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June 29, 2017

Statement of
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and
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before the

Subcommittee on Space
Committee on Science, Space and Technology
U. S. House of Representatives

Mr. Chairman and Members of the Subcommittee, thank you for the opportunity to appear before you today to discuss NASA's work on in-space propulsion systems that will take our astronauts into the solar system on missions of deep space exploration and will increase the capability and reduce the cost of science, commercial, and other Government missions. Validation of these and related capabilities, including the Space Launch System (SLS) and Orion, are necessary elements of NASA's planned deep space exploration architecture.

The Space Technology Mission Directorate (STMD) is developing capabilities for in-space propulsion, including cryogenic propellant storage, power generation and energy storage, and on-orbit refueling. High power solar electric propulsion (SEP) capabilities, scalable to handle power and thrust levels needed for deep space human exploration missions, are considered essential to efficiently and affordably perform human exploration missions to distant destinations such as Mars. In addition, NASA is investing in technologies that will allow for the in-space storage and transfer of cryogenic fuels to meet the needs for future propulsion stages to move crew from Low Earth Orbit to a variety of destinations. A key goal is to demonstrate these new capabilities in the next few years and infuse them into human missions in the next decade. STMD is working closely with the Human Exploration and Operations Mission Directorate's (HEOMD) Advanced Explorations Systems (AES) Division to incorporate and integrate new technologies and innovations as they are matured to the point of infusion.

Solar Electric Propulsion (SEP)

Solar Electric Propulsion (SEP) technology has long been a priority technology investment by STMD, and SEP has been of great interest to NASA and other Government organizations and industry for many years. The focus of the SEP technology project has been on lighter and more efficient solar array structures and electric thrusters including the electronics to power them (called a power processing unit or

PPU) that are about 2.5 times the power level of today's thrusters of that type. Recently, NASA demonstrated full performance compatibility of a high power electric propulsion thruster and power processing unit, with more than 2,500 total hours of testing. The Agency subsequently awarded a contract to Aerojet Rocketdyne for the development and delivery of engineering development units of a 13 kilowatt (kW) thruster and PPU by the end of 2018. Advanced solar arrays developed by NASA and industry partners through a NASA Research Announcement (Deployable Space Systems and Orbital ATK) are two times lighter and use four times less stowed volume for the same amount of electricity produced by commercially available arrays. Deployment of a Rollout Solar Array was recently demonstrated on the International Space Station. These are significant steps forward toward systems that can be utilized in the next few years for science missions, Mars exploration, and widespread use on vehicles in Earth orbit and in cislunar space. The solar array technology is already being utilized in commercial spacecraft designs, and similar adoption of the new electric thrusters is also expected because the new performance levels for both the arrays and thrusters were designed in collaboration with commercial space industry. As such, NASA could potentially become a marginal buyer of the technology in the future, thus lowering overall mission cost.

Lower-power SEP systems are available now and have been used for a variety of spacecraft over the last decade to manage station keeping and provide continuous thrust for deep space missions with the appropriate mission profile. For NASA, examples include Deep Space 1 and Dawn. The current SEP system being developed for a demonstration-class mission will provide between 30 and 50 kilowatts of power. The final objective system that HEOMD envisions for its deep space exploration missions involves a 300 kW system. STMD intends to develop the SEP technology components, as well as fund the integration and flight demonstration of a 30-kW-class high power SEP system. To permit the development of a 300 kW system, many technology elements – including advanced high power solar arrays, advanced high power thrusters and a new generation of power management and power processing systems – will be needed relative to current SEP capabilities. The main purpose of the 30 kW demonstration-class system is to develop, integrate and demonstrate these advanced component technologies to clearly validate extensibility to the 300 kW system. Such a 30 kW demonstration system can also be directly applied to science as well as Department of Defense (DoD) missions which are not feasible today. Furthermore, the component technologies, particularly the advanced solar arrays, will have direct commercial applicability to future communications satellites.

The SEP project illustrates the strength of a multi-customer approach to technology development. The long-term need for human exploration involves deploying a 300 kW SEP space tug for deep space missions. Meanwhile, both the commercial space sector and the Science Mission Directorate have shown interest in utilizing the component technologies – especially the deployable solar arrays at the 5 kW to 30 kW power levels. Commercial satellite firms will soon use these arrays, with their lower weight and improved packaging efficiency, to lower the cost of future communications satellites. As a result of the careful planning by STMD, an architectural pathway now exists that will evolve SEP from the limited capability available today all the way to a human-exploration-class system. Along the way, STMD will provide tremendous benefit to multiple customers including the commercial space industry.

The Asteroid Redirect Robotic Mission (ARRM) portion of the Asteroid Redirect Mission (ARM) made substantial steps towards developing a highly efficient, large scale SEP capability that will be needed in NASA's strategy to position future habitats, landers, and other elements in Mars orbit prior to a crewed mission, and possibly deliver crew to Mars on a vehicle that also uses chemical propulsion. The capability to move multi-ton objects in space, such as cargo for a Mars mission and support reliabilities needed for human-scale Mars missions, will be of critical importance as we prepare for deep space missions beyond the Earth-Moon system. The SEP system is an essential component to deliver cargo for Mars missions, logistics and potentially the propulsive return stage to Mars orbit – efficiently and affordably emplacing these assets prior to the arrival of humans.

Formulation of the ARRM is being closed out and a revised approach to early crewed missions in the lunar vicinity is emerging in NASA plans. Early missions are intended to build toward more extended duration, deeper space human missions. To support longer human stays beyond low-Earth orbit earlier than was possible with the ARRM, the same advanced SEP integrated capability could be used in this cis-lunar capability. Deployment of 30-50-kW-class SEP as an initial step would offer: a highly efficient power and propulsion capability to support longer duration human habitation, a platform for communications and other lunar vicinity services for extended crew presence, the ability to complete a needed integrated flight demonstration, and advance systems use aligned with emerging commercial and other Government needs. Our analyses of in-space orbit transfers in the lunar vicinity show a 5- to 15-fold savings of propellant for this system as compared to chemical-only systems.

In addition to these SEP investments, NASA is also evaluating the different generation of extremely high-power electric propulsion technologies that offer the potential for substantially reduced transit times to Mars and other deep space destinations. These technologies are in the early development stage, with several significant system development challenges that need to be addressed prior to being implemented on a NASA mission. The technologies being evaluated include the Variable Specific Impulse Magnetoplasma Rocket (VASIMR), a nested Hall thruster, and a Lorentz force thruster that are funded as part of the Next Space Technologies for Exploration Partnerships (NextSTEP).

NextSTEP – Advanced Propulsion

NASA's journey to deep space will include key partnerships with commercial industry for the development of advanced exploration systems. In an effort to stimulate deep space capability development across the aerospace industry, NASA released the NextSTEP Broad Agency Announcement in late 2014 and, in 2015, selected 12 projects to advance the development of necessary exploration capabilities – seven in habitation, three in propulsion, and two in small satellites. NASA has since entered into fixed-price contracts with the selectees. Through these public-private partnerships, NextSTEP partners will provide advanced concept studies and technology development projects in the areas of advanced propulsion, habitation systems, and small satellites.

Advanced propulsion technology will be necessary to power exploration into deeper space. Selected partners will further the development of high power electric propulsion (EP) systems in order to lay the ground work for future lifetime testing and eventual technology demonstration missions of the EP systems. Currently, a state of the art electric propulsion engine operates at 5 kW of power, and NASA hopes to eventually achieve an integrated system operating at 300 kW or greater. Partners will demonstrate electric propulsion systems with higher specific impulse, higher efficiency, and higher power for long-duration deep space transportation systems and look at capabilities that are beyond those previously considered.

- **Ad Astra Rocket Company of Webster, Texas** will use the NextSTEP award to develop and test an advanced version of its VASIMR engine, an advanced plasma space propulsion system. Plasma is an electrically charged gas that can be heated to extreme temperatures by radio waves and controlled and guided by strong magnetic fields. The magnetic field also insulates nearby structures so exhaust temperatures well beyond the melting point of materials can be achieved. In rocket propulsion, the higher the temperature of the exhaust gases, the higher their velocity and the higher the fuel efficiency. The engine will be equipped with technological advances for a longer test to demonstrate its new proprietary core design and thermal control subsystem and to better estimate component lifetime.

- **Aerojet Rocketdyne Inc. of Redmond, Washington** will use the NextSTEP award to complete the development on a Power Processing Unit that will convert the electrical power generated by a spacecraft's solar arrays into the power needed for its patented 250 kW multi-channel Nested Hall Thruster. A nested Hall thruster consists of concentric discharge channels that can be operated individually or in combination to produce variable power levels.

- **MSNW LLC of Redmond, Washington** plans to develop a thruster for high-power, exploration-class missions. MSNW LLC will also partner with the University of Washington to develop and test a propulsion system capable of operation from 100 to 300 kW power on both traditional propellants and propellants manufactured using resources available during a deep space mission to the Moon or Mars, minimizing the materials carried from Earth.

These selections were for technologies currently in early research and development, and the objective is to demonstrate integrated electric propulsion systems in ground tests operating at a power level of 100 kW for 100 continuous hours by 2018.

Nuclear Thermal Propulsion (NTP)

An AES project was initiated in 2012 to develop and test reactor fuel elements, a critical nuclear thermal propulsion (NTP) technology development challenge, leading to a recommendation by a joint Department of Energy (DOE) and NASA independent review board in early 2015 to have a primary focus for future fuel development on graphite composite type NTP fuel materials with a secondary focus on cermet materials. The project has also conducted preliminary nuclear rocket engine concept development and initial assessments of the affordability of nuclear ground test methods for NTP. In 2015, the project conducted more rigorous fuel element fabrication and testing of the composite fuel elements. In 2016-17, the project has been working with the DOE to incorporate enriched uranium into the selected material and fuel elements and eventually test active fuel element(s) in a reactor to investigate the effects of radiation on material performance. The NASA Marshall Space Flight Center (MSFC), in partnership with DOE, is leading this project, with the Glenn Research Center (GRC) also providing a significant support role. STMD is investing in development of NTP fuel elements based on low enriched uranium (LEU) enabled by advances in materials processing to support potential future NTP efforts. The project is also completing a feasibility and affordability study of a NTP engine system utilizing a LEU-based reactor. In addition, the project conducted studies regarding licensing for engine ground test activities, and completed preliminary concept design and system sizing of contained ground test facility. These studies will be used to determine the feasibility and cost of advancing NTP via development and testing of a ground demonstration system. STMD is also supporting NTP capabilities with the eCryo project that is advancing our ability to perform long-term in-space storage of liquid hydrogen, a required capability for NTP.

NASA does not expect to require advanced propulsion technologies such as NTP in the initial crewed missions to the Mars system. Other advanced propulsion technologies such as high-powered SEP or EP, combined with chemical systems, meet the needs of U.S. commercial aerospace industry while serving as the core capabilities for the initial in-space propulsion system for the Mars crewed missions.

Additional Advanced Propulsion Investments

STMD is developing several additional in-space propulsion related technologies and advanced concepts. The Green Propellant Infusion Mission will conduct an in-space demonstration of a propulsion system using a propellant that is less toxic and has approximately 40 percent higher performance by volume than hydrazine, which will reduce spacecraft ground processing costs. NASA is also investing in several chemical and EP technologies for small spacecraft to enable future science and exploration missions utilizing cubesats and other small spacecraft. STMD's NASA Innovative Advanced Concepts program is also looking far into the future at revolutionary concepts to potentially enable interstellar robotic missions, such as directed energy propulsion for wafer-sized spacecraft and electric sail concepts that extract thrust from electrostatic repulsion of solar wind protons.

Conclusion

As NASA moves out beyond low-Earth orbit and into deep space, we will need to create a sustainable infrastructure to support the exploration of a variety of destinations in the decades ahead. One key component of this infrastructure is in-space propulsion, which will enable us to move crew and cargo across the vast distances involved in a timely manner. Beyond chemical propulsion (such as that used in the Space Launch System), NASA, along with private sector partners, are developing other options, including Solar Electric Propulsion. The development and demonstration of the advanced solar arrays and the Hall-thruster-based electric propulsion technologies are essential for efficiently performing future deep space human exploration missions, including Mars missions. Furthermore, advanced solar arrays and Hall thrusters have significant crosscutting utility to perform science missions, meet the needs of other Government agencies, and significantly improve the affordability and capability of our Nation's commercial satellites.

Mr. Chairman, we would be happy to respond to any questions you or the other Members of the Subcommittee may have.