PREPARED STATEMENT OF

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Testimony before the Space Subcommittee of the
House Committee on Science, Space, and Technology
United States House of Representatives

Hearing on In-Space Propulsion: Strategic Choices and Options
June 29, 2017

Chairman Babin, Ranking Member Bera, and Members of the Subcommittee, thank you for the opportunity to testify on in-space propulsion in the United States. I thank the Committee for its longstanding support of electric propulsion (EP) and plasma physics research in this country. In this hearing, I will brief the status of MSNW's high power electric propulsion system and provide testimony for our country's future investments in technology. While this technology may seem like a distant future, it is the strategic choices of the here and now that will set us on the path to make the unimaginable possible. I am pleased that the Committee is considering such important topics. The primary points of my testimony are as follows:

- High power electric propulsion is a key technology for humanity's sustained presence in space.
- Investing in technologies such as MSNW's Field Reversed Configuration (FRC) propulsion will allow NASA to build the foundation for long-term sustainable space exploration.
- Like most electric propulsion devices, FRC thrusters have the shared benefit of high specific impulse; this is a metric to measure the propellant efficiency of a propulsion device.
- FRCs have additional benefits of providing throttleable power and performance that allows for an even more efficient trajectory to be established.
- Mars cargo missions will be feasible with lower cost and higher fractions of payload delivered to the destination.
- FRC thrusters have a low specific mass compared to other EP technology, meaning this technology is not only high power, but also very lightweight.
- Born from fusion research, FRCs easily translate into megawatt power levels, opening up the exploration of distant ocean worlds.
- FRC propulsion devices are unique in that they can be fueled by almost any gas or vapor in the solar system, making it possible to refuel at distant locations.

INTRODUCTION

Science, space, and technology have been cornerstones of this country. The United States' prowess in these domains gives us a position of leadership on the world stage. Space holds a specific importance in the hearts and minds of many. This notion seems to transcend age, race, and culture and enthralls us all. The U.S. has been the leader in space technology since its beginnings. Not only is it a proud and identifying part of our culture, it produces countless beneficial impacts for America and humanity as a whole. The future of space exploration leads us past the mere orbit of Earth to explore and colonize our solar system. To do so we must make strategic choices today that will enable us to remain the leaders of tomorrow. One key technology required to build a sustained presence beyond Earth is high-powered in-space propulsion.

To build the foundation for sustainable exploration of our solar system, high specific impulse and high power in-space propulsion systems are required. The increased fuel efficiency associated with high specific impulse enables large payloads to be delivered at decreased costs. High power decreases transit times so that we can perform missions in days rather than years or decades. Both high payload mass fraction and fast trip time are required for a truly sustainable deep space architecture. NASA's NextSTEP program is supporting several projects to research and develop propulsion technologies that can accomplish both of these goals.

One such technology is MSNW's Field Reverse Configuration (FRC) thruster. FRC physics were originally investigated for fusion power applications dating back decades. The technology was first applied to in-space propulsion by MSNW through support from the Air Force Office of Scientific Research's Space Power and Propulsion group which proved that this approach to propulsion was feasible.[1] The technology has grown and developed over the past decade through several Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. The development of this thruster technology was supported by the Air Force Research Laboratory In-Space Propulsion Branch[2] and NASA's Jet Propulsion Laboratories which helped prove scaling to relevant energies and power levels.[3] The related electronics were fostered by the DARPA Tactical Technology Office which for the first time proved continuous operation of a pulsed electromagnetic power supply.[4] FRC thruster technology is currently part of the NASA's Advanced Exploration Systems' (AES) portfolio. In addition to the requirements of this program, FRC thrusters have several advantages including lightweight design, variable power, and the ability to run off almost any gas or vapor.

[1] Slough, J., Kirtley, D., Weber, T. "The ELF Thruster-. International Electric Propulsion Conference" IEPC-2009-265 (2009).
[2] Brown, D., Kirtley, D., et al. "Development of High-Power Electic Propulsion Technology for Near-Term and Mid-Term Space Power". Joint Army Navy Airforce NASA Journal, 2010.
[3] Kirtley, D., Pancotti, A., Slough, J. and Pihl, C. "In-Situ Electromagnetic Propulsion for Martian and Terrestrial Atmospheres". AIAA Joint Propulsion Conference, 2012.
[4] Kirtley, D., Pihl, J., et al. "Development, Vibration, and Thermal Characterization of a Steady Operating Pulsed Power System for FRC Thrusters", Joint Army Navy NASA Air Force Conference, 2015.

ARGUMENTS FOR HIGH POWER ELECTRIC PROPULSION DEVELOPMENT

High power electric propulsion is a key technology for humanity's sustained presence in deep space. Future lightweight solar panels, and possibly nuclear fission, will enable high power propulsion systems to break today's "impulse and coast" approach and advance to continuous direct burns to destinations within our solar system. These power levels enable humans and large-scale cargo missions to the Moon and Mars with a significant reduction in cost and trip time compared to existing EP technologies. These saving are even more dramatic when compared to chemical propulsion alternatives.[5]

When comparing propulsion systems for cis-lunar missions, chemical propulsion systems can deliver small cargo relatively quickly (few days), while high-power EP systems can deliver much larger cargo, albeit at a slower pace (hundreds of days). For example, it was shown[6] that a 1-2 MW EP thruster operating at 3000-5000 seconds of specific impulse allows for a two-fold increase in available transport payload between low-Earth orbit (LEO) and a low-lunar orbit (LLO) when compared to a chemical bipropellant system (32-40 mT versus 18 mT, respectively). The impetus for a high-power EP Earth-Moon cargo tug is strong due to the scope of the proposed scientific and manned missions in cis-lunar space. Furthermore, the entire system could be reused, allowing dramatic mass and cost savings.

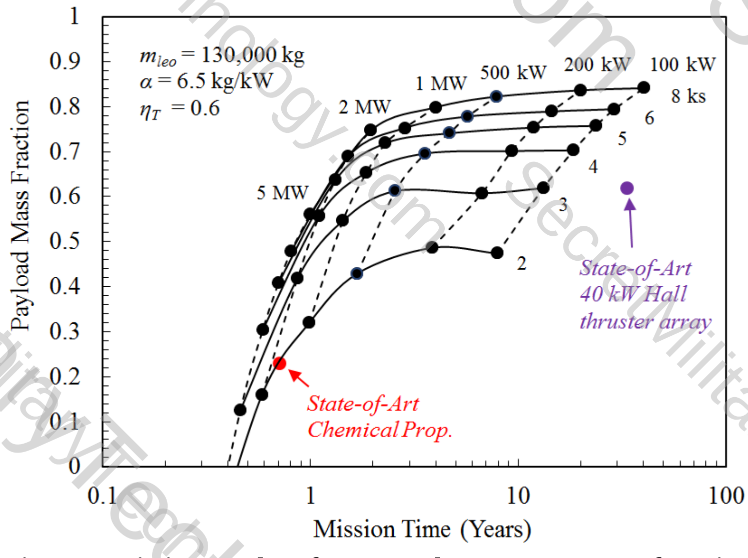

Figure 1: Mission envelope for an Earth-Mars cargo transfer using the FRC propulsion. EP mission model uses a minimum-time transfer between Earth escape and Mars orbit. A Hohmann transfer is used to model the chemical propulsion mission.

High power EP is especially beneficial for solar system exploration missions. Consider, as an example, a cargo transfer between LEO and Mars orbit. The study in Figure 1 calculates the payload mass fraction for a desired mission duration considering a specific impulse range of 2000-8000 s and a power range of 100 kW to 5 MW. As a point of reference, Figure 1 also includes the results for a state-of-the-art chemical bipropellant system (450 s specific impulse) and Hall thruster array (40 kW at 3000 s specific impulse and 60% efficiency[7]).

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[5] Grossman, L. "Ion engine could one day power 39-day trips to Mars", New Scientist, 22 July 2009.
[6] Glover, T., Chang Diaz, F.R, et al. "Projected Lunar Cargo Capabilities of High-VASIMR Propulsion". IEPC-2007-244, 2007.
[7] Brophy, John, et al. "Asteroid retrieval feasibility study." Keck Institute for Space Studies, California Institute of Technology, Jet Propulsion Laboratory (2012).

Of primary importance is the drastic increase in payload mass enabled by high-power EP technology over chemical systems. This increase can amount to nearly three times the delivered payload at high specific impulses. There is also a clear trend showing the benefits of higher power concerning trip time. Notice in Figure 1 the shift towards significantly lower mission times at higher powers. In the extreme case, a 1 MW thruster operating at 8000 s specific impulse could deliver nearly 85,000 kg to Mars orbit in less than three years. While mission duration with high power EP are longer than the equivalent mission using a chemical propulsion system, this can be overcome with more power. A 5 MW system at 5000 seconds specific impulse could make the trip as fast as chemical, but with over twice the payload.

ADVANTAGES OF THE MSNW'S FRC THRUSTER PROGRAM

The technologies currently funded under the NextSTEP program address the fundamental issue of high specific impulse and in varying degrees, high power. Each has its own approach and corresponding advantages and disadvantages. The MSNW's FRC propulsion system is in the early stages of development compared to the other technologies in the NextSTEP portfolio, however it has several distinct advantages.

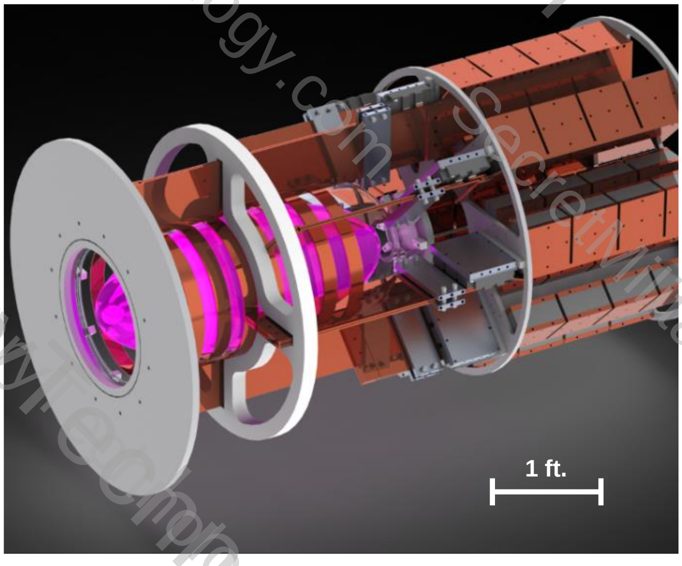

Figure 2 CAD Model of the MSNW's NextSTEP Thruster. Hardware shown is for the experimental hardware to be evaluated in a laboratory environment and are not indicative of flight hardware. Estimated performance is 2000 to 5000 s of specific impulse with Argon and Xenon propellants. System efficiency predicted to be 32 to 75%

In addition to the aforementioned attributes of high specific impulse and high power, FRC propulsion devices have low specific mass. Specific mass is another metric spacecraft designers use similar to specific impulse. Instead of reflecting the mass of propellant like specific impulse, specific mass represents the mass of the thruster itself. It is easy to understand why this metric is important. As with any form of transportation, the lighter the means of transport, the more cargo can be delivered. If humanity intends to explore, build, and ultimately inhabit far off destinations, it will require a transportation system that is lightweight and can effectively deliver goods and materials throughout the solar system.

While there may be debate about the ideal power level, there is a general consensus in the space community that hundreds of kW in the form of Solar Electric Power (SEP) is the best current application, with the ultimate goal of reaching megawatts in the future. FRC propulsion is a strong application for both. An interplanetary mission that uses SEP will have a large variation in power throughout its route. As the spacecraft gets farther from the sun, less power is available. In fact, a 100 kW solar panel at Earth would only produce 42 kW of power at Mars. Because FRC thrusters are pulsed, fixed energy devices, not fixed power devices, they can accommodate a range of power inputs within a single design. For example, the NASA NextSTEP program, the FRC thruster will create 100 J plasma discharges. By repeatedly creating these discharges every millisecond, the thruster operates at 100 kW. By simply slowing down the period to 2.4 milliseconds the thruster can meet the 42 kW constraint enabling one thruster, optimized for a particular energy level, to operate over multiple power inputs. This variability means FRC can be tested and validated with the next generation of power for cis-lunar SEP missions and the exact same hardware and thruster could be applied to Mars transfer missions.

The need for more power is clear and will be required for long-term habitation of the solar system. While FRC propulsion will be demonstrated with hundreds of kW during the NextSTEP program, the physics and technology behind it was originally researched at much higher power levels for fusion applications. Born out of the fusion community, FRCs have always inherently been high power (energy) devices, which the spacecraft propulsion community has previously reduced in size and power to be more applicable to current space applications. The highest energy, currently operational FRC device is at Helion Energy in Redmond, WA and forms 35 kJ FRCs in a deuterium plasma and then compresses them to MJ energies for fusion applications. A one megawatt FRC thruster would only require formation energy of approximately 500 J at 500 Hz. Because FRCs have such a high energy density, scaling laws predict a 500 mm exit diameter at 1 MW. The physical size of such a device is quite practical for fabrication, testing, and fitting within a payload faring. For such a thruster, there would be no need to create large arrays of the thruster in order to achieve higher power. In this manner, FRCs can service the propulsive demands for this generation as well as those that follow. When megawatt-class power is available in space, FRC propulsion will be ready to extend deep space architecture to Mars and the ocean worlds beyond.

The final and most unique characteristic of FRC propulsion is its ability to use a wide variety of propellants. The FRC thruster being developed at MSNW is inductively coupled to the propellant, meaning there is no physical contact with hot plasma. All the process from formation to acceleration are done through interaction of magnetic fields. Consequently, there are no electrodes or nozzles to erode or degrade over time. Moreover, since there is little or no physical interaction with the propellant, almost any propellant can be used. Typically, oxygen, or a

MSR Propulsion Choice	Bipropellant	ELF	ELF with ISRU
Delta V Required: LEO-MOI-LEO	6.5 km/s	8 km/s	8 km/s
Specific impulse	450 s (out)	3000 s (Xe)	3000 s Xe/Ar
Propellant Mass to Mars [kg]	17,561	5,338	5,338
Propellant Mass from Mars [kg]	5,007	4,114	5,338
Solar Panel and Thruster Mass [kg]	0	1,300	1,300
Return payload [kg]	**408**	**12,248**	**16,362**
Payload fraction	<2%	53%	71%

Figure 3. Simplified model of a Mars Sample Return Mission. Model uses a Delta 4 Heavy vehicle (23000 kg to LEO), assumes optimal mars orbit, spiral EP trajectories, propulsive breaking maneuvers, and 5 kg/kW solar panel mass. ELF is 1.5 kg/kW with 200 kW of onboard solar power. Identical payload is assumed to travel and return.

molecular propellant containing oxygen, corrode vital components in electric propulsion system. However, FRC formation has been demonstrated in pure oxygen as well as pure CO_2 and simulated Martian atmosphere. FRCs have also been formed from vaporized water, which is another resource that is easily stored and may be available throughout the solar system[8].

While this ability to operate on various propellants may have some benefits when traveling to Mars and beyond (in terms of depots and waystations), the real advantage is the return mission. Whether the return trip is to bring back explorers or sample materials, or perhaps just to return the spacecraft so it can be used again, the ability to refuel at almost any planetary body with water or an atmosphere is a significant advantage. The cost savings of such mission architectures are large, and is already the subject of NASA's in-situ research utilization (ISRU) initiative.

To illustrate the immense advantages of IRSU, an example 200 kW Martian Cargo and Sample Return Mission was studied at MSNW (see Figure 3). As expected, it showed that the higher specific impulse of an electric propulsion system would yield dramatic mass savings. Even with the additional mass of a large solar panel system, the payload capability of a high power EP mission is much greater than what is attainable with chemical propulsion. Furthermore, an FRC thruster utilizing ISRU Argon from the Martian atmosphere yields can increase the payload returned to Earth by over 4000% over a chemical system.

CONCLUSIONS

We cannot have the future we want tomorrow without investing in its technology today. This is no easy task when there are many expensive and pressing matters that require our attention at home. While too many of those matters cannot be ignored, we must keep our eyes lifted to the horizon and invest in our future. While this task may seem daunting and overwhelming, it happens one step at a time. By making the right strategic choices, the next step we take will put us on a path to the future we want. I applaud NASA and the U.S. government's commitment to space technology and with your continued support, my colleagues and I can make the right next step forward for a better future for all humanity.

The following list is recommendations to further science, space, and technology in this country with regards to in-space propulsion:

1) Continue to fund the development of high power electric propulsion and a follow-on to the NASA NextSTEP program that transitions all of these technologies to flight.
2) Accelerate advances in space power systems that can enable fast transit time while at the same time reduce system mass, cost, and risk.
3) Increase NASA centers capabilities for testing high power EP systems. The demanding test conditions of these new technologies require enhancements for NASA's world-leading facilities.

[8] A. Pancotti, J. M. Little, et al., "Electrodeless Lorentz Force (ELF) Thruster for ISRU and Sample Return Missions." 34th International Electric Propulsion Conference, Kobe, Japan, IEPC 2015-67. 2015.

BIOGRAPHY FOR ANTHONY PANCOTTI

Dr. Anthony Pancotti is the Director of Propulsion Research at MSNW, LLC in Redmond, WA. He earned his Ph.D. in Aerospace Engineering in 2009 from The University of Southern California, were he designed, built, and tested an experimental high-efficiency electro-thermal ablative pulsed plasma thruster, called a capillary discharge.

Subsequently, he was hired by the Air Force Research Laboratory at Edwards AFB to continue his research and development of this concept. It was during this research that he demonstrated unprecedented specific impulse and efficiencies for this class of devices. As part the Advanced Concepts Group at the AFRL, Dr. Pancotti reviewed and investigated a range of advanced propulsion concepts, including FRC propulsion.

In 2011, he joined a team of researchers at MSNW to work on a variety of fusion, propulsion, and plasma concepts. Presently, Dr. Pancotti is the Principle Investigator for MSNW NextSTEP propulsion program. As the Director of this research group, he is a co-investigator on several additional research projects including lower power FRC research for the Air Force and plasma Magnetoshell aero braking for NASA. Currently he holds a portfolio of five advanced propulsion and applied plasma research topics and leads of team of five researchers and technical staff.

Dr. Pancotti is the author or co-author of over 40 refereed research publications on diagnostics, plasmas physics, and space propulsion. He is an active member of his research community, having peer-reviewed papers for the *Journal of Spacecraft and Rockets* and the *Review of Scientific Instruments*. He has served as chair, co-chair, and session organizer for the Joint Propulsion Conference (JPC), The International Electric Propulsion Conference (IEPC), The Joint Army Navy NASA Air Force (JANNAF) Conference, and Advanced Space Propulsion Workshop (ASPW).