Statement of

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and

Co-Chair, Committee on Space Nuclear Propulsion for Human Mars Exploration

before the

Subcommittee on Space and Aeronautics
Committee on Science, Space and Technology
House of Representatives

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Good morning, Chairman Beyer, Ranking Member Babin, and members of the subcommittee. My name is Roger Myers. I am the owner of R Myers Consulting, the President of the Washington State Academy of Sciences, and Chair of the Washington State Joint Center for Aerospace Technology Innovation. I served as the Co-Chair, along with Dr. Robert Braun, of the committee that wrote the National Academies of Sciences, Engineering, and Medicine report, *Space Nuclear Propulsion for Human Mars Exploration*. The National Academy of Sciences was chartered by Congress in 1863 to advise the government on matters of science and technology and later expanded to include the National Academies of Engineering and Medicine. This study was commissioned in early 2020 by NASA's Space Technology Mission Directorate to assess the primary technical and programmatic challenges, merits, and risks for developing and demonstrating space nuclear propulsion systems for human exploration missions to Mars, including both nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) technology options. Specifically, we were asked to assess these factors for an NTP system providing 900s specific impulse, and an NEP system providing at least 1 MW of electric power with a power-to-mass ratio that is substantially better than the current state-of-the-art. Additionally, the propulsion systems were to be ready for a human mission in 2039, with a round trip time, including the Mars surface stay, of less than 750 days. I refer to this as the baseline mission.

Our ad hoc Committee performing this work included highly experienced representatives from industry, the Department of Energy, the Department of Defense, and academia, and we received outstanding support from the National Academies' study director Alan Angleman. Our Committee received input and presentations from NASA, the Department of Energy, several companies, and universities. We held over twenty meetings over the course of the year, completing our work in February of 2021.

By way of background, NTP systems are conceptually similar to chemical rockets, where the combustion chamber has been replaced by a compact, very high-power-density nuclear reactor. To achieve the required specific impulse of 900s, the hydrogen propellant is pumped through the high-temperature reactor and is heated to a temperature of at least 2,700 Kelvin. Achieving this hydrogen temperature requires the nuclear reactor fuel to operate at a temperature of approximately 2900 K or more. The reactor must also start very rapidly compared to other reactors: a start time of less than one minute is best in order to reach the required performance levels rapidly. An NTP system thus requires a liquid hydrogen storage and pumping subsystem, a high-performance nuclear reactor with shielding, and a nozzle that converts thermal energy from the reactor into thrust. By contrast, an NEP system requires a lower temperature, slow-start nuclear reactor with shielding, a power conversion subsystem to generate the electrical power, a heat rejection subsystem consisting of large radiators, an electrical power management and distribution subsystem, and an electric propulsion subsystem, all of which work together for successful NEP system operation. NTP and NEP are very different technologies that have very different challenges.

Based on all the input we received, an extensive review of the available literature, and our Committee deliberations, we arrived at several consensus findings and recommendations. All the relevant background and details are provided in our report (see http://www.nap.edu/25977). For this testimony, I will first address the key findings and recommendations for NTP systems, then I will review those for NEP systems, and finally I will address those that are applicable to both NTP and NEP.

Concerning NTP, our key findings and recommendations are:

First, we found that no currently available nuclear reactor fuels can provide the required temperatures to meet the required performance or engine life. The Committee recommends that NASA should expeditiously select and validate a fuel architecture for the NTP system that can achieve the required 2,700 K hydrogen temperature at the reactor exit without significant deterioration during the mission, including the required rapid engine start transients (1 minute or less). This selection process should consider whether the appropriate fuel feedstock production capabilities will be sufficient.

Second, we found that technology to store liquid hydrogen in space for the required missions does not exist. Our Committee recommends that NASA develop high-capacity tank systems capable of storing liquid hydrogen at 20 K with minimal boiloff in the vehicle assembly orbit and for the duration of the mission.

Third, we found that subscale in-space testing of NTP systems cannot adequately address the baseline mission risks and potential failure mechanisms of NTP systems. Therefore, full-scale and full-thrust integrated ground testing of the NTP system is required. Combining this full-scale ground testing with extensive modeling and simulation enables the use of the precursor cargo missions to Mars to meet the flight qualification requirements for the human mission and eliminates the need for precursor demonstration flights. Our Committee recommends that NASA rely on extensive investments in (1) modeling and simulation, (2) ground testing, including integrated system tests at full scale and thrust; and (3) the use of cargo missions as a means of flight qualification of the NTP system that will be incorporated into the first crewed mission.

Finally, our Committee found that an aggressive program could develop an NTP system capable of executing the baseline mission in 2039. However, to achieve this, our Committee recommends that NASA invigorate technology development associated with the fundamental NTP challenges, which is to develop an NTP fuel system that can heat its hydrogen propellant to approximately 2,700 K at the reactor exit for the duration of each burn. NASA should also invigorate technology development associated with the long-term storage of liquid hydrogen in space with minimal loss, the lack of adequate ground-based test facilities, and the need to rapidly bring an NTP system to full operating temperature (preferably in 1 minute or less).

For NEP, our key findings and recommendations are:

First, our Committee found that developing a MWe-class NEP system for the baseline mission will require increasing the power of several subsystems by orders of magnitude over available technology.

Second, similar to NTP, our Committee found that subscale in-space flight testing of NEP systems cannot adequately address the risks and potential failure modes associated with the baseline mission NEP system. With sufficient modeling, simulation, and ground testing, including modular subsystem tests at full scale and power, flight qualification requirements can be met by the cargo missions that will precede the first crewed mission to Mars. Additionally, NEP systems may not require fully integrated ground testing - modular subsystem tests at full power may be adequate. In order to develop an NEP system for the baseline mission, our Committee recommends that NASA rely on (1) extensive investments in modeling and simulation, (2) ground testing (including modular subsystem tests at full scale and power), and (3) the use of cargo missions as a means of flight qualification.

Finally, our Committee found that as a result of low and intermittent investment over the past several decades, it is unclear if even an aggressive program would be able to develop an NEP system capable of executing the baseline mission. To clarify – we are not saying that it cannot – but rather that we do not have the data on which to base a good assessment. Our Committee recommends that NASA invigorate technology development associated with the fundamental challenge for NEP systems, which is to scale up each subsystem's operating power and develop an integrated nuclear electric system suitable for the baseline mission. Additionally, NASA should put in place plans for (1) demonstrating the operational reliability of an integrated NEP system over its multi-year lifetime and (2) developing a chemical propulsion system that can be used with the nuclear electric system. If NASA plans to apply NEP technology to a 2039 launch of the baseline mission, NASA should immediately accelerate NEP technology development.

Our findings and recommendations applicable to both NTP and NEP are:

First, our Committee found that recent, apples-to-apples trade studies comparing NEP and NTP systems for a crewed mission to Mars in general and the baseline mission, in particular, do not exist. To remedy this gap, NASA should develop consistent figures of merit and technical expertise to allow for an objective comparison of the ability of these systems to meet the requirements of the baseline mission.

Second, both NEP and NTP systems require, albeit to very different levels, significant maturation in areas such as nuclear reactor fuels, materials, and additional reactor technologies; cryogenic fluid management; modeling and simulation; testing; and regulatory approvals. Given those commonalities, some development work in these areas can proceed independently of selecting a particular space nuclear propulsion system.

Third, a comprehensive assessment of reactor fuels using high-assay low-enriched uranium (HALEU) vs. fuels using highly enriched uranium (HEU) for NTP and NEP systems that weighs the key considerations is not available. These considerations include technical feasibility and difficulty, performance, proliferation and security, fuel availability, cost, schedule, and supply chain as applied to the baseline mission. Our Committee recommends that in the near term, NASA and the Department of Energy (DOE), with inputs from other key stakeholders, including commercial industry and academia, conduct a comprehensive assessment of the relative merits and challenges of HEU and HALEU fuels for NTP and NEP systems as applied to the baseline mission.

Finally, we found that terrestrial microreactors, which operate at a power level comparable to NEP reactors, are on a faster development and demonstration timeline than current plans for space nuclear propulsion systems. Development of microreactors may provide technology advances and lessons learned relevant to the development of NEP systems. Similarly, technology advances within the Demonstration Rocket for Agile Cislunar Operations (DRACO) program of the Defense Advanced Research Projects Agency (DARPA) could potentially contribute to the development of NTP systems for the baseline mission. In light of these potential opportunities, our Committee recommends that NASA seek opportunities for collaboration with the DOE and Department of Defense terrestrial microreactor programs and the DARPA DRACO program to identify synergies with NASA space nuclear propulsion programs.

In summary, our Committee found that either nuclear thermal or nuclear electric propulsion systems would provide substantial benefits to human Mars exploration missions but that both systems have significant technical risks today. These risks are very different for NTP and NEP systems, and neither one is at a state of development suitable for selection. There is a need for significant investment in both systems before a data-driven selection between the two can be made.

Thank you for the opportunity to testify. I'm happy to address any questions the Subcommittee might have.

Dr. Roger Myers
Consultant, R Myers Consulting LLC
Woodinville, WA 98072

Experience Summary

Dr. Roger Myers has over 30 years of experience developing, testing and producing for flight space propulsion technologies and systems of all types for NASA, National Security, and commercial space missions. Additionally, he has spent years leading teams studying spacecraft mission requirements, capabilities, designs, and architectures for all space markets and developing strategies and tactics for engineering team leadership and program and business management. His experience ranges from hands-on research and development, to leading small innovative teams, to leading, as General Manager, the world's largest developer and producer of in-space propulsion technologies and systems, Aerojet Rocketdyne's 400+ person site in Redmond, Washington. His experience with chemical, electric, and nuclear propulsion system development and production as well as their integration requirements and challenges for all spacecraft sizes and applications provides a broad foundation for assessing new challenges and opportunities, and his extensive contacts in the U.S. and international space community enable him to facilitate new connections and create new opportunities. Dr. Myers is also the President of the Washington State Academy of Sciences and the Chair of Washington State's Joint Center for Aerospace Technology Innovation, as well as serving on the Boards for the Electric Rocket Propulsion Society (President 2013-2020) and Seattle's Museum of Flight. Additionally, Dr. Myers supports his community serving on National Academies committees and giving speeches and lectures.

Education

BS Aerospace Engineering, summa cum laude, University of Michigan, 1984
Ph.D, Mechanical and Aerospace Engineering, Princeton University, 1989

Experience

July 2016 – present: independent consultant, R Myers Consulting, LLC
2013-July 2016: Executive Director, Advanced In-Space Programs, Aerojet Rocketdyne
2011 – 2013: Executive Director, Electric Propulsion and Integrated Systems, Aerojet
2010 – 2011: Deputy Lead, Space and Launch Systems and Exec. Director, Electric Propulsion & Integrated Systems, Aerojet
2006-2010: General Manager, Aerojet Redmond Operations
2005-2006: Executive Director, Systems and Technology Development, Aerojet
2002-2005: Director, Systems and Technology Development, Aerojet
1996-2002: Director, Electric Propulsion and Space Electronics, Olin Aerospace, Primex Technologies, and GD Space Propulsion
1988-1996: Research Engineer and Group Supervisor (Sverdrup and Nyma) at NASA Glenn Research Center (then Lewis), conducting and overseeing in-space propulsion research

Awards and Honors

Stuhlinger Medal for Outstanding Achievement in Electric Propulsion, Electric Rocket Propulsion Society, 2017
Wyld Propulsion Award, American Institute of Aeronautics and Astronautics, 2014
Member (elected), Washington State Academy of Sciences, 2012
Fellow (elected), American Institute of Aeronautics and Astronautics, 2010
European Space Agency Award for "Outstanding Contribution to SMART-1 Mission", 2003
NASA Award for "Turning Goals into Reality", for outstanding contributions to and exceptional progress toward NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) Team, 2001

NASA Group Achievement Award for the NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) Team, 1999
NASA Award for Exceptional Contributions to the Space Station Alpha Photovoltaic Test, 1995
NASA Award for Outstanding performance in support of NASA's Space Propulsion Technology Division, 1994
NASA Award for Outstanding support of NASA's On-Board Propulsion Branch, 1992
NASA Award for Outstanding contributions to the Space Station Freedom Photovoltaic Array Test, 1992
NASA Award for Attaining highest power and performance levels achieved with MPD thrusters, 1991

Boards and Other Service to Aerospace, Science, and Engineering Community
2020 – Present: President, Washington State Academy of Sciences; Board member since 2016
2012-Present: Board of Directors and Chair, Joint Center for Aerospace Technology Innovation (Appointed by Washington State Governor)
1995-Present: Board of Directors (Founding member) and President (2013-2020), Electric Rocket Propulsion Society
2015 – Present: Board of Trustees, Museum of Flight, Strategic Planning Committee Chair and member of Education and Spaceflight Committees
2006-Present: Visiting Committee, University of Washington, Dept. of Aeronautics and Astronautics
2020 – Feb 2021: Co-Chair: National Academy of Sciences, Engineering and Medicine Committee "Space Nuclear Propulsion for Human Mars Exploration"
2014-Sept 2020: Member, National Academy of Sciences, Engineering and Medicine Space Technology Industry-Government-University Roundtable
2012: Panelist and In-Space Propulsion (TA02) lead, National Academy of Sciences, Engineering and Medicine, "NASA Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space"
2011-July 2016: Board of Directors, Aerojet Rocketdyne Foundation
2010-2012: Advisory Board, Seattle Science Fair
2006: Panelist, National Academy of Sciences, Engineering and Medicine; "High Energy Power and Propulsion and In-Space Transportation"
1993-2008: Associate Editor, Journal of Propulsion and Power
1998-2000: Chair, AIAA Electric Propulsion Technical Committee
1995-2006: Instructor, AIAA Electric Propulsion Short Course
1994: Organizer, Electric Propulsion Sessions, AIAA Joint Propulsion Conference
1990 – Present: Session chair at most Joint Propulsion and International Electric Propulsion Conferences

Invited Speeches, Presentations, and Panels
Invited Speaker/Lecturer (examples only): Graduation Commencement Speaker at Washington State University (5/2013); Banquet speaker, American Junior Academy of Sciences, 2020; Plenary Speaker at 2013 IECEC "Power Generation and Processing Challenges for Near-Term High Power Solar Electric Propulsion"; Pacific Northwest Aerospace Association (5/2015) "The Business of Space in Washington State"; Graduation speaker for Washington Aerospace Scholars program (2014, 2015, 2016); Univ. Washington Jackson School of International Studies "Space in Washington State"; Testimony to Washington Lt. Governor's Summit on Space (12/2015), "Aerojet Rocketdyne in Washington State"; MIT Enterprise Forum Seattle "Human Mars Exploration: How do we do it affordably?" (12/2015); NRO Technology Seminar "Enhanced Mission Affordability thru Advanced In-Space Propulsion" (1/2013) ; NRC Human Spaceflight Committee "Affordable Human Space Exploration Architectures" (6/2013); NASA ASEB "High Power Solar Electric Propulsion" (10/2013); **Invited Panelist** (examples only): Space Propulsion 2016 "Primes and Operators vs. Suppliers Views on Space Propulsion: Spacecraft"; U.S-Japan Space Forum (3/2016); Propulsion and Energy Conference Forum 360: "Government Investments Enabling Advancement of In-Space Propulsion"

(7/2015); AIAA Propulsion and Energy panel on "Keeping it Going: Sustainability and Growth in Technology and Workforce" (7/2014); Seattle Museum of Flight "The Future of Space" (1/2014); AIAA Propulsion and Energy Conference IECEC Panel on Human Exploration (7/2015) "In-Space Propulsion for Exploration"; "International Partnerships" (Space 2013, 9/2013); "U.S. Space Propulsion" (Space Propulsion 2013, 5/2013); "Space Propulsion in the Puget Sound Region" (WashingtonSTEM, 2/2012); "Pushing the Limits of Knowledge" for NASA 50th Anniversary Forum, (2008); Aerospace Lectures @ U of WA (annual from 1997 – present); "Evolution and Future Directions for Space Transportation" (2003); and at many other locations including Cornell, JPL, LANL, LLNL, Michigan Tech., Ohio State U., ORNL, Princeton U., U of Michigan, U of Tennessee Space Institute, and Worcester Polytechnic Institute

Patents

- Helicon Hall Thruster, Brian E. Beal, Roger M. Myers, Kristi H. de Grys and Alfred C. Wilson, U.S. Patent 7,436,122 Oct. 14, 2008
- Uniform Gas Distribution in ion accelerators with closed electron drift, U.S. Patent 6612105, Arnie Voigt, Kristi de Grys, David King, and Roger Myers, Sept. 2, 2003
- Three axis pulsed plasma thruster with angled cathode and anode strip lines; U.S. Patent 6,173,565; R. Joseph Cassady, Roger M. Myers and Robert D. Osborne, 1998
- Pulsed Mode Cathode; U.S. Patent 5,357,747; Roger M. Myers and Vincent K. Rawlin, Oct 25, 1994

Sample Career Accomplishments

Department of Defense Space missions:

Advanced Extremely High Frequency Mission (AEHF): led team that developed and produced the 4.5kW Hall thruster propulsion system (thrusters and power processing electronics) used for orbit raising and station keeping, including development of the world's first zero-erosion long-life Hall thruster (which led to today's magnetic-shielding concepts).
Global Positioning System: Led team that developed and produced propulsion system for all GPS IIF spacecraft
Wideband Gapfiller Mission: led team that produced GEO insertion bipropellant engines for all of these spacecraft
Coriolis: led team that developed propulsion system for the Navy spacecraft
NFIRE: led team that developed and produced propulsion system for Missile Defense Agency spacecraft
Many classified missions

NASA Space Missions:

Mars Science Laboratory: led team that developed and produced the lander engines with continuous 100:1 throttling capability (7 to 700lbf thrust) enabling the Curiosity Rover to land successfully on Mars, and recently used for Perseverance rover landing.
Pluto/New Horizons: led team that developed and built the propulsion system for APL-led mission to Pluto and beyond – providing extraordinary instrument pointing accuracy during high-speed fly-by.
STEREO: led team that developed and built the propulsion systems for the twin spacecraft
Mars Phoenix Lander: led team that produced the lander engines for first ever controlled soft-landing using pulsed-mode throttling.
THEMIS: led team that developed and built the propulsion systems for the 5-spacecraft constellation of small spacecraft
GOES-R: led team that developed and produced the arcjet system for orbit acquisition and control
Earth Orbiter 1: led team that developed and built both hydrazine and pulsed plasma thruster propulsion systems for the New Millennium program demonstrator spacecraft.

Orion: led team developing all the engines for both the Crew and Service modules, including both new monopropellant and bipropellant engines (2005-2011)
Ares: led team that developed 700lbf Roll Control Engines for the Ares launcher
Deep Space 1: performed early lifetests on NSTAR ion thruster and designed plume diagnostics used in initial spacecraft interface assessments. This same engine was used on NASA's **Dawn** mission to the asteroids Vesta and Ceres.
Green Propellant Infusion Mission: led team that designed, developed and produced AF-M31E propellant thrusters and integrated propulsion system for this successful technology demonstration mission.

<u>International Civil Space Missions</u>
European Automated Transfer Vehicle: led team that qualified and produced 100lfb thrust primary orbit adjust engines for the Jules Verne and subsequent ATV vehicles
H-II Transfer Vehicle: led team that qualified and produced 25lbf thrust ACS engines for the HTV vehicle
Smart-1: led team that developed and produced hydrazine attitude control system for European mission to the moon.
DRTS and WINDS: led team that developed and produced the arcjet systems for these two Japanese communications satellites

<u>Commercial Missions</u>
GeoEye-1: led team that developed propulsion system for highest resolution commercial imagery spacecraft
A2100: Led team that developed and continues producing all chemical and electric engine systems (thrusters and power electronics) for Lockheed-Martin's A2100 series of spacecraft (1996-2010)
Star-2: Led the team producing all the chemical and electric attitude control engines for Orbital's (now Northrup Grumman) Star series of commercial spacecraft (2006-2010)
FS 1300: Led the team that developed, qualified and produced the bipropellant apogee engines for Loral's commercial satellites (2006-2010)
Boeing 702: led team that developed and produced bipropellant apogee engine for Boeing's commercial satellites
Eurostar 2000/3000: Led the team producing the bipropellant engines for EADS/Astrium's commercial satellites (2006-2010)

<u>Technology Development – but not yet flown</u>
Led teams which:
- wrote winning proposals for NASA Advanced Electric Propulsion System (AEPS), the NASA Evolutionary Xenon Thruster (NEXT), and the 100kW Nested Hall Thruster System demonstration (NextSTEP) programs. The NEXT ion thruster is currently being integrated onto NASA's DART mission as a flight demonstration.
- demonstrated highest performance 100lbf thrust class NTO/Hydrazine bipropellant engine with Isp of 334s (NASA AMBR program, 2008)
- demonstrated highest thrust-to-power ratio Hall thruster (USAF HPPS program, 2008)
- built the NEXT 7.5kW high performance ion thruster (NASA NEXT program, 2007) – in 2015 awarded flight contract
- developed and qualified a 620s I_{sp} arcjet propulsion system (2002)
- highest power U.S. steady state magnetoplasmadynamic thruster (225kW, 1993)

Publications

Peer-Reviewed Publication

1. "Space Nuclear Propulsion for Human Mars Exploration", R. Braun, R. Myers, S. Bragg-Sitton, J. Cirtain, T. Dodson, A. Gallimore, J. Gilland, B. Lal, P. Moin, J. Sholtis and S. Zinkle, National Academies of Sciences, Engineering and Medicine, 2021, Washington DC, The National Academies Press. https://doi.org/10.17266/25977.
2. "The Technological and Commercial Expansion of Electric Propulsion," D. Lev, R Myers, K Lemmer, J Kolbeck, H. Koizumi and K. Polzin, Acta Astronautica, Vol. 159, June 2019, pp. 213-227.
3. Electric Propulsion Space Experiment (ESEX)", Myers, R. M., *Journal of Propulsion and Power*, Vol. 18, No. 4, July-Aug 2002, p. 721.
4. "Experimental Investigations and Numerical Modeling of Pulsed Plasma Thruster Plumes," Gatsonis, N.A., Eckman, R., Yin, X., Pencil, J., and Myers, R. M., *Journal of Spacecraft and Rockets*, Vol.38 No.3, May – June 2001, pp. 454-464.
5. "Model of Plasma Contactor Performance," Katz, I., Gardner, B.M., Mandell, M.J., Jongeward, G. A., Patterson, M., and Myers, R.M., *Journal of Spacecraft and Rockets*, Vol. 34, No. 6, November-December 1997, pp. 824 – 828.
6. "Advanced Propulsion for Geostationary Orbit Insertion and North–South Station Keeping**;"** Oleson, S. R., Myers, R.M, Kluever, C. A., Riehl, J., and Curran, F. M., *Journal of Spacecraft and Rockets,* 1997, vol. 34 no.1, pp. 22-28.
7. "Introduction to Arcjets and Arc Heaters: Research Status and Needs Special Section,", *Journal of Propulsion and Power*, Vol. 12, No. 6, Nov-Dec 1996, p. 1010.
8. "Mechanisms of Anode Power Deposition in a Low-Pressure Free Burning Arc," *IEEE Transactions on Plasma Science*, Soulas, G. C., and Myers, R. M., Vol. 24, No. 2, April 1996, pp. 478 – 486.
9. Geometric Scaling of Applied-Field Magnetoplasmadynamic Thrusters; Myers, R.M., *Journal of Propulsion and Power*, Vol. 11, No. 2, March-April 1995, pp.343-350.
10. "Anode Power Deposition in an Applied-Field Segmented Anode MPD Thruster"; Gallimore, A.D., Myers, R.M., Kelly, A.J., and Jahn, R.G.; *Journal of Propulsion and Power,* Vol. 10, No. 2, March – April 1994, pp 262-268; see also AIAA-91-2343, July 1991.
11. "Test Facilities for High Power Electric Propulsion," Sovey, J.S., Vetrone, R.H., Grisnik, S. P., Myers, R.M., and Parkes, J.E.; *Journal of Propulsion and Power*, Vol. 10, No. 1, Jan-Feb. 1994, pp. 18-24. See also AIAA 91-3499, Sept. 1991 and NASA TM 105247.
12. "Applied-Field MPD Thruster Performance with Argon and Hydrogen Propellants," Myers, R.M., *Journal of Propulsion and Power*, Vol. 9, No. 5, September – October 1993, pp. 781 – 784.
13. "Electric Propulsion: an Evolutionary Technology," Curran, F.M., Sovey, J.S., and Myers, R.M., *Acta Astronautica*, Vol. 29, No. 9, July 1993, also presented as IAF 91-241, 42nd Congress of the International Astronautical Federation, Montreal, Canada, Oct. 5-11, 1991.
14. "Thermal Nonequilibrium in a Low Power Arcjet Nozzle," Zube, D.M. and Myers, R.M., *Journal of Propulsion and Power*, Vol. 9, No. 4, July-August 1993, see also AIAA 91-2113, July 1991, and NASA CR 187166.

15. "Techniques for Spectroscopic Measurements in a Low Power Arcjet Nozzle," Zube, D.M. and Myers, R.M., *Journal of Propulsion and Power*, Vol. 8, No. 1, Jan-Feb 1992.
14. "Energy Deposition in Low Power Coaxial Plasma Thrusters," Myers, R. M., Kelly, A. J., and Jahn, R. G., *Journal of Propulsion and Power*, Vol. 7, No. 5, Sept. – Oct. 1991. See also AIAA 88-3206, July 1988.
16. "Cathode Phenomena in a Low Power, Steady-State MPD Thruster," Myers, R.M., Suzuki, N., Kelly, A.J., and Jahn, R.G., *Journal of Propulsion and Power*, Vol. 7, No. 5, Sept – Oct. 1991. See also AIAA 88-3206, July 1988.

Book Contributions

Nuclear Electric Propulsion: Status and Future, with Gilland, J., Sovey, J., and Brophy, J., in *A Critical Review of Space Nuclear Power and Propulsion,* 1984-1993, M. El-Genk, ed., American Institute of Physics Press, New York, 1994.

Trade Journal

"Fiber-Optic Switch for Broadband Emission Spectroscopy" DeGroot, W., Myers, R. M., and Zube, D. M., Laser Tech Briefs, Vol. 2, No. 2, Spring 1994, pp. 50 – 54.

Conference Papers

1. "Performance of the Aurora Low-Power Hall Effect Thruster," Sommerville, J., Fruncek, C., King, L., Makela, J., Terhune, K., Washeleski, R., and Myers, R., IEPC-2019-740, 36th International Electric Propulsion Conference, Vienna, Austria, Sept. 2019.
2. "Nuclear Launch Approval: Options for Criteria"; Kowal, K., Locke, J., Myers, R., and Howieson, S., Paper #51 at the 2019 Nuclear and Emerging Technologies for Space Conference, American Nuclear Society Topical Meeting, Richland, WA, Feb 25-28, 2019.
3. "13kW Advanced Electric Propulsion Flight System Development and Qualification," Jackson, J., Allen, M., Myers, R., Soendker, E., Welander, B., Tolentino, A., Hablitzel, S., Yeatts, C., Xu, S., Sheehan, C., Cardin, J., Snyder, J., Hofer, R., Tofil, T. and Herman, D., IEPC-2017-223, 35th International Electric Propulsion Conference, Atlanta, GA, Oct. 2017
4. "100 kW Nested Hall Thruster System Development," Jackson, J., Allen, M., Myers, R., Hoskins, W., Soendker, E., Welander B., Tolentino, A., Hablitzel, S., Hall, S., Gallimore, A., Jorns, B., Hofer, R., Goebel, D. and Pencil, E., IEPC-2017-219, 35th International Electric Propulsion Conference, Atlanta, GA, October 8 – 12, 2017
5. "NEXT-C Flight Ion Propulsion System Development Status," Fisher, J., Ferriauolo, B., Monheiser, J., Barlog, C., Allen, M., Myers, R., Hoskins, W., Bontempo, J., Nazario, M., Shastry R., Soulas, G. and Aulisio, M., IEPC 2017-218, 35th International Electric Propulsion Conference, Atlanta, GA, Oct. 2017
6. "Development of a 13kW Hall Thruster Propulsion System Performance Model for AEPS," Stanley, S., Allen, M., Goodfellow, K., Chew, G., Rapetti, R., Tofil, T., Herman D., Jackson, J., and Myers, R., AIAA 2017-4726, 53rd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, Atlanta, GA, July 2017.

7. "Architecture Sensitivity to Propulsion Choices for Human Mars Missions," Joyner, C. R., Horton, J., Kokan, T.S., Levack, D. J., Long, M., Myers, R., Widman, F., AIAA Space 2016, AIAA-2016-5458, Sept. 2015.
8. "Affordable Exploration Architectures Using the Space Launch System and High-Power Solar Electric Propulsion," Myers, R., Joyner, C.R., Cassady, R.J., Overton, S., Kokan, T., Horton, J., Hoskins W.A., IEPC-2015-492, 34th International Electric Propulsion Conference July, Kobe, Japan, July 2015
9. "Solar Electric Propulsion Architecture for Mars Cargo for Affordable Exploration and Sustained Permanence," Joyner, C. R., Kokan, T., Myers, R., Levack D., and Cassady, R. J., AIAA Space 2015, AIAA-2015-4520, Pasadena, CA, Sept 2015
10. "30 Years of Electric Propulsion Flight Experience at Aerojet Rocketdyne," Hoskins, W. A., Cassady, R. J., Morgan, O., Myers, R. M., King, D. Q., and de Grys, K., 33rd International Electric Propulsion Conference, Washington D.C., October 2013.
11. "Solar Electric Propulsion (SEP) Benefits for Near-Term NASA Exploration," DeMaster-Smith, L., Kimbrel, S., Overton, S., Carpenter, C., Myers, R., and King, D., AIAA-2013-5352, AIAA Space 2013 Conference and Exposition, San Diego, CA, Sept. 2013
12. "A Space Logistics System Based on Efficient In-space Transportation," Carpenter, C., Myers, R., Hoskins, W., Kimbrel, S., AIAA-2012-5128, AIAA Space 2012 Conference and Exposition, Pasadena, CA, Sept. 2012.
13. "High Power Solar Electric Propulsion for Human Space Exploration Architectures", Myers, R. M. and Carpenter, C., IEPC 2011-261, 32nd International Electric Propulsion Conference, Wiesbaden, Germany, September 2011.
14. Overview of Major U.S. Industrial Electric Propulsion Programs, Myers, R. M., AIAA-2004-3331, 40th Joint Propulsion Conference and Exhibit, Fort Lauderdale, FL, July 2004
15. "Overview of major U.S. industrial programs in electric propulsion," Myers, R. M., AIAA-2000-3147, 36th Joint Propulsion Conference and Exhibit, Huntsville, AL, July 16-19, 2000.
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