Performance Testing of Phase Four's Valkyrie Hall Effect Thruster

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Hamza A. K. Malik*
Impulse Space, Redondo Beach, CA, 90278, USA

Susan J. Ossareh†
Aerospace Corporation, El Segundo, CA, 90245, USA

William P. Brabston‡, Dan Lev§, *and* Mitchell L. R. Walker¶
High-Power Electric Propulsion Laboratory, Georgia Institute of Technology, Atlanta, GA, 30318

and

M. Umair Siddiqui‖
Phase Four, Hawthorne, CA, 90250, USA

We present the first performance measurements of Phase Four's Valkyrie Hall effect thruster on xenon and krypton, which is based on NASA's H71M-PM Hall thruster. The thruster was tested from 400 W to 1 kW discharge power and produced up to 66.8 mN of thrust at 1,755 s anode specific impulse, and 56.7% anode thrust efficiency. The results show a slight reduction in thrust compared to measurements performed at NASA Glenn Research Center but largely align with published performances of commercially available magnetically optimized small to medium class Hall thrusters. The measurements presented here represent the highest pumping capacity facility performance test of any H71M family thruster.

Nomenclature

F_T	= thrust, mN
I_{sp}	= specific impulse, s
$\dot{m}_A$	= anode mass flow rate, sccm
$\dot{m}_C$	= cathode mass flow rate, sccm
I_D	= discharge current, A
$I_{D,pp}$	= discharge current oscillations peak to peak, A
T_{body}	= thruster body temperature, degrees Celsius
V_D	= discharge voltage, V

*Electric Propulsion Engineer II, hamza.malik@impulsespace.com
†Plasma Science Engineer, Propulsion Sciences Department, susan.j.ossareh@aero.org
‡NSF Fellow Graduate Research Assistant, Department of Aerospace Engineering, wbrabston3@gatech.edu
§Research Engineer, Department of Aerospace Engineering, dan.lev@gatech.edu
¶W. R. T. Oakes School Chair, Department of Aerospace Engineering, mitchell.walker@coe.gatech.edu
‖President and Chief Technology Officer, umair@phasefour.io

I. Introduction

Valkyrie is a Hall effect thruster product being qualified by Phase Four. The design is licensed from NASA Glenn Research Center and is based on the H71M Hall thruster that is being developed through the Small Satellite Electric Propulsion (SSEP) program.[1] Valkyrie is designed to address the demand for commercially available low-medium power electric propulsion systems (0.6-1 kW), from low Earth orbit (LEO) through cis-lunar space. Phase Four chose to leverage NASA's H71M Hall thruster due to a variety of factors:

- its demonstrated best-in-class thrust-to-power performance on xenon as measured by NASA at Glenn Research Center
- promising initial performance measurements on krypton by NASA
- existing set of cathode cycling data indicating at least 14,000 cycles are achievable with the NASA cathode design, in addition to design heritage dating back to Plasma Contactor
- several short duration wear tests performed by NASA indicating a throughput capability of at least 1.8 MN-s
- its thermal design being intended for LEO through the cis-Lunar environment
- NASA's approach to solving manufacturability issues with prior Hall thrusters, especially in the electromagnet, cathode, and anode designs
- the fact that Northrop Grumman also licesed the thruster, and independently validated many of NASA's initial measurements such as performance and throughput capability.[2–4]

In summary the thruster represents a very high performance system, with decades of thought and heritage in the thruster's design, along with a 3rd party validation, all the while with view of manufacturability issues that have afflicted prior NASA thruster implementations.

In this paper we present performance testing results of Phase Four manufactured Valkyrie pathfinder thrusters, specifically based on NASA's H71M-PM design. Measurements were performed at the Georgia Institute of Technology's High-Power Electric Propulsion Laboratory (HPEPL) in Vacuum Test Facility 2 (VTF-2). This represents the highest pumping speed vacuum facility performance test for any H71M based thruster by a significant margin, as well as the first measurements performed outside of a NASA facility. All prior measurements performed by NASA[1] and Northrop Grumman[2–4] were performed in Vacuum Facility 8 (VF8) at NASA Glenn Research Center. As such, in addition to this paper presenting Valkyrie thrust and efficiency measurements, it represents a high-fidelity point of validation of prior NASA measurements, and a comparison of small, magnetically shielded Hall thruster performance across vacuum facilities with significantly different pumping capacities.

II. Description of the Valkyrie Pathfinder Hall Thruster

The Pathfinder variant of the Valkyrie Hall thruster is the NASA H71M-PM Hall thruster, built to print by Phase Four. Phase Four chose to initially build and test the pathfinder variant of the H71M (as opposed to the engineering model variant, H71M-EM) for several reasons:

- the H71M-PM had a fully released design (at the time of program kickoff)
- NASA has an exhaustive comparison set of data
- the anode channel and magnetic circuit designs are nearly identical to the predicted flight model variant, and
- the PM was simpler and faster to build as only laboratory grade interfaces (as opposed to flight grade) were needed.

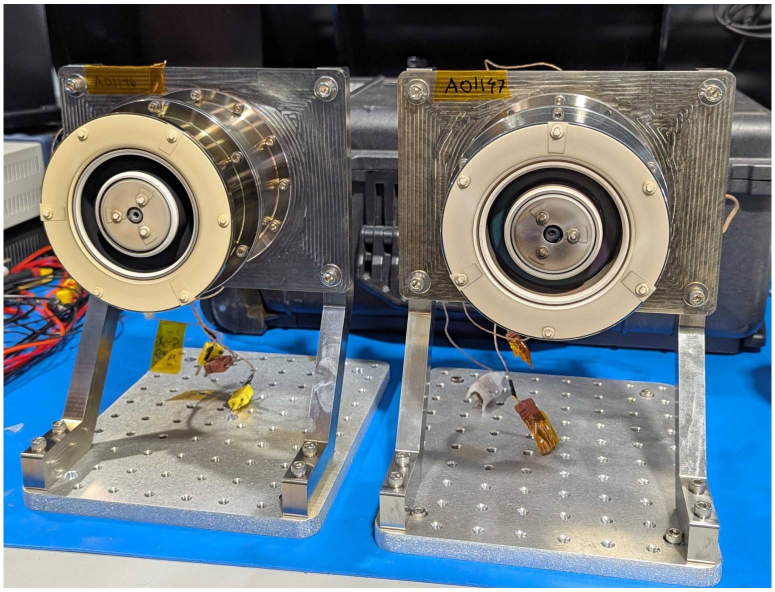

Figure 1. A01146 (left) and A01147 (right) post testing at HPEPL and Phase Four.

The thruster consists of an M26 boron nitride anode channel, 71 mm in major diameter. At the back of the channel the anode / propellant manifold is of a unique NASA design that achieves exceptional azimuthal propellant uniformity (+/- 1%). The thruster body is made of magnetically permeable material, Hiperco 50A, and the magnetic field is generated by hand-wound electromagnets for both the inner and outer poles. The inner and outer front pole covers are made from high-purity alumina. The centrally mounted cathode is similar in design to heritage NASA cathodes from Plasma Contactor,[5] NASA Solar Technology Application Readiness (NSTAR),[6] NASA Evolutionary Xenon Thruster (NEXT)[7] and the Advanced Electric Propulsion System (AEPS).[8] As the Valkyrie PM is a build to print of the NASA H71M-PM, significantly more detail on the thruster anode channel, magnetic circuit, and pole covers can be found in previously presented materials.[9]

Phase Four manufactured two serial numbers of the pathfinder thrusters, A01146 and A01147. The two units were identical to NASA's H71M-PM except that A01146 used a cathode emitter material provided by Plasma Controls, Inc. The Plasma Controls emitter contained a different barium oxide-calcium oxide-alumina mixture than the standard NASA 4-1-1 emitter used in A01147. All the thrust and efficiency measurements taken were performed using A01147 with the standard NASA emitter ratios. A01146 implemented the Plasma Controls emitter due to shorter lead time availability, as well as to determine if there were any noticeable discharge characteristic differences between the two emitter materials. While a pure apples-to-apples comparison between the discharge characteristics was not performed, Phase Four did not observe any significant differences in the steady state operation of A01146 and A01147 in test operations in Phase Four's vacuum facilities. Figure 2 shows A01147 thruster firing on Xe at HPEPL at 1 kW, and Figure 3 shows the A01146 thruster firing on Kr at 400 W at Phase Four.

III. Description of VTF-2 at HPEPL and Test Diagnostics

VTF-2 at Georgia Tech measures 9.2 m in length and 4.5 m in diameter and achieves high vacuum using 10 LN2-cooled CVI TMI reentrant cryopumps with a nominal operational pumping speed of 350,000 L/s of Xe. This represents a significant improvement over the pumping capacity if prior thrust measurements on H71M thrusters, as NASA's VF8 vacuum chamber has a pumping speed of 120,000 L/s on air. Pressure measurements in VTF-2 were taken using an Agilent XGS-600 ion gauge controller and a Kurt J. Lesker G100F ion gauge, following the best practices pressure guidelines outlined in Dankanich et al.[10] Figure 4 shows a schematic and testing configuration for VTF-2, and Figure 5 shows the inside of VTF-2 with the A01147 Valkyrie HET installed on the thrust stand. For all setpoints measured, the chamber pressure was between 5.2×10^{-7} and 1.5×10^{-6} Torr, corrected for the respective gas.

For this test, the A01147 Valkyrie HET was operated on both krypton and xenon propellants, which

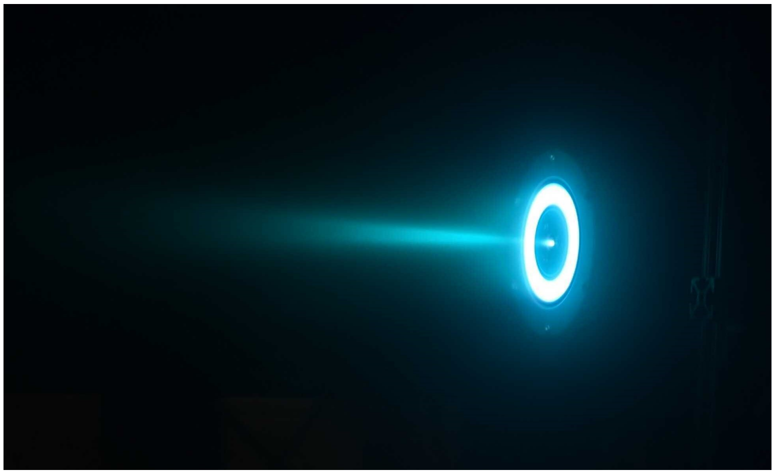

Figure 2. A01147 operating at 1 kW, 300 V, Xe at HPEPL in VTF-2.

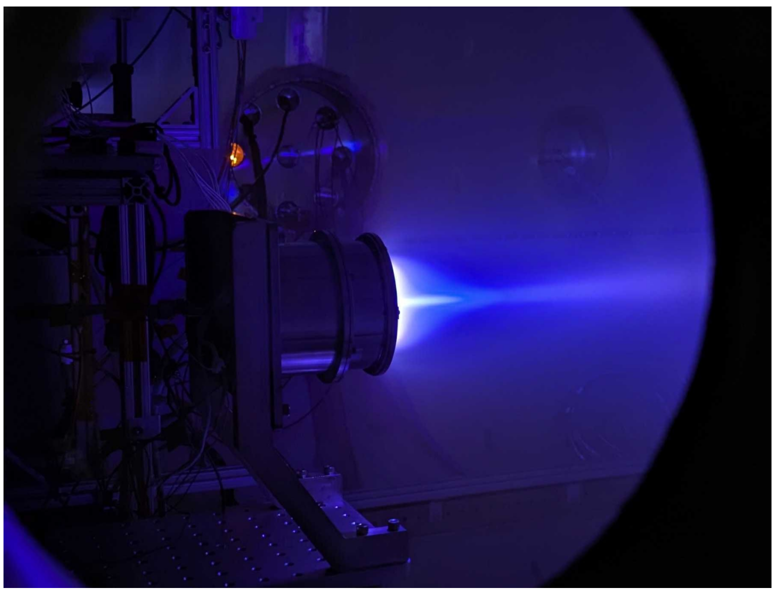

Figure 3. A01146 operating at 400 W, 250 V, Kr at Phase Four.

were supplied using a dedicated mass flow system. Figure 6 shows the propellant feed system employed for this test. MKS GE50A mass flow controllers (MFCs) supplied the gas constituents and a MesaLabs DryCal 800 verified their operational mass flow rates. In addition to DryCal calibration, the propellant feed system underwent an extensive leak check procedure to ensure there was no loss of propellant or air exposure throughout the flow path. This leak check ensured that all leaks rates are below 0.1 sccm at a pressure differential of 40 psi. These propellant feed verification methods lead to a maximum uncertainty of 1% of the flow rate setpoint.

Several diagnostics were used in this test, including a nude Faraday probe to measure beam current and beam divergence, a Teledyne Lecroy HDO6000 oscilloscope to measure thruster discharge current stability parameters, a K-type thermocouple to measure the thruster body temperature, and a null-type inverted pendulum thrust stand to measure thrust. Figure 4 shows a schematic of the Faraday probe (FP) installed on a radial probe arm 1 m downstream of the thruster exit plane. The Faraday probe swept from -90° to +90° and was operated and data processed according to the best practices for Faraday probes outlined in Brown et al.[11]

The null-type inverted pendulum thrust stand was configured as detailed in the recommended practices

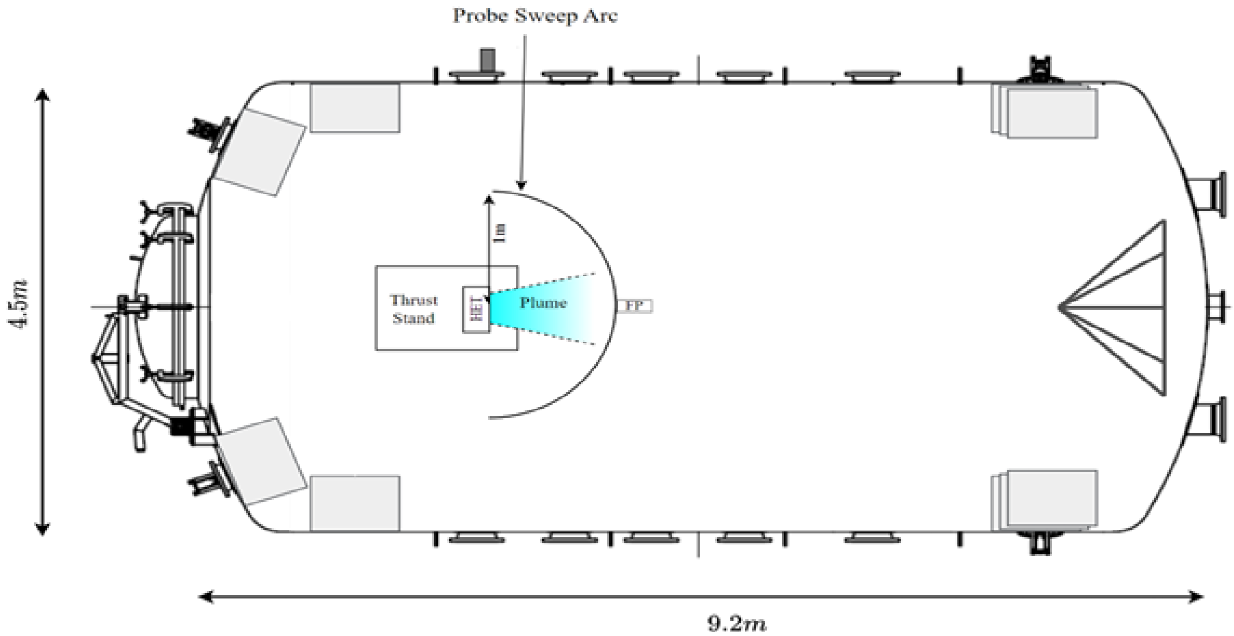

Figure 4. Schematic of VTF-2 at Georgia Tech.

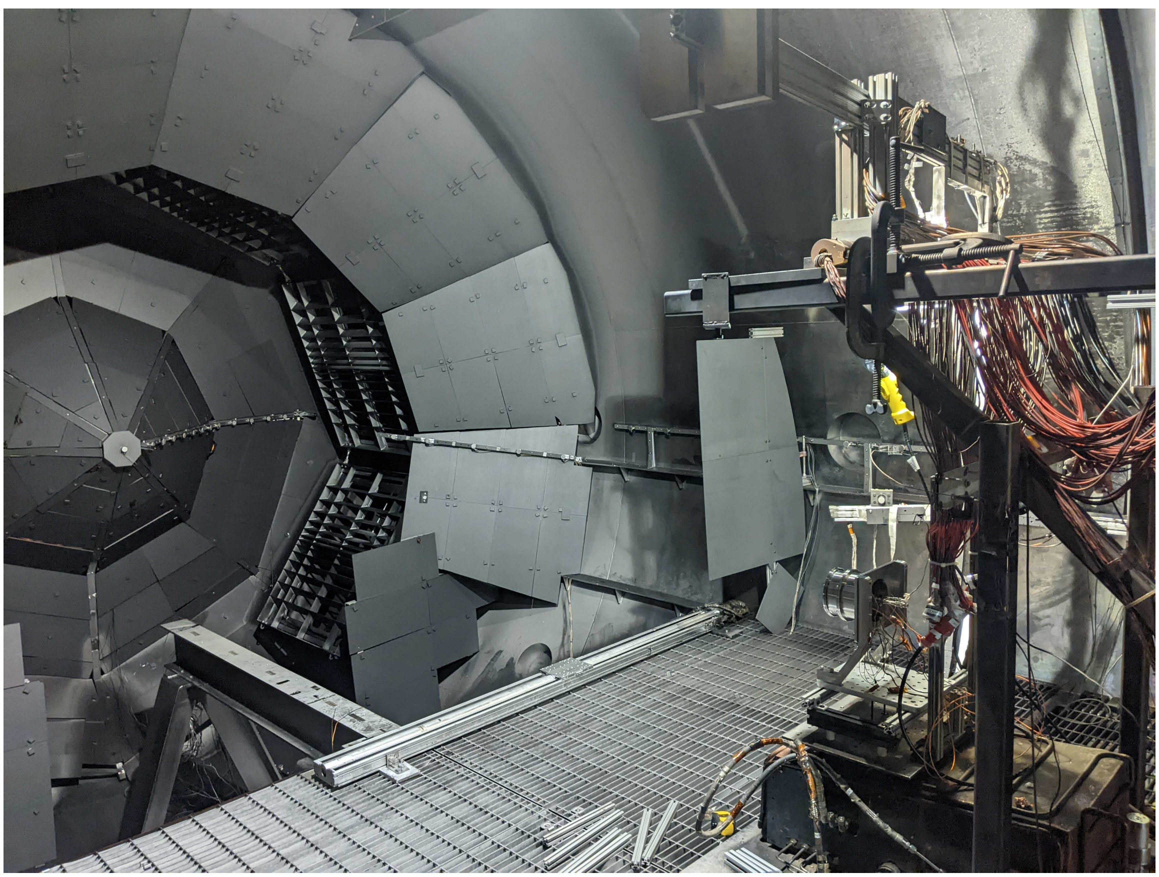

Figure 5. A01147 installed in VTF-2 prior to pump down at HPEPL.

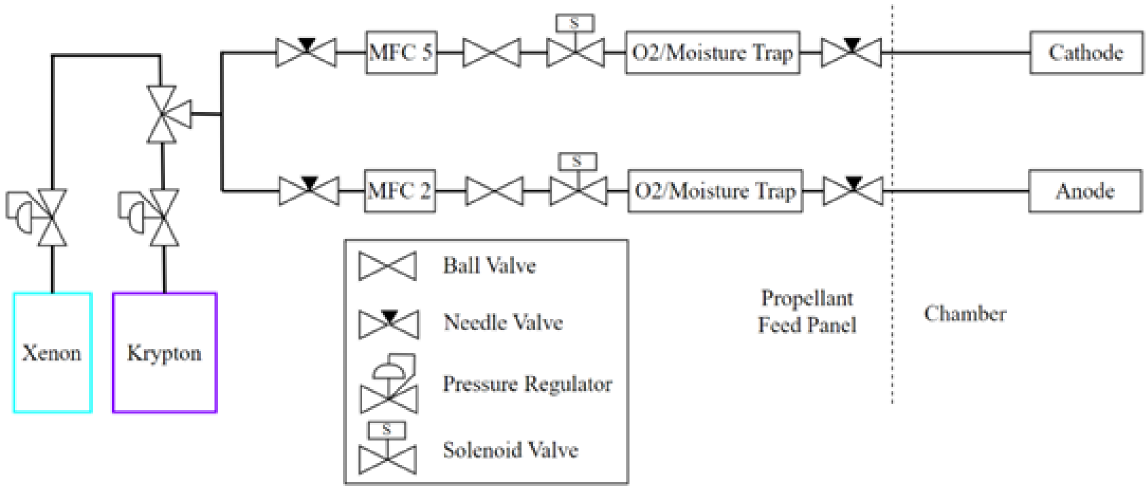

Figure 6. VTF-2 propellant feed system.

for thrust measurements in Polk et al.[12] For this test, the calibration string was set to a weight range of 0–69.65 mN, divided evenly into four steps. This range was based on the predicted thrust response for the underlying thruster operational setpoints. Thrust error propagation was performed by using standard methods outlined in NIST Technical Note 1297.[13] The maximum performance uncertainty for each propellant in this test is shown in the table below.

Propellant	Max thrust uncertainty	Max I_{sp} uncertainty
Xe	± 0.93 mN	± 42.0 s
Kr	± 0.61 mN	± 22.7 s

Table 1: Measurement uncertainties.

IV. Results

Figure 7 presents the thrust and specific impulse data from this test campaign as a function of total input power. Xenon performance was measured between 250 and 300 V, and Kr was measured exclusively at 250 V discharge voltage. Electromagnet current varied between 2 and 3 A for best discharge stability characteristics. For this test, the cathode maintained a common propellant to the anode with a flow fraction between 8.1-9.1% for all xenon setpoints and 7.2-8.1% for all krypton setpoints. The operating parameters for all tests presented here are shown in Table 2 below. Performance is plotted as a function of total thruster power at steady state, including the electromagnet power and the anode discharge power. All measurements were performed after a 2 hour long warm up period to ensure the thruster was at thermal steady state, and that the electromagnets were at their steady state load resistance. The keeper and cathode heater were turned off for steady state operations. Additionally, Figure 7 shows the specific impulse including the cathode flow. At the time of the measurements Phase Four had not yet performed a cathode flow split sensitivity experiment. Subsequently to this thrust measurement campaign Phase Four observed that at the nominal operating point (setpoint A), the thruster was stable down to 4% cathode flow split. To provide margin and operating point flexibility, Phase Four set Valkyrie's flow split to be set in hardware via two orifices, which permanently sets the flight design's flow split to 7% to the cathode. As such the specific impulses presented here are slightly lower than what would be expected in the Valkyrie flight configuration for xenon.

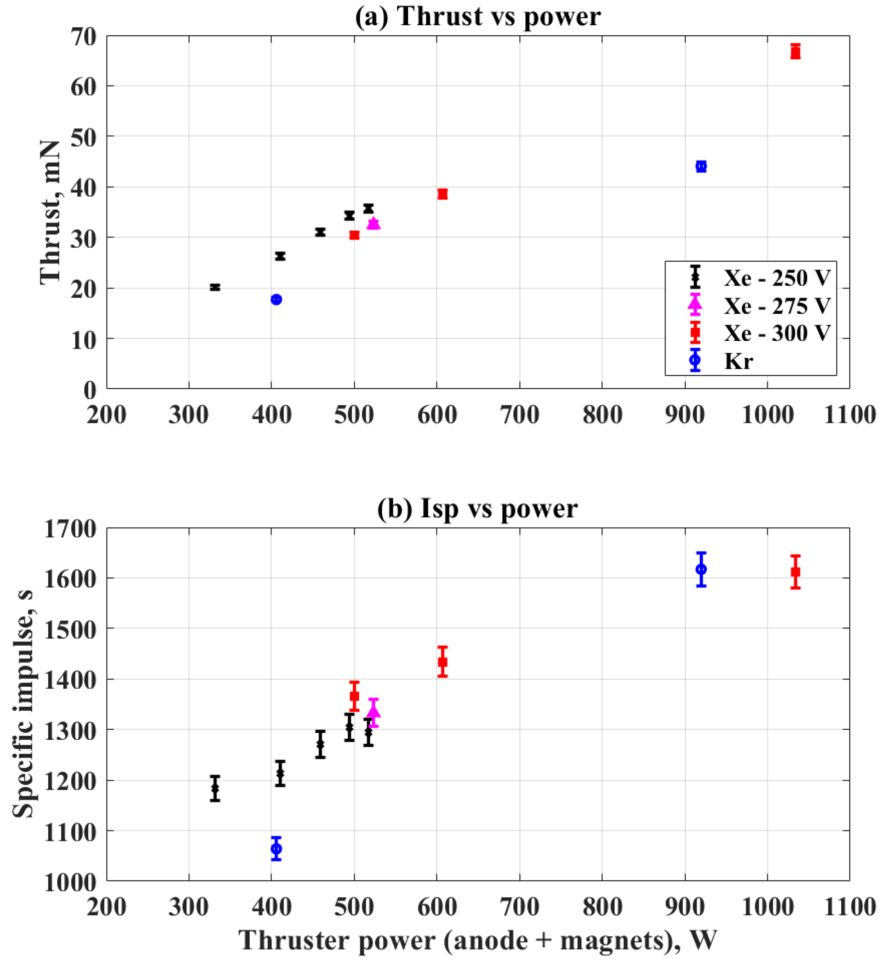

Figure 7. A01147 performance measurements summary plots (a) total thrust and (b) total specific impulse vs thruster power, including electromagnet power.

Setpoint	Gas	$\dot{m}_A$ sccm	$\dot{m}_C$ sccm	V_D, V	I_D, A	$I_{D,pp}$, A	T_{body}, ^{o}C	F_T, mN	I_{sp}, s
A	Xe	25.0	2.3	249.5	1.899	1.06	385.9	34.3	1304
B	Xe	20.5	2.0	249.3	1.567	1.09	360.0	26.3	1213
C	Xe	23.0	2.3	249.4	1.772	0.97	381.0	31.0	1271
C'	Xe	26.0	2.6	249.0	1.997	0.51	374.5	35.7	1295
D'	Xe	25.4	2.5	299.5	1.960	0.69	387.7	38.5	1434
D	Xe	21.0	2.1	299.9	1.600	2.06	381.0	30.4	1366
C"	Xe	23.0	2.3	274.6	1.827	1.73	373.1	32.5	1333
E	Xe	16.0	1.7	250.1	1.248	1.29	332.7	20.2	1184
F	Kr	25.0	2.2	249.5	1.546	0.88	387.5	17.7	1064
G	Kr	41.4	3.2	298.9	3.010	2.85	410.9	44.1	1617
H	Xe	23.0	2.3	237.5	1.800	0.71	351.1	28.9	1185
I	Xe	39.5	3.5	298.3	3.490	1.49	430.0	66.8	1612

Table 2: Operating parameters for all test points of Valkyrie PM at HPEPL

Fig. 7 shows that in general, both thrust and specific impulse increase monotonically as total thruster power increases, and is seen to scale linearly in this power range. The exhibited thrust of the A01147 Valkyrie HET operating on krypton falls below the operation on xenon for similar thruster powers. The A01147 Valkyrie HET demonstrates a decreased specific impulse when operating on krypton at low thruster powers, but demonstrates comparable specific impulses between xenon and krypton at higher thruster powers. The increased relative specific impulse on krypton at higher powers is due to increased mass utilization of the krypton propellant. This is a common trend seen with lightweight propellants operating at increased current densities.[17,18] To further understand differences in operation on the A01147 Valkyrie HET between krypton and xenon propellants, Fig. 8 presents Faraday probe sweeps for xenon and krypton operating at similar discharge conditions. In this figure, $\theta_{d,0.95}$ is the beam divergence angle for a 95% current fraction and I_b is the measured beam current. As seen in this figure, the A01147 Valkyrie HET operating on krypton exhibits a more diffuse plume with higher beam divergence than xenon operation. This is seen with an increase in current density in the wings and a decrease in maximum current density on thruster centerline. Along with this, A01147 Valkyrie HET operating on xenon results in a marginally higher beam current than krypton operation, but similar current utilizations between the two propellants.

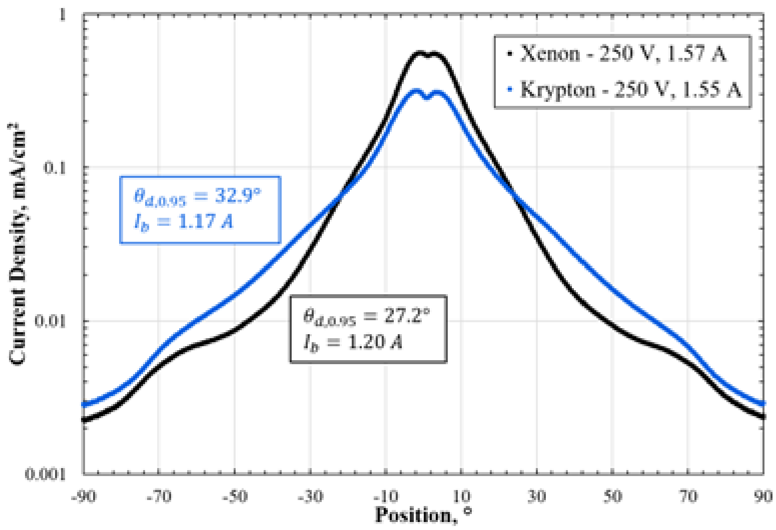

Figure 8. Faraday probe sweeps on xenon and krypton propellants with comparable discharge conditions.

Figure 9 shows a direct comparison of Phase Four's Valkyrie pathfinder thruster (serial number A01147, solid red squares) against NASA's H71M-PM measurements in VF8 (red X's),[1] Northrop Grumman's NGHT-1X performance measurements in VF8 (which is also a NASA H71M design, hollow red circles),[2] Safran's PPS-X00 (black X's),[14] and three different Busek thrusters (hollow black circles).[15] To provide a pure comparison, only anode specific impulse and anode discharge power are plotted, eliminating any laboratory or setup specific cathode flow splits and electromagnet drive power. Generally, all these thrusters represent state of the art small Hall effect thrusters, with some form of magnetic optimization to reduce channel wear and extend thruster lifetime. It is notable that across 1.3 kW of discharge power, all the thrusters' performance fall on the same trendline. Some differences are noticeable in specific impulse, especially between 500 W and 1 kW, however it is important to note that all these thrusters were measured in different facilities. Specifically NASA's H71M and Northrop Grumman's NGHT-1x were tested in VF8 at NASA Glenn Research Center, which has a pumping speed of 120 kL/s on air. Busek's thrusters were tested in Busek's T8 vacuum chamber with a pumping speed of 200 kL/s on xenon, while Valkyrie was tested in VTF-2 at HPEPL with 350 kL/s of pumping speed on xenon. Given the major differences in test facilities it is remarkable that all the thrusters and measurements largely align with each other. When looking at H71M family thrusters specifically (red data) there may be a slight facility effect noticeable in anode specific impulse between 500 W and 1 kW. If repeatable, this effect may be elucidated during the JANUS test across various facilities of the H71M in future measurements.[16]

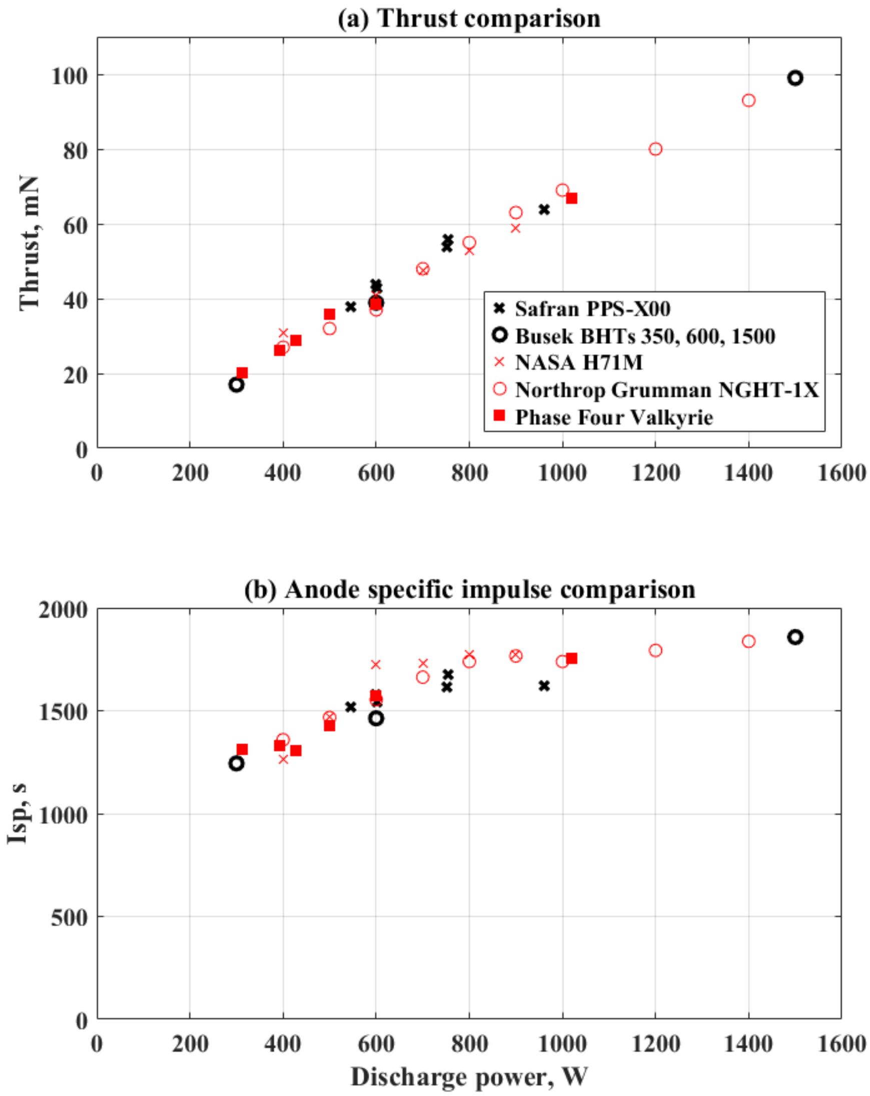

Figure 9. Direct comparison of Valkyrie's anode specific impulse and thrust vs discharge power to Busek's BHT-350, BHT-500, BHT-1500, Safran's PPS-X00, Northrop Grumman's NGHT-1X and NASA's H71M.

Conclusions

The performance results shown here present two main conclusions. First, the Valkyrie Hall thruster test validates previously presented data by NASA and Northrop Grumman on their builds of H71M Hall thrusters. Valkyrie was manufactured to the NASA H71M-PM specification independently by Phase Four, and separately tested by the Geogia Institute of Technology and found to largely align with performance measured by NASA in previous efforts. Second, while slight changes in performance may be deduced in the HPEPL data, generally across a broad discharge power range, the H71M thruster shows performance consistency across NASA's VF8 vacuum chamber and HPEPL's VTF-2 vacuum chamber at thruster beginning of life. This implies that NASA's data in VF8 may be used as a high-fidelity measure of performance to within 9% or better. While the JANUS program will shed more thorough light on facility effects on performance, this suggests that for advanced magnetically optimized Hall thrusters, facility effects between 100 kL/s - 350 kL/s may not be as significant as unshielded thrusters, at least in the sub-1.5 kW range of discharge powers.

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References

[1]Benavides, G. F., Kamhawi, H., Sarver-Verhey, T. R., Rhodes, C. R., Baird, M. J., and Mackey, J. A., "High-Propellant Throughput Sub-kW Electric Propulsion System for Deep Space Science and Exploration," *37th International Electric Propulsion Conference*, 2022-343, Cambridge, MA, 2022

[2]Nikrant, A. W., Glogowski, M. J., Cochran, D. E., Moquin, T, Choi, Y. E., Benavides, G. F., Kamhawi, H., Sarver-Verhey, T. R., Rhodes, C. R., Baird, M. J., and Mackey, J. A.,"Overview and Performance Characterization of Northrop Grumman's 1 kW Hall Thruster String," *37th International Electric Propulsion Conference*, 2022-303, Cambridge, MA, 2022

[3]Switzer, Z., Nikrant, A. W., Martinez, L., and Glogowski, M. J., "NGHT-1X High Current Density Operation on Xenon and Krypton," *AIAA SciTech Forum*, 2024-2163, Orlando, FL, 2024

[4]Nikrant, A. W., Switzer, Z., Martinez, L., Glogowski, M. J., Benavides, G. F., Baird, M. J., and Mackey, J. A.,"NGHT-1X Pole Cover Erosion Measurements on Xenon and Krypton," *AIAA SciTech Forum*, 2024-1140, Orlando, FL, 2024

[5]Patterson, M. J., Hamley, J. A., Sarmiento, C. J., Manzella, D. H., Sarver-Verhey, R., Soulas, G. C., and Nelson, A., "Plasma Contactor Development for the Space Station," *23rd International Electric Propulsion Conference*, 93-246, Seattle, WA, 1993

[6]Polk, J. E., Brinza, D., Kakuda, R. Y., Brophy, J. R., Katz, I., Anderson, J. R., Rawlin, V. K., Patterson, M. J., Sovey, J., and Hamley, J. A., "Demonstration of the NSTAR Ion Propulsion System on the Deep Space One Mission," *27th International Electric Propulsion Conference*, 01-075, Pasadena, CA, 2001

[7]Crofton, M. W., Pollard, J. E., Beiting, E. J., Spektor, R., Diamant, K. D., Eapen, X. L., Cohen, R. B., and Patterson, M. J.,"Characterization of the NASA NEXT Thruster," *AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, 2009-4815, Denver, CO, 2009

[8]Herman, D. A., Tofil, T. A., Santiago, W., Kamhawi, H., Polk, J. E., Snyder, J. S., Hofer, R. R., Picha, F. Q., Jackson, J., and Allen, M., "Overview of the Development and Mission Application of the Advanced Electric Propulsion System (AEPS)," *35th International Electric Propulsion Conference*, 2017-287, Atlanta, GA, 2017

[9]Benavides, G. F., Kamhawi, H., Sarver-Verhey, T. R., Rhodes, C. R., Baird, M. J., Yim., J. T., Ahern, D. M., Huang, W., and Mackey, J. A., "Development and Characterization of a High-Propellant Throughput Sub-kW Hall-Effect Thruster," *12th JANNAF Spacecraft Propulsion Joint Subcommittee Meeting*, 2022-1030, Huntsville, AL, 2022

[10] Dankanich, J., Walker, M., Swiatek, M., and Yim, J.,"Recommended Practice for Pressure Measurement and Calculation of Effective Pumping Speed in Electric Propulsion Testing," *Journal of Propulsion and Power,* Vol 33, No. 3, 3 Aug. 2016

[11] Brown, D., Walker, M., Szabo, J., Huang, W., Foster, J.,"Recommended Practice for Use of Faraday Probes in Electric Propulsion Testing," *Journal of Propulsion and Power*, Vol. 33, No. 3, 16 Sep. 2016

[12] Polk, J. et al.,"Recommended Practice for Thrust Measurement in Electric Propulsion Testing," *Journal of Propulsion and Power*, Vol. 33, No. 3, 21 April 2017

[13] Taylor, B. N. and Kuyatt, C. E., "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," National Institute of Standards and Technology Technical Note 1297, 1994

[14] Vaudolon, J., Cornu, N., and Habbassi, I., "PPS X00 Thruster Development Status at Safran", *36th International Electric Propulsion Conference*, 2019-241, Vienna, Austria, 2019

[15] Hruby, P., Demmons, N., Courtney, D., Tsay, M., Szabo, J., and Hruby, V., "Overview of Busek Electric Propulsion", *36th International Electric Propulsion Conference*, 2019-926, Vienna, Austria, 2019

[16] Walker, M. L. R., Lev, D., Saeedifard, M., Jorns, B., Chew, H. B., Levin, D., Williams, J. D., Yalin, A., Wirz, R., Marian, J., Boyd, I., Hara, K., and Lemmer, K., "Overview of the Joint AdvaNced PropUlsion InStitute", *37th International Electric Propulsion Conference*, 2022-156, Cambridge, MA, 2022

[17] Su, L. L., Marks, T. A., and Jorns, B. A., "Trends in Mass Utilization of a Magnetically Shielded Hall Thruster Operating on Xenon and Krypton," *Plasma Sources Science and Technology*, Vol. 33, No. 6, 2024, p. 065008

[18] Hurley, W. J., and Jorns, B. A., "Mass Utilization Scaling with Propellant Type on a Magnetically Shielded Hall Thruster," *Plasma Sources Science and Technology*, Vol. 34, No. 5, 2025, p. 055010