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Preparation for Hollow Cathode Testing for the Advanced Electric Propulsion System at NASA Glenn Research Center

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Abstract

NASA Glenn Research Center is performing activities to support the unique needs of hollow cathode development and testing for the Advanced Electric Propulsion System (AEPS). Three existing vacuum facilities have been outfitted as cathode test facilities, and each will serve a different role in upcoming testing. Vacuum Facility 67 is being developed to serve as a long-duration test facility for the Engineering Development Unit cathode, which is to be delivered by the AEPS contractor. It will feature a thruster-like magnetic field simulator and cold-cycle capability via a liquid nitrogen-cooled cold plate. Vacuum Facility 17 is being developed as a test facility for short- to medium-duration experiments in order to provide auxiliary support for the long-duration testing. It will feature a magnetic field simulator but not cold-cycling. Finally, Vacuum Facility 1 will be a high-pumping speed cathode development environment, and will feature an array of plasma and temperature diagnostics. In addition to the facility preparation work, a new cathode, referred to as the Mark II, has been designed. The Mark II is an evolution of the Technology Demonstration Unit cathodes that better evokes the geometry, fabrication, and construction of the forthcoming Engineering Development Unit. This cathode serves as a transition between the Technology Demonstration Unit cathodes used during early thruster development and the forthcoming Engineering Development Unit cathodes. It will be used as a means of verifying the new test facilities prior to arrival of Engineering Development Unit hardware. Details of the Mark II design and key features are presented, as well as details of future work to be performed.

1.0 Introduction

Hollow cathodes are used as plasma sources in a variety of electric propulsion devices including gridded ion and Hall thrusters. These cathodes are used to provide discharge electrons, to neutralize the plasma beam, or both. NASA Glenn Research Center (GRC) has a long history of hollow cathode testing and development. This includes the development of the International Space Station plasma contactor unit, which was life-tested to 28,000 hr (Refs. 1 and 2), as well as the discharge and neutralizer cathodes for both the NSTAR and NEXT ion thrusters (Refs. 3 and 4). NASA GRC-developed cathodes have also been demonstrated to 150 A discharge current (Refs. 5 and 6). Each of these cathodes shares lineage and utilizes a barium-oxide (BaO) impregnate insert technology derived from tube dispenser cathodes. The NSTAR

thruster has demonstrated 30,000 hr of operation during ground testing (Ref. 7) and over 46,000 hr of operation in space during the Dawn mission (Ref. 8). The NEXT thruster has demonstrated in excess of 50,000 hr in ground testing (Ref. 9). These long thruster lifetimes were achieved with long-lifetime hollow cathodes.

Recently designed Hall thrusters incorporate a technique known as magnetic shielding (Refs. 10 to 12) to produce lifetimes of multiple 10s of thousands of hours. A 12.5-kW Hall thruster system technology development effort, led by NASA GRC and the Jet Propulsion Laboratory (JPL), began with maturation of the high-power Hall thruster and power processing unit. The Hall thruster is referred to as the Hall Effect Rocket with Magnetic Shielding (HERMeS). HERMeS incorporates magnetic shielding technology and has a xenon throughput requirement of 3400 kg, corresponding to a thruster lifetime of multiple 10s of thousands of hours depending on operating condition (Ref. 13). HERMeS development work included the design and fabrication of three Technology Demonstration Unit (TDU) thrusters, which have undergone extensive characterization at both NASA GRC and JPL (Refs. 14 to 17). Early work included the maturation of both NASA GRC-style BaO cathode technology (Ref. 18) and lanthanum hexaboride (LaB_6) cathode technology led by JPL (Refs. 19 and 20). A down-select of cathode technology was made to pursue the BaO design option for further development, chiefly driven by the need to reduce risk associated with the aggressive development timeline (Ref. 14).

The BaO cathode developed for use with HERMeS shares many features with the plasma contactor, NSTAR, NEXT, and high-current cathodes. While the lifetime of more than one of these cathodes has been demonstrated to be in excess of that targeted for HERMeS, there is still uncertainty in the lifetime of the cathode emitter, particularly in the magnetic environment of the Hall thruster. Thus, a long-duration test will be performed to demonstrate cathode life for the system. Additionally, there is interest in continued investigation of the generation mechanisms of high-energy ions measured in the cathode plume (Refs. 21 and 22). These measurements have potentially significant implications on thruster inner front pole and cathode keeper erosion, the mechanisms of which are not yet well understood for HERMeS (Refs. 15, 21, 23 to 25).

Through a competitive selection process, the Advanced Electric Propulsion System (AEPS) contract was awarded to Aerojet Rocketdyne to complete the development qualification and production of flight hardware based on the HERMeS technology (Ref. 13). This contract includes the delivery of Engineering Development Unit (EDU) hardware, including two thruster units and four hollow cathode units. Two of these EDU cathodes will be paired with the EDU thrusters for characterization and long-duration wear testing; the remaining two will be used by NASA GRC and JPL for component-level testing. A series of acceptance tests, as well as long-duration wear testing and thermal cycle testing, are planned for the EDU hardware.

In anticipation of the delivery of the standalone EDU cathode units, NASA GRC is undertaking a number of preparation activities. Three vacuum test facilities are being prepared for hollow cathode testing. Each facility will serve a different role in the AEPS cathode work: one will be utilized for long-duration testing; another for short-duration testing; and the last for plasma diagnostic interrogation. Each facility has a power console, breakout box, and xenon feed system. Additionally, the long-duration test facility will support a liquid nitrogen (LN_2)-cooled cold plate capable of providing the flight qualification environment and a magnetic field simulator that replicates the magnetic field environment the cathode experiences within the thruster. Additionally, an array of plasma and temperature diagnostics are being developed specifically for the diagnostic test facility.

NASA GRC is also developing new hollow cathode assemblies that are an evolution of the TDU hollow cathodes used during development work. The new cathode design, referred to as the Mark II, incorporates the key features of the EDU cathode and is expected to provide similar plasma and thermal

operation as the forthcoming EDU units. Multiple Mark II units are being manufactured, and these will be used by NASA GRC and by JPL to evaluate testing infrastructure prior to beginning the planned EDU evaluation tests. The first Mark II cathode unit has been assembled, and initial validation testing is ongoing at NASA GRC.

The paper is structured as follows. Details of the test facilities in are presented in Section 2.0, including a description of each of the facilities, the test apparatus (including power console, breakout box, and xenon flow system), the magnetic simulator, and the LN_2 cold plate. In Section 3.0, the Mark II cathode design is discussed, including the key design features and improvements over the TDU design. Finally, conclusions are discussed in Section 4.0.

2.0 Test Facilities

Vacuum Facility 67 (VF-67), Vacuum Facility 17 (VF-17), and Vacuum Facility 1 (VF-1) are simultaneously being reconfigured to serve the unique hollow cathode test needs of the AEPS project. Both VF-67 and VF-17 previously served as thermal vacuum (cold-wall) facilities for non-electric propulsion testing, and VF-1 was last used for magnetoplasmadynamic thruster testing (Refs. 26 to 28). As such, all three facilities required reconfiguration to prepare them for cathode testing.

2.1 Vacuum Facility 67

VF-67, pictured in Figure 1, is a 2.7-m long, 0.9-m diameter cylindrical vacuum chamber that will serve as the wear-test facility. It is pumped by a 0.5 m diameter cryogenic pump and a 0.2 m diameter turbomolecular pump, which typically provide a base pressure in the facility of approximately 1×10^{-7} torr near the cathode test location. The facility features an effective pumping speed of 2300 L/s on xenon, which results in a pressure near the cathode test location of 8.0×10^{-5} torr-Xe during cathode operation at nominal AEPS conditions.

Figure 1.—Vacuum Facility 67.

To serve as the test facility for the long-duration wear test of an EDU cathode unit, VF-67 is being outfitted with a magnetic field simulator and cold plate for thermal cycling, as described below. It will be outfitted with multiple vacuum-compatible cameras inside the facility for visually monitoring cathode operation. Because of the need for the facility to operate stably and reliably over many thousands of hours of cathode operation, no extraneous equipment is being installed. Any diagnostic work (plasma, thermal, etc.) will be performed in either VF-17 or VF-1. Even equipment such as pressure gauges are being installed in such a manner that they can be replaced without cycling the main test volume to atmosphere if a failure were to occur.

2.2 Vacuum Facility 17

VF-17, shown in Fig. 2, is a 2.1-m long, 0.9-m diameter vacuum chamber that will be outfitted to serve as a short-duration, quick-turnaround cathode test facility. It features a 0.3 m diameter cryogenic pump and a 0.1 m diameter turbomolecular pump. The base pressure in the facility is expected to be in the mid 10^{-7} torr range, and cold flow testing demonstrated a pumping speed of approximately 2000 L/s on xenon. This should provide a pressure near the cathode of approximately 9.5×10^{-5} torr-Xe at nominal AEPS operating conditions.

VF-17 is being prepared to serve as an all-purpose cathode test facility. It will be capable of performing short- to medium-duration experiments of varying types to support both the ongoing EDU testing in VF-67 and other cathode development work at NASA GRC. It will feature a magnetic simulator similar to that in VF-67, but it will not have cold-cycle capability. While it is not considered to be a dedicated diagnostic facility, plasma diagnostics can be incorporated if risk reduction requirements dictate a need.

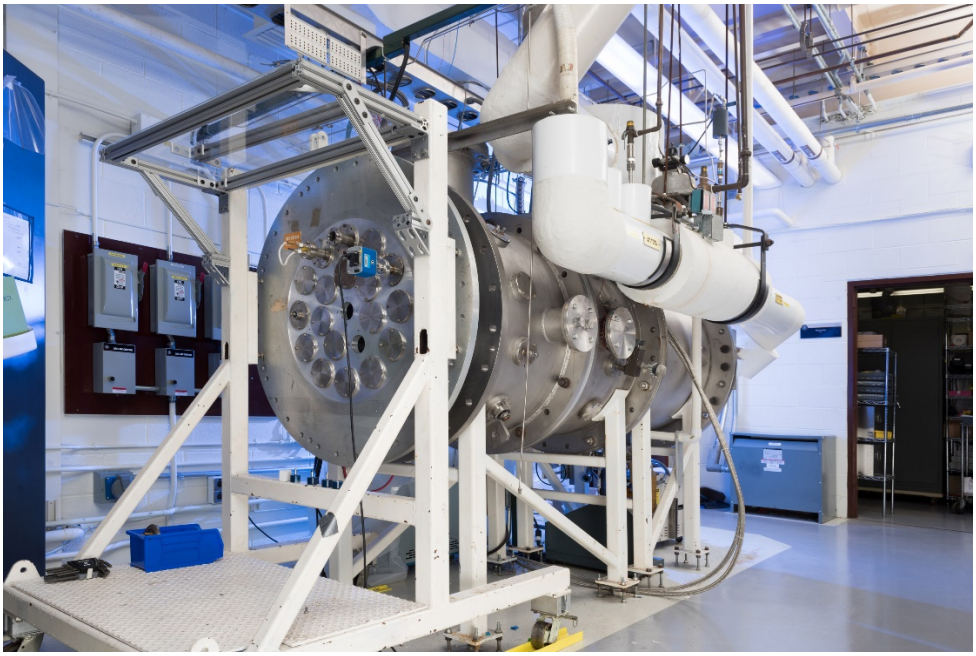

Figure 2.—Vacuum Facility 17.

2.3 Vacuum Facility 1

VF-1 is a 4.5-m long, 1.5-m diameter vacuum chamber. It previously operated on three oil diffusion pumps, and part of this upgrade activity has involved removing those pumps in favor of cryogenic variants. To date, one 1.0 m diameter cryotub has been installed, with the capacity for the addition of two more. In its current configuration, it is expected that the facility will provide base pressures in the low 10^{-7} torr range and a background pressure of 3×10^{-5} torr-Xe in the region of the cathode during nominal AEPS cathode flow conditions.

VF-1 will be outfitted with an array of plasma and temperature diagnostics to study cathode operation in detail. The development of fast-scanning Langmuir probes (Ref. 22), retarding potential analyzers, and other electrostatic plasma diagnostics, as well as an optical scanning pyrometer for assessment of insert temperature (Ref. 29), is ongoing. The facility will also be outfitted to provide access for high-speed camera interrogation (Ref. 30) and for optical emission spectroscopy (Ref. 6).

2.4 Cathode Test Apparatus

Specialized cathode test apparatus will be incorporated into each facility and tailored to the specific needs of the testing that will be conducted. The development of this apparatus will leverage previous efforts for thruster test apparatus during HERMeS development. A goal of this activity is to produce parity between the three cathode test facilities such that hardware, test equipment, and test operators can move easily between facilities.

Figure 3.—Vacuum Facility 1.

2.4.1 Power Console

The cathode power consoles house the power supplies, data acquisition system (DAQ), and xenon flow system control. Each console contains commercial power supplies for the heater, keeper, anode, and electromagnet used in the magnetic field simulator. The DAQ is an off-the-shelf multiplexing data logger controlled by LabView code. During cathode operation, the DAQ typically acquires data on all channels at approximately 1 Hz. The DAQ records critical cathode telemetry, including DC voltages and currents of the heater, keeper, anode, electromagnet; other items of interest such as cathode-to-ground potential; mass flow rates; facility and xenon flow system pressure; and temperatures from up to 6 of both K-type and R-type thermocouples.

The power supplies are tied into an interlock system that interrupts input power (while continuing to provide power to the DAQ and mass flow controller system via battery backup) in the event that a fault state is detected, allowing the cathode to be safely and automatically shut down. Possible fault states that the system protects against include cathode telemetry (any signal being read by the DAQ) or facility telemetry (pressure or cryogenic pump temperature) outside bounds set by the operator. In the event that a fault state is detected and the interlock is tripped, the system is capable of sending out a detailed alert via text message to users.

2.4.2 Breakout Box

Each facility utilizes a breakout box mounted on the atmosphere-side chamber wall at the cathode power feedthroughs. The breakout boxes are very similar to that described by Peterson for NASA GRC's Vacuum Facility 6 (Ref. 31). They serve as a single point of entry to the facility for all cathode power. Unlike the thruster breakout boxes, the cathode versions do not house all of the telemetry measurements; the DC currents are measured by precision shunts that are located within the power console instead of within the breakout box.

2.4.3 Xenon Flow System

The xenon flow systems (XFSs) for the cathode test facilities feature one (VF-17) or two (VF-67 and VF-1) mass flow controllers plumbed to the vacuum facility via electropolished stainless-steel tubing. Having two flow lines allows for increased experimental flexibility, including the ability to perform facility background pressure sweeps or to provide auxiliary cold-gas injection (Refs. 32). These systems are designed to adhere to NASA internal process documents for xenon feed system purity requirements (Refs. 33 to 35). The systems are outfitted nominally with 50 sccm controllers, but the parity between the cathode XFSs and those for thruster operation makes switching controllers between panels straightforward.

2.5 Magnetic Field Simulator

It is important to perform not only the long-duration wear test, but any EDU hollow cathode characterization in an environment (facility pressure, electrical configuration, and magnetic field strength and shape) as similar as possible to that experienced in the EDU thruster. As part of that effort, NASA GRC is developing a magnetic field simulator which is designed to mimic the EDU magnetic field in and around the cathode region of the thruster. This simulator features a magnetic circuit that is similar to the EDU thruster but simplified, with an emphasis on ensuring the field in the region of the cathode matches the EDU thruster as close as possible. JPL used a similar simulator designed to mimic the field of the TDU thrusters during recent investigations of high-energy ions created by the cathode (Ref. 21).

2.6 Cold Plate for Thermal Cycling

Cold-cycle testing is an important component of the long-duration test, so the magnetic field simulator in VF-67 will be mounted to a custom LN_2-cooled cold plate to provide a means of thermally cycling the hollow cathode assembly periodically during the long-duration test. Though the main objective of the NASA GRC EDU cathode test is long-duration wear testing (that is, accumulating a significant number of hours of cathode operation at steady state conditions), this cold-cycling will be performed periodically as an additional lifetime assessment. Dedicated cold-cycling of another EDU cathode will be performed concurrently at JPL, where the main objective will be to assess the cathode's ignition and operation behavior over time as it is subjected to repeated thermal cycling.

Thermal modelling was used to determine that a cold plate mounted on the rear of the magnetic simulator would be sufficient to provide the cold-cycling capability within a reasonable amount of cool-down time. A cold plate was designed to integrate with the LN_2 system at VF-67 and to provide as uniform a temperature at the rear of the magnetic simulator. The cold plate features a dual-flow path design, wherein the two paths travel in opposite directions around the interior of the unit. A computer rendering of the cold plate, which illustrates the counter-flow design, is shown in Figure 4.

Control of the cold plate temperature to within ± 3 K was desired to meet the test requirements for the EDU cathode. The LN_2 system on VF-67 is controlled by a single open/closed solenoid valve, and there was concern that this system would not provide adequate control authority to meet this requirement. An early system checkout was performed with a test cold plate to assess the level of control offered by the system. After initial tuning of control parameters, the system demonstrated capability to hold the plate temperature to within a band of ± 0.5 K at a given location, as shown below in Figure 5. The temperature across the plate, which featured a single flow path direction, was found to vary by approximately 5 K from inlet to outlet. However, as noted, the final cold plate's counter-flow design is expected to reduce this temperature gradient significantly.

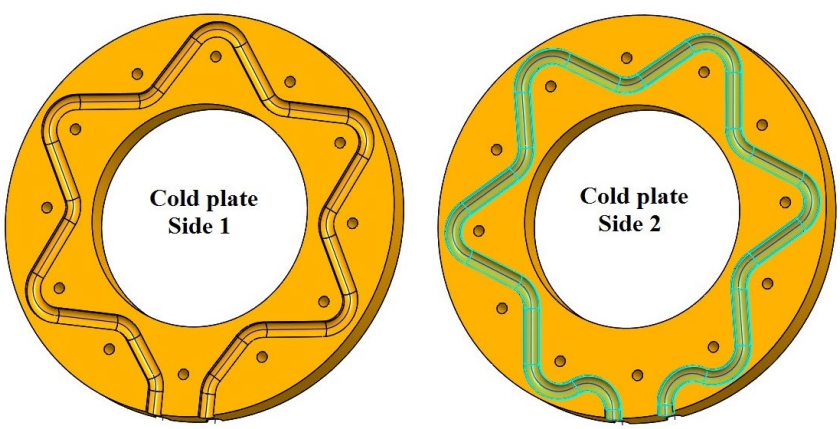

Figure 4.—Computer rendering of cathode cold plate, which features a counter-flow design to provide a uniform temperature across the plate.

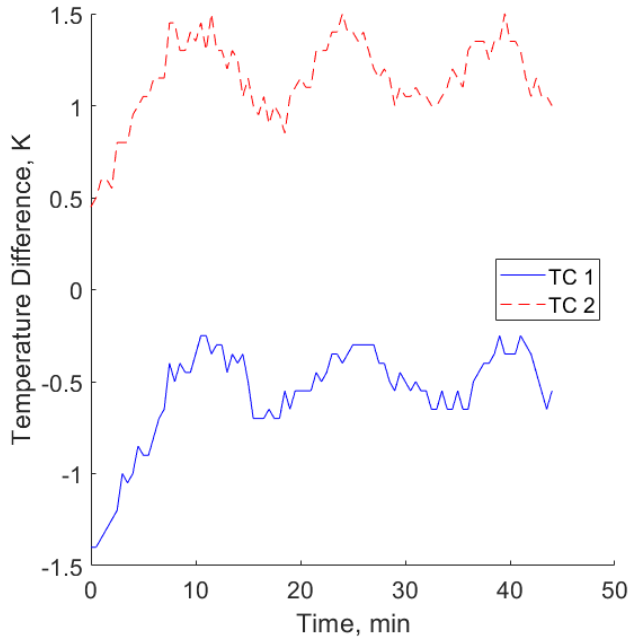

Figure 5.—A subset of temperature control data from early LN_2 system checkout test in VF-67, using a test cold plate. Data shown has been normalized by the targeted control temperature.

3.0 GRC Mark II Cathode

3.1 Description and Motivation

HERMeS thruster development required a hollow cathode capable of providing up to 31 A to enable thruster operation up to at least 13 kW beam power. Development testing began in 2015 with a laboratory hollow cathode that was mechanically assembled, which allowed it to be readily adapted to the frequent changes that manifested. This design was used throughout thruster testing into 2018. However, in order to address hardware concerns for advancement to flight, a new cathode configuration was developed. This cathode design served two significant functions. First, it provided a hardware configuration similar to a flight design that could be analyzed structurally and thermally to understand its behavior under launch loads and thereby expose potential weaknesses. Second, it provided a baseline design recommendation to the thruster contractor that incorporated the experience accumulated by NASA in earlier flight and flight-like hollow cathodes.

High fidelity structural analyses of the new hollow cathode design have been performed both at NASA GRC via an in-house structural group and at JPL through a contract to an external organization. The resulting hollow cathode design evolved to address structural areas of concern (Ref. 16). The cathode design modifications were incorporated into the brazed cathode design recommendation that was provided to the thruster contractor.

In order to improve the fidelity of thruster testing, an effort was initiated in 2017 to fabricate a new generation of laboratory cathodes which incorporated many of the design modifications that came out of the analysis activities. The resulting cathode, referred to as the Mark II, will be installed in the TDU thrusters for on-going thruster characterization and long-duration testing. The Mark II cathode will also be used in the cathode component test facilities at NASA GRC and JPL to validate thruster simulator hardware in preparation for duration testing of the EDU hollow cathodes.

The Mark II laboratory cathode, shown in Figure 6, has evolved from the TDU laboratory cathodes, an example of which shown in Figure 7. The Mark II cathode design included the following features:

1. Brazed joints: The cathode tube assembly and the keeper assembly feature brazed mechanical connections. These braze joints are now included to better represent how a flight hollow cathode would be assembled. Additionally, testing of the long-term performance and mechanical integrity can be assessed in thermally simulated environments that these cathodes would see in space.
2. Improved thermal design: The Mark II configuration provides improved thermal isolation of the hollow cathode emitter by moving the cathode tube support and keeper isolator towards the rear of the thruster. The TDU laboratory cathode did not include this feature in order to accommodate the keeper support.
3. Simplified emitter: The emitter has been simplified by eliminating some extraneous features which reduced its physical size while retaining the same amount of active emission surface. Additionally, the part that maintains the emitter position within the hollow cathode was reduced in size and mass to improve thermal isolation which is expected to allow the cathode to operate more efficiently.
4. Flight-like keeper design: The keeper assembly has been modified to represent the expected flight configuration that will enable improved determination of electrical isolation behavior of the keeper within the HERMeS thruster body.
5. Improved propellant connection: A commercial high-vacuum flange is used to connect the cathode tube assembly to the propellant feed line. This design would not be carried over into a flight cathode but was selected to reduce design complexity relative to the TDU laboratory cathode, which used a mated flange that was specially fabricated and required a specialized sealing material.

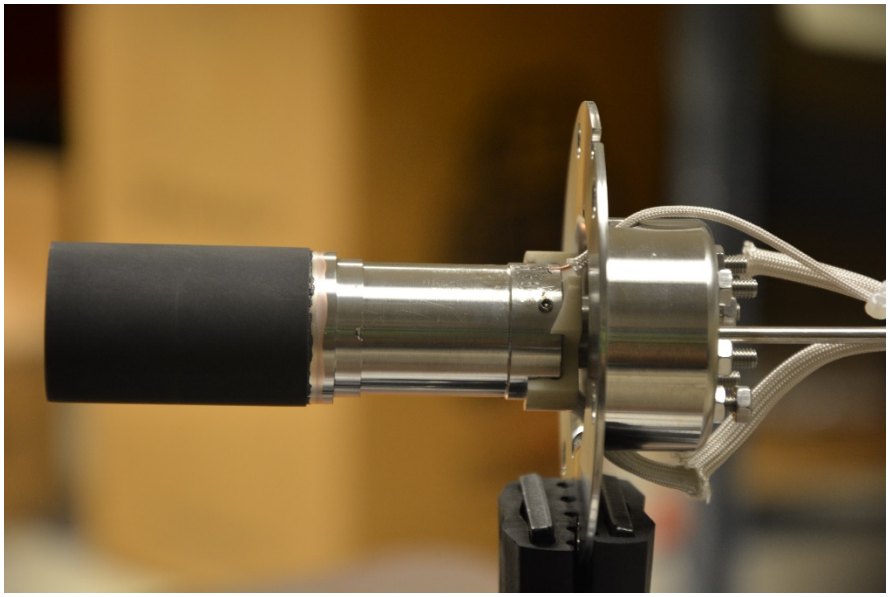

Figure 6.—Mark II cathode.

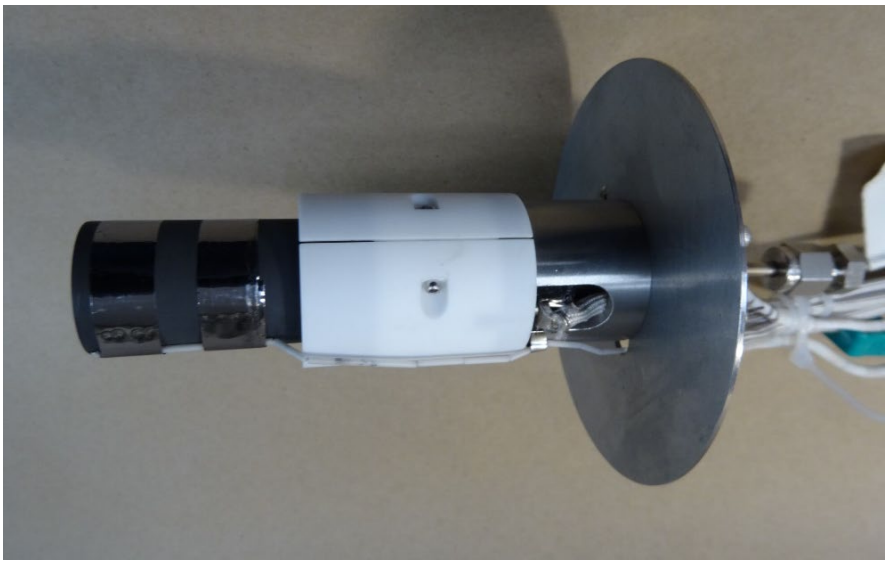

Figure 7.—Technology Demonstration Unit cathode.

The first of three planned Mark II units has been completed and is currently undergoing initial validation testing. A full characterization of the Mark II design is planned to commence in late 2018, with initial focus on thermal assessment of this cathode as validation of thermal modeling for the cathode. Additional testing is planned, including with the cathode integrated into the LN_2-cooled magnetic field simulator described above, the results of which will be used to validate deep thermal cycling operation of brazed cathode technology. Using diagnostic resources at both GRC and JPL, a plasma diagnostic characterization of the Mark II is also planned.

4.0 Conclusion

Three vacuum facilities have been modified to support hollow cathode testing for AEPS at NASA GRC. Each facility will serve a unique role. Vacuum Facility 67 has been outfitted for long-duration testing, which includes a thruster-like magnetic field simulator and a liquid nitrogen-cooled cold plate for cold-cycling of the test article. Vacuum Facility 17 will be used for performance characterization and short- and medium-duration testing alongside the long-duration testing in VF-67. Finally, VF-1 will be used as a high-pumping speed test facility for high-fidelity cathode studies. It is being outfitted with an array of cathode plasma diagnostics to study near- and far-field plasma properties and internal temperature profiles.

Though each facility features different capabilities, the test support apparatus has been developed with parity across not only the new cathode facilities but also the systems developed for thruster operation as part of the maturation of the HERMeS thruster. This includes a standardized power console, breakout box, and xenon feed system. The power consoles contain the heater, keeper, discharge, and electromagnet power supplies and data acquisition system, and feature a safety interlock system that can quickly shut the cathode down if a fault state is detected. The breakout box serves as a single point of entry to the vacuum facility for all cathode power and telemetry. The xenon feed system is designed using decades of lessons learned from both previous cathode development work and thruster development work at NASA GRC and elsewhere.

In addition to the standard test apparatus, two pieces of hardware have been developed for the upcoming EDU testing: a thruster-like magnetic field simulator, which will be used to provide a magnetic

field environment (strength and shape) similar to what the cathode will experience in the EDU thruster, and a LN_2-cooled cold plate that will be attached to the rear of the magnetic field simulator in VF-67 to provide the ability to cold-cycle the EDU cathode periodically during long-duration testing. This cold plate is the product of detailed thermal modeling of the cathode, magnetic simulator, and vacuum chamber environment, and features a counter-flow design that provides two paths for LN_2 to provide a reduction in the temperature gradient across the plate.

Alongside the facility work, NASA GRC has advanced the BaO hollow cathode design used during HERMeS development. This new cathode design, called the Mark II, shares features with the EDU cathode, including a more flight-like brazed construction and similar geometry. The Mark II was developed to provide a path between the development work with the TDU thrusters and cathodes with HERMeS and the eventual EDU characterization and long-duration testing. It also provides a means for NASA GRC to validate the cathode facility updates with hardware that shares critical attributes with the EDU design, allowing for better preparation in advance of EDU arrival as well as support of risk reduction testing.

The first Mark II cathode has been completed, and initial validation testing is ongoing. These Mark II cathodes will undergo a detailed plasma and thermal characterization, results of which will be compared to modeling work completed during the design phase (Refs. 14 and 16). Mark II units will also be used in validation activities for the various test facilities being prepared for EDU testing at both NASA GRC and JPL. All of these activities will help to ensure a smooth transition to EDU testing once that hardware is delivered to NASA.

References

1. Sarver-Verhey, T. R., “28,000 Hour Xenon Hollow Cathode Life Test Results,” *25th International Electric Propulsion Conference, IEPC-1997-168*, Cleveland, OH: Electric Rocket Propulsion Society, 1997.
2. Sarver-Verhey, T. R., “Destructive Evaluation of a Xenon Hollow Cathode After a 28,000 Hour Life Test,” *34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA-98-3482*, Cleveland, OH: American Institute of Aeronautics and Astronautics, 1998.
3. Anderson, J. R., Goodfellow, K. D., Polk, J. E., Rawlin, V. K., and Sovey, J. S., “Performance characteristics of the NSTAR ion thruster during an on-going long duration ground test,” *Aerospace Conference Proceedings, 2000 IEEE*, IEEE, 2000, pp. 99–122.
4. Patterson, M. J., Foster, J. E., Haag, T. W., Rawlin, V. K., Soulas, G. C., and Roman, R. F., “NEXT: NASA’s Evolutionary Xenon Thruster,” *38th AIAA Joint Propulsion Conference*, Indianapolis, IN: American Institute of Aeronautics and Astronautics, 2002.
5. Kamhawi, H., and VanNoord, J., “Development and Testing of High Current Hollow Cathodes for High Power Hall Thrusters,” *48th Joint Propulsion Conference*, Atlanta, GA: AIAA, 2012.
6. Thomas, R. E., Kamhawi, H., and Williams, Jr., G. J., “High Current Hollow Cathode Plasma Plume Measurements,” *33rd International Electric Propulsion Conference*, Washington D.C.: 2013.
7. Sengupta, A., Brophy, J. R., Anderson, J. R., Garner, C., de Groh, K., Karniotis, T., and Banks, B., “An Overview of the Results from the 30,000 Hr Life Test of Deep Space 1 Flight Spare Ion Engine,” *AIAA paper*, vol. 3608, 2004.
8. Garner, C. E., Rayman, M. D., and Brophy, J. R., “In-Flight Operation of the Dawn Ion Propulsion System-Arrival at Ceres,” *34th International Electric Propulsion Conference*, Kobe-Hyogo, Japan: 2015.

9. Shastry, R., Herman, D. A., Soulas, G. C., and Patterson, M. J., "End-of-test Performance and Wear Characterization of NASA's Evolutionary Xenon Thruster (NEXT) Long-Duration Test," *Proc. 50th AIAA/ASME/SAE/ASEE Joint Propuls. Conf*, 2014.
10. Mikellides, I. G., Katz, I., and Hofer, R. R., "Design of a Laboratory Hall Thruster with Magnetically Shielded Channel Walls, Phase I: Numerical Simulations," *47th Joint Propulsion Conference, AIAA-2011-4809*, San Diego, CA: American Institute of Aeronautics and Astronautics, 2011.
11. Hofer, R., Goebel, D., Mikellides, I., and Katz, I., "Design of a Laboratory Hall Thruster with Magnetically Shielded Channel Walls, Phase II: Experiments," *48th Joint Propulsion Conference, AIAA-2012-3788*, Atlanta, GA: American Institute of Aeronautics and Astronautics, 2012.
12. Mikellides, I. G., Katz, I., Hofer, R. R., and Goebel, D. M., "Design of a Laboratory Hall Thruster with Magnetically Shielded Channel Walls, Phase III: Comparison of theory with experiment," *48th Joint Propulsion Conference and Exhibit, AIAA-2012-3789*, Atlanta, GA: American Institute of Aeronautics and Astronautics, 2012.
13. Herman, D. A., Tofil, T., Santiago, W., Kamhawi, H., Polk, J. E., Snyder, J. S., Hofer, R. R., Picha, F., Jackson, J., and Allen, M., "Overview of the Development and Mission Application of the Advanced Electric Propulsion System (AEPS)," *35th International Electric Propulsion Conference, IEPC-2017-284*, Atlanta, GA: Electric Rocket Propulsion Society, 2017.
14. Hofer, R. R., Polk, J. E., Mikellides, I. G., Ortega, A. L., Conversano, R., Chaplin, V. H., Lobbia, R. B., Goebel, D. M., Kamhawi, H., Sarver-Verhey, T., Williams, G., Mackey, J. A., Huang, W., Yim, J. T., Herman, D. A., and Peterson, P. Y., "Development Status of a 12.5 kW Hall Thruster for the Asteroid Redirect Robotic Mission," *35th International Electric Propulsion Conference, IEPC-2017-231*, Atlanta, GA: Electric Rocket Propulsion Society, 2017.
15. Williams, G., Gilland, J. H., Peterson, P. Y., Kamhawi, H., Huang, W., Swiatek, M., Joppeck, C., Yim, J., and Haag, T., "2000-hour Wear-Testing of the HERMeS Thruster," *52nd AIAA/SAE/ASEE Joint Propulsion Conference*, 2016, p. 5025.
16. Hofer, R. R., Polk, J. E., Sekerak, M. J., Mikellides, I. G., Kamhawi, H., Sarver-Verhey, T. R., Herman, D. A., and Williams, G., "The 12.5 kW Hall Effect Rocket with Magnetic Shielding (HERMeS) for the Asteroid Redirect Robotic Mission," *52nd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA-2016-4825*, 2016.
17. Kamhawi, H., Haag, T., Huang, W., Herman, D. A., Thomas, R., Shastry, R., Yim, J., Chang, L., Clayman, L., Verhey, T., and others, "Performance Characterization of the Solar Electric Propulsion Technology Demonstration Mission 12.5-kW Hall Thruster," *34th International Electric Propulsion Conference, IEPC-2015-007, Kobe, Japan*, 2015.
18. Sarver-Verhey, T. R., Kamhawi, H., Goebel, D. M., Polk, J. E., Peterson, P. Y., and Robinson, D. A., "Hollow Cathode Assembly Development for the HERMeS Hall Thruster," *52nd Joint Propulsion Conference, AIAA-2016-5026*, Salt Lake City, UT: American Institute of Aeronautics and Astronautics, 2016.
19. Goebel, D. M., and Polk, J. E., "Lanthanum Hexaboride Hollow Cathode for the Asteroid Redirect Robotic Mission 12.5 kW Hall Thruster," *34th International Electric Propulsion Conference, IEPC-2015-043*, Kobe-Hyogo, Japan: Electric Rocket Propulsion Society, 2015.
20. Polk, J. E., Goebel, D. M., and Guerrero, P., "Thermal Characteristics of Lanthanum Hexaboride Hollow Cathodes," *34th International Electric Propulsion Conference, IEPC-2015-044*, Kobe-Hyogo, Japan: Electric Rocket Propulsion Society, 2015.
21. Polk, J. E., Lobbia, R. B., Barriault, A., Guerrero, P., Mikellides, I., and Ortega, A. L., "Inner Front Pole Cover Erosion in the 12.5 kW HERMeS Hall Thruster Over a Range of Operating Conditions,"

35th International Electric Propulsion Conference, IEPC-2017-409, Atlanta, GA: Electric Rocket Propulsion Society, 2017.

22. Goebel, D. M., Jameson, K. K., Watkins, R. M., Katz, I., and Mikellides, I. G., "Hollow cathode theory and experiment. I. Plasma characterization using fast miniature scanning probes," *Journal of Applied Physics*, vol. 98, 2005, p. 113302.
23. Williams Jr, G. J., Gilland, J. H., Peterson, P. Y., Kamhawi, H., Huang, W., Ahern, D. M., Yim, J., Herman, D. A., Hofer, R. R., and Sekerak, M., "Wear Testing of the HERMeS Thruster," *52nd Joint Propulsion Conference, AIAA-2016-5025*, Salt Lake City, UT: American Institute of Aeronautics and Astronautics, 2016.
24. Ortega, A. L., Mikellides, I. G., and Goebel, D. M., "Numerical Simulations for Life Assessments of the BaO and LaB6 Cathode Options in the Hall Effect Rocket with Magnetic Shielding (HERMeS)," *35th International Electric Propulsion Conference, IEPC-2017-152*, Atlanta, GA: Electric Rocket Propulsion Society, 2017.
25. Ortega, A. L., Mikellides, I. G., and Chaplin, V. H., "Numerical Simulations for the Assessment of Erosion in the 12.5-kW Hall Effect Rocket with Magnetic Shielding (HERMeS)," *35th International Electric Propulsion Conference, IEPC-2017-154*, Atlanta, GA: Electric Rocket Propulsion Society, 2017.
26. LaPointe, M. R., and Mikellides, P. G., "High power MPD thruster development at the NASA Glenn Research Center," *37th Joint Propulsion Conference and Exhibit, AIAA-2001-3499*, Salt Lake City, UT: American Institute of Aeronautics and Astronautics, 2001.
27. LaPointe, M., and Mikellides, P., "Design and operation of mw-class mpd thrusters at the NASA Glenn research center," *38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, 2002, p. 4113.
28. LaPointe, M., Strzempkowski, E., and Pencil, E., "High power MPD thruster performance measurements," *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, 2004, p. 3467.
29. Polk, J. E., Marrese-Reading, C. M., Thornber, B., Dang, L., Johnson, L. K., and Katz, I., "Scanning optical pyrometer for measuring temperatures in hollow cathodes," *Review of Scientific Instruments*, vol. 78, 2007, p. 093101.
30. Georgin, M. P., Jorns, B. A., and Gallimore, Alec D., "An Experimental and Theoretical Study of Hollow Cathode Plume Mode Oscillations," *35th International Electric Propulsion Conference, IEPC-2017-298*, Atlanta, GA: Electric Rocket Propulsion Society, 2017.
31. Peterson, P. Y., Kamhawi, H., Huang, W., Yim, J., Haag, T., Mackey, J., McVetta, M., Sorrelle, L., Tomsik, T., and Gilligan, R., "Reconfiguration of NASA GRC's Vacuum Facility 6 for Testing of Advanced Electric Propulsion System (AEPS) Hardware," *35th International Electric Propulsion Conference, IEPC-2017-028*, Atlanta, GA: Electric Rocket Propulsion Society, 2017.
32. Chu, E., Goebel, D. M., and Wirz, R. E., "Reduction of Energetic Ion Production in Hollow Cathodes by External Gas Injection," *Journal of Propulsion and Power*, vol. 29, 2013, pp. 1155–1163.
33. Soulas, George C., and Patterson, Michael J., *Xenon Feed System Requirements*, NASA, 1995.
34. Soulas, George C., and Patterson, Michael J., *Xenon Feed System Bake-Out*, NASA, 1995.
35. Soulas, George C., and Patterson, Michael J., *Xenon Feed System Leak Rate Determination*, NASA, 1995.