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The use of krypton as an alternative to xenon for Hall thruster propellant is an interesting option for satellite system designers due to its lower cost. However, this cost-savings comes at the expense of thrust efficiency. Reduction in efficiency can be caused by energy losses from Joule heating, radiation, and the ionization process as well as degradation of plume quality from an increase in velocity distribution spread (most often from an increase in multiply charged ion populations) and geometric beam divergence.[1] In order to quantify this performance reduction for the case of the flight model SPT-100 HET (1.35 kW), an ongoing series of experimental measurements is being conducted to measure how various thruster efficiency terms change with propellant and operating condition. This study will combine thrust measurements with plume data from electrostatic probes. This paper presents the results of performance measurements made using an inverted pendulum thrust stand. Krypton operating conditions were tested over a large range of operating powers from 800 W to 3.9 kW. Analysis of how performance is impacted by propellant and operating condition is presented. A simple mission analysis was done based on these measurements to evaluate the practicality of krypton propellant for an SPT-100 subsystem using krypton propellant for north-south station keeping (NSSK) for a typical communications spacecraft in geosynchronous orbit..

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A Performance Comparison of Xenon and Krypton Propellant on an SPT-100 Hall Thruster

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The use of krypton as an alternative to xenon for Hall thruster propellant is an interesting option for satellite system designers due to its lower cost. However, this cost-savings comes at the expense of thrust efficiency. Reduction in efficiency can be caused by energy losses from Joule heating, radiation, and the ionization process as well as degradation of plume quality from an increase in velocity distribution spread (most often from an increase in multiply charged ion populations) and geometric beam divergence.[1] In order to quantify this performance reduction for the case of the flight model SPT-100 HET (1.35 kW), an ongoing series of experimental measurements is being conducted to measure how various thruster efficiency terms change with propellant and operating condition. This study will combine thrust measurements with plume data from electrostatic probes. This paper presents the results of performance measurements made using an inverted pendulum thrust stand. Krypton operating conditions were tested over a large range of operating powers from 800 W to 3.9 kW. Analysis of how performance is impacted by propellant and operating condition is presented. A simple mission analysis was done based on these measurements to evaluate the practicality of krypton propellant for an SPT-100 subsystem using krypton propellant for north-south station keeping (NSSK) for a typical communications spacecraft in geosynchronous orbit.

Nomenclature

θ	thruster cant angle
ΔV	velocity change for a spacecraft
I_{sp}	specific impulse
g_e	gravitational constant
m	atomic mass
$\dot{m}_a$	anode propellant mass flow rate
$\dot{m}_i$	ionized propellant mass flow rate
M_0	initial spacecraft mass
M_P	propellant mass for a spacecraft

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q particle charge
V_a ion acceleration voltage
V_d anode discharge voltage

Introduction

Due to a number of engineering reasons, xenon is the propellant of choice for Hall effect thrusters. These include its high mass (131 amu) and its relatively low ionization potential (12.1 eV). Furthermore, the inert nature of xenon eliminates the safety concerns that plagued early electrostatic propulsion efforts when mercury and cesium were the propellants of choice. Although xenon is a noble gas, it is the most massive, and due to its non-ideal gas behavior, it is possible to pressurize and store at specific densities that exceeded unity. As such, it can be stored at higher densities than the common liquid monopropellant hydrazine.[2]

While xenon will likely remain the ideal propellant for electrostatic electric propulsion thrusters, there are several concerns that have driven the Hall effect thruster community to explore alternative propellants. As orbit raising missions of longer duration and larger payloads are proposed for Hall effect thrusters, the mass of required propellant increases. Xenon production is a byproduct of the fractional distillation of atmospheric gases for use primarily by the steel industry. Due to the low concentration of xenon in the atmosphere (87 ppb), worldwide production appears to be limited to approximately 6,000 m^3 per year. Increasing industrial demand for items such as high efficiency lighting and windows has produced wide price swings in the past decade. Xenon prices have varied by as much as a factor of ten.

For high thrust to power missions, bismuth has been demonstrated as a viable alternative Hall effect thruster propellant. Bismuth, with its high atomic mass (209 amu) and low ionization potential (7.3 eV) appears to have advantages for missions where high thrust at reduced specific impulse is advantageous, primarily for orbit raising missions. Bismuth's main drawback is that the metal must be vaporized to be ionized and accelerated within a Hall effect thruster. The requirement for high temperatures (boiling point of 1,837 K) require special engineering considerations compared to the relatively simple gas distribution systems used for xenon. In addition, the use of vapor as a propellant has tended to cause concern for spacecraft operators despite the assurances of thruster developers. The risk of metal redeposition from the propellant on solar arrays and sensitive instruments is a large concern that will strongly limit bismuth's appeal to spacecraft designers.

For missions that can benefit from higher specific impulse, krypton may have some benefits. Krypton has a lower atomic mass (83.8 amu) and a higher ionization potential (14.0 eV) than xenon. However like xenon, krypton is a noble gas and could be easily integrated into existing xenon propellant management systems without much modification. The small difference in ionization potential is unlikely to dramatically affect the efficiency of a Hall effect thruster, and the lower mass would produce a 25% increase in specific impulse assuming there were no offsetting losses. The increase in specific impulse would be useful for missions such as GEO communications satellite north-south station keeping. For missions such as orbit raising, increasing the specific impulse will increase trip time due to power limitations. However as solar electric power system specific power decreases, increasing the specific impulse of the propulsion system is advantageous.

Krypton is approximately 10 times more common in the atmosphere (and hence in production) than xenon, and when accounting for mass is approximately 6 times less expensive. One disadvantage for krypton is that its tankage fraction appears to be substantially higher than that of xenon due to reduced van der Waals interactions. As such, compressed gas tankage fractions could be as high as 37%. At least one study has examined this issue and has identified space rated cryo-coolers that could liquefy krypton (120 K boiling point), or for that matter xenon (165 K boiling point), and reduce tankage fractions to less than 2%.[2]

Experimental studies have often shown thrust efficiency with krypton propellant to be inferior to that of xenon.[3,4,5] However, for a 50 kW HET similar thrust efficiency was attained with krypton propellant.[6] Russian studies[4,7,8] have investigated using a mixture of krypton and xenon propellant for SPT thrusters to achieve a performance compromise at a cost cheaper than either pure xenon or pure krypton. This mixture of xenon and krypton is a byproduct of liquid oxygen manufacturing and costs 15 times less than pure xenon and 2-3 times less than pure krypton.[7] Its use has shown promising results on the SPT-100 and SPT-140 thrusters.

The goal of this ongoing study is to characterize the differences between xenon and krypton performance and plume characteristics for a Hall effect thruster with extensive flight heritage. The SPT-100 thruster was chosen for this study because it is among the most well-established Hall effect thrusters in the space propulsion industry. SPT design heritage dates back to the 1960s and 70s in the former U.S.S.R. After the break up of the Soviet Union, the Ballistic Missile Defense Organization (BMDO) lead efforts to transfer SPT technology to the United States so that western spacecraft could benefit from their attractive combination of thrust and efficiency.[9] The SPT-100 thruster, designed and built by Fakel, was extensively tested for lifetime[9] and performance[9,10] by NASA in the early 1990's. In 1991, Space Systems/Loral (SS/L) partnered with Fakel to flight qualify the SPT-100 and a corresponding power processing unit (PPU) for U.S. flight standards. To date, SS/L has launched seven spacecraft with SPT-100 propulsion subsystems and has eleven more spacecraft under construction. This SPT subsystem now has more than thirteen years of cumulative on-orbit experience with a single thruster accumulating over 6 years of near-daily operation.[11]

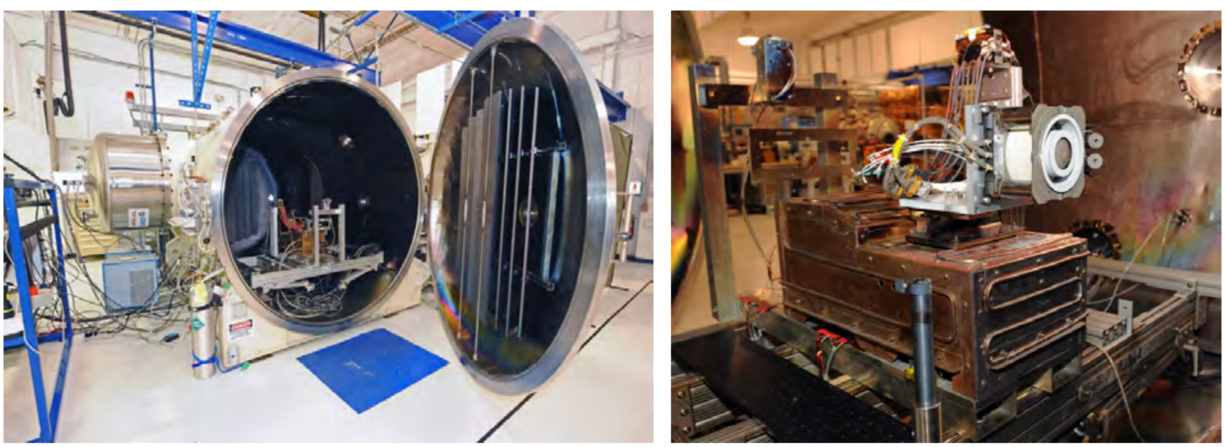
This paper will present the results from the thruster performance testing phase of the current study. Probe measurements are scheduled to be taken in the future. Although the design of the SPT-100 is optimized for xenon, this exploratory investigation should provide some insight into the possibilities of using krypton as a propellant in Hall effect thrusters, primarily due to its low cost and possible application as a low-development overhead replacement for existing xenon Hall effect thruster systems.

Experimental Apparatus and Techniques

Test Facility

The tests performed in this study utilized Chamber 1 at the Air Force Research Laboratory at Edwards Air Force Base. Chamber 1 is a cylindrical non-magnetic stainless steel vacuum chamber 2.4 m in diameter and 4.1 m in length. Pumping is provided by two liquid nitrogen baffled (70 K), 1.2 m flanged gaseous helium two stage cryogenic (15 K) vacuum pumps. Chamber pressure is monitored with a cold cathode gauge. Background pressure for nominal thruster operation was measured to be 1.1×10^{-5} Torr for xenon (at 56.4 sccm propellant flow rate) and 1.0×10^{-5} Torr for krypton (at 65.4 sccm propellant flow rate) with gas correction factors applied.

The interior of the chamber is covered with nuclear grade, low sulfur, flexible graphite 1.8 mm in thickness. Both chamber ends contain louvered beam dumps manufactured in-house using 13 mm thick, 15 cm wide graphite panels to reduce redeposition of sputtered materials on the thruster during extended firings. The chamber floor is protected using a carbon-carbon woven blanket that allows for ease of placement and removal.



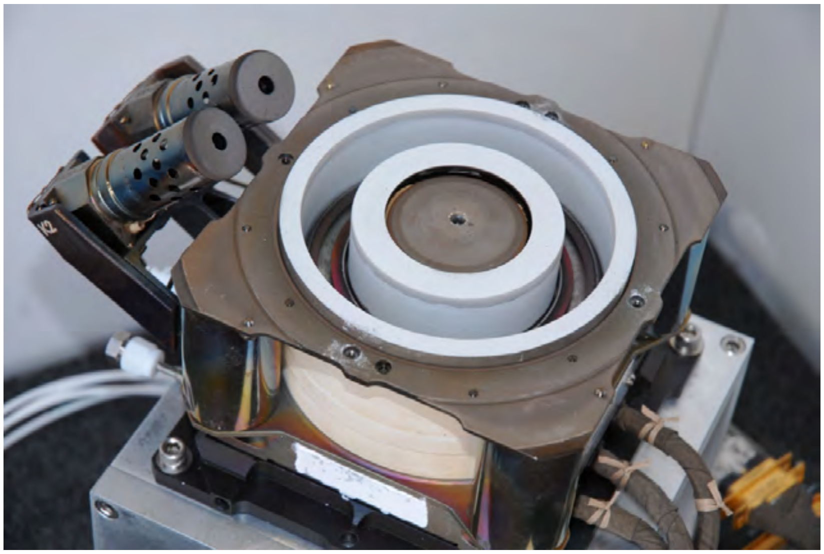
(a) Chamber 1 test facility.

(b) The null-type inverted pendulum thrust stand used for performance measurements.

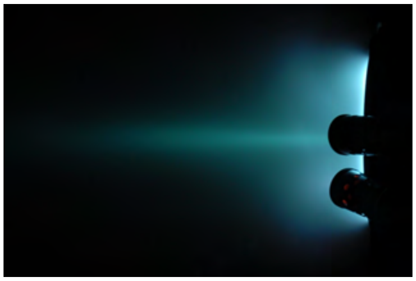
Figure 1. Hall thruster testing facilities at the Air Force Research Laboratory at Edwards Air Force Base.

Hall Effect Thruster

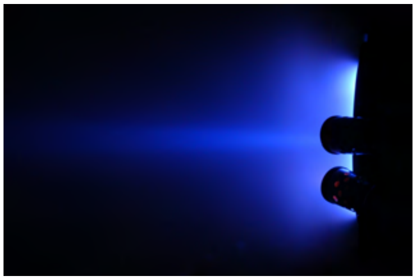
A flight model SPT-100 Hall effect thruster was used in this study. The axisymmetric thruster is equipped with two lanthanum hexaboride (LaB_6) cathodes (only one was used during these tests). Photographs of the thruster are shown in Fig. 2. This thruster has a conventional five magnetic core (one inner, four outer) magnetic circuit. Discharge current is routed through the magnetic circuit and thus no extra power source for the magnets is required. The acceleration channel of the thruster has a 100 mm outer diameter, a 50 mm inner diameter, and an acceleration length of 21 mm. The thruster has been characterized to have a thrust of 83 mN with a specific impulse of 1,600 s, yielding an anode efficiency near 50%.[9] The thruster and cathode were powered with commercial off-the-shelf Sorenson power supplies instead of the PPU used on-orbit. A computer data acquisition system recorded the potential and current outputs of the power supplies used in the thruster operation at a rate of 2 Hz during this study. For propellant flow, digital mass flow controllers from Aera dispersed gas to the anode and cathode taking the place of the xenon flow control system (XFC) used on-orbit.



(a) SPT-100 Hall effect thruster flight model.



(b) Thruster operating on xenon propellant.



(c) Thruster operating on krypton propellant.

Figure 2. Photographs of the SPT-100 Hall effect thruster used in this study.

Thrust Stand

The thrust stand used in these performance measurements was of the widely-used null-type, inverted pendulum design by Haag[12] at NASA Glenn Research Center. As force is applied to the inverted pendulum, translation is counteracted by an electromagnetic force generated by a feedback system using a PID controller. Displacement of the pendulum relative to a mirror is detected optically with a linear displacement gap transducer (LDGT) with a fiber optic sensor. When displacement is detected from a given zero point, current is flowed through a null coil to generate a restoring force applied to a concentrically mounted magnetic rod connected to the pendulum. This restoring force is linearly proportional to the voltage applied to null coil. A calibration curve correlating null coil voltage to restoring force is generated mechanically by loading and unloading weights of known value to the pendulum with a pulley system. The constant of the linear calibration curve is sensitive to the thermal changes of thrust stand and therefore thrust measurement values tend to drift as an operating thruster dissipates heat to the thrust stand. To prevent large temperature swings, chilled ethylene glycol was flowed through tubing on the thrust stand's copper shroud.

Testing Matrix and Methodology

Testing Matrix

The goal of this study was to test the performance of the SPT-100 operating on krypton gas over a large range of thruster power conditions through variations in both discharge potential and propellant flow rate and to test a smaller set of xenon cases for comparison. The krypton testing matrix for this study emphasized higher than nominal power (1.35 kW) cases. Studies of krypton propellant have documented that increased flow rate will improve the propellant utilization fraction.[13] A lower propellant utilization fraction is one of the major reasons krypton performance has been known to be inferior to that of xenon. A promising feature of krypton is that it can potentially have a higher specific impulse than xenon due to its lower atomic mass. Therefore, exploration of operating conditions at higher than nominal discharge potential was of interest (specific impulse is proportional to the square root of discharge voltage) to see if advantageous specific impulse could be realized in spite of krypton's inferior propellant utilization. It should be noted that for lower than nominal power krypton cases, anode ignition was more difficult and sometimes required ignition at nominal discharge voltage before dropping the discharge voltage to a lower value. Besides the expected low performance at low power, this ignition difficulty may render lower than nominal power conditions impractical for implementation on a flight PPU.

Exploratory runs of the thruster were conducted with both propellants to ascertain the mass flow rate value that produced the nominal 4.5 A discharge current for thruster operation. In order to mimic the XFC used for the on-orbit PPU subsystem, a 13:1 propellant split was maintained between the anode and the cathode for all operating conditions so that cathode flow rate accounted for approximately 7% of the total propellant usage. (In this study, performance parameters are calculated using the combined anode and cathode mass flow rates.) The nominal flow rates for this study were 5.54 mg/s for xenon and 4.09 mg/s for krypton. Off-nominal flow rate conditions were set relative to these values in the testing matrix.

It was noted that the nominal xenon flow rate for this study was a little higher than reported in other studies.[9,10] This discrepancy may be due to variation in calibration between the XFC used in these studies and the digital mass flow controllers used here. The mass flow controllers in this study were calibrated with a molbloc system from DH Instruments using xenon gas. The molbloc system measures pressure and temperature differences in laminar flow across a calibrated flow element to determine flow rate. These xenon calibrations for the mass flow controllers were assumed to also apply to krypton due to the fact the manufacturer's calibration conversion factors from the surrogate gas of argon to the actual operating gas are the same for xenon and krypton (due their similar thermal properties). For the krypton testing matrix, a total of 7 mass flow rates and 12 discharge current potentials were tested. Mass flow rates ranged from -20% to +40% of the nominal vaule. For discharge potential, values between -20% to +90% of nominal were tested. Parameters were varied in increments of 10% of their nominal values as ilustrated in Table 1. For xenon testing, mass flow rates and discharge potentials ranging from -30% to +30% relative to their nominal values were also tested in increments of 10% of their nominal value. However for xenon, combinations of off-nominal flow rates and off-nominal discharge voltages were not tested. From the large matrix of krypton cases, several conditions of interest will be selected for future plume characterization through electrostatic probes.

It should be noted that no magnetic field optimization was performed for any operating condition on this flight model thruster. The magnet current was purely determined by the operating condition discharge current. No additional current was added to the magnetic circuit via an extra power supply. The goal of this study was to explore of the possibility of using krypton as a low overhead replacement for xenon on a flight qualified thruster and PPU subsystem. Therefore, optimization of the magnetic field and thruster geometry was beyond the scope of these tests.

Table 1. Krypton operating condition test matrix. Table values are operating condition power (W).

Flow Rate ⇒ Dis. Potential ⇓	-20% (3.27 mg/s)	-10% (3.68 mg/s)	**Nominal** **(4.09 mg/s)**	+10% (4.50 mg/s)	+20% (4.90 mg/s)	+30% (5.31 mg/s)	+40% (5.72 mg/s)
-20% (242 V)	813	950	1083	1209	1339	1476	1606
-10% (272 V)	915	1069	1220	1363	1511	1671	1820
Nom. (302 V)	1015	1187	**1356**	1516	1681	1863	2033
+10% (332 V)	1121	1306	1491	1670	1852	2054	2258
+20% (363 V)	1242	1431	1628	1823	2023	2248	2468
+30% (393 V)	1356	1561	1769	1977	2208	2445	2675
+40% (423 V)	1468	1693	1913	2143	2376	2615	2878
+50% (453 V)	1567	1821	2061	2302	2547	2799	3078
+60% (483 V)	1662	1938	2213	2463	2720	2987	3276
+70% (513 V)	1751	2048	2347	2624	2895	3195	3481
+80% (544 V)	1857	2171	2480	2765	3063	3389	3690
+90% (574 V)	1960	2289	2605	2929	3245	3589	3913

Table 2. Xenon operating conditions tested. Table values are operating condition power (W). Note: Blank values represent untested conditions.

Flow Rate ⇒ Dis. Potential ⇓	-30% (3.88 mg/s)	-20% (4.44 mg/s)	-10% (4.99 mg/s)	**Nominal** **(5.54 mg/s)**	+10% (6.10 mg/s)	+20% (6.65 mg/s)	+30% (7.21 mg/s)
-30% (211 V)				945			
-20% (242 V)				1077			
-10% (272 V)				1213			
Nom. (302 V)	916	1061	1207	**1351**	1508	1666	1829
+10% (332 V)				1493			
+20% (363 V)				1638			
+30% (393 V)				1785			

Testing Methodology

Before and after each series of thrust measurements, an in situ calibration of the thrust stand was performed using its mechanical weight loading system to produce a calibration curve. After the initial thrust stand calibration, the thruster was turned on at its nominal operating condition. As the thruster warmed up, its anode current would rise during the first minute of operation and then gradually fall to the nominal 4.50 A value over the course of about half an hour. When the discharge current stabilized at its nominal value, the thruster was considered to be warmed up. For off-nominal flow rate tests, an extra warm up period was given where the propellant flow rate was adjusted to its new value and then the thruster was run until its discharge current stabilized (typically 15 minutes or less).

After thruster warm up was complete, an updated linear thrust stand calibration constant was determined by turning off the anode discharge (both voltage and mass flow) for about 1 minute so that the null coil voltage could be recorded. The cathode discharge was maintained during this period by applying potential to the igniter. The anode discharge was then reignited with the desired operating conditions for testing. The operating condition for testing was run for 15 minutes. Then the anode discharge was turned off again to find the new calibration constant. This process was repeated for a series of measurements. The slope of the calibration curve was found to be stable to three digits of precision even after several hours thruster operation. For operating conditions in the krypton test matrix, conditions with the same mass flow rate were typically tested consecutively.

During post test data analysis, the thermal drift rate of the calibration constant for each test condition was linearly approximated using its values before and after the test and the time between its measurements. Thrust data was sampled from the end of the testing time period for a duration where the thermal drift was estimated to be no more than 0.1 mN in most cases. However, sampling duration was constrained to be between 1 and 5 minutes.

Results and Discussion

Performance Data

The results of the performance measurements are presented in Figs. 3 and 4. Figure 3(b) shows that anode current was very stable (less than 2% variation) at any given mass flow rate condition throughout the range of discharge potential tested. Thrust measurements were found to be very repeatable throughout most of the testing (to within better than ±0.5 mN in most cases). However, a small data continuity issue arose toward the end of the krypton matrix testing. Thrust measurement values became slightly higher compared to data points taken earlier by about 2% and thus appeared slightly discontinous compared to the exisiting performance data. Unfortunately, the reason for this discrepancy was never determined. Performance variation was seen in other reported tests,[9] but this was over the course of several thousand hours during a life test. Measurements affected by this issue were at the +30% propellant flow rate condition (discharge potentials: 390, 510-570 V) and the +40% propellant flow rate conditions (discharge potentials: 330-570 V). Despite this minor discrepancy issue, the trends of the krypton performance data are still apparent.

Thrust values are plotted as a function of discharge potential in fig. 3(c) and thruster power in fig. 3(d). At the nominal operating condition, the thrust value for krypton (62.9 mN) was lower than that of xenon (82.1 mN) by 23%. Thrust was seen to increase in an approximately linear manner with increasing discharge voltage. In the case of krypton, there was a noticable point of diminished gains around 510 or 540 V. Thrust also increased in a linear manner for increasing propellant flow rate throughout the range of flow rates test.

Specific impulse data for the tested cases are presented in Figs. 3(e), 3(f), and 4(b). One of the main physical reasons that krypton is an interesting alternative propellant choice for low-thrust missions is for its potentially greater specific impulse due it its lower atomic mass relative to xenon. However, this potential gain in specific impulse was not realized in the case of the SPT-100 flight model thruster. At nominal conditions, krypton specific impulse was measured at 1568 s, which was virtually no improvement over the 1511 s measured for xenon. The ideal anode specific impulse for a given anode voltage can be calculated as

$$I_{\mathrm{sp}} = \frac{1}{g_e}\sqrt{2\frac{q}{m}V_a} \tag{1}$$

when all of the propellant is assumed to be completely converted into singly charged ions that are accelerated through the entire anode potential. Ideally, krypton would have a 25% greater specific impulse than xenon. Figure 4(b) shows a comparison of the measured anode specific impulse to the ideal value. (Note that the anode specific impulse calculation uses only the anode mass flow rate instead of the total flow rate.) Nominal flow rate krypton cases were found to have an almost constant 1000 s gap between their actual anode specific impulse and the ideal value across the range of tested anode potential. This translated into a 37% deficiency at the nominal 302 V condition. Xenon propellant cases were found to have an approximately 520 s difference between their actual value and their ideal values. The performance gap at 302 V was 24% for xenon. The reason for the lower realization of ideal specific impulse for krypton compared to xenon was likely its inferior propellant utilization fraction ($\dot{m}_i/\dot{m}_a$). Non-ionized propellant decreases the bulk velocity of the plume and thus lowers specific impulse. Due to the faster neutral velocity and lower ionization cross section of krypton, a higher specific mass flow rate ($\dot{m}_a$/m) is needed for effective propellant ionization than for xenon for a given channel length and cross section.[14] However, only small improvements were made in specific for impulse for krypton as mass flow was increased above the nominal value.

Thrust efficiency (calculated with the combined anode and cathode flow rate) is plotted in Figs. 4(c) and 4(d). For the nominal operating condition, the efficiency value was 44% for xenon and 36% for krypton. For krypton, efficiency was observed to rise with anode potential until a peak value around 510 to 540 V and then decrease at the highest potentials. To acheive a similar efficiency for krypton, higher thruster operating power is required. For the nominal flow rate, an anode potential of 453 V would be necessary, resulting in a 700 W operating power increase. Increasing propellant flow rate improved efficiency, most noticeably for low flow rate conditions, which can be explained by better propellant ionization.

In studies of a laboratory model SPT-100 operating on krypton by Kim,[4] current to the magnetic coils was adjusted to minimize anode current. Anode efficiency data were presented at an anode flow rate of 5 mg/s, which was a similar flow rate to the +30% flow rate setting of the present study where anode flow rate was 4.93 mg/s. Comparison of the present study (Fig. 4(e)) to Kim's data enabled the effects of magnetic field optimization to be observed. In Kim's data, anode efficiency was about 4% greater for anode potentials less than 400 V. However, anode efficiency for both data sets matched well for anode potentials of

400 V and higher, which may indicate the presence of an ideal magnetic field for these high anode potential conditons for the flight model SPT-100. Kim also tested a thruster configuration that used an additional magnetic coil to dramatically change the magnetic field topography of the thruster. This alteration was seen to signficantly improve anode efficiency for krypton. For one operating condition, the anode efficiency of krypton was improved by about 6%. Surprisingly, there was signficant disagreement in anode efficiency data for xenon between these two studies. The lack of magnetic field optimization may be why values in the present study were lower.

Krypton Mission Example

A simplified example mission was studied to evaluate the possibility of using krypton propellant for the flight model SPT-100 on a spacecraft based on the performance measurements in this study. This example mission was intended to replicate the general requirements of a propulsion system for north-south station keeping on a communications satellite in geosynchronous orbit. In this example, the spacecraft would have the following characteristics and requirements:

- Initial spacecraft mass: 3760 kg
- Mission lifetime: 15 years
- Thruster cant angle: 40 ° (directional cosine loss)
- Quantity of SPT-100 thrusters: 2
- Delta-V required: (51 m/s/year)×15 years = 765 m/s

The propellant mass required for this mission can be calculated from the basic rocket equation as:

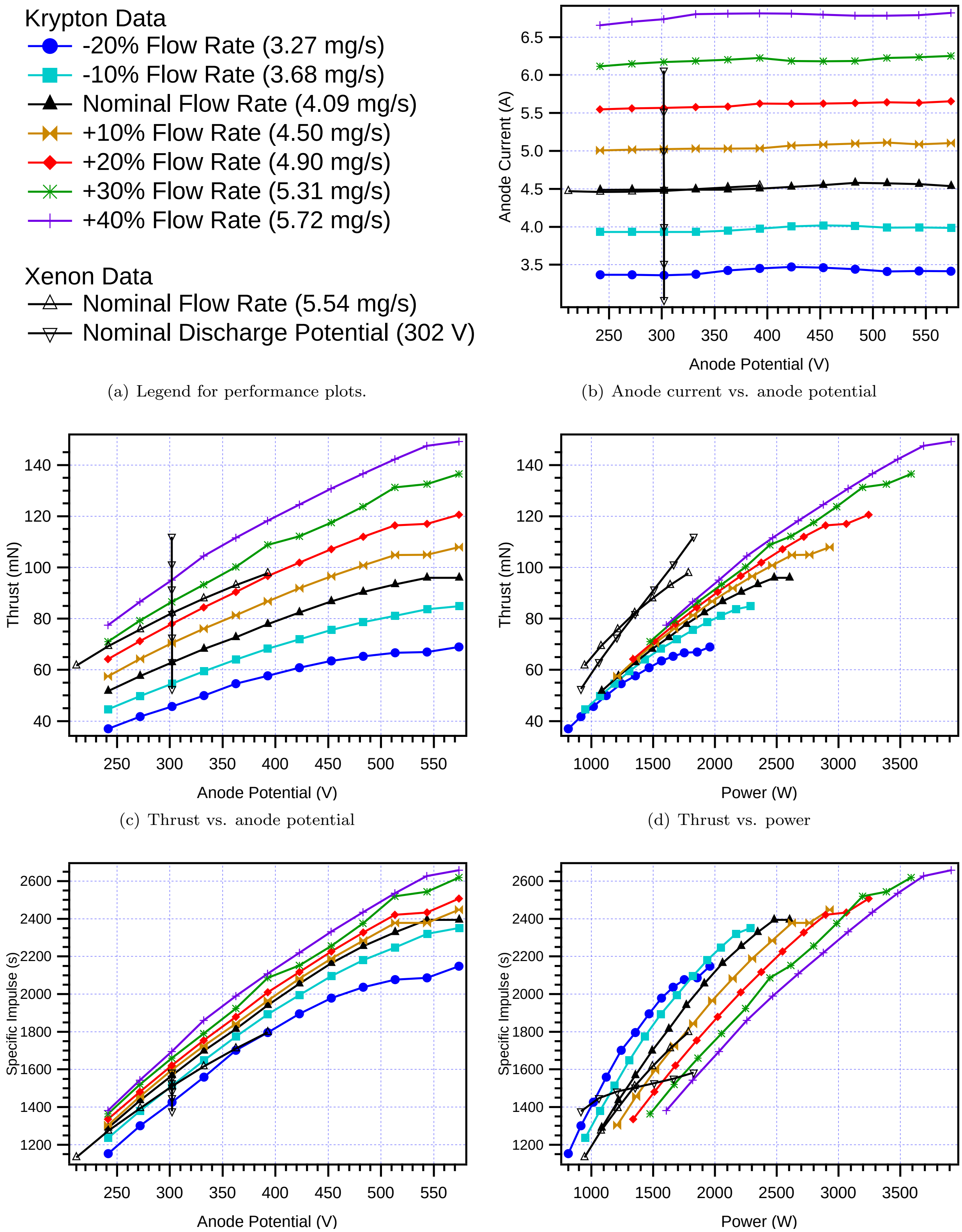
$$M_p = M_0 - M_0 \exp\left(\frac{-\Delta V}{g_e I_{\text{sp}} \cos\theta}\right) \tag{2}$$

The resulting propellant mass for the mission is divided between the two thrusters. The number of required operational hours for each thruster is determined by dividing the propellant mass for each thruster by the propellant flow rate for its operating condition. The results of this analysis are plotted in Fig. 5.

In Fig. 5. propellant mass per thruster is plotted versus the required operational time per thruster for the matrix of krypton operating conditions tested. Operating condition data points fall along lines of propellant flow rate. Linear interpolation was used to create contours for the operational power required per thruster for krypton propellant. As propellant mass and operational time requirements decrease, the power requirement increases. The tested xenon operating conditions are also displayed for reference.

A mission using xenon at the nominal operating condition (1356 W) would require 6.1 years of operational time per thruster and 120 kg of propellant per thruster. This condition is marked for reference on the plot. The data for xenon operating with the nominal discharge potential as propellant flow rate varies is marked with a red line. This forms a boundary for operating conditions that would have a propellant mass savings relative to xenon operating at its nominal discharge voltage. Tests have validated the SPT-100 life time as exceeding 2.71 million N-s (equivalent to approximately 9000 hours of operational time) for xenon at the nominal condition.[15,11] This boundary is also marked in red for reference. Some krypton operating conditions within these boundaries may be feasible for completing this mission. Although it should be noted that most of these krypton cases require a significantly higher power throughput than the life tested nominal xenon condition and thus may limit the lifetime of the thruster to values lower than the validated xenon figure. Thruster erosion rates with krypton are unknown so life testing would be required to determine reasonable operational times.

One krypton operating condition that may be appropriate is the 390 V, nominal flow rate setting. Using this setting, 54 kg of total propellant mass could be saved relative to the nominal xenon operating condition. However, 400 W of extra power per thruster and an extra 400 hours of firing time for each thruster would be required. It should be noted that off-nominal condition xenon cases could be chosen for fuel savings and they would offer better overall performance than the krypton operating conditions studied. As seen in the performance data, the krypton operating conditions did not offer significantly better specific impulse than xenon so choosing krypton propellant for potential mass savings may not be a good idea. Also, krypton propellant has a higher tankage fraction and may require larger or more massive tanks for storage. The potential benefit krypton propellant could offer would be its cheaper price.



(a) Legend for performance plots.

(b) Anode current vs. anode potential

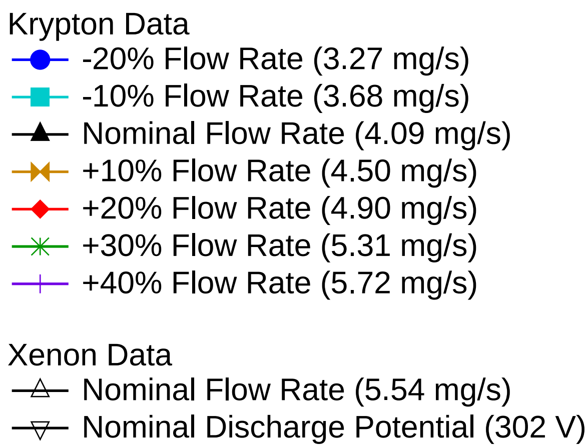
(c) Thrust vs. anode potential

(d) Thrust vs. power

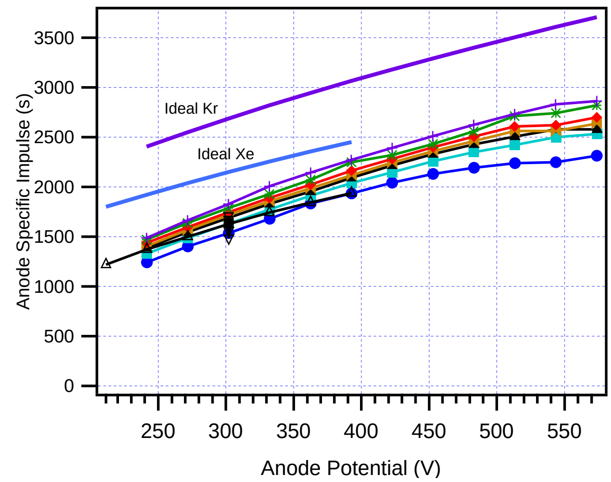
(e) Specific impulse vs. anode potential

(f) Specific impulse vs. power

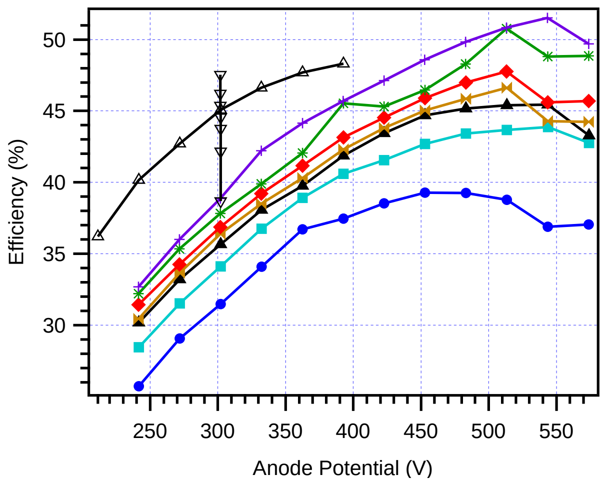
Figure 3. Thruster performance data.



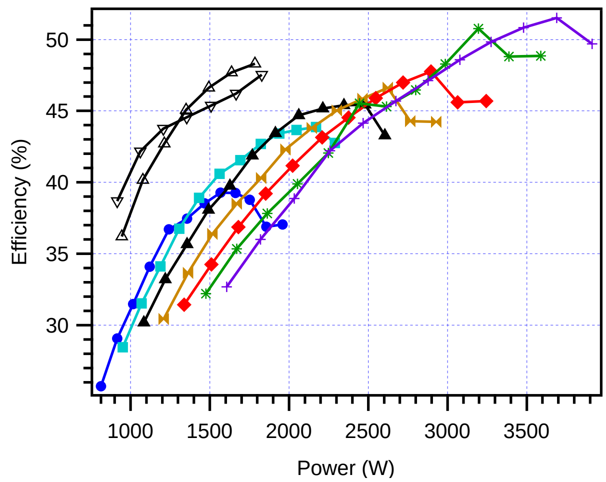
(a) Legend for performance plots.



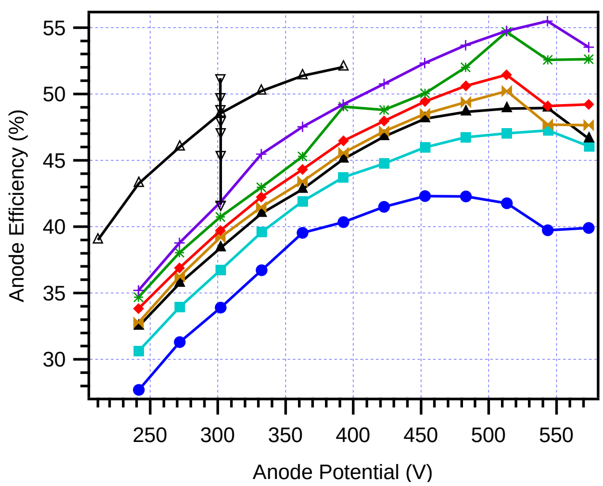
(b) Anode specific impulse vs. anode potential. Ideal values are shown for reference. (Note: Anode specific impulse calculation does not include cathode flow.)



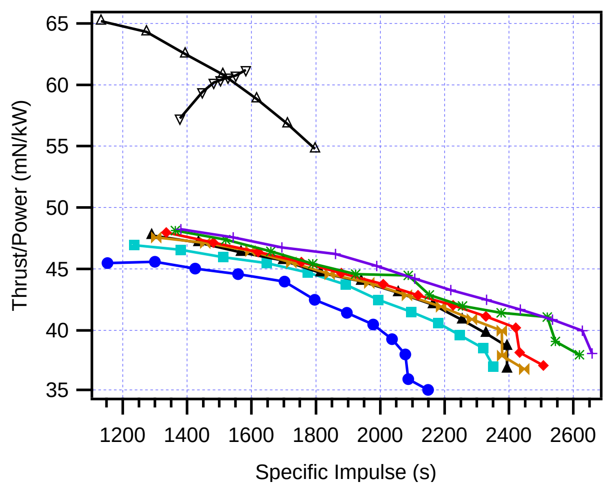
(c) Thrust efficiency vs. anode potential



(d) Thrust efficiency vs. power



(e) Anode efficiency vs. anode potential (Note: Anode specific impulse calculation does not include cathode flow.)



(f) Thrust to power ratio vs. specific impulse

Figure 4. Thruster performance data continued.

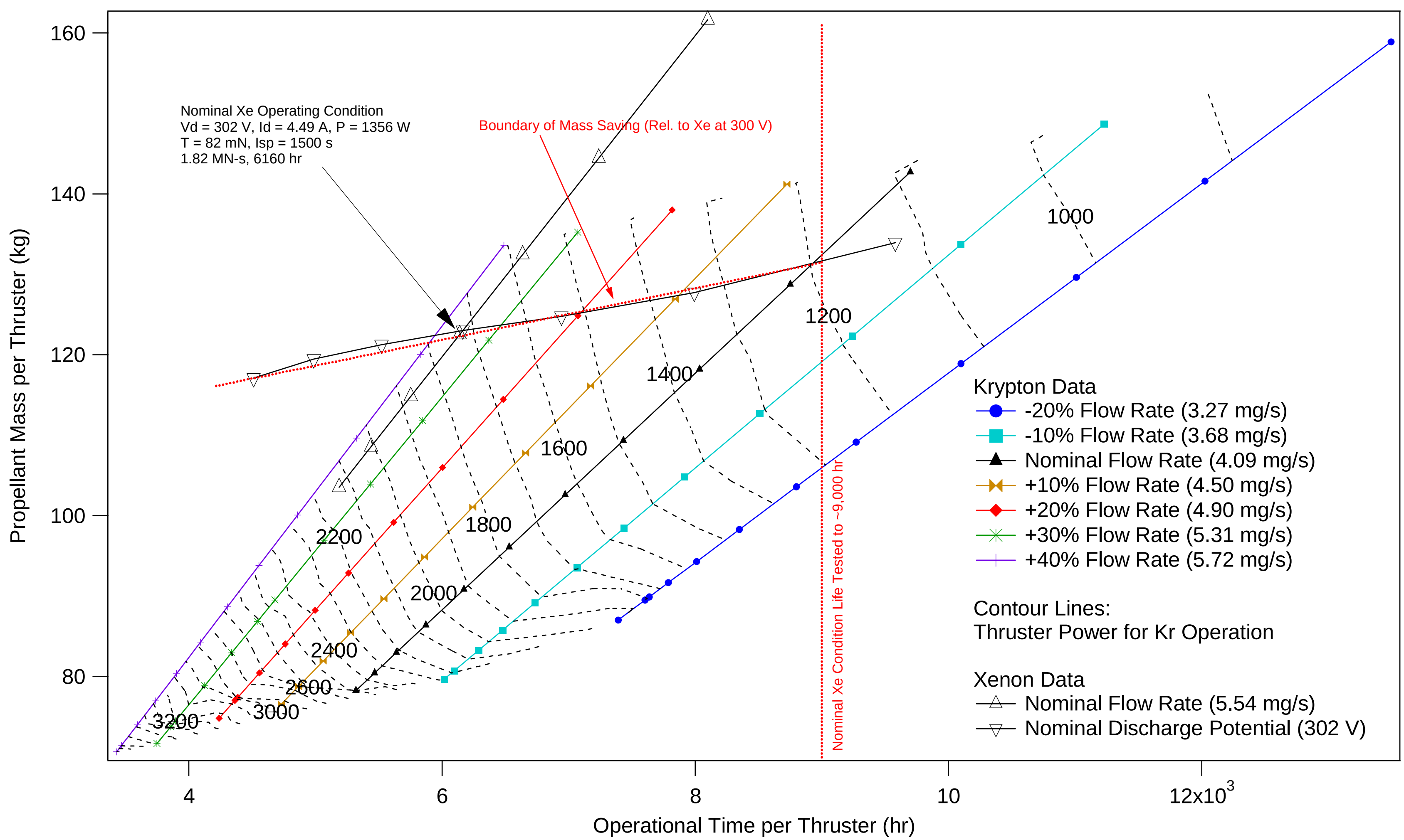


Figure 5. Simplified mission analysis for an SPT-100 propulsion subsystem with two thrusters operating on krypton propellant for north-south station keeping. In this example, the spacecraft has an initial mass of 3760 kg and a lifetime delta-V requirement of 765 m/s.

Conclusions

A large range of krypton operating conditions spanning a power range of 800 W to 3.9 kW were tested for performance for the flight model SPT-100. Thruster performance was significantly lower compared to operation on xenon propellant. Specific impulse for krypton operation was not substantially higher than that of xenon, which does not make krypton a practical choice for propellant mass savings. The disparity of krypton's performance is largely due to its lower propellant utilization fraction, which is not surprising because the acceleration channel geometry design was optimized for xenon. Thruster efficiency on krypton was about 8% lower than for xenon at the nominal operating condition, but it is possible to increase krypton thruster efficiency to levels around 50% using higher power operating conditions. However, the higher operating power required to improve the performance may lead to a shorter life time. If krypton is to be seriously considered for on-orbit use, erosion studies and life testing would be required to validate the thruster's ability to meet mission duration specifications. If xenon prices increase dramatically in the future, krypton may still be a feasible fuel alternative for the SPT-100. Despite reduced performance, krypton still may be able to fufill station keeping requirements for certain missions. The thruster performance also has the potential to be improved for krypton though design modificatons as Kim[4] has demonstrated using an altered magnetic field configuration for the SPT-100 laboratory model.

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