Written Statement of
Dr. Mitchell L. R. Walker
Georgia Institute of Technology
to the
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Committee on Science, Space, and Technology
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on
In-Space Propulsion: Strategic Choices and Options
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Mr. Chairman, Ranking Member Bera, and members of the Subcommittee, thank you for the honor of appearing before you today to discuss strategic investments in in-space propulsion technology. My name is Mitchell L. R. Walker. The views I express today are shaped by a 17-year aerospace engineering career. For the past 12 years, I have been fortunate to serve on the faculty of the Daniel Guggenheim School of Aerospace Engineering at the Georgia Institute of Technology. As director of Georgia Tech's High-Power Electric Propulsion Laboratory, I lead an active research and educational program focused on experimental and theoretical studies of advanced plasma propulsion concepts for spacecraft and fundamental plasma physics. The hands-on skills in experimental in-space propulsion being developed by the undergraduate and graduate students at Georgia Tech are of significant interest to NASA, the Office of Naval Research, the U.S. Air Force, DARPA, industry, and others in academia. It gives me great pride to work closely with these students, as they develop into the space propulsion engineers and scientists of our nation's future.

I presently serve as the vice chair of the American Institute of Aeronautics and Astronautics Electric Propulsion Technical Committee, an associate editor of the *Journal of Spacecraft and Rockets*, and the general chair of the 2017 International Electric Propulsion Conference. I am here today as an individual and the views I express are mine alone.

U.S. Leadership in Electric Propulsion

Electric propulsion is the acceleration of propellant with electrical energy to generate thrust for spacecraft. In the case of solar electric propulsion (SEP), the electrical energy is supplied by solar arrays on the spacecraft. Hall effect thrusters and gridded ion engines are successful examples of electric propulsion technology used in commercial, defense, and civil applications. Electric propulsion offers a significant advantage over chemical rockets because the exhaust velocity is not limited by the amount of energy released from the chemical bonds of the propellant. Compared to chemical propulsion, this approach enhances the efficiency of the thruster by more than an order of magnitude and leads to significant mass reductions – a change that allows us to include more payload mass on the same launch vehicle. Thus, electric propulsion systems enable space missions that could never take place with chemical propulsion alone. In spite of the fact that electric propulsion systems have large exhaust velocities, they do not have large thrust levels because of the limited available spacecraft power.

NASA has been a leader in the development and flight of electric propulsion technology since its introduction in the late 1950s. NASA flew its first electric propulsion device in 1964 as part of the Space Electric Rocket Test 1. In 1998, the NASA Solar Technology Application Readiness (NSTAR) ion propulsion system flew on the Deep Space 1 spacecraft. It marked the first use of electric propulsion as the primary propulsion system on a NASA mission. The NSTAR ion engine enabled a 163-million-mile trip that included flybys of the asteroid Braille and the comet Borelly. In 2007, NASA launched the DAWN spacecraft that also uses the NSTAR ion engines as primary propulsion. To date, DAWN has orbited both Ceres and Vesta, protoplanets in the asteroid belt between Mars and Jupiter. NASA’s continuous investment in electric propulsion across the last 20+ years has made the U.S. the world leader in electric propulsion technology. One can only imagine the knowledge that will be created as scientists embrace the unique capabilities of this technology for future exploration of the solar system.

Paradigm Shift

Inspired by new technologies, our world has gradually shifted to a space-based infrastructure – one where space is a commodity. Modern infrastructure include GPS, satellite radio, satellite TV, cellphone backhaul, DoD communications, and weather monitoring systems. Earth imaging, a new generation of space service enabled by miniaturization of electronics and low-cost access to space, has also emerged. Companies such as Google/Terra Bella and Planet Labs sell near continuous imaging of most locations on Earth. The images will have a tremendous impact on commerce, agriculture, natural resources, and the stock market. The success and advantages of electric propulsion has not gone unnoticed by Earth-centric satellite operations.

We stand in the midst of a paradigm shift in the propulsion system requirements of satellites and deep space probes from traditional chemical propulsion to electric propulsion. This shift is the result of dramatic increase in satellite available power for payloads. During the last 20 years, investments in solar array technology have increased geosynchronous satellite power from approximately 1 kW to over 25 kW. As available power climbed, electric propulsion transitioned from an efficient technology used to perform stationkeeping to the primary propulsion system. In 2015, this trend culminated in the launch of Boeing’s first all-electric commercial satellites. All-electric satellites use electric propulsion to perform the transfer maneuver from geostationary transfer orbit (GTO) to geostationary orbit (GEO) and provide 15 years of stationkeeping for applications such as DirecTV and military communications. Electric propulsion uses the existing solar power system on the satellite during the orbit transfer before the payload is in use. The enormous propellant mass savings allows two all-electric satellites to launch on a smaller, less expensive launch vehicle. The ability of electric propulsion to perform orbit raising as well as stationkeeping maneuvers has virtually eliminated the need for in-space chemical propulsion in many applications. Current projections show that 50-75 percent of all future geostationary satellites will use electric propulsion technology because of its ability to deliver the same service or capability as chemical propulsion at a significantly lower cost. In parallel, high-power EP devices are a core theme of NASA’s technology roadmap.

The enabling performance and resultant competitive advantage of electric propulsion technology are appreciated around the world. The introduction of all-electric spacecraft coupled with the low-cost Falcon 9 launch vehicle enabled our nation to recapture the global launch vehicle market for commercial satellites. To remain economically competitive with this success, launch vehicle providers are forced to upgrade their systems. Competitiors in this market include the Ariane 6 of Europe, the Proton of Russia, the H3 of Japan, and the new Geosynchronous Satellite Launch Vehicle (GSLV) of India. The global response is not limited to launch vehicle providers. Europe has made significant investments in electric propulsion technology for both commercial satellites and science missions. Russia is building on its historic success in the electric propulsion field. China launched its first electrically-propelled geostationary satellite (a gridded ion engine, SJ-13) in April 2017. India launched its first electrically-propelled satellite (a Hall effect thruster, GSAT-9) in May 2017. Japan is actively developing a Hall effect thruster for its all-electric commercial satellite schedule to launch in 2021. All of these countries are establishing their presence in the global space communications and exploration markets using electric propulsion technologies. In addition, multiple countries, including Brazil and Turkey, have initiated electric propulsion research programs. The importance of electric propulsion in their technology portfolios cannot be overstated. It is a recognized factor in their competitiveness.

There are three activities that I strongly believe will bolster our nation's leading position in electric propulsion technology. First, investments are required in electric propulsion technology across the spectrum of expected time to return on investment. Second, the nation must invest in ground-based test facilities to develop and then fly the next generation of high-power electric propulsion devices. Third, NASA must maintain a steady stream of investment in university research programs to ensure that the intellectual talent required to fly high-power electric propulsion systems exists when the nation is ready to execute on these ambitious missions.

Investment Spectrum

Investments are required in the development of electric propulsion technology across the spectrum of expected time to return on investment. This approach ensures a robust technology development pipeline and inspires younger generations of scientists and engineers.

<u>Near-term Investments</u>
In the near term, the performance of electric propulsion is well aligned with many valuable NASA science missions, all-electric geostationary commercial satellites, and DoD communication satellite requirements. The U.S. commercial satellite industry faces strong international competition from Russia, China, India, Japan, and Europe. Investment in electric propulsion technology below 15 kW has a valuable immediate return on investment to the nation for exploration and science as well as to enhance competitiveness in the commercial satellite market. In particular, the low level of thrust provided by electric propulsion at current satellite power levels yields multiple month orbit transfers. To reduce the transfer time, significant increases are required in the operating power and performance (thrust-to-power ratio) of electric propulsion devices, but the thrust-to-power ratio of contemporary electric propulsion devices has plateaued. We must continue to invest in electric propulsion device thrust-to-power ratio to reduce orbit transfer times. Our international competition will seize this opportunity if we do not. Thus, aligning NASA investment with opportunities in industry will enable our nation to lead the "next" electric propulsion market.

Mid-term Investments

New upcoming mission demands will require significant propulsion system performance, but possibly in a different operational regime. As a sign of the promise and impact of electric propulsion, both OneWeb (initial investors include Airbus, Coca Cola, and Intelsat) and SpaceX have baselined Hall effect thrusters to maintain the operational orbit of their constellations. Electric propulsion will be part of the solution to our growing space debris challenge. To date, all envisioned solutions for removing objects from valuable orbits and require efficient propulsion systems. The low thrust, highly tunable performance of electric propulsion enables multiple sciences missions. The unprecedented GOCE mission (2009) used electric propulsion to balance the drag force experienced by the spacecraft. This enabled scientists to completely map the gravity field of the Earth. This knowledge is broadly used for to geodesy, oceanography, solid-earth physics, and has advanced our understanding of water location as a function of season. Electric propulsion enables precise control over spacecraft position and orientation for planetary scale studies of predicted physical phenomena, e.g., gravitational waves predicted by Einstein's theory of general relativity in 1915. The capability and flexibility of electric propulsion will be leveraged to address new upcoming mission demands.

Long-term Investments

The electrical power of spacecraft will continue to increase with advances in photovoltaics, deployable structures, and battery technology. At some time in the future, we will have the ability to fly spacecraft with several hundred kilowatts of power available on orbit. One application for this class of spacecraft is the delivery of supplies to Mars to prepare for the eventual arrival of humans. Note, multiple studies show that we can place humans on the surface of Mars with chemical propulsion. The efficiency of electric propulsion dramatically reduces the amount of propellant and number of launch vehicles required to deliver hardware to Mars. These reductions have significant financial advantages. There are at least two intermediate power flight demonstrations required as we move from 5-kW electric propulsion systems to the desired 100+ kW systems envisioned in NASA's future.

As a point of reference, NASA demonstrated a 100-kW gridded ion engine electric propulsion system in 1962. NASA immediately realized that the real issue was available electrical power. Thus, it is insufficient to merely consider the performance of the thruster, one must consider the performance of the propulsion system. This fact highlights the need to make a parallel investment in high-performance electrical power generation in space if we seek to fly high-power electric propulsion devices.

Facilities

The low thrust level of electric propulsion at available on-orbit power levels requires the technology to operate flawlessly for years to enable a successful mission. To generate this level of understanding and reliability requires extensive research and development testing in ground-based vacuum facilities. Unlike chemical propulsion, electric propulsion operation is unique because it accelerates individual particles. Thus, it is sensitive to the operating pressure within the vacuum facility. Second, the ground-based vacuum facility required to operate EP devices has a non-negligible impact on the performance and operation of EP devices. Above a certain pressure, the background gas can change the exhaust plume and alter the physical processes within the thruster. This physical process is a significant issue in ground-based facilities that must remove propellant as quickly as enters the facility from the thruster. Thus, the success of electric propulsion hinges on our ability to accurately predict the performance of the devices in ground-based vacuum facilities. To maintain the vacuum of space in ground-based facilities while the thruster is operating requires extensive pumps that can remove the propellant from the facility at the same rate that it is exhausted from the thruster.

The impact of the vacuum facility on EP device operation may be exacerbated as the required power level of EP devices continues to grow. Many national vacuum facilities are physically large enough to test thrusters at powers levels up to 100 kW, but their pumping speeds must be increased by at least an order of magnitude to avoid facility pressure effects for performance characterization, plume interaction studies, and life testing.

As a point of reference, the NSTAR ion engine that propelled Deep Space 1 and currently propels the DAWN mission has a nominal operation power of 2.3 kW. The gridded ion engines that compose the XIPS on Boeing spacecraft and the Hall effect thrusters on Lockheed Martin spacecraft possess nominal operating power slightly less than 5 kW. The capabilities of existing ground-based test facilities are well aligned for these devices. Investments are required to upgrade facilities to enable high-fidelity characterization of the near-term electric propulsion devices that will operate at nearly 15 kW. This infrastructure investment is required within the next 10 years for the U.S. to maintain its leading position in the in-space propulsion market. As we extrapolate this trend farther into the future, the nation must make the investment in several facilities (upgraded and new) to operation 100-kW class electric propulsion devices of the next generation of electric propulsion test facilities. This investment should be informed by a thorough optimization study of the number of facilities, their capability, and location. These investments are critical to NextSTEP thruster development.

Workforce Development

The long-term success of high-power electric propulsion requires a continuous investment in university research programs to ensure that the talent is available to develop and qualify these systems. Development programs such as NextSTEP electric propulsion systems provide a grand vision that excites and inspires students. The NASA Space Technology Research Fellowship is a critical support structure in the existing talent portfolio pipeline. The unprecedented demand for talent in electric propulsion from the Department of Defense and industry absorbs the vast majority of the graduates produced by the university with electric propulsion research programs. To attract and retain vibrant, talented students in high-power electric propulsion requires NASA to remain visibly active in this technology. We must sustain or develop the human capital required to develop and fly next-generation EP devices in the 2030 time frame and beyond.

Summary

The efficiency, reliability, and flexibility of propulsion systems impact our ability to explore and monetize space. Electric propulsion technology is advantageous in all these dimensions. The role of electric propulsion in the exploration of our solar system, economy, and security will increase in the coming decades.

First, investments are required in electric propulsion technology across the spectrum of expected time to return on investment. Near-term investment aligned with commercial spacecraft help U.S. industry retain a leading position in the global space industry. Mid-term investments will allow us to tackle the new mission requirements of smallsats, space debris, and planetary-scale investigations of fundamental physics. Second, the nation must invest in ground-based test facilities to develop and then fly the next generation of high-power electric propulsion devices. Third, NASA must maintain a steady stream of investment in university research programs to ensure that the intellectual talent required to fly high-power electric propulsion systems exists when the nation is ready to execute on these ambitious missions.

Investments in NASA's electric propulsion program aids the economic competitiveness our nation, enhances our understanding of the physical world, and inspire current and future generations to pursue STEM careers. This testimony includes examples of the impact of electric propulsion on the global economy and our ability to make scientific discoveries. It also demonstrates our nation's leading position in space technology.