ELECTRIC PROPULSION FED BY CRYOSTORED PROPELLANTS FOR HIGH POWER MISSIONS

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Abstract

All noble gases can be stored in liquid form at cryogenic temperature. However this possibility is not yet used in the field of electric propulsion. This paper describes the performances of propulsion subsystems using liquid xenon or krypton for three missions : orbit topping, solar electric interplanetary probe and nuclear electric 100 kW heavy probe. In each case, the use of liquid storage enables a significant dry mass saving huge volume gain and simplified ground operations.

The other great interest of liquid storage is the possibility to replace xenon by krypton without major modification of the propulsion subsystem.

1. Introduction

Present Electric Propulsion flight missions utilizing ion or Hall-effect (stationary plasma) propulsion devices all use supercritical storage of xenon.

Storing xenon in a supercritical state typically in high-pressure (up to 150 bar), carbon-over-wrapped titanium tanks, however, has three main drawbacks:

- The tank mass fraction (~10%) is typically higher than for chemical propulsion;
- High-pressure valves and a regulator must be placed in-between the propellant tank and the thrusters, which results in a penalty in terms of mass and reliability;
- The safety margins of the tank are usually insufficient to permit unrestricted presence of personnel around the structure after the tanks have been filled out.

Storing the propellant in a liquid state presents several advantages:

- The density is higher (3057 kg/m^3 versus 1200 – 1600 kg/m^3 for xenon), meaning a smaller tank for the same mass;
- The tank pressure may be controlled so as to match the required feed pressure of the thrusters, so that the high-pressure regulator is rendered unnecessary;
- There are no rapid fluctuations of the feed pressure, a phenomenon common with some pressure regulators.

For future heavy, high-power electric propulsion missions requiring large propellant loads, krypton, argon or neon become very attractive, but high-pressure storage of these propellants becomes impractical, while liquid storage is very attractive.

The cryogenic liquid state storage has not been yet retained because the cryogenic system is perceived as complicated, compounded by the phase separation problem in microgravity. These expected drawbacks are analysed and eliminated by a proper design of the system.

2. System aspects

- The low-pressure tank mass is reduced compared to that of a supercritical storage system;
- The tank fill-in operations may be very fast, whereas fill-in operations on a supercritical system may require several days. The supercritical filling speed is limited by the xenon heating by compression, complicated by the poor thermal conductivity of tank walls.

- For future heavy, high-power electric propulsion missions requiring large propellant loads and possibly propellants other than xenon, such as krypton or neon which have a much lower density, high-pressure storage of the propellant becomes impractical.

An additional benefit of cryo-refrigeration in a condensed state for missions requiring large propellant loads is that this technology renders viable alternate propellant options, such as krypton, which would otherwise carry an unacceptable mass penalty with high-pressure, supercritical storage systems. This in itself is a strong motivation, given that the price of xenon has seen a three- to five-fold increase since late 2007.

The low pressure storage has a big advantage : the operators can continue to walk around the spacecraft without problem : the safety coefficient is greater than 5.
The storage duration is comprised between two months for orbit raising, up to 5 years for a Jupiter mission. The propellant needs to be actively cooled. This could be easily performed by a small Cryocooler such as those qualified for space use [6].
In orbit, the propellant is under microgravity and in equilibrium with its vapour. The thruster operation induces a very small acceleration (in the range 2.10^{-5} - 5.10^{-5} g).
This is compatible with the use of a classical PMD (Propellant Management Device), as in the case of surface tension tanks for storable propellants.
The method is to perform cryogenic liquid acquisition and to vaporise it for thruster use.

3. Cryogenic storage design

The Snecma's heritage and know-how in terms of cryogenic space propulsion systems is very useful to design a cryogenic storage system for noble gases, operating in microgravity.
Its experience in the launch vehicle engines development [1] (Vinci, Vulcain X, VEDA), and production (HM-7B, Vulcain, Vulcain 2) is very useful, especially in the field of material properties at low temperature, hermetic sealing and handling.
Low-cost cryogenic propulsion (LCCP) systems for on-board propulsion on space exploration missions have also been studied [2]. This is especially interesting since LCCP applied to interplanetary missions implies control of cryogens in microgravity for an extended period of time : active refrigeration becomes necessary. LCCP implies also phase separation between vapour and liquid during coast phases (microgravity), the same requirement applies to noble gases liquid storage.

The impact at system level of storing xenon – or other candidate propellants for EP – in the liquid state has been briefly discussed in Ref. [3]. References [4] and [5] have also discussed the possibility of storing cryo-refrigerated solid xenon to achieve an even greater density.

The figure 3.1.1 shows the generic layout of the propulsion subsystem : the tank is located in the centre of the spacecraft in order to avoid centre of mass disturbance. A fill and drain line vacuum insulated is located at tank bottom. The cryocooler is also located at tank bottom. It cools the tank PMD thus insuring that liquid is always available near PMD. The tank walls are cooled by conduction. The evaporated propellant feeds the thrusters.
The Cryocooler is itself cooled by a cooling loop or a heat pipe linked to a radiator.

The figure 3.1.2 shows the schematic diagram of the vacuum insulated tank. The inner tank is superinsulated. The conduction through the mechanical support (low loss straps) is very low. For a 600 kg capacity tank, the overall loss is less than 5 W. This is consistent with the performance of space qualified cryocoolers [6].

The tank can be filled several days in advance. The vacuum insulation enables several days’ autonomy without power (after fairing closure). The tank can be actively cooled in the payload preparation room.

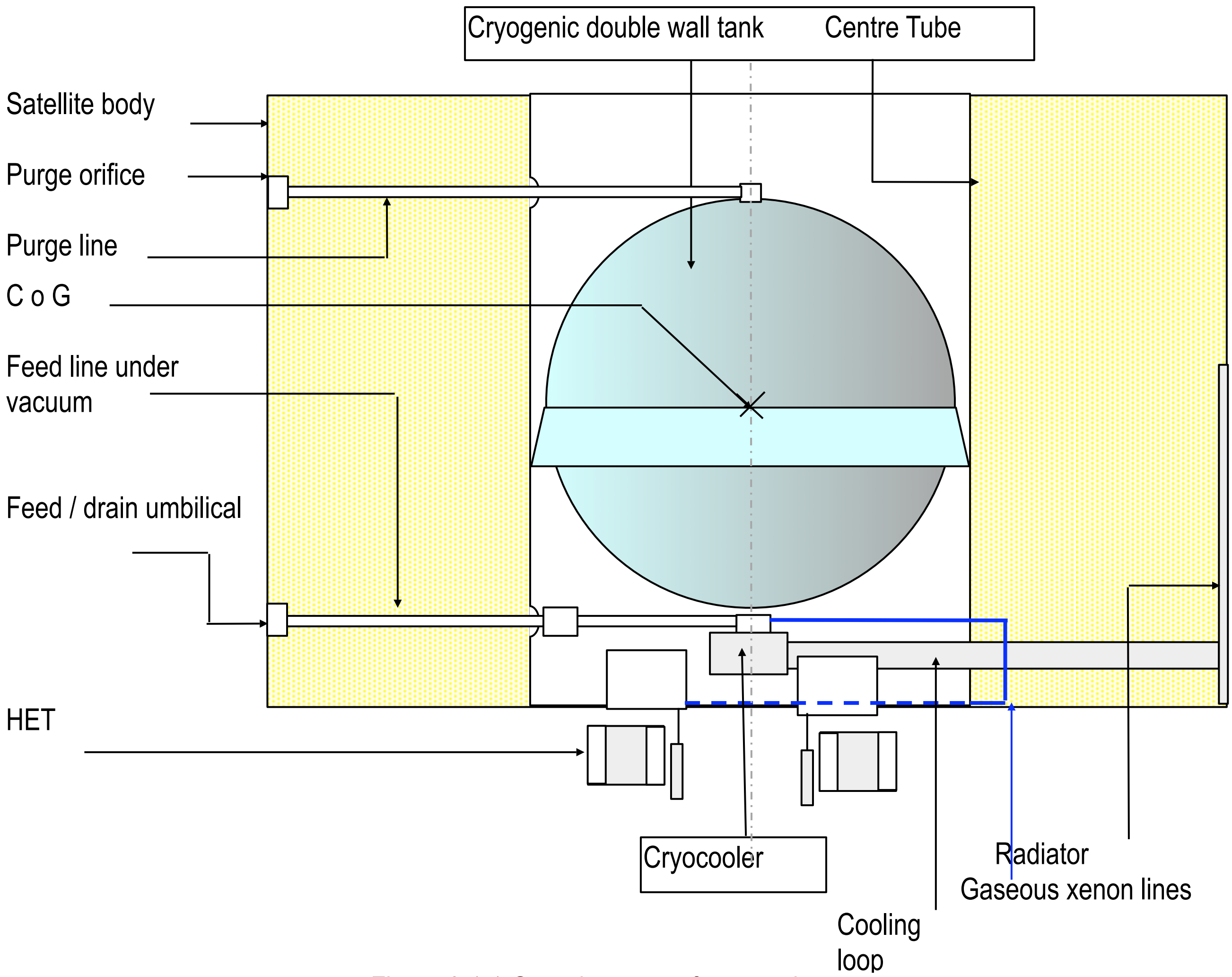

Figure 3.1.1 Generic layout of cryogenic storage

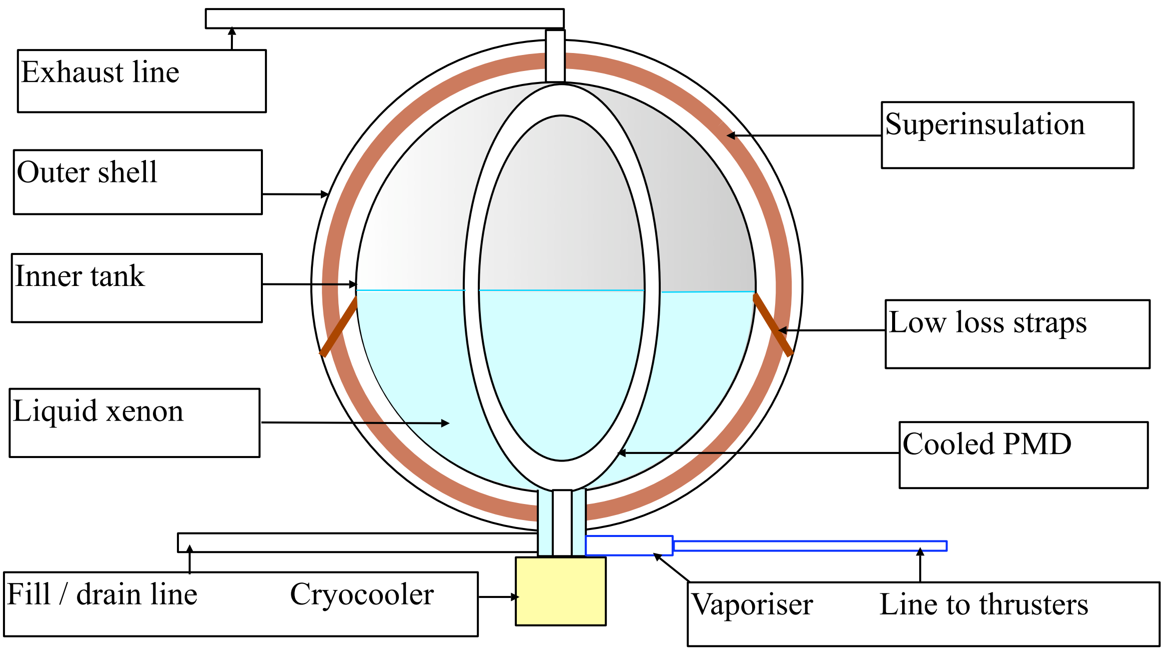

Figure 3.1.2 Schematic diagram of the vacuum insulated tank

4. Mission examples

4.1. Telecommunication satellite with orbit topping

For a typical High Power telecommunication satellite with a mass of 4240 kg in geostationary orbit, the orbit topping shall provide a ΔV of 933 m/s corresponding to a Hohmann ΔV of 633 m/s. It is performed by two PPS ® 5000 (5 kW each) mounted on wide angle TOM (Thruster Orientation mechanism) in order to fire near orbit plane during transfer. In these conditions, the (GTO) launch mass is = 5938 kg. An all chemical transfer satellite would weigh 6968 kg.
The weight gain between chemical and electrical transfer is therefore **one ton**. Cryo storing liquid xenon in this scenario permits to accommodate the extra xenon required for orbit topping on a commercial satellite where only NSSK is performed with electric propulsion.

Xenon Mass	260	kg		
Tank mass	15	kg		
Useful power	10000	W		
go.Isp	15691.2	N.s/kg		
Efficiency	0.56			
Total thrust	0.71	N		
Transfer Duration	5 715 676	s	i. e. 66.15	days

Liquid xenon storage conditions : T = 184 K p = 2,67 bar, liquid density = 2809,78 kg/m^3.

The liquid xenon tank is actively cooled by a Cryocooler during the 2 months 5 days transfer. Owing to the high reliability and lifetime (> 10 years) of Cryocooler, the cooling failure probability is very low.

The interest of liquid stage in this case is the ability to use the same volume than a supercritical storage tank (figure 4.1.1). The modifications of a standard satellite (with HET used only for North South Station Keeping (NSSK)) are therefore minimised and amount to adding an equivalent-volume liquid-storage xenon tank if an empty space allocation for optional xenon or helium tanks remains available. The supercritical tanks are used for NSSK after exhaustion of liquid xenon for GTO+ / GEO transfer.

4.2 Solar electric Interplanetary probe (12 kW)

The probe is similar to the NASA DAWN interplanetary probe, but with HET instead of ion bombardment thrusters.
Three PPS®5000 are embarked; two can be used simultaneously (provided solar flux is sufficient).

Xenon Mass :	= 600 kg
Solar panel nominal power (1 AU)	= 12 000 W
PPU input power	= 10 600 W
PPU efficiency	= 94%
House keeping power	= 1400 W

(The PPU losses (600 W) should be added for the total heat dissipation).

Xenon is stored in a spherical tank, located at the centre of probe (figure 3.1.1).

The computed performances indicate a ΔV of ~ 11 000 m/s.

go.Isp	19614 N.s/kg		
Thruster total efficiency	0,56		
Total thrust	0,57 N		
Operating Duration	5724,84	hours	(at full power)
Total Impulse	11 768 400	N.s	(subsystem level)
Launch Mass	1400	kg	
Final Mass	800	kg	

Delta V	10976.30	m/s

The tank mass is ~ 30 kg, its inner volume is 230 dm^3. The outer diameter is 815 mm.
This results in a very compact layout for the probe. A structural centre tube of ~ 850 mm is sufficient to house the xenon tank.

For the same mission, krypton can then be considered instead of xenon.
Reducing the krypton mass by 10 % is sufficient (HET Isp with krypton is 10% higher)

Krypton Mass	550	kg
go.Isp	2 1967.68	
Thruster total efficiency	0,51	
Total thrust	0,46	N
Operating Duration	7 228,17	hours
Total Impulse	12 082 224	N.s
Launch Mass	1 400	kg
Final Mass	850	kg
Delta V	10 961,68	m/s

The noble gases liquid storage is very efficient for interplanetary probes. It allows for a very simple upgrading from xenon to krypton without major probe modification. The same propellant tank is used.

4.3 Nuclear Electric Propulsion module (NEP)

For missions to the satellites of outer planets, NEP may become necessary.
A 100 kW probe - launched in GTO equivalent by ARIANE 5 ME - is proposed. The launch mass is 12 tons.

go.Isp =	25 000 N.s/kg,
Efficiency =	0.58,
Thruster power=	22 000 W,
Total thruster power =	88 000 W.
PPU input power =	90 700 W (efficiency 97 %)
Housekeeping =	4 000 W
Total	95 000 W (margin 5000 W)

Engine thrust = 1,021 N,
Total thrust = 4,083 N

Operating Duration	6802,94	hours
Total Impulse	100 000 000	N.s
Launch Mass	12 000	kg
Final Mass	8 000	kg
Delta V	10 136.63	m/s

The xenon tank volume is 1.54 m^3 (ullage = 8% of xenon volume).

The tank could be either spherical (inner diameter = 1.44 m) or cylindrical (diameter = 1 m Length = 2.3 m). The tank mass is only 55 kg including the Cryocooler head, i. e. 1.3% of xenon mass.
Due to the very high xenon mass, a foam insulation combined with multilayer insulation can provide thermal insulation during ground operation, thus avoiding the mass penalty of an external vacuum shell.

As in the previous case, krypton could be used instead of xenon. In both cases, the use of cryogenic liquid has a decisive advantage : The weight gain is ~ 400 kg (i. e. an increase of 400 kg of the scientific payload). The effective volume gain is ~2 m^3.

The tank volume could be easily tailored to a specific mission by adaptation of the cylindrical length.

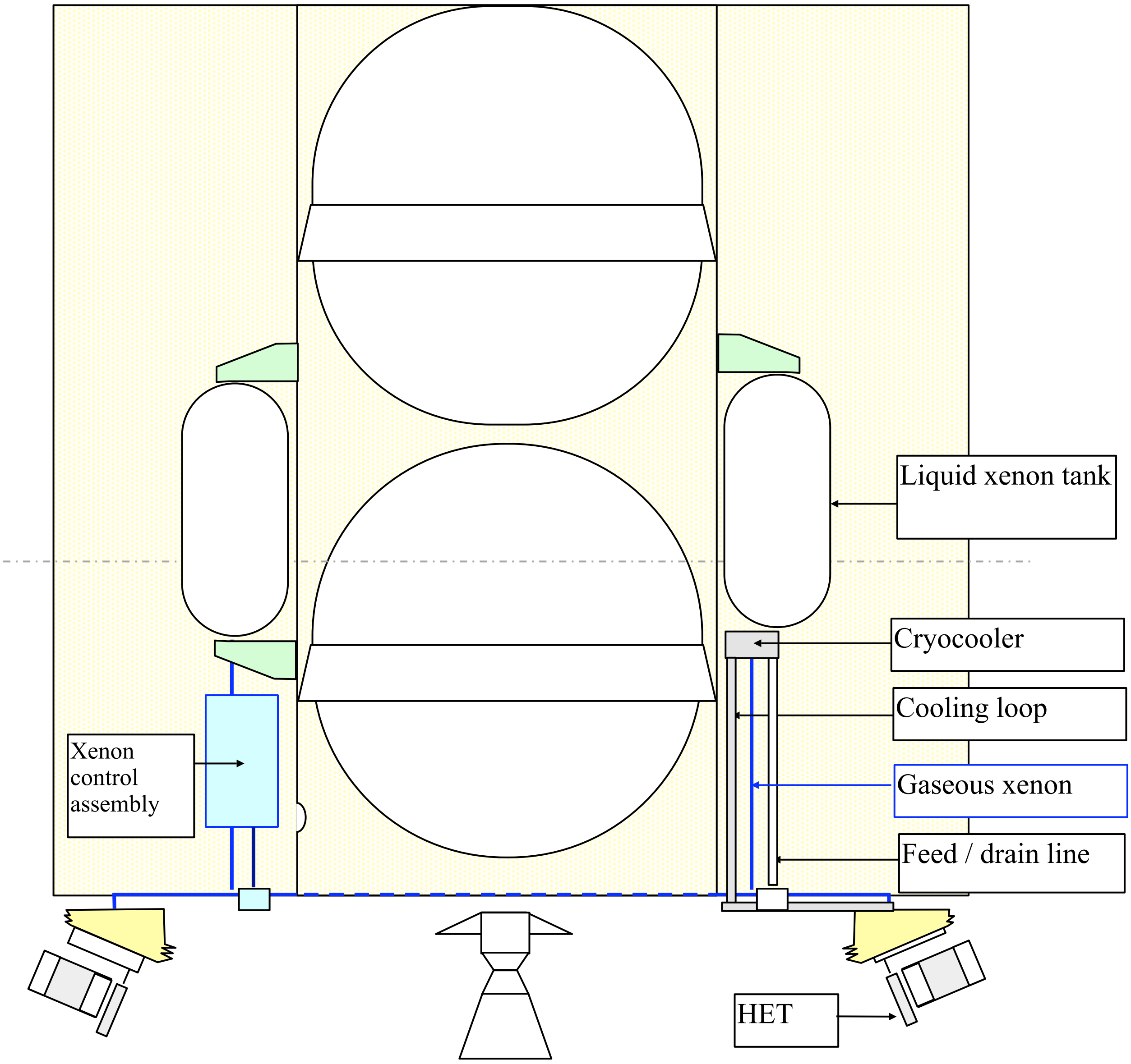

Figure 4.1.1 Telecommunication satellite with liquid xenon tank for orbit topping

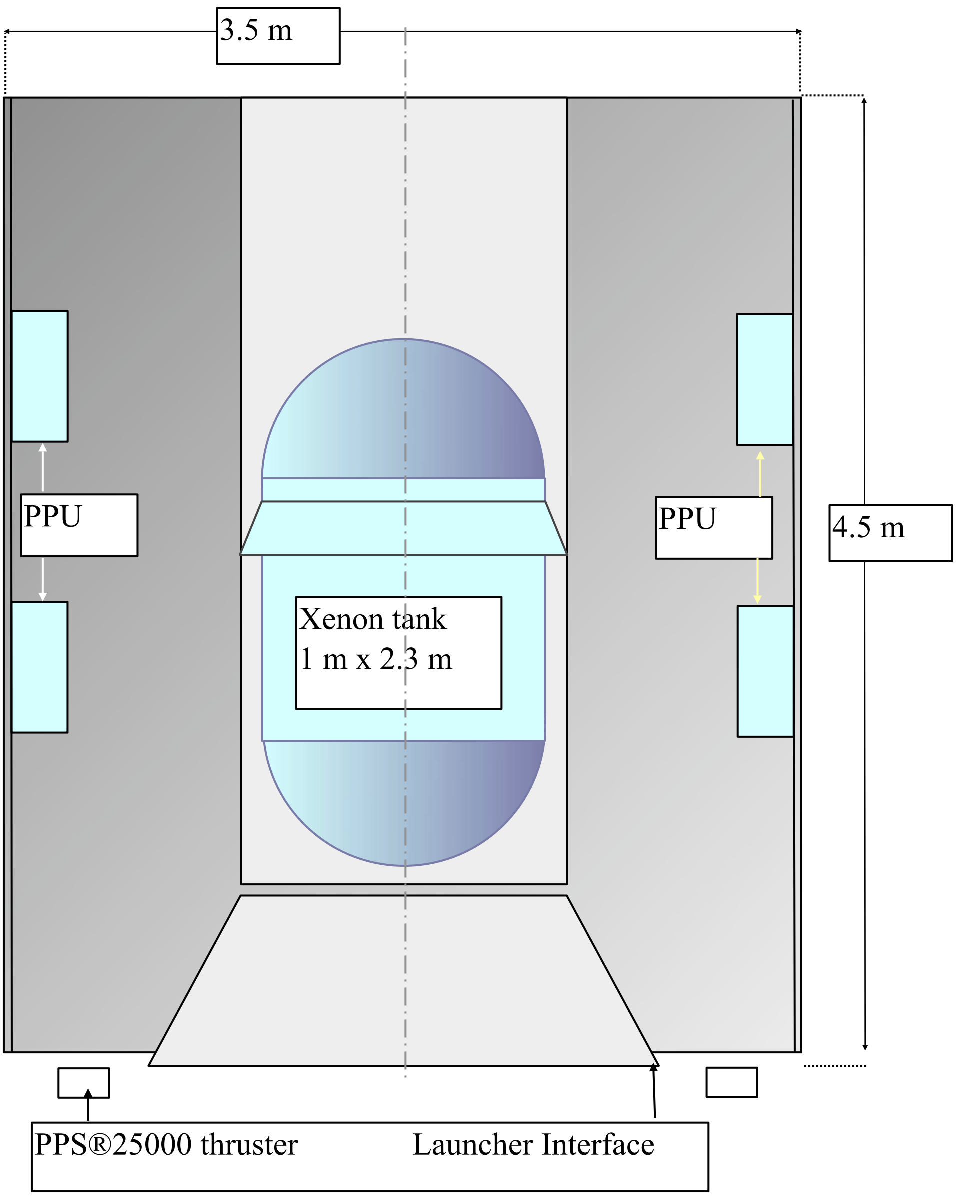

Figure 4.3.1 NEP propulsion module

5. Conclusion

The cryogenic storage of noble gases for electric propulsion is a promising technology. With a tank volume reduced by almost a factor two compared to supercritical (high pressure) storage, a lower dry mass and a much reduced pressure, it renders electric propulsion even more “user friendly”. The other great advantage is the possibility to replace xenon by krypton on a given propulsion subsystem without major modification. On the contrary, supercritical krypton storage will induce major modification : Although krypton becomes more attractive than xenon precisely for high-DV missions where a larger Isp and lower propellant costs are desired, the volume and mass of a high-pressure tank also becomes impractical for krypton. Cryostorage fixes this drawback while keeping the benefit.

The tank cooling is performed by a small cryocooler available off the shelf. The phase separation by surface tension is well proven on most satellites.

The tank capacity is not limited by tooling constraints ; the mass range for xenon starts at 100 – 200 kg and extents beyond 4000 kg.

Another advantage of liquid storage is its flexibility. Using cylindrical wall with hemispherical ends allows for easy capacity adaptation by adaptation of cylindrical length.

In the same spirit, a supercritical tank can be replaced on an existing spacecraft by a cryogenic one thus allowing increasing the capacity by ~80%.

Acknowledgements

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