



Lessons Learned from Recent DHe3 Tokamak Power Reactor Studies

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Power Reactor Studies**

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Introduction

Previous papers in this Conference have described recent progress in the design of D-T tokamak reactors [1,2]. The thrust of this paper is a bit different in that it will address only the lessons that have been learned in the design of D-³He tokamak reactors. Unlike the previous work, scientists and engineers have only been working on advanced fueled tokamak reactors for less than 3 years [3-5] compared to more than the 20 years of experience developed on D-T tokamaks. Therefore one should expect that the *rate* of progress in the future may be higher for the D-³He systems than for the D-T.

Physics

The D-³He reaction is generally familiar to the scientific community (Figure 1). Even though both the reactants and the reaction products are not radioactive, a small amount of radioactivity comes from the DD branch. The recent Apollo [3-5] and ARIES [2] studies have quantified the form in which the energy is released and that is displayed in Figure 2.

Whereas the D-T reaction gives 80% of its energy in neutrons and roughly 10% each to photons and charged particles, the D-³He reaction gives up 75% of its energy in the form of photons, more than 20% in transport, and only a few percent in the form of neutrons even when the D/³He ratio is 2 to 1. The exact partitioning for the D-³He reaction will depend on the D/³He ratio, but the representation shown in Figure 2 is characteristic of what reactor designers have to deal with in a power reactor.

Before going any farther, it should be pointed out that even in present machines, scientists are getting valuable experience on the D-³He reaction. Recently, in JET, the world's record controlled thermonuclear energy release has been set, not with D-T, not with D-D, but with D-³He (Figure 3). Thus far, 140 kW of thermonuclear energy has been released in JET with no major surprises from what has been predicted based on previous experience from D-T physics devices.

In addition to present physics experiments, there have been two major D-³He tokamak reactor studies, the Apollo project [3-5], which started in 1988 supported by industry, and the ARIES project, which started in 1990 and was supported by the U.S. Department of Energy.

What are the major lessons that have been learned? First, it is evident that D-³He tokamak reactors will require high plasma currents. Figure 4 shows the level of tokamak plasma current, in mega-amperes (MA), both from a historical viewpoint and also from what should be accomplished in the next round of tokamak fusion facilities. It is obvious

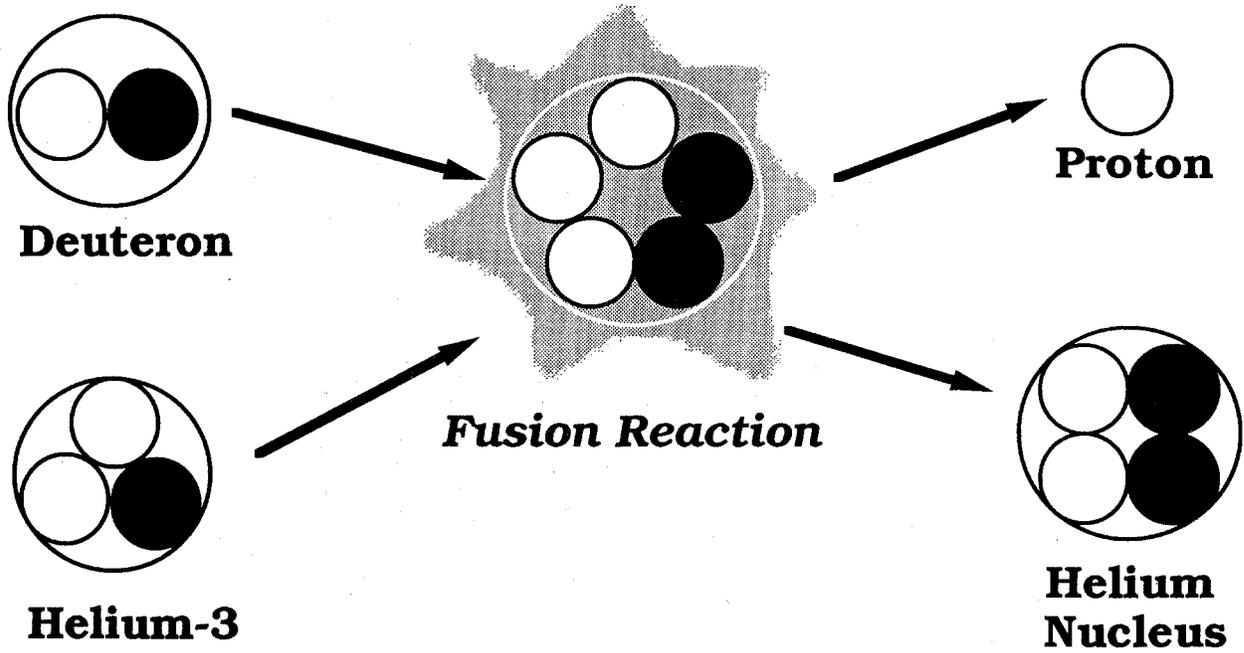


Figure 1. None of the fuel atoms nor the reaction products of the $D-{}^3\text{He}$ reaction is radioactive. A small number of side DD reactions do release neutrons.

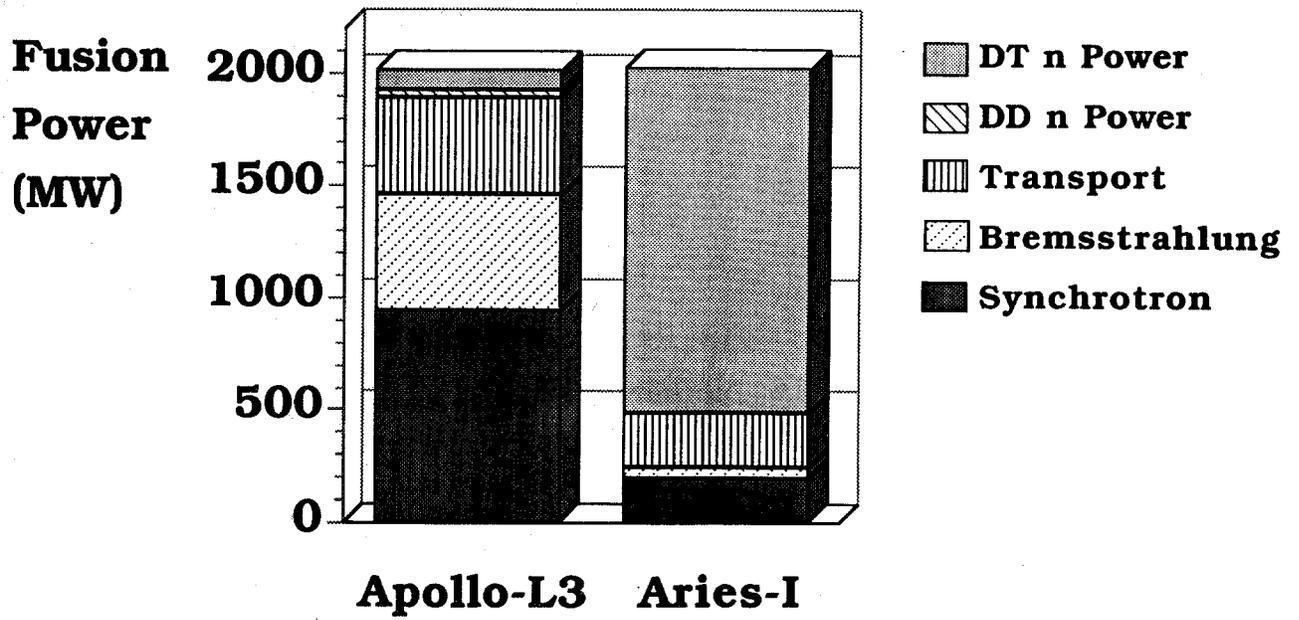


Figure 2. The energy released in D-³He reactors is dominated by photons.

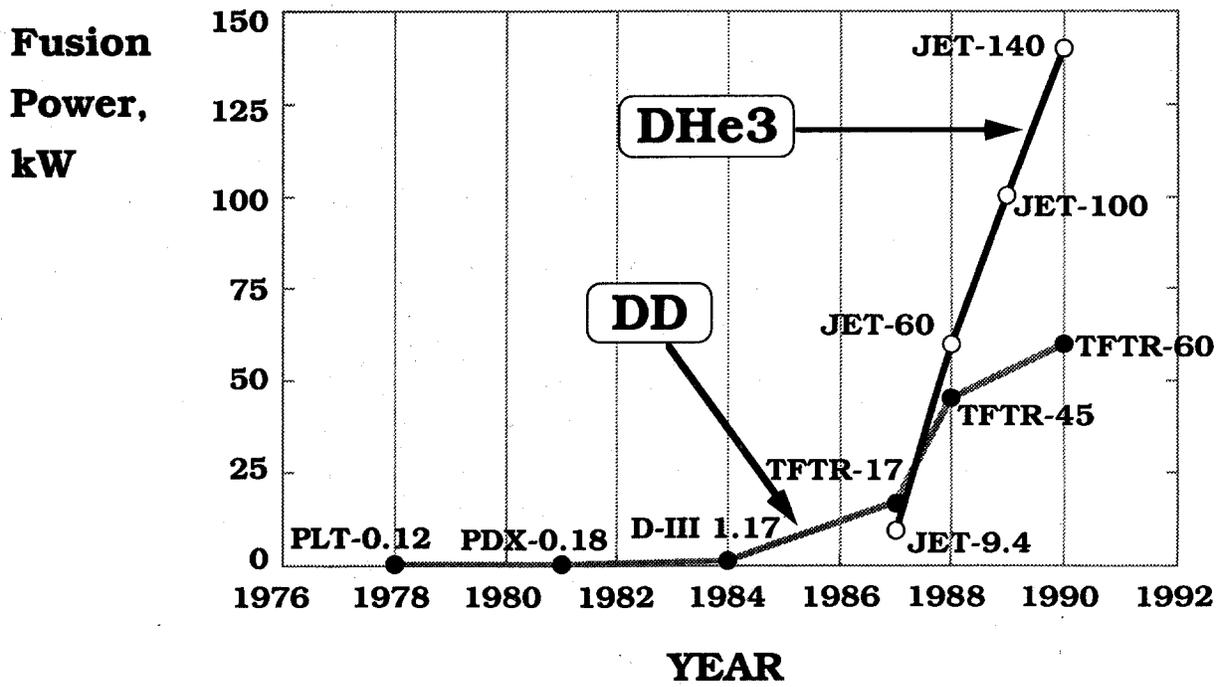


Figure 3. The world record for controlled thermonuclear energy release on Earth is from the D-³He reaction in JET.

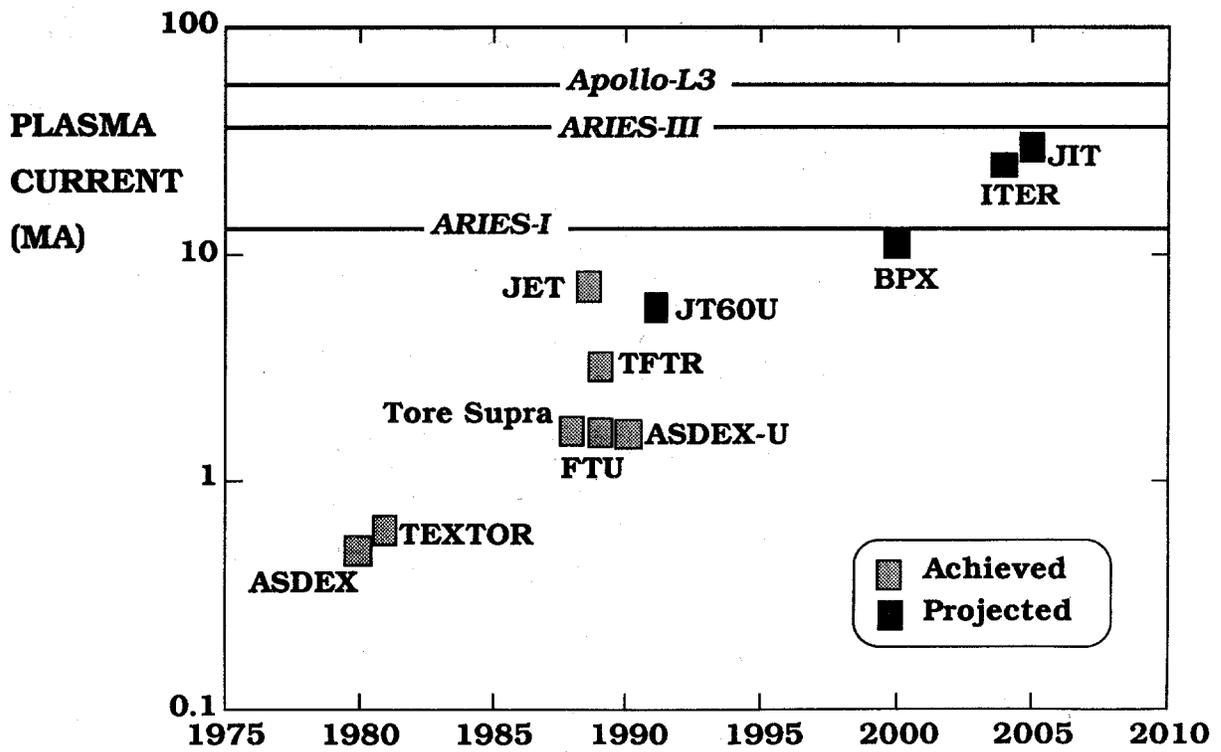


Figure 4. The historical and planned future levels of plasma current in tokamaks shows that they will approach D-³He reactor conditions by ≈ 2010 .

that the first stability ARIES-I tokamak will require relatively low currents (10-20 MA) while D-³He tokamaks will require from 40 to 50 MA depending on whether they are 1st or 2nd stability. The concern is obviously for disruptions and the ability to design a first wall to withstand them. One saving feature of D-³He reactors is that they do not have to breed tritium and therefore they can be designed in a much more rigid fashion. It is felt that from the Apollo designs [3-5], a blanket can be designed which will comfortably withstand a 50 MA disruption.

The next major lesson learned has to do with the H mode multiplier and the τ_p/τ_E ratios needed to have a reasonably performing D-³He plasma. It is evident that D-³He reactors need higher energy confinement times than D-T reactors. Fortunately, the requirements are about the same as values recently achieved in D-IIID [6]. Because particle confinement times typically exceed energy confinement times, fusion ash may dilute the plasma unacceptably unless the recent results on TFTR and TEXTOR L mode plasmas scale into the higher confinement regimes. Otherwise active pumping of fusion product ash will be necessary. However, if the L mode plasma behavior can be translated into H mode, then it is possible that the first stability D-³He tokamaks will perform quite well. A perspective on how the physics requirements of Apollo and ARIES-III compare with current experimental results is shown in Figure 5.

Other issues related to the first stability are the need to verify classical synchrotron current drive and to demonstrate that direct conversion of the synchrotron radiation via rectennas is possible. On the other hand, the 2nd stability operation requires a demonstration of 2nd stability, and the need to counter the bootstrap current overdrive requires a large amount of recirculating power.

Technology

Countering these physics difficulties are the advantages from the technological side (Figure 6). The lower number of neutrons produced per electrical watt from ³He will certainly result in much lower levels of radioactivity produced. In fact, the waste from 30 full power years of operation in a D-³He power plant can be easily treated as low level waste and disposed of in near surface land burial sites similar to the radioactive waste from hospitals.

Perhaps one of the greatest advantages of the D-³He cycle is the reduced radiation damage from neutrons. This advantage is apparent in Figure 6 where the operating temperature and displacement damage levels for two Apollo designs, ARIES-I, STARFIRE [7], and TITAN [8] are compared. Superimposed on Figure 6 is the estimate of the dpa/temperature regime in which a material will last for 30 full power years. Clearly, the D-³He plants will

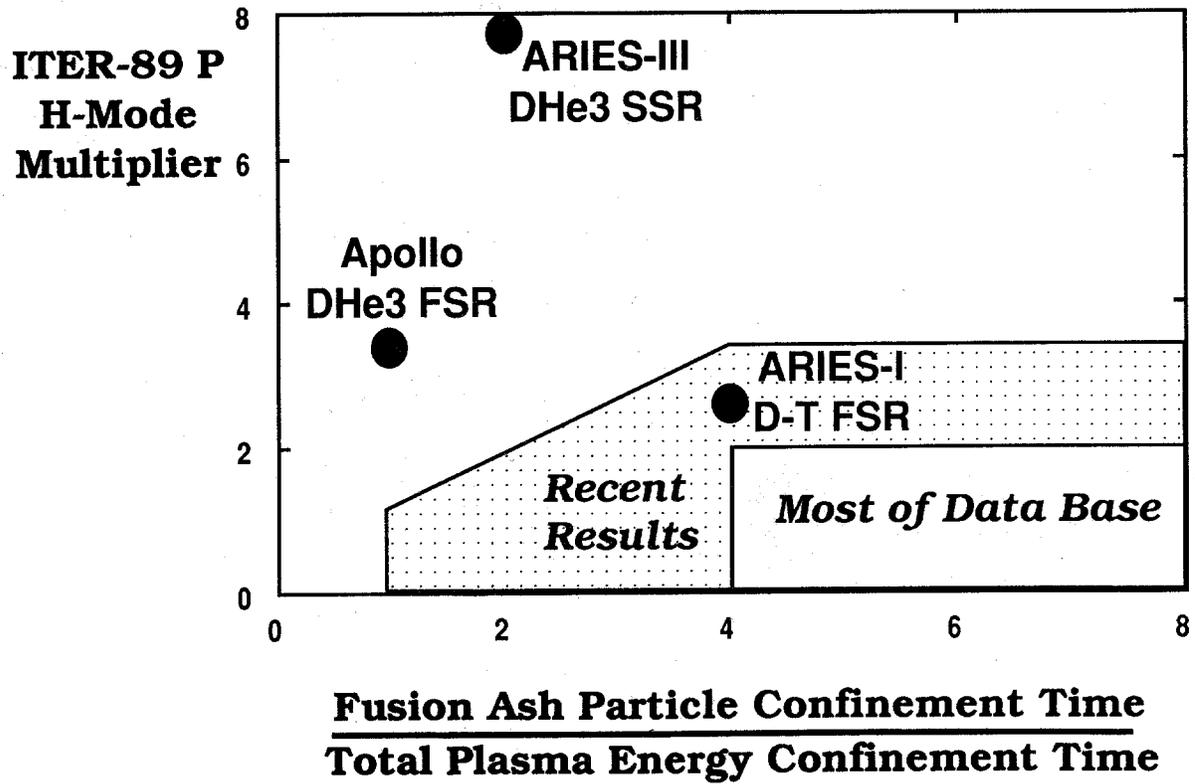


Figure 5. A comparison of the present database and two D-³He reactor designs (Apollo and ARIES-III) reveals the level of progress needed for power reactor operation.

- **Much Lower Radioactivity Than DT System**
- **Very Low Radiation Damage, i.e. Permanent FW**
- **Much Improved Safety, Inherently Safe**
- **Higher Net Efficiency**
- **Potential for Lower Cost of Electricity**

Figure 6. There at least 5 key technological features of D-³He plasmas that makes them extremely attractive for the generation of safe and clean fusion power.

be able to operate for the entire design lifetime without scheduled downtime for first wall replacement. The will have safety as well as economical advantages over a DT system. The increased availability will be on the order of 5 to 10% higher than for a DT system which will translate into a 5–10% lower cost of electricity.

The fact that a D-³He power plant does not need to breed tritium, coupled with a much lower inventory of radioisotopes, will result in a dramatically safer plant than is achievable with a DT system. There is some tritium produced by DD reactions in the plasma, and those end up in the plasma exhaust or buried in the divertor or first wall region of the reactor. Figure 8 illustrates that the total tritium inventory in an Apollo-like reactor is on the order of ≈ 10 grams, on the order of 100 to 1000 times lower than the realistic inventories of a DT power plant. Even if all the tritium were released in an accident, the exposure at the fence would be far less than 1 millirem to anyone at the fence (less than half of the increased dose received by anyone on a transatlantic flight). Another example of the increased safety associated with this fuel cycle can be found in a paper by Brereton and Kazimi [9]. Figure 9 is extracted from reference 5 and it shows that in addition to lower radioactivity and lower tritium inventory, there is a greatly reduced afterheat level and consequently, a lower temperature in the first wall in the event of a LOCA.

Another advantage of the D-³He cycle is that essentially all of the energy released can be converted directly to electricity. The charged particles, which comprise roughly 25% of the power in a tokamak, can be converted to electricity at $\approx 80\%$ and the photons, which make up $\approx 75\%$ of the power, could be converted by rectenna at 70–80%. This means that the overall net efficiency of a D-³He power plant could be in the 50–70% range depending on the amount of current drive or heating required. This advantage will translate into lower cost electricity and offsets the higher costs associated with high field magnets and higher plasma currents.

The overall costs of a D-³He power plant should be less, or at the most equal to the costs of a DT power plant before waste disposal and licensing delays associated with a DT plant are considered. This is illustrated in Figure 10 where the cost of electricity (COE) for Apollo (1st stability D-³He), ARIES-I (1st stability DT) and ARIES-III (2nd stability) are compared. From Figure 8 it is apparent that at the level of knowledge today, the advanced fuel systems are at the least competitive if not slightly more economical than DT reactors.

Overall Observations

To summarize the current situation with the use of D-³He in terrestrial fusion power plants, it is convenient to compare the major factors governing the success of any commercial power plant. Figure 11 makes that comparison to DT in terms of Harder/Similar/Easier.

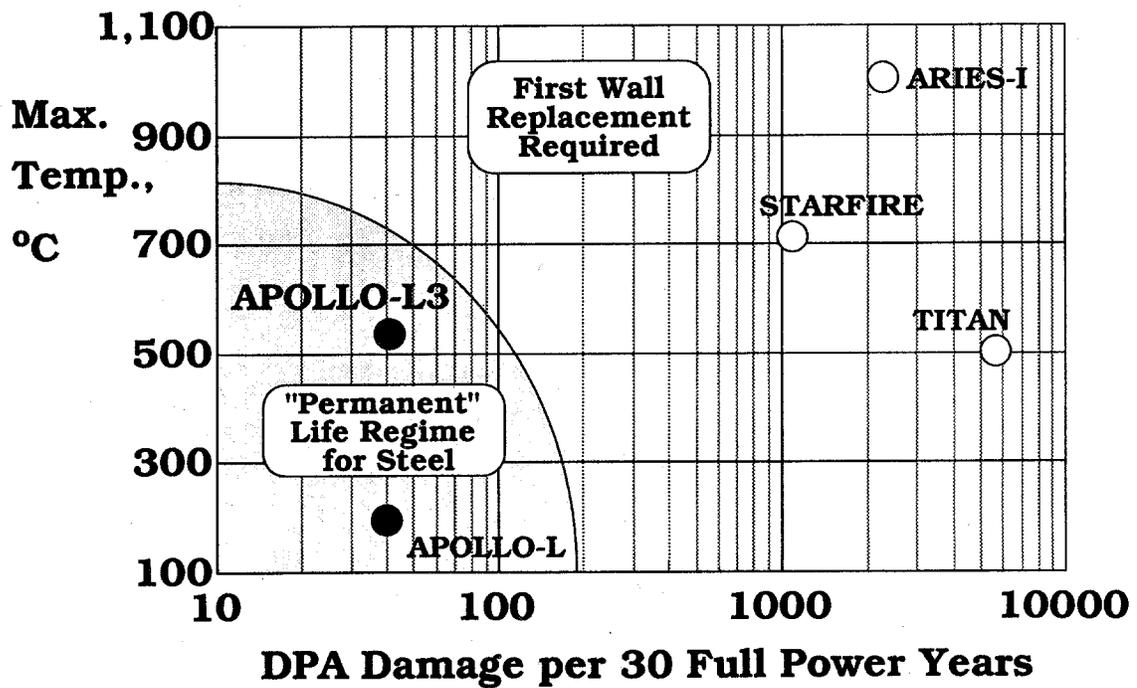


Figure 7. The low levels of radiation damage in D-³He reactors allow permanent first walls to be designed. They should allow D-³He reactors to have much higher availabilities than corresponding DT reactors.

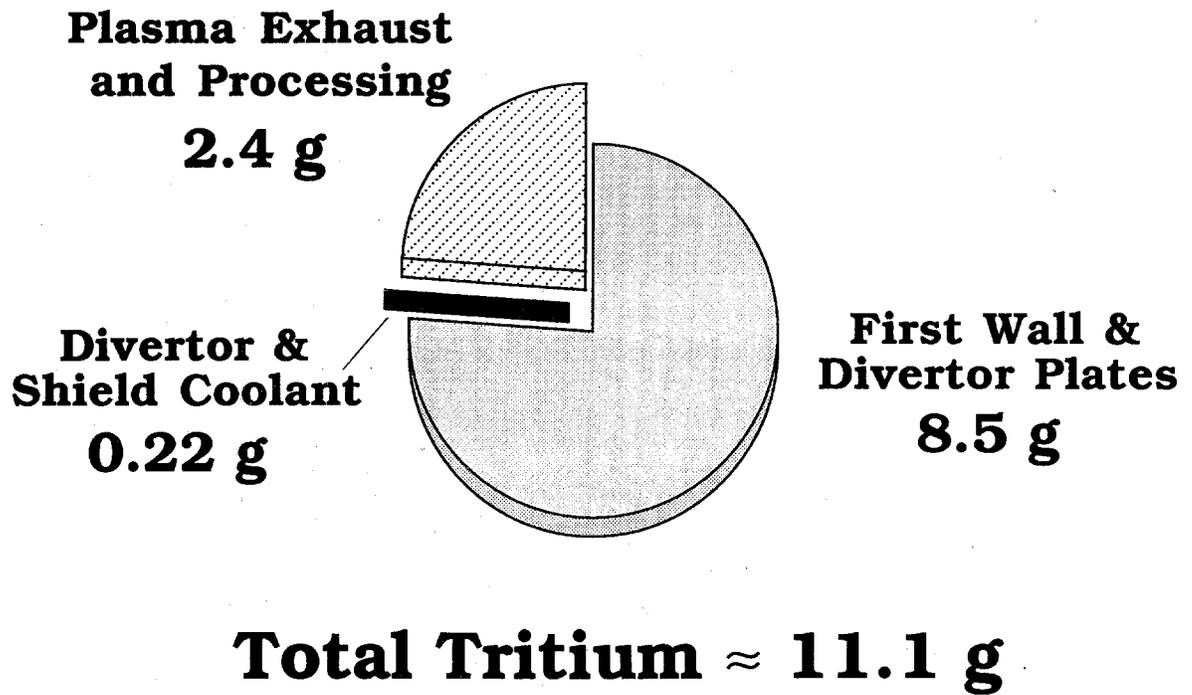


Figure 8. The tritium inventory in Apollo-L3 is very low with less than 3 grams in an active system.

	<u>DT</u>	<u>DHe3</u>
T₂ Inventory (MCi)	50	0.7
T₂ Release to Atmosphere (Ci/y)	5720	85
Offsite T₂ Dose (mrem/yr)	4.7	0.047
Total Decay Heat End of Life (W/cm³)	0.197	0.009
FW Temperature 10 hr of LOCA (°C)	780	480
FW Crit. Dose at Site Boundary (mrem)	29	0.005

Figure 9. Studies at MIT [9] illustrate the superior safety advantages of D-³He vs. DT.

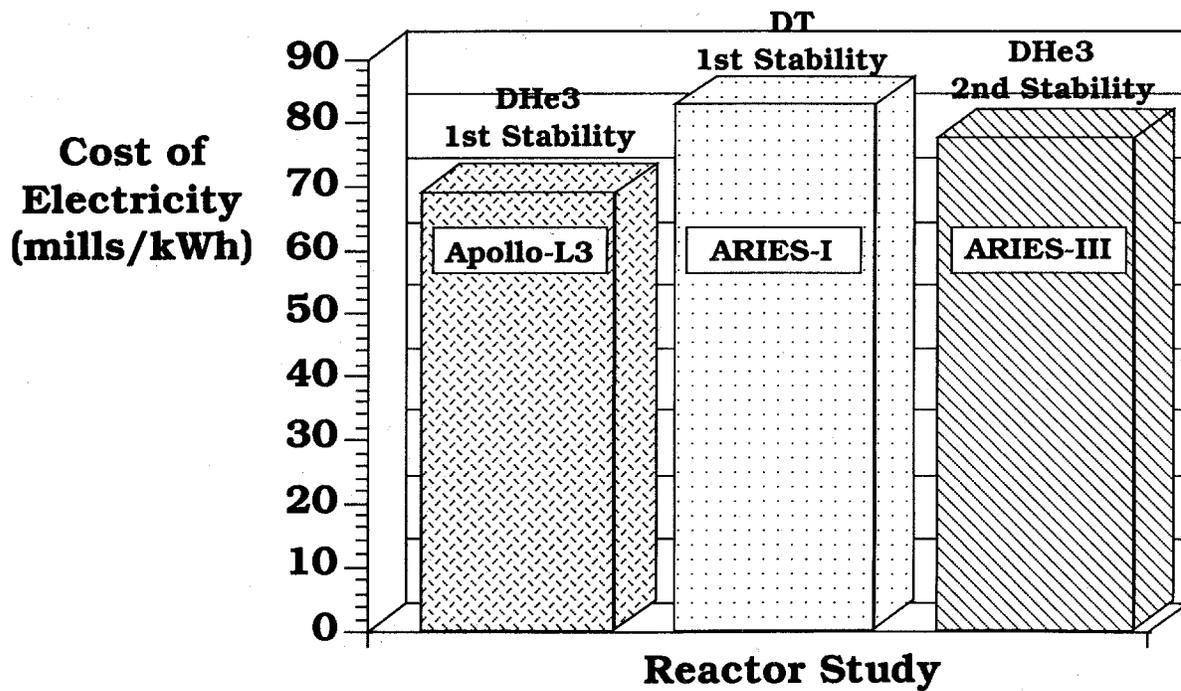


Figure 10. The cost of electricity from D-³He fusion reactor designs (Apollo-L3 and ARIES-III) is less than from the most recent DT reactor design (ARIES-I).

	Harder	Similar	Easier
Physics			
Fueling			
Heating			
Current Drive			
FW Heat Flux			
Materials			
Higher Eff. Operation			
Safety			
Environment			
Licensing			
Decommissioning			

Figure 11. The much easier technology requirements for D-³He more than offset the more difficult physics requirements.

While it is admitted that the physics and fueling of a D-³He reactor is harder than a DT system, this is more than balanced by the much easier technology items of Materials, High Efficiency, Safety, Environment, Licensing, and Decommissioning. The technologies associated with Heating, Current Drive, and First Wall Heat Fluxes appear to be of equal difficulty.

Possible changes to the U.S. fusion program needed to take advantage of the D-³He fuel cycle are listed in Figure 12. In the near term (1991–2), it is important to investigate how the D-³He fuel cycle will perform in current devices like TFTR, JT-60U, and JET, as well as in the current designs of BPX and ITER. Next, the goal should be the possible modification of BPX and/or ITER to enhance the performance of D-³He (as well as DT). In the near term, it is also important to form a liaison with NASA to investigate both the fuel supply issue and to examine the possibility of using fusion power for propulsion in space. It has been shown that D-³He rockets could develop specific impulses of over a million seconds [9] compared to ≈ 800 seconds for our best fission rocket of today. In effect, fusion could be to space travel what the fission reactor was to the submarine.

In the mid-term (1992–2005), it is possible that with slight changes in BPX or ITER, one might be able to demonstrate breakeven and ignition in a D-³He plasma. It should also be possible in that time period to investigate the use of high beta magnetic confinement schemes for D-³He plasmas. It is well known that because of the low beta nature of tokamaks, such a configuration may not be the most attractive for D-³He fuel. Finally, in the long term (2005–2015), it may be possible to modify the ITER device into an electricity producing demonstration plant. This might be accomplished with a minimum delay and with basically the same ITER facility because of the low induced activity of the ³He fuel cycle. If there is success with high beta systems, then small (100's of MW) demonstration reactors could be constructed in this time period. All of these technology demonstrations could occur on the same (or even earlier) time scale as those now scheduled for the DT cycle.

Conclusions

In conclusion, the advantages of the D-³He fuel cycle are compelling but the challenges are great (Figure 13). The economics of a fusion power plant with a permanent first wall, especially in terms of availability and reliability, should translate into an attractive future option for society. The safety and environmental features of this type of power could make this energy source irresistible for a world choked by pollution and racked with wars over the remaining scraps of fossil fuel energy. These advantages will not come free; the physics in terms of higher $n\tau T$'s, larger plasma currents, ash removal requirements, and the need to use fuel from settlements on the Moon (which should be in place long before we need ³He for

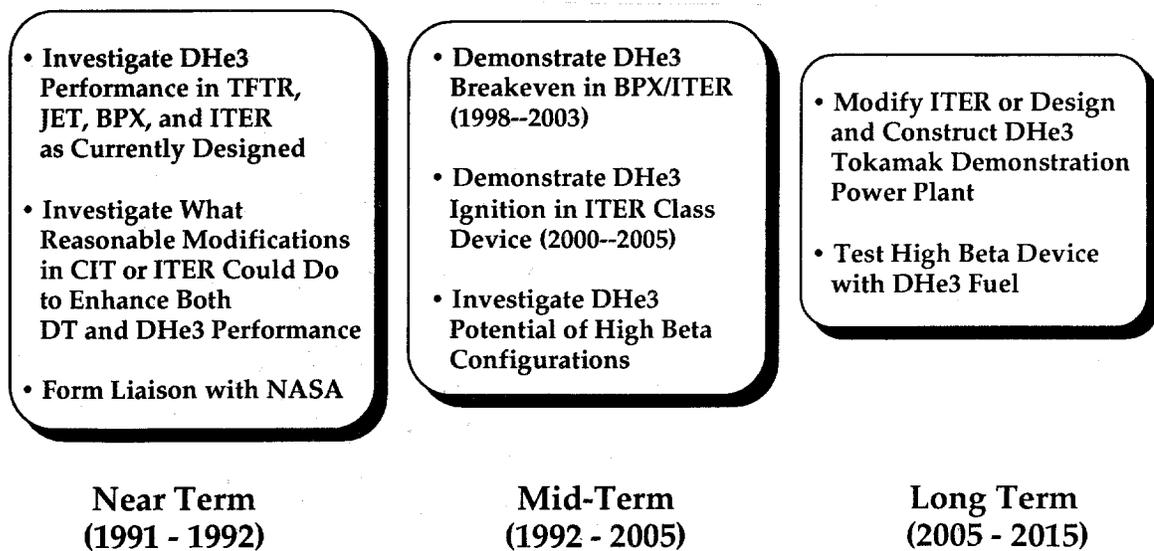


Figure 12. There are several near, mid- and long-term modifications to the U.S. fusion program that could be made to take advantage of the D-³He fuel cycle.

Advantages are Compelling

- **Permanent First Wall**
- **Availability/Reliability**
- **Environmental**
- **Safety**

Challenges are Great

- **Higher $n\tau T$**
- **Larger Plasma Current**
- **Ash Removal**
- **Fuel Procurement**

Figure 13. The conclusions of recent D-³He reactor studies make it clear that while the challenges are great, the advantages may be compelling to develop this new energy source.

power reactors) are all problems that need to be solve in the next 20 years. The benefits to mankind surely will overweigh these latter problems and the nation, or nations who develop this energy source will have an important strategic advantage in the 21st century.

Acknowledgement

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