PPS®NG: Hall Effect thruster for next generation spacecraft

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Abstract: The successful applications of Hall-Effect thrusters on-board numerous spacecraft demonstrated their reliability and they are now widely recognised as a mature technology. It is thus natural that the role of this technology will expand beyond orbit control and station keeping. Scenarios with full electric satellites may in particular be considered for mid-term comsats. Today the interest for those devices concerns not only satellite applications but also exploration missions. On this basis, Snecma propose a design of a thruster featuring operating power modularity with attractive performance over the whole power range typically [1.6-3.2kW]. Our experience acquired both on ground and in space for more than 40 years, constitutes a significant background which enables quick development and qualification of this next generation thruster. This paper presents the technical proposal to develop and qualify such a thruster, the so-called PPS®NG.

Nomenclature

Br = radial magnetic component
F = Thrust
g = gravitational acceleration
Id = Discharge current
Im = Coil current
Isp = Specific impulse
M = spacecraft mass
$\dot{m}$ = total (anode + cathode) mass flow rate
n_e = plasma density
Pd = Discharge power
Ud = Discharge voltage
v_e = electron velocity
v_0 = atom velocity
σ_i = ionisation cross section

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Δt = thruster operating time for a maneuver
Δv = speed increment

I. Introduction

PROPULSIVE maneuvers on spacecrafts are mainly of two types. The first one is to ensure either satellites topping typically from Geostationary Transfer Orbit (GTO) to Geostationary Earth Orbit (GEO) or primary propulsion in the case of space probes. The second one is to correct periodically orbit and attitude in order to compensate perturbations moving the satellite aside from its theoretical orbit. From kinematic and Kepler equations the speed increment, Δv, corresponding to a maneuver can be expressed as a function of the thrust, F, the maneuver duration, Δt, and the spacecraft mass, M:

$$\Delta v = \frac{F.\Delta t}{M} \tag{1}$$

That is to say the thrust level conditions the time necessary to achieve the maneuver. The following table lists the different propulsive missions and the corresponding orders of magnitude for Δv:

Maneuver	**Δv**
Orbit transfer from GTO to GEO	**1500-2000 m/s**
Station acquisition	**8 m/s**
Station keeping operations, or NSSK maneuvers, for a service life of 15 years	
N/S control	**50 m/s/yr**
E/W control	**2 m/s/yr**
Intermediate repositioning if necessary	**34 m/s**
Momentum management during GEO mission	**4 m/s/yr**
Transfer to graveyard orbit at satellite end of life	**15 m/s**
Other missions such as primary propulsion on board space stations or exploration probes e. g for SMART-1	**2800 m/s**

Table 1. Propulsive missions.

Electric propulsion systems have already demonstrated their ability to perform these maneuvers on satellites or space probes.[1-4] It is indeed fully conceivable to use electric propulsion to achieve orbit transfer since time spent to reach GEO from GTO is reasonable and not penalizing neither on the power required for primary functions, nor on the duration of the satellite exploitation.

To give a basic illustration let's assume for instance a 5 tons-class satellite released on GTO. During transfer 90% of available power can be dedicated to the propulsive system, let's say 18kW. With a set of 3kW-class Hall Effect Thruster (HET) able to deliver a global thrust of 1.2N it would take less than 2 months and a half with continuous firing to achieve the satellite circularization, i.e less than 2000 hours of continuous operation.

A drawback could be the radiation dose received by crossing the Van Allen belts. They indeed can cause degradation in solar array performance, comparable to a 15-year GEO mission in worst case calculations. However the SMART-1 experience demonstrated the solar array degradation caused by the successive crossings of the Van Allen belts was lower than expected and even insignificant beyond 5 900km.[3] The GTO-to-GEO full electric transfer should thus remain acceptable in terms of radiation dose.

II. Interest for a versatile thruster

A. HET intrinsic features

Up to now, electric propulsion systems based on Hall Effect thrusters (HET) are mainly used on heavy commercial satellites for North/South Station Keeping (NSSK) maneuvers, while orbit raising is currently performed with chemical apogee thrusters. Plasma propulsion is preferred to chemical propulsion mainly for benefits in terms of operating flexibility and mass savings. The thruster specific impulse, *Isp*, indicates the propellant utilization efficiency:

$$Isp = \frac{F}{\dot{m}.g} \tag{2}$$

In the above equation, $\dot{m}$ is the total mass flow rate and g the gravitational acceleration. *Isp* is 5 times greater in the case of HET than for chemical propulsion.

From Eq.1 the range of thrust required to achieve these propulsive functions must be quite wide to reduce the duration of maneuvers with high Δv. However HET performance reached in a wide range of discharge voltage and current also confirms interest for extended missions.

B. Trend analysis of the Comsat market

Development of versatile thrusters is fully in line with the current significant evolutions at satellite level.

First a constant increase in the maximum mass of geostationary telecommunication satellites has been observed over more than 35 years (Fig.1), and this trend shall continue in the next years. Launchers capacity increases continuously in order to inject telecommunication satellites with constant increasing mass. Ariane 5 performance are besides expected to be improved at least up to 2020.[5] Based on Eq.1 the challenge is to achieve a maneuver with minimized duration. Consequently the delivered thrust - and in turn the thruster operating power in order to preserve *Isp*- shall increase. Further details are provided in Ref. 6 and 7 but to summarize the studies, by using more powerful thruster, the resulting increased thrust will allow reducing N/S nodes firing duration and thereby improve thrust efficiency, and subsequently, xenon mass saving.

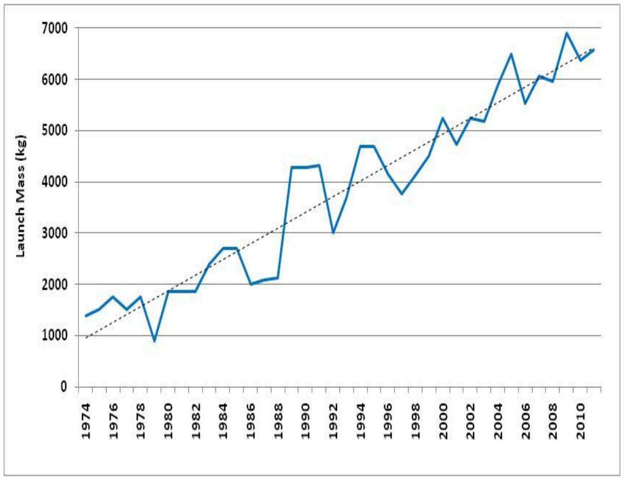

Figure 1. Evolution of comsat maximum launch mass (from Ref.6).

One shall also notice constant improvement of the satellites equipments technologies which enables to envisage more powerful electric propulsion systems. For instance we observe a constant improvement of the batteries and solar array efficiency together with resolution of obsolescence issues on electronic components. Both lead to expand applications to higher power thrusters up to 2.5kW or more. In pratical terms, a new generation of power processing units, Power Processing Unit (PPU) MK2 based on the HPPU technology,[8] is designed to cover a wide range of platforms such as for instance Alphabus, SpaceBus or Eurostar. Astrium and TAS, the main European leading space companies, are involved in the development of a next generation power unit designed to meet the needs of the above platforms with compliant extended specifications compatible with thrusters of 1.5kW-class and more.

Finally existing and future platforms, very different in terms of ranges of mass, design and needs, justify a modularity approach for the propulsive system.

C. Towards full electric satellites

Commercial communications satellites are drastically cost-constrained by international competition. A solution is to put forward full electric satellites for the resulting mass and cost savings.[6,7,9-11] Going back to the illustration given in introduction the space maneuvers would be performed by a single propulsion system with thrusters delivering in a first phase a high continuous thrust for orbit transfer then standard moderate "pulsed" thrust (firing few tens of minutes each day) for station keeping operations. The advantages to put forward full electric satellites are the followings:

- Simplification of the propulsive sub-system: power supply, xenon feed, wiring;
- Savings of secondary propulsive systems by removing chemical engines to ensure additional support functions such as top-up provided the thrusters operation modularity;
- Cost and mass savings.

D. Space probes

Available power on space probes depends on the spacecraft exposure to sun which periodically generates low-power constraints. The flight experience of the PPS®1350-G on board the ESA SMART-1 lunar mission demonstrated the capability of the thruster to operate under power limitation in the range [462 - 1190 W].[3] The electric propulsion system indeed provided the thruster with more or less electrical power so led to more or less delivered thrust. As a main feature of the SMART-1 program, the thruster was able to be started and continuously used with a variable input electrical power without failure nor anomaly.[12]

The PPS®1350-G thus allowed the probe to cover more than 100 millions of km consuming only 82 kg of propellant (Xe) accumulating 4960 h of operation, a world record in flight. The SMART-1 experience is therefore very relevant to possible future applications of HET to spacecraft, and in particular it allowed considering scientific mission with higher Δv needs (up to 10 km/s).

E. Synthesis

The HET performance is demonstrated in various operating and environmental conditions. It clearly evidences their capability to achieve a wide range of space missions, including scientific and commercial ones.

The main driver for the development of new equipments is the recurring cost. It precisely justifies that one thruster with adjustable power range must be extensively studied and quickly developed. The current trend shows that the [1.6-3.2kW] power range is well adapted. State of the art showed that this need is not covered so far by any of the current existing electric thruster (Fig.2).

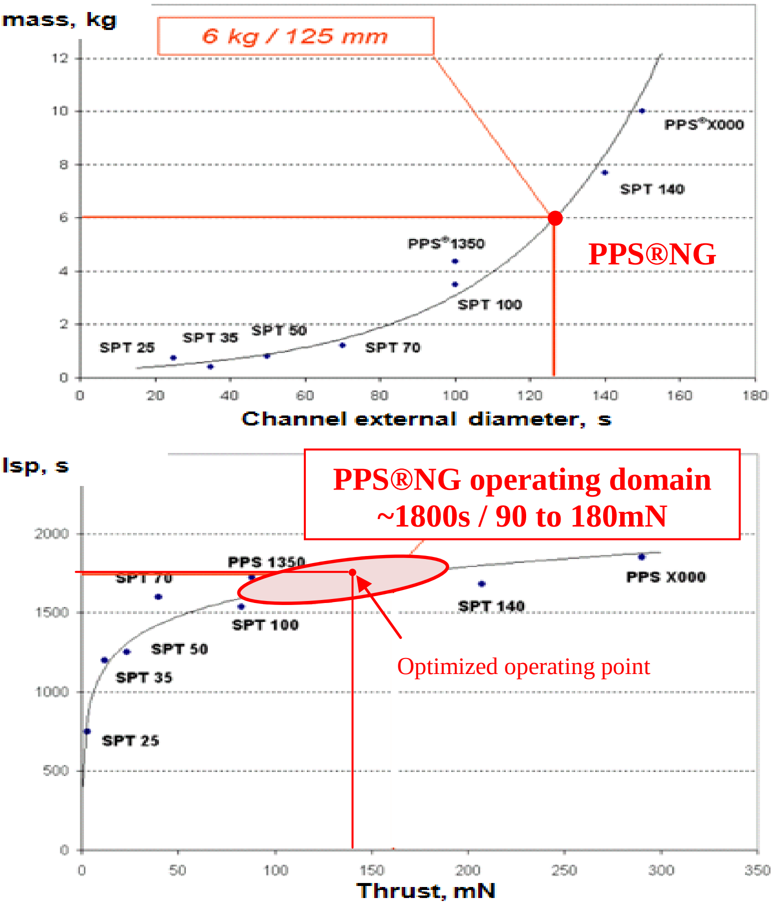

Figure 2. Evolution of the thruster sizes and performance (thrust and Isp) for the HET family

In front of this, Snecma is developing a next generation Thruster called PPS®NG featuring thrust modularity by varying mass flow rate. The feasibility of such a thruster has been demonstrated with attention paid to enhancement of performance, enlargement of operating capabilities, consolidation of reliability as well as improvement of competitiveness.[13]

The following section gives a description of the main features of the thruster and the work performed on the PPS®NG preliminary design.

III. PPS®NG Description

Since 2009 extensive pre-design works have been performed on this new generation thruster. These works concerned the thruster design and architecture, the identification of the more promising technologies, the design justification including thermal behavior at high power and the thermo-mechanical constraints and a preliminary definition. These works led to a consolidated design taking into account the lessons learned of the PPS®1350-G and the new technologies developed in the frame of the PPS®X000 activities.

It is important to note that at this stage of the development the [1.6 – 3.2 kW] power range still can be adapted depending on the spacecrafts needs.

A. Return of experience

Snecma experience is rich in terms of characterization of the operating range of the Hall thrusters (Fig.3 and 4).

An extended characterization test campaign carried out in 2003 on the PPS®1350-EM has clearly highlighted the flexibility and robustness of the engine.[14]

More recently a validation campaign of five new key technologies for high power operation was carried out in the frame of an ESA TRP[15]. Characterization tests and a 300hr-partial life test were performed with the PPS®X000 technology demonstrator. This campaign showed a significant improvement in the thruster performance and the benefits of the technological choices on the dynamic behavior and functional potential of the thruster (thermal and magnetic margins).[16,17] These tests, in addition to determining the ranges of operation of these technologies, enable to assess - or confirm - the role of the architecture (magnetic circuit, thermal architecture) on the extent of the thruster capacity.

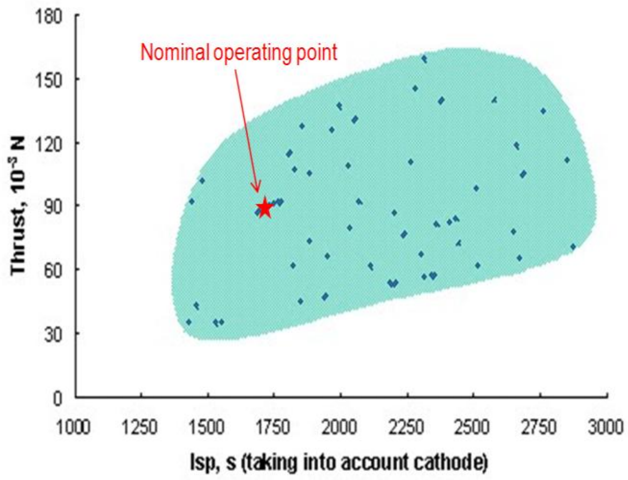

Figure 3. PPS®1350 operating domain

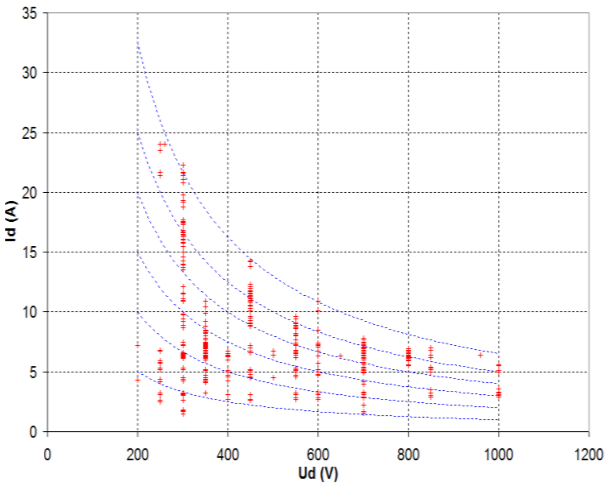

Figure 4. PPS®X000 IV characterization domain.

B. Conceptual studies

1. Magnetic aspects:

Magnetostatic simulations were carried out with 2D finite-element software to design the thruster magnetic circuit (for further details on the modelizations please refer to Ref.18). A parametric study was then carried out in order to optimize the magnetic circuit design, to assess the magnetic capabilities and to determine the optimized magnetic settings. It showed that the radial component of the magnetic induction along the thruster channel centreline, *Br*, evolves linearly with the coils current, *Im*, and that the magnetic circuit doesn't face saturation issues in this range (Fig. 5).

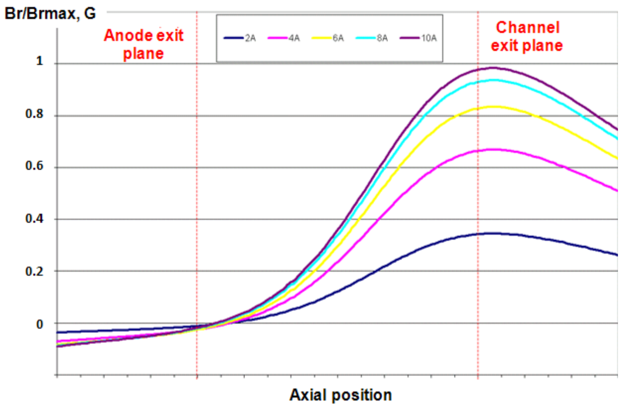

Figure 5. Evolution of the induction radial component on the channel centerline for various coils currents.

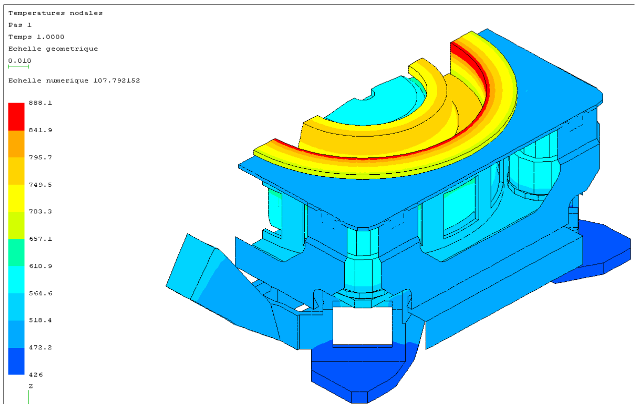

Figure 6. Thermal worst case modelization of the PPS$^{®}$NG (Temperature in Kelvin).

2. *Thermal aspects:*

Another significant issue is the temperature gradients inside the thruster. Changes in performance may be induced by different thermal regimes. This necessitates a transient as well as steady-state thermal analysis of critical components, e.g. ceramics, magnetic material, anode. The results of thermal modelizations for a worst thermal load case show the thermal architecture derived from the PPS®5000 one yields to margins (Fig. 6).

In addition minimizing the effect of the conducted and radiated heat on the spacecraft is a significant design challenge.

3. *Electrical aspects:*

Oscillations in the 20-30 kHz frequency range are related to ionization instability[19-21] and were monitored during the PPS®1350-G characterization campaign. The evolution of the oscillating level in this frequency range with thruster parameters didn't reveal any dependence on mass flow rate whereas dependence on discharge voltage was more complex to analyze.

In addition, to date, the status of sensitive technologies (electrical cables, power electronics) and the understanding of the operation at high voltage on long the duration are not sufficiently mature to be able to develop without risk a Hall thruster operating under high voltage. And moreover the commercial needs don't require much higher *Isp* level.

In other words, as an increase of thruster discharge voltage for higher *Isp* may complicate HET design from a thermal-mechanical standpoint, we have limited discharge voltage to 350 V.

4. *Other limitations:*

   a. *Low power operation*

Behavior at low mass flow rate appears as a limitation of the operating domain. This can be understood assuming that in order to obtain a good ionization efficiency, the ionization mean free path has to be smaller than the length of 'active' zone of the thruster. Mean free path for an atom before ionization, or $mfp_{atom}^{ionization}$, can be written as a function of the atom and electron velocities, respectively v_0 and v_e, the plasma density ne, and the ionization cross section σ_i:

$$mfp_{atom}^{ionization} = \frac{v_0}{n_e < \sigma_i v_e >} \tag{3}$$

Plasma density being directly proportional to the mass flow rate it can be easily understood that ionization mean free path is inversely proportional to mass flow rate. Increase of ionization mean free path can therefore be an explanation for the ionization efficiency reduction at very reduced mass flow rate. Ref.14 evidences the thruster efficiency decreases below a critical mass flow rate, however only discharge voltage dependence was observed.

That said the success of the SMART-1 mission demonstrated the possibility to use the PPS®1350-G thruster at operating power lower than the nominal one. Constrained by the available power the PPS®1350-G operated during 16 months at a discharge voltage between 220 and 350V and a discharge current between 2.1 and 3.5A delivering thrust from 30 to 70 mN. The lowest operating power was of about 25% the nominal one demonstrating the HET ability to operate at low throttling.

b. High power operation: temperature

Operation at high power may be limited due to additional electrical stresses and thermo-mechanical loads. Moreover considering the fast increase of erosion with temperature, the thermal behavior contributes to making the ceramics erosion issue more critical for high power operating points.

Based on these experiences the main challenges for the development of a versatile thruster are to yield margins for the different operating points, i.e. over the whole power range. To do this it is necessary to specifically study erosion processes, discharge stability and cathode and XFC operating capabilities through partial lifetests.

5. Feasibility study of a plasma engine working on a wide power range

Dimensional and functional engine envelopes have been evaluated using in-house code and the scaling laws, with 2500 W and 350 V respectively as power and voltage specifications. Table 2 below gives the major characteristics of the engine.

Id A	Thrust mN	ISP s	Channel mean diameter mm	Footprint (Lxlxh) mm	Mass Kg
7.14	140	1800	125	203x203x108	6

Table 2. PPS®NG main features at 2.5kW and 350V operating point

By applying the same principle for given discharge voltage and geometry, the thruster and functional envelops were assessed and are presented hereafter (Table 3).

Performance	Low Power Operation	Nominal Power	High Power Operation
Power, W	1600	2500	3200
Voltage, V	350		
Thrust, mN	90	140	180
Total impulse, MNs	5		
Lifetime, h *	10 000		

**Duration voluntary limited in order to limit the ground life-test duration*

Table 3. PPS®NG Expected performances over the operating power range.

C. Application of flight proven technologies

Currently one of the main drivers for the development of future thrusters is the cost. The PPS®NG development, which is in line with it, is turned towards mature technologies with high Technology Readiness Level (TRL) together with the sub-system simplification following lessons learned from PPS®1350-G and PPS®X000 demonstrator. Indeed Snecma is involved in numerous developments and research and technology activities (with internal, ESA and CNES support). Thus key technologies have already been tested or qualified in the frame of previous or current developments and studies.[15,22-24]

Even if testing campaigns carried out on prototypes demonstrated the viability of the HET concept for operating power lower or greater than nominal one, designing very competitive thrusters remains a challenge from scientific and technological point of view.

Basically the chosen architecture and technologies are adapted to high power operation, i.e. for high level of discharge current and temperature.

The thruster architecture relies on a Snecma patent[25] and key technologies selection derived from scientific studies carried out in the frame of R&T programs. Specific development programs, on progress, deal with thermal aspects (architecture optimization and materials), mechanical robustness (anode, materials, connectors), lifetime capabilities (channel design and material, magnetic circuit).

All these elements have already been taken into account in the PPS®NG preliminary design.

D. Engine design optimization

This study was conducted to refine the optimization of the PPS®NG mechanical design (assembly, stack up, thermomechanical resistance) with regard to the dimensional constraints of the imposed magnetic configuration, the thermo-mechanical behavior and the mass objective. This preliminary analysis also provided a first list of the critical technologies that should ensure the robustness of the thruster on the operating range.

A more advanced version of design was validated by the satisfactory results obtained by thermal and magnetic modeling, based on the above considerations and requirements. The thruster preliminary design was thus determined; Figure 7 shows a 3D view of the PPS®NG thruster.

Concerning cathode and XFC, we will use on-the-shelf equipments - e.g. derived from PPS®1350-G ones with few adaptations - in order to reduce development activities. The baseline configuration is the use of single cathode. This single-cathode version of the thruster unit was first proposed and selected in 1999 for the Skybridge program with the so-called PPS®1350-S. Although all stationary plasma thrusters that have flown to date were fitted with two cathodes, life qualification requirements have always been met with single-cathode operations,[12,26-28] and nowadays several Hall thruster designs feature a single cathode.[29,30] It should finally be pointed out that thruster cold redundancy can still be in effect. A solution that enables cathode cross firing - without modification on electronics or impact on the reliability - is proposed in the frame of the TMA-NG:[6] any of the two thrusters can be fired with any of the two cathodes, i.e. its own cathode or the other thruster's one.

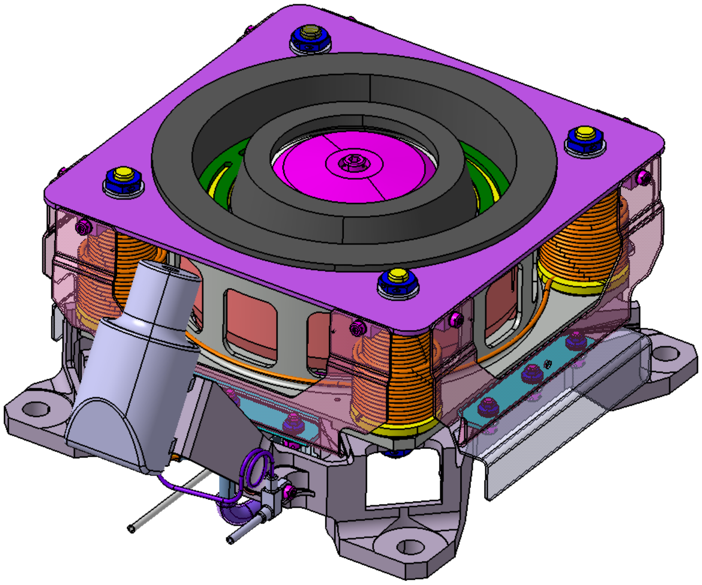

Figure 7. Sketch of the PPS®NG thruster

E. Technology maturation

The thruster is fully based on ESA technical standards. Its development benefits from Snecma experience in the field of electric propulsion since more than 45 years and in the field of HET since the early 1990s. Our know-how has been recently confirmed by the successful testing campaigns carried out on the first prototypes of the 500W-class PPS®X00[23] and the 20kW-class PPS®20K[24] thrusters.

Based on the above considerations the technological readiness level of the PPS®NG is TRL4/5 allowing entering in a preliminary design phase (Phase B). The expected TRL at the end of the work is TRL 8 corresponding to a ground qualification in relevant environment (vacuum) including life test, i.e. to bring the thruster to a "qualified for flight" status.

IV. Development plan and logic

Thanks to the technical choices (flight proven technologies, qualified processes, and on-the-shelf equipments), the PPS®NG development plan and logic are simplified and subsequently cheaper.

A. Objectives

The aim is to qualify a thruster efficient and hard-wearing in a wide power range under strong competitiveness constraints. Taking into account the maturity status of the functional inputs, the points requiring further investigations in the following phases have been identified. The development and qualification logic is based on:

- Application of scientific knowledge on physical mechanisms with simulation codes and prediction models improved and validated throughout research results;
- Implementation of thruster technologies and materials developed for the PPS®1350-G and PPS®5000;
- 2000 h life test milestone achieved before the RCD to demonstrate the ageing behavior is in accordance with predictions.

B. Project Phases and description of the activities

The development program of the PPS®NG will be performed in three main phases each of them being completed by a dedicated review (successively Preliminary Design Review, Critical Design Review, Qualification Review).

1. Preliminary definition phase (phase B):

The studies will mainly relate to the PPS®NG functional, mechanical and thermo-mechanical characteristics. The aim is to finalize the thruster design through specific calculation codes (mechanical, thermal and magnetic modelizations and performance predictions) and technologies trade-offs in order to manufacture a limited number of models required for the development (Structural and Thermal Model, Engineering Model, Demonstration Model). This phase will basically focus on the finalization of the current outline issued from the predevelopment phase :

- Resolution of the residual issues relative to adaptation and/or feasibility of the proposed concepts;
- Selection of technologies with high TRL with demonstration tests at component level;
- Achievement of the thermo-mechanical and electro-mechanical justification.

2. Development phase (phase C):

Most of the manufacturing processes that will be used on the PPS®NG thruster are qualified, i.e. only a limited number of processes will have to be validated during this phase.

The development phase is thus mainly dedicated to the realization of development tests to validate performances and mechanical, thermal, functional and endurance behavior, by achieving a partial 2000h endurance test including partial End-to-End (E2E) tests. This phase will enable in particular to demonstrate the thruster ability for orbit transfer operations.

3. Qualification phase (phase D):

The qualification phase will include the manufacturing of the qualification model. The Qualification Model will be submitted to the qualification test program, including mechanical and thermal environmental tests as well as life test.

Major key point lies in the ability of the thruster to ensure its functional performances over its life (15 years in orbit leading to more than 6,000 to 7,000 hours of cumulated firing time and 5000 cycles of thruster ignition). The demonstration of this ability in lifetime is thus based on a life test including a 1.5 qualification margin factor. This leads to 10,000 hours for ground qualification testing in vacuum chamber to simulate the operation in orbit. It implies a duration of the endurance test of 20 000 hours with a 50% rate of ON / OFF cycles.

C. Facilities

Several facilities are available in Europe with the suitable thrust balance, arm probe, cold box, and power supplies. It includes Snecma own benches: electric and pumping capacities are indeed compatible of the nominal operating point of 8 mg/s throughput. For tests at high power - delta-qualification at high-flow or characterization campaigns - other test facilities will then be involved in the development program: e.g. the CNRS “Pivoine” bench with pumping capabilities of the order of 20 mg/s Xenon and equipped with necessary diagnostic.[24]

The mechanical (vibrations, shocks) and EMC (Electromagnetic Compatibility) tests will also be performed on European facilities - existing or under development - with no need of modification.

V. Conclusion

The missions to be covered by the propulsive system and the range of comsats classes are widening so that the next generation propulsive system shall evolve. Thanks to scientific and technological advances, optimum propulsion system on board comsats is today based on the use of HET to complete the functions. Basically orbit topping would be fulfilled at maximum power in order to offer the maximum thrust, and attitude control at minimum thrust in order to save power for the payload functions. The resulting upshot is also to increase the propulsive system performance: at short-term by reducing significantly the amount of chemical propellant and at mid-term by totally removing chemical propulsion.

The development of more efficient Hall thrusters represents certain design and technological challenges. The PPS®NG, derived from the extensive heritage on PPS®1350-G and PPS®5000, will provide quickly an adapted solution to the market need. The expected performance of this new thruster addresses the needs of the incoming heavy comsats for the two next decades and is also well adapted for space probes with a cost effective design.

Besides performances improvement and functions extension, the drivers of this development are reduced cost (both recurring and not recurring), increased reliability and quick availability of qualified hardwares.

The results obtained by the Snecma PPS® family demonstrate the technology for these applications is mastered. They also helped to made technological trade-offs for the PPS®NG design with attention paid to reliability. The chosen key technologies have reached sufficient TRL to proceed to the development of this next generation thruster with drastically reduced risks and improved competitiveness.

Acknowledgments

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