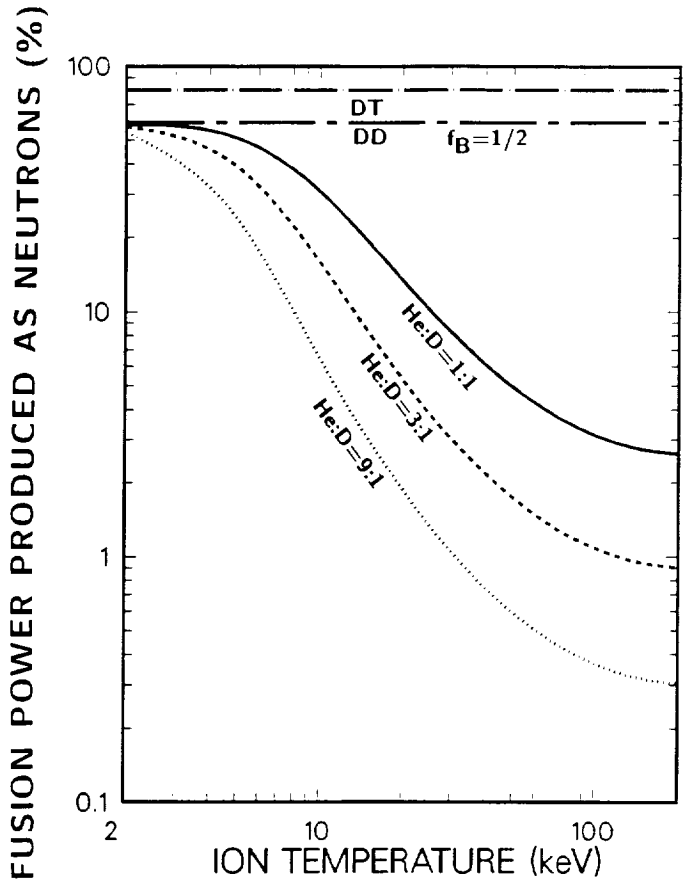

Fig. 2. Percent of fusion power in neutrons (50% tritium burnup).

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 (*Barr and Moir*, 1983). 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 (unpublished data, 1986) 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 electricity via rectennas 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.

Returning to Figs. 1 and 2, it is evident that D-He^3 plasmas will have to be operated at temperatures about three times higher than DT power plants. Experiments at TFTR (*Strachan et al.*, 1989) have already achieved temperatures equivalent to ~20 keV and methods to get to 60-keV ion temperatures in tokamaks have already been discussed for the Next European Torus (NET) (*Emmert et al.*, 1989). Considering that in the past 2 decades the plasma temperatures in tokamaks have been increased 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 the actual amount of thermonuclear power that has been produced in the laboratory is examined, it is found that the situation is quite favorable for D-He^3. Figure 3 plots the power released from DD plasmas in magnetically confined devices since 1978 (no DT plasmas of any significance have been operated to date). It can be seen that starting with PLT in 1978 and progressing to TFTR in 1987, the DD fusion power released in the laboratory has increased to the level of almost 45 kW for a few seconds (D. Meade, personal communication, 1988). Recent experiments by *Jacquinot et al.* (1987) at JET had released over 9 kW from D-He^3 reactions and in 1988 reached the 50-kW level. It is anticipated that this energy release will be over 100 kW when all the heating is installed on JET in 1988.

How could the breakeven and ignition experiments for D-He^3 be conducted? *Emmert et al.* (1989) have shown that for the present European design of NET, simply inserting a D-He^3 plasma in place of the reference DT plasma could 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 achieved 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.* (1987) when a combination of thinner inboard shields, a slightly more elongated plasma, and a 20% higher magnetic field on TF coils was examined. It was found that NET could actaully 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 overall design and would allow scientists to study ignited D-He^3 plasmas in the 1999-2000 time period (assuming the 1993 construction start date is maintained). This is less than five years after it is hoped to reach ignited conditions in a DT plasma in CIT (*Schmidt et al.*, 1986). It is therefore quite possible that the scientific community could enter the twenty-first century with experience on ignited plasmas containing both D-He^3 and DT fuel.

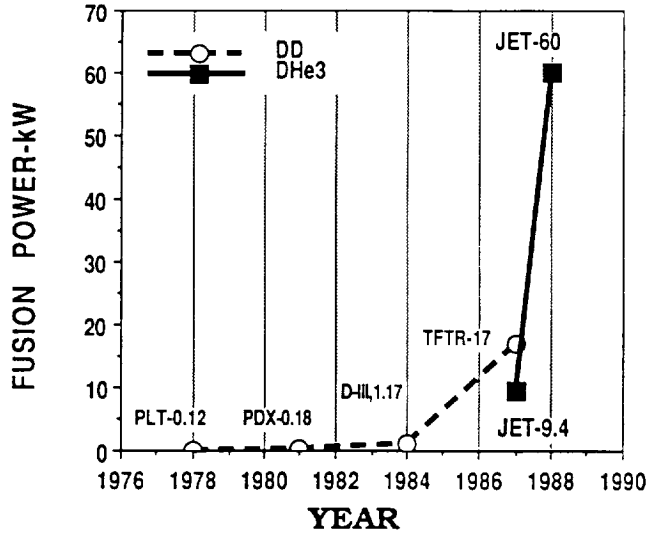

Fig. 3. Actual thermonuclear power produced in fusion devices.

In summary, the physics of the D-He^3 reaction are well established and, in fact, some D-He^3 experiments are being included in the research programs of 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 that scientists and engineers are interested in this fuel cycle from a commercial standpoint.

IMPACT OF D-He^3 FUEL CYCLE ON ELECTRIC POWER ISSUES

Assuming that a well-controlled, sustainable D-He^3 fusion plasma can be produced, what technological advantages would an electric power economy based on that fuel cycle have over one based on DT fusion or, in some cases, even a fission reactor economy? The areas where the D-He^3 fuel cycle can impact the major issues of concern to electric utilities of today are summarized in Table 1. These issues include radioactive wastes; inherent safety; increased availability and reliability; simplified maintenance; and cost. It can be seen from Table 1 that the main reason that the D-He^3 fuel cycle impacts these issues is because of the very low fraction of power in neutrons, as well as the greatly reduced radioactivity in the reaction by-products. Each of these issues will now be addressed primarily in the context of a DT fusion economy, but some observations will also be made with respect to a fission reactor economy.

Radioactive Wastes

It stands to reason that if fewer neutrons are produced per unit of power, then the amount of radioactivity induced in the structural material will also be reduced. The magnitude of this effect can be appreciated if one compares the structural radioactivity associated with the operation of two similar-sized tandem mirror reactors, one operating with a DT fuel (MINIMARS; *Laurence Livermore National Laboratory,* 1986) and the other operating with a D-He^3 fuel (Ra; *Santarius et al.,* 1987). A comparison of the key operating parameters of MINIMARS and Ra is given in Table 2. It will be noticed that the total net power is the same (600 MWe) but the Ra reactor handles less thermal power to produce that electricity because of the predominance of charged particles and the extensive use of direct conversion in that cycle. Of course, the neutron wall loading is less by a factor of 66 in the Ra design.

Attaya et al. (1991) have calculated the waste disposal ratings (WDRs) from the two reactors and have shown how they would differ given realistic radiation damage lifetimes, as well as accounting for adequate magnet and personnel shielding. A summary of their results is given in Table 3 for three different structural materials: a low-activation austenitic steel like Tenelon, and a low-activation and a commercial ferritic steel like HT-9. Because the currently envisioned life of a structural component is only 15-20 MW-yr/m^2, the MINIMARS blanket must be changed approximately every 4-5 years and the average volume of compacted (100% dense) blanket waste discharged during operation is 3 m^3/yr or ~100 m^3 in total. The low neutron damage level (see section on availability and reliability) in the D-He^3 system means that the Ra first wall and shield (there is no blanket needed) will last the entire life of the reactor and still only accumulate less than 10% of the damage associated with the MINIMARS components when they are discharged. The only time that the radioactive structure needs to be changed in the Ra reactor is at the end of the plant life, and then the volume will be roughly half of the shield in a DT reactor.

TABLE 2. Key features of the DT MINIMARS and the D-He^3 Ra tandem mirror fusion reactors.

Parameter	MINIMARS	Ra
Fuel	DT	D-He^3
Net Electric Power (MWe)	600	600
n Wall Loading (MW/m^2	3.3	0.05
Fusion Power (MWt)	1231	1227
Total Thermal Power (MW) (including blanket multiplication)	1684	1237
Net Conversion Efficiency (%)	36	49

It is seen from Table 3 that the low activation structural wastes from a D-He^3 power plant qualify as Class A wastes when the plant is decommissioned. This means that instead of burying the wastes in a deep geologic repository (perhaps as much as a mile below the surface) as is now envisioned for fission reactor wastes, they could be disposed of in trenches near (within 1 m) the surface with no special requirements for containers. The shorter half life and relatively stable form of activated structure from a D-He^3 reactor should significantly reduce decommissioning costs and alleviate the public fear (however exaggerated) of sequestering wastes for thousands of years.

In contrast with the D-He^3 system, the wastes from a DT power plant, even if low-activation steels are used, can only qualify for Class C waste levels. These wastes have to be sequestered in stable form, at least 5 m from the surface, for 300 years.

Finally, if it were decided that present commercial ferritic alloys were the most economical and most radiation-damage-resistant structural materials, the use of the D-He^3 cycle would still permit surface land burial (Class C). This would not be the case for a

TABLE 1. Areas in which the D-He^3 fuel cycle can impact issues of major concern for the electric utility industry.

	Major Issues				
D-He^3 Fuel Characteristics*	Inherent Safety	Increased Availability	Simplified Maintenance	Radioactive Wastes	Cost
Reduced radioactivity	X	X	X	X	X
Reduced radiation damage	X	X	X	X	X
Direct conversion			X		X
Shorter path to commercialization					X

* Relative to DT fusion and fission.

TABLE 3. Waste disposal characteristics of structural materials used in DT and D-He^3 fusion reactor designs.

Structural Components*	DT Fuel MINIMARS	D-He^3 Fuel Ra
Neutron Wall Loading	3.3 MW/m^2	0.05 MW/m^2
Average Discharge (tonnes/yr)	24	0
Decommissioning (tonnes)	2560	1520
Low Activation Austenitic Alloy Tenelon	Class C	Class A
Low Activation Ferritic Alloy HT-9	Class C	Class A
Present-day Ferritic Alloy HT-9	Deep Geologic Waste Repository	Class C

* Compacted wastes, 10CFR61, 10-year decay before disposal.

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 m from the surface and in chemically and structurally stable container for 300 years. Deep Geologic Waste Repository—Must be sequestered from the public, at least 200 m below the surface, usually for periods exceeding several thousand years, and continuously monitored. Details considered on a case-by-case basis.

DT reactor and one would have to employ the deep geologic waste disposal sites for the structural material discharged from these reactors.

No matter how the subject of radioactive wastes is addressed, it is clear that from either an annual discharge volume, decommissioning volume, or surface vs. deep geologic burial, the D-He^3 cycle has significant advantages over a DT cycle. The contrast is even more evident when comparing the D-He^3 cycle to fission reactor wastes. The intangible effect of being able to avoid a centuries-long radioactive waste repository will be hard to quantify, but, as evidenced by the multibillion-dollar nuclear waste program in the U.S., it should have both political and financial benefits.

Inherent Safety

The safety of fusion power plants has been recently defined (*Holdren,* 1987) by the U.S. Department of Energy Committee on Environment, Safety, and Economic Aspects of Magnetic Fusion Energy (ESECOM) in terms of four levels of safety assurance (LSA):

Level 1: Inherent safety. Safety is assured by passive mechanisms of release limitation no matter what the accident sequence. The radioactive inventories and materials properties in such a reactor preclude a fatal release regardless of the reactor's condition.

Level 2: Large-scale passive protection. Natural heat transfer mechanisms suffice to keep temperatures below those needed—given radioactivity inventories and materials properties—to produce a fatal release unless large-scale geometry is badly distorted.

Level 3: Small-scale passive protection. Safety is assured by passive mechanisms of release limitations as long as severe violations of small-scale geometry—such as a large break in a major coolant pipe—are avoided, i.e., fatal release can only be assured if the coolant system is substantially intact.

Level 4: Active. There are credible initiative events that can only be prevented from escalating to a fatality—capable release by means of active safety systems.

On the basis of these definitions, current fission reactors are at level 4 and under some circumstances advanced LWRs (not yet built) could qualify at level 3. "Traditional" liquid metal cooled DT reactors also fall into levels 3 or 4. The D-He^3 fusion reactor qualifies for level 1 (inherently safe) according to the ESECOM report, even with a 1:1 D-to-He^3 ratio.

Calculations at Wisconsin, performed by *Sviatoslavsky* (1987) even before the ESECOM report, show that the consequences of a complete and instantaneous coolant loss are indeed minimal and that even a steel-structured D-He^3 power plant can qualify for LSA levels 1 or 2. The basis for this statement is that the temperature increase in the shield region would never reach levels required to volatilize radioactive isotopes in the structure. Sviatoslavsky found that even with absolutely no heat leak during the accident (i.e., as if a perfect thermal insulator were 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 (see Fig. 4). After a week the temperature increase is only 50°C and after one month it would only increase by 200°C. Increasing the D-He^3 ratio to 1:1 only results in a 350°C increase after one month, again with no heat loss. It is obvious that a meltdown is virtually impossible in a D-He^3 reactor because of the low afterheat levels and because there always would be some heat leakage by conduction to the support structure or convection to the air in the building. Without the possibility of a major thermal excursion in the event of a highly unlikely, but theo-

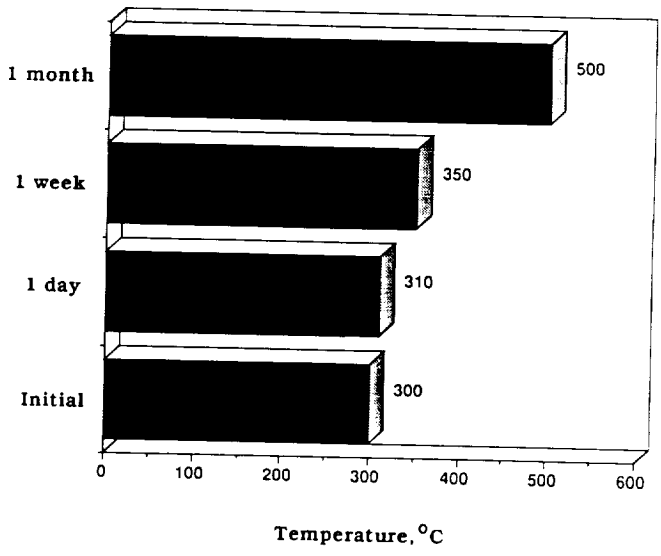

Fig. 4. Maximum temperature increase in a D-He^3 blanket.

retically feasible, accident, the safety regulations on such a plant should be eased and the label of "inherently safe" could be given to such a reactor.

Another area of interest is the loss of T 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 T in the reactor in the form of tritiated water (HTO) and have the accident occur during the worst meteorological conditions. Assessing such an event for the MINIMARS plant (*Lawrence Livermore National Laboratory,* 1986), it was found that the maximum exposure to a member of the public who lives at the plant boundary from the entire 485 g T_2 inventory 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 (2 g) in Ra (the T comes from one of the side DD reactions discussed in the section on the physics of the D-He^3 fusion reaction), the corresponding exposure to the public would be only 0.1 Rem, or roughly equivalent to the annual exposure of the natural background radiation (see Fig. 5). The lack of significant public exposure in the event of a catastrophic accident should be reflected in lower costs of construction and, hence, lower costs of electricity.

Availability and Reliability

There are several features of nuclear power facilities that generally have a negative impact on the reliability of the power plant and the fraction of time that it could be available for generating electricity. Four of these features are (1) radiation effects; (2) radioactivity; (3) necessity to insure that decay heat can be always removed; and (4) extremely stringent regulations on control equipment and the several levels of backup controls required to insure that no substantial release of radioactivity can occur.

The detrimental effect of radiation damage on mechanical properties causes designers to place very conservative operating limits on nuclear power plants. This can result in reduced temperatures, reduced pressures, and even premature replacement of components to be absolutely certain that there are no potential failures that could occur in the reactor.

In order to assess the difference between a D-He^3 cycle compared to DT fusion or fission reactors, it is neccesary to define a unit of damage that is meaningful to all systems. The materials community uses the dpa unit, which stands for displacements per atom, and is a measure of how many times a given atom is displaced during the metallic component's lifetime. A value of 10 dpa per year means every atom is displaced 10 times during 1 year of operation. It is possible for every atom to be displaced several times during the lifetime of a component because most of the displaced atoms simply and rapidly recombine with other vacant lattice positions. However, it takes only a small fraction of the displaced atoms to precipitate in the solid to produce damage and this is a function of the temperature of irradiation; usually the higher the temperature, the worse the effect.

To gain some perspective on the nature of this problem, it is instructive to use the Ra and MINIMARS reactor designs as reference points. It is known that after 30 FPY (full power years), the total DT damage to the first wall of MINIMARS is over 1100 dpa or every atom is displaced 1100 times. The materials community does not yet know how to make materials last for much over 150 dpa even in fission reactors, so the entire inner

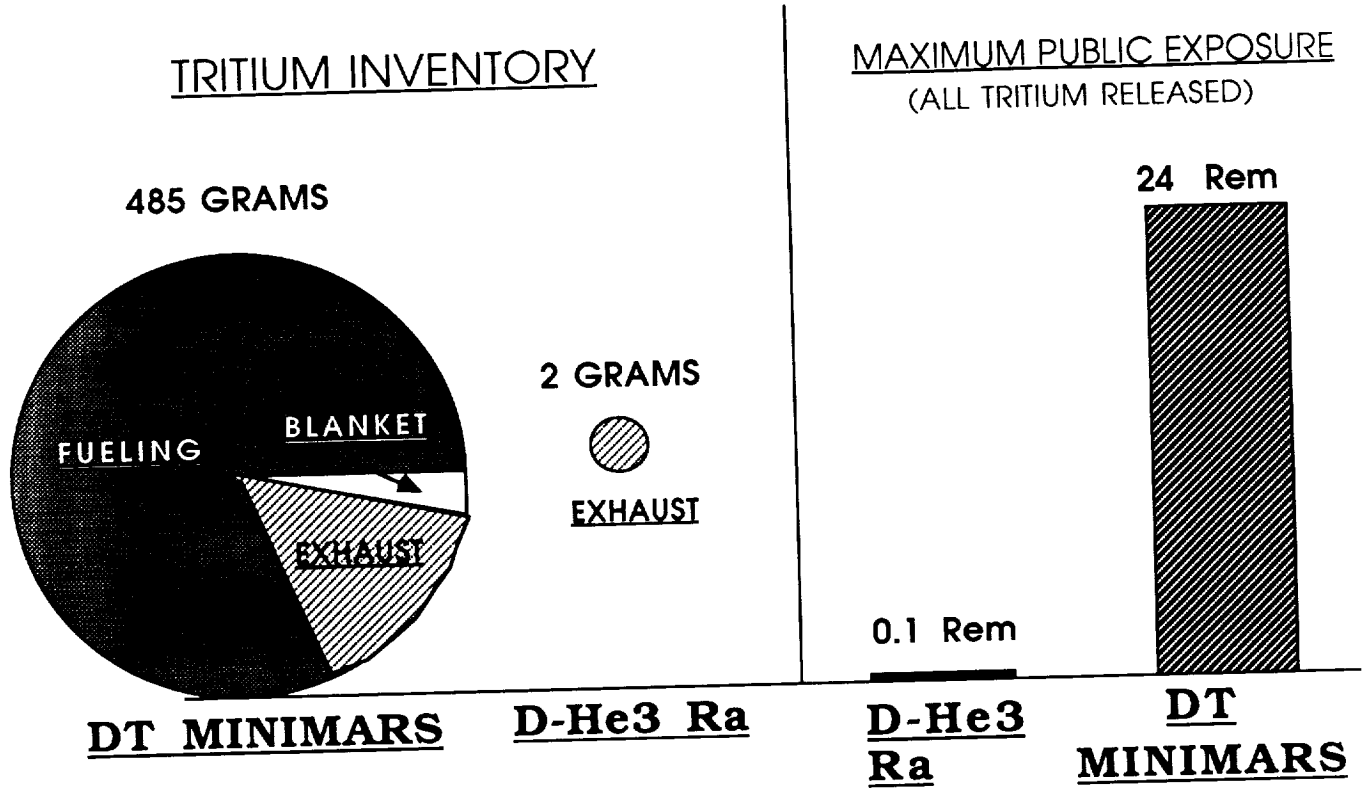

Fig. 5. Major safety differences between D-He^3 and DT-fueled 600-MWe reactors.

structure of the MINIMARS reactor must be replaced on the order of 5-10 times during the reactor lifetime. This causes loss of availability (higher electricity costs), as well as a larger volume of radioactive waste (see section on radioactive wastes).

On the other hand, it is found that in order to produce the same amount of electrical power, the components of the D-He^3 Ra reactor suffer only less than 20 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 6 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 from fission reactors. It is clear that the level of radiation damage produced in a DT reactor is much larger than anything that has been 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 one expects that a reactor can be constructed that will last the lifetime of the plant. This single feature alone, i.e., no need to have scheduled replacement of reactor components should increase the availability of the plant by ~5% (2-3 weeks per year) over DT fusion or fission reactors (which periodically require refueling). The much more benign reactor environment should also help in reducing the risk of failure in the metallic components of the reactor making it more reliable and increasing our confidence in its safety.

The presence of radioactivity in the reactor as well as in the coolant system requires strict personnel access control and greatly hampers any component replacement or maintenance procedures. Simple tasks that take minutes in a nonnuclear system can take days in a nuclear plant. Furthermore, repairs seldom can be made to vital components while the plant is running for fear of promoting an accident that could release radioactivity. The above situation is familiar to those associated with fission reactors and the short-term (days) radiation levels in a DT facility are not much different than those in a fission reactor. As shown in the section on radioactive wastes, the total radioactivity associated with the D-He^3 cycle is ~20 to 80 times less than in a comparably sized DT plant so that the radiation levels should also be correspondingly lower. There is no way to quantify how this reduced radioactivity will affect the availability, but it should increase it if there is less T_2 to worry about and the radiation from the structure is down by more than an order of magnitude.

The necessity to protect against thermal excursions in the event of an accident has resulted in very complicated and expensive emergency core cooling systems (ECCS) on fission reactors. The associated instrumentation and the need to periodically test the system has a negative effect on both the reliability and availability

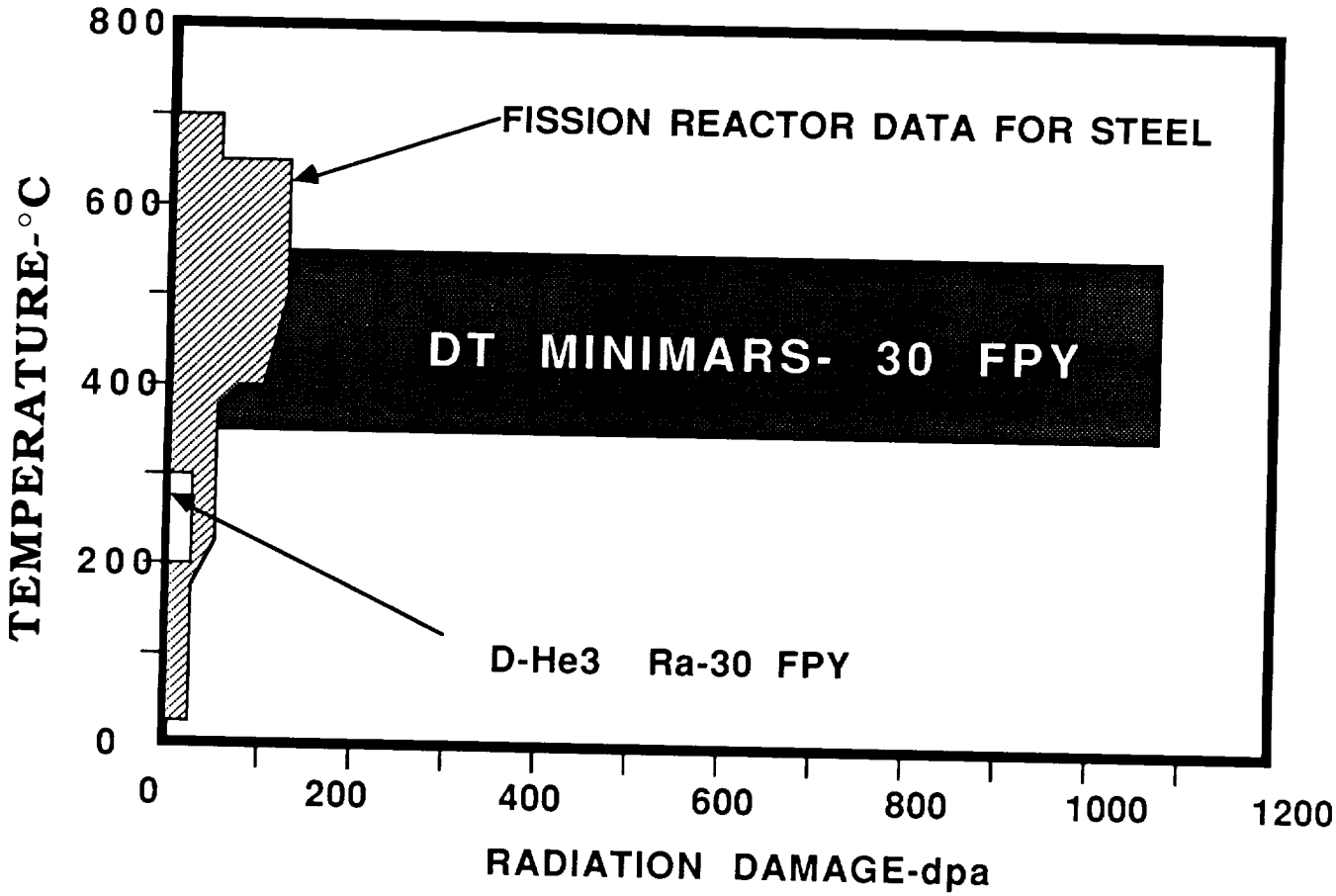

Fig. 6. Radiation damage in D-He^3 fusion reactors is much less than in DT systems.

of the reactor. DT fusion reactors will also require some form of cooling for specific components such as inboard magnetic shields in tokamaks, divertor plates, or limiters. However, the afterheat power densities are at least an order of magnitude less than in a fission reactor so that the time required to respond to an accident is correspondingly longer. This, coupled with the fact that the amount of harmful radioactivity that could be released in the event of a thermal excursion is lower, means that the emergency cooling system for a DT system can be less sophisticated.

On the other hand, the fact that a D-He^3 reactor does *not* need active cooling at all to prevent overheating means that fewer auxiliary systems and controls are required. This should mean that reliability is higher than in the DT reactor if all other systems are the same.

Finally, the need for several levels of containment to prevent a fatal release of radiation from fission reactors currently requires complex, costly, and sensitive control equipment having nothing to do with the primary function of generating electricity. The random failure of this equipment and the need to shut down the plant while it is being replaced is a current nuisance for some fission reactors in the U.S. Similar, although somewhat less sophisticated, equipment would be needed to guard against T_2 release from a DT power plant. However, the extremely low inventory of volatile radioisotopes (e.g., only a few grams of T_2) in a D-He^3 power plant should greatly relieve its operators from such complex and in-depth containment structures with corresponding increase in reliability of the reactor.

It is clear from the above discussion that the general lack of radiation damage, the low T_2 inventory, the lack of a need for an ECCS, and the much reduced containment requirements for a D-He^3 reactor should lead to a more reliable fusion power plant. This should also carry over to the availability for D-He^3 vs. DT reactors. Because fusion power plants may, in general, be more complicated than fission plants from a control standpoint, it is too soon to speculate on a quantitative advantage for fusion vs. fission.

Maintenance

It is difficult to speculate at this time on the degree of maintainability of a D-He^3 fusion power plant vs. fission reactors. Since fusion and fission reactors are so different in size, components, and environment (e.g., magnets, cryogenics, vacuum equipment, etc.), it is pointless to attempt any quantitative comparison until a fusion power plant is built. Nevertheless, if one compares DT vs. D-He^3 fusion reactors, one would be tempted to believe that the 1 to 2 order of magnitude reduction in radioactivity in the He^3 system should make it easier to maintain vital equipment. The lack of a need for any liquid metals in a D-He^3 system should also reduce the time necessary to get a coolant system ready for repairs. Finally, the fact that most of the energy could be converted to electricity with static equipment (as opposed to rotating equipment) and the large heat exchangers/pumps associated with a Rankine cycle should mean fewer failures and less need for maintenance.

It is probably safe to say that the maintainability of a D-He^3 fusion reactor is qualitatively better than a DT reactor but any speculation on fusion vs. fission is premature at this time.

Cost

It is obviously too early to calculate the absolute cost of electricity from any fusion power plant. However, the *relative* costs of the DT and D-He^3 fusion cycles can be compared with some confidence. The MARS (*Lawrence Livermore National Laboratory,* 1984), Ra (*Santarius et al.,* 1987) (1200 MWe version), and STARFIRE (*Baker et al.,* 1980) reactors serve to illustrate the advantages that lower neutron production and increased conversion efficiency can have. Using the same costing algorithms from the MARS and the MINIMARS studies, as well as other algorithms derived from the U.S. commercial tokamak reactor study program, a detailed cost breakdown of these systems is given in Table 4. The costs are given in 1986 dollars and are for a mature industry (i.e., not the first plant ordered).

The first part of Table 4 gives a brief summary of the operating conditions for both the tokamak (STARFIRE) and tandem mirrors (MARS and MINIMARS) reactors. All the plants are normalized to 1200 MWe and the same availabilities and construction times are assumed. The two major differences are the (1) much lower neutron wall loading in Ra (0.05 MW/m^2 vs. ~3-4 MW/m^2 in MARS, MINIMARS, and STARFIRE) and (2) much higher conversion efficiency to electricity for the D-He^3 Ra reactor (60% vs. 34-49% for the DT systems).

Because the charged particles can be directly converted to electricity with 80% or higher efficiencies, one can generate electricity from D-He^3 fusion reactors at roughly twice the efficiency from fossil or fission power plants (see Fig. 7). The DT and DD systems have only 20% and 50% respectively of their energy released in charged particles and therefore have lower overall efficiencies than for the D-He^3 case. However, the fusion systems are generally higher than the thermodynamically limited systems used in light water fission reactors (LWFRs) and fossil plants. The higher efficiency can significantly decrease the cost of electricity and has the additional benefit of reducing the size of the heat transport system, the turbine buildings, and the waste heat facilities, as shall be seen in the following analysis.

Some of the more striking observations that can be made from Table 4 are

1. The direct capital cost of a D-He^3 fusion reactor could be one-half that of DT tokamaks or DT tandem mirrors.
2. Building costs of a D-He^3 plant can be reduced because of the lower radioactivity and volatile T_2 inventory.
3. The lack of a T_2 breeding blanket and reduced magnet shielding in a D-He^3 system can greatly reduce the reactor internal cost.
4. The magnet costs of Ra are reduced over MARS because of the different end-cell physics configuration.
5. The extensive use of direct conversion results in a greatly reduced heat transport system, as well as much smaller turbine and electric plant costs.
6. Without adding in the fuel costs, the COE from the 1200-MWe Ra reactor is ~40% of the DT systems studied.

The question of He^3 fuel costs can now be addressed in a parametric fashion. Figure 8 shows how the COE in Ra varies with the cost of He^3. It can be seen that the COE increases approximately 1 ml per kWhr for every additional ~$80/g one is willing to pay for the fuel. It can be seen that the crossover point between DT and D-He^3 systems is at ~$2500-3500/g (or 2.5 to 3.5 billion dollars per tonne). Even though the COEs would be similar at that level, society would still reap the benefit of lower thermal pollution, much less radioactive waste, no need for deep geologic burial (or even Class C in some cases), greater safety assurances, and better reliability and higher availability. While the exact numbers should not be overemphasized at this time, the possibility of buying He^3 at several billion dollars (or more) per tonne should provide sufficient economic incentive to aggressively develop a commercial market for this fuel.

TABLE 4. Cost comparisons between DT and D-He^3 fusion reactor designs.

Key Parameters	STARFIRE	MARS	MINIMARS	Ra
Reactor Type	Tokamak	Mirror	Mirror	Mirror
Fuel	DT	DT	DT	D-He^3
Net Electrical Power (MWe)	1200	1200	1200	1200
Fusion Power (MW)	3510	2600	2295	2008
n Wall Loading (MW/m^2)	3.6	4.3	4.5	0.05
Net Conversion Efficiency (%)	30	42	38	60
Availability (%)	75	75	75	75
Construction and Licensing Time (yr)	6	6	6	6
Costs $M (1986$)				
Land	5	5	5	5
Building and Site	527	280	228	145
Reactor				
Internals	488	233	209	138
Magnets	261	558	107	180
Heating	55	113	158	106
Power Conditioning	89	96	†	181
Heat Transfer	138	457	138	34
Fueling	70	64	72	31
Instr. and Control	36	28	22	25
Maintenance Equipment	58	29	28	40
Turbine Plant	312	308	220	76
Electric Plant	178	179	81	91
Heat Transfer	67	9	32	16
Miscellaneous	62	37	41	36
Direct Costs (M$)	2345	2397	1342	1110
Total Capital Costs (M$)	3648	3658	2043	1690
O & M Costs (M$)	30	22	19	23
Repl. and Fuel (M$)	26	9	24	0
Capital Costs ($M/kWhr)	3040	3048	1702	1408*
Total Cost ($M/kWhr)	53	52	28	21*

* Fuel costs extra.
† Included in other accounts.

Data from *Kulcinski et al.* (1987).

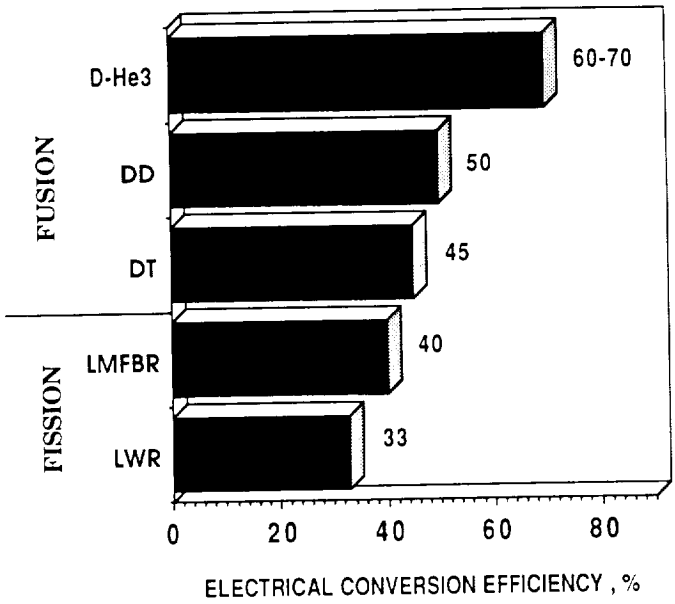

Fig. 7. Comparison of nuclear energy electrical conversion efficiencies.

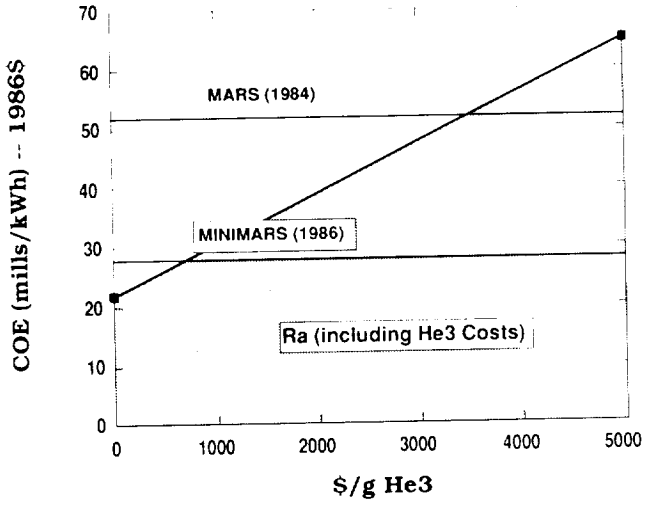

Fig. 8. Effect of He^3 costs on cost of electricity from fusion plants (1200-MWe versions).

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. For example, as shown in Fig. 6, the full lifetime exposure of a typical DT fusion first wall is over 1000 dpa. While it is not anticipated that the materials community would ever expect to develop a material that would last that long, economics dictate that the first wall life be at least ~10-15 MW-yr/m^2 (130-200 dpa). It is current engineering practice to extrapolate no more than a factor of ~3 from well-documented data in order to commit to building a facility. This would imply that data in the 40-70-dpa range from 14-MeV neutrons would be required. To date, the highest 14-MeV neutron exposure to any metal is less than 0.1 dpa and dramatically illustrates why materials test facilities will be needed for the DT system. In addition to materials test facilities, 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 Fig. 9.

On the DT side it begins with the CIT (*Schmidt et al.*, 1986) device scheduled for operation in the early 1990s. The main objective of this device is to demonstrate ignition of DT plasmas, presumably about the middle of the 1990s.

Plans to build an engineering test facility that would follow the CIT project are already underway in several countries (*Abdou et al.*, 1986). Using the generic name of an engineering test reactor (ETR) for this device, it can be seen that current plans call for construction in 1993 and operation in the late 1990s. 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 and accumulate ~30 dpa in test modules. 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 (Demo) that would integrate the plasma, materials, and full T 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. Finally, if all went well, a commercial facility would be built sequentially to the Demo, hopefully to be ordered by an electric utility. The total time from now until the first operation of this DT commercial unit could be 50 years or more.

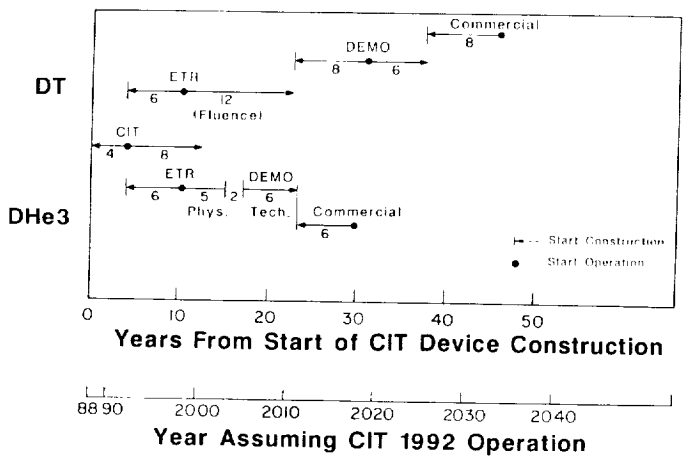

Fig. 9. Development scenarios for fusion.

On the other hand, if the experiments with the D-He^3 cycle in the ETR facility were to be successful, then an alternative 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, one does not need a long testing program for materials, and because there is no need to breed T, one does not need to test blanket concepts. Moving directly to a Demo on the same site by adding direct conversion and power generation equipment saves both time and capital investment. If the Demo can be successfully operated in an electricity producing mode for four to five years, the engineering community would then be ready to move on to a commercial unit. The overall time savings could 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 shall be seen later, because it determines when one would begin to require He^3 from nonterrestrial sources.

WHAT ABOUT He^3 RESOURCES FOR NEAR-TERM RESEARCH?

Thus far the question of fueling the near-term test reactors until a larger external source of He^3 fuel for commercial operation can be obtained has not been addressed. The answer lies with the terrestrial resources of He^3, which fall into two categories as shown in Table 5 (*Wittenberg et al.*, 1986). 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 5 shows that the underground U.S. strategic He storage caverns contain some 30 kg of He^3. If one were to process the entire U.S. resource of natural gas, another 200 kg might be obtained, 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 T ($t_{1/2}$ = 12.3 yr). When T decays, it produces a He^3 atom and a β particle. Simple calculations of the inventory of T in the U.S. thermonuclear weapons show 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 U.S.S.R. The equilibrium production of He^3 (assuming no future change in weapons stockpiles) is around 15 kg per year in each country. It may seem strange to rely on a by-product from weapons for a civilian application, but He^3 is commercially available today from just such a process. One can purchase up to 1.38 kg of He^3 per year directly from the U.S. government (10,000 l at STP), all of which comes from T decay. Obviously, considerably more is available and simple calculations of the T production from U.S. facilities at Savannah River indicate that T production is in the 10-20 kg/yr range. This would imply an "equilibrium" He^3 production rate of ~10-20 kg/yr minus losses in processing.

TABLE 5. Reserves of He^3 that could be available in the year 2000.

Source	Cumulative Amount (kg)	Production Rate after Year 2000 (kg/yr)
Primordial-Earth		
• U.S. helium storage	29	—
• U.S. natural gas storage	187	—
Tritium Decay		
• U.S. nuclear weapons	300	~15
• CANDU reactors	10	~12
Total	>500	~17

Note: 1 kg of He^3 burned with 0.67 kg of D yields 19 MW-yr of energy.

One could also get smaller amounts of He^3 from the T 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.

It should be noted again that 1 kg of He^3, when burned with 0.67 kg of D, produces approximately 19 MW-yr of energy. This means that by the turn of the century, when there could be several hundred kilograms of He^3 at our disposal, the potential exists for several thousand MW-yr of power production. The equilibrium generation rate from T resources alone could fuel a 300-MWe plant indefinitely if it were run 50% of the time.

Clearly, there is enough He^3 to build an ETR (few hundred megawatts running 10-20% of a year) and a demonstration power plant of hundreds of megawatts run for many 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 the year 2020. The next major question is whether one can get the He^3 fuel from the Moon on a timescale consistent with our development path.

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

Wittenberg et al. (1986) were the first to publish their discovery of He^3 in the regoliths on the Moon. 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 the solar wind. Using data that showed that the solar wind contains ~4% He 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 b.y. 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 surface of the regolith particles (0.1 μm). The fact that the surface of the Moon is periodically tilled as the result of frequent meteorite impacts results in the He being trapped in soil particles to depths of several meters.

Analysis of Apollo and Luna regolith samples revealed that the total He content in the Moon minerals ranges from a few to 70 wtppm (see Fig. 10) (*Cameron*, 1987). 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

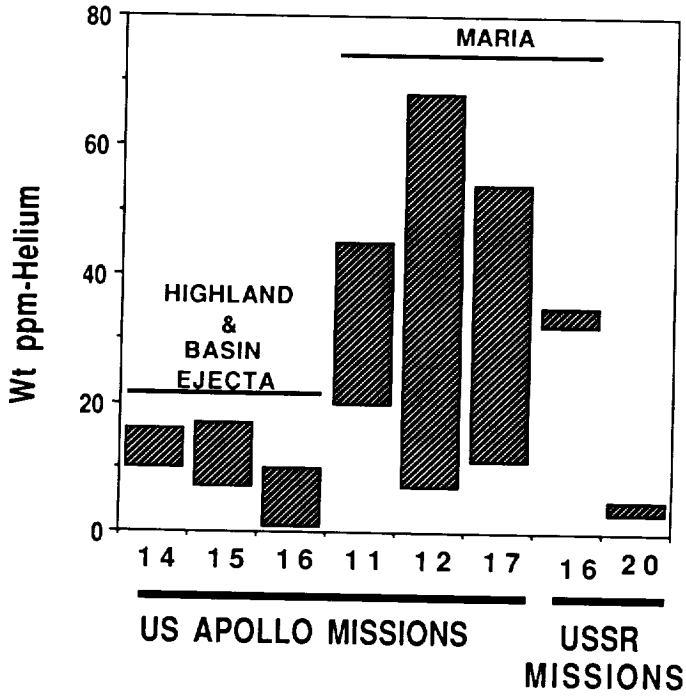

Fig. 10. Measured He content in lunar samples.

TABLE 6. He^3 content of lunar regolith.

Location	% Lunar Surface	Average He Concentration (wtppm)	Tonnes He^3
Maria	20	30	600,000
Highlands and Basin Ejecta	80	7	500,000
Total			1,100,000

calculated that roughly a million metric tonnes of He^3 are still trapped in the surface of the Moon (*Wittenberg et al.*, 1986) (see Table 6).

The next step is to determine the most favorable location for extracting this fuel. *Cameron* (1987) has shown (Fig. 11) 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 Tranquillity (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 Tranquillity would be the prime target for initial investigations of lunar mining sites. This one area alone appears to contain more than 8000 tonnes of He^3 to a depth of 2 m. A backup target is the TiO_2-rich basalt regolith in the vicinity of Mare Serenitatis sampled during Apollo 17 (*Schmitt*, 1973).

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 et al.* (1970) found that heating lunar regolith caused the He^3 to be evolved above 200°C, and by 600°C, 75% of the He gas could be removed (Fig. 12).

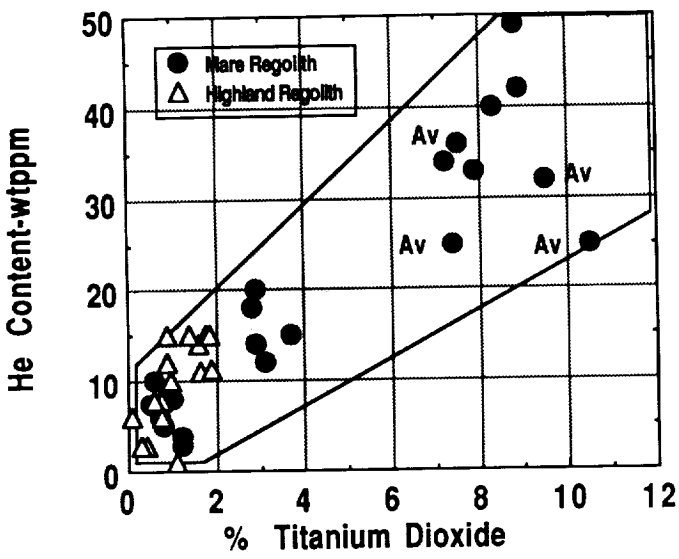

Fig. 11. Relationship between He content and TiO_2 in lunar regolith.

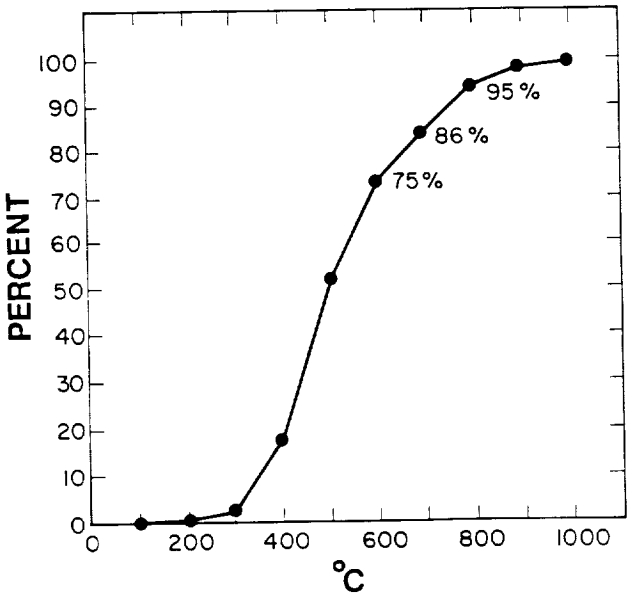

Fig. 12. He^3 evolution from lunar soil. Data from *Pepin et al.* (1970).

There are several methods by which the He could be extracted and a schematic of one approach is shown in Fig. 13 (*Sviatoslavsky*, 1988). 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 μm 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). After beneficiation, the concentrate is preheated by heat pipes and then fed into a solar-heated retort. At this point it is anticipated that heating to only 600 or 700°C is required and the volatiles (H_2, He^4, He^3, C compounds, and N_2) are collected with the spent concentrate being 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 one-sixth-g 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 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 He 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 (*Wilkes*, 1978).

For every tonne of He^3 produced, some 3300 tonnes of He^4, 500 tonnes of N, over 400 tonnes of CO and CO_2, and 6100 tonnes of H_2 gas are produced (see Fig. 14). The H_2 will be extremely beneficial on the Moon for lunar inhabitants to make water and for propellants. Transportation of that much H_2 to the Moon, even at $1000/kg (less than one-half of present launch costs), would cost ~6 million dollars. 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 growth, the C for manufacturing or atmosphere control, and the He^4 for pressurization and as a power plant working fluid.

HOW MUCH IS THE He^3 WORTH?

While it is hard to anticipate the cost of energy in the future, one can extrapolate these costs based 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-yr of potential thermal energy on the Moon. This is over 10 times more energy than that contained in economically recoverable fossil fuels on Earth. This amount of energy is also 100 times the energy available from economically recoverable U on Earth burned in LWRs on a once-through fuel cycle, or roughly twice the energy available from U used in LMFBRs.

The second point to note is that only 25 tonnes of He^3, burned with D in Ra-type reactors, would have provided the entire U.S. electrical consumption in 1986 (some 285 GWe-yr). The 25 tonnes of condensed He^3 could fit in the cargo bay of a spacecraft roughly the size of the U.S. shuttle.

A third point of interest is that in 1986 the U.S. spent over 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 25 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 that is economically worth bringing back to Earth.

An obvious question at this point is how much does it cost to obtain He^3 from the Moon? The answer depends on three things: (1) Will the U.S. develop a Moon base for scientific or other mining operations without the incentive of obtaining He^3?

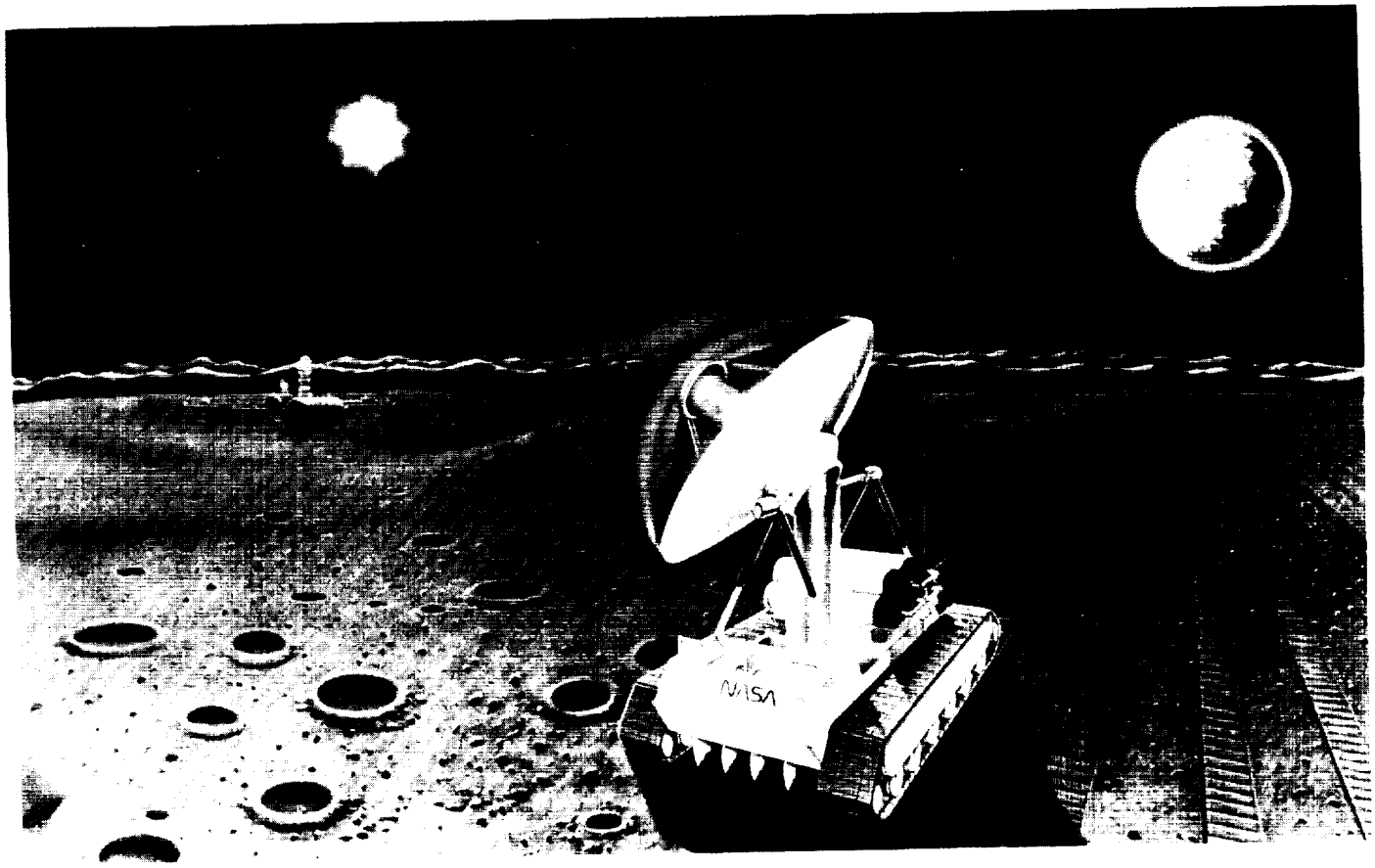

Fig. 13. Design of lunar vehicle to extract He^3 from regolith using direct solar radiation.

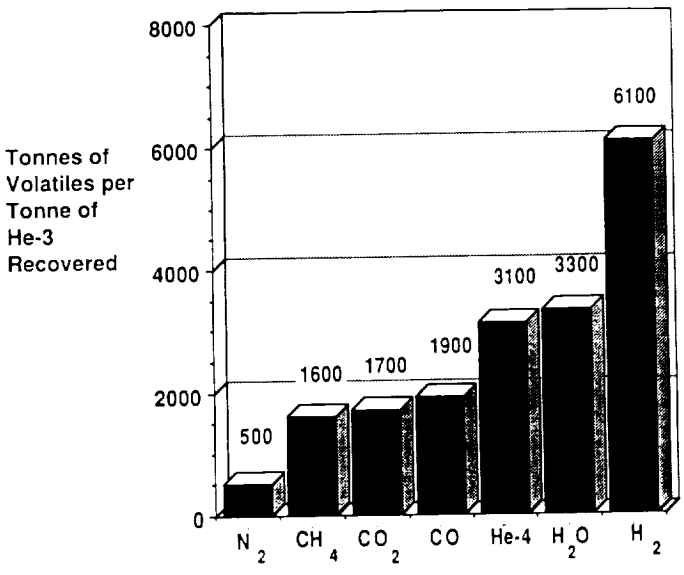

Fig. 14. By-products of lunar He^3 mining.

(2) If the answer to the preceding question is yes, then how much will the *incremental* costs of mining He^3 be after manned lunar bases are already in place? (3) How will the benefits of the side products be treated? For example, will one be able to "charge" the lunar colony for the H_2, N_2, He, or C compounds extracted from the lunar regolith?

The answer to question (1) is probably yes. In a report to NASA by *Ride* (1987), it was stated that one of the four major programs in NASA should be a return to the Moon and the establishment of a manned base early in the twenty-first century. This recommendation was made without any reference to the He^3 mining possibilities. At this time it appears reasonable to assume that the cost of returning to the Moon will be borne by the U.S. government as a general investment in science.

The answer to question (2) cannot be given at this time, but should be the subject of study in the near future. It appears, based on the mobile mining concept described earlier, that the equipment could be transported to the Moon for well under a billion dollars (e.g., at $1000/kg this would allow 1000 tonnes to be transported to the Moon). Operational costs should be well under a billion dollars per year even if everything has to be transported to the Moon and no use of lunar materials is allowed.

The possibilities of "selling" the by-products of the He^3 to lunar colonies is very intriguing. The by-products from mining just 1 tonne of He^3 would support the annual lunar needs of 1400 people for N_2 (food and atmosphere), 22,000 people for CO_2 used to grow food, and 45,000 people for H_2O. If the cost of transporting the equipment to extract these volatiles from the lunar regolith is written off against the savings in sending up life support elements such as H_2, N_2, or C for manned lunar bases, then it is possible that the cost of He^3 may in fact be negligible. If that were true, then the COE from D-He^3 fusion power plants would indeed be much cheaper than from DT systems (see Fig. 8 and Table 2) and possibly even from fission reactors (without taking credit for all the environmental advantages of this fuel cycle).

To answer the question posed by the title of this section, it is our opinion that a realistic figure for the worth of He^3 on the Earth is ~1 billion dollars per tonne. This would still allow D-He^3 fusion plants to be competitive with DT systems and provide adequate incentive for commercial retrieval from the Moon.

IS THE TIMETABLE REALISTIC?

It was shown in the section on the impact of the D-He^3 fuel cycle on electric power issues that no He^3 would probably be required from the Moon before 2015. A recent study by *Sviatoslavsky* (1988), using conservative U.S. energy growth rates (2%) and conservative penetration rates of fusion beginning with the first plant in 2015, resulted in the He^3 demand curve shown in Fig. 15. This demand results in the cumulative He^3 requirements shown in Fig. 16. It can be seen that the demand reaches the ~1 tonne per year level in 2030, 10 tonnes per year in 2032, and by 2050, a cumulative total of 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 (1986) shown in Fig. 17. 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 than 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 manufacturing colony on the Moon.

CONCLUSIONS

It is shown in this paper that the D-He^3 fusion fuel cycle is not only credible from a physics standpoint, but that its breakeven and ignition characteristics could be developed on roughly the same time schedule as the DT cycle. It was also shown that the extremely low fraction of power in neturons, the lack of significant radioactivity in the reactants, and the potential for very high conversion efficiencies, can result in definite advantages for the D-He^3 cycle with respect to DT fusion and fission reactors in the twenty-first century.

More specifically, the D-He^3 cycle can

1. Eliminate the need for deep geologic waste burial facilities and the wastes can qualify for Class A, near-surface land burial;
2. Allow "inherently safe" reactors to be built that, under the worst conceivable accident, cannot cause a civilian fatality or result in a significant (>100 mrem) exposure to a member of the public;
3. Reduce the radiation damage levels to a point where no scheduled replacement of reactor structural components is required, i.e., full reactor lifetimes (~30 FPY) can be credibly claimed;

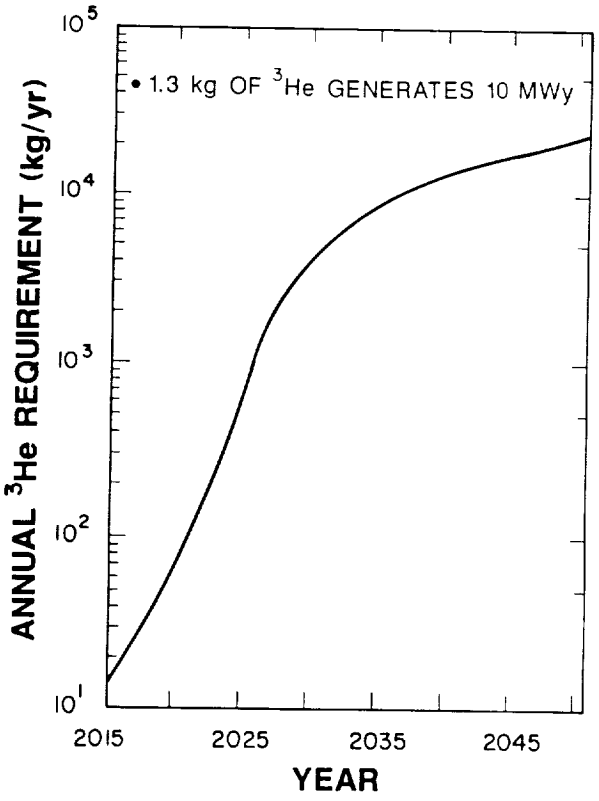

Fig. 15. He^3 demand curve.

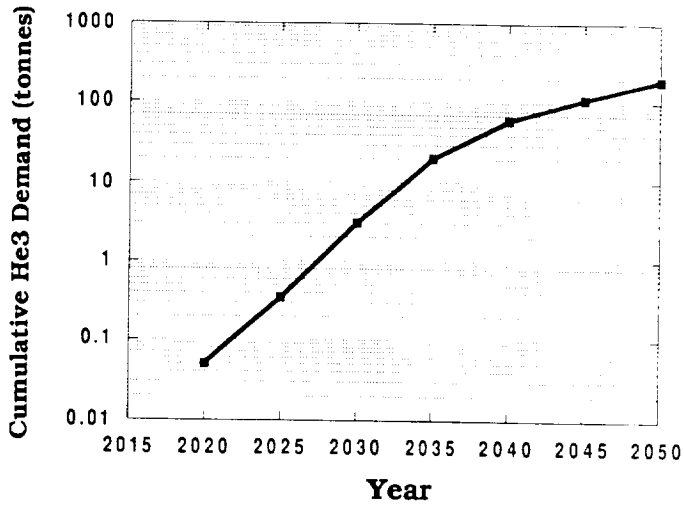

Fig. 16. Projected utility requirement for He^3 fuel.

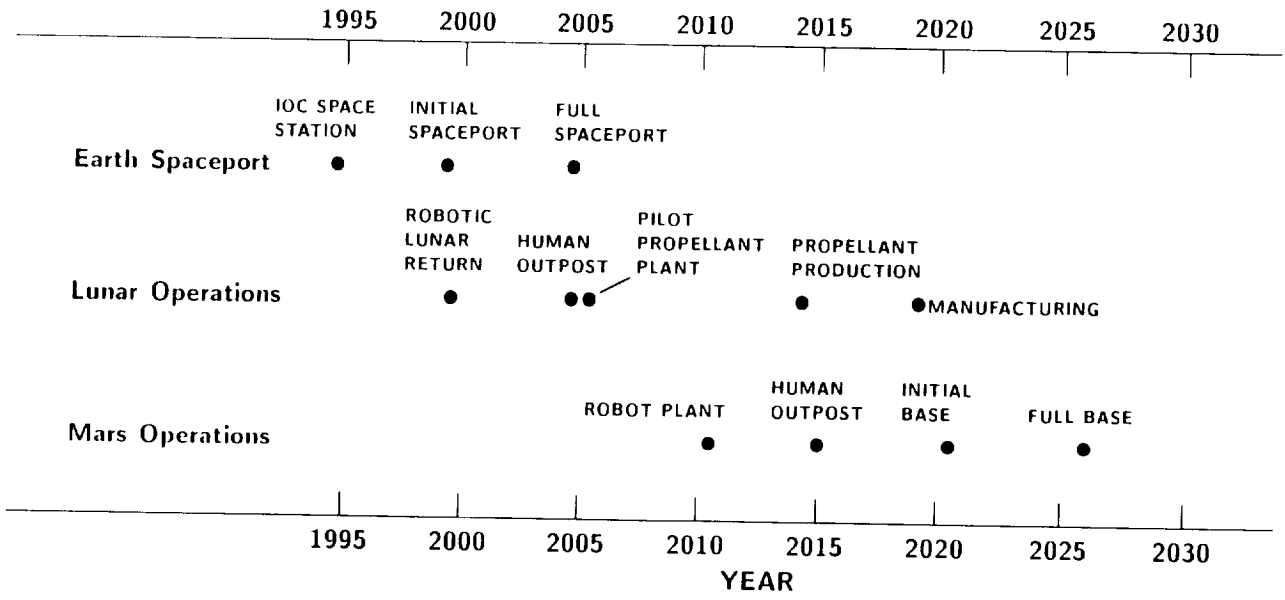

Fig. 17. Present plans for access to the inner solar system.

4. Increase the reliability and availability of fusion reactors compared to DT systems because of the greatly reduced radioactivity, the low neutron damage, and the elimination of T breeding; and

5. Greatly reduce the capital costs of fusion power plants (compared to DT systems) by as much as 50% and present the potential for a significant reduction in the COE.

Some key remaining questions are

1. Will the fusion community design future facilities such that they can validate the plasma physics scaling of both DT and D-He^3?

2. Can direct conversion concepts be tested in the near term for tandem mirrors or tokamaks to validate the high conversion efficiencies?

3. Will more detailed tokamak D-He^3 studies be performed to quantify perceived advantages relating to reliability, maintainability, and availability?

4. Will He^3 be extracted from lunar regolith at planned NASA bases in the early twenty-first century?

5. How much will it cost to obtain He^3 from the Moon with or without credit from other volatiles such as H_2, N_2, or C needed by manned lunar bases?

Finally, the concepts presented in this paper tie together two of the most ambitious high-technology endeavors of the twentieth century: the development of controlled thermonuclear fusion for civilian power applications and the utilization of outer space for the benefit of mankind on Earth. Given the talents and resources associated with these programs, it should not be surprising that this coupling has occurred. The main question now is how soon can these programs join forces to prepare for the needs of the twenty-first century?

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