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FOR INTERPLANETARY FUSION PROPULSION APPLICATIONS

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THE VISTA SPACECRAFT -- ADVANTAGES OF ICF
FOR INTERPLANETARY FUSION PROPULSION APPLICATIONS

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Abstract

Inertial Confinement Fusion (ICF) is an attractive engine power source for interplanetary manned spacecraft, especially for near-term missions requiring minimum flight duration, because ICF has inherently high power-to-mass ratios and high specific impulses. We have developed a new vehicle concept called VISTA that uses ICF and is capable of round-trip manned missions to Mars in 100 days using A.D. 2020 technology. We describe VISTA's engine operation, discuss associated plasma issues, and describe the advantages of DT fuel for near-term applications. Although ICF is potentially superior to non-fusion technologies for near-term interplanetary transport, the performance capabilities of VISTA cannot be meaningfully compared with those of magnetic-fusion systems because of the lack of a comparable study of the magnetic-fusion systems. We urge that such a study be conducted.

Introduction

Deuterium-tritium fusion, with its energy release of up to 3.4×10^{11} J/g, is an attractive engine power source for interplanetary manned spacecraft because it provides power-to-mass ratios of ten to several hundred watts per gram, and specific impulses of tens of thousands of seconds. The inherent advantages of fusion over other technologies can be realized by use of magnetic thrust chambers, as originally proposed in 1972 for Inertial Confinement Fusion (ICF) by Hyde, Wood, and Muckolls[1]. Magnetic confinement of the fusion-heated propellants isolates the hot plasmas from first walls and eliminates the thermal constraints that mechanical thrust chambers impose.

Beginning with Hyde's 1983 concept of a laser-fusion rocket,[2] we conducted a detailed study based on A.D. 2020 technology and developed a new spacecraft concept called VISTA (Vehicle for Interplanetary Space Transport Applications). This vehicle uses DT fusion and is described in detail in the final report of our study.[3] VISTA assumes a 6%-efficient excimer-laser driver operating at 1000 K with an output of 5 MJ, and uses pellets that allow energy gains from 200 up to perhaps 1500.[3] Such pellet gains are highly speculative and are based on extrapolations of analytic modeling.[3] The effective specific impulse is about 17,000 s, with a jet efficiency near 36%. When operating at a maximum pellet repetition rate of 30 Hz, VISTA's power system has a power-to-mass ratio near 20 W/g, a mass flow rate of 1.5 kg/s, a thrust of 2.4×10^5 N, and a jet power of 2.0×10^4 MW. These parameters allow a round trip to Mars with a 100-metric-ton payload in about 100 days with a launch mass near 6,000 metric tons.

This performance is potentially superior to that provided by any other near-term technology, including chemical propulsion, nuclear-electric propulsion, and even antimatter-matter annihilation propulsion.[3] However, VISTA performance depends on significant technological advances in many areas, including the development of a 5-MJ excimer-laser driver, very high pellet gains, very low-specific-mass heat-pipe radiators for waste-heat rejection, and a special inductor power-conversion system.[3] Nevertheless, such short-duration missions are crucial for astronauts to avoid radiation exposures from cosmic-ray-induced neutron showers, with the resultant cancers, as well as to avoid significant physiological deterioration in zero-gravity environments exceeding 100 days.[3] Longer missions must incorporate massive onboard shielding and spacecraft rotation to provide artificial gravity.

In this paper, we focus on just three aspects of VISTA: 1) the plasma issues in the magnetic thrust chamber, 2) the potential performance capabilities of VISTA and magnetic-fusion systems for the particular case of fast interplanetary missions, and 3) the use of DT fuels, as opposed to DD or D-He³ fuels, for near-term applications.

Operation of the Magnetic Thrust Chamber

Figure 1 gives an artist's conception of the systems layout. Thrust is obtained by positioning pellets at a repetition rate of 1 to 30 Hz at a particular site on the spacecraft axis where laser beams can ignite the fusion fuel. This ignition site is located behind the plane of a 12-T superconducting magnet such that the neutron-gamma shield for the coil casts a hollow conical shadow with a half-angle of 50 deg. This half-angle maximizes the jet efficiency of the thrust chamber, as determined by Hyde.[2] All spacecraft structure and systems are placed in the conical shadow of the coil shield to prevent vehicle surface heating from fusion neutrons. The conical spacecraft geometry is thus required for DT fuel, which emits copious neutrons. The conical shape is also structurally efficient.

The fusion pellet consists of a laser target surrounded by typically 50 g of added (expellant) mass. After fusion ignition, the expellant is heated and forms a hot plasma debris cloud. The plasma expands and cools by converting the plasma's thermal energy into radial ion kinetic energy. When the portion of the plasma headed towards the magnet gets close enough so that the magnetic pressure becomes significant compared to the dynamic kinetic-energy pressure, the debris begins to be deflected rearward into a relatively small solid angle to form the

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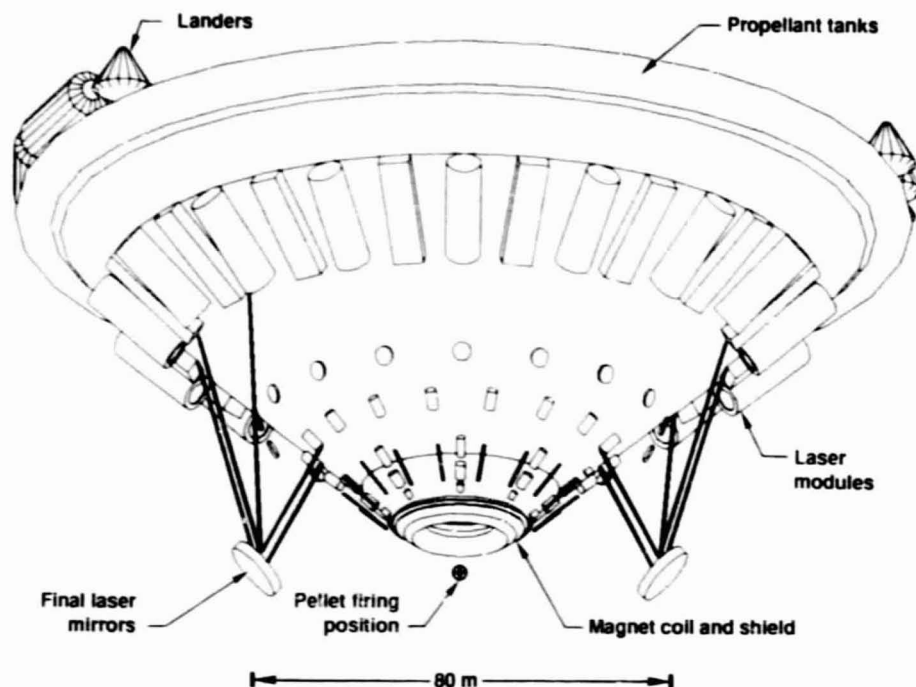


Figure 1. VISTA systems layout. Two final laser focusing mirrors are shown, but optional configurations incorporate multiple mirrors.

exhaust plume and create thrust. The magnet thereby acts as a large spring, converting the ion kinetic energy into potential energy, and then returning the energy to plasma headed in the direction of the exhaust. The plasma thus exits the thrust chamber without significant change in the high ion speed established by the fusion microexplosion, thus providing very high specific impulses. This is the main advantage of fusion over technologies employing mechanical thrust chambers.

The overall measure of the efficiency of the thrust chamber is given by the jet efficiency of the spacecraft, that is, the ratio of the power in the propulsive force projected in the direction of the exhaust, to the power in the plasma in the thrust chamber. This efficiency is determined primarily by the geometrical divergence of the exiting exhaust. However, the efficiency can be lowered by other effects, such as a spectrum of exiting exhaust speeds, or a magnetic field embedded in the plasma in the thrust chamber that must be removed in the plume.

High efficiency of thrust-chamber operation imposes requirements on the history of plasma conductivity. If the plasma conductivity remains high enough throughout its transit through the thrust chamber so that magnetic field is effectively excluded from the plasma, then engine operation can be modeled by the fluid techniques developed by Hyde[2]. If the conductivity falls enough to allow some magnetic field to diffuse into the outer portions of the plasma as it is deflected, which we think is the realistic case, then jet efficiency is degraded because of the drag resulting when the exhaust decouples from the magnetic field in the plume. An accurate assessment of the jet efficiency is dependent on the degree of this drag, but the drag can not be calculated without a great deal more study to consider the occurrence of complex physical processes. For example, because the time scale for the debris to transit the thrust chamber is only 10^{-4} s, instabilities (collective effects) should

be negligible, but we don't know for sure. Even the role played by the plasma conductivity in the plume is not certain, and this conductivity is difficult to calculate.

The conductivity of the plasma is difficult to calculate throughout its transit through the thrust chamber and into the plume because complex physical processes are involved. Temperature gradients can be rather large in the pellet material immediately after the fusion reactions. The pellet expansion which then occurs is not simply adiabatic, but can involve complex hydrodynamic processes (shocks) that complicate the radiative processes. For example, hydrogen expellant has no bound electrons when ionized and would thus not radiate as much as heavier expellants. High-Z expellant would not radiate effectively until the hot interior thermal wave propagated through the expanding plasma debris cloud to reach its outer surface. By the time the outer plasma radius is about 1 m, the plasma temperature due to internal random particle motions has dropped to roughly 1 eV, while the directed radial ion kinetic energy associated with the plasma expansion is near 1/2 to 1 keV/ion (for hydrogen/deuterium expellants). Even so, the conductivity is still within about 3 orders of magnitude of metallic conductivities. The important question is then whether recombination will heat the plasma as it continues to expand, thereby maintaining sufficient conductivity to effectively exclude magnetic field. VISTA may be required to use higher-Z expellant to maintain suitable plasma conductivity. More study of these issues is needed because the extent of the ionization occurring in this highly collisional plasma during the first 100 μ s is perhaps the most critical issue governing feasibility of this ICF application.

Efficient decoupling of the plasma from the magnetic field in the plume is essential to minimize unwanted particle flow forward around the field lines and onto spacecraft structure. Simple mechanical decoupling

requires a large beta in the plume. Beta, which is the ratio of the particle pressure to the magnetic pressure (i.e., the ratio of the plasma's kinetic-energy density to the magnet-field energy density), is proportional to the ratio of the total energy density of the plasma and the square of the magnetic field intensity. Beta should increase in the plume because the square of the magnetic field decreases faster than the plasma number density, while the particle energy remains essentially constant. Decoupling should therefore be efficient, but precise calculations are lacking. Such calculations are required to understand the feasibility of this pulsed-plasma magnetic nozzle, not just to determine the design details.

Comparison of ICF and Magnetic-Fusion Systems

Magnetic fusion uses magnets to contain a plasma at moderately high density to enable fusion reactions to occur, and thereby avoids the thermal constraints imposed by mechanical thrust chambers, just as in VISTA. One concept using magnetic fusion employs a magnetic mirror machine, that is, a cylindrical magnetic field with magnetic mirrors on each end, with one end purposely leaky to form the exhaust plume. In the ideal case, expellant mass is added to the fusion plasma before it enters the exhaust nozzle, thereby ensuring efficient mixing of the hot and cold fluids and thus high jet efficiency. In the hybrid-plume concept of the magnetic mirror, additional cold propellant is added in the nozzle region to add to the mass flow rate.[4] In this case, the resulting dispersion in nozzle speeds causes a lowered jet efficiency (and therefore poorer performance), but the degradation is not significant unless the added mass rate is more than that comparable to the fusion exit flow rate. Some other magnetic fusion concepts are discussed by Borowski.[5]

No accurate comparison between ICF and magnetic-fusion propulsion systems can be made at this time because a systems study comparable to ours has not yet been conducted for the magnetic-fusion systems. To be sure, magnetic-fusion systems can not use DT fuel because the neutron emission from their large burn region is distributed (i.e. not point-like). Excessive shielding mass would therefore be required to protect all of their superconducting magnets, and performance would be degraded. Magnetic-fusion systems must hence use advanced fuels like DD or D-He³, and therefore require both the more advanced fusion technology and a suitable source of the fuel. VISTA avoids these problems by its conical structure, which intercepts only about 3% of the neutron emissions. In addition, preliminary estimates of the power-to-mass ratios for magnetic-fusion systems are in the 5 to 10 W/g range,[5] while VISTA operates in the 10 to 20 W/g range. We suspect that the slight advantage for ICF systems results because the mass of the magnets for the magnetic-fusion systems becomes larger at high engine power levels than the driver mass for the ICF system. Moreover, throttling for the magnetic-fusion systems would be accomplished by changes in expellant flow rate, which also changes the specific impulse, while throttling in VISTA is accomplished by merely changing the repetition rate, which is independent of the target physics. On the other hand, the magnetic-fusion systems would provide continuous thrust and therefore simpler structure, and would alleviate the neutron irradiation problems encountered when other spacecraft are in the

vicinity.[3] The magnetic-fusion systems may therefore be better for near-Earth applications. In general, however, the uncertainties are too large to make meaningful comparisons of the potential performance capabilities before a comprehensive study of the magnetic-fusion systems is conducted with assumptions similar to those incorporated for VISTA.

DT vs. Advanced Fusion Fuels

One might wonder why VISTA does not use DD or D-He³ fuels. These fuels emit more energy in charged particles, which the magnet utilizes to create thrust. A crucial factor for magnetic thrust chambers, however, is that the fusion process results in gain (more energy output than supplied to the pellet). Thus, the important quantity is the product (G^*f_{cp}) of the pellet gain and the charged-particle fraction.

The gain for the advanced fuels is about one-fifth to one-sixth of the gain for DT, so when targets are operated with large expellant masses, the G^*f_{cp} product is always less than that for DT (G^*f_{cp} is about 1/3 for DD and 1/2 for D-He³ when the product is normalized to unity for DT). This suggests that advanced fuels could never compete with DT. However, if different flight optimizations and operating conditions are considered, it is possible for advanced fuels to outperform DT when pellet gains get very large (e.g., larger than 200 for the advanced fuels, which corresponds roughly to gains above 1000 for DT).[3] The added performance in terms of reduced trip time, however, is insignificant (a trip to Mars is shortened by only a few percent). The advanced fuels do lessen the radioactivity hazards associated with the use of about 2 metric tons of tritium, and lower the emitted neutron flux that causes hazards for neighboring spacecraft.[3] However, the pellet technology for the advanced fuels does not exist, and pellet gains above 200 for these fuels represent extremely advanced technology. In addition, sufficient quantities of He³ are not available on earth, so use of He³ would necessitate the mining of the lunar surface or the Jovian atmosphere. Thus, advanced fuels may prove useful for far-term applications, but DT is definitely the best choice for near-term interplanetary applications using VISTA.

Conclusions

We have summarized how ICF has great advantage over competing technologies for fast interplanetary transport, and have described the VISTA spacecraft concept. We explained that the performance advantages for VISTA arise from the high fusion energy gain and the avoidance of thermal constraints by the use of a magnetic thrust chamber. We have indicated that the feasibility of VISTA as a viable interplanetary transport rests primarily on whether the jet efficiency is degraded significantly by plasma processes in the magnetic thrust chamber and in the exhaust nozzle. Future studies must address the issues relating to plasma conductivity, decoupling in the plume, and collective effects. We also indicated that it is difficult to compare the performance capabilities of magnetic-fusion systems with those of VISTA because no comprehensive study of the magnetic-fusion systems has been conducted using assumptions similar to those incorporated for VISTA. We therefore recommend that such a study of magnetic-fusion concepts be undertaken. Finally, we explained why VISTA performs best with DT fuel, and not with DD or D-He³, for near term missions.

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