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Alternate propellants for PPS® Hall-Effect Plasma Thruster

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ABSTRACT

CURRENT flight missions utilizing ion or Hall-effect (stationary plasma) propulsion devices all use supercritically-stored xenon as propellant. While historically cesium and mercury were the first sources of accelerated ions utilized in Electric Propulsion (EP)[1], they were progressively abandoned for complexity and environmental reasons, and were progressively replaced by xenon. The use of xenon itself results from a combination of several advantages: it is a chemically inert gas, *i.e.*, safe to implement in ground testing facilities, even in relatively large amounts; its first ionization potential (12.13 eV/ion)[2] is relatively low, at least compared to that of other inert gases; and it is relatively easy to pump in vacuum facilities by means of condensation on cryopumps.[3] As a consequence, xenon has been the only propellant used in flight for electrostatic EP since the 1980s.

The main drawbacks of xenon, however, are its cost and limited availability. Xenon, the rarest of all rare gases (Table 1) is separated as a by-product in the liquid oxygen production process. Its current cost has seen a sharp increase from about 1 €/g in 2006 (Table 2) to a peak price of about 4 to 5 €/g.

A typical xenon load for current western geostationary satellites featuring stationary plasma thrusters is 160 kg. For exploration missions, past and present flight experience ranges from approximately 80 kg (*Deep Space 1*, *Smart-1*) up to 450 kg (*Dawn*).

The current tendency for EP missions is for increased xenon loads for individual spacecraft, as a result of augmented total xenon throughput capability per thruster[5] and increasingly ambitious missions[19] (Figure 1). This, in conjunction with the rapidly growing number of spacecraft using electric propulsion[6] as well as the expansion of non-propulsive applications for xenon, has made the availability of xenon a real issue. In fact and for the first time in 2008, the procurement of flight-grade xenon in Europe for the whole year was fully allocated by February of that year.[8] World production estimates, depending on the source, seems to vary between 20 tons (Table 2) and 50 tons.[14,15]

Table 1. Normalized composition of dry air.[4]

Constituent	Symbol	Volume %
Nitrogen	N_2	78.084
Oxygen	O_2	20.947
Argon	Ar	0.934
Carbon dioxide	CO_2	0.0350
Neon	Ne	0.001818
Helium	He	0.000524
Methane	CH_4	0.00017
Krypton	Kr	0.000114
Hydrogen	H_2	0.000053
Nitrous oxide	N_2O	0.000031
Xenon	Xe	0.0000087

Table 2. Estimated production potential and price[1] for air products.[7]

Gas		Estimated max. world production (tons/yr)	Estimated production yield (%)	Estimated price, Grade 48 (€/kg)	Estimated price, Grade 50 (€/kg)
Argon	Ar	1,580,202	95	4.2	
Neon	Ne	15,604	95	140	180
Krypton	Kr	192	75	440	480
Xenon	Xe	23	75	840 – 1040	900 – 1100

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[1] 2006 values.

A number of studies have looked for alternate propellant options for EP[9-13]. Krypton has frequently been considered for stationary plasma thrusters, with argon being other candidates. Oxygen or nitrogen have been considered in the context of *in situ* resource utilization[16] or air breathing EP mission studies.[17,18] Alkali metals may also be considered,[9,13] with Li, Na, K, Rb and Cs being the alkali equivalents to, respectively, the neutral gases He, Ne, Ar, Kr and Xe. Finally, bismuth has been considered as another condensed propellant at TsNIIMASH in Russia starting back in the 1960s and up until recently in the US for high power, high propellant-load missions.[10-12]

The selection of an alternate propellant must consider the following aspects:

- Propulsive performance aspects, such as atomic mass or ionization cross section;
- Systems aspects, such as density, phase changes, electrical conductivity or materials compatibility;
- Testing aspects, such as pumping and contamination issues;
- Industrial aspects, such as cost, abundance, toxicity, etc.

A lot of work has been dedicated to assessing the propulsive performance of the different propellant options, including bismuth as a promising low cost, non-toxic, high density, high atomic mass, room-temperature condensable propellant. Noble-gas fed devices, however, constitute nearer-term solutions for electrostatic EP devices in that they pose no contaminations risk on the spacecraft surfaces[10] and they benefit from a high Technology Readiness Level (TRL) for the propellant distribution and regulation components.[11]

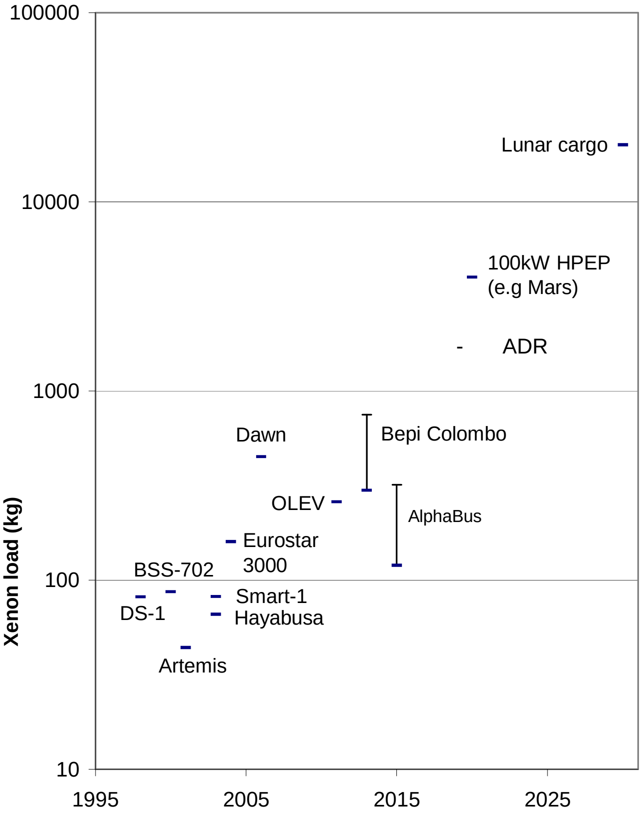
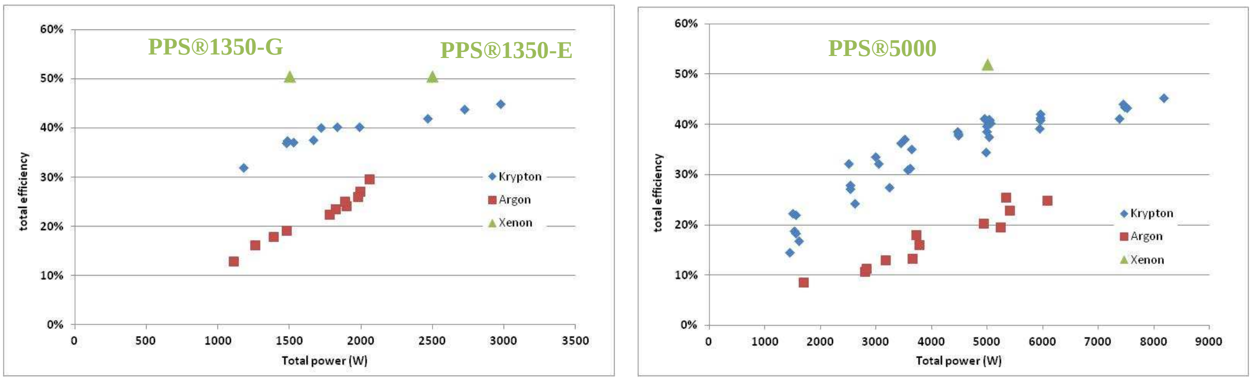


Figure 1. Total xenon load for example past, current or projected EP missions.

However, with Xenon dedicated design thruster, performance obtained with Krypton and especially with Argon remains substantially lower than those obtained with Xenon. In 2012, Snecma has conducted a Krypton and Argon test campaign on a PPS®1350-G, a PPS®5000 and a PPS®20K.



Thruster	Power	Xenon	Krypton	Argon
PPS®1350	1500W	50%	38%	20%
PPS®1350	2500W	50%	42%	/
PPS®5000	5000W	52%	41%	25%

Figure 2. Total efficiency *vs* Total power results during PPS®1350 and PPS®5000 Krypton & Argon 2012 test campaign.

Moreover, correlated to the loss of efficiency, higher temperatures than with Xenon have been observed on ceramic chamber. The temperatures increased with the anode discharge voltage and the anode flowrate. Higher divergences than with Xenon have been measured with Krypton and Argon.

The firsts results of this 2012 Krypton and Argon test campaign show the necessity to work on a specific thruster design and on specific ceramic materials to obtain acceptable performance and total impulse with alternate propellant.

For this purpose, a 2013 Krypton and Argon test campaign is in progress on an improved 5000W class thruster (PPS®5000EM). Two dedicated thruster designs coupled with two dedicated chamber's materials are tested in order to :

- Increase total efficiency by increasing ionization rate
- Reduce voltage sensitivity
- Reduce erosion by increasing temperature tolerance

This paper will report 2012 Xenon, Krypton and Argon test campaign results and first conclusions together with 2013 ones and noticed improvements.

Another section of the paper will concentrate on the systems aspects of propellant options for gas-fed EP devices. The state-of-the-art supercritical storage option will be traded against cryostorage for several candidate gaseous EP propellants. This trade-off will finally be illustrated by mission examples computations that highlight the main benefit of using alternate gaseous propellant options, such as krypton.

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