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50 KW Class Krypton Hall Thruster Performance

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50 KW CLASS KRYPTON HALL THRUSTER PERFORMANCE

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ABSTRACT

The performance of a 50-kilowatt-class Hall thruster designed for operation on xenon propellant was measured using krypton propellant. The thruster was operated at discharge power levels ranging from 6.4 kilowatts to 72.5 kilowatts. The device produced thrust ranging from 0.3 newtons to 2.5 newtons. The thruster was operated at discharge voltages between 250 volts and 1000 volts. At the highest anode mass flow rate and discharge voltage and assuming a 100% singly charged condition, the discharge specific impulse approached the theoretical value. Discharge specific impulse of 4500 seconds was demonstrated at a discharge voltage of 1000 volts. The peak discharge efficiency was 64% at 650 volts.

INTRODUCTION

High-power Hall thrusters have long been considered as a leading solar electric propulsion (SEP) candidate for time-critical missions or missions requiring transportation of large payloads. Such applications include piloted Mars scenarios, the space solar-power concept and reusable tugs for LEO to GEO transportation.[1-4] Recent studies have also identified high-power Hall propulsion systems as enabling technology for various space telescope missions that require near-space to libration point transfers.[5-7] NASA Glenn has been performing research and development of high-power Hall thrusters in support of these kinds of missions. The efforts have resulted in the design, fabrication and test of a moderate specific impulse, 50-kilowatt (kW) Hall thruster designated the NASA-457M. At the design point of 500 volts (V) and 100 amperes (A), the thruster produced 2.3 newtons (N) of thrust, a 2500 second discharge specific impulse, and had a discharge efficiency of 62%.[8] While research of moderate specific impulse, xenon Hall thrusters is on-going, higher specific impulse, high-power Hall thrusters may be desirable for a different class of NASA missions.

NASA recently established Project Prometheus to develop technology in the areas of radioisotope power systems and nuclear power and propulsion. These technologies are enabling for deep space science missions, which are central to NASA's mission to explore the universe and search for life. While the Jupiter Icy Moons Orbiter (JIMO) has been identified as the first space science mission to potentially utilize Prometheus-developed technology, the Project is also sponsoring broad-based research and development for future missions. One of these Nuclear Propulsion Research tasks pertains to research of alternate propellants for electric propulsion devices. The motivation for alternate propellants include the potential cost and availability issues for extremely large-scale, xenon-fueled propulsion systems and the potential system performance benefits achievable using alternate propellants. Initial work on this Nuclear Propulsion Research task considered the effect of operating a high-power Hall thruster on the alternate propellant krypton.

Using krypton as the propellant has potential performance benefits for deep space missions because the theoretical specific impulse for a given voltage

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using krypton propellant is 20% higher than xenon due to the lower molecular weight of krypton. However, past investigators have observed a reduction in thruster efficiency of up to 20% in lower-power Hall thrusters operated on krypton relative to xenon, negating the benefit of using krypton.[9,10] The objective of this work was to assess the performance of a high-power Hall thruster using krypton as the propellant. The results of operating the NASA-457M on krypton were investigated and compared with the performance of the same engine operated on xenon.

APPARATUS

The NASA-457M Hall thruster, which was designed for operation at 50 kilowatts (kW) on xenon propellant, was used in this investigation. Details of the thruster, including its performance on xenon propellant, have previously been reported.[8] The NASA-designed hollow cathode used in previous testing of the NASA-457M thruster was also used for this investigation. (Details of the cathode have also been reported elsewhere.[11]) The cathode, located along the central axis of the thruster, was operated on krypton propellant and the flow rate was maintained at 6.6 milligrams per second (mg/s) throughout the tests. No attempt was made to optimize the location or flow rate of the cathode. Figure 1 is a photograph of the thruster and cathode.

This performance investigation was conducted in NASA Glenn's Vacuum Facility 5 (VF 5). VF 5 is a cryogenically pumped chamber, 5 meters in diameter by 20 meters in length and has been described in detail previously.[12] Background pressure was measured behind the thruster using an ion gauge calibrated for air. At the highest krypton flow rate of 1.1 standard liters per minute, the pressure was 1.8 x10^{-5} Torr corrected for krypton. The test apparatus was located in a cylindrical test port measuring 2 meters in diameter and 2.5 meters in length, which could be isolated from the main portion of the chamber. The laboratory power console consisted of commercially available power supplies. The discharge supply was a 60 hertz (Hz), silicon-controlled rectifier (SCR)-regulated unit with a rated output of 100 A and 2000 V. An output filter consisting of a capacitor bank placed between the anode and cathode electrodes had a total capacitance of 21 millifarad (mF). Separate DC power supplies were used to power the inner and outer magnets, the cathode heater and the keeper. Thrust was measured continuously on a NASA GRC-designed inverted pendulum thrust stand. The thrust stand design was similar to previously described NASA thrust stands, but incorporated provisions for increased thruster mass and

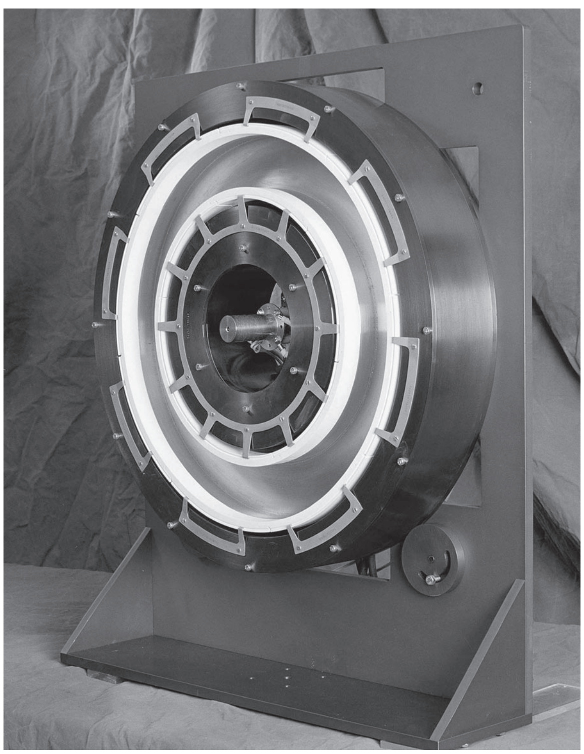

Figure 1. NASA-457M Hall thruster with NASA's high-current hollow cathode.

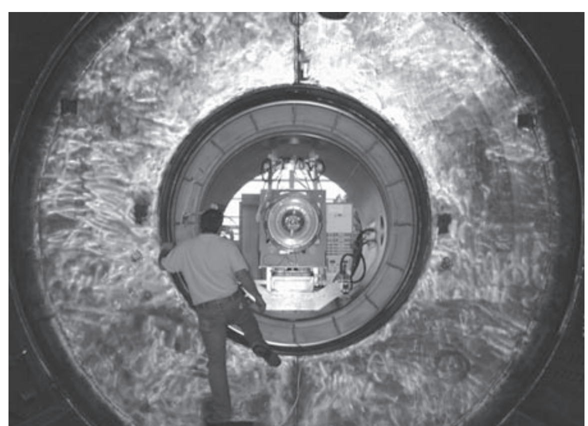

Figure 2. NASA-457M Hall thruster shown on the thrust stand in Vacuum Facility 5.

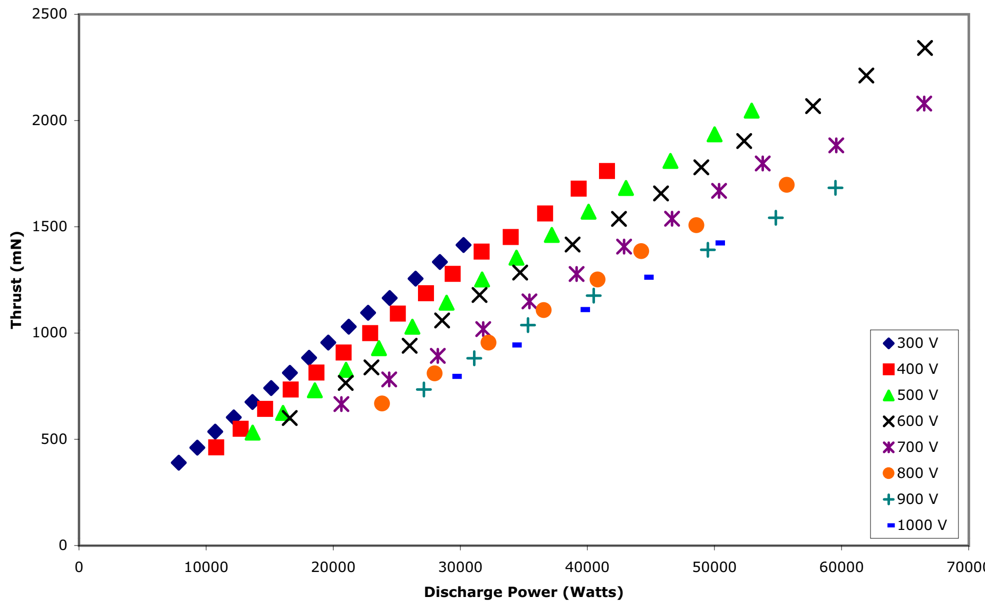

Figure 3. Thrust versus discharge power for a range of discharge voltages.

discharge current.[13,14] The stand employed a closed-loop inclination control circuit to minimize thermal drift. Calibration was performed in-situ, using three 0.1 kilogram (kg) masses applied along the thrust vector over a pulley. Figure 2 shows the thruster, thrust stand and test port.

RESULTS AND DISCUSSION

Performance of the NASA-457M thruster operating on krypton was measured over a range of input powers from 8.5 kW to 74.0 kW. Thrust was measured at anode flow rates ranging from 19.5 to 66.0 mg/s and discharge voltages ranging from 300 V to 1000 V. (A table of the operating parameters and performance data are provided in the appendix.) The relationship between thrust and discharge power is shown in Figure 3. The relationship is linear as expected. The thrust produced ranged from a minimum of .39 N at 7.8 kW to a maximum of 2.5 N at 72.5 kW. These data were collected by varying the anode flow rate at a given discharge voltage. Stable thruster operation was achieved for anode mass flow rates ranging from 19.5–66.0 mg/s and discharge voltages up to 650 V. At discharge voltages above 650 V, the anode flow rate at which stable operation could be achieved decreased with increasing voltage. Under the high-voltage, high current density conditions, the discharge would extinguish without provocation. Hofer has also observed this phenomenon while operating at high current and power density in a lower power device.[15] While no effort was made to mitigate or understand this behavior, the combination of high current density and high voltage resulted in anomalous operation in both devices.

The functional relationship between discharge specific impulse (specific impulse calculated without the cathode flow) and discharge voltage is presented in Figure 4. Experimental data taken with the thruster operating on krypton and xenon from reference 8 are presented. Theoretical specific impulse curves generated by assuming that the propellant is singly ionized are also included for both krypton and xenon. The krypton specific impulse is lower than the theoretical value at each discharge voltage, indicating that not all the propellant is ionized as assumed, or that the ions are not accelerated through the total applied electric potential. The specific impulse does become increasingly closer to the theoretical value as the propellant flow rate and voltage increase. For a given voltage, the higher specific impulse points correspond to higher efficiency operating points due to higher anode propellant flow rate. (This effect is discussed in more detail below.) In nearly all cases, the specific impulse of krypton is greater than the specific impulse of xenon for a given voltage. While this result is expected based on the differences in

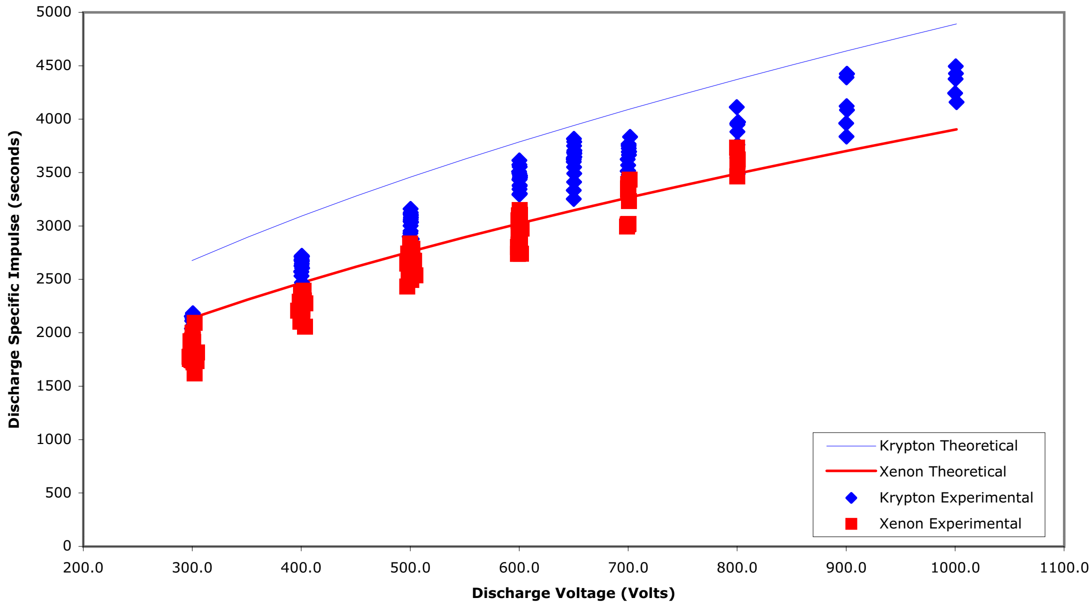

Figure 4. Comparison of experimental and theoretical specific impulse of xenon and krypton.

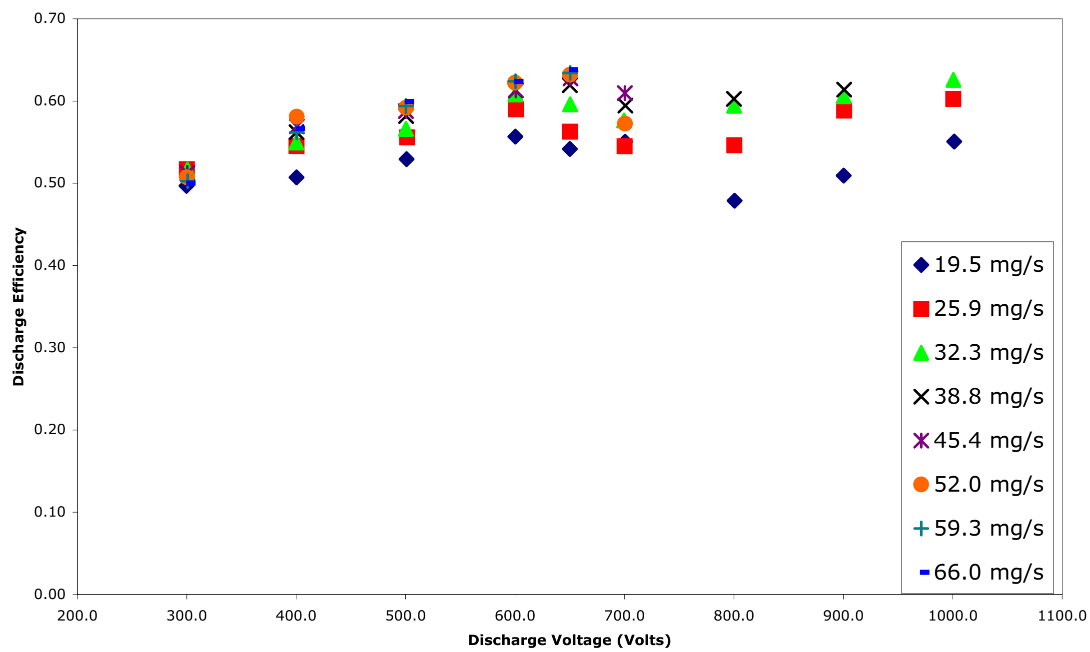

Figure 5. Discharge efficiency versus discharge voltage for a range of anode mass flow rates.

molecular weight of the two propellants, past krypton Hall thruster experiments have shown that significant improvements in specific impulse were not realized due to reductions in thruster efficiency.[9,10]

Figure 5 depicts the effect that increased current density had on thruster efficiency. Discharge efficiency (calculated with anode flow and discharge power) is plotted verses discharge voltage for a range of anode mass flow rates. For each mass flow rate, the efficiency increased from 300 V to a maximum efficiency, which occurred between 600 V and 650 V. The efficiency then began to decrease with increasing voltage. This relationship of efficiency and discharge voltage has been observed with other lower-power Hall thrusters operated on xenon; the potential causes have been discussed elsewhere.[16,17] However, after the initial decrease, the efficiency reached a minimum before beginning to increase. The trend was present for all mass flow rate cases. In the case of the SPT-1 operating on xenon, Manzella suggested this decrease in efficiency was attributed to an increase in electron current with increasing discharge voltage. The SPT-1 peak efficiency corresponded to a point where the discharge voltage/discharge current relationship became nonlinear which supported this theory. Because the NASA-457M krypton data exhibits a nearly linear discharge voltage/discharge current relationship, increasing electron current is not suspected in this case. Because the efficiency increased after reaching a minimum value, it is possible that an unstable operating regime, which occurred only between 650 V and 800 V, caused the decrease in efficiency. Because the magnetic field was constant over the range of operating points, it is likely that the field was not optimum for all operating points. Although thruster operating parameters were not optimized at each operating point, efficient thruster operation (48% to 64%) was demonstrated using krypton propellant at the same propellant number density as previous xenon experiments.

NASA-457M krypton performance measurements were made at the same volumetric flow rates as the previous xenon performance measurements. This permitted direct comparison of the krypton and xenon performance data without the effect of propellant density on performance. The functional relationship between the krypton and xenon discharge efficiency and discharge voltage is shown for two volumetric flow rates in Figure 6. The two flow rates are upper and lower cases of molecular density in the discharge channel at which the thruster was operated. There is no significant difference in thruster efficiency between krypton and xenon for most discharge voltages. For the lower flow rate case, the krypton data points fall between xenon data points

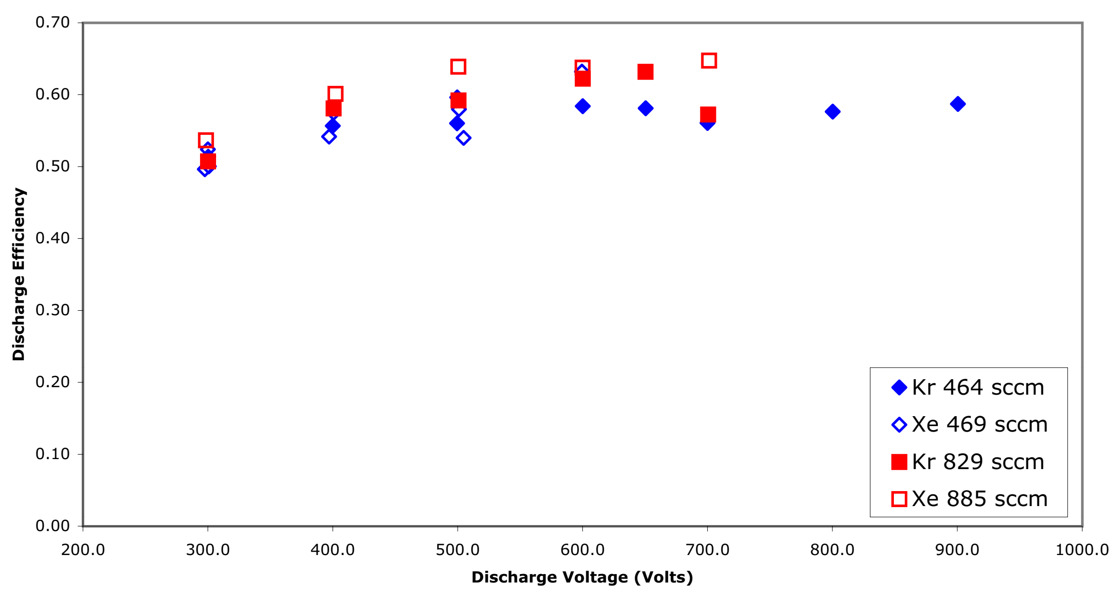

Figure 6. Comparison of krypton and xenon efficiency at the same propellant number density.

generated by optimizing the thruster operating conditions. No optimization of cathode flow or magnetic field was done during krypton performance testing. The krypton efficiency may match the xenon efficiency if similar optimization were performed during krypton operation. Differences in efficiency for the higher flow rate condition ranged from 2–8%. The point at which there was an 8% difference corresponded to the 700 V discharge voltage case, which is where the efficiency minimum occurred for all krypton operating points. Additionally, no krypton or xenon data was available for this flow rate at higher voltage. The trends shown in Figure 5 indicate that there may be less of a difference between krypton and xenon efficiency for this flow rate at elevated voltages. Previous krypton Hall thruster work has shown that it is necessary to increase the propellant or current density in order to achieve efficient krypton operation.[18,19] These results indicate that efficient krypton operation can be achieved at the same number density as xenon.

Past investigators have attributed the reduction in krypton Hall thruster efficiency to a reduction in the propellant utilization fraction.[20] Because the efficiency of the NASA-457M operating on krypton and xenon was nearly equivalent for the same propellant number density, the propellant utilization fraction was estimated for several operating points. The propellant utilization fraction was defined as the percentage of ions required to achieve a given average ion velocity assuming all ions are singly charged. An accelerating voltage was estimated by subtracting the cathode floating potential from the applied discharge voltage. The estimated propellant utilization fraction was found to increase with increasing discharge voltage and mass flow rate. The estimated values ranged from 0.79 to 0.96 for discharge voltages and mass flow rates from 300–900 V and 19.5–66.0 mg/s, respectively. These estimated propellant utilization fractions indicate that efficient ionization was achieved for the range of operational parameters, which corresponded to efficient thruster operation. While measurements will be made to quantify the plasma parameters, this estimate of the propellant utilization fraction provides insight regarding the ionization process. Although the reasons that efficient krypton ionization was achieved with the NASA-457M are not completely understood, differences in the magnetic field and channel geometry compared to other NASA thrusters are thought to be contributing factors.

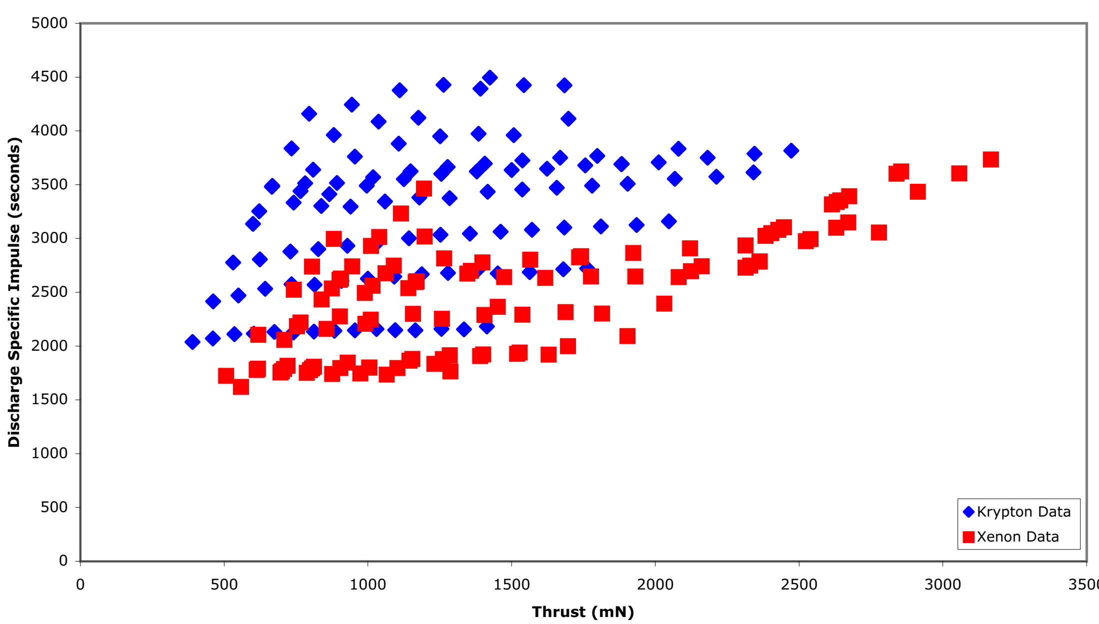

Figure 7. Performance regime of the NASA-457M operating on krypton and xenon.

The discharge specific impulse is plotted as a function of thrust for both krypton and xenon in Figure 7. The differences in the performance envelope for the two propellants are shown. The specific impulse and thrust achieved by operation with the different propellants overlaps for specific impulses between 2000 seconds and 3000 seconds (s) and thrust between 0.7 N and 1.8 N. The krypton envelope extends to significantly higher discharge specific impulse at 4500 s and a thrust of nearly 1.7 N, while the xenon envelope extends to higher thrust at lower specific impulse values. These data illustrate the unique performance regimes achievable with a high-power Hall thruster that uses krypton propellant.

CONCLUDING REMARKS

NASA's Project Prometheus is currently sponsoring technology development in the areas of radioisotope power systems and nuclear power and propulsion for ambition space science missions. While xenon-fueled, electric propulsion devices are being considered for these missions, alternate propellants may offer performance and cost benefits for large-scale missions with intensive propulsion requirements. Under a Nuclear Propulsion Research task, the effect of operating a high-power Hall thruster on krypton propellant was considered.

Krypton performance of the NASA-457M Hall thruster was measured at input power ranging from 6.4 kW to 72.5 kW. The thrust ranged from 0.3 N to 2.5 N and the specific impulse ranged from 2040 s to 4500 s. The discharge specific impulse approached the theoretical value at high discharge voltage and high propellant flow rate as a result of increasingly efficient thruster operation.

Previous krypton-fueled Hall thruster investigations conducted at lower power have shown reductions in thruster efficiency as compared to xenon-fueled thruster performance. This has been attributed to a reduction in the propellant utilization fraction. Increasing the krypton propellant density has been shown to improve efficiency while introducing thermal issues. In the case of the NASA-457M, the differences between xenon and krypton discharge efficiencies at the same propellant number densities were not significant. An estimate of the propellant utilization fraction indicated efficient ionization of the krypton propellant.

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APPENDIX

Discharge Voltage	Discharge Current	Discharge Power	Anode Mass Flow Rate	Floating Voltage	Thrust	Discharge Specific Impule	Discharge Efficiency
Volts	Amps	Watts	mg/s	Volts	mN	seconds	
299.7	26.19	7849	19.5	-17.1	390	2039	0.50
300.8	30.95	9310	22.7	-17.4	461	2070	0.50
300.0	35.75	10725	25.9	-18.0	536	2111	0.52
300.2	40.57	12179	29.1	-18.6	603	2115	0.51
300.6	45.43	13656	32.3	-19.3	675	2131	0.52
300.5	50.32	15121	35.5	-19.9	741	2126	0.51
300.4	55.26	16600	38.8	-20.6	812	2135	0.51
300.3	60.28	18102	42.1	-21.2	884	2141	0.51
300.4	65.29	19613	45.4	-21.5	955	2146	0.51
300.8	70.56	21224	48.7	-21.3	1030	2158	0.51
300.1	75.80	22748	52.0	-22.6	1095	2148	0.51
300.6	81.33	24448	55.3	-23.0	1165	2147	0.50
300.7	88.05	26477	59.3	-24.1	1256	2160	0.50
299.6	94.76	28390	63.1	-25.2	1334	2155	0.50
300.6	100.67	30261	66.0	-25.8	1414	2183	0.50
400.2	26.96	10789	19.5	-16.2	462	2415	0.51
400.7	31.73	12714	22.7	-16.7	550	2471	0.52
400.3	36.58	14643	25.9	-17.4	643	2533	0.55
400.0	41.64	16656	29.1	-17.9	734	2574	0.56
400.1	46.69	18681	32.3	-18.4	814	2570	0.55
400.8	51.95	20822	35.5	-19.1	908	2605	0.56
400.3	57.23	22909	38.8	-20.0	1000	2627	0.56
400.5	62.65	25091	42.1	-20.1	1092	2646	0.56
400.5	68.16	27298	45.4	-21.5	1187	2669	0.57
400.3	73.45	29402	48.7	-21.3	1279	2679	0.57
400.6	79.09	31683	52.0	-22.3	1383	2713	0.58
400.5	84.82	33970	55.3	-23.2	1452	2676	0.56
400.4	91.60	36677	59.3	-24.1	1563	2687	0.56
400.2	98.25	39320	63.1	-25.3	1680	2713	0.57
400.5	103.73	41544	66.0	-26.1	1763	2721	0.57
500.8	27.29	13667	19.5	-15.5	531	2776	0.53
500.2	32.09	16051	22.7	-15.9	624	2806	0.54
501.4	37.00	18552	25.9	-16.4	730	2878	0.56
499.5	42.06	21009	29.1	-17.1	827	2901	0.56
500.2	47.18	23599	32.3	-17.7	929	2932	0.57
500.3	52.43	26231	35.5	-18.8	1030	2953	0.57
500.4	57.79	28918	38.8	-19.3	1143	3002	0.58
500.8	63.33	31716	42.1	-19.7	1253	3035	0.59
500.3	68.81	34426	45.4	-19.5	1355	3045	0.59
500.5	74.32	37197	48.7	-20.9	1462	3062	0.59
500.6	80.10	40098	52.0	-21.3	1571	3081	0.59
500.6	85.98	43042	55.3	-22.2	1683	3102	0.59
500.3	93.02	46538	59.3	-22.9	1811	3113	0.59
500.5	99.93	50015	63.1	-24.3	1935	3125	0.59
500.3	105.79	52927	66.0	-25.0	2047	3160	0.60

Discharge Voltage	Discharge Current	Discharge Power	Anode Mass Flow Rate	Floating Voltage	Thrust	Discharge Specific Impule	Discharge Efficiency
Volts	Amps	Watts	mg/s	Volts	mN	seconds	
600.3	27.62	16580	19.5	-15.0	600	3136	0.56
600.5	34.95	20987	22.7	-15.4	766	3441	0.62
600.6	38.32	23015	25.9	-15.5	838	3303	0.59
600.1	43.36	26020	29.1	-16.4	940	3296	0.58
600.3	47.60	28574	32.3	-17.1	1059	3344	0.61
600.4	52.48	31509	35.5	-17.4	1179	3381	0.62
600.5	57.80	34709	38.8	-17.8	1285	3375	0.61
600.2	64.71	38839	42.1	-18.0	1417	3434	0.61
600.7	70.72	42482	45.4	-18.6	1537	3455	0.61
600.8	76.23	45799	48.7	-19.1	1657	3472	0.62
600.1	81.60	48968	52.0	-19.7	1780	3491	0.62
599.9	87.24	52335	55.3	-20.2	1904	3509	0.63
600.4	96.21	57764	59.3	-21.6	2068	3555	0.62
600.1	103.22	61942	63.1	-22.5	2212	3574	0.63
600.2	110.90	66562	66.0	-23.9	2342	3615	0.62
650.0	28.19	18324	19.5	-14.7	622	3252	0.54
650.0	34.06	22139	22.7	-14.6	742	3334	0.55
650.3	39.58	25739	25.9	-14.9	866	3411	0.56
650.5	45.12	29351	29.1	-15.4	996	3491	0.58
650.4	50.56	32884	32.3	-16.0	1125	3551	0.60
650.0	55.93	36355	35.5	-16.6	1255	3601	0.61
650.1	60.84	39552	38.8	-17.3	1379	3623	0.62
650.1	65.62	42660	42.1	-17.9	1500	3636	0.63
650.7	71.12	46278	45.4	-17.8	1623	3648	0.63
650.6	76.87	50012	48.7	-19.0	1756	3679	0.63
650.4	82.86	53892	52.0	-20.0	1882	3690	0.63
650.6	89.09	57962	55.3	-20.7	2012	3708	0.63
650.3	97.33	63294	59.3	-21.6	2182	3751	0.63
650.5	105.24	68459	63.1	-23.0	2345	3787	0.64
650.2	111.55	72530	66.0	-23.8	2473	3817	0.64
700.5	29.47	20644	19.5	-13.6	666	3480	0.55
699.6	34.89	24409	22.7	-13.9	782	3514	0.55
700.0	40.33	28231	25.9	-14.4	892	3516	0.55
700.0	45.43	31801	29.1	-15.1	1018	3570	0.56
699.6	50.65	35435	32.3	-15.6	1149	3625	0.58
700.7	55.88	39155	35.5	-16.2	1278	3664	0.59
700.8	61.19	42882	38.8	-16.9	1406	3696	0.59
700.5	66.62	46667	42.1	-17.7	1538	3726	0.60
700.4	71.90	50359	45.4	-18.1	1669	3751	0.61
700.4	76.80	53791	48.7	-18.6	1798	3766	0.62
700.5	85.06	59585	52.0	-21.0	1883	3693	0.57
701.7	94.78	66507	55.3	-22.1	2080	3834	0.59

Discharge Voltage	Discharge Current	Discharge Power	Anode Mass Flow Rate	Floating Voltage	Thrust	Discharge Specific Impule	Discharge Efficiency
Volts	Amps	Watts	mg/s	Volts	mN	seconds	
800.6	29.80	23858	19.5	-12.9	668	3489	0.48
800.1	34.98	27987	22.7	-13.3	810	3639	0.52
800.3	40.28	32236	25.9	-13.8	955	3761	0.55
800.2	45.70	36569	29.1	-14.5	1107	3882	0.58
800.2	51.00	40810	32.3	-15.6	1252	3950	0.59
800.8	55.26	44252	35.5	-14.6	1385	3973	0.61
800.1	60.72	48582	38.8	-14.9	1507	3960	0.60
799.7	69.65	55699	42.1	-14.6	1697	4113	0.61
900.3	30.14	27135	19.5	-12.9	734	3838	0.51
900.1	34.55	31098	22.7	-13.7	882	3962	0.55
900.8	39.22	35329	25.9	-14.4	1037	4086	0.59
900.5	44.97	40495	29.1	-13.5	1176	4122	0.59
900.3	54.96	49480	32.3	-14.6	1392	4392	0.61
900.8	60.87	54832	35.5	-14.7	1543	4425	0.61
900.7	66.08	59518	38.8	-14.0	1684	4424	0.61
1001.4	29.44	29481	19.5	-12.2	796	4159	0.55
1000.0	34.20	34200	22.7	-12.6	944	4244	0.57
1000.5	39.55	39570	25.9	-13.1	1111	4377	0.60
1000.8	44.54	44576	29.1	-13.4	1263	4428	0.62
1000.6	50.16	50190	32.3	-13.8	1424	4495	0.63

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13. ABSTRACT ***(Maximum 200 words)***

The performance of a 50-kilowatt-class Hall thruster designed for operation on xenon propellant was measured using kryton propellant. The thruster was operated at discharge power levels ranging from 6.4 to 72.5 kilowatts. The device produced thrust ranging from 0.3 to 2.5 newtons. The thruster was operated at discharge voltages between 250 and 1000 volts. At the highest anode mass flow rate and discharge voltage and assuming a 100 percent singly charged condition, the discharge specific impulse approached the theoretical value. Discharge specific impulse of 4500 seconds was demonstrated at a discharge voltage of 1000 volts. The peak discharge efficiency was 64 percent at 650 volts.

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