NASA's Electric Propulsion Development Activities for Space Nuclear Propulsion Applications

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Given increased worldwide support for advanced nuclear technology for terrestrial applications, there is a renewed interest in the possibility of nuclear-reactor-powered spacecraft. NASA continues investing in the technology areas necessary to support NASA's future scientific and exploration goals. One of those technologies areas is electric propulsion, a highly efficient means for in-space propulsion that increases fuel economy by ionizing and accelerating an onboard propellant using spacecraft electrical power. The current NASA portfolio of electric propulsion investments in support of space nuclear applications focuses on a range of future applications with total system power levels of 50 kilowatts to multimegawatt. These investments support a fast-paced incremental rate for technology development advancement to support these applications. Systems at the 50-kilowatt power level can be accomplished today with existing technology and systems at the multimegawatt level will require further technology developments over the coming decade. Propulsion systems based an array of multiple Hall thrusters have been identified the most likely technology option for the near-term applications and systems utilizing lithium-fueled magneto-plasma-dynamic thrusters have been identified as the most promising alternative technology option for the far-term applications at very high-power levels.

1.Introduction

As part of its Moon to Mars strategy NASA continues investigating architectures and long-term strategies for human space exploration. There are two aspects of that current strategy that influence the possibility of future space nuclear propulsion activities: the objective of a sustained lunar surface presence reliant on nuclear fission power systems and the inclusion of nuclear electric propulsion transportation options for human missions to Mars. Fission surface power has been identified as the preferred technology option to enable sustainable lunar bases in the vicinity of the lunar south pole.[1] The lunar south pole is being targeted due to the presence of frozen water in permanently shadowed craters in that region. Fission surface power offers a technical solution for sun-independent, high-reliability power generation to power a lunar base near the south pole, and water ice with sufficient power generation enables the possibility of in-situ resource generation that could support a sustainable long-duration lunar settlement.

Investments are currently being made through a collaboration between NASA and the US Department of Energy to develop reactor systems for this application. The stated goal for this investment is the deployment of an operating system on the lunar surface by the end of the decade with a reactor power level reported as something between 40 and 100 kilowatts. The successful development of flight-qualified reactor system at this power level would also enable the possibility of free-flying spacecraft utilizing nuclear electric propulsion. This would allow robotic exploration of the outer solar system as envisioned by NASA for the Jupiter Icy Moons Orbiter mission concept from the early 2000's.[2] This type of mission is not as easily performed using solar electric propulsion as decreasing solar generation capability with increasing heliocentric distance drives the need for electric propulsion systems with deep-throttling capabilities.

At the same time, NASA has been studying transportation options for opposition-class human exploration missions to Mars.[3] Opposition class missions were considered, despite the increased propulsive demand relative to conjunctive class missions, due to the possibility of limiting total mission duration to two years with a short stay at Mars versus a three-year mission with a one year stay at Mars. One of the architectures studied in detail is a hybrid approach relying on a combination of chemical propulsion and nuclear electric propulsion. This hybrid architecture takes advantage of the benefits of impulsive chemical maneuvers in the vicinity of the planetary gravity well and the high specific impulse of electric propulsion during the interplanetary cruise phase. This effectively offloads the total amount of required chemical propellant while accommodating the low thrust penalty of electric propulsion. The reactor power level considered for this application was 2 megawatts. The size and scale of this spacecraft system would likely necessitate on-orbit vehicle assembly, and the cost of the spacecraft system would necessitate reusability enabling multiple Mars round-trip applications.

The result is an environment in which NASA could conceivably utilize electric propulsion systems with space-based nuclear systems at power levels ranging from the 40 kilowatts to multimegawatts (see Figure 1). Matching electric propulsion technology to this wide range of power levels presents a unique technology development challenge. This challenge is compounded by both the desire for NASA missions to have development timelines of 5 years or less to minimize the impact of variability in yearly appropriated funding levels and changes in Agency priorities that have occurred with administration changes and the reality that electric propulsion system developments have historically taken as long as a decade from inception to delivery of flight-qualified hardware.

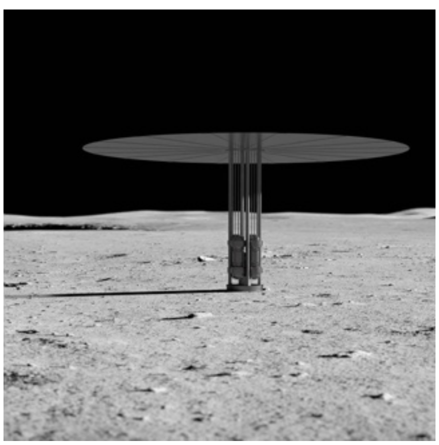
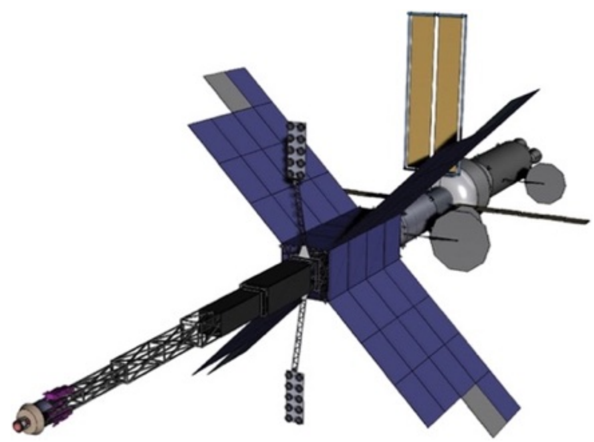



Figure 1: Lunar fission surface power and MW-class Chem/NEP hybrid spacecraft

With this wide range in power levels for future nuclear electric propulsion systems, it useful to consider a phased progression with increasing capability and power over time starting at 50 kilowatts and evolving to multimegawatts. Based on the rate of technology advancements historically observed in other technology areas, an incremental, but fast-paced, rate for technology development advancement (~3X) was assumed. This establishes a framework for applications that start at power levels of approximately 50 kilowatts that evolves in a stepwise fashion to system power levels of nominally 200 kilowatts, then 700 kilowatts, and eventually 2 megawatts over the course of two decades of more. A radical or transformative rate of technology advancement (>10X), which is higher risk and less likely for a capital-intensive activity with a low-volume application like deep-space exploration, was considered unlikely without the type of external factors that could arise from new economic pressures, such as the establishment of a new commercial cis-lunar economy or a sustained “moon-shot” type of national prioritization in this technology area.

2. Background

Two different types of electric propulsion technology were previously selected for development by the Space Nuclear Propulsion Project, as documented in their technology maturation plan for application to multi-megawatt human exploration applications. Those technologies are propulsion systems based on Hall effect thrusters (HETs) and magnetoplasmadynamic thrusters (MPDs).[4] These technologies were selected because of significant prior investments that experimentally demonstrated critical functionality, a qualitative assessment of development risk relative to alternative technologies, and limitations on the resources available to support technology maturation. It should be noted that while HETs and MPDs were chosen for development this does not preclude the possibility of NASA considering the use of alternate propulsion technologies. An example of such a technology is the variable specific impulse magnetoplasma rocket (VASIMR) which is being privately developed with limited NASA support, in the future if deemed advantageous. The development status and history of HETs and MPDs are considered below.

2.1 Hall Effect Thruster Background:

HETs are a mature electric propulsion technology with systems in operational use continuously since the early 1970's. There are currently well over a thousand spacecraft flying HET propulsion systems with single unit power levels of up to 5 kilowatts. HETs have also been built and tested at power levels up 100 kilowatts for high power applications such as those envisioned for the human exploration of Mars using nuclear electric propulsion. This includes a series of thrusters and tests conducted at the NASA Glenn Research Center in the late 1990's through the early 2010's[5,6] and a follow-on activity to develop a 100-kilowatt system that started in the mid 2010's with the thruster work led by a team at the University of Michigan.[7] Photographs from each of these efforts are included in Figure 2. The activities demonstrated that high power HETs are technically viable as an option for future high power NEP applications with system powers extending to the multi-megawatt level by clustering multiple 100 kilowatt-class thrusters together.

Figure 2: High power Hall thruster demonstrations (50kW NASA-457M and 100kW X3)

Concurrent with these high-power investigations, 5-kilowatt class HETs were first being qualified and flown on several western spacecraft. The data from those operational missions highlighted the possibility of ground-to-space operational differences and the need to properly understand test-facility effects to accurately predict in-space HET operational characteristics.[8] Studies subsequently conducted to understand these phenomena concluded that testing at vacuum pressures of 10-5 Torr or less was necessary to accurately predict in-space performance, and testing at pressures at or below 4x10-6 Torr was necessary to accurately simulate in-space operations.[9] The facility pressures for the high-power HET testing referenced above were greater than 10-5 Torr, suggesting that these tests and thrusters at these power levels are not wholly sufficient for predicting in-space HET operational characteristics. HET based propulsion systems at power levels up to 12 kilowatts have been flight qualified and the development of higher power HET systems will not need additional technology developments aside from the thruster itself.[10]

2.2 Magnetoplasmadynamic Thruster Background

MPD thrusters are an electric propulsion technology that has been the investigated intermittently since the 1960's. The physical processes responsible for propellant ionization and acceleration in MPD thrusters become increasingly efficient at high power making them an attractive option for future MW-class applications in either applied-field or self-field configurations. Because of the very high power required for efficient operation much of the past research into this thruster technology has investigated pulsed operation. Significant exceptions to pulsed or quasi-static developments were conducted in late 60's and early 70's when Soviet engineers first demonstrated steady-state, self-field operation at a power level of 500 kilowatts using lithium propellant.[11] Similar follow-on developments were conducted in the 1990's at the NASA Jet Propulsion Laboratory and Princeton University with applied-field, lithium-fueled MPDs at power levels ranging from 100 to 250 kilowatts.[12,13] There were also applied-field, argon-fueled MPD development activities in the mid 2010's at the University of Stuttgart at a power level of 100 kilowatts[14] and recent developments at 150 kilowatts developments in China.[15] Lithium is a more attractive propellant option for ground testing because facility pumping can be achieved using water-cooled panels to condense lithium vapor from the gas phase. System level developments for MPD thrusters operating at 100's kilowatts with kiloampere current levels have been limited to date as investigations have focused on demonstrating performance and stable operation at the thruster level.

3. Applications

A framework was developed to guide the NASA nuclear electric propulsion development strategy assuming an incremental rate of advancement support applications ranging from 50 kilowatts to 2 megawatts. This approach was designed to support near term missions such as a 50-kilowatt class nuclear electric propulsion demonstration mission as well as multimegawatt applications as envisioned for human exploration class missions to Mars utilizing a hybrid chemical NEP transportation architecture. This framework is depicted in Figure 3.

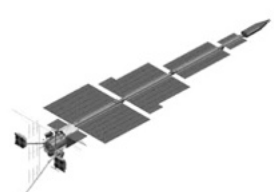
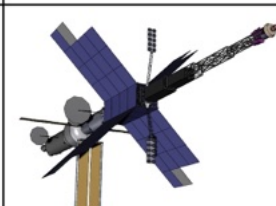
Present (< 3 years)	Near Term (3-5 years)	Mid Term (5-10 years)	Far Term (>10 years)
			
50 kW	200 kW	700 kW	2 MW
12 kW HET	12 kW HET	50 kW HET	50kW HET or 500kW MPD
xenon propellant	Xe or Kr propellant	Krypton propellant	Kr or Li propellant

Figure 3: Notional evolution of nuclear electric propulsion spacecraft power levels

An initial free-flying nuclear electric propulsion mission is most likely at the 50-kilowatt power class. This power level enables commonality with the developments currently planned for lunar surface systems, is consistent with size and mass of a spacecraft that can be launched to a nuclear safe orbit with existing launch vehicles, can utilize an existing commercial spacecraft bus to minimize much of the development cost, and is possible with existing electric propulsion technology requiring no additional EP developments. This is also the same size and scale considered for other previously investigated nuclear electric propulsion demonstrators such as the SP-100 flight experiment proposed in the 1990's.[16] This system, designed to operate at a power level somewhere between 30 and 100 kilowatts, was never fully developed due to schedule delays, cost overruns, and shifting priorities, and lack of a specific mission – a cautionary tale and an example of the challenges any future NEP mission will have to overcome as has been written about in detail by Bhavya.[17]

The electric propulsion system that would be well matched to this application is the 12-kilowatt HET system that was developed and is currently completing flight qualification to support the NASA Power and Propulsion Element (PPE).[18] This electric propulsion system utilizes multiple thruster strings to operate at power levels up to 48 kilowatts and a combined specific impulse of approximately 2,500 seconds and a propellant load of just less than 3,000 kilograms of xenon. The power processing unit that drives the thrusters on PPE operates with a 100 Volt regulated input, and it is unclear if a 50 kilowatt-class NEP demonstrator would utilize a similar regulated DC bus as commonly utilized by spacecraft utilizing photovoltaic power generation. This is the only technology development that may be required to support a near-term 50-kilowatt class NEP application.

Follow on applications at the 200 kilowatt-class power level could similarly use multiple strings of the existing 12-kilowatt HET systems. Fifteen to twenty individual thruster strings are many more than are currently being utilized on any single spacecraft, but large number of engines is a commonplace strategy for launch vehicles. The SpaceX Starship booster, for example, employs thirty-three individual pump-fed cryogenic Raptor engines. It is conceivable, perhaps even likely that 200 kilowatt-class would be launched on a super-heavy booster like Starship enabling such a mission with a single launch, avoiding the complications of on-orbit assembly. No new electric propulsion technology beyond what was used at the 50 kilowatt level would be required, however, given on the order of five to ten years until such systems are likely to be deployed, there is an opportunity to update the 12-kilowatt system, avoiding the development of a complete new system, but proving enhancements that could feed forward to higher-power follow-on applications. One such opportunity could be the consideration of krypton as the propellant. The cost savings for the 200 kilowatt-class mission from transition from xenon to krypton would be on the order of thirty million dollars based on present day prices and would great simplify the propellant acquisition strategy based on the more than twelve times higher natural abundance. Present day low-Earth orbit satellite constellations utilizing HETs have already almost entirely transitioned to krypton as a propellant due to the cost and availability considerations.

At the 700 kilowatt-class level the number of 12-kW HET strings is likely to become untenable suggesting a transition to fewer higher power HETs strings. Prior work on high power HETs have demonstrated the understanding necessary to scale power levels up to 100 kilowatts. The practical limitation for the per thruster power level is likely to be ground-test facility based on limitations discussed above. There is even greater motivation to transition from xenon to krypton propellant at this system power level, as the cost savings to fuel the vehicle is on the order of 100 million dollars. At these system power levels MPD thrusters may also be a viable option if the technical risks associated with performance, lifetime, and system level considerations have been addressed at a thruster power level of approximately 100-150 kilowatts. At this system power level, it is likely that spacecraft size and scale will necessitate on-orbit assembly. On-orbit assembly introduces new challenges such as how a system assembled in space is acceptance tested. For present day systems that is done through ground testing. For these high-power vehicles, the question of if they will be architected to also allow ground testing at a module level, or if acceptance testing occurs in orbit following assembly remains unanswered. It is also likely that the cost of such a high-power vehicle would necessitate reuse either through refueling or the use of orbital replacement units. Each of these factors, as well as development cost and risk, would be part of a future trade study informed by future higher power HET developments and MPD developments to identify the preferred electric propulsion approach at the 700 kilowatt-class level.

At the 2 megawatt-class level high power HET thrusters are a viable option with a reasonable number of thruster strings if ground test facility limitations are addressed and the per thruster power level can be increased to 50 kilowatts or greater. These facility limitations will be addressed either through upgrades to existing facilities, estimated to cost between twenty and fifty million dollars or with a new facility with an estimated cost of more than one hundred million dollars. The testability of MPD thrusters make them a more attractive technology option from a development perspective at the multimegawatt power level if the technical risks associated with performance, lifetime, and system level considerations can been successfully addressed. At this power level, it would be advantageous to have a per string power level of 200 kilowatts or less from a reliability and redundancy perspective. This assumes that some level of failure tolerance will be integrated into such a large and complicated spacecraft. That can be accomplished by carrying extra thruster strings, that are not used until there is a failure, carrying extra thruster strings, and running all strings in a derated fashion until there is a failure, or carrying no extra strings and performing the mission in a derated fashion if there is a failure. It's also possible to implement a strategy that utilizes a hybrid of these different approaches. At 500 kilowatts per thruster, any of these strategies may pose a challenge from a mass perspective. A potential solution is for these thrusters to be capable of operation at approximately 700 kilowatts to compensate in the event of a single thruster failure and planning to run in a degraded mode at 1.4 Megawatts if there are two failures. A 2-megawatt system of 50-kilowatt HETs could have 42 thrusters for an 5% mass increase with the cold spares failure tolerance approach or require operation of thrusters at 5% above nominal power level using the derating failure tolerance approach. Either option would have a much lower impact than the MPD failure tolerant configurations.

4. Planned developments

The currently planned electric propulsion development activities are designed to generally reduce the technology risk for this range of applications with no direct connection to specific system applications. There is content focused on HETs and MPDs. The HET strategy starts with the currently qualified 12-kilowatt flight-qualified HETS. Developments are planned to investigate clustering multiple thrusters together, operation on krypton, power processing units for space nuclear power systems, and facility test limitations and how that impacts the size of next generation thrusters. The MPD strategy brings online a test facility for lithium-fed MPD thrusters at power up to 2 megawatts, first explores thruster operational challenges at 100-200 kilowatts, and begin work on 500-kilowatt design like what the Soviets tested in the 70's.

4.1 Hall Thruster Planned Development Activities include testing two 12-kilowatt HETs at variable distance from one another to investigate and characterize thruster-to-thruster interactions including thermal effects, ion sputtering, and any potential plasma interactions including interactions related to discharge current oscillations and transient events. This investigation includes operation on xenon and krypton propellant. There are two overall objectives of these activities: to begin developing and understanding of the engineering considerations that need to be considered when designing a HET system utilizing multiple thrusters in proximity and to obtain the experimental data necessary for model validation. The thrusters being used are technology development units from the program that is flight qualifying thrusters for NASA's Power and Propulsion Element. The tests are being conducted in Vacuum Facility 6 at the Glenn Research Center (see Figure 4). This is a large-scale thermal vacuum facility used for both power system testing and high-power electric propulsion testing. It is 7.6

m diameter by 21 m long with a cryogenic pumping system capable 4 x10^{-7} torr base pressure and a pressure of 1x10^{-6} torr with a xenon flow rate of 310,000 liters per second.[19]

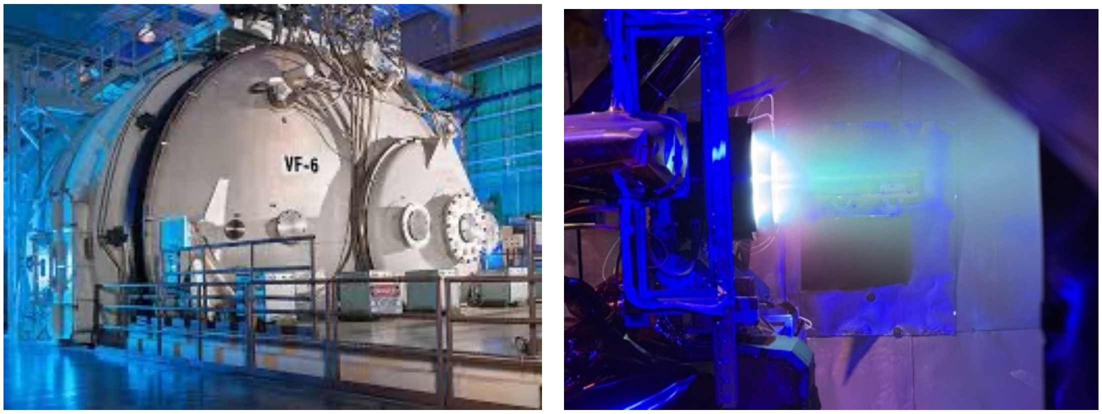


Figure 4: Vacuum facility 6 at NASA GRC and initial 2 thruster HET cluster testing

A several hundred-hour wear test of one of these thrusters is also being conducted. This test will assess the efficacy of magnetic shielding to provide long operating lifetimes using krypton propellant. Magnetic shielding is a technology that was developed to increase xenon-fueled HET operational lifetimes by 5X or more.[20] The design of this thruster was intended for xenon operation, so it is expected that design changes may be required to optimize for krypton operation. Higher current densities are required when operating on krypton due to the lower molecular mass relative to xenon to achieve similar thruster power levels. That and the higher sputter yield of krypton result in significant reductions in the observed thruster operational lifetimes for non-shielded configuration.[21] Increasing lifetime to something on the order of 15,000 hour while operating on krypton is necessary to align with the mission needs for an application like the Earth-to-Mars-to-Earth transit identified for the hybrid chemical electric propulsion system mentioned previously for human exploration applications. This represents an approximately 50% increase in life relative to unshielded xenon fueled HETs, but only a third of the projected HET lifetime for the 12-kilowatt HET being investigated. Measurements of ion and neutral properties are subsequently being obtained using laser induced fluorescence to provide the data necessary for extending the use of existing HET predictive models to krypton operation. These models will be critical tools in informing future HET design optimizations if it is determined that the propellant cost benefits that can be realized through this change can be accessed without significant penalties. One disadvantage in changing to krypton is lower storage density. This can be significantly mitigated through increasing propellant storage pressures from the mass optimized value of 140 bar for xenon storage to 350 bar. The non-ideality of xenon results in much reduced density benefits in increasing xenon storage to these pressures. As shown in Figure 5, while xenon density increases by less than 20% with this pressure increase, krypton density increases by nearly 220% resulting in a krypton storage density penalty of only 30%.

Lastly, the potential implications associated with NEP vehicle reuse either through refueling or the use of orbital replacement units as previously mentioned is being investigated through a conceptual design study with the NASA in-space assembly team from the Langley Research Center. This activity anticipates both the in-space assembly of NEP spacecraft once their power reaches a level too great to enable system deployment in a single launch and the desire for vehicle reuse to support the multiple potential out-and-back transits envisioned for future human exploration applications of Mars. The conceptual design study is investigating the viability of various approaches to the design of the individual electric propulsion modules. Specific items being considered included module power level, propellant tank size and configuration, PPU location and heat rejection, thruster size and power level, vehicle attitude and controllability including the potential need for thruster gimballing, EP reliability and fault tolerance, EP module location on the vehicle, EP module interfaces and ease of robotic installation, EP module launch configuration, EP module ground testability, and finally EP module development and recurring costs.

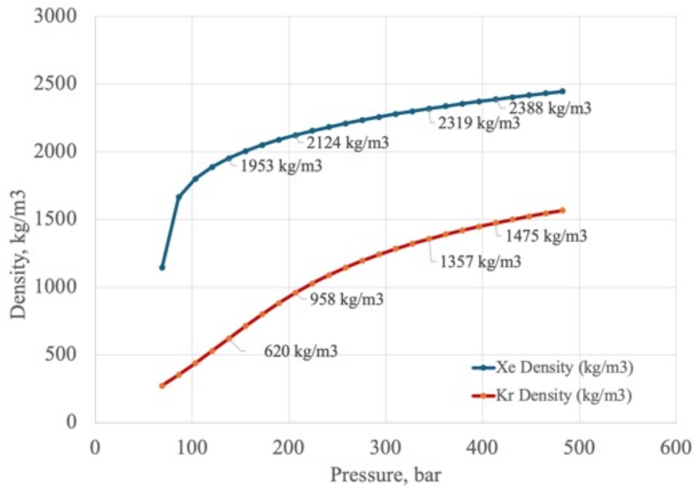


Figure 5: Propellant storage density at 25˚C for xenon and krypton

4.2 Magnetoplasmadynamic thruster Planned Development

MPD activities are focused on establishing a new test facility capability and performing thruster firings initially with a 200-kilowatt class thruster. The facility, shown in Figure 6, is the Condensable Metal Test (CoMeT) Facility located at the Jet Propulsion Laboratory. It is 3m in diameter and 8m long. It has a 7×10^{-7}

Figure 6: Condensable Metal Test (CoMeT) Facility at the Jet Propulsion Laboratory.

Tor base pressure and a 74,000 liter per second pumping speed using oil diffusion pumps. There is also a water-cooled liner capable of absorbing up to 2 megawatts of power. This results in an anticipated pumping capacity of 3,000,000 liter per second for lithium vapor. The test article is supplied power using multiple parallel terrestrial power supplies capable of producing 300 kilowatts of thruster input power at currents up to 8000 Amperes. Another part of the facility is a vapor lithium feed system that can be used to provide between 80 and 160 milligrams per second of propellant.

Initial thruster tests are being used to demonstrate stable operation of the thruster and feed system at fixed flow rate The objective is to measure thrust, demonstrate reliable thruster ignitions with no arcing, nominal plasma attachment to the anode with no visible asymmetries or hot spots, and a rapid transition to thermionic cathode emission. Initial firings have been successfully conducted, and photographs of this thruster are shown in Figure 7.

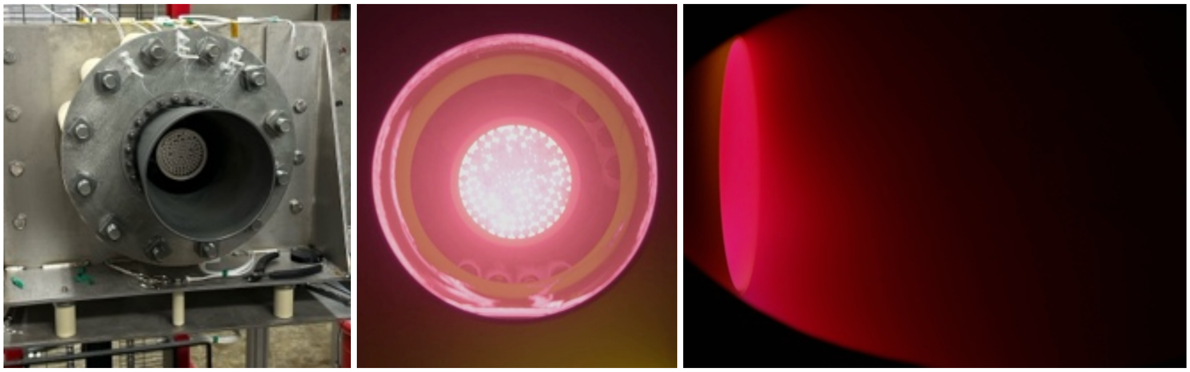


Figure 7: 200 kilowatt MPD thruster, operation at 120 kilowatts and 4250 Amperes

The MPD experimental work is being complimented by modelling and simulation activities designed to accurately predict both anode and cathode physics. The objective of the modelling and simulation is to gain the technical insight needed to overcome current operating limitations and to inform design choices needed for future higher power test articles. This includes investigations into multi-channel hollow cathodes geometry and operation and how that can affect lifetime. The results from both the experimental investigations and the modelling and simulation investigations will be used to produce a next generation 500-kilowatt thruster design that will be fabricated and tested including steady-state operation for up to 100 hours continuously.

5. Summary

A framework was developed to guide the NASA nuclear electric propulsion development strategy assuming an incremental rate of advancement support applications ranging from 50 kilowatts to 2 megawatts. This approach was designed to support near term missions such as a 50-kilowatt class nuclear electric propulsion demonstration mission as well as multimegawatt applications as envisioned for human exploration class missions to Mars utilizing a hybrid chemical NEP transportation architecture. The propulsion technologies selected for development are HETs and MPDs. The HET strategy leverages the currently qualified 12-kilowatt flight-qualified HETS. Future developments investigate clustering multiple thrusters together, operation on krypton, power processing units for space nuclear power systems, and facility test limitations and how that impacts the size of next generation thrusters. The MPD strategy initial focus is bringing online a test facility for lithium-fed MPD thrusters at power up to 2 megawatts, first exploring thruster operational challenges at 100-200 kilowatts while eventually developing and testing an MPD thruster at 500 kilowatts.

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