A Strategy for D-^{3}He Fusion Development

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A Strategy for D-^{3}He Fusion Development

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INTRODUCTION

This paper presents a strategy for the development of D-^{3}He fusion for terrestrial and space power. The approach relies on modest plasma confinement progress in alternate fusion concepts and on the relatively less challenging engineering, environmental, and safety features of a D-^{3}He fueled fusion reactor compared to a D-T fueled fusion reactor. The D-^{3}He benefits include full-lifetime materials, reduced radiation damage, less activation, absence of tritium breeding blankets, highly efficient direct energy conversion, easier maintenance, and proliferation resistance.

The deuterium-tritium (D-T) tokamak dominates today's fusion research planning, but the question of whether conventional tokamaks, such as the International Thermonuclear Experimental Reactor (ITER), lie directly on the path to economic fusion power remains open. The present paper explores a strategy that requires further physics progress but reduces the obstacles on the engineering and safety paths.

This strategy begins with an intense, simultaneous research effort on proof-of-principle physics experiments of modest cost, and it progresses, with substantial winnowing, through integrated test experiments, burning plasma experiments, and a demo. The strategy aims to develop at least one innovative confinement concept capable of high β (plasma pressure/magnetic-field pressure) and suitable for burning the combination of deuterium and helium-3 (D-^{3}He) fuel. Such concepts include the field-reversed configuration (FRC), spheromak, spherical torus (ST), dipole, magnetized-target fusion (MTF), reversed-field pinch (RFP), and possibly others. Notable non-magnetic concepts in this context include fast-ignitor inertial-confinement fusion and inertial-electrostatic confinement (IEC) fusion. The strategy's foundation lies in the recognition that D-^{3}He fusion's greatly reduced neutron production compared to D-T fusion should significantly speed engineering development, as discussed in Section *Engineering, Safety, and Environment*. An overview of physics issues for D-^{3}He fuel appears in Section *Physics*. Section *Fuel Supply* addresses the source of ^{3}He fuel, which is rare on Earth. Section *Development Path* delineates the development path time frame and structure of the decision tree.

PHYSICS

The main fusion fuels are:

$$D + T \rightarrow n\ (14.07\ \text{MeV}) + {}^4He\ (3.52\ \text{MeV})$$
$$D + D \rightarrow n\ (2.45\ \text{MeV}) + {}^3He\ (0.82\ \text{MeV})\ \{50\%\}$$
$$\rightarrow p\ (3.02\ \text{MeV}) + T\ (1.01\ \text{MeV})\ \{50\%\}$$
$$D + {}^3He \rightarrow p\ (14.68\ \text{MeV}) + {}^4He\ (3.67\ \text{MeV})$$

The D-^{3}He fusion cross-section is lower than for D-T fuel, as shown in Fig. 1. Consequently, D-^{3}He requires a density-confinement time (nτ) product that is ~50 times higher and a fusion power density in the plasma that is ~80 times higher than for D-T.[1,2] Burning D-^{3}He fuel thus requires substantial, continued progress in plasma physics, but only relatively small progress beyond the progress already accomplished in the historically well-funded tokamak program. The crucial physics issues for advanced fusion configurations are confinement and controlling the resulting fusion ash buildup. In the innovative confinement concepts mentioned in the Introduction, the key physics issues have been identified, but resources to test issues adequately have not been available. Power density, which scales as β^2B^4, can be regained for high-β concepts by increasing the B-field, because designs optimize for D-T operation at a relatively low B~3 T.[1]

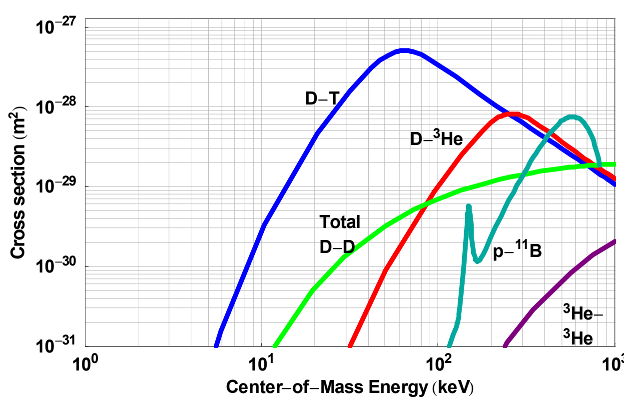

Fig. 1. Cross-sections for key fusion fuels as a function of center-of-mass energy.

ENGINEERING, SAFETY, AND ENVIRONMENT

The reduced neutron flux of D-^{3}He fuel would facilitate power-plant engineering, and much of the required D-^{3}He reactor technology already exists.[1] The neutron power fractions for D-T, D-D, and D-^{3}He Maxwellian plasmas, assuming 50% burnup of secondary tritium, are 0.8, 0.6, and 0.01-0.06, respectively, with the D-^{3}He value depending on the D:^{3}He ratio. The advantages of D-^{3}He over D-T appear as full-lifetime materials, reduced radiation damage, less activation, absence of tritium breeding blankets, highly efficient direct energy conversion, easier maintenance, and proliferation resistance.[1-5]

In FRCs, spheromaks, and dipoles the hot plasma core is surrounded by a linear external magnetic-field geometry. Essentially all of the charged-particle transport losses will thus flow out the device ends. There, they can be directly converted to electricity or allowed to follow an expanded flux tube until their heat flux reaches manageable levels. The first wall in a D-^{3}He fusion core must handle mainly bremsstrahlung and synchrotron radiation losses, which will be 25-30% of the fusion power for D-^{3}He with low heat flux peaking.

FUEL SUPPLY

Economically accessible ^{3}He on Earth exists in sufficient quantities (a few hundred kg, equivalent to a few thousand MW-years of fusion power) for an engineering development program, but not for a fusion economy.[6,7] Therefore, the million-tonne ^{3}He resources of the Moon, first pointed out two decades ago, must be mined.[6,7] A bucket-wheel excavator has been designed that would dig ~3 m into the lunar surface, convey the regolith through the mining vehicle, heat it to ~700 °C, collect the outgassed ^{3}He and other volatiles, and process them. The required technologies have essentially been demonstrated.[7] The cost of lunar ^{3}He depends strongly on the assumed pace and financing methods of lunar development,[8] and estimates range from $500/g to $1,000/g,[7] which would add ~5-10 mill/kWh to the cost of electricity.

DEVELOPMENT PATH

One potential D-^{3}He fusion development plan, with a Demo in an ITER time frame, appears in Fig. 2.[9] All D-^{3}He fusion systems require significant physics research, so the plan puts considerable resources into early proof-of-principle experiments and integrated test experiments. The cost estimates stem from the costs of present innovative confinement concepts, with the added assumption of increased power and diagnostic capabilities to speed the research. The modest time frame and cost for burning plasma experiments and a Demo reflect the anticipated relatively low engineering development times predicted to follow from using D-^{3}He fuel. The plan compromises between an approach driven by a lack of urgency and one driven by a crisis mentality.

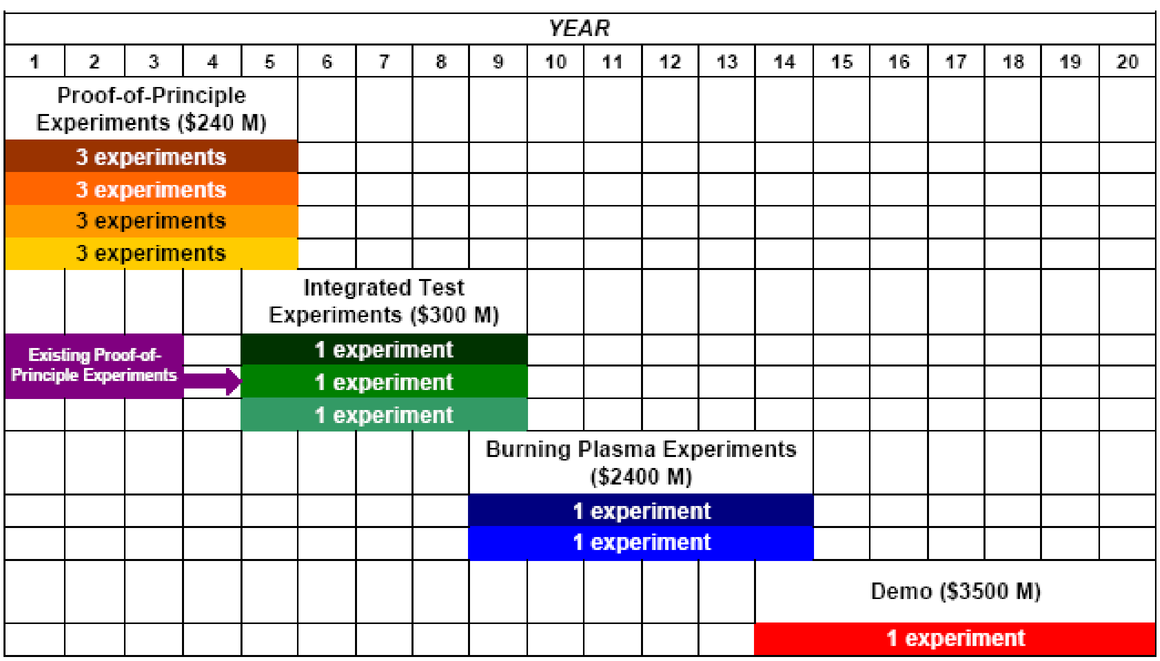

Fig. 2. One potential D-^{3}He fusion development approach; slightly modified from Ref. 9.

SUMMARY

Preliminary investigations suggest that a fusion power plant burning D-^{3}He fuel could be developed on a modest budget and time scale. The experiments required for testing physics issues in the concept exploration and proof-of-principle stages typically cost considerably less than those required for testing in the engineering development phases. Fusion using D-^{3}He fuel requires significant physics development, particularly of plasma confinement in high-performance alternate fusion concepts. Countering that cost, engineering development costs should be much less for D-^{3}He than for D-T fuel, because D-^{3}He greatly ameliorates the daunting obstacles caused by abundant neutrons and the necessity of tritium breeding. A D-^{3}He fueled fusion reactor would also possess substantial safety and environmental advantages over D-T. Lunar ^{3}He resources would be required, but only for the Demo reactor and beyond. Efficient D-^{3}He fusion energy would benefit terrestrial electricity, space power, and space propulsion.

ACKNOWLEDGMENTS

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REFERENCES

1. J.F. Santarius, G.L. Kulcinski, L.A. El-Guebaly, and H.Y. Khater, “Could Advanced Fusion Fuels Be Used with Today's Technology?” *Journal of Fusion Energy* **17**, 33 (1998).
2. J.F. Santarius, “Advanced-Fuel Heat Flux, Power Density, and Direct Conversion Issues,” *Transactions of Fusion Technology* **27**, 567 (1995).
3. G.L. Kulcinski, J.P. Blanchard, G.A. Emmert, L.A. El-Guebaly, H.Y. Khater, C.W. Maynard, E.A. Mogahed, J.F. Santarius, M.E. Sawan, I.N. Sviatoslavsky, and L.J. Wittenberg, “Safety and Environmental Characteristics of Recent D-^{3}He and D-T Tokamak Power Reactors,” *Fusion Technology* **21**, 1779 (1992).
4. G.H. Miley, *Fusion Energy Conversion* (American Nuclear Society, Hinsdale, Ill., 1976).
5. J.F. Santarius, G.L. Kulcinski, and L.A. El-Guebaly, “A Passively Proliferation-Proof Fusion Power Plant,” *Fusion Science and Technology* **44**, 289 (2003).
6. L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski, “Lunar Source of ^{3}He for Commercial Fusion Power,” *Fusion Technology* **10**, 167 (1986).
7. L.J. Wittenberg, E.N. Cameron, G.L. Kulcinski, S.H. Ott, J.F. Santarius, G.I. Sviatoslavsky, I.N. Sviatoslavsky, and H.E. Thompson, “A Review of Helium-3 Resources and Acquisition for Use as Fusion Fuel,” *Fusion Technology* **21**, 2230 (1992).
8. H.H. Schmitt, *Return to the Moon* (Praxis, New York, 2006).
9. J.F. Santarius, “Fusion Space Propulsion—a Shorter Time Frame than You Think,” *Proc. 53rd JANNAF Propulsion Meeting* (Monterey, 5-8 Dec 2005).