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Parameter Studies for the VISTA Spacecraft Concept

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Parameter Studies for the VISTA Spacecraft Concept

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Abstract:

The baseline design for the VISTA spacecraft concept employs a diode-pumped solid-state laser (DPSSL) driver. This type of driver is now under development at LLNL and elsewhere as an extension of the mature solid-state (glass) laser technology developed for terrestrial applications of inertial confinement fusion (ICF). A DPSSL is repratable up to at least 30 Hz, and has an efficiency soon to be experimentally verified of at least 10%. By using a detailed systems code including the essential physics of a DPSSL, we have run parameter studies for the baseline roundtrip (RT) to Mars with a 100-ton payload. We describe the results of these studies as a function of the optimized (minimum) RT flight duration. We also demonstrate why DT fuel gives the best performance, although DD, D^3He, or even antimatter can be used, and why DT-ignited DD is probably the fuel most preferred. We also describe the overall power flow, showing where the fusion energy is ultimately utilized, and estimate the variation in performance to the planets dictated by variations in target gain and other parameters.

1. Introduction

We have already described the VISTA spacecraft concept powered by inertial confinement fusion (ICF) in a companion paper in this Workshop [1]. Because VISTA has the most detailed systems-analysis basis, the methodology for VISTA can perhaps serve as a guide for systems analyses for other fusion space-propulsion concepts. We therefore describe here the basis for the numerical modeling that allowed the optimization of VISTA's design in a hope that it might prove instructional to others. Our intent here is hence not to describe design features or give performance results for certain missions, which are described in Ref. [1], but to illustrate some of the results of parameter and sensitivity studies that show how VISTA's performance varies for different values of the essential parameters.

2. Method of Numerical Modeling for Flight Durations

We used our own analytic trajectory code called IFRTRIP to estimate roundtrip (RT) flight durations. This analytic code uses sophisticated rocket equations derived for relativistic conditions (i.e., based on an additive velocity parameter), which were then simplified for velocities much less than the speed of light. The code includes all of the systematics of the ICF spacecraft with a pulsed engine, including coasts, and computes the minimum roundtrip (RT) flight time between two end points by simultaneously varying and optimizing four parameters: the total fusion energy expended during the trip, the fraction of this energy used in the outgoing leg, the jet power, and the effective specific impulse (i.e., the product of the specific impulse and the square-root of the jet efficiency). Additional assumptions were as follows:

1. Trajectories are one-dimensional, except that the distance traversed is specified three-dimensionally.
2. The magnetic thrust chamber does not alter the speed of the exhausted plasma.
3. Propellant is consumed at a constant linear rate while the engine is operating.
4. The target firing reprate is constant throughout the mission, while the engine is operating.
5. The target mass including expellant is constant throughout the mission.
6. All propellant is consumed by the end of the mission.
7. The distance going is identical to the distance coming back.

8. The time to spiral out from or into a planetary orbit must be added to the trip time calculated by the code.
9. There is no change in vehicle velocity during coasts (i.e., ignore acceleration or deceleration during coasts due to solar gravity).
10. There is no change in solar gravity during the trip except that which accounts for the overall change in gravitational potential, and account for the latter can be included at the end points of the trajectory legs through negative velocities.

As a check on the accuracy of our code, we compared its output for a Mars mission using the parameters shown in Table 1 with the optimized output obtained from JPL's NASTRAN code, which was run excluding the VISTA systematics (Fig. 1). Note that the agreement is satisfactory, considering that the JPL calculation indicates the extreme case of minimum trip time for a given "alpha." This alpha parameter is the ratio of the spacecraft dry mass (with no propellant) and the jet power, in units of kg/kW, and is the only parameter governing this minimum trip time. VISTA's curve falls below the optimum because the calculations for VISTA include the inefficiencies in the various onboard systems.

Table 1: Parameter Values Assumed for the Advanced-Technology Case

Parameter	Value	Parameter	Value
Driver energy	5 MJ	Extra kg/kW$_{th}$ for micrometeoroid shield	0.007
Driver efficiency	12%	Induction electrical system efficiency	50%
Expellant density, g/cm^3	0.077	Jet efficiency (calculated)	32%
Expellant type	H_2	Magnet coil radius (m)	13.0
Fuel type	DT	Maximum pulse rate (Hz)	30
Fuel compressed $\rho\Delta r$ (g/cm^2)	5.0	Radiator T, coil (K)	1500
Fuel capsule gain	1500	Radiator T, driver (K)	900
Heat-pipe radiator kg/kW$_{th}$ @ 1000 K	0.07	Radiator Temperature, thermal systems (K)	1000
Specific impulse with engine on	constant	Gravity	included

3. Results of the Parameter Studies

Our calculations reveal that the critical parameters for VISTA are the target gain G and the engine mass (i.e., the combined mass of the laser driver, magnet coil, and especially the magnet neutron and gamma-ray shield). Other important parameters include the driver efficiency and operating temperature. Figure 2 illustrates the sensitivity to target gain and the temperature of the driver's heatpipe radiators. Note that $G > 300$ steadily decreases the trip time. Moreover, the RT flight duration to Mars can be less than roughly 2/3 year for target gains above 500. Such performance is beyond that of any other known concept. In contrast, there is great advantage in having a driver radiator temperature at least as high as 500 to 800 K, but the advantage increases less markedly for temperatures above ~800 K. Figure 2 also shows the sensitivity to payload mass, which is of course equivalent to changes in the masses of any of the other systems. Mass increases obviously decrease performance.

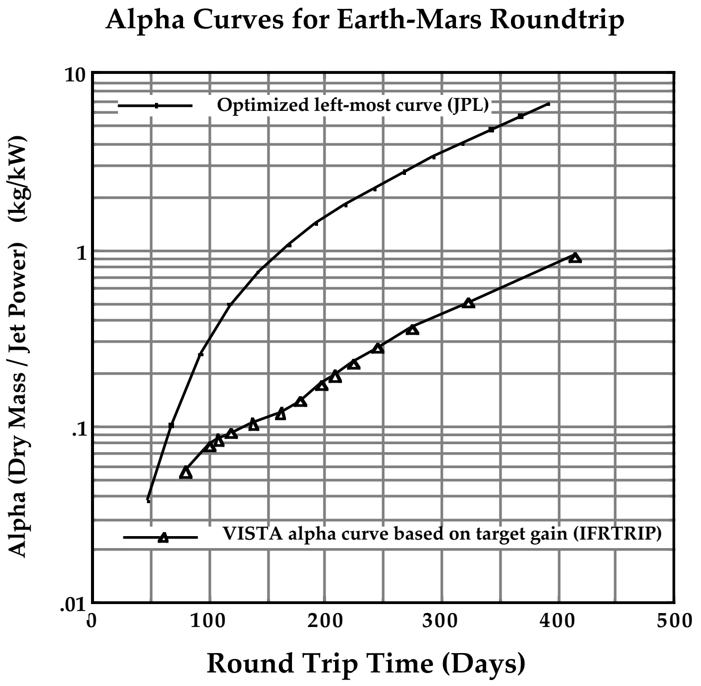

Figure 1: Comparison of one particular VISTA alpha curve with the exact JPL curve indicating the minimum RT time for any given alpha for any spacecraft to Mars.

Figure 3 illustrates the sensitivities to driver efficiency and radiator technology. Note that driver efficiency is important up to ~12% but little reduction in trip time results for further increase in this parameter. It is therefore possible that a DPSSL might be used for a VISTA application, because a DPSSL cannot exceed ~700 K in operating temperature.

4. Advanced Fuels

The minimum temperature to initiate DT burn is about 4.5 keV, but the minimum for DD is 16 keV, and the minimum for D^3He is 38 keV. Moreover, most target designs are based on achieving temperatures at least 50% larger than these minima to ensure reliable ignition. Unfortunately, it is somewhat impractical to compress a fuel to temperatures much above 10 to 20 keV by normal means, so it is a challenge to ignite the advanced fuels by themselves, especially D^3He.

For these reasons, all advanced fuels considered here will be assumed to have a core of DT to act as a hotspot to ignite the advanced fuel. This core, if it is going to “trap” the charged reaction products, must be at least one alpha-particle mean free path in radius at the minimum burn temperature (i.e., 0.30 to 0.35 g/cm^2). To promote higher burn temperatures and hence more vigorous burn, we shall instead use 0.5 g/cm^2.

In any fusion reaction, only a fraction f_{burnup} of the total fuel mass is able to burn before the target blows itself apart. This fraction, which is also called the burn efficiency, depends primarily on the column density x_{fuel} of the compressed fuel in g/cm^2, but also on a term Ψ_i dependent on the cross section at the burn temperature of the specific fuel utilized. A general expression, based on depletion of the needed ions, is shown in Eq. (1).

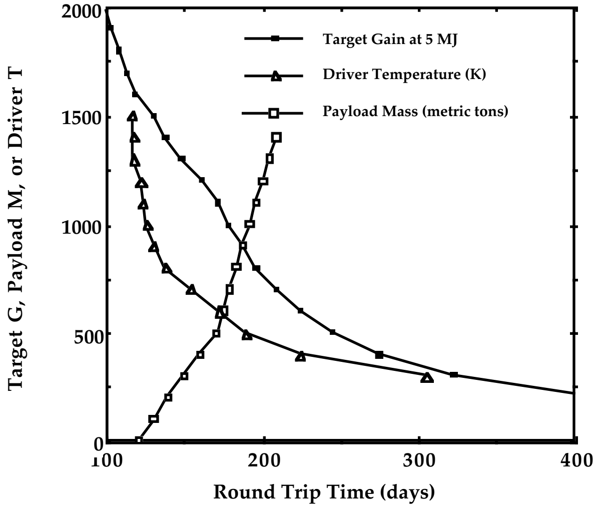

Figure 2: Variation of Advanced-Technology Mission Performance to Mars With Variation in Target Gain, Driver Radiator Temperature, and Payload Mass

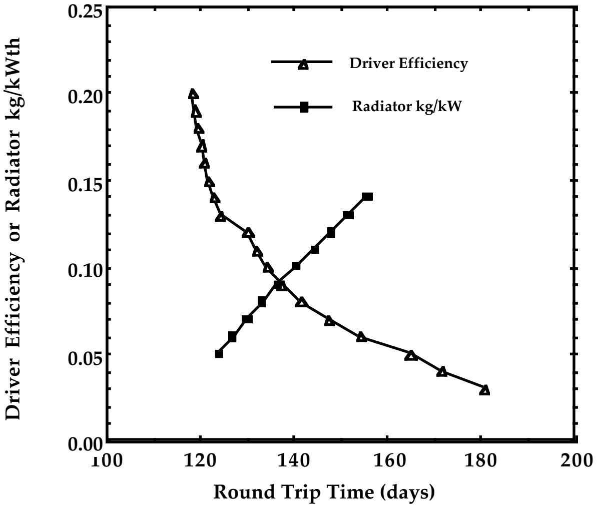

Figure 3: Variation of Advanced-Technology Mission Performance to Mars With Variations in Driver Efficiency and Radiator Technology

$$f_{burnup}(fuel\ i) = \frac{x_{fuel}}{x_{fuel} + \Psi_i} \qquad (1)$$

where Ψ_i is as follows: [2]

1. DT: 5 to 6 g/cm^2 at 70 to 80 keV (5 g/cm^2 at 50 keV, rising to ~20 g/cm^2 at 300 keV);

2. DD: ~60 g/cm^2 at 70 to 80 keV (~70 g/cm^2 at 50 keV, falling to 50 g/cm^2 at 100 keV, falling to ~35 g/cm^2 at 220 keV);
3. D^{3}He: ~50 g/cm^2 at 70 keV (~70 g/cm^2 at 50 keV, falling to ~39 g/cm^2 at 100 keV, falling to ~34 g/cm^2 at 220 keV).

In short, Ψ_i is ~5.5 g/cm^2 for DT, ~60 g/cm^2 for DD, and ~50 g/cm^2 for D^{3}He (unless the advanced fuels can somehow be made to burn at temperatures well over 100 keV). Consequently, f_{burnup} is roughly 35%, 4.8%, and 5.7% for DT, DD, and D^{3}He (respectively) for a capsule with a compressed column density of 3 g/cm^2, and 47.6%, 7.7%, and 9.1% for a capsule with a compressed column density of 5 g/cm^2.

Target gain is equal to the product of the fuel mass, the burnup fraction f_{burnup}, various ablation and hydrodynamic efficiencies, the fusion energy release per gram, and the inverse of the driver energy ($1/E_{dr}$). Thus, for the same E_{dr}, the same fuel mass, and the same x_{fuel}, the target gain for DD is only about one-seventh to one-sixth that for DT due to the different burnup fractions, and the target gain for D^{3}He is only about one-sixth to one-fifth that for DT. However, for an inertial fusion engine with a magnetic thrust chamber, the important quantity is not the gain, but the product of the gain and the fraction of the fusion energy going into debris plasma f_{debris}—that's because it is the energy in charged debris plasma that is converted into thrust by the magnetic thrust chamber. If this Gf_{debris} product is normalized to unity for DT, it is 0.42 to 0.51 for DD without expellant (0.40 to 0.57 for D^{3}He) for x_{fuel} = 3 to 5 g/cm^2, and only one percentage point higher with 50 g of expellant. However, use of DD greatly reduces the tritium inventory, and can reduce the neutron emissions slightly. Similarly, D^{3}He is not aneutronic because the DT-hotspot neutrons convert the ^{3}He to tritium, so most of the yield from D^{3}He fuel is from DT reactions. [3]

For a compressed fuel column density of 5 g/cm^2, a total vehicle mass of 6,000 metric tons, and the parameter values listed in Table 1, advanced fuels like DD or D^{3}He *reduce* VISTA's performance as calculated via IFRTRIP as shown in Table 2. Note that DD ignited with a hot spot of DT is still advantageous, however, because it requires three orders of magnitude less on-board tritium and DD can be obtained from sea water. In addition, the advantage of DD increases for compressed fuel column densities larger than 5 g/cm^2, but increased x_{fuel} requires a larger driver mass (i.e., a larger laser) to compress the larger target. Therefore, if compressions larger than 5 g/cm^2 are to be considered, a detailed systems analysis must assess whether the additional driver mass will offset the advantage of lowered tritium inventory and improved Gf_{debris} for DD (or D^{3}He).

Table 2 shows that there is only marginal advantage of D^{3}He over DD—there is a significant lowering of the total neutron irradiation of nearby spacecraft, but otherwise, the two advanced fuels have similar performance. Therefore, if ^{3}He proves to be difficult to obtain, as is expected, and if a suitable cryogenic state of D^{3}He proves to be unattainable, as is expected, there is no need to pursue the use of D^{3}He—DD is sufficient. Even if non-cryogenic gaseous targets are considered, DD is probably still sufficient.

Most everyone might think that antimatter fuel would be the ultimate fuel for VISTA, but this is probably not the case. Antimatter-matter annihilations release energy in the form of charged pions and neutral pions, the latter decaying into gamma rays. These pions have energies of ~1 GeV, and hence have very long mean free paths in material (~140 g/cm^2). Thus, less than 4% of the tremendous energy produced can interact in target material to produce plasma debris for redirection by the magnetic thrust chamber. Consequently, the performance with antimatter fuel is much worse than that with DT fuel even though the mass-conversion efficiency for antimatter fuel is unity (see Table 3). This inability of the antimatter products to interact quickly requires a mass of antimatter (5×10^{27} antiprotons) that is enormous in comparison to even extrapolated antimatter production rates.

Table 2 Mars Missions With a 5-MJ Driver and Different Target Fuels

Item	*DT fusion*	*DD fusion*	*D^3He fusion*
Minimum Mars roundtrip time	145 days	261 days	241 days
Mass of tritium used	2237 kg	2.206 kg	2.074 kg
Engine alpha (kg/kW)	0.104	0.41	0.33
Vehicle mass ratio	3.23	3.97	3.96
Jet power	17.8 GW	3.64 GW	4.56 GW
Thrust	0.23 MN	0.092 MN	0.106 MN
Effective I_{sp}	15.5 ks	8.1 ks	8.8 ks
Total number of emitted neutrons	1.04×10^{29}	1.08×10^{29}	0.15×10^{29}

Table 3 Mars Missions With DT or Antimatter Fuel

Item	*DT fusion*	*Antimatter*
Minimum Mars roundtrip time	145 days	220 days
Fuel mass required (DT or antiprotons)	3728 kg	9.07 kg
Engine alpha (kg/kW)	0.104	0.25
Vehicle mass ratio	3.23	3.71
Jet power	17.8 GW	6.6 GW
Thrust	0.23 MN	0.13 MN
Effective I_{sp}	15.5 ks	10.0 ks

5. Power Flow

Figure 4 shows the overall power flow for VISTA for a piloted Mars mission with target gain G = 1500 (advanced technology) using the inductor power system (30 Hz). Note that 206 GW of the 225 GW of fusion power are simply radiated to space! The neutron-multiplication factor of 1.15 adds 0.74 GW of waste heat in the coil shield A little more than 1% must be recycled to operate the driver through the induction power system. Obviously, one effective way to increase the performance of VISTA is to improve the efficiencies of the various subsystems.

6. Target Gain

For transport to other planets, keeping the total (wet) mass near 6000 metric tons and ignoring any “spin out” to leave a planetary orbit, we calculate the VISTA performances shown in Table 4 for the advanced technology case (Table 1). By relaxing the restriction on total propellant mass, these flight times can be shortened by ~25% at most.

Table 4 VISTA total RT mission durations from Earth to the outer planets for different target gains G

Destination Planet	*RT Time (G=600) (days)*	*RT Time (G=1000) (days)*	*RT Time (G=1500) (days)*
Mars	229	184	145
Jupiter	632	486	422
Saturn	1081	842	735
Uranus	2093	1637	1425
Neptune	3236	2527	2134
Pluto	4087	3191	2692

7. Conclusions

A detailed systems-analysis code is considered to be essential for the analysis of any credible concept for fusion space propulsion. Such a code allows parameter and sensitivity studies, which are critical to determine the parameters that have the most leverage upon a particular design and its performance. Even more importantly, a systems analysis code permits more well-defined values for vehicle performance once the details for the various systems are known. Lacking such information, no credible performance estimates are possible.

VISTA was designed using a detailed system code. The critical parameters are the target gain and the total engine mass (especially the mass of the coil shield). Other important parameters include the radiator kg/kW and the driver efficiency and operating temperature. A complete power flow diagram is also essential, to identify where overall efficiency can be improved. VISTA's power-flow diagram shows that efficiency improvements would be advantageous in almost every system.

Although there are many areas where VISTA needs further R&D, [1] we hope our results serve as an illustration of what a systems analysis can provide. We therefore offer this approach as a guide for investigators who want to analyze other fusion space propulsion concepts.

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[2] C. Orth, "VISTA: A Vehicle for Interplanetary Space Transport Application Powered by Inertial Confinement Fusion," University of California, Lawrence Livermore National Laboratory, Report UCRL-LR-110500, in final preparation.

[3] M. Tabak, *Nuclear Fusion*, **36** (1996) 147.

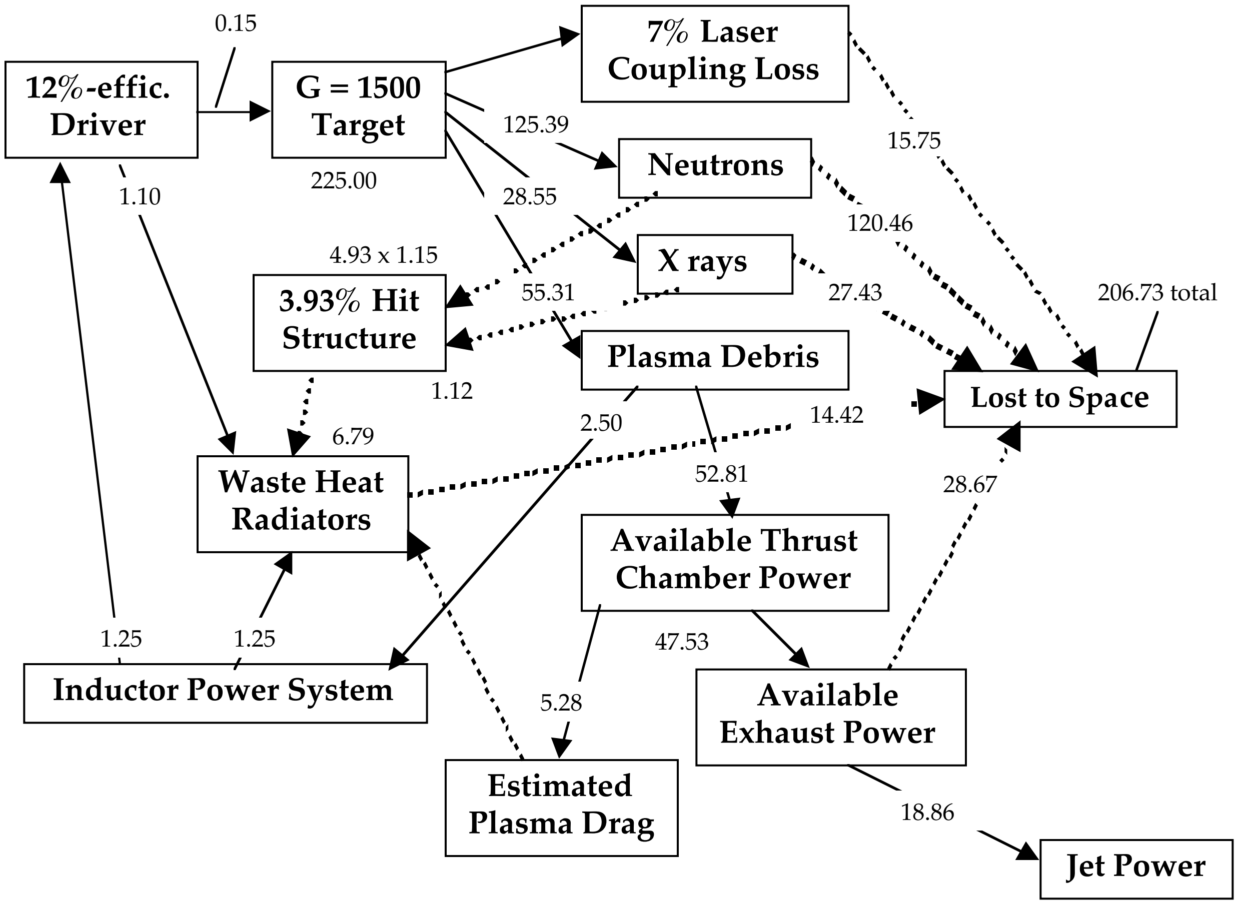

Figure 4: Overall Power Flow (in GW) for the Advanced-Technology Mission to Mars Using the Inductor Power System