High Performance Green Propulsion (HPGP): A Flight-Proven Capability and Cost Game-Changer for Small and Secondary Satellites

Aaron Dinardi
Ecological Advanced Propulsion Systems, Inc.
2900 K St NW, Suite 501, Washington DC 20007 USA; (+1) 202-536-1603
aaron.dinardi@ecaps-us.com

Mathias Persson
ECAPS AB
Box 4207, SE-171 04 Solna, Sweden; (+46) 8-627 6390
mathias.persson@sscspace.com

ABSTRACT

In recent years, the capabilities (and as a result, the wider acceptance) of small satellites has increased tremendously. This has been primarily due to advances in payload technologies, which have allowed sensor components to better operate within the volume and power constraints imposed by smaller platforms. However, in order for small satellites to provide a truly viable alternative to a greater number of missions and customers, the platforms themselves must begin offering increased capabilities – more on par with those of larger satellites. An important area where the capability of small satellites has continued to lag significantly behind their larger cousins is propulsion. The reasons for this are many, including: platform mass and volume limitations, personnel safety concerns, hazard limitations of existing integration facilities, costs associated with propellant transportation and launch site processing, or “blanket restrictions” imposed on secondary/rideshare satellites (due to concerns regarding possible adverse impacts to the primary satellite). But regardless of the specific reasons applicable to any individual mission, the resulting capability limitation is the same: small satellites are usually “stuck” in the orbit they are initially injected into; which adversely affects their scientific utility and can make them a non-option for many customers.

High Performance Green Propulsion (HPGP) provides a flight-proven solution to each of the many concerns which typically preclude the inclusion of a liquid propulsion system on small satellite missions. Additionally, the many benefits of HPGP provide a game-changing capability increase for small satellites; thus allowing them to further close the gap with larger platforms. This paper will: 1) provide a PRISMA mission overview and short “2 year update” of the on-orbit HPGP data, 2) delve into the details of each of the issues identified above, and 3) provide examples of the capability increases and cost savings able to be achieved through the implementation of various HPGP hardware solutions on small satellite platforms.

I. INTRODUCTION

High Performance Green Propulsion (HPGP) provides a flight-proven solution for increasing the capabilities of small satellite missions. Whereas historically most small satellites have typically not included liquid propulsion, often due to volumetric constraints or restrictions imposed on secondary/rideshare satellites resulting from the hazards associated with hypergolic propellants, low-toxicity “green” propellants such as HPGP provide a new opportunity for small satellites to expand their mission utility.

Benefits of High Performance Green Propulsion

HPGP provides a number of important new benefits to small satellite missions, including increased performance over monopropellant hydrazine [1-3], simplified handling and transportation, and significantly reduced mission life-cycle costs as compared to hydrazine [6,7]. A brief overview of the details within each of these benefit areas is provided below:

Increased Performance: HPGP has been successfully demonstrated on-orbit (on the PRISMA mission) for over two years [3], and shown to provide a 32% mission average performance increase over monopropellant hydrazine [1-3]. As a result, a smaller tank is able to provide an equivalent overall delta-v to that of a larger hydrazine system. Alternatively, a simple orbit-raising and/or de-orbit capability could be achieved with a very small tank; thus either extending the useful mission lifetime for small satellites injected into low-altitude orbits, or allowing those injected into higher-altitude orbits to still meet the 25 year “orbital debris mitigation” limitation.
Simplified Handling and Transportation: Unlike hydrazine, which requires a rigorous regime of safety procedures, HPGP handling does not require any specialized safety equipment (such as SCAPE suits) or facility-related precautions (such as explosion-proof electrical outlets and air scrubbers). This is due to the fact that HPGP has very low toxicity, is extremely stable (insensitive to mechanical shock, air and humidity) and non-flammable. Additionally, HPGP has received a transport classification of UN and DOT 1.4S; thus allowing it to be transported on commercial passenger aircraft. When taken together, these many benefits provide significantly increased “responsiveness” (on a much smaller budget) and may also even allow the future possibility of shipping some satellites to the launch site already pre-fueled (thus completely avoiding the need for any fueling operations during the launch campaign).

Reduced Costs: For the PRISMA launch campaign, the HPGP propellant was shipped to the launch site by air along with the satellite and all fueling activities were declared to be “non-hazardous operations” by the Range Safety authority. As a result of the simplified transport and handling, greater than 2/3 cost savings were realized for the HPGP transportation and fueling activities as compared to the equivalent set of activities performed for the hydrazine system which was also flown on PRISMA.

Restrictions on Secondary/Rideshare Satellites: For fueling activities performed at the launch site, “non-hazardous” HPGP operations allow for shorter, more responsive launch campaign processing timelines; as well as the execution of concurrent payload processing activities (i.e. - HPGP fueling operations do not adversely impact the processing schedule of other payloads). Furthermore, the safe and insensitive characteristics of the HPGP propellant pose significantly less risk (both physical and schedule) to a primary satellite; thus enabling propulsion systems on secondary payloads where they have previously been forbidden.

**REACH**

An additional important aspect to consider for future applications is that hydrazine was added to the European Chemicals Agency (ECHA) REACH (Registration, Evaluation, Authorization and Restriction of Chemical substances) list of Substances of Very High Concern (SVHC) on 20 June 2011. As a result of being added to the SVHC list, hydrazine may be banned from future use within the European Union; whereas all of the constituents of the HPGP propellant LMP-103S are already registered in the REACH system without any such concerns.

II. PRISMA MISSION SUMMARY

The PRISMA spacecraft (financed by the Swedish National Space Board), shown in Figure 1, were successfully launched together with the Picard spacecraft from CNES on a Dnepr launch vehicle from the Yasny launch base in Russia on 15 June 2010. The Dnepr launch service was provided by ISC Kosmotras (Russia) and the Dnepr rocket was manufactured by Yuzhmoye (Ukraine).

**Mission Description**

The PRISMA HPGP propulsion system is the first in-space demonstration of the HPGP technology and is used for providing the required ΔV for the PRISMA main satellite maneuvers. The PRISMA spacecraft, mission objectives and overview have been described in numerous papers [1-4, 8-12]. ECAPS holds numerous worldwide patents with respect to the HPGP technology, including propellant formulation and thruster catalyst.

![Figure 1. The PRISMA spacecraft](image_url)

The PRISMA main satellite “Mango” has three propulsion systems, as shown in Figure 2. The monopropellant hydrazine propulsion system is equipped with six 1N thrusters and has a capacity to provide a total ΔV up to 120 m/s. The HPGP propulsion system has two 1N thrusters and can provide a total ΔV of up to 60 m/s (with a tank which has less than half the volume of the hydrazine tank). The two liquid propulsion systems are capable of being operated either simultaneously or separately. This capability also adds redundancy. Specific demonstrations were planned and executed uniquely for the HPGP system with the objective to demonstrate this technology to TRL 9 and perform the first in-space qualification.
The PRISMA HPGP propulsion system uses the first "green" storable monopropellant qualified for space flight, which is the ADN-based LMP-103S. LMP-103S is a blend of ADN, water, methanol and ammonia. The most harmful chemicals in LMP-103S are methanol (in a significantly lower concentration than what is used in typical camping stoves) and ammonia (in a lower concentration than regular household cleaning agents). LMP-103S has a theoretical ≥ 6% higher specific impulse (I\text{sp}) and ≥ 30% higher density impulse than hydrazine. From a mission average standpoint (taking into account all of the different types of thruster firings performed), the PRISMA results have shown the HPGP system to provide an overall 8% higher I\text{sp} than the hydrazine system [1-3].

The LMP-103S blend has low toxicity, is non-carcinogenic and is environmentally benign. Spacecraft propellant loading therefore does not require the use of SCAPE suits. The constituents of LMP-103S are all registered within the REACH system. LMP-103S has moderate vapor pressure. Unlike hydrazine, the LMP-103S propellant is not sensitive to air or water vapor. Since 2003, LMP-103S has undergone extensive ground testing with respect to performance, sensitivity, thermal characterization, compatibility, radiation sensitivity and storability. The propellant has been stored for 6.5 years (and ongoing) in a ground propulsion system end-to-end test; without any indication of degradation or pressure build-up.

Monopropellant LMP-103S has a design shelf-life of one year in its current standard 5L polyethylene shipping container. The spare propellant container for PRISMA was transported to the launch site in Yasny as air cargo, and then returned to Sweden by truck. It has since then been kept in a storage room rated for energetic substances. Recently, about 2.5 years after the propellant was blended, the contents of the container were analyzed. Within the limits of accuracy of the analytical methods used, no change in the composition of the propellant can be detected. There has been no decomposition of the ADN and no contamination from the container. The only measurable change was a 0.1% weight-loss of the container, which indicates that a few grams of the liquid components have escaped. However, this would have a negligible effect on the performance of the propellant.

Despite its high energy content, LMP-103S is classified as an insensitive substance (NOL 1.3) and further classified for transportation as a UN 1.4S and US Department of Transport (DOT) 1.4S article (when stored in its designated transport container), which allows for shipment as air cargo on commercial passenger aircraft.

### PRISMA 1N HPGP Thruster

The design and function of the thrusters developed for ADN-based monopropellant blends have several similarities with hydrazine thrusters. The Flow Control Valve (FCV) is a normally closed series redundant valve with independent dual coils. The FCV is manufactured by Moog and has extensive flight heritage. In the HPGP thruster the propellant is thermally and catalytically decomposed and ignited by a pre-heated reactor. Nominal preheating is regulated between 340-360ºC, which requires an average power consumption of about 7.3W per thruster in the PRISMA application. Detailed information is provided in [4]. For thermal control, the thruster is equipped with redundant heaters and thermocouples.
developed and patented a unique high temperature resistant catalyst. For some operational modes the HPGP thruster has a more efficient combustion than a comparable hydrazine thruster.

**Figure 4. 1N HPGP thruster firing**

Prior to the PRISMA mission, the HPGP thruster was subjected to qualification life tests with a propellant throughput of 25 kg, accumulating 60,000 pulses and 25 hours firing time, which is more than four times greater than the basic PRISMA mission requirements.

**PRISMA HPGP Propulsion System**

The PRISMA HPGP system consists of one diaphragm-type propellant tank with a capacity of 5.5 kg (i.e., 4.5L) of LMP-103S propellant, two service valves, one pressure transducer, one system filter, one isolation latch valve, a CRES pipework and two 1 N HPGP thrusters. The propellant and the pressurant gas are stored in the tank and are separated by means of a diaphragm. The pressurant (Helium) acts on the flexible diaphragm and feeds the propellant via the system filter to the thruster via the propellant FCV. A propellant flow restricting orifice is placed between the tank and the pipework to eliminate pressure surges associated with valve opening during system priming (also called water hammer).

**Figure 5. PRISMA Mango spacecraft**

The system operates in blow-down mode, meaning that the feed pressure decreases due to the amount of propellant consumed. The nominal Beginning of Life (BOL) feed pressure is 18.5 bars at 20°C which gives a Maximum Expected Operational Pressure (MEOP) of 22 bars at 50°C. The nominal blow-down ratio is 3.8:1, allowing the feed pressure to decrease to approximately 5 bars when all the propellant is consumed. The thrust will decrease, due to the change in feed pressure, from its BOL thrust of nominally 0.9 N, down to 0.25 N at End of Life (EOL). The HPGP system dry mass is 4.3 kg (including brackets and thermal hardware) and wet mass is 9.9 kg. All fluid components, including the thruster flow control valve are conventional “Commercial Off-The-Shelf” (COTS) components with extensive flight heritage. The hydraulic schematic and the system layout are shown in Figure 7. The spacecraft system level design with regards to incorporation the HPGP system including environmental, thermal and plume characteristics can be found in [4].

**Figure 6. PRISMA HPGP flight system**

**Figure 7. PRISMA HPGP hydraulic schematic and system layout**
**PRISMA Launch Campaign**

The PRISMA spacecraft, Ground Support Equipment (GSE) and the HPGP propellant LMP-103S were shipped by air from Sweden to Orsk near the Yasny launch base, Russia. Transport of the LMP-103S propellant by air was made possible since it has been approved for transport according to UN Class 1.4S. The only item that could not be included as part of the air shipment was the hydrazine. Due to its hazardous nature, the hydrazine propellant had to be transported from Germany by ship to St. Petersburg and then transported by truck to Yasny, months in advance of the launch campaign. The launch campaign started on 20 May 2010, and lasted for only 18 days in total. The campaign included the following main activities:

1. Main (Mango) & Target (Tango) satellite checkout
2. Propulsion systems checkout
3. Target mating to Main
4. Pressurizing the cold-gas Micropropulsion system
5. Fueling/pressurizing the HPGP propulsion system
6. Fueling/pressurizing the hydrazine propulsion system
7. Final preparation, arming and red tags removal
8. Mounting on the Dnepr Space Head Module

During the PRISMA launch campaign, the benefits of loading a “green” propellant compared to hydrazine became readily apparent. As the HPGP propellant has low toxicity and is non-carcinogenic, loading the spacecraft with LMP-103S was performed without SCAPE. Both the fueling and pressurization of the HPGP system were declared as a “Non-Hazardous Operations” by the Yasny launch base Range Safety. As a result, other activities such as launch preparation of the other co-passenger satellite (Picard) could continue without restrictions during the HPGP fueling operations. In contrast, all activities were stopped and both the CNES and SSC teams were required to vacate the Yasny launch base for two days during the PRISMA hydrazine fueling operations.

All activities related to the HPGP propulsion system loading (unpacking, GSE preparation pre-loading checkouts, spacecraft functional checkout, safety meetings, fueling, pressurization, decontamination and packing) were performed by a crew of only three personnel (two specialists and a PRISMA team part-time technician) over a period of seven days, of which a cumulative total of two effective working days were required for all HPGP propellant handling, fueling and decontamination. In comparison, the hydrazine fueling activities required a crew of five specialists for fourteen days. In addition, the launch base hydrazine fueling support team (safety, medical, fire, etc.) consisted of more than twenty specialists.

Decontamination of the hydrazine loading cart and waste handling of hydrazine was also a major operation compared to that required for LMP-103S. The hydrazine fueling cart decontamination required a team of three people over three days. The toxic waste from the hydrazine operations was 29 liters of hydrazine (the spare batch), 400 liters of contaminated de-ionized water and 70 liters of IPA. The destruction of the hydrazine was characterized as a “significant operation” by the Launch Base. In contrast, decontamination of the HPGP fueling cart was performed within one hour by a single technician. The HPGP-related waste was 1 liter of propellant and 3 liters of contaminated, but non-toxic, IPA/de-ionized water; which were disposed of by the launch base team at no charge. Even though the pre-loading checkout and fueling procedures followed the same principal steps for both of the two liquid propellant systems, the total man hours required during the launch campaign for hydrazine preparation, fueling and decontamination were more than three times higher than for LMP-103S. The pre-campaign hydrazine-related issues also required much more effort to handle than those for LMP-103S as well.

**III. PRISMA TWO-YEAR UPDATE**

The PRISMA and Picard spacecraft were successfully launched with Dnepr from the Yasny launch base, Russia as planned at 14:42:16 UTC on 15 June 2010. The spacecraft were injected into a dawn-dusk sun synchronous orbit with an inclination of 98.28°. Initial perigee was 720 km and the apogee was 780 km. The first contact with PRISMA was established at 16:14 UTC on 15 June during its first passage over the Esrange ground station and commissioning started at SSC’s Mission Control Center in Solna, Sweden.

On June 24, 2010 the first in-space HPGP firings were performed. The first firing sequence was a pulse train of forty 100 ms pulses at a duty cycle of 1%. The firing resulted in the predicted 2.1 cm/s ΔV increase as measured by GPS data. The propellant consumption for the maneuver was nominal. The HPGP propulsion system was thus declared “GO” for mission operations.

The basic in-space flight demonstration of the HPGP propulsion system was comprised of commissioning, four blocks of HPGP-specific firings, and combined firings of the HPGP and hydrazine systems during different formation flying experiments. The firing sequences are defined as continuous, pulse mode, single pulse firings and combined thrusters firings. The test plan is summarized in Table 1. After six months in space, on 17 December 2010, the primary HPGP in-space demonstration objectives had been successfully met; thus successfully achieving TRL-7.
Following completion of the basic mission requirements, ECAPS performed the HPGP-4 demonstrations on PRISMA from DLR’s Ground Control Center in Oberphaffenhofen, Germany between 14 April and 27 May 2010. During the HPGP-5 demonstration, about twenty invited guests from three NASA Centers (Goddard Space Flight Center, Marshall Space Flight Center and Ames Research Center), as well as representatives from ESA, Astrium, SSTL, ATK and Moog witnessed the HPGP firings in situ at the PRISMA Mission Control Center.

After two years of in-space operations the demonstration of 1N HPGP technology has evolved into a qualification, thus achieving TRL-9 for this category of missions.

**HPGP In-Space Life Demonstration**

The HPGP in-space demonstrations have thus far been executed during a cumulative total of 62 days, comprising of 314 HPGP-specific firing sequences. In addition, more than 100 firings have been performed in combined HPGP and hydrazine operation. A total of more than 50,000 HPGP pulses have been fired, the accumulated firing time is 3 hours, and the generated ΔV is more than 37m/s. To date, 63% of the propellant has been consumed, leaving approximately 2 kg of the HPGP propellant which will be used for providing ΔV for new mission objectives during the remainder of the mission through decommissioning.

At End of Life, the HPGP system will have accumulated a total firing time of 5 hours and reached the total predicted ΔV capacity of 60m/s. The current ΔV delivered for the mission is shown in Figure 8; the in-space projection of ΔV versus propellant consumption has also been compared to the maximum ΔV performance achievable based on the steady state performance model. The difference in reduced in-space performance is due to the HPGP system being operated in pulse mode. Propellant consumption for the first half of the mission is shown in Figure 9.
Figure 8. PRISMA HPGP ΔV provided

Figure 9. PRISMA HPGP propellant consumption

**HPGP Performance Comparison with Hydrazine**

A theoretical Isp improvement of 6% was expected for the HPGP system as compared to hydrazine. However, the back-to-back in-space comparison demonstrates higher performance in most cases, as detailed in Table 2. For the first half of the mission, the HPGP system has provided an average Isp increase of 8% over the hydrazine system. The comparison has been performed with the same type of sensors and according to the same process. The comparison is performed at comparable thrust levels.

For continuous firings with near Steady-State conditions, the improvement in HPGP Isp over hydrazine is 6% at BOL, with a trend towards 12% at EOL.

For Single Pulses, the improvement in HPGP Isp over hydrazine is 10% at BOL, with a trend towards 20% at EOL.

For Pulse Mode at very low duty and low propellant feed pressure, the HPGP performance is comparable to hydrazine performance. However, for some pulse modes the HPGP performance provides up to 12% higher Isp than hydrazine. Additionally, the I-Bit difference between the HPGP and hydrazine thrusters for commanded ON times ≥ 100ms is small.

**IV. BENEFITS OF HPGP OVER HYDRAZINE**

HPGP provides numerous benefits to small satellite missions, as described in Figure 10 and Table 3.

![Figure 10. Benefits of HPGP to small satellite missions](image)

**Table 2. HPGP Performance vs. Hydrazine Summary**

<table>
<thead>
<tr>
<th>HPGP PERFORMANCE VS HYDRAZINE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steady-State Firing:</strong> ( I_{sp} ) for last 10 s of 60 s firings</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Single Pulse Firing:</strong> ( T_{on} ): 50 ms – 60 s. (First half of the mission)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Pulse Mode Firing:</strong> ( T_{on} ): 50 ms – 30 s. Duty Factor: 0.1 – 97%</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
The many benefits of HPGP as compared to other liquid propulsion technologies serve to eliminate or reduce the various concerns which typically preclude the inclusion of a liquid propulsion system on small satellite missions, as described below:

**Volume and Mass Limitations**

The demonstrated performance improvements of HPGP over hydrazine (Table 2) also provide for additional, corollary performance increases – beyond Isp and density impulse – in the form of propellant tank volume reductions, and the resulting mass savings. A recent analysis performed by the NASA Goddard Space Flight Center (GSFC) indicates that the overall mass of satellites incorporating HPGP can be significantly reduced [14]. Since satellite structures are often sized specifically to accommodate the propellant tank, a reduced tank volume also allows a reduction in the mass of the supporting structure.

Although the GSFC analysis examined the Lunar Reconnaissance Orbiter (LRO), which was by no means a small satellite, the general conclusions of the analysis are also applicable to smaller satellites as well. Table 4 shows a side-by-side comparison of the as-flown LRO configuration (with hydrazine) versus the mass savings which could have been achieved if it had been flown with a HPGP system instead. Implementing a HPGP system would have allowed for reductions of the total propellant mass by 26% and the required tank volume by 39%. This translates to an estimated 12% savings in total satellite dry mass, and an almost 19% savings in wet mass at launch. Mass savings of this magnitude could have potentially allowed the mission to launch on a smaller launch vehicle or fly with either more scientific payload – both of which are very important considerations for small satellite missions.
**Personnel Safety and Facility Hazard Limitations**

The environmentally benign nature of HPGP enables significantly simplified storage and handling of the propellant as compared to hydrazine. As the first and only flight-proven, storable “green” propellant available, HPGP systems allow satellite missions to meet ever more stringent environmental restrictions. Additionally, with significantly reduced requirements for facility safety measures and personnel protective equipment, operations with HPGP result in reduced preparation time and costs for all pre-launch activities. Simplified ground operations are particularly attractive to help reduce the costs of small satellite missions.

Furthermore, when considered independently from any specific mission, the reduced handling complexity of HPGP translates directly into lower infrastructure and associated overhead costs (facility construction, operation and maintenance, personnel safety certifications, waste disposal, etc.) – which enables smaller organizations such as universities or Small and Medium-Sized Enterprises (SMEs) to establish facilities and processes for propellant handling and fueling operations; thus opening up completely new capability areas for them.

**Transportation and Processing Costs**

Simplified transportation and launch site processing translate to significantly reduced life-cycle costs [6,7] – which is always of paramount importance to small satellite missions. Additionally, the ability for fueling operations to be performed as “non-hazardous operations” (without SCAPE, and on a non-interference basis with a primary and/or other secondary satellites) is also an important selection criterion for many small satellite missions.

Notwithstanding the significant benefits described above, the most important benefits for the majority of small satellite missions are likely are the facts that HPGP utilizes a “heritage” architecture [4] (based on flight-proven, commercial off-the-shelf components) and provides increased performance over hydrazine [1-3], as shown in Table 2.

**V. BENEFITS TO SMALL SATELLITES**

When applied to small satellites, the benefits of HPGP provide new opportunities for both increased mission capabilities [14] and reduced costs as compared to other liquid propulsion technologies, as described below:

**Higher Performance resulting in Increased Impulse**

Small satellite missions will benefit from HPGP due to its improved density impulse over hydrazine.

Replacing a hydrazine system with a HPGP system of the same size can extend the mission life significantly. From a performance perspective, an HPGP system is able to provide an effective increase in propellant for a specific mission ΔV of up to 36%, as compared to hydrazine. This allows for an increased ΔV to be provided to the mission lifetime, or more margin to be included, if an equivalent tank size is employed as would have been used for a hydrazine-based system solution. As a specific example, a transition to HPGP on the Myriade platform was assessed to provide an increase in the total impulse by 28%; when the blow-down model used in the analyses resulted in a 24% increase in the ΔV provided [5].

Alternatively, HPGP can provide an equivalent mission ΔV with a reduced propellant tank size, as compared to hydrazine. Beyond the direct benefit of a smaller and less expensive satellite, the indirect benefit of an overall reduction in the total satellite wet mass at launch can also provide additional launch vehicle related cost savings to a small satellite mission, as described in section IV above.

**Reduced Mission Costs**

As described throughout this paper, the numerous benefits of HPGP provide opportunities for simplified operations and associated cost savings. Although it is difficult to quantify the exact level of cost savings that any specific mission would be able to realize (due to mission-specific differences in flight hardware, propellant volumes, launch sites, etc.), the following analysis provides a top-level summary and a few examples of the potential savings able to be achieved for common small satellite mission configurations.

In order to put the scope of the overall analysis into context, it is helpful to first examine a “non-space” example. Table 5 summarizes a study performed by the US Department of Energy in 2011, which evaluated the life-cycle costs Wal-Mart would incur to replace standard florescent light bulbs with low-energy LEDs in their customer parking lots.

**Table 5. Wal-Mart LED lighting cost analysis**

<table>
<thead>
<tr>
<th>Item</th>
<th>100% PSHA Typical Design</th>
<th>40% PSHA Alternative</th>
<th>LED Installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole Cost</td>
<td>25</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Luminaire Cost</td>
<td>47</td>
<td>74</td>
<td>72</td>
</tr>
<tr>
<td>First Cost of System</td>
<td>$17,357</td>
<td>$10,400</td>
<td>$14,400</td>
</tr>
<tr>
<td>Analysis Period (years)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Annual Energy Costs</td>
<td>$13,825.38</td>
<td>$8,998.19</td>
<td>$5,519.64</td>
</tr>
<tr>
<td>Life-Cycle Cost (PV)</td>
<td>$192,257.76</td>
<td>$103,892.02</td>
<td>$55,196.44</td>
</tr>
<tr>
<td>Annual Maintenance Costs</td>
<td>$5,476.00</td>
<td>$5,476.00</td>
<td>$1,840.00</td>
</tr>
<tr>
<td>Life-Cycle Maintenance Cost (PV)</td>
<td>$47,610.00</td>
<td>$47,610.00</td>
<td>$11,400.00</td>
</tr>
<tr>
<td>Total Life-Cycle Cost (PV)</td>
<td>$242,257.76</td>
<td>$249,392.02</td>
<td>$220,596.44</td>
</tr>
<tr>
<td>Comparison with LED System</td>
<td>$321,484.86</td>
<td>$327,527.32</td>
<td>$330,527.32</td>
</tr>
</tbody>
</table>


Dinardi
The US Department of Energy study considered both the up-front infrastructure and commodity costs, plus the continued costs of operation and maintenance. As shown in the right hand column of Table 5, despite the fact that the up-front cost of the LED solution was 42% - 88% higher than the two florescent-based solutions evaluated, the significant cost savings provided by the LED solution in the areas of operation and maintenance resulted in the “green” option being less expensive from a complete life-cycle standpoint.

Taking a similar approach, Table 6 identifies the primary satellite propulsion system cost categories of 1) flight hardware, 2) propellant and its transportation to the launch site, 3) launch campaign processing, and 4) propellant waste disposal and facility infrastructure; broken down into their respective sub-categories. For each sub-category, a “delta cost” comparison is presented (i.e. – the difference in cost between equivalent system solutions based on either HPGP or hydrazine). Positive values (highlighted in green) identify items for which the HPGP-based solution provides a cost savings over a hydrazine-based solution, and negative values (highlighted in red) identify items which by themselves cost more than an equivalent hydrazine-based solution.

It is important to point out that, for the sake of maximum conservatism, some sub-categories which can provide significant cost advantages to HPGP-based solutions have been excluded from the analysis. Such areas include the propellant tank (item 1b), propellant transportation to the launch site (item 2b), SCAPE valet and associated communication services (item 3b) and propellant waste disposal (item 4e).

For the propellant tank, HPGP allows a smaller, and therefore less expensive, tank to be employed – while retaining the same total mission ΔV. However, the analysis assumes that an identical tank size is used for both system solutions.

In the area of propellant transportation, it is possible to procure hydrazine at some launch sites (such as Cape Canaveral and Vandenberg); whereas it must be shipped by the satellite provider to others (such as Kodiak and Wallops). For the former, there would be no net cost delta for either system solution – since the HPGP can be shipped together with the satellite. However, if the launch occurs from a site which does not have the ability to hydrazine as a “local commodity”, the cost of transporting hydrazine to/from the launch site must also be taken into consideration – and would result in a significant cost delta in favor of the HPGP-based solution.

SCAPE valet services are often charged on as “as used” basis, so the cost to an individual mission would depend on the pre-launch processing requirements. Again, since SCAPE operations are not required when handling HPGP, the addition of these costs will result in a further advantage to the HPGP-based system solution.

Finally, propellant waste disposal costs vary widely at different launch sites, depending on their distance to the nearest hydrazine destruction facility – or whether the satellite provider is responsible for shipping the waste and any unused hydrazine back from the launch site themself. However, since HPGP waste products are able to be destroyed by “open burn”, a satellite provider can avoid nearly all waste disposal costs by simply
burning any propellant waste products on-site. As an example, in the case of the PRISMA launch campaign, the Yasny Range Safety performed an open burn of the HPGP waste products at no additional cost.

Taking the delta cost values identified in Table 5 and applying them to specific small satellite mission configurations yields the life-cycle cost savings able to be achieved by implementing a HPGP-based solution shown in Figures 11 and 12.

Figure 11 considers missions which employ a single thruster (of varying size) and include propellant volumes between ~ 5L – 15L (5.5 kg – 25 kg). For the smallest mission, with a single 1N thruster and 5.5 kg of propellant, the HPGP-based solution provides a life-cycle cost savings of $453K over an equivalent hydrazine-based solution; whereas the largest mission, with a single 22N thruster and 25 kg of propellant, the HPGP-based solution provides a life-cycle cost savings of $420K.

Figure 12 considers missions which employ multiple thrusters (of varying sizes) and include propellant volumes between ~ 5L – 15L (5.5 kg – 25 kg). For the smallest mission, with a mix of 1N & 5N thrusters and 5.5 kg of propellant, the HPGP-based solution provides a life-cycle cost savings of $368K over an equivalent hydrazine-based solution; whereas the largest mission, with a mix of 5N & 22N thrusters and 25 kg of propellant, the HPGP-based solution provides a life-cycle cost savings of $320K.

It must however be reiterated that the analysis was performed in an overly conservative manner; so even greater cost savings would be achieved on an actual mission – when each of the excluded items (a smaller HPGP propellant tank, transportation of hydrazine to/from the launch site, SCAPE valet services for hydrazine processing, and propellant waste disposal) are also taken into consideration.

VI. CONCLUSION

HPGP eliminates or reduces the typical concerns which often preclude the inclusion of a liquid propulsion system on small satellite missions, thus enabling small satellites to achieve increased scientific utility. Furthermore, the combined benefits of higher performance and simplified transportation/handling provided by HPGP result in overall satellite mass reductions and significantly reduced mission life-cycle costs, as compared with hydrazine-based systems of similar performance.

When taken together, the many flight-proven benefits of HPGP make it a “game changer” for both increasing the capabilities and reducing the costs of small satellite missions.

Acknowledgments

This PRISMA mission has been executed under contract from the Swedish National Space Board (SNSB). The authors wish to acknowledge the sustained support from SNSB, SSC, OHB-Sweden and the European Space Agency (ESA). The authors also acknowledge the strong support from SSC’s management and the effort of all co-workers in this project from ECAPS, SSC, OHB-Sweden, the Swedish Royal Institute of Technology and EURENCO-Bofors. The authors also wish to acknowledge OHB-Sweden’s very supportive and professional Mission Control team in Solna and the DLR colleges at the German Space Operations Center (GSOC) in Oberpfaffenhofen for providing GPS data and for performing the mission operations during the HPGP-4 operations in May 2011. Finally, the ground station personnel at Esrange, Weilheim and Inuvik all deserve our thanks as well.
References


3. Anflo, K. and Crowe, B., Two Years of In-Space Demonstration and Qualification of an ADN-Based Propulsion System on PRISMA, AIAA/ESMA/CNES Space Propulsion Conference, Bordeaux, 7-10 May 2012.


13. Dinardi, A., and Persson, M., Benefits, Applications and Opportunities for Small and Secondary Satellites provided by High Performance Green Propulsion, 4S Symposium, Portorož, 4-8 June 2012.