Modern In-Space Electric Propulsion

John R. Marcantonio[1]
University of Colorado Boulder, Boulder, CO, 80301

This paper has sought to explore the modern methods of electric propulsion for in-space applications aboard spacecraft. The motivation for this research is to assist in the knowledge base for the upcoming career of the author as a propulsions engineer for Lockheed Martin Corp. The investigation has been made into four major classes of electric propulsion technology which include electrostatic, electromagnetic, electrothermal, and electrodynamic tethers. Within these technologies, focus was set on upcoming developments and breakthroughs into high efficiency and advancedments for the commercial industry. These projects include the NEXT ion thruster, the older BPT-4000 Hall effect thruster, the VASIMR mission, the PROITERES nano-satellites, and a Marshall spaceflight center electrodynamic tether. Each of these technologies represent the most recent advancements with individual pros and cons. The NEXT thruster is a long life, high efficiency proven ion grid thruster which is in contention for NASA's discovery class missions. The BPT-4000 is a industry standard Hall effect thruster with a large flight history and utilization on many standard spacecraft buses. The VASIMR is a very promising mission which could provide a high power, and relatively high thrust electromagnetic thruster with a 5000s I_{sp} which could be utilized for accelerated missions to Mars. The PROITERES nano-satellites were micro propulsion units which have recently proven flight heritage for the nano-satellite class making them less dependent on primary payload orbits. The last is the electrodynamic tether investigation into "propellantless" technology for using the Earth's magnetic field. Each of these topics are discussed in further detail below with a rough overview of how each works.

Nomenclature

EDT = Electrodynamic Tether
HET = Hall Effect Thruster
I_{sp} = Specific Impulse [s]
NASA = National Aeronautics and Space Adminstration
NEXT = NASA Evolutionary Xenon Thruster
RF = Radio Frequency
RTG = Radioisotope thermoelectric generator
TRL = Technology Readiness Level
VASIMR = Variable Specific Impulse Magnetoplasma Rocket

I. Introduction

THIS paper will be used to assess and guide the validity of many different types of modern electric propulsion options for in-space travel. It will provide an in depth look into multiple different technologies, their applications, and potential performance. In general, the method of electric propulsion is rather new comparatively to chemical propulsion and provides a much high specific impulse generally than all other current methods. The downside to this technology is the usually low thrust values given as these technologies couldn't be used to leave the Earth's surface. Given the ability to generate electricity from the sun or an RTG, this allows for a large amount of electricity to be collected/generated during the mission thus making it more feasible for long missions. The first section of this report will focus on the technologies and a small look at the physics behind it. After that, there will be a look at the types of modern systems currently available and what has already had proven flight heritage.

---

[1] BS/MS student, Aerospace Engineering Sciences.

There are several advantages to the electric propulsion spacecraft. Significantly higher specific impulse values mean that there is a reduced necessity for fuel mass. Looking at Table 2 below developed by a Princeton University based group, it can be seen that the benefits to each launch site in both payload weight increase and propulsion mass fraction decrease are significant. The figure below comes from a NASA report on in-space propulsion technologies and gives the estimate roadmap for the future of all in-space propulsion. It can be seen here that the importance of electric propulsion is only increasing with time and relied on more heavily. This is especially true in fields of orbital debris maintenance, deep space travel, and inexpensive (both cost and mass) orbital maintenance.

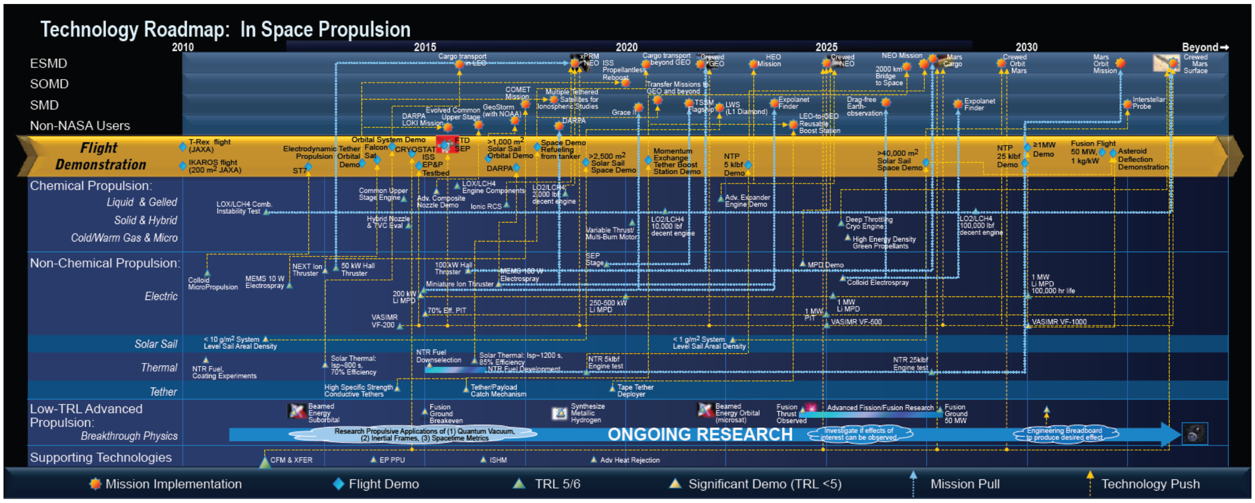


Figure 1: NASA In-Space Propulsion Road Map [12]

II. Electric Propulsion Types

There are many different types of electric propulsion out there. These different types of propulsion each have pros and cons. The main benefit though over conventional chemical propulsion, is that each of these techniques produce high specific impulse values although generally at very low thrust values. For this reason, it is seen as more feasible to have an in-space electric propulsion based spacecraft. These spacecraft can then more efficiently use propellant over time. Additionally, with the collection of power based on solar panels, most of the mass of the spacecraft can be dedicated toward propellant and mission payloads as opposed to power sources or less efficient chemical propellant methods of propulsion.

The most common types of electric propulsion are electrostatic, electrothermal, and electromagnetic. These three different types of propulsion each take advantage of a different law of physics to produce thrust and have varying ranges of thrust and efficiency which have been proven by modern applications and vary from 500s to 10000s of specific impulse and microNetowns to greater than five Newtons. With the advancements made in electric propulsion, more and more satellites have been seen entering space with some form of this propulsion as payload in order to be used for station keeping, attitude control, or even as the main propulsion system as is seen in Boeing's new 702SP line of all electric satellites [3].

These types of propulsion are extremely important to consider due to their rising popularity in the last decade for use in all space organizations across the globe. Many future missions, such as the discovery class NASA missions, are considering using all solar electric powered propulsion for all future flights.

A. Electrostatic Thrusters

Electrostatic thrusters work off of ionizing a particular heavy ion. These heavy ions are then passed through grids with high voltage differences in order to take advantage of the ionization and accelerate the particles. The ionization of these particles give them a particular charge and when passed through an open votage grid causes massive accelerations due to the Coulomb force. This force is what is traditionally considered the source of thrust for any electrostatic thruster. These thrusters can be separated into many different categories including inert gas thrusting ion propulsion and hall effect thrusters.

Of the many different types of electrostatic thrusters there is also a wide range in performance between the several different types. Hall effect thrusters (HET) which are coming into popularity lately, have high thrust and lower efficiencies. One of the most popular HETs in use today is the BPT-4000. This thruster has been utitlized on many payloads for both attitude control and as the main propulsion system such as the A2100 spacecraft bus for Lockheed Martin [4].

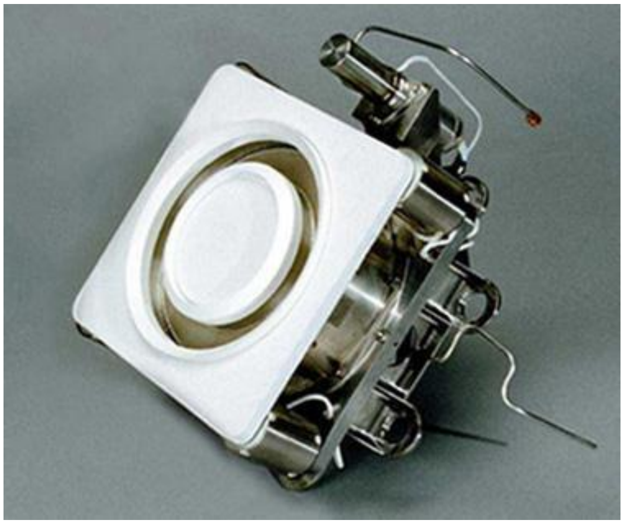


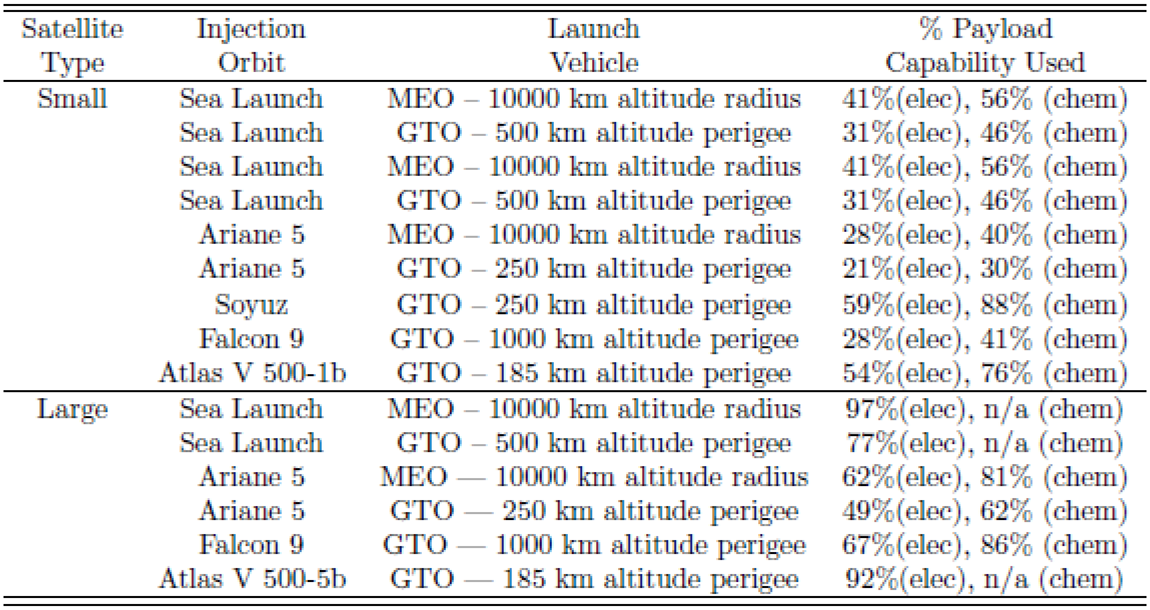
Figure 2:Aerojet BPT-4000 Thruster

Table 1:BPT-4000 Thruster Characteristics

BPT-4000 Thruster Characteristics	Value		
Thruster Type	Hall Effect Thruster		
Propellant Type	Xenon		
Thrust [N]	0.132	0.195	0.290
Specific Impuse [s]	1858	1920	2020
Input Power [kW]	2.0	3.0	4.5
Mass [kg]	< 12.3 kg		
Thruster Life [hrs]	>10,000		

Using this thruster, analysis has been done into the potential savings that could be afforded using 4 of these as compared to a traditional chemical rocket. The metric that has been compared against is the necessary propulsion mass fraction as a whole. These values and potential savings can be seen in Table 2. The study was done by a group of Ph. Ds at Princeton University and was supported by SES out of Germany [6].

Table 2: Mass Fraction Comparison of Chemical and Electrical Propulsion Satellites [6]



Satellite Type	Injection Orbit	Launch Vehicle	% Payload Capability Used
Small	Sea Launch	MEO – 10000 km altitude radius	41%(elec), 56% (chem)
	Sea Launch	GTO – 500 km altitude perigee	31%(elec), 46% (chem)
	Sea Launch	MEO – 10000 km altitude radius	41%(elec), 56% (chem)
	Sea Launch	GTO – 500 km altitude perigee	31%(elec), 46% (chem)
	Ariane 5	MEO – 10000 km altitude radius	28%(elec), 40% (chem)
	Ariane 5	GTO – 250 km altitude perigee	21%(elec), 30% (chem)
	Soyuz	GTO – 250 km altitude perigee	59%(elec), 88% (chem)
	Falcon 9	GTO – 1000 km altitude perigee	28%(elec), 41% (chem)
	Atlas V 500-1b	GTO – 185 km altitude perigee	54%(elec), 76% (chem)
Large	Sea Launch	MEO – 10000 km altitude radius	97%(elec), n/a (chem)
	Sea Launch	GTO – 500 km altitude perigee	77%(elec), n/a (chem)
	Ariane 5	MEO — 10000 km altitude radius	62%(elec), 81% (chem)
	Ariane 5	GTO — 250 km altitude perigee	49%(elec), 62% (chem)
	Falcon 9	GTO — 1000 km altitude perigee	67%(elec), 86% (chem)
	Atlas V 500-5b	GTO — 185 km altitude perigee	92%(elec), n/a (chem)

The other system that deserves recognition here is the NASA Evolutionary Xenon Thruster (NEXT). This thruster is an Xenon ion grid thruster. This thruster has set many records and now maintains the precedence for what is considered groundbreaking in the field of electrostatic thrusters [6]. This thruster is a candidate for the next set of all of NASA's discovery class missions and would most likely require the use of many thrusters [7]. These thrusters are incredibly versatile and could be integrated for missions in all types of environments from LEO to GEO to beyond the asteroid belt.

Table 3: NEXT Thruster Characteristics [4,6]

NEXT Thruster Characteristics	Value
Thruster Type	Ion Grid Thruster
Propellant Type	Xenon
Thrust [N]	0.235
Specific Impuse [s]	>4100
Input Power [kW]	0.6-6.9
Mass [kg]	< 13.3 kg
Thruster Life [hrs]	>10,000

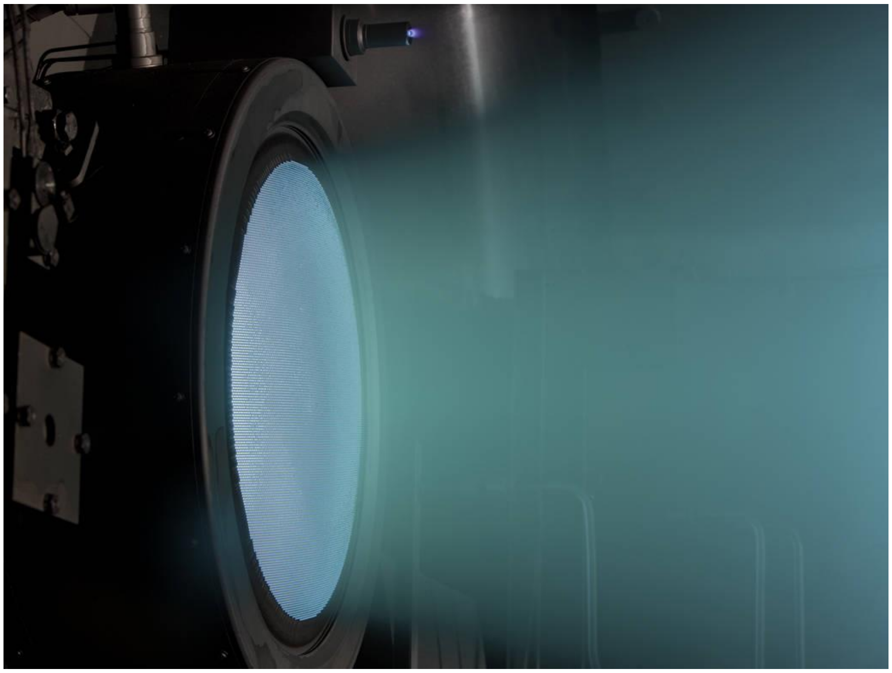


Figure 3: NASA NEXT Ion Thruster [6]

B. Electromagnetic Thrusters

Electromagnetic thrusters are similar in theory to the electrostatic thrusters above with one significant difference. The working ‘fluid’ in an electromagnetic thruster is a plasma where as in the electrostatic thrusters it is ionized particles. This is a significant difference as it is what drives the actual particles and it also means that the Lorentz force is governing the interactions as opposed to the Coulomb force. The plama is created using RF waves and in general the plasma is surrounded by superconducters in order to direct the flow and contain the electromagnetic field. This means that the particles within the engine are rotating in opposite ways due to the way that the forces act on the particles. These engines have been around for a long time (Russia in the 70s) but only recently have been reinvestigated by many countries. These represent great promise in interstellar travel with high specific impulse and thrust area desities. The one of these engines that will be delved into is the VASIMR [8,10].

The Variable Specfic Impulse Magnetoplama Rocket (VASIMR) engine has been recently developed by the Ad Astra Company in Houston, Texas. This engine has a planned testing on the side of the international space station as a way of increasing the TRL level and proving it fit for integration onto spacecraft systems. The engine consists of multiple RF generators which are used to ionize/create the plasma from the propellant and also heat the mixture. This all occurs within a superconducting magnetic coil which creates a strong magnetic field. This strong magnetic field acts with the plasma to produce the Lorentz force which accelerates the particles out the nozzle of the engine [8,9,10]

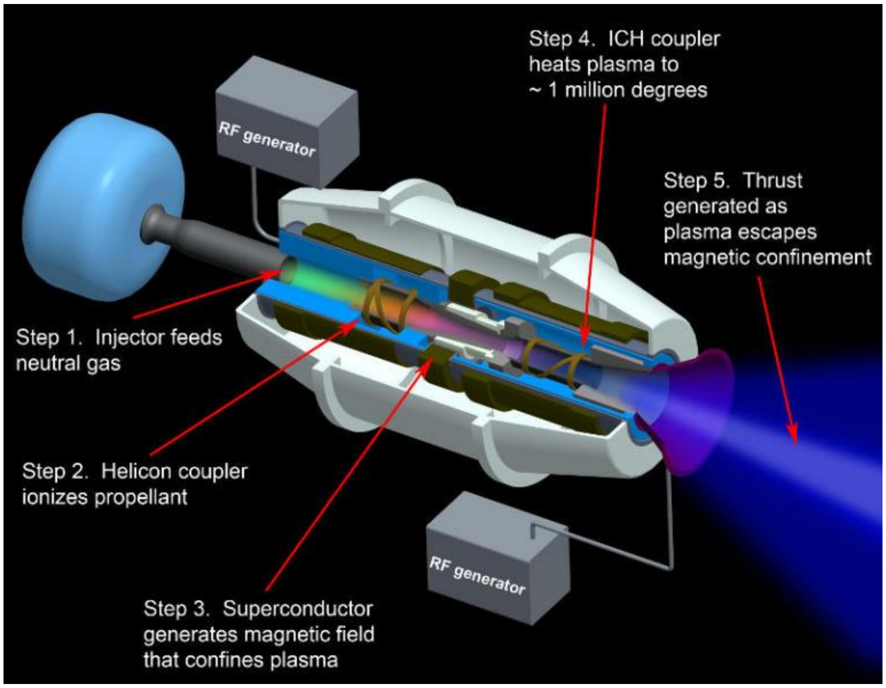


Figure 4: VASIMR Block Diagram Representing Physics [8]

The downside to this thruster is that it that it consumes relatively a large amount of power. It requires 200 kW of power to achieve a 5.8 N thrust value. The benefit is that the engine is also throttlable by the amount of propellant put in and the RF power fed through the system. Additionally, this engine was demonstrated using argon but can function with other propellants and is believed to achieve specific impulse values of over 10,000 s using Hydrogen [8,9,10].

Table 4: VF-200 Thruster Characteristics

VF-200 Thruster Characteristics	Value
Thruster Type	Magnetoplasmic Rocket
Propellant Type	Argon (others possible)
Thrust [N]	5.8
Specific Impuse [s]	4900
Input Power [kW]	200
Mass [kg]	Couldn’t locate
Thruster Life [hrs]	>10,000

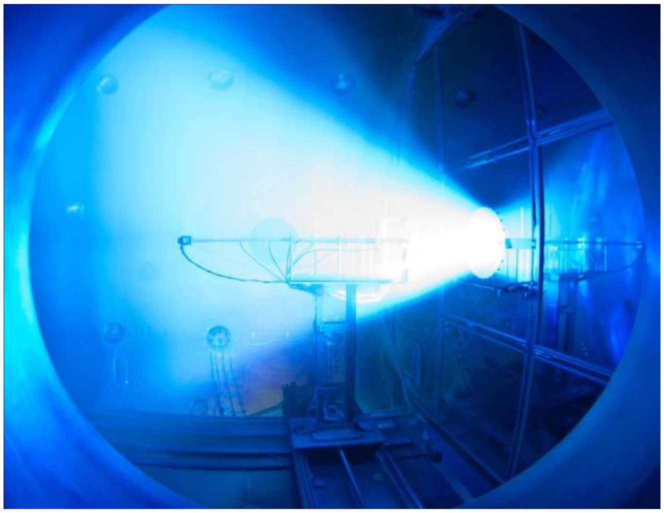


Figure 5: VX-200 During Maximum Power Testing [10]

The true potential for this technology is in human rated missions to Mars. It is estimated that the trip to Mars using VASIMR technology could be achieved in 39 days, far short of current conventional systems as it is an accelerated journey. The VASIMR engine would be multiplied multiple times for an increased thrust. In addition to this mission, it is believed that these engines in combination with an RTG could provide transportation of supplies or payload to anywhere in the solar system. Lastly, the company has looked to sell the propulsion system as a workhorse for cleaning up orbits of space debris due to the lifetime of the engine [8,11].

C. Electrothermal Thrusters

Electrothermal thrusters are split into three major categories: arcjets, resistojets, and microwave arcjet. All of the thrusters in this category function more similar to the standard chemical propulsion rockets although this technology is the oldest commercially available that will be discussed in this report. The basic principle of all of these is that a propellant is heated up and expelled through a nozzle. This technology is ideal for systems with excess energy and sees a typical specific impulse value of around 500-1000s. It was first flown in the 60s and has been commercially available and developed since the 80s. Due to this rather low efficiency, it does have the lowest efficiency of any of the systems delved into in this paper. It also achieves reasonably low thrust and represents a technology that has great heritage but has plateaued [13,14].

The technology has not died though and is seeing some additional research into high power flex fuel applications with specific impulse values reaching 1100 and pulsed plasma electrothermal thrusters for nano satellites [13,14]. The PROITERES nano satellites were launch by ISRO in order to prove a functional electrothermal pulsed plasma thrusters. With the increasing popularity of the small/nano-satellite market, this field has reinvigorated interest as most of these secondary or tertiary payloads are stuck in the primary payload’s orbit. This is a solution for missions trying to achieve an alternate orbit with as little as a 1 kg system and 5W power consumption [13,14].

PROEITERES II Thruster Characteristics	Value
Thruster Type	Pulsed Plasma
Propellant Type	PTFE
Total Impulse [Ns]	10,000
Specific Impuse [s]	300-1100
Input Power [W]	62
Mass [kg]	Couldn’t find
Thruster Life	>1 year

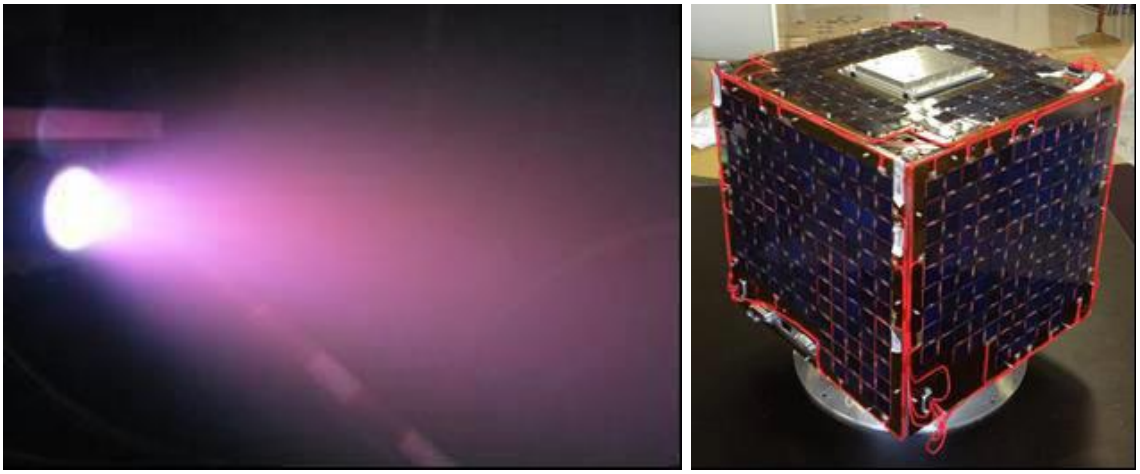


Figure 6: PROITERES Thruster test (left) and Nano-Satellite (right)

D. Electrodynamic Tether

The electrodynamic tether (EDT) harnesses the earth's electromagnetic field as well as the excess electrons and ions in the atmosphere to create a current and power. The idea comes from using the Lorentz electrodynamic force to create a net thrust on the vehicle. The vehicle would collect electrons from a source in the host spacecraft and then run them along the conducting tether to produce a current. This current would be induced by the earth's electromagnetic field and would utilize induction. These electrons would then be expelled through a hollow cathode plasma contactor. The current induced at a certain voltage by the collected electrons would then produce the thrust required and boost the spacecraft to a higher orbit. This vehicle could also be used for energy generation when not propelling the spacecraft. This could be utilized in interstellar missions although has generally been found to not be feasible [2]. This vehicle would utilize many other flight tested technologies although there hasn't been a test of this technology yet.

Due to the lack of a necessity to carry a propellant. The specific impulse seen from this technology is significantly higher than all other traditional electric propulsion technologies and is shown in Figure 7. The restrictions to this technology are significant as it currently is only designed to be used in a low-mid orbit around the earth where the earth's magnetic field and ionosphere could be utilized for the propulsion.

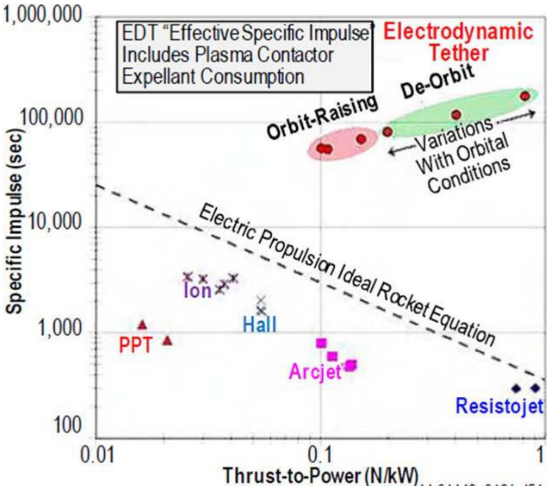
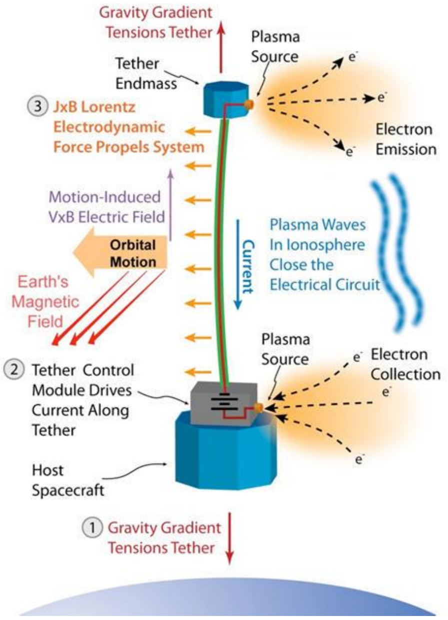


Figure 7: Effective Specific Impulse of Selected Electric Propulsion Technologies [1]

The practical spacecraft designed in this application comes from a mission design done by NASA's Marshall spaceflight center. The work being done there is to design a demonstration mission to raise the TRL level of the technology and to put a functional spacecraft in a low earth orbit for a demonstration. The theoretically designed system can be viewed below in Figure 8. The designed mission would require a multiple kilometer long current conducting tether but would provide enough thrust to raise or deorbit a spacecraft. The expected thrust value from this application would still most likely fall under a Newton of force. The applications of this technology also stretch to satellite clean up for low cost, orbit raising for primary payloads at low cost, variation on orbits over the course of a mission, energy generation, and much more [1,2]



v

Figure 8: Electrodynamic Tether Operation [1]

III. Conclusion

Many promising developments have occurred in electric propulsion recently using all of the different methods of propulsion. The key progress here came from the VASIMRs thruster. This thruster is a large leap forward with high power RTG applications and a potential to be the technology that can get humans to Mars. The NEXT thruster is also a very promising development with extremely high efficiencies proven and long life times. This makes the thruster perfect for missions to reaching past the asteroid belt with much greater payload that was possible before. Another promising technology was the electrodynamic tether. With propellantless orbital adjustments through using the ionosphere and Earth’s magnetic field, electric power is the only restriction to maintaining satellites indefinitely. Lastly was the nano-satellites propulsion which seemed like a much less impressive achievement but would allow great freedom in the up and coming popular market of nano and small classed satellites. Overall, it looks to be a promising decade to come with these technologies being introduced and tested in the satellite industry.

Acknowledgments

The author would like to thank Dr. Kantha for his knowledgable teaching of the course and constant excitement for the subject. Additionally, for providing a constant stream of relevant current news and events.

References

1. Bilen. Sven G., Johnson, C. Les, Wiegmann, Bruce M., Alexander, Leslie, Gilchrist, Brian E., Hoyt, Robert P., Elder, Craig H., Fuhrhop, Keith P., Scadera, Michael, Stone, Nobie, “PROPEL Electrodynamic Tether Demonstration Mission.” AIAA SPACE 2012 Conference and Exposition. AIAA 2012-5293. September 2012.
2. “Electrodynamic tether” http://en.wikipedia.org/wiki/Electrodynamic_tether. 5 May 2015.

3. Feuerborn, Steven A., Neary, David A., and Perkings, Julie A., "Finding a way: Boeing's "All Electric Propulsion Satellite." 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference. AIAA 2013-4126. July 2013.
4. "Aerojet Electric Propulsion Data Sheet." https://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Electric%20Propulsion%20Data%20Sheets.pdf. 05/23/2006
5. Dutta, Atri, Libraro, Paola, Kasdin, N. Jeremy, Choueiri, Edgar, Francken, Philippe, "Design of Next-Generation All-Electric Telecommunication Satellites" 31st AIAA International Communications Satellite Systems Conference. AIAA 2013-5625. October 2013.
6. "Ion Thruster Sets World Record." http://www.nasa.gov/multimedia/imagegallery/image_feature_2416.html. May 2015
7. Oh, David Y., Snyder, John Steve, Geobel, Dan M., Hofer, Richard R., and Randolph, Thomas M., "Solar Electric Propulsion for Discovery-Class Missions." Jounal of Spacecraft and Rockets. Vol. 51, No. 6, November-December 2014.
8. "Ad Astra: VASIMR: Missions" http://www.adastrarocket.com/aarc/missions.
9. "VASIMR Performance Results" 46th AIAA/ASME/SAW/ASEE Joint Propulsion Conference and Exhibit. July 2010
10. "VASIMR®: Deep Space Transportation for the 21st Century" AIAA SPACE 2011 Conference and Exposition. September 2011.
11. Ilin, Andew V., Cassady, Leonard D., Glover, Tim W., Chang Diaz, Franklin R., "VASIMR Human Mission to Mars" Space, Propulsion & Energy Sciences International Forum. March 2011.
12. Meyer, Mike, Johnson, Les, Palaszewski, Bryan, Goebel, Dan, White, Harold, and Coote, David, "DRAFT In-Space Propulsion Systems" NASA, November 2010.
13. Litchford, Ron J., "High Power Flex-Propellant Arcjet Performance" 43rd AIAA Plasmadynamics and Lasers Conference. June 2012.
14. "Development of Electrothermal Pulsed Plasma Thruster Systems onboard Osaka Institute of Technology PROITERES." Nano-Satellites. Propulsion and Energy Forum. July 2014.