Aneutronic Fusion Propulsion for Earth-to-Orbit and Beyond

by H.D. Froning, Jr.,Flight Unlimited, 5450 Country Club, Flagstaff, AZ 86004
and Robert W. Bussard, Energy/Matter Conversion Corporation,
680 Garcia Street, Santa Fe, NM 87505, <emc2qed@comcast.net>

Abstract

Previous work by Bussard has indicated that certain aneutronic fusion rocket propulsion systems could enable establishment or self-supporting space colonies throughout the solar system at transportation costs less than one-tenth current costs to place satellites in orbit around earth. This paper shows that such colonization costs would not significantly increase, even if fusion propulsion performance that is significantly less than that estimated by Bussard would cause increase in the masses and flight times of some of the vehicles. Costs for some colonization missions would significantly increase if colonization vehicles could not be used for other space missions. But even under such circumstances, transportation costs would be extraordinarily low compared to those currently envisioned for solar system exploration.

Introduction

Although there is no official plan to send humans beyond earth orbit, periodicals such as Aviation Week and Space News indicate that NASA is performing preliminary work on transportation concepts that could send as many as 6 astronauts to Mars sometimes between 2010 and 2015. And these periodicals indicate that a cost goal of about 25 billion dollars, spent over about 8 years has been set forth by the NASA Administrator for such a Mars mission. It would, of course, be desirable that such initial landings be followed by larger scale explorations by many people. NASA is, therefore, examining advanced propulsion concepts that could enable economical large scale solar system exploration by many people.

One example of an advanced propulsion concept that could conceivably enable such economical large scale exploration is the "Quiet Energy Discharge" (QED) fusion power and propulsion system.[1,2,3,4] Bussard indicates that QED engine systems could enable colonies of: 4,000, 1,200, and 400 people to be emplaced upon celestial bodies such as Luna, Mars and Titan for less than one-half the current NASA budget for 10 years.[5]

In this respect, Bussard[5] reflects our best current estimates of QED fusion propulsion performance for colonizing Luna, Mars and Titan. But since history reveals that developed aerospace vehicles sometimes posses less propulsion performance and higher costs than original estimates, one of us (Froning) looked at the sensitivity of colonization costs to significantly lower QED engine performance and to more conservative cost estimation assumptions.

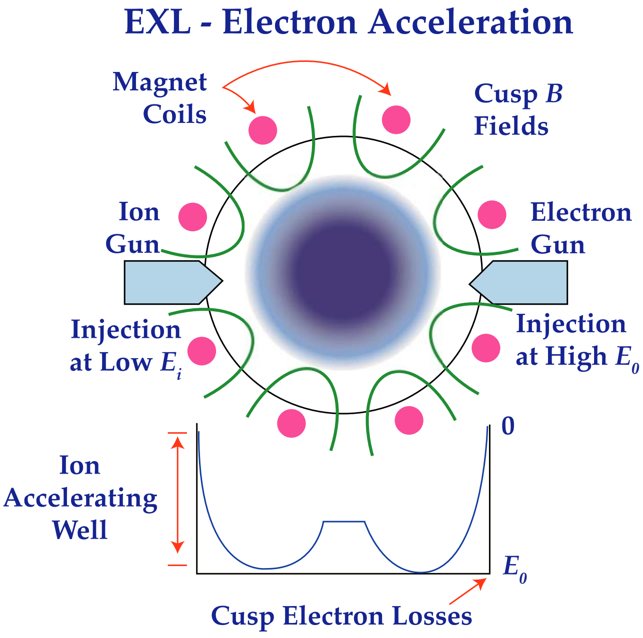

Figure 1a — Aneutronic Fusion by Electrostatic Confinement

OED Fusion Propulsion

QED engines are described elsewhere in this and previous STAIF Proceedings and therefore will only be very briefly summarized here. As shown in Figure 1a, aneutronic fusion reactions (that emit no neutrons and cause no radioactivity) are accomplished within a reactor core as protons and Boron-11 ions are driven into sufficiently close proximity by the electrostatic repulsion of surrounding electrons that are confined within the central portion of the reactor by quasi-spherical polyhedral magnetic fields.

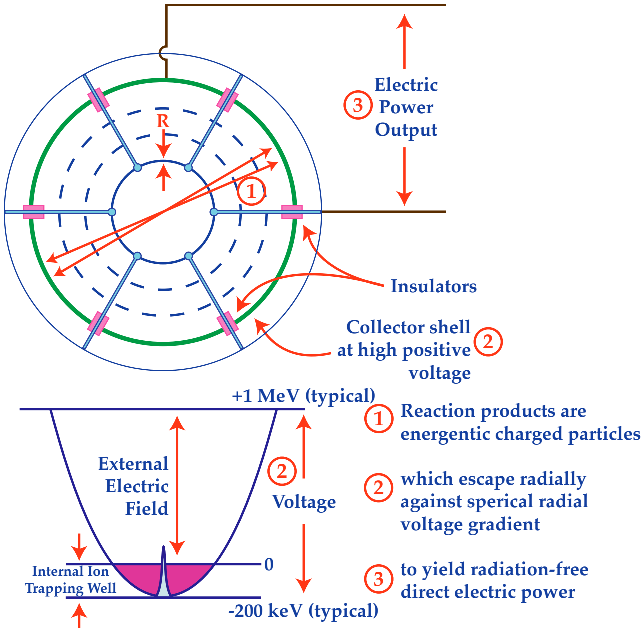

Figure 1b — Spherical grid structure used to extract energy

Outward expanding fusion products are Helium 4 ions whose energies and charges allow them to be effectively slowed and collected as electricity by spherical grid structures that are maintained at appropriate voltage gradients. The collected electricity is transformed into electron beams that deposit their energy into flowing propellant within a chamber, producing a very high temperature gas/plasma which expands within a magnetically insulated exhaust nozzle to produce thrust at very high specific impulse (I_{sp}). A typical QED engine concept is shown in Figure 2.

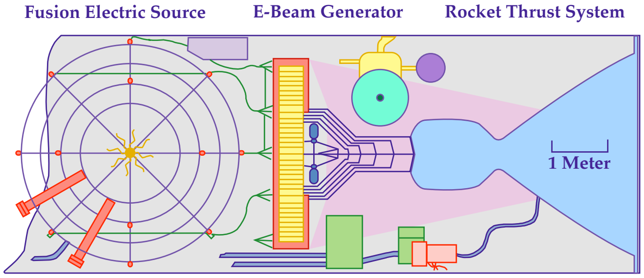

Figure 2 — QED Fusion Rocket Propulsion System.

Because the emitted fusion energy contains no neutrons or radioactivity; and because most of it is transformed into electricity rather than dissipated in waste heat, only modest shielding mass is required, and cooling/thermal protection needs are minimal. And because generation of fusion energy is accomplished without massive masses and its conversion into electrical energy for propellant heating is accomplished within thin structures of relatively modest size and mass, QED engine thrust-to-weight ratios for any I_{sp} level are two to three orders of magnitude greater than those of other fusion propulsion systems that have been proposed for future flight. Furthermore, QED fusion can achieve high specific impulse with simple and inexpensive, non-cryogenic propellants (such as water) which would enable much simpler and lower cost fueling operations and support on the surface and in space. The “clean” exhaust and relatively high thrust-to-weight of QED engines are, therefore, attractive, not only for flight beyond earth orbit, but flight from earth to orbit as well.[1,6]

Colonization vehicles powered by QED fusion could, of course, only be built after the basic QED engine is developed. Work by the authors believe that such development could be accomplished in 15-17 years. An additional 8-10 years of vehicle development would therefore allow the colonization missions described here to start about 2022-2024.

Solar System Colonization

The cost of establishing colonies of 4000, 1200 and 400 people on the Moon, Mars and Titan (the largest moon of Saturn) by means of reusable vehicles powered by QED fusion propulsion have been estimated by Bussard.[5] Colonization of each celestial body would be accomplished by: reusable launch vehicles that transport required colonization peoples and materials and transfer vehicle elements to low earth orbit (LEO) and provide earth return transportation as well; reusable transfer vehicles that make the relatively long transits between orbits around earth and orbit around the colonized celestial body; and reusable shuttle vehicles that take colonization personnel and materials down from orbit to the celestial body surface - and back up to orbit, to return personnel and materials back to earth. And because many people and enormous amounts of materials must be frequently and rapidly transferred between earth and the colonized bodies during their 10 year colonization period, many flights are made by each reusable vehicle.

Colonization Vehicle Types

A fusion powered, single-stage-to-orbit winged vehicle (that employed horizontal takeoff), was configured for taking all peoples, materials and vehicle elements for all colonization missions from earth to low earth orbit (E/LEO). The Luna Colony Mission required an additional vehicle type for transfer of people and materials from LEO to low lunar orbit (LLO) and to then land them on the lunar surface (L). This LEO/L transfer vehicle was fueled in earth orbit with water and then “refueled” on Luna with water for return from Luna to LEO (L/LEO). Two additional vehicles are required for the Mars Colonization Mission: a transfer vehicle to take colonization personnel and materials between LEO and low orbit about Mars (LMO) and a LMO/M shuttle vehicle to take personnel and materials from LMO to Mars surface (M) and to return personnel, materials and propellants to LMO for return to earth by the LEO/LMO vehicle. Thirty transfer vehicles are assigned to the Mars colonization mission - with 80 round-trip transfer flights per year required between LEO and LMO over the 10 year colonization period.

Two additional vehicle types are also required for the Titan Colonization Mission: a LEO/L TO transfer vehicle for transportation between LEO and low orbit about Titan (LTO) and a LTO/T shuttle vehicle for landing on and taking off-from Titan's surface (T). Table 1/2 show the estimated mass characteristics of each vehicle type for each colonization mission, together with estimated engine mass and performance for each. In some instances vehicle and engine characteristics and flight durations differ somewhat from those shown in Bussard[5] because they reflect more conservative engine performance estimates.

Table 1 and 2 — Colonization Vehicle Characteristics

	Earth to Orbit Vehicle	Lunar Transfer & Shuttle Vehicle	Mars Transfer Vehicle	Mars Shuttle Vehicle	Titan Transfer Vehicle	Titan Shuttle Vehicle
Gross Weight (MT)	500	500	500	250	400	138
Propellant Mass (MT)	210	304	329	60	252	27
Payload Mass (MT)	80	80	78	100	45	45
Dry Mass (MT)	210	116	171	90	103	66
Propulsion (MT)	80	40	100	22	45	26
No. of Engines	(6)	(3)	(2)	(1)	(1)	(2)
Engine Thrust (kN)	320	320	110	320	31	320
Engine I_{sp} (s)	2,550	2,550	3,575	2,550	70,000	2,550
Impulsive v (km/s)	10.7	15.8	39.0	7.0	343	5.5
Flight time	42 minutes	20 hour	2.9 months		3.6 months	

QED Fusion Engine Types

Engines of the reusable launch vehicles and shuttle vehicles used only regenerative cooling, which limited I_{sp} to approximately 3800 for water - which was the selected propellant for all colonization vehicles. Space radiators were added to Mars Transfer Vehicles to carry off more waste heat This enabled I_{sp} as high as 5500 and average one-way transit times between Earth and Mars as short as 50 days. The enormous distance between Earth and Titan required a QED engine specific I_{sp} of approximately 70,000 in order to reduce one-way transit times to less than 3 months. Such enormous I_{sp} requires QED fusion energy to be directly deposited within working fluid - without an intermediate electrical energy conversion cycle. This required containment of the QED fusion reaction within a spherical toroidal magnetic field - which traps expanding fusion ions until sufficient collisions with diluent ions (that are also confined by the field) collects their energy. A highly heated diluent/propellant mixture is therefore created - which expands to enormous exhaust velocity through a magnetic diverter nozzle. This diluted fusion product (DFP) engine was described in more detail by Bussard.[2,5]

Estimated Colonization Cost

Estimated colonization transportation costs are extraordinarily low because of:

a) High payload mass/vehicle mass ratios made possible by the high engine thrust/mass and I_{sp} of QED fusion propulsion

b) Inexpensive, easy-to-handle non-cryogenic propellant - water

c) A high degree of vehicle reusability that was assumed to be achievable for the very large number of colonization flights.

Further cost reduction resulted from assuming that vehicle reliability, maintainability, and flight lifetime goals set forth by NASA[7] for highly reusable space transportation could be achieved - thereby enabling colonization vehicles to be used for many more missions and over a much longer time than their 10 years of colonization use. Thus, only a portion of the vehicle acquisition costs were amortized over the colonization flights. Table 3 shows the total mass delivered to each colonized celestial body, together with the numbers of flights used in transporting materials and colonists between earth and each colonized body.

Table 3 also shows the total transportation costs of $16.9B, $21.1B. and $21.9B to colonize Luna, Mars, and Titan respectively. Bussard envisions use of the colonization vehicles to return colonists to earth periodically, together with commercial and scientific materials obtained from the colonized bodies. Since the cost for a return trip would be roughly the same as that for an outbound colonization trip, Table 2 also shows the approximate costs of returning payloads to earth. In this respect, Table 3 shows that if values of returned materials of products from Luna, Mars and Titan are greater than $169, $337 and $911/kg respectively, return transportation would make a profit for the transportation provider.

Table 3 — Colonization Costs

	Luna	Mars	Titan
Colonization people	4,000	1,200	400
Earth/LEO vehicles	4	4	3
Transfer vehicles	4	30	27
Shuttle vehicles	0	4	3
Colonization mass delivered (MT)	100,000	60,000	24,000
Total colonization Cost ($B)	$16.9	$21.1	$21.9
Return Payload Cost ($/kg)	$169	$337	$911

Sensitivity to Propulsion Efficiency and Costing Assumptions

Because developed aerospace vehicles sometimes possess less propulsion performance than that predicted in original estimates, we briefly examined the sensitivity of colonization costs to increased vehicle mass or flight time caused by significantly lower QED engine performance than that estimated.[5]

For the reusable launch vehicle used on all colonization missions, we investigated the effect of reducing QED engine I_{sp} 35 percent below Bussard's estimated value. And, for this lower value, we increased engine mass 35 percent above the value estimated by Bussard. This 35 percent degradation in engine specific impulse and thrust-to-weight resulted in a 25 percent vehicle dry mass increase (from 120 to 150t) and a 50 percent gross mass increase (from 250 to 380t) for Bussard's 35t payload mass.

However, it was found that use of the reduced engine performance in a vehicle with 80t payload capability (which is currently being considered in NASA heavy lift vehicle studies for Mars missions) resulted in a 500t vehicle with payload/dry mass and payload/gross mass ratios of 16 and 38 percent (compared to 14 and 29 percent for Bussard's vehicle with a 35t payload). Greater payload capability would also reduce the number of E/LEO flights required for initial assembly of Mars and Titan transfer vehicles by more than a factor of 2. Thus, it was concluded that reduced QED engine performance should not increase E/LEO delivery costs by Bussard[5] if E/LEO vehicle payload mass is increased.

Some benefit was gained for E/LEO vehicles from the higher thrust that was associated with lower I_{sp}. Higher thrust, coupled with more optimal trajectory shaping and propulsive energy management than was used in Bussard[5] significantly reduced ascent drag and gravity losses - which resulted in about a 25 percent reduction in required impulsive velocity. Such benefit is, of course, not achievable with Mars or Titan transfer vehicles that fly in almost drag and gravity free conditions. Therefore, it was a 35 percent degradation in engine I_{sp} and mass would have a much more profound effect on the masses of these vehicles if transit time is held constant.

If vehicle mass and payload (rather than transit time) is held constant, transit time between Earth and Mars and between Earth and Titan would increase by about 35 percent - resulting in average transit times of approximately 80 and 110 days respectively. Since even the longer transit time to Titan is much less than the 6 month transit times that are currently considered acceptable for manned journeys to Mars, longer flight times (rather than heavier vehicles or lighter payloads) was deemed the best way of minimizing cost increases if QED engine performance is significantly less than that estimated in Bussard.[5]

The vehicle masses, impulsive velocities and flight times shown in Table 1 reflect 35 percent less engine I_{sp} and thrust/weight than that which Bussard estimates to be achievable for QED fusion engines. This can also be viewed as a 35 percent performance or design margin to cover contingencies or things that are yet unknown. Similarly, the costs shown in Table 3 reflect a 35 percent cost margin - an arbitrary 35 percent increase above the colonization costs estimated in Bussard.[5]

Amortizing the entire acquisition cost of the transfer and shuttle vehicles over only the 10 years of colonization flights each flew (rather than over the total number of flights they could fly within their lifetime) was also considered. This effect was not significant for Luna and Titan colonization missions - which did not require acquisition of large numbers of vehicles. But large numbers of transfer vehicles were required for the Mars colonization mission. Here, amortization of the entire acquisition cost of 30 LEO/LMO transfer vehicles over only the 10 years of Mars colonization flights would increase colonization costs from about $21B to $40B. But even this higher Earth to Mars space transportation cost - which would be approximately $667/kg - would be about a factor of 10 less than current transportation costs to earth orbit, and no more than desired costs set forth by NASA for future highly reusable earth to LEO space transportation. The colonization cost per person associated with this higher cost transportation would be less than one-hundredth NASA's hoped-for cost per person to land (for a short stay) the first people on Mars.

Conclusions

Just as Columbus could not forecast the worth of colonizing a new world before setting forth on his first voyage to the Americas, so the values of colonies on Luna, Mars, and Titan are almost impossible to quantify today. However, history shows that those who open up new frontiers invariably underestimate the eventual values of their explorations. And we are encouraged that our estimated transportation costs to remote celestial bodies are roughly 10 times less than those which some commercial concerns are willing to pay for much shorter space travels to satellite orbits around earth.

On the other hand, just as air flight was not revolutionized until propellor propulsion was replaced by jet propulsion. so it is conceivable that spaceflight will not be revolutionized until jet propulsion is replaced by a new mode of impulsion (such as field propulsion) for future flight. But., at present., we believe that QED fusion powered jet propulsion systems offer the only known means of beginning space colonization - of beginning the actual expansion of humanity beyond the limits of earth.

This work was performed under internal funds by Flight Unlimited.

Publishing History

First published January 15, 1998. Reformatted and color illustrations added by Mark Duncan. References updated April 2009.

References

[1] Robert W. Bussard and Lorin W. Jameson; "The QED Engine Spectrum: Fusion-Electric Propulsion for Air-Breathing to Interstellar Flight," 29th Joint Propulsion Conference, Monterey, CA. Paper #AIAA.4.1-93-2006.

[2] Robert W. Bussard, Lorin W. Jameson and H.D. Froning; "The QED Engine: Fusion-Electric Propulsion for CIS Oort/Quasi-Interstellar (QIS) Flight," 7th Interstellar Space Exploration Symposium Proceedings of the 44th IAF Congress, Oraz, Austria, Paper #IAA.4.1-93-708.

[3] Robert W. Bussard and Lorin W. Jameson; "The QED Engine System: Direct-Electric Fusion-Powered Rocket Propulsion Systems," in Proc. 10th Symposium of Space Nuclear Power and Propulsion, CONF-930103, MS. El-Genk and MD. Hoover, editors, American Institute of Physics, NY, AIP Conference Proceedings 271, Volume 3: pg 1601-1611.

[4] Robert W. Bussard and Lorin W. Jameson; "Design Considerations for Clean QED Fusion Propulsion Systems," in Proceedings 11th Symposium on Space Nuclear Power and Propulsion, CONF 940101, MS. El-Genk and M.D. Hoover, editors, American Institute of Physics, NY, AIP Conference Proceedings 301, volume 3: pg 1289-1296.

[5] Robert W. Bussard; "System Technical and Economic Features of QED-Engine-Driven Space Transportation," 33rd Joint Propulsion Conference, Seattle, WN, Paper # AIAA-97-3071.

[6] H.D. Froning and Robert W. Bussard; "Fusion-Electric Propulsion Technology for Hypersonic Flight," 44th Congress of the International Astronautical Federation, Graz, Austria, Paper # IAF-93-5.3.473.

[7] NASA (1996) "A Cooperative Agreement Notice — Highly Reusable Space Transportation", Advanced Concepts Office, George C. Marshall Space Flight Center, Huntsville, AL.