UCRL-JC-129237
PREPRINT

Interplanetary Space Transport Using Inertial Fusion Propulsion

C. D. Orth

This paper was prepared for and presented at the
9th International Conference on Emerging Nuclear Energy Systems
Tel-Aviv, Israel
June 28-July 2, 1998

April 20, 1998

INTERPLANETARY SPACE TRANSPORT USING INERTIAL FUSION PROPULSION[a]

Charles D. Orth

Lawrence Livermore National Laboratory
L-490, P. O. Box 808, Livermore, CA 94550-0808, USA
Telephone: (925) 422-8665; FAX (925) 423-1076; E-mail: orth2@llnl.gov

Why Consider Inertial Fusion?

Interest in the transport of astronauts and cargo beyond the near-Earth vicinity and especially to Mars seems to be on the increase. Engines based on liquid or solid chemical rockets are severely limited for such missions because chemical reactions have a very low energy yield per unit of fuel mass, and therefore have rather low burn temperatures (< 1 eV). Consequently, even though chemical reactions can produce very large thrusts because of large mass-flow rates (and hence for only short durations), their exhaust speeds are necessarily very low. This is a significant fact because exhaust speed determines the upper limit for a spacecraft's velocity.

These principles are important when considering the transport of astronauts and cargo to Mars and beyond because the limitations of chemical reactions translate into propellant masses that are excessive and round-trip flight durations that exceed 2 or 3 years. Such long flight durations are thought to be very damaging to human health for two reasons: (1) the exposure to zero gravity for more than about 100 days causes such serious physiological deteriorations that astronaut functionality is significantly impaired, and (2) any exposure to cosmic rays for more than about one year causes significant risk of leukemias from tissue damage caused by neutron showers generated in

[a] This work was performed under the auspices of the US DOE by LLNL under contract number W-7405-Eng-48 for the Ninth International Conference on Emerging Nuclear Energy Systems (ICENES'98), Tel-Aviv, Israel, June 28 – July 2, 1998 (LLNL document number UCRL-JC-129237).

the spacecraft structure by incoming cosmic-ray protons. The only known means to circumvent these physiological deteriorations is to incorporate artificial gravity (e.g., to rotate the spacecraft) and to use a power source that can provide a high-temperature high-mass-flow-rate exhaust and hence a short flight duration.

We would normally expect fission, fusion, and antimatter-matter annihilation to provide high-temperature exhausts because their mass-energy conversion efficiencies are relatively high: 0.0009, 0.0038, and 1.0, respectively. Nevertheless, fission produces neutrons and gamma rays, and antimatter-matter annihilation produces pions and gamma rays, and all of these particles are difficult to form directly into an exhaust having any significant mass-flow rate. If an indirect approach is considered whereby centimeters of matter are used to absorb the energy of these particles, then the exhaust temperature is usually limited to the melt temperature of the material used to stop the particles (<1 eV). Fusion, on the other hand, has a charged plasma debris of temperature ≥1 keV, depending on the amount of extra mass (expellant) the fusion reactions must heat up. Said differently, chemical reactions and fission-powered engines can provide high power/mass ratios but only low exhaust velocities for significant mass flow rates, and nuclear-electric propulsion usually provides high exhaust velocities but only low power/mass ratios because of inefficient energy conversion—but fusion can theoretically provide both high power/mass ratios and high exhaust velocities. Therefore, in this paper, we will address the real possibility of using fusion for space propulsion.

In particular, Inertial Confinement Fusion (ICF) appears to be an ideal technology to power self-contained single-stage manned spacecraft within the interplanetary system because it has been shown to work in principle, and it can be utilized with a magnetic thrust chamber to form an exhaust directly from the emitted plasma debris. Although it is not well known, Halite/Centurion experiments conducted at the U. S. Nevada Test Site using energy from underground explosions to implode an inertial fusion capsule have already allowed the demonstration of excellent performance, putting to rest the fundamental questions about the basic feasibility to achieve high gain. In fact, the good performance of one capsule in this series provides a new, higher level of confidence that it will indeed be possible to design working laboratory capsules, such as those for the U. S. National Ignition Facility (NIF). Moreover, when capsule charged-particle emissions are redirected with a magnetic field, it is possible to avoid the plasma thermalization and resultant degradation of exhaust velocities that are unavoidable in systems where the exhaust contacts a mechanical thrust chamber that must not melt. Consequently, ICF can provide high power/mass ratios at high exhaust velocities.

On the other hand, when ICF involves a fusion target with a surrounding mass of roughly 50 g of expellant, as in the VISTA concept considered here, about 3/4 of the fusion energy is not used, and is simply allowed to pass out into space in the form of neutrons and x rays. Such loss would seem to give up a significant fraction of the energy advantage of fusion, were it not for the difficulties experienced by other technologies in forming an exhaust plume composed of the primary particles emitted from the reaction site. The fusion loss is also in a form that can be hazardous to both onboard astronauts and nearby spacecraft. The neutron and x-ray emissions thereby place significant constraints on the design of the spacecraft to avoid undesirable irradiations and to expel the waste heat deposited by any of these particles that do impinge on spacecraft structures. For ICF, however, unlike for magnetically confined fusion, the main issue is not whether the fusion will work, but whether it can be made efficient enough at laboratory scale and adapted safely for space propulsion in a form that provides sufficient jet power per unit of engine mass.

The VISTA Concept

With these thoughts in mind, and starting with Rod Hyde's 1983 description of an ICF-powered engine concept using a magnetic thrust chamber,[1] we and others conducted a more detailed systems study in 1986–1987 to develop a viable, realistic, and defensible spacecraft concept based on ICF technology projected to be available in the first half of the next century. This was not a conceptual study based simply on rocket equations, but a systems study considering all known elements of the spacecraft including heat rejection, micrometeoroid shields, structural vibrational problems, astronaut shielding, heat transfer, etc. A preliminary report was written, [2] and the final report is nearing completion.[3] The results include an entirely new conical spacecraft conceptual design

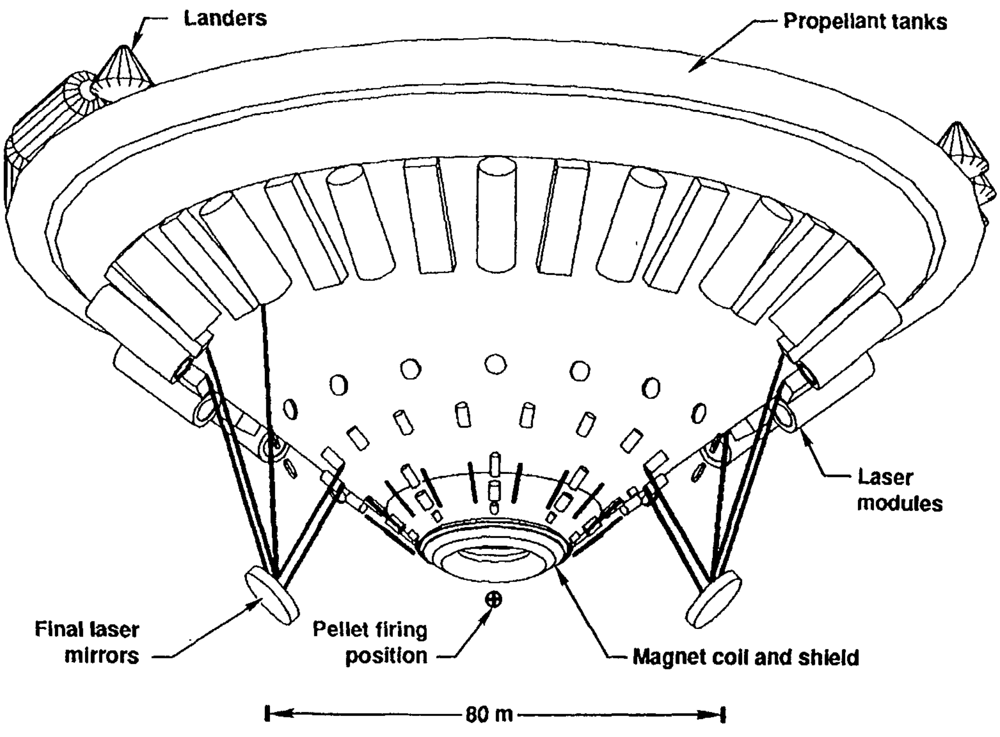


Figure 1 A schematic drawing of the VISTA spacecraft.

called VISTA—Vehicle for Interplanetary Space Transport Applications (Fig. 1).

The VISTA spacecraft would be assembled from sections launched into low earth orbit (LEO), and the assembled ship would be translated into an orbit above the radiation belts (e.g., a 700-km nuclear-safe orbit) for fueling and final checkout before being manned. VISTA would then become a self-contained single-stage "mother" ship to transport cargo and personnel from one planet to another without ever landing on a planet. Onboard landing craft would be deployed for planetary surface missions.

The VISTA engine consists of a laser system to irradiate ICF targets (pellets) positioned at the apex of the conical structure of the spacecraft, and a 12-Tesla "warm" superconducting magnet to deflect the plasma debris into a rearward plume for thrust (only ~4% of the neutron and x-ray emissions strike the spacecraft because of the conical shape). Throttling is accomplished by varying the target firing rate between 0 and 30 Hz. Variable exhaust velocity (variable I_{sp}) is also available by varying the amount of expellant used for each target. Calculations show that peak engine performance is given by a jet efficiency ε_{jet} of 34%, a thrust $< 2.4 \times 10^5$ N, a jet power $<$ 1.9×10^4 MW, and a product of specific impulse and $(\varepsilon_{jet})^{0.5}$ of 1.6×10^4 s.

VISTA's large inside and outside conical surface, where it is not blocked with laser and other equipment, consists of a system of trusses supporting heat-pipe radiators to expel waste heat using near-existing radiator technology. VISTA also offers propellant-based shielding of personnel from cosmic rays, and on-board artificial gravity through spacecraft rotation about its axis.

Assumed Technology

Some degree of subjectivity enters our systems analysis through the values of the performance parameters assumed for the various systems. For example, we have arguments to defend an average specific radiator mass of about 0.07 kg/kW at 1,000 K, which is about a factor of two better than today's technology. Although we have added another 0.007 kg/kW for micrometeoroid shielding, we still lack a very detailed radiator design, and are hence not certain whether this specification is really sufficient. The type of laser driver needed to ignite the fusion targets could be an excimer laser, or maybe better, a diode-pumped solid-state laser (DPSSL).[4] A DPSSL is pumped with laser diodes at ~900 nm wavelength, and lases at ~1047 nm wavelength. This type of laser can be pulsed at the necessary rate, and is thought to be extendible to both terrestrial power production and high-temperature space operation. We estimate the mass of a DPSSL for VISTA to be about 150 metric tons, excluding radiators. Other parameter assumptions are listed in Table 1. We limited the propellant mass to ≤ 4165 metric tons (i.e., total spacecraft mass ≤ 6000 metric tons) to accommodate assembly in low Earth orbit using the Heavy-Lift Launch Vehicle or equivalent. We considered DT target gains from 300 to 2000 to include advanced highly speculative target concepts such as the fast ignitor,[5] which employs less sophisticated capsule compression followed by a ~200-ps 10^{18} W/cm^2 laser pulse to "channel" through to the fuel core, and then a ~30-ps 10^{20} W/cm^2 laser pulse to ignite the fuel through the channel. Such a concept holds the promise of target gains in the 500 to 1000 range.

Table 1 Parameter Values Assumed for the Advanced Base Case

Parameter	Value	Parameter	Value
Driver energy	5 MJ	Extra kg/kWth for micrometeoroid shield	0.007
Driver efficiency	12%	Induction electrical system efficiency	50%
Expellant density	0.077 g/cm^3	Jet efficiency	34%
Expellant type	H_2	Magnet coil radius (m)	6.5
Fuel type	DT	Maximum pulse rate (Hz)	30
Fuel compressed $\rho\Delta r$ (g/cm^2)	5.0	Temperature, coil (K)	1500
Fuel capsule gain	1500	Temperature, driver (K)	900
Heat-pipe radiator kg/kWth @ 1000 K	0.07	Temperature, thermal systems (K)	1000

Performance

When configured for the baseline mission to Mars with a 100-ton payload and a total (wet) spacecraft mass of 6000 metric tons, the total VISTA round-trip mission durations are less than 6 months with very advanced DT fusion technology (target gains >1000). Fuels emitting fewer neutrons (DD or DHe^3) can also be used, but they do not provide as much performance as DT because the target energy gain for these fuels is worse by a factor of about six (and they require a larger more-massive laser system to initiate the fusion reactions). Nevertheless, advanced fuels (especially DHe^3) would reduce the tritium hazards experienced with DT, and could reduce neutron irradiation of nearby spacecraft.

To perform parametric studies while retaining the systems aspect of our study, we wrote a computer program (IFRTRIP) for flight trajectory analysis based on algebraic equations for travel times including coasts. This program minimized the travel time by varying four quantities: the total fusion energy expended during the trip, the fraction of the total energy used in going to the destination, the average jet power (i.e., the power in the directed exhaust), and the exhaust velocity (I_{sp})—all of which were assumed to be constant while the engine was operating at any time during the trip. Figure 2 compares the output of this program with the optimized results calculated by the Jet Propulsion Laboratory (JPL).[6] 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. Using IFRTRIP and the parameters shown in Table 1, we calculate a total flight time to Mars and back of 130 days, with a mass distribution as listed in Table 2.

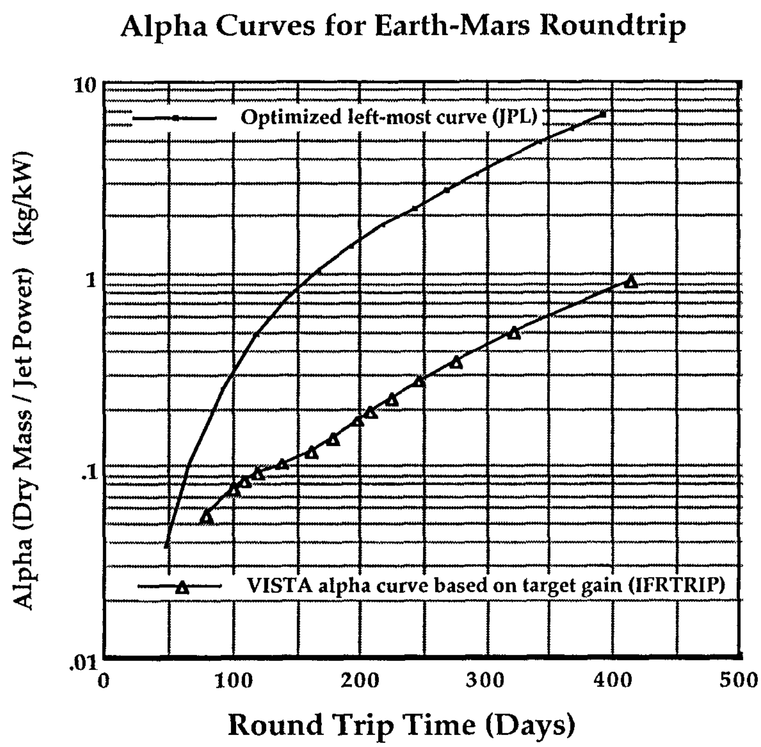


Figure 2 Comparison of one particular VISTA alpha curve with the exact JPL curve indicating the minimum trip time for any given alpha for any spacecraft to Mars.

Our calculations reveal that the critical parameters are the engine mass (i.e., the mass of the magnet coil/shield and the laser driver), and the target gain (see Fig. 3). Note that the shapes of the curves in Fig. 3 reveal that it is not really necessary to have a driver efficiency much above ~10% or a driver radiator temperature much above ~700 K, because little reduction in total trip time results for further increases in these parameters. It is therefore possible that a DPSSL might be used for a VISTA application, because it cannot exceed 700 K in operating temperature. On the other hand, steady improvement in performance occurs for increased target gain or improved radiator technology.

For transport to other planets, keeping the total (wet) mass near 6000 metric tons, we calculate the VISTA performance shown in Table 3. By relaxing the restriction on total propellant mass, these flight times can be shortened by ~25%.

Table 2 Distribution of mass in metric tons for VISTA advanced baseline mission to Mars

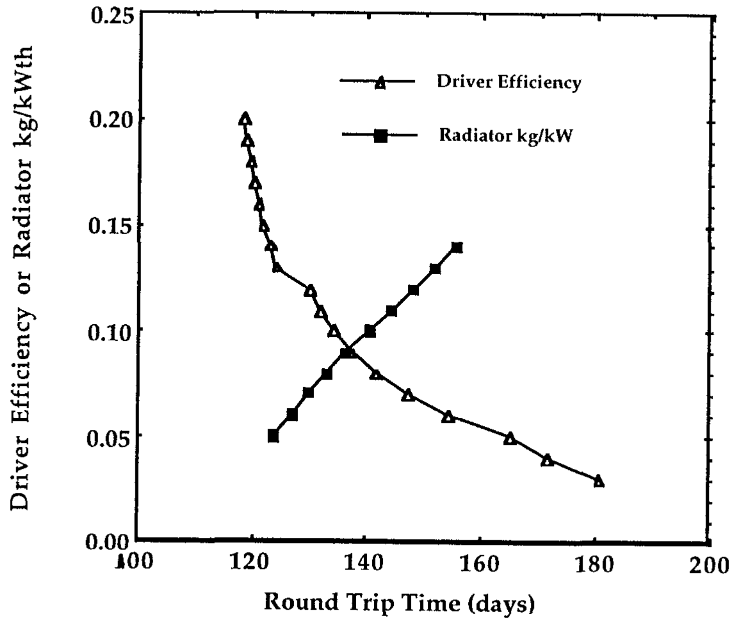
Sub-system	Mass	Total Mass
Payload System		289.
Payload	100.	
Payload Shield	189.	
Propellant System		4423.
DT fuel	41.	
Expellant (0.077 g/cm^3 H_2)	4124.	
Tritium refrigerator	50.	
Propellant tanks	208.	
Driver System		269.
Laser driver	150.	
Driver radiators	119.	
Thrust Chamber System		835.
Coil	216.	
Coil shield + structure	523.	
Radiators	96.	
Auxiliary Systems		184.
Startup reactor equipment	5.	
ALL radiator shields	21.	
Trusses	43.	
Inductor-coil power system	115.	
Total DRY MASS		**1835.**
TOTAL WET MASS		**6000.**

Table 3 VISTA total round trip mission durations to the planets for target gain 1500.

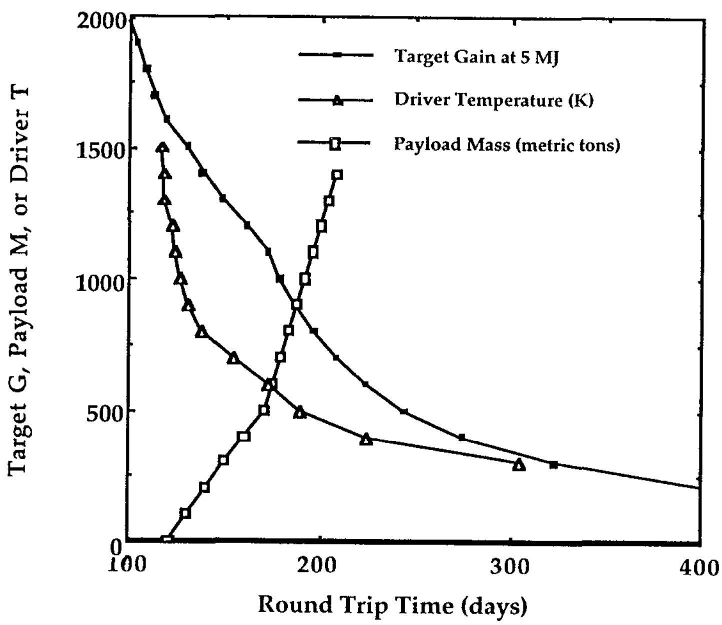
Destination Planet	Mission Duration
Mercury	145 days
Venus	97 days
Mars	130 days
Jupiter	403 days
Saturn	699 days
Uranus	1350 days
Neptune	2078 days
Pluto	2620 days

Comparison with other advanced technologies

We do not see a need to compare our results with those from antimatter-matter-annihilation concepts because the energy costs in making sufficient antimatter make this propulsion source essentially impractical. For single-stage self-contained spacecraft that must go round trip without using questionable maneuvers (e.g., air braking in the Martian atmosphere), VISTA performance (e.g., round trips to Mars in ~4 months) will necessarily be better than the performance for nuclear-thermal and nuclear-electric



3a



3b

Figure 3 Dependence of total flight duration on several parameters.

fission systems ($\geq$ 2/3 year) because the effective exhaust temperature (i.e., specific impulse) is roughly ten times larger for high mass flow rates. In fact, as seen from Fig. 3b, VISTA performance is unsurpassed (< 2/3 year) for target gains $\geq$500.

Conclusions

In this paper, we indicate how the great advantages that ICF offers for interplanetary propulsion can be accomplished with the VISTA spacecraft concept. The performance of VISTA is expected to surpass that from other realistic technologies for Mars missions if the energy gain achievable for ICF targets is above several hundred. Based on the good performance expected from the U. S. National Ignition Facility (NIF), the requirements for VISTA should be well within the realm of possibility if creative target concepts such as the fast ignitor can be developed.

We also indicate that a 6000-ton VISTA can visit any planet in the solar system and return to Earth in about 7 years or less without any significant physiological hazards to astronauts. In concept, VISTA provides such short-duration missions, especially to Mars, that the hazards from cosmic radiation and zero gravity can be reduced to insignificant levels. VISTA therefore represents a significant step forward for space-propulsion concepts.

References

[1] R. A. Hyde, "A Laser Fusion Rocket for Interplanetary Propulsion," UCRL-88857, University of California, Livermore, CA (1983), and the 34th International Astronautical Federation, held in Budapest, Hungary, 10-17 October 1983.

[2] C. D. Orth, G. Klein, J. Sercel, N. Hoffman, K. Murray, and F. Chang-Diaz, "Transport Vehicle for Manned Mars Mission Powered by Inertial Confinement Fusion," AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, San Diego, CA, June 29 – July 2, 1987, Paper AIAA-87-1904 Rev. 1.

[3] C. D. Orth, G. Klein, J. Sercel, N. Hoffman, K. Murray, and F. Chang-Diaz, "VISTA: A Vehicle for Interplanetary Space Transport Applications Powered By Inertial Confinement Fusion," Report UCRL-LR-110500, University of California, Lawrence Livermore National Laboratory, Livermore, CA 94550 (1998).

[4] C. D. Marshall, L. K. Smith, R. J. Beach, M. A. Emanuel, K. I. Schaffers, and S. A. Payne, "Diode pumped ytterbium-doped $Yb:Sr_5(PO_4)_3F$ laser performance," IEEE J. Quantum Electronics, **32**, #4, p. 650, 1996 (and ibid., 1995 ASSL Conference Proceedings); C. D. Marshall, L. K. Smith, S. Sutton, M. A. Emanuel, K. I. Schaffers, S. Mills, S. A. Payne, W. F. Krupke, and B. H. T. Chai, "Diode-pumped gas-cooled-slab laser performance," *OSA Trends in Optics and Photonics on ADVANCED SOLID STATE LASERS, Vol 1*, Ed. S. A. Payne and C. R. Pollock, Topical Meeting January 31 – February 2, 1996, San Francisco, CA, Optical Society of America, pp. 208–212, 1996.

[5] Max Tabak, J. Hammer, M. Glinsky, W. Kruer, S. Wilks, J. Woodworth, E. M. Campbell, M. Perry, and R. Mason, "Ignition and High Gain with Ultra-Powerful Lasers," *Physics of Plasmas*, Vol. 1 # 5, pp. 1626–1634 (1994); and Max Tabak, private communication (1998).

[6] Carl Sauer, Andrey Sergeyevsky, and Joel Sercel, Jet Propulsion Laboratory, private communication (1987).

Technical Information Department **• Lawrence Livermore National Laboratory**
University of California • Livermore, California 94551