Mach-Lorentz Thruster Spacecraft Applications

Paul March

309 Sedora Drive, Friendswood, TX 77546 USA
281-996-9265, paulmarch@sbcglobal.net

Abstract. At STAIF-2006, the author presented research into the Mach-Effect and its spin-off, the Mach-Lorentz Thruster (MLT); both of which were created by Woodward. Herein, these MLTs are assessed to see how they could impact the transportation industry if the MLT's force output scales as predicted by Woodward. These MLT force scaling rules, which are that the MLT output force varies with the cube of the cap voltage and operating frequency but linearly with the B-field, provide a viable path to increasing the MLT's current specific thrust of ~$1x10^{-5}$ Newton per Watt (N/W) up to ~1.0 N/W, but to do so these MLTs have to overcome their already evident material and control technology issues. However, a preliminary MLT powered spacecraft design demonstrates the enhanced performance capabilities of such a vehicle assuming the availability of 100 Watt/kg electrical power supplies, while illuminating some of the MLT design difficulties as well. This 26.5 metric tonne MLT powered spacecraft points to new capabilities such as traveling from the surface of the Earth to the surface of the Moon using *only* electrical fuel cell and battery derived energy. Roundtrip times for such an Earth-Moon-Earth journey, carrying a crew of two with a 2-metric tonne payload both ways, could be under 12-hours *without refueling*; assuming 0.50-to-1.50 Earth-g's continuous accelerations and decelerations for the various flight segments. If perfected, this MLT propulsion technology could also power land, sea and air vehicles back on Earth.

Keywords: Mach-Effect, Mach-Lorentz Thruster, MLT, recycled propellant, fuel cells, spacecraft, moon.
PACS: 89.40.-a.

INTRODUCTION

Could the Mach-Lorentz Thruster (MLT) usher in a new era in space exploration? If the nascent MLT technology scales as Woodward's theory predicts, then it might. (Brito and Elaskar 2003; Mahood, March and Woodward 2001; March and Palfreyman 2006; Woodward 2004, 2005) It could allow us to go anywhere interesting in our solar system in less than three weeks; travel times limited only by the specific power of the available power supplies available and the accelerations human physiology can endure. However, there's a large chasm between this vision of what could be and where we are today, for there are several MLT engineering challenges to be overcome first before we can make this vision a reality. We still need to determine experimentally what the MLT's actual specific thrust and thrust to weight ratio scaling rules will be by constructing more powerful MLTs than the tens to hundreds of micro-Newton test articles that have been demonstrated thus far. MLT capacitor aging issues also need to be solved. (March and Palfreyman 2006; Woodward 2006), but given that these engineering tasks are not insurmountable, what new capabilities could these MLTs offer a spaceship designer?

The basic performance parameters of an MLT powered vehicle include the MLT's *specific thrust*, electrical input energy, MLT subsystem mass, operating lifetime, the vehicle's electrical power subsystem's *specific power* ratio, gross-lift-off-weight (GLOW), and obtainable payload mass fraction. All of these parameters interact with each other, but the primary parameters of interest in an MLT powered vehicle are the MLT's specific thrust in N/W and the vehicle's electrical generation subsystem's specific power in watts per kg (W/kg). A quick survey of existing high performance turbofan jets and rockets shows that the current specific thrust values for these engine types runs in the range of ~$2.5x10^{-3}$ N/W for high bypass turbofan jets to ~$2.5x10^{-4}$ N/W for the Space Shuttle Main Engine (SSME) rocket. Electrical power generation subsystems run in the 10-to-200 W/kg range dependent on their run-times, which is driven by their energy source. Due to the fact that the MLT's recycle their onboard propellant, their specific thrust could be much higher than these current engine examples and may be as high as 10 N/W or higher dependent on the desired peak acceleration and other gravinertial issues not explored in this paper. For this MLT capabilities study, a variable specific thrust range of 0.5-to-1.0 N/W was chosen to allow peak vehicle accelerations of up to 2.0 Earth-gravities (E-g = 9.81m/sec^2) while allowing economy cruise at ~0.5 E-g when in deep space.

Given the foregoing constraints, what could an MLT vehicle with variable specific thrust MLTs accomplish if we combined them with an electrical power subsystem with a specific power of ~150 Watts/kg? This design study indicates then that we could perform routine missions to the Moon and beyond safely, quickly, conveniently and economically. This MLT powered vehicle could fly from the Earth to the Moon and back carrying a crew of two and two metric tonnes of cargo per round trip, in less than twelve hours, *without refueling* the MLT's fuel cell tanks. Back on Earth, the same variable specific thrust MLT's could provide the means to construct the fabled "flying car" as well as ultimately replacing all internal and external combustion engines in land, sea, and air applications.

BUILDING A 1.0 N/W MLT

Current experimental MLT's are operating in the 1x10^{-6} to 1x10^{-4} N/W specific thrust ratios, which indicates that four to five orders of magnitude improvement in the MLT's specific thrust is needed before the desired 0.5-to-1.0 N/W performance levels can be met. Figure-1 shows how this thrust per watt relationship is affected by the MLT operating frequency and cap voltage, indicating that MLT operating frequencies of at least 10 MHz will be needed to obtain the desired specific thrust range. If we allow for performance margins, an operating frequency in the range of 20-to-80 MHz will be needed for a robust 0.5-to-5.0 N/W MLT design.

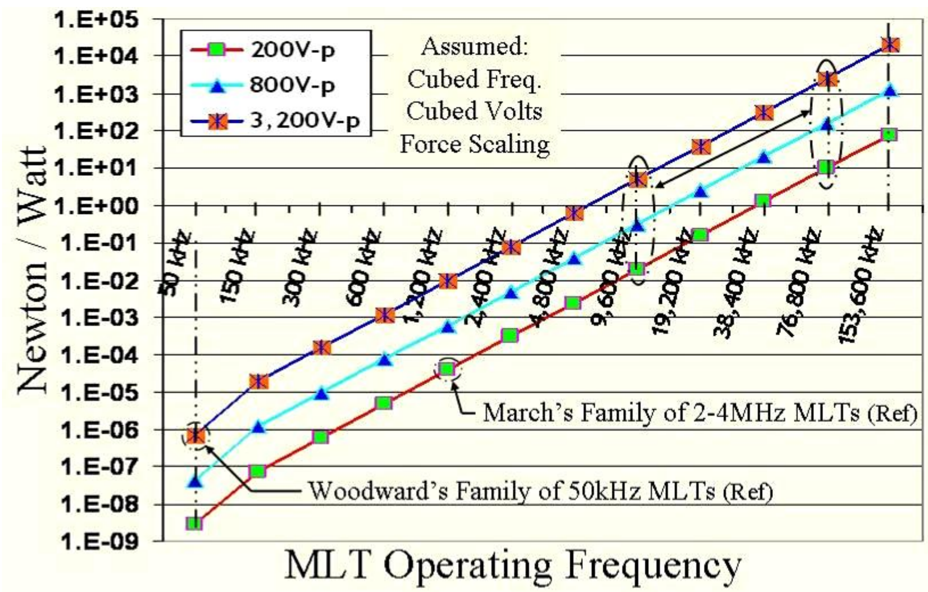

FIGURE 1. MLT Specific Thrust (N/W) Scaling with Increasing MLT Cap Voltage and Operating Frequency.

The other major concern that will have to be addressed before reliable MLTs can be built is the issue of MLT capacitor ageing. MLT thrust falls off with accumulated operating time, while operating with constant input power and operating frequency. To date, we have seen MLT capacitor life-times on the order of tens of minutes to approximately one hour of cumulative operating time before their MLT thrust signatures disappeared. We believe this is due to a known dielectric ageing effect first seen in multi-crystalline energy storing ceramic capacitors and ceramic piezoelectric actuators. These types of ceramic devices suffer from a decline in their capacitance which follows an exponential decay rate with time that is roughly proportional to the capacitor's dielectric constant, total number of charge/discharge cycles, and the magnitude of the energy stored per cycle. (Moulson and Herbert 2003; and Jaffe and Cook 1971) This is very similar to the cyclic fatigue limit in a load bearing structure like a cyclically loaded bridge truss. Heating the capacitors above their Curie temperature for several hours seems to reverse temporarily this MLT thrust decay problem, but better solutions need to be found if this capacitor ageing and fatigue cycle-limit problem is to be solved to the point that we can provide MLT operating times greater than 1,000 hours.

FIRST GENERATION MLT SPACESHIP – THE WARPSTAR-1

Provided we have built a 0.5-to-1.0 N/W, 10^{15} cycle life time MLT, what could this first generation human crewed MLT powered spacecraft look like? MLT's lend themselves quite easily to very large spacecraft designs, but for a first generation vehicle, it would be prudent to keep the vehicle small, providing for a crew of two and a payload in the 2 metric tonne class. MLT's also provide great engine mounting location flexibility due to the fact that their "momentum exhaust" is a gravinertial wave which can be transmitted either directly from the MLT to/from the distant mass in the universe, or by first going through the vehicle's local structures and passengers with no anticipated distress to either. This WarpStar-1 vehicle concept is shown in Figure 2.

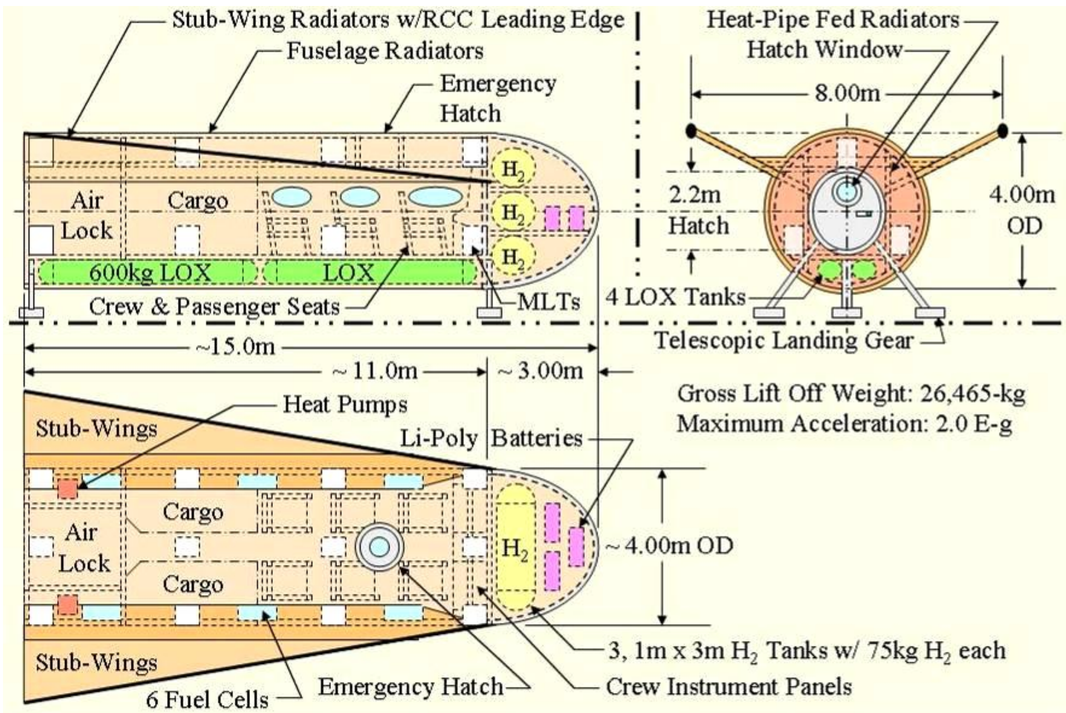

FIGURE 2. 3-View Drawing of the WarpStar-1 MLT Concept Spacecraft.

Safety concerns indicate that a first generation electric spacecraft should include conventional aerodynamic backup systems. In the event of primary propulsion failure, aerodynamic lift and control surfaces, along with heat resistant ceramic tiles would enable it to make unscheduled hypersonic reentries much like the Space Shuttle. Other safety concerns suggest it should be equipped with a redundant fuel cell and battery electrical power subsystem that drives an array of twelve (12) "Tesseract" MLT propulsion assemblies mounted throughout the spacecraft. If two of the fuel cells and up to five MLT Tesseract assemblies failed, the craft could still fly above the Earth and land normally. It could also fly with four failed fuel cells and eight failed Tesseract assemblies while over the Moon.

Fast transit is a result. This design could provide round-trip service to the Moon in under 12-hours or less accelerating half way there, then decelerating the rest. If it was driven past the human comfort zone of approximately 1.0 E-g and instead accelerating at the WarpStar-1's maximum of 2.0 E-g acceleration; it could execute a one way trip from the Moon to Earth in as little as 2.5 hours assuming MLTs with 1.0 N/W specific thrust.

Convenience and Utility are intrinsic. The design provides vertical takeoff and landing (VTOL) along with hover capabilities. It could fly continuously in the Earth's atmosphere at subsonic and low supersonic speeds as the need dictates, and land silently with no downwash in any landing area large enough to *park* a business jet. In space, the preferred operating mode for the vehicle would be a near constant acceleration of 1.0 E-g at an angle normal to the cabin deck. The crew and passengers would not be bothered with high-g stress or zero-g adaptation issues and it would allow easy movement about the WarpStar cabin during the trip. While operating on the Moon with 1.0 L-g (1.62 m/sec^2) conditions, it could provide up to 175 lunar metric tonne lift capability, acting as a "Lunar Sky Crane."

Economy is built in. The WarpStar's VTOL ability removes the need for most of the support infrastructure needed to service conventional spacecraft for both Earth and Moon operations. If it avoids hypersonic reentry during its trip back from the Moon, which would be its standard operational mode, there is every reason to believe it could refuel its fuel cells, refresh its life support subsystem and be headed back to the Moon in less than an hour. A single, small vehicle like the WarpStar-1 could deliver over 1,100 metric tonnes of materials and/or personnel to/from the Moon in a single year if we can build these 0.5 to 1.0N/W MLTs.

WarpStar-1 Subsystems

The design is powered by an array of twelve (12) "Tesseract" MLT assemblies with each assembly providing a maximum thrust of +/- 45,000 Newton in the X or Z axes, and +/- 15,000 Newton in the y-axis per Figures 3 and 4.

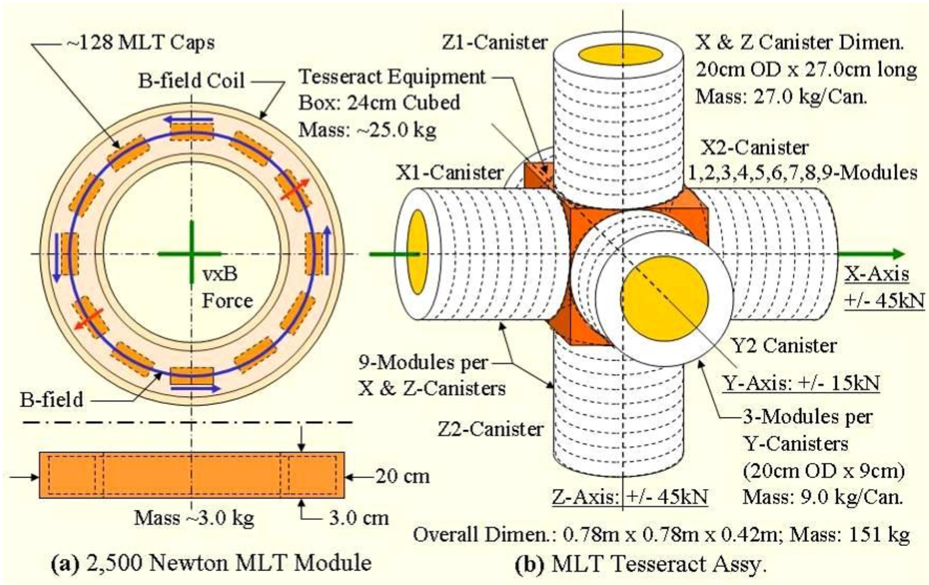

FIGURE 3. 2,500 Newton MLT Module and 3-Axis 45kN/45kN/15kN Tesseract MLT Propulsion Assembly.

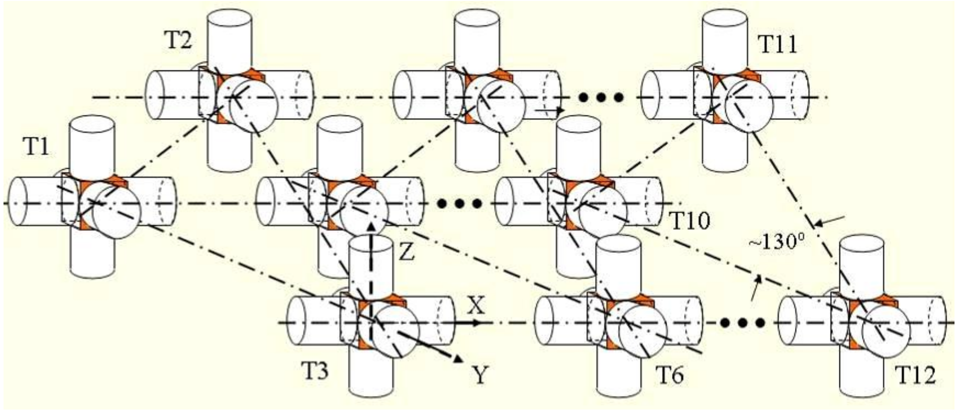

FIGURE 4. WarpStar-1 Tesseract MLT Propulsion Assembly Mounting Arrangement.

Each of the X and Z-axis Tesseract MLT canisters would be made from nine, +/- 2,500 Newton MLT modules for a total of +/- 22,500 Newton thrust per MLT canister. The MLT modules would dissipate approximately 2% of their input power as waste heat. The Y-axis canisters would be supplied with three, 2,500 Newton Modules for a total thrust of +/- 7,500 Newton per canister. Two canisters per thrust axis yielding a thrust of +/- 45-kN in the X & Z-axes and +/- 15-kN in the Y-axis would then be mounted around the Tesseract Power Electronics Cube that would provide all six MLT canister's ac power oscillator and cooling interfaces needed to drive and cool the MLT modules contained therein. These Tesseract MLT Assemblies could be mounted anywhere in or outside the vehicle since MLTs are based on a gravinertial recycled propellant design, but to facilitate their cooling and heating needs, they would be mounted in the pressurized portion of the vehicle. They also should be mounted as far apart as possible from each other as shown in Figure 4 to provide the highest torque generation capability between the Tesseract MLT assemblies' force couples as well as to minimize possible collateral damage from outside sources.

The second noteworthy subsystem is the electrical power generation and distribution subsystem. As defined in Figure 5, it consists of six polybenzimidazole (PBI) based proton exchange membrane (PEM) fuel cells using liquid oxygen (LOX)/liquid hydrogen with a low heat stoichiometric energy density of 33.4-kW-hr/kg. (PEMEAS, 2006) Each fuel cell would use 386-cells (~270 Vdc) that are capable of producing up to 100 kW average at ~55% system efficiency, 130 kW peak power for ~10 minutes and weigh ~100 kg, providing a *fuel cell* specific power level of 1.0 kW/kg with a cooling loop temperature of 190C. This provides a base-load vehicle power supply of 600 kW average and 780 kW peak. Two fuel cells would power a single electrical power distribution and control (EPDC) power bus that are in turn diode cross-tied with the other two main EPDC power distribution buses. Each 270 Vdc power bus would feed power to the closest four Tesseract MLT assemblies and one of the ship's three power buses feeding its Guidance Navigation and Control (GN&C) and Environmental Control & Life Support Subsystem (ECLSS). The fuel cells would also provide water to the ECLSS for human consumption along with temperature control of the ship's interior. To provide energy for the WarpStar-1's start-up, power surge and emergency power needs, three, 115 kg lithium-poly battery packs with ~175.0 W-hr/kg specific energy, paralleled with ultra-capacitor packs yielding ~5.0 kW/kg specific power would be installed. These battery/ultra-cap packs will free the WarpStar-1 of the need for ground starts from auxiliary power carts, provide MLT energy surge needs while performing maneuvers, and provide fail-safe energy reserves in case of fuel cell and/or EPDC bus malfunctions.

A high performance WarpStar-1 flight could make a 5.0-hour lunar round trip using a 2.0 E-g thrust profile. For this high performance run, the six PBI/PEM fuel cells would be provided with 225 kg of liquid hydrogen and 1,800 kg of LOX provided in three individual cryostats for each reactant type, with the LOX located under the vehicle's floor boards and the hydrogen located in the WarpStar's nose Avionics/Battery bay. These reactant amounts provide up to a 100% energy storage margin for contingencies dependent on the selected acceleration profiles and trip times.

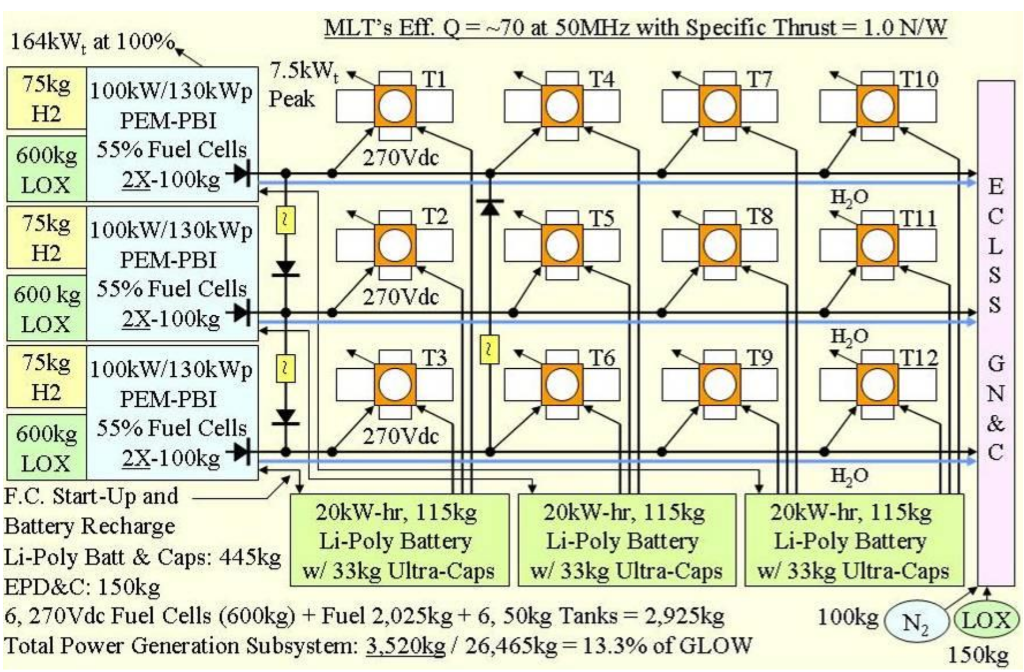

FIGURE 5. WarpStar-1 6-Fuel Cell and 3-Battery Electrical Generation Subsystem for 2.0 E-g Missions.

The last major WarpStar-1 subsystem examined in this paper is the Thermal Control (TC) subsystem that will have to eject the heat generated by the fuel cells, Tesseract MLT assemblies, batteries, avionics, crew and cargo into its surroundings including deep space while the vehicle is operating. This TC subsystem is shown in Figure 6.

The WarpStar-1's TC would use a dual redundant heat pump based cooling subsystem for the MLTs and ECLSS utilizing an environmentally benign 410A or equivalent refrigerant gas. These four heat pumps will boost the MLT's (60C) and ECLSS' (30C) waste heat streams up to ~190C as shown in Figure-6's external fuselage and stub wing radiator areas that will enable them to radiate the WarpStar-1's maximum heat load of 612 $kW_{-thermal}$ obtained at 2.0 E-g steady-state acceleration. (Grossman, 1990) This waste heat will be radiated into deep space via infrared (IR) electromagnetic radiation in all directions per the Stefan-Boltzmann T^4 radiation law. Even with the use of almost all of the WarpStar-1's exterior surfaces for this radiator function, the radiator surfaces will be running at over 190C at peak thrust, which will pose a secondary thermal load into the vehicle that will have to be mitigated with the use of a high efficiency cryogenic like multilayer, Aerogel, or Space Shuttle Fibrous Refractory Composite Insulation (FRCI) ceramic insulation systems between the radiators and the ship's pressure vessel. The power to drive the heat pumps will also have to be supplied by the fuel cells and their waste heat dissipated as well.

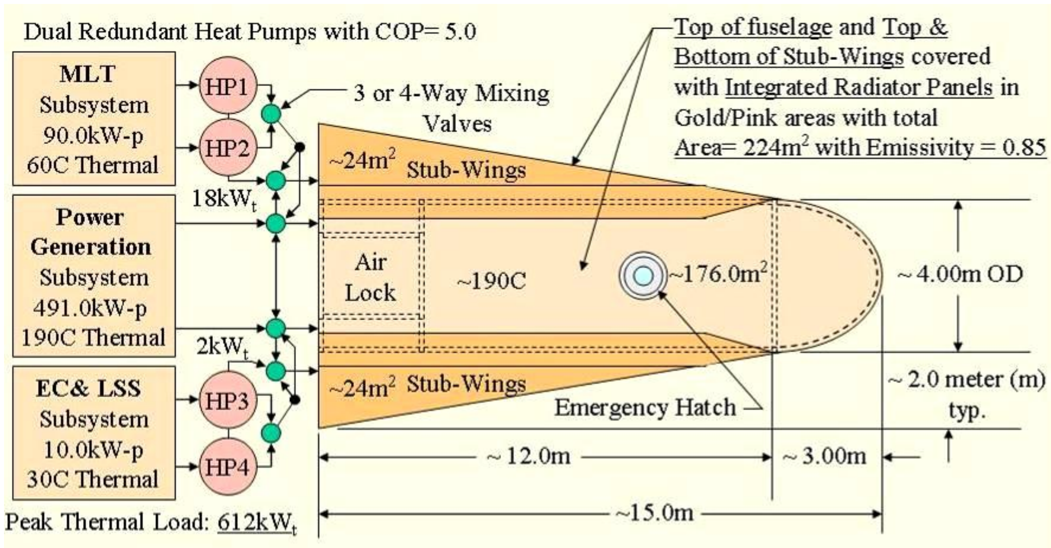

FIGURE 6. WarpStar-1 Thermal Control (TC) Subsystem.

The WarpStar-1 subsystem weights determined the sizing of the Tesseract MLT Thruster Arrays per Table 1.

TABLE 1. Approximate WarpStar-1 Subsystem masses with Total Vehicle Mass.

Vehicle Subsystems	Mass
Graphite/Polyimide Pressure Vessel, Floor & Ceiling	5,400 kg
Graphite/Polyimide Air Lock and Aft Pressure Bulkheads	900 kg
Graphite/Polyimide Stub-Wings Structure	600 kg
Hull Thermal Insulation: 4.0 cm thick layer of Space Shuttle FRCI	2,700 kg
High Density Polyethylene (HDPE) Radiation Shielding at 1.0g /cm^2	1,900 kg
Qty. 6, 100 kW PEM/BPI Fuel Cells + Batteries + EPDC + Fuel + Tanks Subsystem	3,520 kg
MLT Tesseract Propulsion Assemblies at 151 kg each, Qty. 12	1,812 kg
Heat Rejection Radiators, Heat Pipes Heat Pumps at 5kg / kW x 612 kW_t	3,060 kg
Environmental Control and Life Support System with Gas Consumables	750 kg
GN&C + Passenger Avionics	400 kg
Deployable Tricycle Landing Gear	600 kg
Six Seats = ~300 kg + 2-Crew Persons and Food Consumables	600 kg
Mass Subtotal = 22,242 kg x 10% growth allowance	24,465 kg
WarpStar-1 Payload (Includes 4-passengers and 1,460 kg Cargo	2,000 kg
WarpStar-1 Mass Grand Total	**26,465 kg**

These masses are first order estimates based on the desired payload, destination and energy needs of the 1.0 N/W Tesseract MLT propulsion assemblies that provide a variable 0.5-to-2.0 E-g acceleration for a full 12-hour run-time period, assuming LOX / hydrogen fuel cells with 55% chemical to electrical conversion efficiency are the primary MLT energy source. Also included in these mass estimates is a 1.0 g/cm^2 layer of high density polyethylene

(HDPE) radiation shielding layer over most of the interior surfaces of the vehicle's pressure vessel. This level of radiation shielding should protect the crew from solar wind proton or electron radiation while in flight or on the surface of the Moon during a solar flare event, as well as help protect the crew from the ever present cosmic ray radiation flux. (NASA, 2006b)

Other MLT Space Applications

One way to organize possible space applications for the MLT is around the power source. For short trips, batteries and solar arrays are convenient. Robotic MLT driven craft dedicated to lifting satellites into various Earth orbits and supplies to the International Space Station would be much easier and cheaper to build and maintain if they flew on high energy density batteries. These storage mediums would be adequate to this task given MLT's with specific thrust performance of greater than 1.0 N/W.

In order for human space-flight to extend beyond the Moon, we will find it more useful to generate electrical power in situ rather than rely upon power stored by capacitor, battery, or fuel cell. One viable approach could be to upgrade the USA's 1990's SP-100 space nuclear generator with a higher efficiency (~30%), Stirling cycle power conversion subsystem. (NASA, 2006a) Given this nuclear system as an MLT power source, spacecraft could be large, (on the order of a Boeing 767-400), and be able to reach Mars in 2 to 5 days dependent on the distance between these planets. This type of power source would also be sufficient to travel anywhere in our solar system. Another approach to powering future MLT spacecraft is the Focus Fusion Reactor (FFR), an aneutronic system (Lerner, 2004) currently in development. The FFR would not require the extensive cooling system that a fission reactor does, it would lower the radiation shielding requirements as compared to a fission reactor of equal power, and it would yield a higher performance spacecraft due to its higher specific energy and power capabilities.

SUMMARY & CONCLUSIONS

The advent of the Mach-Lorentz Thruster is in many ways like previous technologies that have transformed society. Domesticating the horse gave humankind vast mobility and with that change came unpredicted growth of all sorts. Harnessing the wind made us able to cross oceans. The Conestoga wagon opened up a continent. Rail transport, steam power, the internal and external combustion engines have all contributed to explosive growth in cultures and societies around the world and throughout human history. Mobility matters. This study shows that the MLT is like these previous technologies in that it offers a revolutionary leap in mobility through safe, quick, convenient and economical transportation. This is something that chemical rockets, because of their energy limitations, have never been and will never be able to provide us. We are therefore looking at the dawning of the true golden age in human space flight if the MLTs can be developed to these foreseen performance levels.

This study explored the possibilities of what a first generation 0.5-to-1.0 N/W MLT propelled spacecraft, powered with fuel cells & batteries, could provide in the way of payload and range of operation. It was found that it could carry a crew of two people with a payload of 2-metric tonnes from the surface of the Earth to the surface of the Moon, accelerating at 1.0 E-g during the first half of the course segment and decelerating the last half, and back again; all in under 12-hours *without refueling* the WarpStar-1's fuel cells. While on the Moon, the WarpStar-1 could provide heavy lift crane services to Moon-based astronauts that could lift up to 175 lunar metric tonnes. This ~26,500 kg MLT propelled spacecraft would be a major advancement over any known spacecraft design to date, and should be an inducement to push the development of these devices towards the 1.0 N/W specific power class Mach-Lorentz Thrusters needed to make it happen.

With this 1.0 N/W MLT technology in hand, we could send our planetary scientists to walk on distant worlds. We could send groups of explorers to the Moon in less than 3 hours, to Mars in under 5 days, to the asteroid belt in 6 days, to Jupiter's moons Io, Europa, Ganymede and Callisto in 7 days, or to Titan and Saturn's rings in 9 days. In fact, this 1.0 E-g constant acceleration transport technology could easily prove to be so inexpensive to operate that we find ourselves compelled to build permanent outposts on all these worlds in our solar system. And when we finally find ourselves at the solar system's boundary with interstellar space, Woodward's "Wormhole term" may provide the keys to viable interstellar travel as well. (Woodward, 2004)

NOMENCLATURE

AU = Astronomical Unit = 93.0 x 10^6 miles or 149.6 x 10^9 meters
E-g = Earth gravity at its surface
FRCI = Fibrous Refractory Composite Insulation used on Space Shuttle
GLOW = Gross Lift Off Weight
L-g = Lunar gravity at its surface
RCC = Reinforced Carbon-Carbon ceramic leading edge used on Space Shuttle

ACKNOWLEDGMENTS

Many thanks go out to Ron Stahl for his very helpful editorial comments, and Andrew Palfreyman, Sonny White, David Fletcher, and Ryan March, for providing many illuminating discussions on the MLT topic while preparing this paper.

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