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Future Directions for Fusion Propulsion Research at NASA

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Fusion propulsion is inevitable if the human race remains dedicated to exploration of the solar system. There are fundamental reasons why fusion surpasses more traditional approaches to routine crewed missions to Mars, crewed missions to the outer planets, and deep space high speed robotic missions, assuming that reduced trip times, increased payloads, and higher available power are desired. A recent series of informal discussions were held among members from government, academia, and industry concerning fusion propulsion. We compiled a sufficient set of arguments for utilizing fusion in space. If the U.S. is to lead the effort and produce a working system in a reasonable amount of time, NASA must take the initiative, relying on, but not waiting for, DOE guidance. Arguments for fusion propulsion are presented, along with fusion enabled mission examples, fusion technology trade space, and a proposed outline for future efforts.

Nomenclature

a = acceleration

Introduction

There are wonderful things that can be accomplished with the ability to liberate the nuclear binding energies of the light molecules and convert that energy into usable power. There is enough deuterium in the word's oceans to meet the world's energy needs for thousands of years. The byproducts of the reactions can be completely clean and environmentally friendly. Within the known physics, round trip manned missions to the outer planets can only be achieved with fusion or antimatter.

In order to reach the goal of harnessing fusion energy, scientists and engineers must endeavor to overcome a host of technical challenges stemming from the Coulomb potential barrier of light atomic nuclei. Temperatures must reach 10 to 100 keV. The plasma must hold together with a density and residence time sufficient to yield more power from fusion reactions than supplied to the system. The energy from the reactions must be converted into a usuable form of energy, such as electricity or directed plasma jet exhaust. The entire cycle must be repeatable. It also needs to be affordable.

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Fusion research has taken many paths, but the landscape is dominated by two schemes, inertial confinement fusion (ICF)(Weynants 2002) and magnetic fusion energy (MFE)(Weynants 2002). MFE devices confine plasmas with magnetic field. The magnetic field pressure must be higher than the plasma pressure, thus requiring strong magnetic fields and relatively low densities. Reactor size scales with the inverse of density, thus MFE devices, of which tokamaks are the most actively pursued, need to be rather large. The development of the International Tokamak Experimental Reactor (ITER), a concept designed to demonstrate fusion breakeven, has a multibillion dollar pricetag. An affordable fusion reactor based on tokamak-like technology is likely many years away. As stated by Siemon et al., a more timely and economical approach to fusion will probably require a different physics regime and technological approach(Siemon, Lindemuth et al. 1999). If fusion is to ever be used for in-space propulsion, then the time to start working on the effort is now.

A recent series of informal discussions were held among members from government, academia, and industry concerning fusion propulsion. In this paper, we discuss the arguments for utilizing fusion in space, based on those discussions. We then explain why NASA must take the initiative, relying on, but not waiting for, guidance from the Department of Energy (DOE). We present a summary of some fusion propulsion approaches that have been investigated, as well as some mission examples. Finally, we propose an outline for a sustained fusion program at NASA.

Advantages of Fusion Propulsion

In order to successfully fulfill the President's vision for space exploration, there must be a long term strategy to develop propulsion systems that enable routine manned trips to Mars and manned missions to the outer solar system. Technology to reach Mars is within near term reach in the form of chemical, nuclear thermal, and perhaps nuclear electric propulsion (NEP). However, if fast trips times of the order of 3-4 months are desirable then alternatives that permit high specific impulse (~5000 s) and high specific power (~10 kW/kg) are required.

Fusion propulsion has the potential to meet and exceed these criteria. Electric power requires *energy conversion* from a reactor or other source. *Thermal/electric conversion*, required for nuclear electric propulsion (NEP), is about 30% efficient limited by Carnot cycle (2nd Law) efficiency. Thus, much of the energy has to be rejected by heavy radiators. The primary reason fusion propulsion systems have theoretically much higher specific powers compared with NEP is because thermal/electric inefficiencies can be offset in a high gain fusion system(Bussard 1990). Further, large propulsion system masses are offset by added jet power. Direct conversion of the plasma exhaust energy, a viable approach for fusion, can approach 70% efficiency of the total fusion reaction

The Incentives for a NASA-Led Fusion Program

First, it is important to summarize the NASA-DOE relationship(Schulze 1991), especially the common knee-jerk reaction to the suggestion of a NASA-sponsored program is to 'wait for DOE to do it'. DOE's mandate is primarily to develop terrestrial power generation. A premium is on cost effective (i.e. fuel efficient, high containment) power generation, not mass limitation.

NASA requires a lightweight propulsion system with high exhaust velocities. Electrical power generation is of secondary importance. Therefore, a fusion reactor for propulsion may not necessarily look like, or operate in the same physics regime, as a power plant. A comparison between chemical rockets and coal burning power plants is a good example. Nevertheless, DOE is actively pursuing tokamak research for terrestrial power production. DOE sponsored investment in fusion terrestrial power generation has generated a substantial database of basic physics and engineering knowledge relating to fusion physics. NASA can leverage the basic research being developed by DOE to develop fusion propulsion technologies.

NASA must seed technologies so they are in the maturation pipeline. An internal fusion science and engineering capability is necessary to properly evaluate usefulness of technologies coming from industry, academia, and other government agencies. A sustained and steady development program is required now to generate usable results in the near future.

NASA can leverage efforts in other areas which overlap with the fusion program. High voltage and power distribution and management are common elements in NEP and fusion. Neutron and gamma shielding are necessary for all nuclear approaches. Fusion reactions with a gain less than unity can be used to increase specific impulse of magnetically confined electric thruster concepts. Fission ignited fusion, both steady state (UF_4 gas entrained in fusion plasma to increase temperature and pressure) and pulsed (fission explosion to confine fusion plasma to very high densities) may also be considered. Finally, lunar and outer planet abundance of ^3He gives further impetus for exploration(Santarius 1992).

A historical perspective indicates advanced propulsion systems require long lead times for development, giving further merit to beginning now. Flightweight aircraft engine - ~ 15 years
Late 1800's it was accepted that a flightweight reciprocating engine was required to enable human flight
Wright brothers developed a barely adequate engine (12 hp/140 lb) but combined with adequate aerodynamics and phenomenal propellant efficiencies (70%) was a success
Jet engine - ~ 15 years
Frank Whittle proposed turbofan engine in 1928 and it received little interest
The Messerschmitt Me 262 started mass production in 1942
Liquid propellant rocket engine – 30-45 years
Theorized by Tsiolkovsky in late 1890's
First test flight by Goddard in 1929
Used in V-2 rockets in 1944
Electric propulsion thrusters - ~ 40 years
First proposed in the 1950's by several
First flight of Ion thruster for main propulsion was Deep Space 1 in 1990's

Fusion Enhanced/Enabled Missions and Examples

Figure 1 illustrates the different mission regimes by category. It is expected that fusion propulsion will be overpowerd for the closer missions to LEO and Lunar space. However there is good reason to believe that fusion will enhance missions to the inner planets. In fact for continuous exploration of Mars (such as the case if we establish a Martian base) fusion propulsion will be required to give access to Mars at non-optimal departure and arrival points.

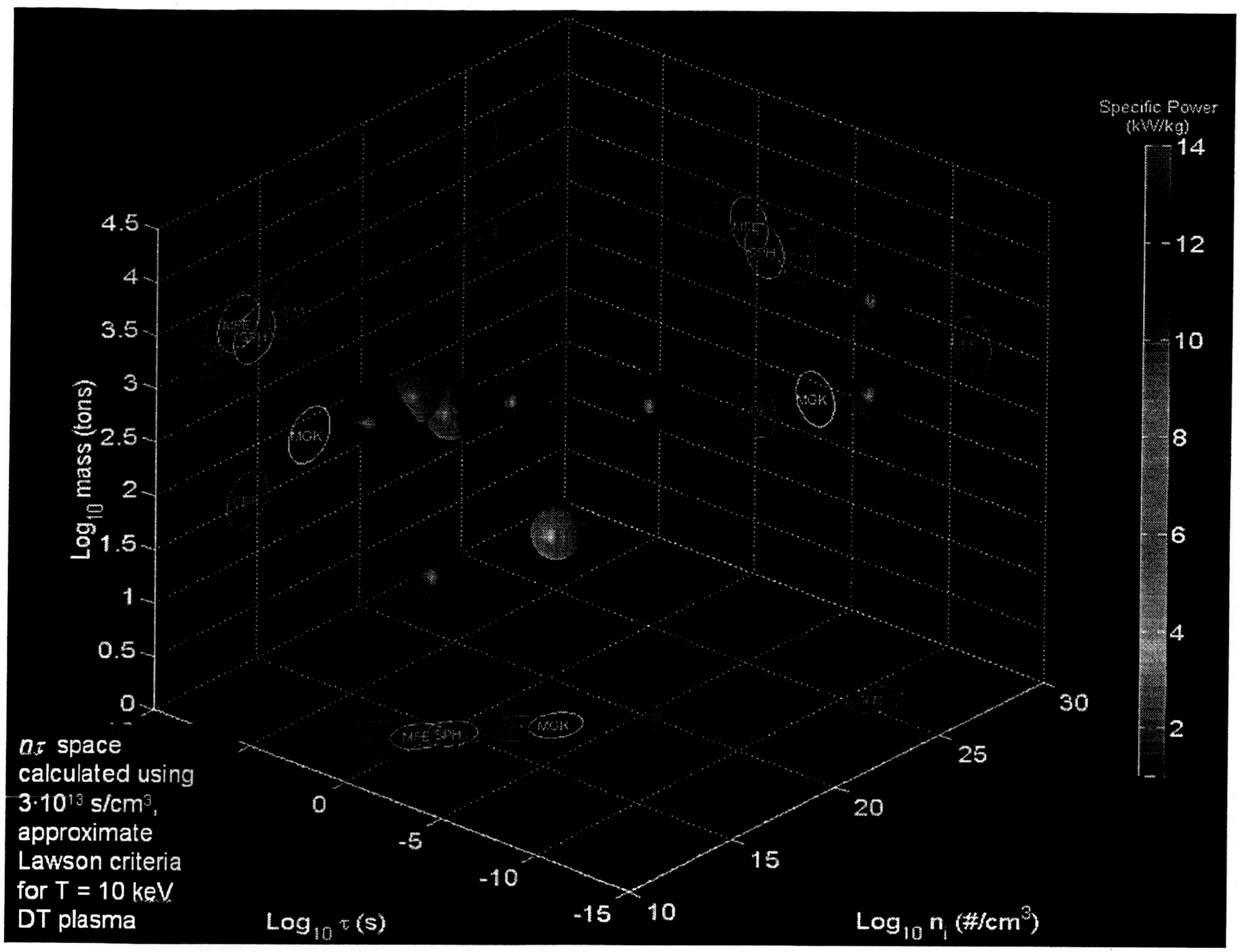
Beyond Mars fusion propulsion is essential for crewed exploration. Defense of this assumption is given in Adams et al. 2003. The referenced study considered crewed missions to Jupiter's moon Callisto. Non fusion options were marginal to achieve this mission and trip times exceeded 5 years. The long duration mission made limiting crew radiation exposure problematic. Figure 2 illustrates the vehicle trajectory for a Callisto vehicle using Magnetized Target Fusion. Here the entire mission is accomplished in 654 days. An illustration of the MTF Callisto vehicle is given in figure 3.

Fusion Technology Trade Space

Concept	α (kW/kg)	n (#/m^3)	Freq. (Hz)	Mass (mT)	Source
Steady State					
Quiet Electric Discharge (QED				)	Use author name
Inertial Electrostatic Confinem				)	
Gas Dynamic Mirror (GDM)				25	
Tandem Mirror (SOAR)				20	
Spheromak				50	
Field Reversed Configuration (				00	
Colliding Beam FRC					
Dipole				00	
Spherical Torus				30	
Pulsed					
Inertial Fusion Rocket (IFR)				0	
Inertial Confinement Fusion (I				00	
Magnetized Target Fusion (M				0	
Magneto-Kinetic Expansion ([illegible]					

Note: Need to label these Figure's. Text above references 3 Figures, but only 2 are shown.

- Next chart maps technologies of interest to density vs. temperature of confinement plasma
- Charts on each technology follow
  - Pulsed
    - **Magnetized-Target Fusion (MTF)**
    - Magnetokinetic-Compression Fusion
    - Fast-Ignitor Inertial Fusion Energy
  - Steady-State
    - **Field-Reversed Configuration (FRC)**
    - Dipole
    - Spherical Torus (ST)
    - Gas-Dynamic Trap (GDT)
    - IEC (POPS, Polywell®)



Proposed Outline for Future Efforts

- Definition of actual funding levels were discussed but were considered premature at this time
- However, to sustain a research program funding levels for the next few years are expected to be in the 2-10 million dollar range
- Initial objectives should include
  - Deeper research into DOE efforts and how they can be adapted for NASA's purposes
  - Research announcements soliciting ideas for developing benchmark experiments
  - Periodic workshops with fusion community to create fusion propulsion system development roadmap, review of research developments
  - Development/enhancement of analytical codes to further system design and development

- Emphasis on coordinating code and experimental work to be broadly applicable to the wide range of fusion propulsion concepts
- Coordinate efforts with common technology requirements for other propulsion systems (NTP, NEP, etc.)

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