Mission Cost for Gridded Ion Engines using Alternative Propellants

IEPC-2019-831

Presented at the 36th International Electric Propulsion Conference
University of Vienna, Austria
September 15-20, 2019

Nazareno Fazio*, Steve B. Gabriel† and Igor O. Golosnoy‡
University of Southampton, Southampton, SO17 1BJ, United Kingdom

and

Birk Wollenhaupt§
OHB-System AG, Bremen, Germany

Abstract: Xenon is the preferred propellant for electric propulsion thrusters, providing high thruster efficiency and long life. However, xenon is very expensive and has limited availability, which could impose serious constraints on the use of electric propulsion in some future missions. This report investigates the effect on mission cost of operating a gridded ion engine on either xenon, krypton or a 1:4 Xe/Kr mixture. Calculations of payload fraction, propellant mass, thrusting time, propellant cost, and propellant-related mission cost have been performed over a range of mission Δvs (1-5 km/s) using two different approaches: fixing the thrust, which leads to increase required power over xenon, and fixing the power available for the electric propulsion system, which leads to loss in thrust. The former approach results in significant improvements for propellant cost, but either no substantial advantages can be obtained on the overall mission cost or the cost reduction can be achieved only at higher velocity increments, which are not relevant for typical mission Δvs. The latter approach produces a relatively small (within 10% over xenon) cost reduction but at a cost of increased thrusting times. If the "New Space" approach (mega constellations) is considered, which implies a sensible reduction in the hardware cost, the outcome of the analysis is completely different and alternative propellants become advantageous over xenon for the considered Δv range (1-5 km/s).

Nomenclature

$cost_p$	= propellant cost [£]
$cost_{mission}$	= mission cost [£]
$cost_{power}$	= power generation cost [£]
$cost_{tank}$	= tankage system cost [£]
EPS	= Electric Propulsion System
g_0	= gravity acceleration [= 9.1 m/s^2]
GIE	= Gridded Ion Engine
GIESEPP	= Gridded Ion Engine Standardised Electric Propulsion Platform
HET	= Hall Effect Thruster
Isp	= specific impulse [s]

*PhD Student, ECS, n.fazio@soton.ac.uk
†Professor, ECS, sbg2@soton.ac.uk
‡Associate Professor, ECS, I.Golosnoy@soton.ac.uk
§Propulsion System Engineer, birk.wollenhaupt@ohb.de

$\dot{m}$	=	propellant mass flow rate [mg/s]
m_0	=	overall spacecraft mass [kg]
m_p	=	propellant mass [kg]
m_{pl}	=	payload mass [kg]
m_{power}	=	power generation mass [kg]
$m_{S/C}$	=	spacecraft platform mass (not only structure but without propulsion) [kg]
m_{prop}	=	propulsion dry mass [kg]
P	=	power input [W]
pmf	=	payload mass fraction
T	=	nominal thrust [mN]
TFC	=	Thrust Correction Factor
tf	=	tankage fraction
tt	=	thrusting time [s]
u_e	=	exhaust velocity [m/s]
V_B	=	beam voltage [V]
Δv	=	velocity increment [m/s]
η_m	=	mass utilisation efficiency

I. Introduction

The Gridded Ion Engine Standardised Electric Propulsion Platform (GIESEPP) project, the first European Plug and Play GIEs, aims at reducing the cost of these systems and increasing their production capacities. In the attempt to achieve these objectives, functionality of the GIESEPP systems with propellants alternative to xenon is of relevant importance and the impact of these propellants on mission costs needs to be assessed.

Xenon is the most common propellant used for space applications, particularly in Gridded Ion Engines and Hall Effect Thrusters (HETs), thanks to its particular physical and chemical properties, such as low first ionization energy, high atomic mass, and chemical inertness. However, this gas is extraordinarily costly due to its limited availability and highly expensive production process.

Within the project, the impact on the different parts of a GIE EPS had been investigated for a range of candidate propellants[1] and, based on these preliminary results, krypton appeared to be the only viable alternative to xenon within the scope of the project. Krypton is cheaper and more readily available than xenon although some degradation in performance is expected and has been observed in the past.[2–4] The lower atomic mass of krypton leads to an increased power requirement for a given thrust, while the higher ionization potential reduces the discharge efficiency.[2] As well as the reduction in performance, discharge stability is also affected and had been observed in the past.[2] The reduction in stability is evident principally in the hollow cathode,[5,6] where higher mass flow rates are required for the plume to spot transition and, in particular, to maintain the spot mode. A possible mitigation to these problems (i.e. loss of performance, discharge stability and discharge efficiency), which, at the same time, would allow a consistent saving on the price of the propellant, could be to operate the thruster with a Xe/Kr mixture.[5,6] The storage ratio of 1:4 Xe/Kr is investigated since this is the production mixture obtained as a by-product of the separation of air into oxygen and nitrogen using conventional methods.[7] It should be noted that the possible presence of residual elements (e.g. traces of oxygen, methane, carbon dioxide) in the mixture, which could affect the purity grade, must be taken into account.

In this report, the effects on mission performance of operating an EPS with alternative propellants are investigated. Different scenarios (spacecraft mass and size, and number of thrusters) and different approaches (fixed thrust and fixed available EP power) were considered and calculations of payload fraction, propellant mass, thrusting time, propellant cost, and propellant-related mission cost were compared for different propellants (xenon, krypton, and 1:4 Xe/Kr mixture) over a typical Δv range of 1-5 km/s.

II. Calculation procedure

Space propulsion tasks are characterised by the velocity increment that must be imparted to the spacecraft to implement them. These can range from around 1 km/s for LEO manoeuvres to around 4-5 km/s for the entire lifetime of a GEO satellite, as reported in Table 1.

Table 1. Typical mission Δv values for EPS in m/s

GEO station keeping	700-1000
Orbit raising GTO to GEO	2400
Orbit raising LEO to GEO*	4000
LEO applications (up to 1200 km): e.g. station keeping & orbital manoeuvres	800
* Currently not considered for mission analysis because of long transfer time and high radiation dose	

Given the mission Δv and the propulsion system Isp, the propellant mass fraction, which is the ratio of propellant mass to overall spacecraft mass, can be calculated using the well know 'Rocket Equation':

$$\Delta v = u_e \ln \left(\frac{m_0}{m_0 - m_p} \right) \tag{1}$$

with u_e exhaust velocity, m_0 overall spacecraft mass, and m_p propellant mass.

Re-arranging this equation, the propellant mass fraction can be written as:

$$\frac{m_p}{m_0} = 1 - \exp \left(-\frac{\Delta v}{g_0 Isp} \right) \tag{2}$$

In order to calculate m_p and m_0 explicitly, the following expression for m_o, which is simply the sum of all the individual spacecraft subsystem masses, can be used:

$$m_0 = m_{pl} + m_{S/C} + m_{prop} + m_{power} + (1 + tf)\, m_p \tag{3}$$

with m_{pl} payload mass, $m_{S/C}$ spacecraft platform mass (not only structure but without propulsion), m_{prop} propulsion dry mass, m_{power} power generation mass (obtained by multiplying the required power and the 'power cost', assumed to be about 20 kg/kW)[a], tf tankage fraction (given by tank mass over propellant mass). The tankage fraction values were calculated as reported in Appendix A and their values are equal to 0.073 for xenon, 0.173 for krypton and 0.151 for the Xe/Kr mixture. Equations (2) and (3) can be solved for m_p and m_0, and hence the payload mass fraction and mission thrusting time can be calculated from:

$$pmf = \frac{m_{pl}}{m_0} \qquad \text{and} \qquad tt = \frac{m_p}{\dot{m}} \tag{4}$$

The overall mission cost is difficult to estimate since many factors must be taken into account and it is beyond the scope of this report. Consequently, the focus was on propellant-related costs, as the choice of a particular propellant would have most effect on the propellant cost, power generation cost, and tankage system cost. It follows that propellant cost and propellant-related mission cost can be calculated using the following equations:

$$cost_p = m_p * price_p \tag{5}$$

$$cost_{mission} = cost_p + cost_{power} + cost_{tank} \tag{6}$$

where $price_p$ is the propellant cost, $cost_{power}$ is the cost of the required power (given by EPS power times specific cost of the power generation), and $cost_{tank}$ is the tankage system cost (given by propellant mass times tank specific cost). The power generation specific cost and the tank specific cost were assumed to be

[a]B. Wollenhaupt, private communication, Mar. 2019

about 1M£/kW and around 1-3 k£/litre, respectively.[b] The assumed values for propellant unit costs were £2460 per kg for xenon, £185 per kg for krypton, as provided by Air Liquide UK[c] for small quantities. The price for the Xe/Kr mixture is assumed to be 2-3 times cheaper than pure krypton,[8] resulting in a price of £74 per kg. The lower cost for the Xe/Kr mixture is related to the separation process of pure Xe and pure Kr. Essentially, these two gases are conventionally obtained as a by-product of liquid oxygen and nitrogen production from atmosphere by cryogenic distillation, since krypton and xenon are present in Earth's atmosphere at concentrations of 1.14 and 0.087 ppm, respectively. The penultimate by-product stream from air separation consists of 80% krypton and 20% xenon.[9] This mixture is then sent to a separate Xe–Kr separation plant to undergo another cryogenic distillation to obtain pure xenon and pure krypton. Therefore, the lower cost comes from the missing separation stage. It should be noted that the purity levels and the exact composition of the mixture are not completely clear (e.g. possible traces of oxygen, methane, carbon dioxide), since they are dependent on the particular distillation process.

III. Spacecraft Assumptions

In the last few years, the use of EPS on spacecrafts is increasing and is becoming more and more frequent on telecom platforms and not only on occasional scientifically driven missions, such as Deep Space 1, Artemis, Hayabusa, Dawn, GOCE and Bepi Colombo to name few missions that have flown in the last two decades. This growing adoption is justified by the high level of maturity reached by EPS and by its economic advantage over chemical platforms. As a consequence, several full-electric platforms with no chemical propulsion mounted on board have been and are being developed, where the EPS performs all major manoeuvres, such as orbit raising, North/South (inclination vector) and East/West (eccentricity vector and longitude) station keeping, wheels offloading, station relocation and final de-/re-orbitation for disposal.

In order to analyse the impact of alternative propellants on mission costs for these all-electric spacecrafts, various scenarios (different spacecraft masses and sizes, and number of thrusters) have been considered:

- CASE I – GOCE spacecraft (scientific mission in LEO):
  - 1 T5-type thruster, up to 1 kW EP power and ∼1 t (metric ton) dry mass
- CASE II – ELECTRA spacecraft (medium size GEO satellite):
  - 2 T6-type thrusters, up to 10 kW EP power and 2-3 t (metric ton) dry mass
- CASE III – big size GEO spacecraft:
  - 4 T6-type thrusters, up to 20 kW EP power and 4-6 t (metric ton) dry mass

The spacecraft component masses are based on data available online[10] for the GOCE spacecraft and on the relative mass distribution of typical GEO spacecrafts provided by the system integrator (OHB)[d] for the GEO cases, specifically: payload mass about 20-30% of the dry mass, spacecraft platform mass about 60% of the dry mass, and propulsion dry mass about 10-15% of the dry mass. All the masses used in the calculations are summarised in Table 2. Furthermore, propellant is assumed to be supplied to the thrusters from a single central storage tank.

Table 2. Spacecraft component masses, in kg

	Case I - GOCE	Case II - ELECTRA	Case III - "big" GEO
Payload mass, m_{pl}	205	750	1200
Spacecraft platform mass, $m_{S/C}$	600	1500	2400
Propulsion dry mass, m_{prop}	60	250	400

As listed above, the thrusters used in this analysis are the QinetiQ's T-series GIEs and, in particular, the small T5, which has 10-cm diameter grids and it was actually used for the GOCE mission, and the bigger T6, which has 22-cm diameter grids. Typical operating values for the two thrusters on xenon are available in Ref. 11 and Ref. 12, respectively, and they are reported in Table 3.

[b]B. Wollenhaupt, private communication, Mar. 2019
[c]Quotation no. 03RS1550101082018, Aug. 2018
[d]B. Wollenhaupt, private communication, July 2019

Table 3. Nominal thrusters' performance parameters

	T5 (Ref. 11)	T6 (Ref. 12)
T [mN]	25	150
$\dot{m}$ [mg/s]	0.720	3.415
Isp [s]	3359	4323
V_B [V]	1100	1850
P [W]	658	4628
TFC	0.948	0.945
η_m	0.864	0.86

In order to estimate the thrusters' performance parameters for the alternative propellants, some assumptions were made, such as constant operational points (e.g. beam voltage), unmodified thruster's (e.g. size, magnets' position and strength) and grid's geometry (e.g. thicknesses, diameters, transparencies, TCF). Furthermore, two different approaches were considered:

- Fixed thrust – it is assumed that a constant thrust could be developed by each propellant;
- Fixed EP power available on board – it implies that the thrust developed by the different propellant would be different.

The first approach, used in previous calculations,[1] leads to a required power increase for krypton and the 1:4 Xe/Kr mixture, and consequently to larger mass and cost associated with power generation. The estimated thruster performance parameters for the three propellants are presented in Table 4. The values for krypton are taken from previous calculations[1] for the T5 and following the same procedure as described in Ref. 1 for the T6. The values for the Xe/Kr mixture, which are an average of the performance values for pure Xe and pure Kr, are calculated assuming a non-interacting mixture rule (as if they behave independently inside the discharge chamber and at the extraction grids with the same parameters as for pure Xe and pure Kr). These values have no experimental verification since no tests have been performed with such mixtures on GIEs, but the values chosen are considered to be within a realistic range. It is worth to note that the Xe/Kr mixture at different mixture ratios was tested on HETs and the non-interacting mixture rule appeared to be applicable for HETs.[13–16]

Table 4. Estimated thrusters' performance parameters – fixed thrust

	Xenon		Krypton		1:4 Xe/Kr	
	T5[11]	T6[12]	T5[1]	T6	T5	T6
T [mN]	25	150	25	150	25	150
$\dot{m}$ [mg/s]	0.720	3.415	0.606	2.861	0.637	3.015
Isp [s]	3359	4323	3991	5159	3795	4915
V_B [V]	1100	1850	1100	1850	1100	1850
P [W]	658	4628	829	5800	781	5484
η_m	0.864	0.86	0.82	0.82	0.834	0.832
tf	0.073		0.173		0.151	
propellant price [£/kg]	2460		185		74	

The second approach, which fixes the maximum power level to the value available when the thrusters run on xenon, has the consequence of removing the power supply and power generation contributions from the mass and cost results, but significantly increasing the thrusting time required to achieve the mission Δv. This increased thrusting time could lead to loss in revenues, increased radiation exposure, and thruster lifetime problems if the EPS is used for orbit raising tasks and the economic impact of these mission delays is not easy to estimate, while it could have minimal impact if the EPS is used for other tasks. The estimated performance parameters for the three propellants using this approach are presented in Table 5. The values for krypton are obtained with the assumptions that the grid system and its operational parameters are the same of the fixed thrust approach, which leads to identical values of the beam voltage and specific impulse, while the impact of the reduced available power is evident in the lower values of the propellant mass flow rate and, consequently, of the thrust compared to the other approach. The values for the Xe/Kr mixture are calculated using the same assumptions of the first approach, i.e. as an average of the performance values for the pure gases.

Table 5. Estimated thrusters' performance parameters – fixed power

	Xenon		Krypton		1:4 Xe/Kr	
	T5[11]	T6[12]	T5	T6	T5	T6
T [mN]	25	150	19.8	121.7	21	127.7
$\dot{m}$ [mg/s]	0.720	3.415	0.479	2.274	0.535	2.511
Isp [s]	3359	4323	3991	5159	3795	4915
V_B [V]	1100	1850	1100	1850	1100	1850
P [W]	658	4628	658	4628	658	4628
η_m	0.864	0.86	0.82	0.82	0.834	0.832

IV. Results and discussion

Mission performance calculations, including payload fraction, propellant mass, thrusting time, propellant and propellant-related mission costs have been carried out as described in the previous sections for the three propellants, i.e. xenon, krypton, and 1:4 Xe/Kr mixture, over a typical Δv range (1-5 km/s). It is worth to note that no limitations on power available on board, no volume constraints and other system parameters were considered in this analysis.

Effect of Propellant Choice

The atomic or molecular mass of an ion thruster propellant directly affects the exhaust velocity and specific impulse of the thruster. A low atomic mass propellant will produce a higher exhaust velocity and specific impulse (in fact, both are inversely proportional to the square root of the propellant molecular mass).

1. Payload fraction and tankage mass

Payload fraction results for the three propellant can be seen in Figure 1 for the LEO case (refer to Figure 9 in Appendix B for the other cases) and the values are very similar for each case and each approach. The reasons for these results are the follows:

- the ion thrusters' efficiencies (i.e. directly mass utilisation efficiency, and, consequently, electrical and total efficiency) are reduced when operating on alternative propellants, so the specific impulse is lower than would have been expected if the efficiencies would stay the same as for xenon;
- the tankage fraction is greater for the lower molecular mass propellants (see Table 4), due to the required higher storage pressure and the consequently higher tank mass (Figure 2, see Figure 10 in Appendix B for the other cases).

Overall, even if we can reduce the propellant mass (due to higher Isp), the gain is consumed by reduction in efficiencies and by heavier tanks. Let's show an example how these effects combine and counteract any advantage which might have been expected for the lower molecular mass propellants. For the GOCE case with the fixed thrust approach and a Δv of 5 km/s, the propellant mass decreases from ∼146 kg for xenon to ∼130 kg for the mixture and to ∼123 kg for krypton. However, for the same Δv, there is also a slight increase in components masses: e.g. tankage contribution increases ∼9 kg for the mixture and ∼11 kg for krypton compared to xenon (Figure 2).

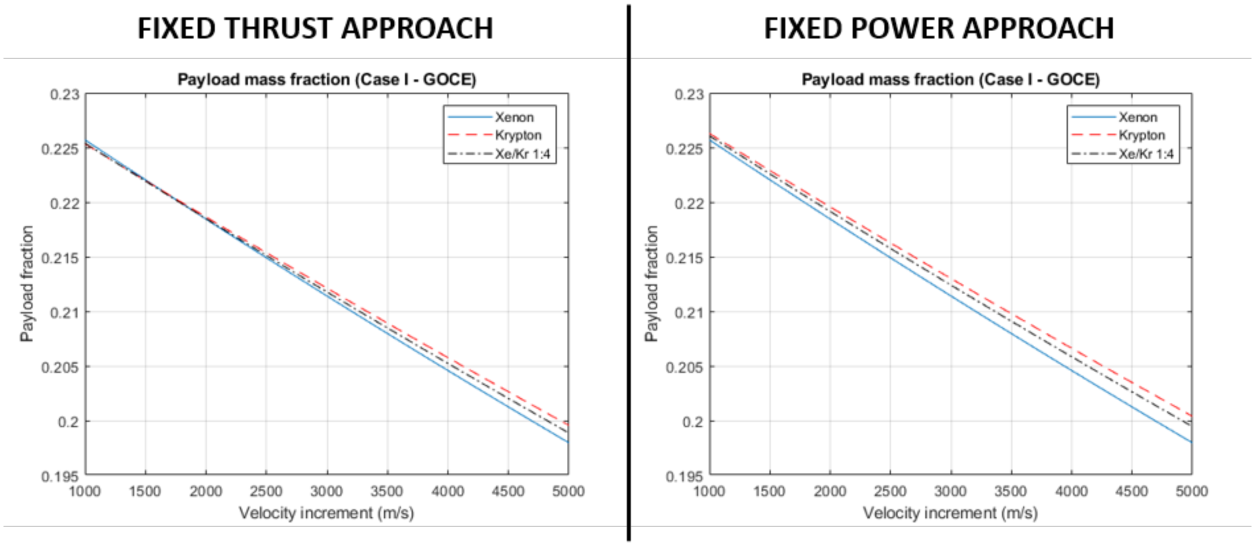

Figure 1. Payload fraction vs velocity increment

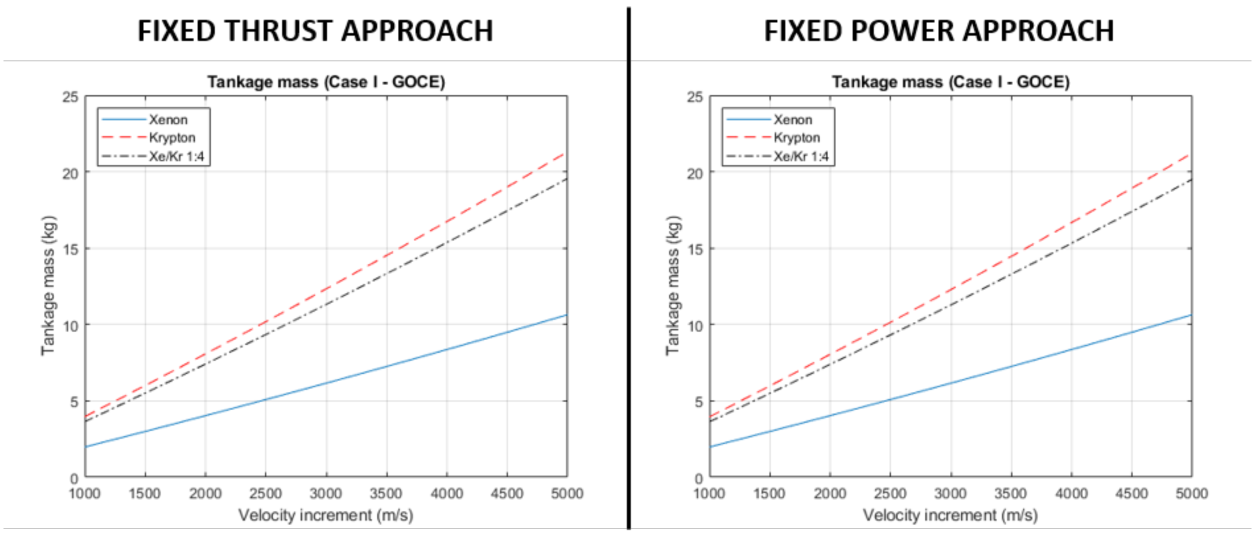

Figure 2. Tankage mass vs velocity increment

2. *Thrusting time*

The results for thrusting time are shown in Figure 3 for the ELECTRA case. As expected, the results are identical for the fixed thrust approach. On the other hand, the lower molecular mass propellants develop a lower thrust in the fixed power approach, and this leads to a longer thrusting time required to achieve the mission Δv. This extra time is approximately 26% for krypton and 19% for the Xe/Kr mixture throughout the considered Δv range (1-5 km/s) and for three analysed cases (see Figure 11 in Appendix B for the other cases), and its impact is different for the different tasks the EPS is required to perform, e.g. undesirable for orbit raising task, minimal (from an economical point of view) for the other tasks (station keeping, disposal, etc.).

3. *Propellant cost and propellant-related mission cost*

The main aim of this report was to investigate the effect of propellant on mission cost. A simple comparison of just propellant and overall propellant-related mission costs has been made and the results are presented

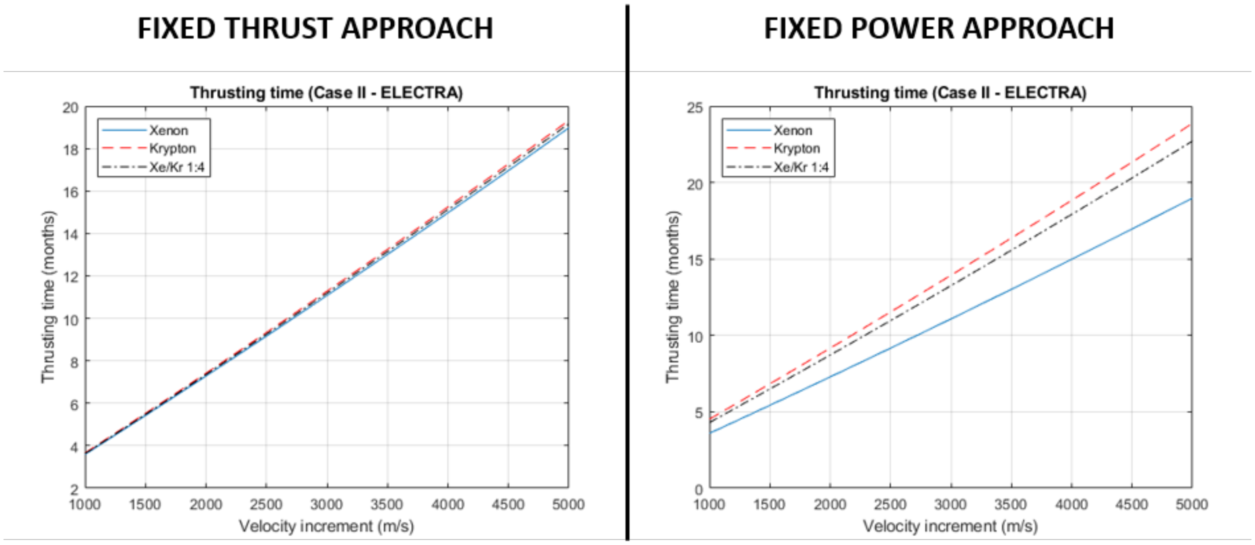

Figure 3. Thrusting time vs velocity increment

in Figure 4 for the ELECTRA case and Figure 5 for the different cases and different approaches. It is clear that substantial savings on compressed gas orders are possible using the cheaper, more readily available propellants. The cost reduction comes from the fact that not only the propellant unit costs are lower than for xenon, but the propellant mass required is also less due to the higher specific impulse. From these calculations (and with the assumptions made above), the saving on propellant orders can be up to about 16 times for pure krypton and up to about 38 times for the mixture Xe/Kr compared to pure xenon throughout the considered Δv range (1-5 km/s) and for different analysed cases and different approaches (see Figure 12 in Appendix B for the other cases).

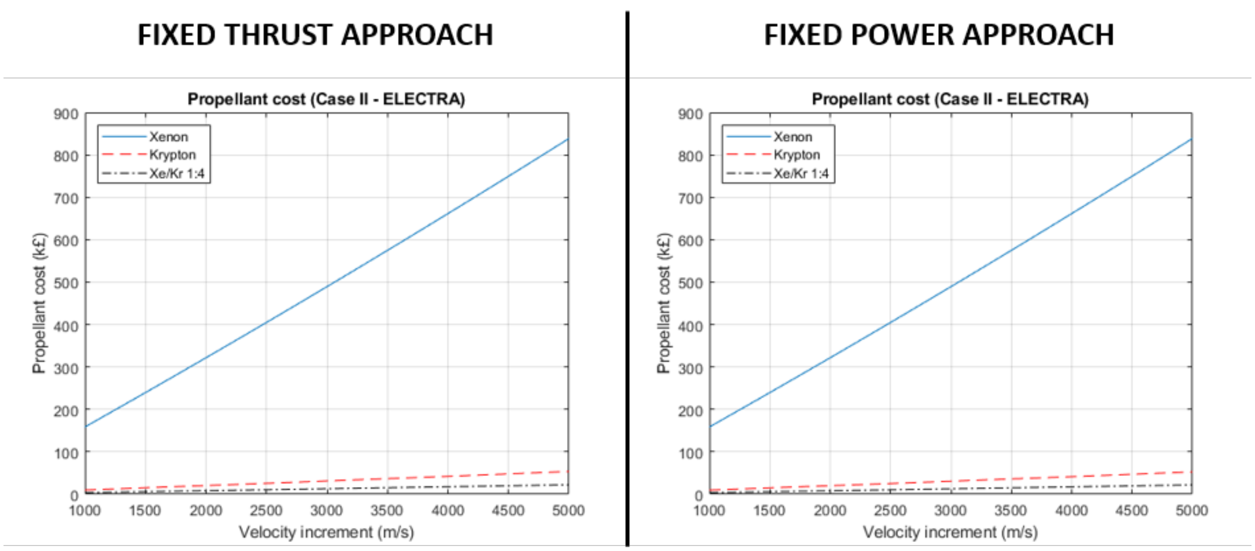

Figure 4. Propellant cost vs velocity increment

The propellant-related mission cost is affected by propellant, power generation and tankage system costs. As shown in Figure 5 (see Figure 13 in Appendix B for the big GEO case), the outcome is different on a case-to-case basis for the fixed thrust approach:

- Case I: the use of alternative propellants becomes profitable only for velocity increments around 2.2 km/s for the Xe/Kr mixture and around 3.4 km/s for pure krypton; so, for satellites of around 1 t placed on LEO, the Xe/Kr mixture offers an attractive alternative only in particular cases and very long missions.

- Cases II & III: alternative propellants cannot match the overall cost of a xenon system; overall such arrangement does not gain from switching to Kr or Xe/Kr.

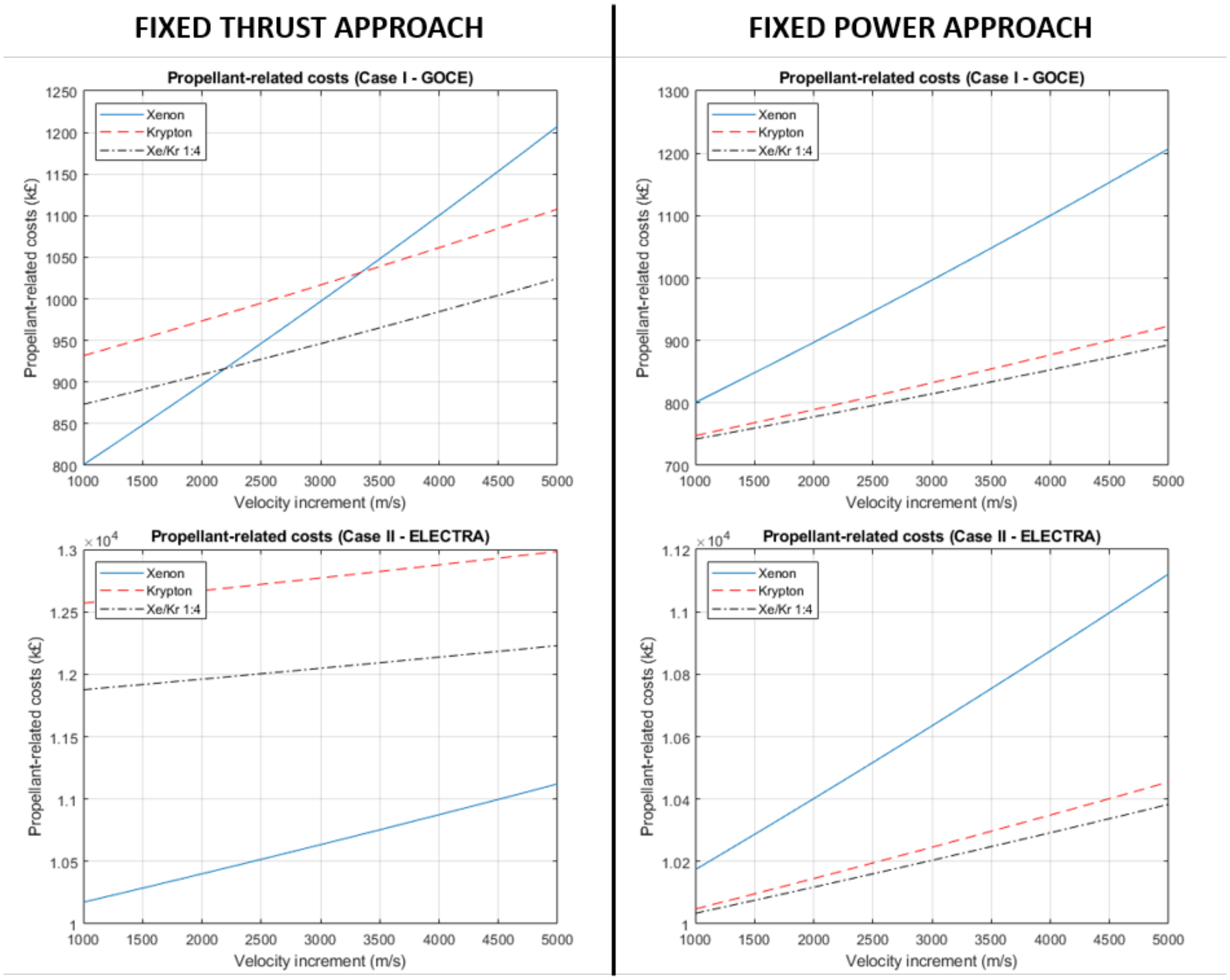

Figure 5. Propellant-related mission cost vs velocity increment

These results indicate that benefits of replacing Xe with Kr or Xe/Kr in existing GIEs are minimal or not existent for the fixed thrust approach. This is due to the extra costs related to the increment of required power, the added complexity and, consequently, cost of the tankage system. Of course, this conclusion assumes that the extra costs would stay as they are at the moment for the future missions. It may be not true for mega constellations where significant reduction in hardware costs are expected. This case is considered in Section V of this report.

The outcome is different when the fixed power approach is considered due to the removal of extra power supply and power generation contributions from the cost results. In fact, the savings are substantial for the GOCE case (i.e. up to about 30% for krypton and up to about 35% for the mixture for Δv of 5 km/s, but just above 10% for both propellants for more typical LEO mission Δv of 1.5 km/s) and relevant for the GEO spacecraft (up to about 10% for Δv of 5 km/s).

In conclusion, no current mission gets an overall cost reduction out of the reduced price of krypton and the Xe/Kr mixture in the fixed thrust approach: these results are for typical satellites shown in Table 2 and for the typical mission Δv values reported in Table 1. ***If the existing price-tags*** for the hardware remains the same, the only future missions to benefit using these alternative propellants would be rather deep space mission or reusable space tugs (see Appendix C). The future is a bit brighter for alternative propellants when the fixed power approach is considered. The GOCE-type spacecrafts in LEO missions would take advantage from the change of propellant while having minimal penalties related to the longer thrusting times to cover a given Δv, while the GEO missions would have a smaller overall cost reduction but the impact of longer mission times is not easy to estimate.

V. Starlink case: the "New Space" approach

In May 2019, SpaceX launched the second batch of satellites for the Starlink constellation, which it is expected to be completed by the end of 2027 with nearly 12000 satellites in LEO. This second set of 60 satellites are said to be "production design — v0.9", since they do not have satellite interlink capabilities and they are only able to communicate with stationary ground antennas. They present the following characteristics:

- Propulsion system: Hall Effect Thrusters (HETs) using krypton for orbit raising and station keeping,
- Satellite mass: ~230 kg,
- Estimated propellant mass: ~10 kg of krypton,
- Insertion/Operational altitude: 440 km / 550 km,
- Duration: 6-12 months.

The final version will present slightly different characteristics, such as bigger satellite and propellant mass, operational altitudes (5 different orbit levels), and longer lifetime (5-10 years).

SpaceX targets a cost of $500k-$1M per satellite instead of a typical cost of $100M per satellite of similar mass. This is one of the reasons of using krypton instead of xenon: the cost of hardware is orders of magnitude lower (based on SpaceX claims), while xenon price does not change (or, eventually, will increase because of the extra demand). A second reason is the availability of xenon: for example, if each of the 12000 satellites requires 10 kg of xenon and the lifetime of the satellites is 10 years, that amount to a consumption of ~12 metric tons of xenon per year, while the entire world production is currently around 50-60 metric tons per year.[17]

When this "New Space" approach is applied to the calculations of the mission costs as outlined in Sections II and III, the results for the LEO case are shown in Figure 6 for an assumed 10-times reduction of the cost of power and tank and in Figure 7 for an assumed 100-times reduction (see Figure 14 and Figure 15 in Appendix B for the other cases).

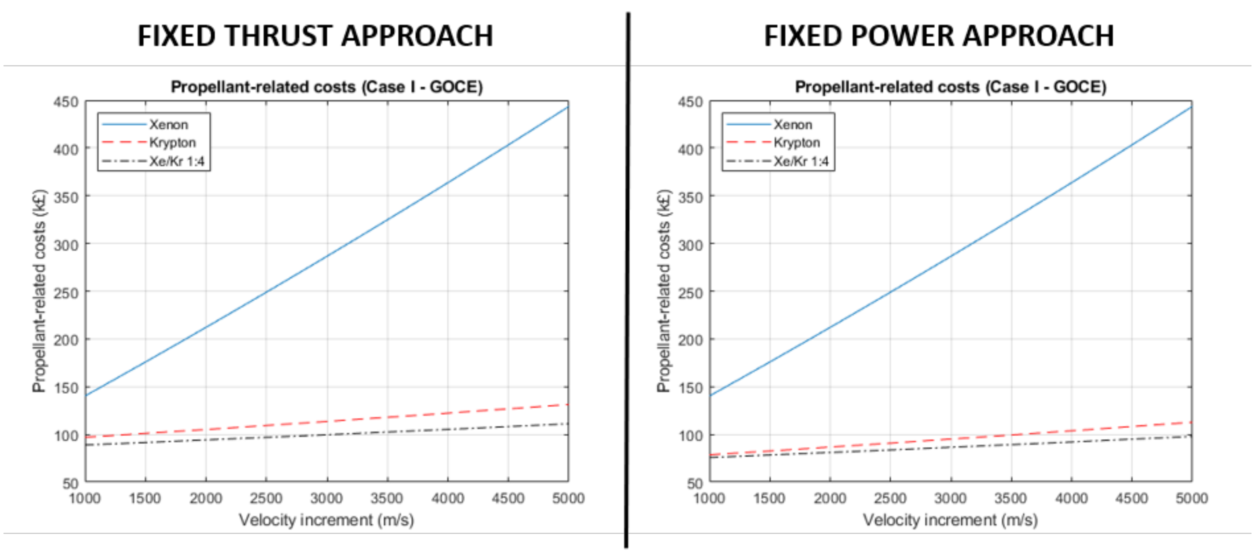

Figure 6. Propellant-related mission cost vs velocity increment: "New Space" approach, 10-times reduction

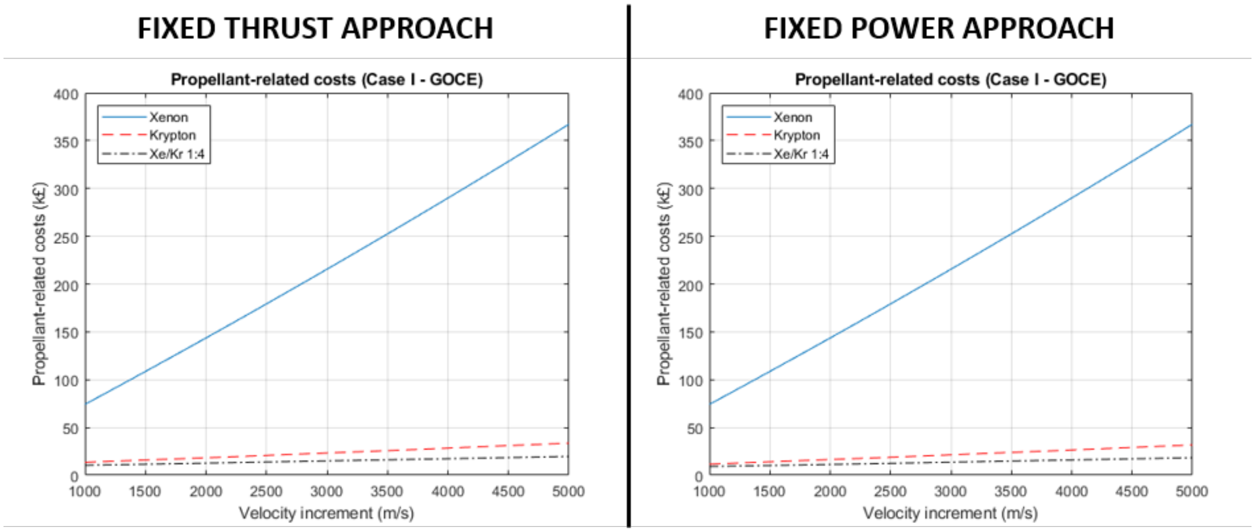

Figure 7. Propellant-related mission cost vs velocity increment: "New Space" approach, 100-times reduction

It is clearly seen that as a consequence of this reduction in power and tank prices, the use of xenon is not cost advantageous anymore in any of the considered cases, setting aside its availability problems. So, the cost reduction for electric propulsion should come from two directions: the first one is by dramatically reducing the hardware prices and the second one is switching to more available, cheaper propellants (krypton and/or the Xe/Kr mixture).

VI. Conclusion

The calculations performed in this report indicate that the choice of propellant can have a pronounced effect on mission performance and cost. Overall, for xenon, lower power levels are required, and higher discharge stability makes operation of GIEs more reliable. However, Xe is expensive and its availability limited. On the other hand, krypton, although requiring higher power levels and introducing some degradation in engine performance and stability, does not have the availability/cost problem of xenon, being available at roughly ten times the quantity of xenon (as expected considering their natural availability ratio of 11:1 in volume). Although the 1:4 Xe/Kr mixture looks promising over pure krypton from a performance and/or stability point of view, and over xenon from a propellant cost point of view, very little data exists in the literature on such a mixture and the assumptions made in this report (simple mixture rules) need to be tested by further experiments.

As results of these calculations, payload fractions and thrusting times were seen to be fairly insensitive to propellant choice (for fixed thrust, given the assumptions made on spacecraft masses, thruster performance and power level are valid, at least approximately), while propellant and mission costs were seen to vary significantly. Taking into account additional costs associated with additional power and mass (and consequently cost) of the tank when moving from Xe to alternatives, there is a clear indication that, at mission cost level, no substantial saving can be obtained for typical mission Δv when the fixed thrust approach is considered (for existing hardware prices).

If the fixed power approach is adopted, it makes more sense to use alternative propellants especially in LEO when the reduced thrust and, consequently, the longer mission times do not have a relevant impact on the overall mission, while allowing a substantial saving on the propellant-related cost. In GEO, the savings related to alternative propellants on the overall cost could be cancelled by longer thrusting times for orbit rising, which could lead to a loss in revenues, increased radiation exposure, and thruster lifetime problems.

The above conclusions change completely if the "New Space" approach is considered. In this case, a significant reduction in hardware prices due to mass production makes xenon choice not profitable anymore when compared with krypton and the Xe/Kr mixture, especially if availability problems are to be taken into account.

On the whole, the final choice of EPS configuration / propellant type will depend on the specific mission for which it is proposed. More detailed, mission specific calculations will need to be made in order to ascertain the optimal configuration for each set of mission requirements.

Appendix

A. Tankage fraction and tankage cost

The propellants considered in this report are naturally in gaseous state and they need to be stored as high-pressure supercritical fluids in a volume-limited spacecraft. In this state, a substance is at temperature and pressure above its critical point, where distinct liquid and gas phases do not exist. In Figure 8, density as a function of storage pressure (above P_c) at a temperature of 300 K is plotted using the data tabulated on the NIST website.[e] The values for the mixture are calculated using the formula for the density of a mixture. It is evident that replacing xenon with krypton or the Xe/Kr mixture causes substantial penalties even increasing the pressure considerably.

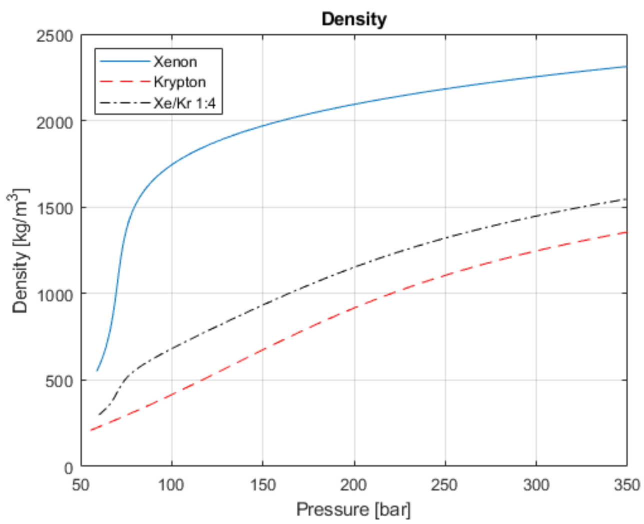

Figure 8. Density as a function of storage pressure for different propellants at 300 K

Using the above graph for the densities and for given tank mass-to-volume ratios (~150 g/l for Xenon at 186 bar, and ~220 g/l for Krypton at 310 bar with the same value assumed for the mixture)[f], it was possible to calculate the tankage fractions (given by tank mass over propellant mass) for the three propellants:

- The density for Xe at 300 K and 186 bar is 2063.6 kg/m^3 resulting in a tankage fraction of 0.073,
- The density for Kr at 300 K and 310 bar is 1270.7 kg/m^3 resulting in a tankage fraction of 0.173,
- The density for Xe/Kr at 300 K and 310 bar is 1470 kg/m^3 resulting in a tankage fraction of 0.151.

The same procedure was used to calculate the tankage cost for the three propellants starting from the tank specific cost of 1-3 k€/litre[e] (here used ~2 k£/litre) and with the above values for the densities:

- Relative cost of xenon tank = 0.969 k£/kg of propellant,
- Relative cost of krypton tank = 1.574 k£/kg of propellant,
- Relative cost of 1:4 Xe/Kr mixture tank = 1.361 k£/kg of propellant.

[e] Available online: http://webbook.nist.gov/chemistry/fluid/
[f] B. Wollenhaupt, private communication, Mar. 2019

B. Supplementary figures

In the following figures, all the different cases and approaches are represented for payload mass fraction (Figure 9), tankage mass (Figure 10), thrusting time (Figure 11), propellant cost (Figure 12), propellant-related cost (Figure 13), and propellant-related cost for the "New Space" approach (Figure 14 and Figure 15).

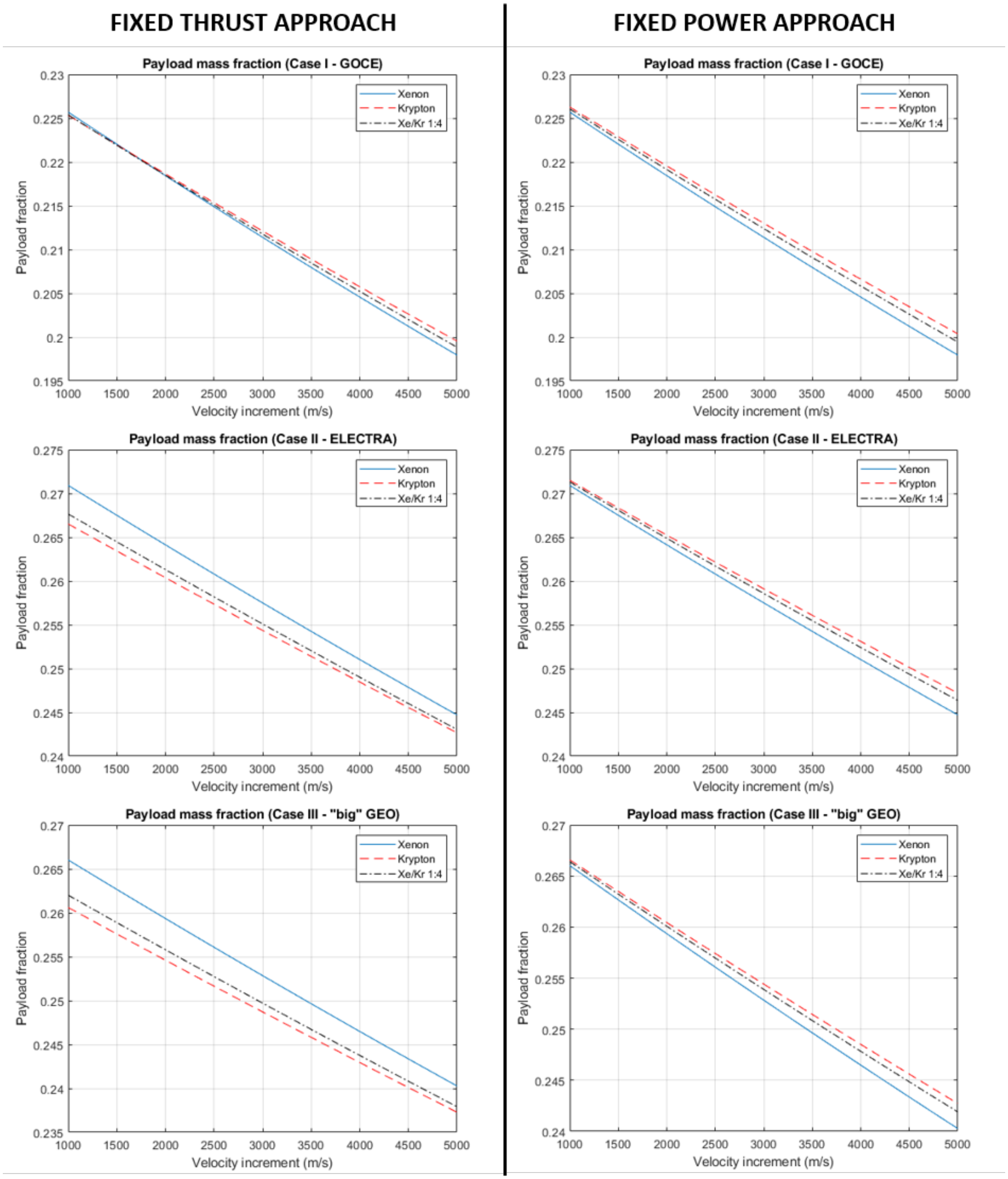

Figure 9. Payload fraction vs velocity increment

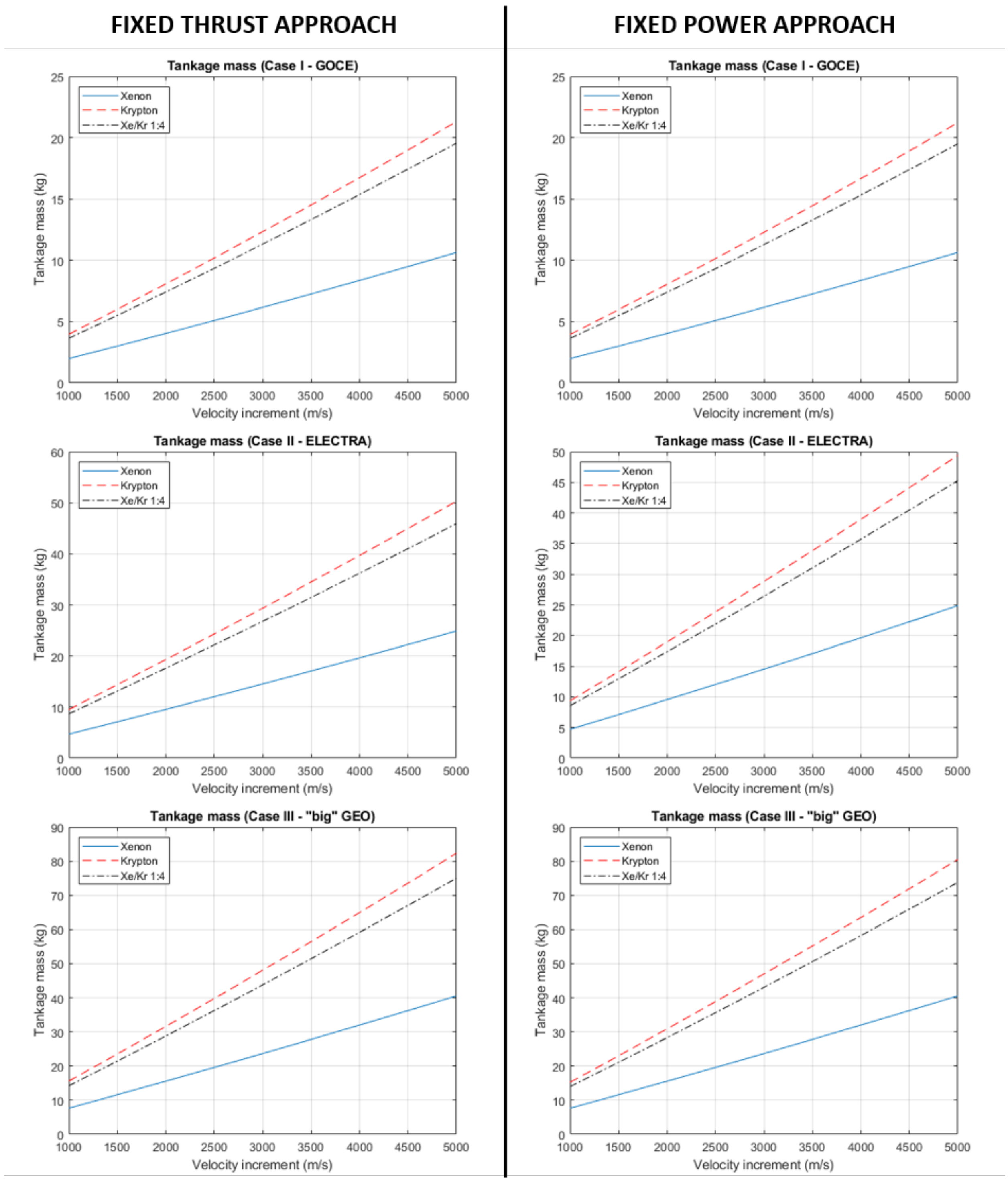

Figure 10. Tankage mass vs velocity increment

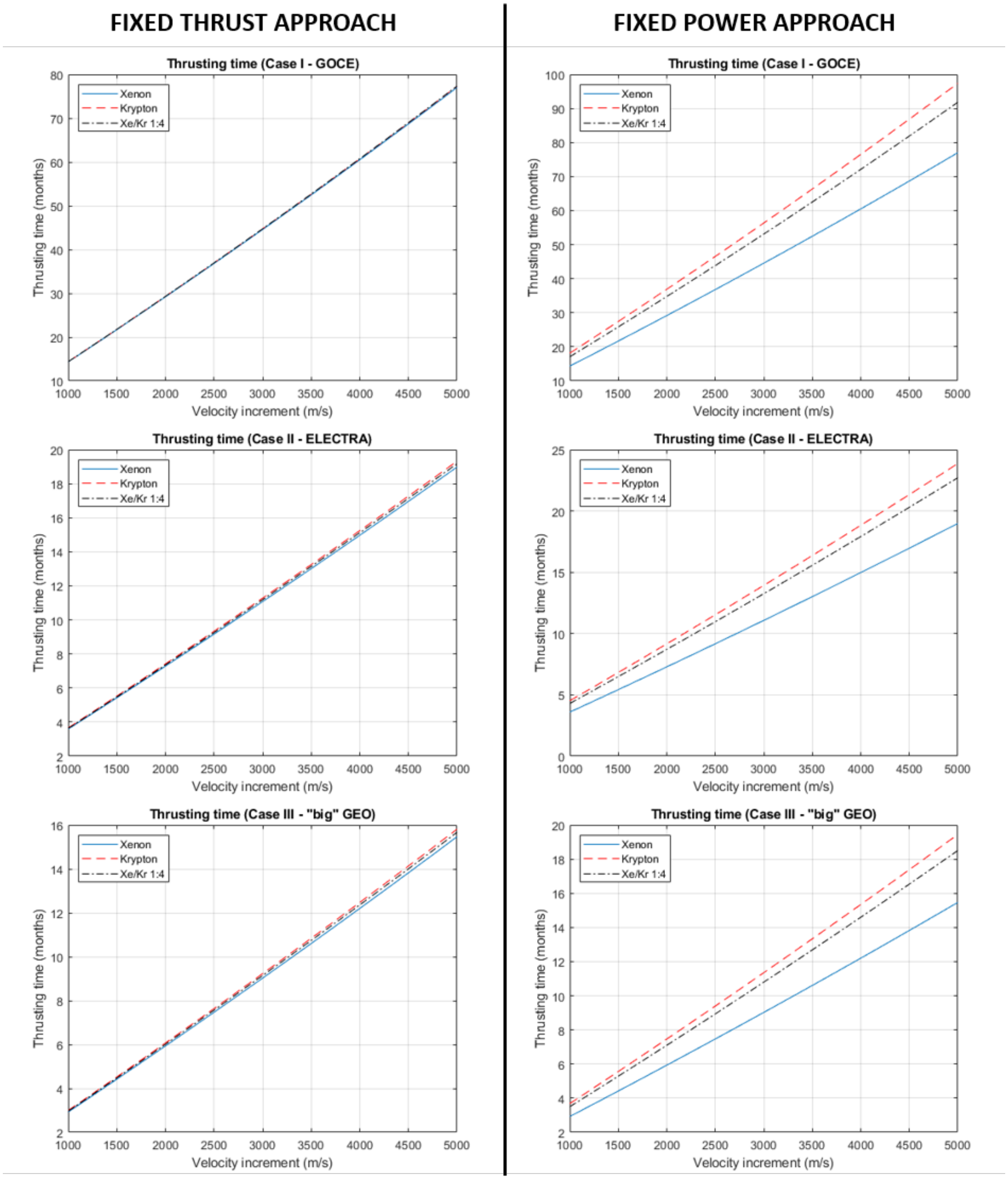

Figure 11. Thrusting time vs velocity increment

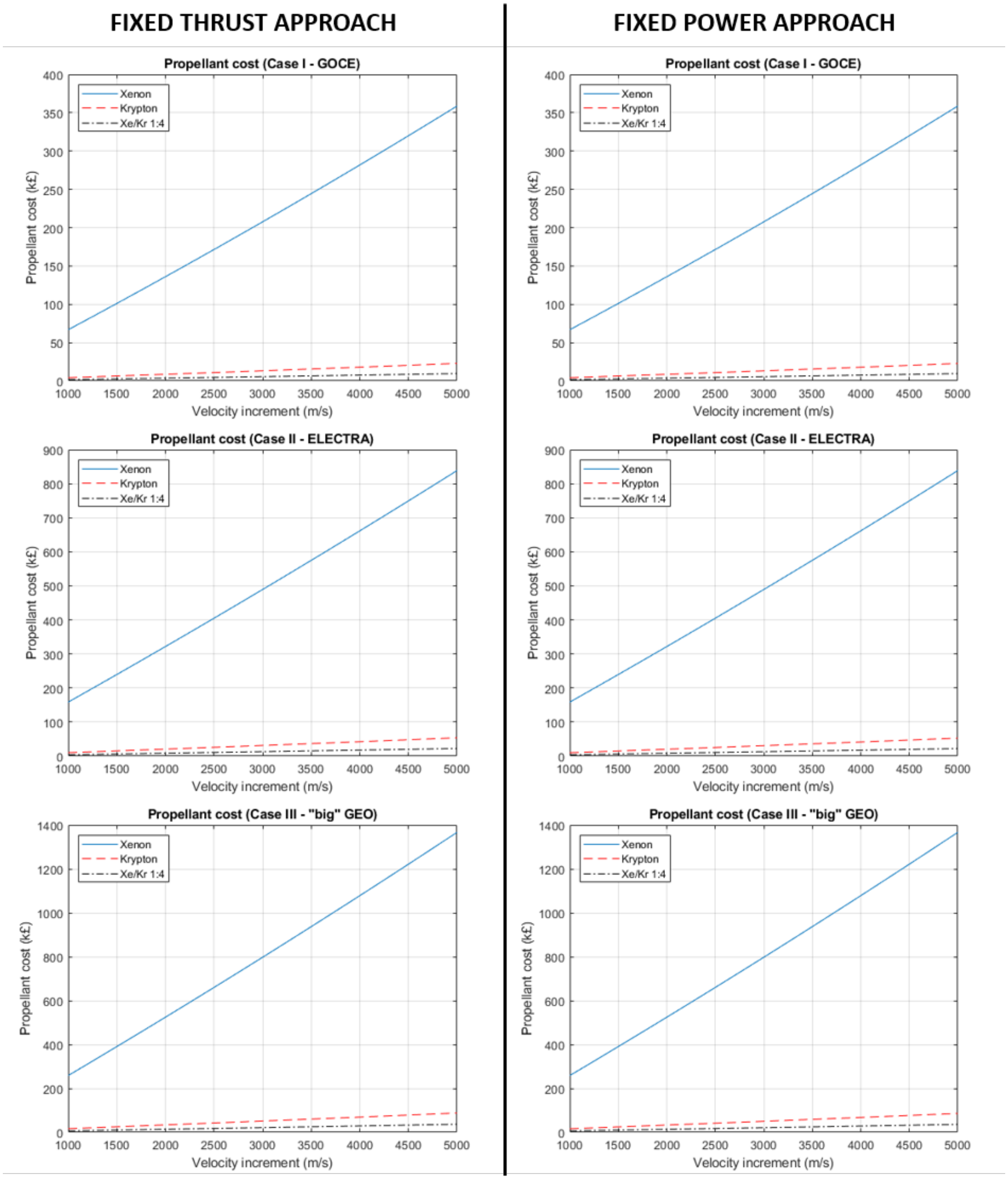

Figure 12. Propellant cost vs velocity increment

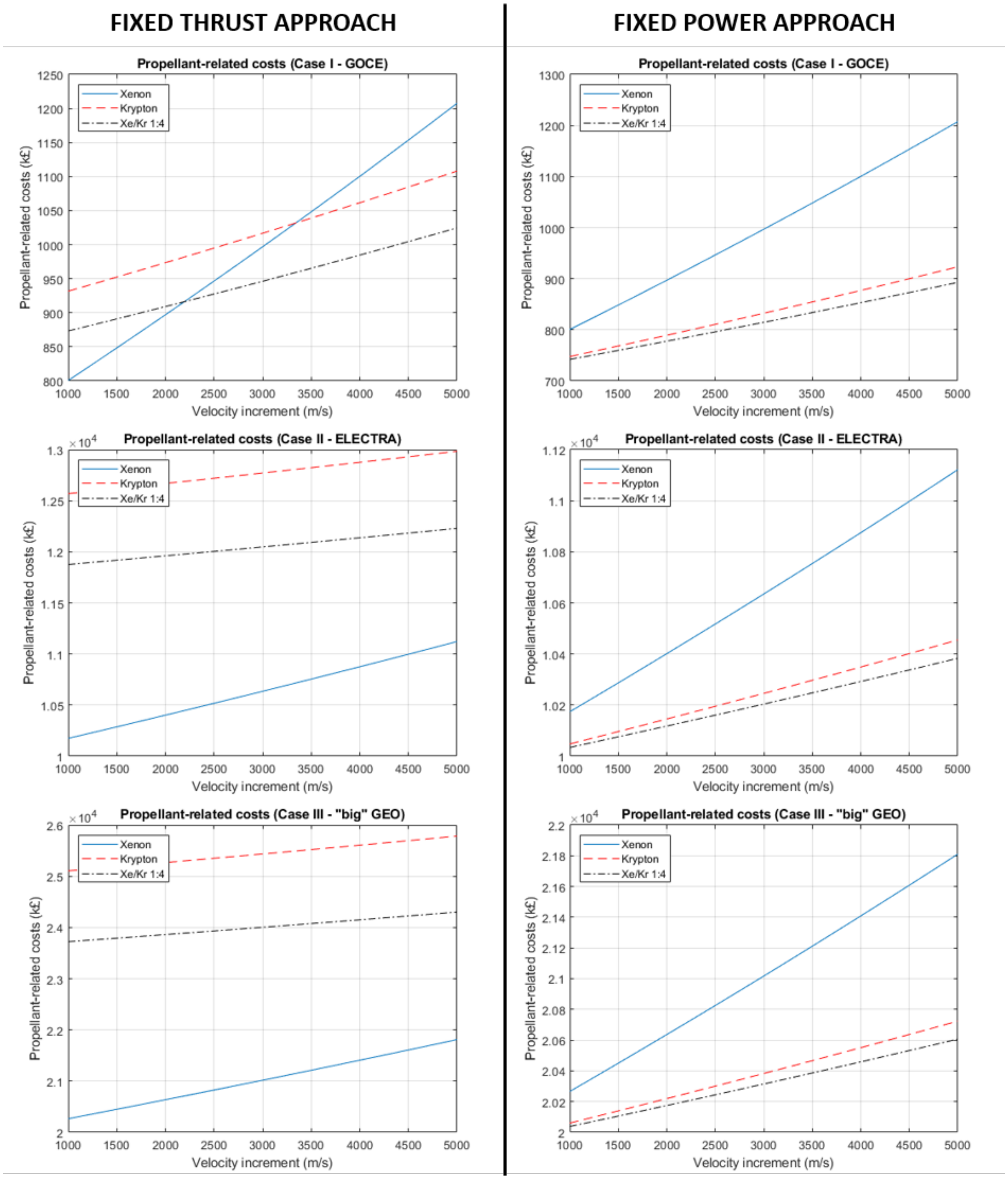

Figure 13. Propellant-related mission cost vs velocity increment

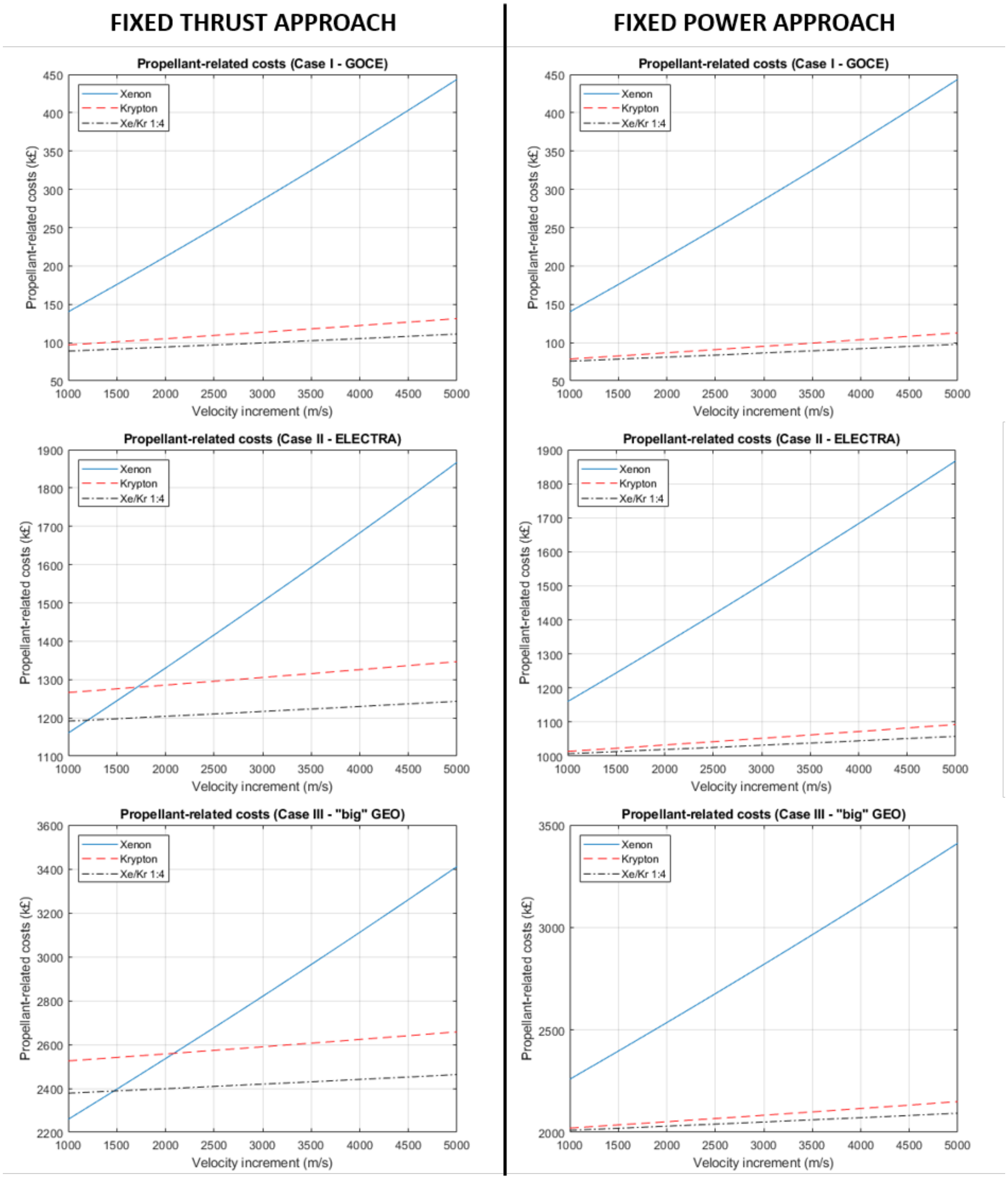

Figure 14. Propellant-related mission cost vs velocity increment: "New Space" approach, 10-times reduction

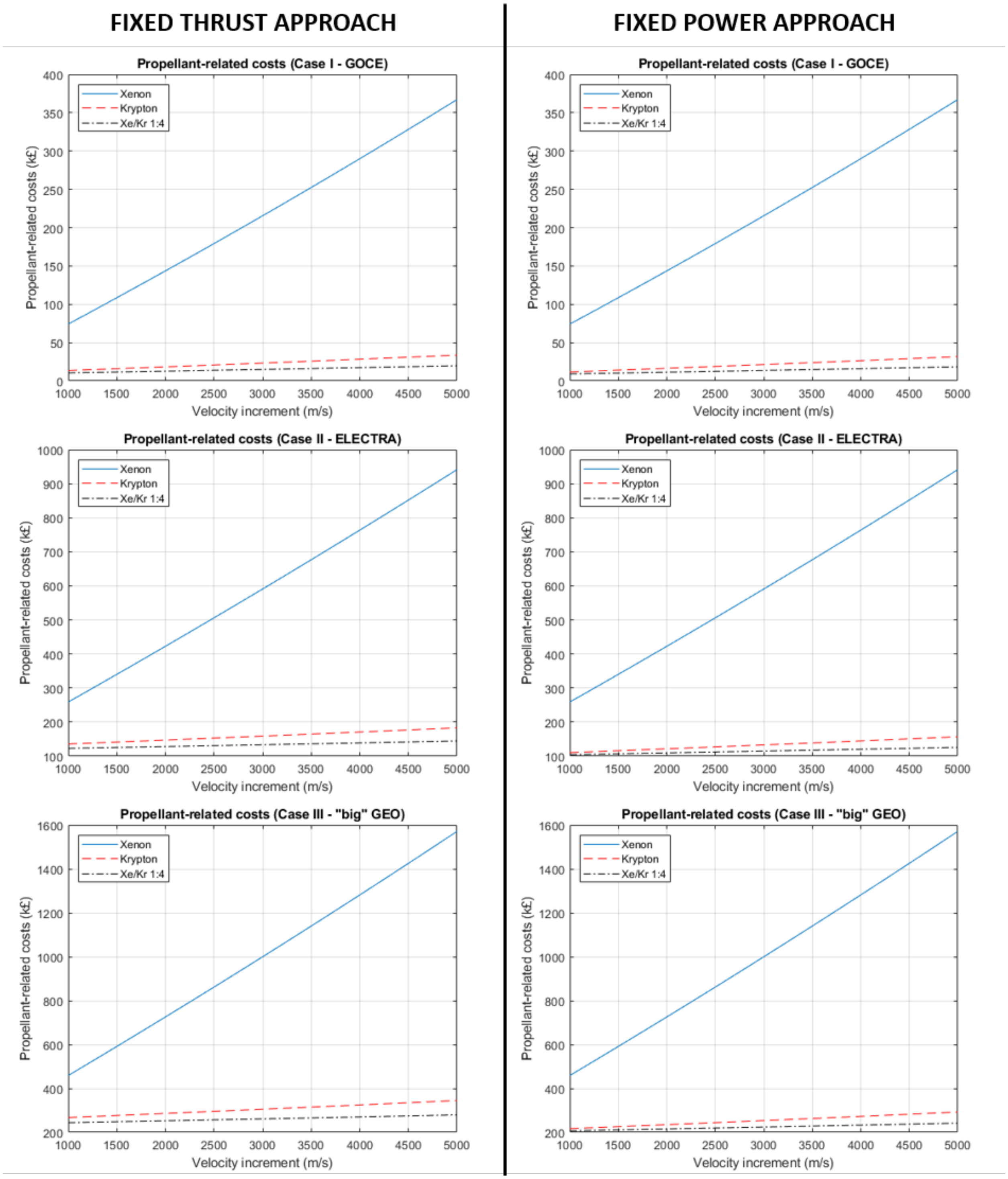

Figure 15. Propellant-related mission cost vs velocity increment: "New Space" approach, 100-times reduction

C. Extended Δv range

In Figure 16, the propellant-related mission cost is presented for an extended Δv range of 1-40 km/s. The cost advantage of alternative propellants is clear at higher velocity increments.

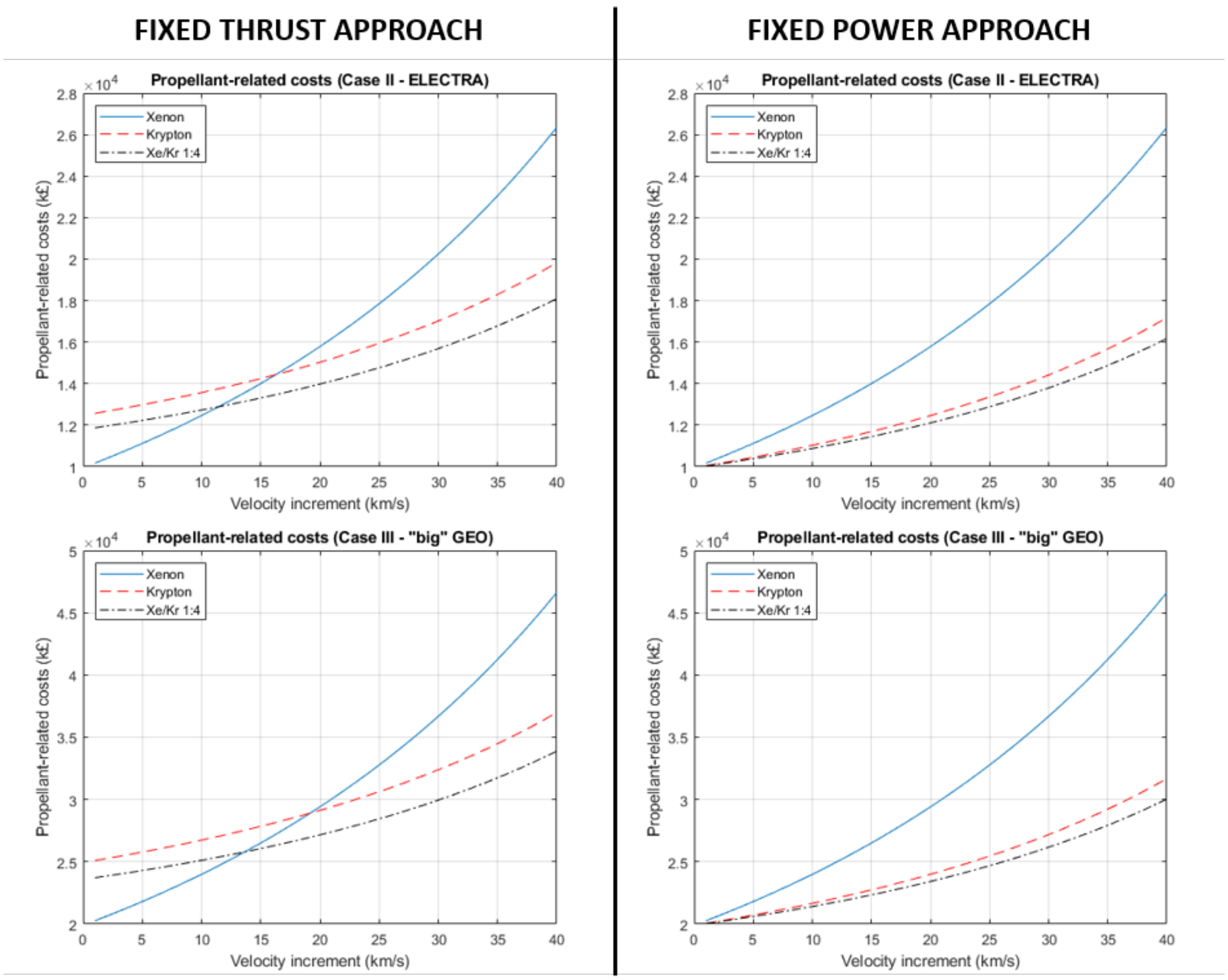

Figure 16. Propellant-related mission cost vs velocity increment (extended range)

Acknowledgments

The authors would like to thank the University of Southampton for the support. This research has been funded by the European Commission in the scope of the GIESEPP project, within the frame of the H2020 Research program - COMPET-3-2016-a SRC - In-Space Electrical Propulsion and Station Keeping, Incremental Line - Gridded Ion Engines of the European Union (Research and Innovation contract No.730002).

References

[1] N. Fazio, S.B. Gabriel, and I.O. Golosnoy, "Alternative Propellants for Gridded Ion Engines," in *6th Space Propulsion Conference*, 2018, pp. 1–8.

[2] V.K. Rawlin, "Operation of the J-Series Thruster Using Inert Gas," in *16th AIAA/JSASS/DGLR International Electric Propulsion Conference*, 1982.

[3] J.S. Sovey, "Improved Ion Containment using a Ring-Cusp Ion Thruster," *J. Spacecr. Rockets*, vol. 21, no. 5, pp. 488–495, Sep. 1984.

[4] M.J. Patterson and J.G.J. Williams, "Krypton Ion Thruster Performance," in *28th AIAA/SAE/ASME/ASEE Joint Propulsion Conference and Exhibit*, 1992.

[5] I.F.M. Ahmed Rudwan and S.B. Gabriel, "Investigation of the Discharge Characteristics of the T6 Hollow Cathode Operating on Several Inert Gases and a Kr/Xe Mixture," *AIP Conf. Proc.*, pp. 294–297, 2003.

[6] S.B. Gabriel, A.N.J. Daykin-Iliopoulos, M. Praeger, and M. Coletti, "Hollow Cathode Operation with Different Gases," in *35th International Electric Propulsion Conference*, 2017.

[7] C.M. Simon, R. Mercado, S.K. Schnell, B. Smit, and M. Haranczyk, "What Are the Best Materials To Separate a Xenon/Krypton Mixture?," *Chem. Mater.*, vol. 27, no. 12, pp. 4459–4475, Jun. 2015.

[8] M.R. Nakles, J.W.A. Hargus, J.J. Delgado, and R.L. Corey, "A Performance Comparison of Xenon and Krypton Propellant on an SPT-100 Hall Thruster," in *32nd International Electric Propulsion Conference*, 2011.

[9] F.G. Kerry, *Industrial Gas Handbook: Gas Separation and Purification*, 1st ed. Boca Raton, Florida, USA: CRC Press, 2007.

[10] C. Steiger, N. Mardle, and P.P. Emanuelli, "GOCE End-of-Mission Operations Report," 2014.

[11] M.W. Crofton, "Evaluation of the United Kingdom Ion Thruster," *J. Spacecr. Rockets*, vol. 33, no. 5, pp. 739–747, 1996.

[12] R.A. Lewis, J. Pérez Luna, N. Coombs, and F. Guarducci, "Qualification of the T6 Thruster for BepiColombo," in *Joint Conference of 30th International Symposium on Space Technology and Science, 34th International Electric Propulsion Conference, and 6th Nano-satellite Symposium*, 2015.

[13] B.A. Arkhipov *et al.*, "The Results of Testing and Effectiveness of the Kr-Xe Mixture Application in SPT," in *27th International Electric Propulsion Conference*, 2001.

[14] V.P. Kim, G.A. Popov, V.I. Kozlov, A.I. Skrylnikov, and D.P. Grdlichko, "Investigation of SPT Performance and Particularities of its Operation with Kr and Kr/Xe Mixtures," in *27th International Electric Propulsion Conference*, 2001.

[15] B.A. Arkhipov, I.A. Khoromsky, and V.M. Murashko, "Problems of Designing EPS's with SPT's Working on Krypton-Xenon Mixture," in *38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, 2002.

[16] C. Ducci *et al.*, "Investigation of a 5 kW Class Hall-Effect Thruster Operating with Different Xenon-Krypton Mixtures," in *Joint Conference of 30th International Symposium on Space Technology and Science, 34th International Electric Propulsion Conference, and 6th Nano-satellite Symposium*, 2015.

[17] D.A. Herman and K.G. Unfried, "Xenon Acquisition Strategies for High-Power Electric Propulsion NASA Missions," in *7th JANNAF SPS Subcommittee Meeting*, 2015.