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ABSTRACT

Inertial confinement fusion (ICF) is an ideal engine power source for manned spacecraft to Mars because of its inherently high power-to-mass ratios and high specific impulses. We have produced a concept for a vehicle powered by ICF and utilizing a magnetic thrust chamber to avoid plasma thermalization with wall structures and the resultant degradation of specific impulse that are unavoidable with the use of mechanical thrust chambers. This vehicle is capable of 100-day manned Mars missions with a 100-metric-ton payload and a total vehicle launch mass near 6000 metric tons, based on advanced technology assumed to be available by A.D. 2020. Such short-duration missions minimize radiation exposures and physiological deterioration of astronauts.

INTRODUCTION

An inertial confinement fusion (ICF) microexplosion utilizing deuterium-tritium (DT) fuel releases up to 3.4 x 10^{11} J/g in the form of neutrons, x rays, and plasma debris. Such huge specific energies afford very high power-to-mass ratios (ten to several hundred watts per gram) and very high specific impulses (tens of thousands of seconds). ICF is thus well suited as a engine power source for short-duration manned Mars missions, provided the high specific energy can be utilized without thermalization with wall structures in a mechanical thrust-chamber enclosure.

Thermalization can be avoided by using a magnetic thrust chamber, as originally proposed in 1972 by Hyde, Wood, and Nuckolls.[1] In 1983, Hyde[2] developed a complete concept of a pencil-shaped, laser-fusion-powered vehicle for interplanetary transport using pure-deuterium fuel; Hyde assumes a pellet gain of 1000 at a driver energy of 2 MJ. His thrust chamber incorporates a 16-T superconducting magnet to redirect the pellet debris, and operates at 100 Hz with a jet efficiency of 42% based on imperfect collimation of the exhaust plume.

We extended Hyde's concept by conducting a more complete and detailed systems study. Our objective was to specify a viable system concept for missions to Mars incorporating technology likely to be available by A.D. 2020. Our results, published elsewhere[3] and summarized here, include an entirely new spacecraft concept called VISTA (vehicle for interplanetary space transport applications). VISTA is capable of manned Mars missions with a payload of 100 tons, a total vehicle launch mass near 6000 tons, and a total mission duration of roughly 100 days, including a stay on the planet of about 10 days. We emphasize that this concept depends on the development of the advanced technology assumed for many of the vehicle systems, including advanced laser drivers, very high pellet gains, and advanced heat-pipe radiators. Note that, in this paper, "ton" means a metric ton (10^6 g).

SPACECRAFT DESIGN CONCEPTS

Figure 1 gives an artist's conception of the systems layout. The primary spacecraft structure is a cone. Crew systems are located at the rim of the cone, buried inside the propellant tanks for added radiation-exposure protection. A 13-m-radius, 300-kA/cm^2 warm-superconducting magnet generates a magnetic field that has a peak strength of about 12 T and that defines the boundaries of a thrust chamber. Pre-assembled pellets are filled enroute with liquid deuterium (D) and tritium (T) fuel, which are isotopes of hydrogen. The fuel pellets are surrounded by about 50 g of added material (expellant) and are accelerated, injected, and positioned in the thrust chamber at a repetition rate that is variable from zero up to about 30 Hz. Beams from an excimer laser delivering about 5 MJ of 0.5-μm light with an efficiency of at least 6% (at 1000 K) are focused on the pellet. The laser beams cause the pellet to implode and release up to 7500 MJ in neutrons, x rays, and plasma debris energy as the fusion reactions convert the pellet and the surrounding expellant into an expanding debris cloud.

Approximately one-fourth of the DT fusion energy is released as plasma debris kinetic energy. This plasma, being conductive, expands away from the pellet firing location until the bulk plasma pressure drops below the magnetic field pressure. The debris is then deflected by the magnet, which stores an energy that is at least 5 times the debris kinetic energy. The debris, which is cooling and decreasing in conductivity, leaves the thrust chamber in a limited solid angle, producing thrust and propelling the spacecraft with its blunt end forward. A small amount of debris leaks forward along the magnet axis and is considered below in the estimate of jet efficiency.

Note that VISTA obtains its thrust by converting the thermal energy from the fusion reactions into directed kinetic energy of the debris. The thrust can be varied by changing the engine repetition rate (or the expellant mass, or possibly even the pellet gain). The pellet gain (the ratio of the energy produced by the fusion reactions to the driver energy supplied to the pellet) can be as high as about 1500 for very advanced DT technologies (see below). Such gains allow the ICF engine to have a power-to-mass ratio of about 10 W/g.

VISTA's overall geometry is that of a 50°-half-angle cone. This shape is required to avoid massive radioactive shielding and to keep fusion neutrons (and x rays) from striking and heating vehicle surfaces. The 50° half angle maximizes jet efficiency, and is determined by selecting the optimum pellet

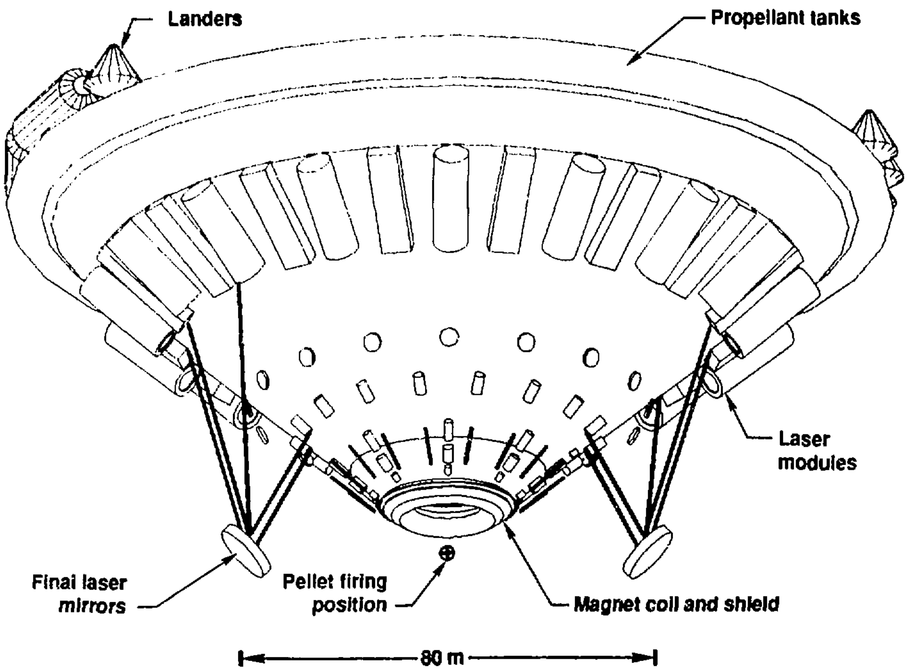

Figure 1. VISTA systems layout. Two final laser focusing mirrors are shown, but optional configurations incorporate multiple mirrors.

firing position along the axis of the cone with respect to the plane of the magnet coil, in a manner similar to that done by Hyde.[2]

The conical shape is primarily a result of the use of DT fusion fuel. With 50 g of expellant per fusion pellet, about 60% of the energy released is in neutrons, whose initial energy is 14 MeV. To prevent neutron heating of the superconducting medium of the magnet coil, a 1.5-m-thick shield of liquid lithium is placed on the pellet side of the magnet coil to absorb all incident neutrons. The fraction of fusion neutrons and x rays striking this shield depends on the minimum size of the magnet windings and on the distance of the coil from the pellet.

The overall scale of the thrust chamber is made large enough to avoid x-ray ablation of structures during an engine pulse that releases 7500 MJ. This requires that the coil shield be about 15 m from the pellet; the coil windings therefore subtend a fractional solid angle of 2% at the pellet. To allow for edge effects, we find that the coil shield must intercept about 3% of the pellet neutrons and x rays. The final laser turning mirrors and the pellet injector outlet port intercept an additional 1%. The remaining 96% of the neutrons and x rays stream out isotropically into space, and do not strike or heat vehicle surfaces.

The coil shield required for the magnet thus casts a conical shadow devoid of pellet emissions. We therefore chose the VISTA geometry to be a cone with its apex at the pellet, and placed all vehicle systems in the shadow of the coil shield. This structure is not only mechanically rigid, but is stable during steering maneuvers. The cone itself serves both as a structural support for attachment of vehicle systems (laser drivers, power conditioners, etc.) and as a surface for radiating waste heat. In fact, the core heat pipes are designed to give the cone its structural support; suitable stiffeners are added for local attachments, while the branch heat pipes form the main conical surface.

This geometry has two disadvantages. First, it is not as effective as planar geometries in utilizing both sides of its surface as radiating surface area, because the interior conical surface partially views itself. Second, the conical geometry is not as conducive to protection from micrometeoroids as a plane moving with one of its edges forward, as in Hyde's scheme.[2] Fore and aft micrometeoroid shields (not shown in Fig. 1---see Ref. 3) must therefore be included to protect the main conical surface in both acceleration and deceleration orientations relative to vehicle motion.

PELLET SYSTEMS

Reference 3 gives detailed analyses of the pellet systems and gains. Even though terrestrial power reactors require pellets with gains of only 50 to 200 for current laser-driver concepts, we assume that very advanced pellet technology will permit gains up to 1500. Such high gains are possible according to the Meyer-ter-Vehn analytic model,[4] which in essence shows that pellet gain can be as high as $G = 877E_d^{1/3}$, where the driver energy E_d is in megajoules; such gains, however, should be regarded as speculative.

About 44 mg of DT fuel are needed to produce 7500 MJ of fusion output (5 MJ input energy at gain 1500) if the fusion burn is 50% efficient. Each pellet therefore contains 26.5 mg of tritium. A 100-day Mars mission will require 35 to 40 tons of DT fuel, which will include 20 to 25 tons of tritium. This tritium generates 0.33 W/g of radioactive decay heat, which means 8.3 MW for all of the tritium. It is therefore impossible to keep the tritium at cryogenic temperatures; it must be stored in a tank that will reach its own elevated equilibrium temperature as the decay heat is radiated to space. The deuterium fuel and hydrogen expellant, however, can be stored cryogenically with modest tankage and refrigeration. Reference 3 discusses other types of expellant material that can be used.

There are several reasons why VISTA uses DT fuel rather than advanced fuels such as DD or D^3He, even though tritium presents difficulties because of its radioactivity. For VISTA, the important quantity is the product of the pellet gain and the fraction of fusion output in debris energy. Although the advanced fuels have much higher debris fractions, their gains are lower by a factor of about 6. As a result, the product of gain and debris fraction is slightly lower for the advanced fuels than for DT, suggesting that advanced fuels would never outperform DT. It is possible, however, for advanced fuels to outperform DT at gains above about 200 by choosing different operating conditions for the different fuels. However, the added performance is insignificant (the trip time is on the order of few percent shorter).

In addition, the pellet technology for the advanced fuels does not now exist, and pellet gains above 200 for advanced fuels represent extremely advanced pellet technology, and therefore very far term. Besides, the required quantities of ^3He are not available on earth, so the use of ^3He would necessitate mining the lunar surface and/or the Jovian atmosphere. For these reasons, we chose DT as the best fuel for the near term.

DRIVER SYSTEMS

The laser driver is modular, both for redundancy and to make it possible to assemble the final beams from smaller-diameter beams without exceeding the maximum allowable fluence on any optical component. Considerable development would be needed to make any driver concept currently being developed for terrestrial use applicable for use in a space propulsion system. The concept most likely to achieve high efficiency, low mass, and high operating temperature (to minimize radiator mass) seems to be some form of excimer laser. We therefore chose an excimer laser operating at 1000 K and at about 0.5 μm wavelength, with an efficiency of 6% for a radiating temperature of 900 K, and a mass of 300 tons. This system must operate reliably for 10^8 repetitions.

Such a driver concept represents an extrapolation of existing technology in a number of ways. Foremost, no terrestrial concept with acceptable total mass can fire 10^8 times without hardware changes (KrF foils, light-ion diodes, etc.). Other extrapolations pertain to the lifetimes and damage thresholds for laser optics and coatings operating at sub-micron wavelengths, which are not well known (especially for materials subjected to high neutron fluences). Also, very high beam quality (uniformity) is required to focus the light from the final turning mirrors onto the pellet, and this beam quality is probably beyond current technology. Even the energy and efficiency estimates are extrapolations of existing technology. Nevertheless, the terrestrial ICF program has similar end requirements in nearly all areas, so it is highly likely that the required extrapolations will be realized before A.D. 2020.

THRUST CHAMBER

We do not fully understand the plasma processes that are vital for effective thrust-chamber operation. Expansion of the pellet debris and interaction of the debris with the magnetic field occur on time scales on the order of tens to hundreds of microseconds. We have assumed that the plasma would maintain enough conductivity to resist significant magnetic field penetration during its transit through the thrust chamber. We have also assumed that the exhaust would decouple at high beta (the ratio of particle pressure to magnetic field pressure), so that debris particles would not spiral around the field lines and return to strike spacecraft components. Studies are under way to determine the validity of these assumptions, and whether jet efficiency would be degraded by plasma field penetration. If it is necessary to increase jet efficiency by further restricting the solid angle of exhaust exit, the plume can be shaped by employing other magnets, but not without additional dry mass and structural complexity.

We estimate that the thrust chamber is about 60% efficient in converting the mass flow into directed exhaust momentum. [In obtaining this estimate, we account for the non-colinearity of the exiting debris particles, for a small drag generated in the thrust chamber by the nonzero resistivity of the cooling plasma (which allows magnetic field penetration of the plasma, and hence difficulties in decoupling the exhaust from the magnetic field), and for a small loss of debris forward along the magnet axis.] Squaring this figure, we find that VISTA is 36% efficient in converting debris energy into jet power. Multiplying the debris exhaust speed of 3×10^5 m/s by the 60% momentum efficiency, we calculate VISTA's effective specific impulse to be near 20,000 s. This specific impulse is possible only because the debris particles do not contact any surrounding structures.

POWER SYSTEMS

The power systems must be capable of supplying approximately 1 MW of auxiliary dc power, and up to 2.5 GW in pulsed power to run the inefficient laser driver (driver input pulses are 600 kV for 0.4 μs at typically 1 to 30 Hz, each pulse supplying 83 MJ). This power must come from the fusion process. Two types of power conversion systems have been considered: (1) a Rankine cycle utilizing waste neutron heat deposited in the liquid lithium that forms the magnet coil shield, and (2) an inductor pickup coil[2] that generates an emf through magnetic induction when the magnetic field lines are compressed by the expanding pellet debris and pass through the inductor coil "windings."

The Rankine option must be only 20% efficient for minimum mass per unit power (as opposed to maximum efficiency), and operates in a dc (not a pulsed) mode. Its use requires lateral extension of the coil shield into a lithium "blanket" to accept tens of percent of the neutron energy instead of the 3% accepted by the shield. As a result, its 1000 tons would essentially double the vehicle dry mass. The Rankine system is therefore not competitive.[3]

The inductor would operate at the same frequency as the driver, which is the main power demand, so an advanced power system can be designed that compresses the inductor pulse to the 0.4-μs pulse duration needed by the driver, without going through an intermediate dc stage. A fallback option utilizes rectification of the inductor pulses, with capacitive storage.[3]

With either inductor option, the electrical energy is extracted from the debris energy, but without significant reduction in vehicle thrust. Because the inefficiency in the engine arises primarily from the relatively large solid angle of emission of the debris trajectories exiting the thrust chamber (and not simply from loss of debris energy), the ratio of the inductor power extracted from the debris and the power in the debris traveling through the thrust chamber is the inverse of the product of the pellet gain, the driver efficiency, and the fraction of fusion energy in debris. For VISTA, this ratio is about 4% for a gain of 1500.

The inductor subsystem itself adds essentially no mass, because the interior surface of the coil shield can serve as the coil "windings." We have added 25 tons for all inductor systems, including the power-conditioning subsystems. If the fallback capacitive inductor power-conditioning option is exercised, however, we would have to add 200 to 400 tons. Such a mass would restrict vehicle performance.

The 1 MW of auxiliary power (for crew systems and housekeeping, refrigeration subsystems, pellet filling and injection subsystems, reaction control, communications, etc.) is easily extracted from the main power system. A separate 100-kW fission reactor for engine startup is also required to melt the lithium in the coil shield and to supply the 83 MJ necessary to fire the first driver pulse.

THERMAL SYSTEMS

Heat-pipe radiators are used to remove waste heat arising from inefficiencies in the driver and power systems, and from pellet-emission depositions in the final laser mirrors, the pellet injector port, and the coil shield (with the liquid lithium acting as the transfer fluid). Thermal control (refrigeration) is required to maintain the temperature of the superconductor for the magnet and the temperature of the propellant tanks, and to liquefy tritium.

The design of the heat-pipe radiators affects vehicle performance unless their mass is small compared with other vehicle dry mass. Radiator design begins to affect performance above about 0.1 kg/kWt at 1000 K. For results presented here, we have assumed the equivalent of 0.07 kg/kWt at 1000 K. Current technology is 0.15 kg/kWt at 1000 K, and this would have to be increased to perhaps 0.2 kg/kWt for VISTA because the VISTA radiator surface is also a structural load-bearing surface that needs added strength. The radiator design is thus one area in which VISTA is dependent on future technological advance.

Up to 2400 MW must be radiated at 900 K for the driver operating at 1000 K, and up to 10,000 MW must be radiated at 1500 K for the coil shield. The fore and aft micrometeoroid shields allow thin, double-walled construction of the branch heat pipes to meet the 0.07 kg/kWt specification at these power levels. We designed the structural layout of the branch radiator assemblies in the conical mesh of stronger core heat pipes using the NASTRAN and other computer codes. Local stiffening is provided as needed in the shell to support mounted components and to provide structural attachment points. Peak acceleration is less than 0.02g, and stresses are typically less than 3 kpsi.

RADIATION HAZARDS

The radioactivity of the tritium fuel presents a hazard during boost into orbit and during onboard pellet filling and transfer, and requires storage of the tritium in a temperature-elevated tank because of its decay waste heat of 0.33 W/g. These hazards are presumed to be manageable.

The crew can be adequately shielded from solar flares and cosmic rays (and some stray fusion neutrons) by placing the crew systems inside the expellant tanks and by surrounding them with mass associated with other vehicle systems. However, operation of VISTA does present a hazard for unshielded personnel in nearby spacecraft or in a space station, if VISTA is initially at rest relative to these vehicles. Each fusion pulse releases over 10^{20} neutrons, so at peak engine operation, there is a hazard for unshielded nearby personnel for several hours until VISTA has moved off several thousand kilometers. This hazard would of course be mitigated by providing shielding for the personnel in these other spacecraft.

MISSION PERFORMANCE

Table 1 shows a typical power flow for VISTA, and Table 2 lists the masses and other parameters for the various systems. Note that VISTA, at about 6000 tons, is a very heavy vehicle, requiring the equivalent of 30 trips of NASA's heavy-lift launch vehicle for assembly in orbit. Nevertheless, it serves as a fast transport to Mars, with round-trip travel times near 100 days (with coasts), including about 10 days on the planet. Typical vehicle coast velocities are 40 to 60 km/s. Such short durations reduce the leukemia and other cancer hazards for astronauts while they are not protected by vehicle shielding, which must be equivalent to about 1-m-thickness of water. Short missions also minimize astronaut calcium losses. If mission durations longer than 100 days would be acceptable, lower vehicle launch masses could be employed. Reference 3 documents other performance results, and a parametric analysis.

If radiator or driver technology develops even faster than we anticipate, vehicle dry mass could be lower, and performance could improve and/or vehicle launch mass could be much lower. With the current estimates of technology advances, the flight duration for VISTA is at least a factor of 2 or 3 shorter than with nuclear electric propulsion, and is roughly a factor of 10 shorter than with chemical rockets, for mimimum-mass configurations. Such performance is dependent on the development of very high pellet gains.

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Table 1. Approximate power flow (MW) in VISTA at 5 Hz (driver output energy 5 MJ, pellet gain 1500). For 30 Hz, multiply values by 6.

Driver	
Input	420
Radiators	395
Output	25
Pellet	
Input	25
Output	37 500
Debris (1/4 total)	9 400
Thrust chamber	
Direct loss to space (neutrons and x rays)	27 000
Jet power	3 380
Unused debris power	4 900
Radiated power	1 800
Electrical inductor power output	420

Table 2. Masses and other parameters of VISTA vehicle systems.

Driver		
Energy output (MJ)	5	
Efficiency (1000 K) (%)	6	
Radiator temperature (K)	900	
Pellet		
Fuel	DT	
Gain	≤1500	
Expellant mass per pellet (g)	50	
Engine		
Effective specific impulse (s)	17 000	
Power per unit mass (W/g)	~0.6 x repetition rate	
Mass flow rate at 30 Hz (kg/s)	1.5	
Thrust at 30 Hz (N)	2.4×10^5	
Jet power at 30 Hz (MW)	2.0×10^4	
Jet efficiency (%)	36	
Approximate system masses at 30 Hz (metric tons)		
Payload		100
Crew shield		140
Propellant		4 390
Fuel	40	
Expellant	4 100	
Refrigeration/liquefaction	50	
Tankage	200	
Driver		500
Equipment	300	
Radiators	200	
Thrust chamber		475
Coil	20	
Coil shield	100	
Radiators	330	
Structure and equipment	25	
Startup reactor		5
Power systems		90
Misc. structure and radiator shield		100
Total		5 800
Dry mass	1 660	
Propellant	4 140	

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