## EXPANDING THE ADN-BASED MONOPROPELLANT THRUSTER FAMILY

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#### **ABSTRACT**

The development of High Performance Green Propulsion (HPGP) was initiated with the goal of meeting the requirements for future satellite missions. The HPGP technology includes a storable monopropellant blend based on Ammonium DiNitramide (ADN) and a thruster with a high-temperature resistant thrust chamber and catalyst. After more than 10 years of R&D, the HPGP technology is emerging as an enabling technology for improved performance, enhanced volumetric efficiency, reduction of propellant handling hazards and safer launch operations. The development has been performed by ECAPS under contract from the Swedish Space Corporation, the Swedish National Space Board and the European Space Agency (ESA). The progress of the development has been presented in several papers since 2000. Ref. 1-11. ECAPS, ATK and Moog are in partnership to pursue new applications for this novel technology.

This paper describes current status of the implementation of HPGP technology for satellite programs and the latest results from the development of larger HPGP thrusters.

### **NOMENCLATURE**

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|     |   |          | _ |  |

ACE = Advance Concept Engine ADN = Ammonium DiNitramideCVD = Chemical Vapor Deposition

HPGP = High Performance Green Propulsion

 $I_{sp}$  = Specific Impulse LMP = Liquid Monopropellant

MEOP = Maximum Estimated Operating Pressure

MMH=Mono Methyl HydrazineMON=Mixed Oxides of NitrogenPVD=Physical Vapor DepositionR&D=Research and Development

SCAPE = Self-Contained Atmospheric Protective Ensemble

TRL = Technology Readiness Level

w.r.t. = with respect to

## INTRODUCTION

ECAPS has developed LMP-103S, which is a storable ADN-based monopropellant blend with up to 30% higher density impulse compared to hydrazine. The propellant is essentially a premixed bi-propellant (fuel mixed with oxidizer) with high energy content but low sensitivity. LMP-103S is a low toxicity and environmentally benign propellant therefore SCAPE operations are not required during propellant handling. LMP-103S is also approved for shipping as air cargo in limited quantities. The effort to gain approval for air transport of fueled spacecraft is an ongoing activity.

The first in-space flight demonstration of the HPGP subsystem will be performed on the PRISMA mission, which is an international technology demonstration program for autonomous formation flying. Ref 12. The development of the 1 N HPGP thruster has been completed and the HPGP subsystem has been qualified for the PRISMA mission. The launch of PRISMA is planned for late 2009. The HPGP technology has also been selected as the propulsion baseline for several new small European and U.S. missions where improved density impulse is of major importance.

To expand the HPGP thruster family for additional market segments, new development models have been designed. 0.5 N, 5 N and 22 N thrusters have been successfully test fired. The demonstrated performance of these models agrees with design requirements. The 0.5 N has reached flight prototype level while the 5 N and 22 N models are proceeding towards flight designs.

To assess the potential for designing future engines for launch vehicle applications (i.e., roll and attitude control), spacecraft apogee engines and lander engines using reduced hazard propellants the Advance Concept Engine (ACE) program has been initiated.

A simplified comparison between State-of-the-Art storable space propulsion thruster performance (monoand bipropellant) and demonstrated and predicted performance for HPGP thrusters (using LMP-103 and 103S monopropellants) is shown in Figures 1 and 2.

Figure 1 shows the typical delivered vacuum specific impulse for MMH/MON (bipropellant), hydrazine (monopropellant), LMP-103 and LMP-103S (monopropellants at different thrust levels).

Figure 2 shows the typical delivered density impulse for MMH/MON (bipropellant), hydrazine (monopropellant), LMP-103 and LMP-103S (monopropellants at different thrust levels).

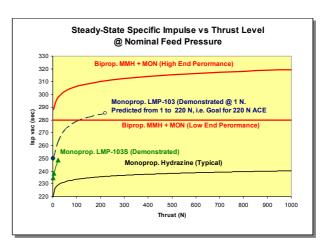


Figure 1: Specific Impulse (I<sub>sp</sub>) Comparison

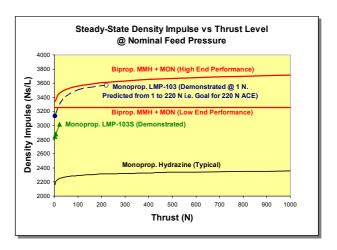


Figure 2: Density Impulse

## **PROPELLANTS**

LMP-103S is a monopropellant blend of Ammonium Dinitramide (ADN), i.e.,  $NH_4N(NO_2)_2$ , water, methanol and ammonia. ADN is primarily the oxidizer, which is dissolved in water with methanol and ammonia as fuel components. Ammonia also acts as a stabilizer. The propellant has successfully passed extensive testing w.r.t. performance, hazards, compatibility, radiation, storability, purity, transportability and handling. LMP-103S, in its shipping container, was approved and classified to UN 1.4S by the Swedish authorities in 2006. Transport by air is therefore possible.

LMP-103 is a candidate for higher performance within the family of ADN-based monopropellants developed by ECAPS.

#### FIRST IN-SPACE FLIGHT DEMONSTRATION

The first in-space flight demonstration of the HPGP technology will be performed on PRISMA (to reach TRL 7). PRISMA includes two satellites in LEO orbit. The primary objective is to demonstrate autonomous formation flying and rendezvous maneuvers. ECAPS HPGP system will provide about 60 m/s delta-V capability. PRISMA is scheduled to be launched on a Dnepr launch vehicle from Yazny (Russia) in late 2009. Ref. 5-6 and 12.

The PRISMA HPGP subsystem has conventional monopropellant architecture and operates in blow-down mode. Figure 3 shows the HPGP subsystem during integration into the PRISMA main satellite. The propulsion subsystem consists of one diaphragm-type propellant tank with a capacity of 4.5 L (5.6 kg) of propellant, two service valves, one pressure transducer, one system filter, one isolation latch valve and two 1 N HPGP monopropellant thrusters. All fluid components are conventional hydrazine "Commercial Off-The-Shelf" (COTS) components. The propellant tank PEPT-230 manufactured by Rafael has been delta-qualified with a silica free diaphragm. The system filter was filter made by Sofrance was also delta-qualified for PRISMA. The pressure transducer is made by Bradford and the latch and service valves are manufactured by Moog.

PRISMA has passed the Flight Acceptance Review (FAR) and is being prepared for transport to the launch site.

The loading of LMP-103S does not require SCAPE operations.

Figure 4 shows the PRISMA satellites during the sun simulation test at Intespace (Toulouse).



Figure 3: Integration of the HPGP Subsystem

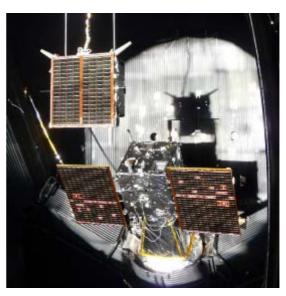


Figure 4: PRISMA Satellites in sun simulation testing at Interspace

## HPGP THRUSTER DEVELOPMENT

ECAPS has built and tested some 50 thrusters operating on ADN-based propellants since 1999. The steady-state specific impulse and density impulse at MEOP for the different HPGP thrusters are summarized in Table 1. For comparison the performance has been normalized w.r.t. an expansion ratio of 150:1 for a Rao nozzle.

**Table 1: HPGP thrusters** 

| Thrust<br>Level | Propellant | I <sub>sp</sub> (Ns/kg) | Density<br>Impulse<br>(Ns/L) | Status |
|-----------------|------------|-------------------------|------------------------------|--------|
| 0.5 N           | LMP-103S   | 2210*<br>(~225 sec)     | 2730                         | TRL 5  |
| 1 N             | LMP-103S   | 2310*<br>(~235 sec)     | 2860                         | TRL 6  |
| 5 N             | LMP-103S   | 2340*<br>(~238 sec)     | 2900                         | TRL 4  |
| 22 N            | LMP-103S   | 2445*<br>(~249 sec)     | 3030                         | TRL 4  |
| 50 N            | LMP-103    | 2515**<br>(~256 sec)    | 3120                         | TRL 2  |
| 220 N           | LMP-103    | 2800**<br>(~285 sec)    | 3580                         | TRL 2  |

- \* Delivered steady-state vacuum specific impulse at MEOP
- \*\* Predicted steady-state vacuum specific impulse at MEOP

In the HPGP thrusters, the propellant is thermally and catalytically decomposed, ignited and combusted in the reactor. The reactor is nominally preheated to +350°C prior to firing. Emergency starts require > +200°C but the thruster can not be cold started. To conserve energy the heater is only operated when the reactor temperature is below +400°C. The reactor heater nominally operates on 28 VDC and has redundant heating elements. The reactor temperature is measured with redundant thermocouples, which are monitored by the spacecraft system unit.

The combustion temperature is significantly higher for LMP-103S compared to Hydrazine. A novel high temperature catalyst has been developed and verified for ADN-propellants. The exhaust gases for LMP-103S are the same as for MMH/MON bipropellant thrusters, i.e.,  $H_2O$ ,  $N_2$ ,  $H_2$ ,  $CO_2$  and CO.

The HPGP thruster assembly is built with high temperature resistant materials, which require advanced fabrication and joining processes. Fabrication processes such as CVD, PVD, EL-Formed<sup>TM</sup> etc have been evaluated. Materials such as platinum, molybdenum alloys and iridium/rhenium are used. Material selection and fabrication method is selected pending the application and thruster size.

The thruster propellant Flow Control Valves (FCV) are COTS components with extensive flight heritage and are manufactured by Moog Inc.

#### 1 N THRUSTER

The 1 N HPGP thruster has been designed for attitude and orbit control of small spacecraft. It is designed for operation in steady-state and pulse mode. The thruster is aimed to replace hydrazine thrusters in conventional blow-down monopropellant systems with significant density impulse improvement. The 1 N HPGP thruster has been qualified for the PRISMA mission w.r.t. operational, performance, environmental and life requirements. The demonstrated life is summarized in Table 2. Figure 5 shows the 1 N HPGP flight model. The performance mapping of the 1 N HPGP thruster is shown in Figure 6, and the thrust as a function of propellant feed pressure in Figure 7. The steady-state I<sub>sp</sub> as a function of propellant feed pressure is finally shown in Figure 8. The thruster has a conical nozzle and an expansion ratio of 100:1.



Figure 5: 1 N HPGP thruster

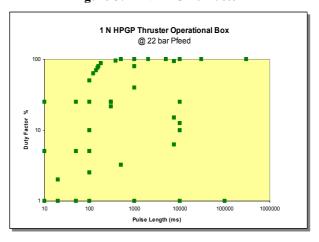


Figure 6: Performance Mapping

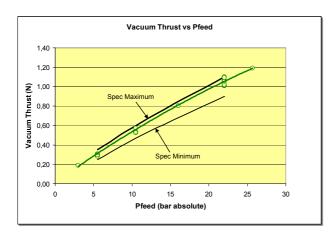


Figure 7: Thrust vs  $P_{feed}$  for the 1 N Thruster

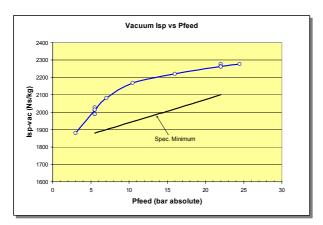


Figure 8: Steady-state  $I_{sp}$  vs  $P_{feed}$  for the 1 N Thruster

Table 2: Demonstrated Life for 1 N HPGP thruster

| Parameter                | Demonstrated Life |
|--------------------------|-------------------|
| Accumulated Firing Time  | 25 hours          |
| Longest Continues Firing | 1.5 hours         |
| Propellant Throughput    | 24 kg             |
| Number of Pulses         | 60500             |
| Thermal Cycles           | 1500              |
| Total Impulse            | 50 kNs            |

## **5 N THRUSTER**

The 5 N HPGP thruster is based on the 1 N HPGP thruster design and is intended to be used for attitude and orbit control of small to medium size spacecraft. It is designed for operation in steady-state and pulse mode. The first 5 N HPGP development thruster (Figure 9) was operated with a propellant feed pressure between 5.5 and 22 bar (abs), thus delivering thrust between 1.5 and 6 N. It accumulated 677 pulses, 8 minutes and a longest continuous burn of 1 minute, with a propellant throughput of 1 kg. The delivered  $I_{\rm sp}$  at 5 N was 2300 Ns/kg with a conical nozzle and an expansion ratio of 50:1. Firing of the first development model of the 5 N HPGP thruster is shown in Figure 10.

The measured performance is fully coherent with the predicted performance.

An upgraded development model has been fabricated which will be subjected to performance and limited life testing. The next objective in the 5 N HPGP thruster development is to reach TRL 5.



Figure 9: 5 N HPGP thruster

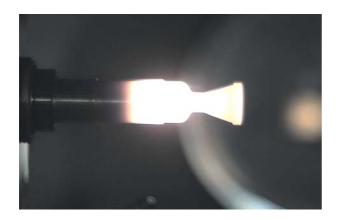


Figure 10: Firing the 5N HPGP thruster

## 22 N THRUSTER

The 22 N HPGP thruster is designed for orbit control of medium size spacecraft. It is also designed for operation in steady-state and pulse mode. The 22 N development model (Figure 12) was operated with a propellant feed pressure between 5 and 25 bar (abs), thus delivering thrust between 5 and 22 N. The second 22 N development model accumulated 200 pulses and 5 minutes burn time. Also continuous burns of 30 seconds were performed. The propellant throughput was 1.5 kg. The delivered  $I_{sp}$  at 22 N was 2400 Ns/kg with a Rao nozzle with an expansion ratio of 47:1. Firing of the second development model of the 22 N HPGP thruster is shown in Figure 11.

The measured performance is consistent with the predicted performance.

An upgraded development model has been fabricated (Figure 14) and will be subjected to performance and limited life testing. The next objective in the 22 N HPGP thruster development is to reach TRL 5.

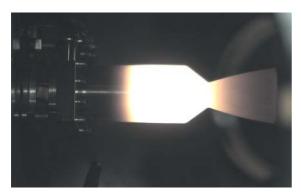


Figure 11: Firing the 22 N HPGP thruster



Figure 12: 22N HPGP thruster

## THE ACE CONCEPT

ACE is a 220N test engine for ADN-based storable liquid propellants with the objective to demonstrate significantly higher thrust levels and performance. The goal of the ACE engine is to demonstrate higher thrust levels with a specific impulse and a density impulse which are comparable to bipropellant engines using storable propellants. A 50 N test engine is being developed as intermediate step between the 22 N HPGP thruster and the 220 N ACE.

The ACE is designed for operation in steady-state and pulse mode with the following design features and objectives:

- Modular design
- Multi-fuel capability
- Dual mode
- Throttling capability
- Increased performance
- Increased thrust level (> 100 N)

Further objectives are to minimize preheating requirements and to demonstrate rapid response times

Improvements of the specific impulse require higher combustion temperatures. ADN-based propellant formulations for higher performance have been identified. With the objective to enable future thruster designs for higher performance, a three year R&D program has been started to improve the high temperature resistant catalyst life in order to sustain even higher temperatures. ECAPS leads a Swedish consortium and the program is financed by the National Space Research Program (NRFP).

The major technical challenges for the development of ACE are:

- Propellant formulation
- Reactor design
- Thermal management

The initial work for ACE is funded by SSC.

The first 50 and 220 N ACE engines have been fabricated and are currently undergoing pre-functional and thermal-vacuum testing (Figure 13).



Figure 13: The 220 N HPGP engine (ACE)

# CONCLUSIONS AND FUTURE WORK

1 N HPGP thrusters have been tested to qualification levels (performance, environmental and life). The first ADN-based propulsion system has been delivered for flight demonstration on PRISMA and is scheduled for launch in late 2009.

ADN-based propulsion systems are baseline for several new European and US missions and proposals have been submitted. Work on performance improvement, up-scaling to higher thrust levels and the development of 5 and 22 N HPGP thrusters is ongoing.

The first hot firings of 50 N and 220 N are planned for August/September 2009 using LMP-103S as propellant (Figure 14).



Figure 14: 22 N, 50 N and 220 N HPGP thrusters

## Acknowledgements

This work has been performed under contract from the Swedish Space Corporation (SSC). The authors acknowledge the sustained support from SSC, SNSB and ESA. The authors also acknowledge the strong support from the management and the effort of all coworkers in this project from ECAPS, Swedish Space Corporation, Swedish Defense Research Agency (FOI), Royal Institute of Technology, Chalmers University of Technology, SWEREA-KIMAB, Edotek and Eurenco-Bofors.

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