



The Commercial Potential of D-He3 Fusion Reactors

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Abstract

Many fusion scientists consider the D-He3 nuclear fueled reaction as the best prospect for generating clean energy in the next century. Although somewhat more difficult to initiate than the DT reaction, it holds the promise of substantial reduction in radiation hazard, full lifetime reactor components, low decay heat, no T_2 breeding, class A waste disposal, and major safety benefits. Because of the potentially higher electrical conversion efficiency, there are also important economic benefits that can be achieved. The He3 can be obtained from the moon, where conservative estimates indicate that $>10^6$ tonnes of it is loosely bound in the lunar regolith. This paper describes the first estimates of the commercial prospects for the D-He3 reaction, a proposed development path, and the benefits such a fusion based economy can bring to mankind.

Introduction

The D-He3 fueled nuclear fusion reaction has long been recognized as one of the most attractive for generating clean fusion energy. Although aware of its virtues, fusion researchers had despaired of ever using it because they did not know where to obtain large amounts of He3. Recently [1], Wisconsin scientists, upon reviewing data on constituents of lunar samples, confirmed their suspicion as to the amount of He3 in lunar regolith. Helium-3 is produced in the sun via the proton cycle and is transported by the solar wind where it has been implanted in the lunar surface over four billion years. It is estimated that over one million tonnes of He3 are loosely bound in lunar regolith.

The outstanding feature of D-He3 is that neither the fuel nor the primary reaction products are radioactive



Unfortunately, side reactions from the deuterium component do produce neutrons but only at 1-3% that of the DT reaction [2], depending on the He:D ratio and the ion temperature (see Figure 1). The bulk of the energy (97-99%) comes out in the form of energetic charged particles and potentially can be converted directly to electricity at 70-80% efficiency. With sufficient confinement, D-He3 cycles allow up to 2/3 of the fusion power output to be in the form of microwaves [3] which can be coupled out of the reactor by low-loss waveguides, mitigating first wall and divertor heat loads.

The major attraction of this fuel cycle can be traced to its low neutron production. Several technological advantages immediately appear. These include: permanent first wall components versus periodically replaceable components, simple heat removing blankets versus breeding blankets, low after-heat versus the safety concerns associated with high afterheat blankets, and near surface waste disposal versus long term, deep geological deposition. Some advantages are difficult to quantify, such as the

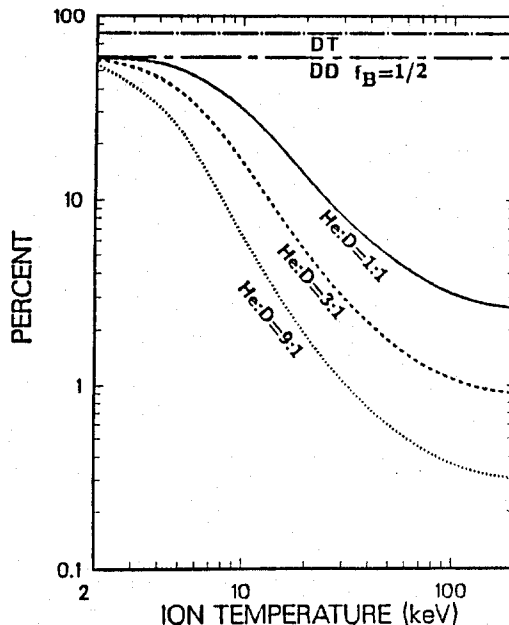


Figure 1. Neutron production in DT, D-He3 and DD.

effect on availability by virtue of not having to change out reactor components due to radiation damage. Eventually these advantages will be defined sufficiently to result in significant economic advantages.

On the other hand the D-He3 cycle requires a higher ion temperature, 50-60 keV as compared to 10-20 keV for DT and a higher nT_E product (by a factor of 4 to 6). Fueling D-He3 with pellets would be more difficult than DT systems, but plasma gun fuelling would work equally for both systems.

A more complete discussion of the physics [4] and technological features of D-He3 tokamaks is given elsewhere. The purpose of the rest of this paper is to concentrate on two items:

1. The first self-consistent cost estimates of a commercial D-He3 tandem mirror reactor, and
2. An analysis of a reasonable time scale for commercialization of D-He3 reactors and how this would fit in with proposed settlement of the moon.

Cost Estimates of Electrical Power from a D-He3 Fusion Power Plant

It is well known that engineers and economists have a poor record in predicting absolute COE (cost of electricity) values for future energy sources. We certainly do not claim to have the solution to that problem. However, relative cost estimates do have more significance when similar costing assumptions are used. It is in that vein that we focus the rest of this section.

We will use as a basis of the D-He3 costs the Ra [5] tandem mirror design. It is useful to compare the cost of electricity (COE) from Ra to that

Table 1

Cost Comparison of STARFIRE, MARS, MINIMARS and Ra (1986 \$)

Parameter	STARFIRE		MINI-	Ra
	MARS	MARS	MARS	D-He3
Fuel	DT	DT	DT	D-He3
Net Electric Power-MWe	1200	1200	1200	1200
Fusion Power-MW	3510	2600	2295	2008
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-y	6	5.75	6	6
Costs - M\$				
• Land	5	5.6	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 Cond. & Vacuum	89	96	**	181
• Heat Transfer	138	457	138	34
• Fueling	70	64	72	31
• Instrum. & Control	36	28	22	25
• Maint. Equip.	58	29	28	40
• Turbine Plant	312	308	220	76
• Electric Plant	178	179	81	91
• Heat Rejection	67	9	32	16
• Miscellaneous	62	37	41	36
Bare Direct Costs M\$	2345	2397	1342	1110
Total Capital Costs M\$	3648	3658	2043	1690
Specific Capital Cost \$/kWe	3040	3048	1702	1408
• O & M costs M\$/y	29	22	19	23
• Comp. Repl. & Fuel M\$/y	26	9	24	0*
Total Cost of Electricity - mills/kWh	53	52	28	21*

*No Fuel Costs (see text).

**Parts of this account included in Reactor Internals, Fueling and Heat Transfer

of the STARFIRE [6], MARS [7] and MINIMARS [8] reactor designs. Furthermore the results are all normalized to 1200 MWe and in 1986 \$.

The cost data from STARFIRE, MARS, MINIMARS and Ra are compared in Table 1. The information in Table 1 shows that the D-He3 tandem mirror reactor is over 50% lower in capital cost than either STARFIRE (tokamak) or MARS (tandem mirror), and 20% lower than the MINIMARS tandem mirror. This is attributable to the net effect of three items. The first is the net efficiency of Ra (60%) compared to 30% in STARFIRE, 42% in MARS and 38% in MINIMARS. However, this advantage is somewhat offset by the second effect--the lower power density of the D-He3 fuel cycle compared to the DT system. The third effect is a lower Balance of Plant (BOP) cost of the direct conversion cycle which accounts for the final advantage of the D-He3 fuel cycle. The MARS and the MINIMARS designs also have direct conversion in their power cycle, but it accounts for lower fraction of the total electric power output.

The operating costs are somewhat lower for D-He3 because of the permanent first wall life in Ra.

The resulting COE's in Table 1 show that the D-He3 cycle has significant advantage over the DT system before the fuel cost for He3 is included. The cost of the fuel, which is negligible in DT systems, can be significant in the case of D-He3. This is illustrated in Figure 2 where the COE for Ra is plotted as a function of He3 cost. It is calculated that about 100 M\$/tonne of He3 translates into 1 mill per kWh hr. On that basis, one could afford to pay 1 billion dollars per tonne of He3 before the COE of Ra would be equal to the COE of MINIMARS, and over 3 billion dollars per tonne to approach the COE of STARFIRE and MARS. It should be remembered that no credit has been given to Ra for a higher availability or for the reduced safety and licensing costs that should be associated with a low neutron producing fuel. A final observation is that a complete assessment of the COE from a D-He3 tokamak will also depend on how successful we are at finding a direct conversion scheme for tokamaks. However, even if all the energy is taken as heat it is expected that the COE of a D-He3 tokamak might be equal to STARFIRE and MARS without accounting for the much more favorable safety aspects.

EFFECT OF He-3 COSTS ON COST OF ELECTRICITY FROM FUSION PLANTS (1200 MWe VERSIONS)

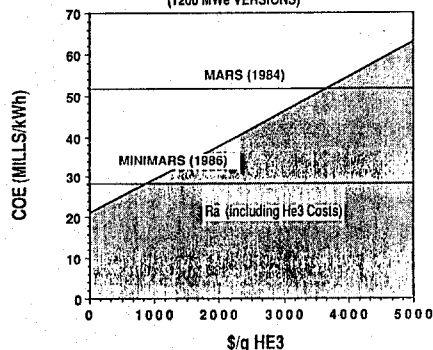


Figure 2. Cost of electricity in Ra as a function of He3 cost.

Schedule for Development of D-He3 Reactors and He3 Resources

One of the great advantages of the D-He3 fuel cycle is the fact that once it can be ignited, (see reference [9]), 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 the upper (DT) part of Figure 3.

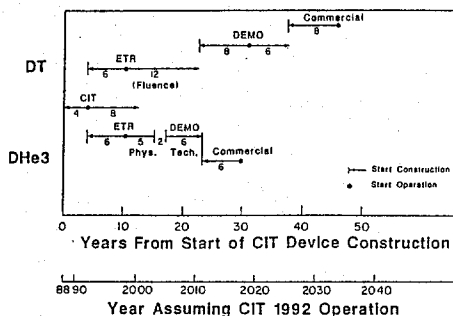


Figure 3. Development Scenarios for Fusion.

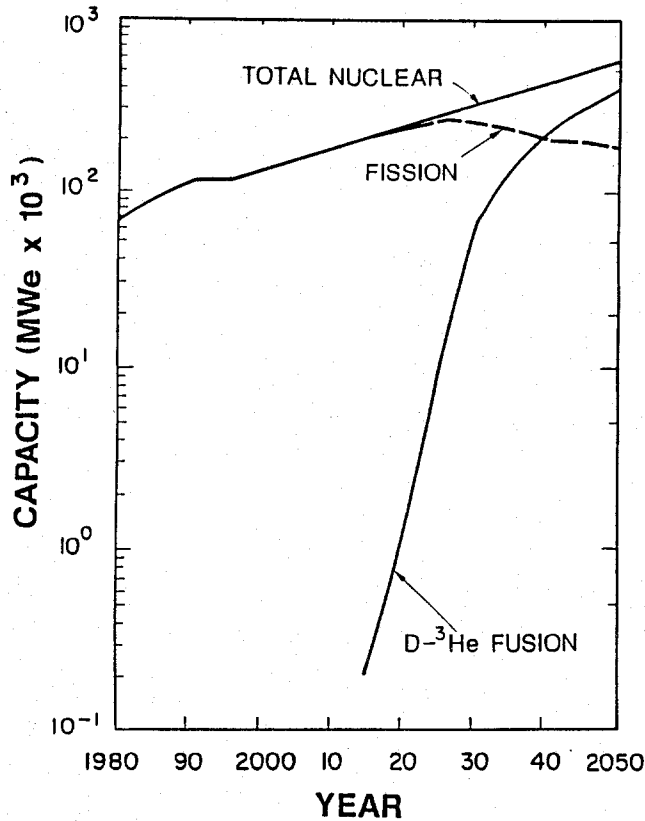


Figure 4. Nuclear electric plant growth and split between fission and fusion.

On the DT side it begins with the CIT [10] 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 an engineering test facility which would follow the CIT project are already underway in several countries [11]. 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 blanket modules that could be inserted into 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.

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-He3 cycle in the ETR facility were to be successful, then an alternate schedule could be pursued. Since the D-He3 fuel cycle causes much less induced

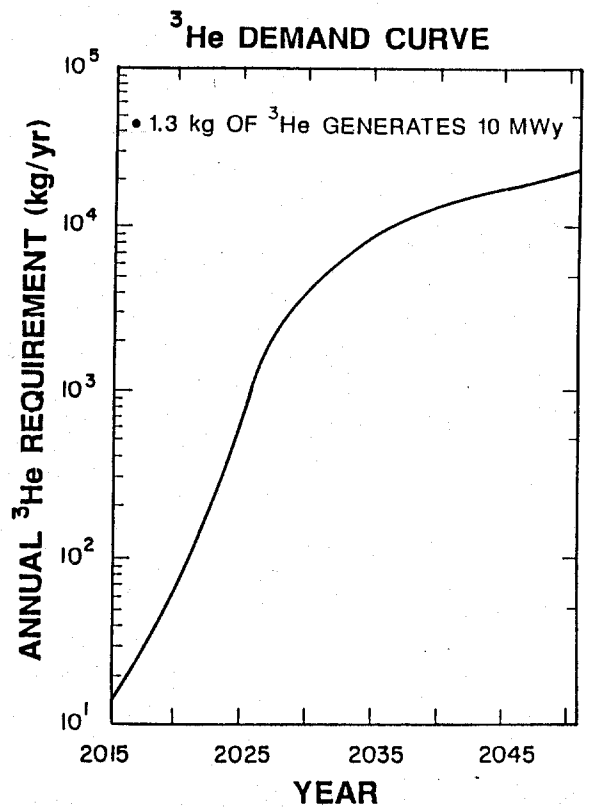


Figure 5. He3 annual demand curve.

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-He3 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 may well be the only way to have commercial fusion power reactors by the year 2020. This time period is important as we shall see next because it determines when we would begin to require helium-3 from nonterrestrial sources.

The next question we ask ourselves is how much He3 would we need on Earth and when? This has been studied by Sviatoslavsky [12] and only the results will be quoted here. The growth in U.S. electrical demand was conservatively assumed to be ~2% per year. Nuclear energy growth was held at 3% per year and geothermal/solar at 2% per year. No more fission plants will be commissioned after 2020 and the retired ones will be replaced by D-He3 plants with the first commercial unit operating in 2015. The rate at which fusion plants would be needed is shown in Figure 4. This growth was then translated into a He3 demand curve shown in Figure 5. The cumulative He3 demand is shown in Figure 6.

It can be seen from this analysis that the He3 demand could (optimistically) reach 1 tonne per year in ~2025, 10 tonnes per year in 2040, and ~20 tonnes per year by 2050. The cumulative amount of He3

liquid oxygen exporting operations from the Moon and even at optimistic reactor start dates and penetration rates, the transportation costs would be small compared to other space operations of a permanent base on the Moon.

Acknowledgements

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References

- [1] L.J. Wittenberg, J.F. Santarius and G.L. Kulcinski, "Lunar Source of He3 for Commercial Fusion Power," *Fusion Technology*, Vol. 10, No. 2, Sept. 1986.
- [2] G.L. Kulcinski and H.H. Schmitt, "The Moon: An Abundant Source of Clean and Safe Fusion Fuel for the 21st Century," 11th International Scientific Forum on Fueling the 21st Century, September 29 - October 6, 1987, Moscow, USSR.
- [3] G.B. Logan, "Economical D-He3 Fusion Using Direct Conversion of Microwave Synchrotron Radiation," *Fusion Power Associates Annual Meeting*, April 1986, Washington, DC.
- [4] B. Deng and G. Emmert, "High Aspect Ratio D-He3 Tokamak Reactors," *University of Wisconsin, 12th Symposium on Fusion Engineering*, October 1987, Monterey, CA.
- [5] J. Santarius et al., "Ra: A High Efficiency, D/He3 Tandem Mirror Fusion Reactor," *12th Symposium on Fusion Engineering*, October 1987, Monterey, CA.
- [6] "STARFIRE - A Commercial Tokamak Fusion Power Plant Study," ANL/FPP-80-1, September 1980.
- [7] "MARS - Mirror Advanced Reactor Study," UCRL-53480, Lawrence Livermore National Laboratory, July 1984.
- [8] J.D. Lee, editor, "MINIMARS Conceptual Design," Final Report, UCID-20773, Lawrence Livermore National Laboratory, September 1986.
- [9] G.A. Emmert et al., "Near Term Possibilities for Breakeven and Ignition of D-He3 Fusion Fuel in NET," *Fusion Power Associates*, August 1987, to be published.
- [10] T. Shannon, "The Compact Ignition Tokamak (CIT) Project Overview," *12th Symposium on Fusion Engineering*, October 1987, Monterey, CA.
- [11] J.F. Clarke, Opening Session Talk, U.S. Dept. of Energy, *12th Symposium on Fusion Engineering*, October 1987, Monterey, CA.
- [12] I.N. Sviatoslavsky, "He3 Demand for the Commercial Development of D-He3 Fusion," to be published.
- [13] National Commission on Space Report to the President.

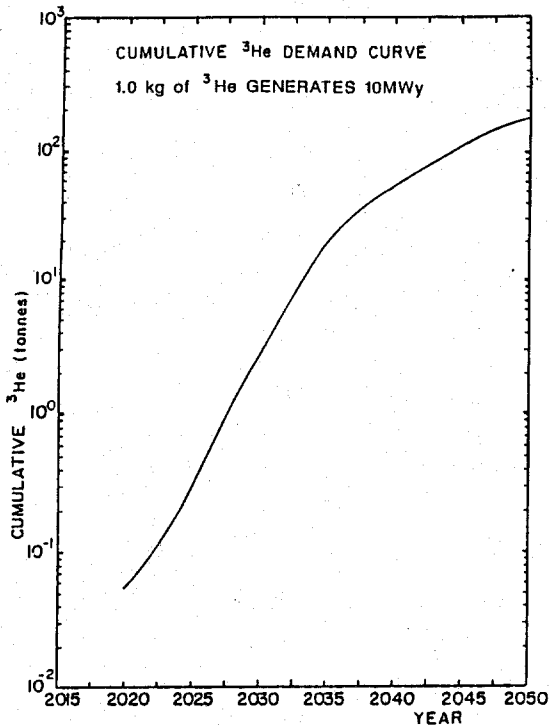


Figure 6. He3 Cumulative demand curve.

required by 2050 would (again optimistically) be ~ 200 tonnes. If each ship bringing liquified He3 from the moon carried 20 tonnes of payload (the size of the current U.S. shuttle) then only one flight per year would be required for transport and in the early years, the He3 would represent a small fraction of the payload.

It is impossible at this time to fix a cost for extracting and transporting He3 but preliminary studies at the University of Wisconsin indicate that costs in the 500 million\$/tonne range could result in significant profit without adversely affecting the COE from D-He3 power plants. Future reports in this area will quantify these numbers in more detail.

Finally, is it reasonable to think of lunar mining operations on the Moon by the year 2015? A recent report [13] to the President by the National Commission on Space calls for a permanently manned U.S. base on the moon by 2005 and ~ 500 tonnes per year production of oxygen for the space stations by the year 2015. If this schedule is met, then the ~ 1 tonne per year requirement of He3 by the year 2025 is reasonable.

Conclusions

The discovery of a large source of He3 on the Moon has opened new horizons for the D-He3 fuel cycle. The relatively low neutron production offers many advantages with respect to radioactivity, radiation damage, safety, efficiency, cost and possibly an even shorter development time to a commercial reactor. The procurement of He3 from the Moon would only be required after the U.S. intends to establish much larger