Hot-Firing tests using a low temperature derivative of LMP-103S

K. Anflo, P. Thormählen and M. Persson
ECAPS,
P.O. Box 4207, 171 04, Solna, Sweden

Abstract

The development of High Performance Green Propulsion (HPGP) was initiated as an alternative to hydrazine, with the goal of meeting new requirements for small satellite missions. The HPGP technology includes storable monopropellant blends based on Ammonium DiNitramide (ADN) and thrusters with high temperature resistant thrust chambers and catalyst.

In order to handle significantly lower storage temperatures (down to about -30ºC) than specified for traditional storable mono-propellants (e. g. hydrazine), a low-temperature derivative of the ADN-based in-space qualified LMP-103S has been conceived and tested in a 22 N development thruster. The propellant blend with test series number 1127-3, have 20% higher density than hydrazine and combusts at a lower temperature than LMP-103S, giving a specific impulse comparable with the Isp for hydrazine. For a given volume of a tank this would enhance the delta-V capability by 20%. The lower combustion temperature may enable the usage of less expensive materials for the thrust chamber assembly as compared with the baseline design for HPGP thrusters.

1. Introduction

High Performance Green Propulsion (HPGP) provides a flight-proven solution for increasing the capabilities of small satellite missions [4] and the feasibility to replace hydrazine for mono propulsion systems in general. ECAPS holds numerous worldwide patents w.r.t. HPGP technology; including propellant formulations, catalyst and thruster design. The HPGP technology has been developed with the goal to use hydrazine COTS components and take benefit of the heritage of the existing fluid components, e.g. valves, filters and tanks, etc. The HPGP is based on 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. LMP-103S has theoretically >6% higher specific impulse and >30% higher density impulse than hydrazine and has moderate vapour pressure. Unlike hydrazine the LMP-103S propellant is not sensitive to air or water vapour. In spite of its high energetic content, LMP-103S is classified as an insensitive substance (NOL 1.3) and further classified as a UN 1.4S article for transportation which allows for shipment as air cargo. The blend has low toxicity, is not reported to be carcinogenic and is environmentally benign. Spacecraft or launcher RCS propellant loading does therefore not require the use of SCAPE. Furthermore, an 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.

Since 2003 this propellant has undergone extensive ground testing w.r.t performance, sensitivity, thermal characterization, compatibility, radiation sensitivity and storability. The propellant has been stored for more than 7.5 years in a ground system End-to-End test without any indication of degradation or pressure build up. Accelerated testing (STANAG 4582) indicates more than 20 years of stability for long term storage. Monopropellant LMP-103S has an on-the-shelf life of at least one year in its current standard 5L polyethylene shipping container. The spare propellant container for PRISMA transported to the launch site in Yasny, Russia, as air cargo, and then returned to Sweden by land transport. It has since then been kept in storage for energetic substances. About 2.5 years after the propellant was manufactured, the content of the container was analysed. Within the limits of accuracy of the analytical methods used, no change in the composition of the propellant can be detected. There is no decomposition of the ADN and no contamination from the container.

LMP-103S has a wider temperature storage range than hydrazine, but there is an interest to consider propellants that can be stored and operational at temperatures well below 0ºC (e.g. for propulsion systems close to cryogenic tanks [5], deep space missions or just in order to keep the power needed for temperature control of a propulsion system at a minimum).

2. ADN-based propellants

LMP-103S, developed by ECAPS, is an energetic blend of ADN (Ammonium DiNitramide), Methanol, Ammonia and Water. LMP-103S can be rapidly decomposed, ignited and combusted by a pre-heated catalyst whereby the hot gaseous reaction products generate thrust. As well as offering good propulsive performance, LMP-103S represents a significant advancement in reducing the health and safety hazards, which are characteristic of many of the existing storable liquid propellants. In particular, it presents greatly reduced hazards in terms of toxicity, both through inhalation and skin contact. The nominal operational temperature for LMP-103S is the same as for hydrazine, i.e., 10-50°C. However, LMP-103S has been successfully fired in thrusters with a propellant inlet temperature down to -5°C. By modifying the composition of LMP-103S it is possible to change the properties of the propellant.

Table 1: Propellant Properties

Propellant	Hydrazine	LMP-103S	LMP-103S/1127-3
Chemical formula	N_2H_4	Blend	Blend
Molecule mass	32.05	46.9	39.1
Saturation point	NA	-7ºC	-30ºC
Melting or freezing point	2ºC	-90ºC	ND
Boiling point	113ºC	120ºC	110ºC
Heat of vaporization (kJ/kg)	1256	NA	NA
Specific heat (kJ/kg-K)	3.17	2.40	ND
Specific gravity at 15ºC	1.02	1.24	1.21
Viscosity (centipoise) at 15ºC	~1	3.9	2.7
Vapour pressure (MPa) at 15ºC	~0.01	0.09 bar	ND

Table 2: Theoretical Rocket Performance (frozen Conditions)

Propellant	LMP-103S	LMP-103S/1127-3
Chamber pressure (Pc)	15 bar	15 bar
Combustion Temperature (T_c)	1600 ºC	1330 ºC
Molecule Mass ($\mathfrak{M}$)	19.7	19.2
Specific Heat Ratio (γ)	1.23	1.23
Exhaust Species (Mole fractions)	-	-
- H_2O	50%	54%
- N_2	23%	22%
- H_2	16%	16%
- CO	6%	3 %
- CO_2	5%	5%
Mach number Exit (M)	4.9	4.6
Thrust Coefficient (Cf)	1.73	1.72
Specific Impulse (Isp)	2438 Ns/kg	2267 Ns/kg

Several low temperature propellant blends have been prepared and evaluated by ECAPS. The most promising candidate, a derivative of LMP-103S i.e.1127-3, table 1, show that it has a saturation temperature (solid ADN crystals start to form in the liquid solvent mixture) at approximately -30°C. The theoretical specific impulse is on par with hydrazine but has 20% higher density. As the 1127-3 blend contains the same compounds as LMP-103S, only the composition is somewhat different, most other chemical and physical properties are similar to LMP-103S. Theoretical performance the specific impulse (Isp) of 1127-3 was made using the CEA/CET93 thermo-chemical program, [1][2]. Assuming a nozzle expansion ratio of 100, the vacuum specific impulse was found to be 2340 Ns/kg (-7% compared to LMP-103S, but on par with hydrazine) and with a combustion temperature of about 1330°C (-270°C compared to LMP-103S), table 2.

3. Experimental results 1127-3

3.1 Low-temperature saturation

1127-3 was placed in a freezer and cooled stepwise (5°C per step) until saturation with respect to ADN occurs, followed by stepwise heating until ADN re-dissolves. The temperature was kept for one week after each step change. During the test, it became apparent that the propellant can be super-cooled by several degrees centigrade. That is, the sample can be cooled without ADN crystallization below the temperature at which saturation is observed after long-term exposure. The results show that propellant blend 1127-3 becomes saturated when kept below -30°C and slowly starts to re-dissolve at -20°C (more rapid dissolution occurs at -15°C). During the tests, no solidification of the propellant 1127-3 solvent mixture was observed. This was expected since the similar solvent mixture of LMP-103S solidifies at -90°C.

3.2 BAM fall-hammer impact sensitivity test

This test was performed to measure the sensitivity of propellant blend 1127-3 to drop-weight impact, to ensure safe handling and transport. The test is made according to United Nations Recommendations (www.un.org).
Using the liquid sample container suggested by the UN handbook ([3] page 81), where the propellant is confined between two steel cylinders with an air gap (provides adiabatic compression) and using a 5 kg drop-weight ([3] page 77), no reaction was detected for propellant blend 1127-3 up to the maximum drop-height 1.26 m for the present test equipment. With LMP-103S a reaction can be detected from a drop-height of about 0.8 m. It can therefore be concluded that 1127-3 is less sensitive than LMP-103S to mechanical shock.

3.3 Safety review of propellant at EURENCO Bofors and FOI

To ensure safe handling and to get approval to transport propellant blend 1127-3, a safety review were performed at EURENCO Bofors where the propellant is prepared. Information and conclusions from this review meeting were sent to MSB (Swedish Civil Contingencies Agency) that granted permission for road transport of kilogram quantities of the propellant to the hot firing test facility at FOI. The permit has several limitations and a full UN transport classification of the propellant is needed to perform general transports. Thereafter, in order be able to run hot firing tests with propellant blend 1127-3 at ECAPS test facility located at FOI, a safety review was performed. Input from the safety tests were reviewed by the FOI safety board and the hot firing test were then approved with limited amounts of propellant. Propellant compatibility with wetted surfaces of the hot firing test system was assessed to not be a problem, as the propellant composition is similar to LMP 103S.

3.4 Micro-calorimetric study of saturation temperature

This test was performed to further investigate the saturation temperature (with respect to formation of solid ADN crystals) at low temperatures and to identify any other thermal stability issues of propellant blend 1127-3. An amount 10 g of propellant was transferred to a sample vial (gold plated to be inert), which was sealed with a gas-tight lid. The sample was then placed in an apparatus for Differential Scanning Calorimetry (Perkin Elmer Diamond DSC), which measures the heat-flow from the sample as a function of temperature.

The propellant sample was cooled by 0.5°C per minute from ambient temperature down to -30°C, held there for 48 hours and then reheated by 0.5°C per minute to ambient temperature. The recorded heat-flow is shown in figure 1, which reveals that nothing else happens than just cooling and heating of the liquid (formation of solid ADN crystals would result in a peak at a certain temperature in the heat-flow). It can therefore be concluded that propellant blend 1127-3 remains a stable homogeneous liquid at temperatures down to -30°C.

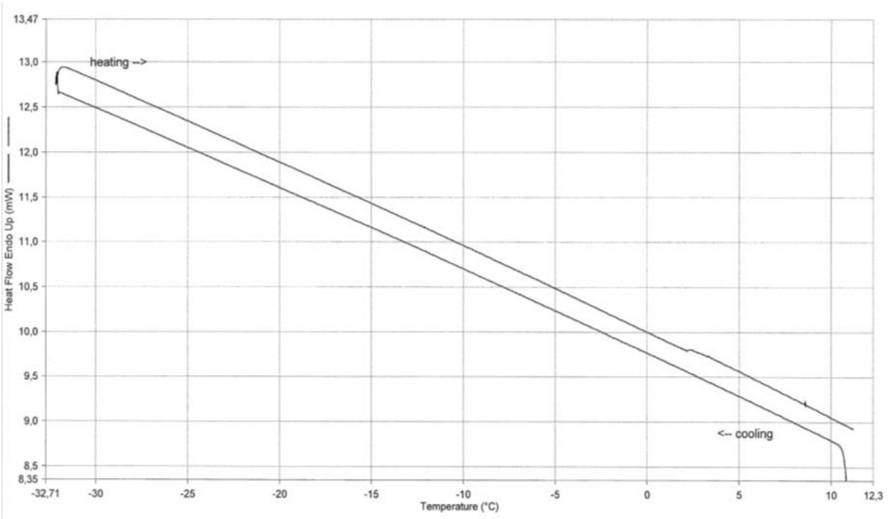

Figure 1. Heat-flow from propellant blend 1127-3 measured by DSC

3.5 Measurement of dynamic viscosity as a function of temperature

The flow of propellant entering the thruster when the FCV is opened is mainly restricted by the pressure-drop induced by the feed-tube and the nozzle. The flow-rate in the feed-tube depends on the viscosity of the propellant and it must be known in order to make a proper design. The viscosity as a function of temperature (-30 to +50 °C) of propellant blend 1127-3 was measured by a BROOKFIELD DV-E viscometer equipped with a temperature controlled sample cell (called "UL Adapter). The UL Adapter is designed for viscosity measurements in the range of 1-10 cP. The measured dynamic viscosity as a function of temperature is shown for both LMP-103S and 1127-3 in figure 2. The viscosity of 1127-3 is found to be similar to LMP-103S but slightly lower in the temperature range of 0 - 50°C. At lower temperatures the viscosity increases rapidly, as it does for most other liquids. For comparison, the viscosity of IPA increases from about 5 cP at 0°C to 25 cP at -30°C.

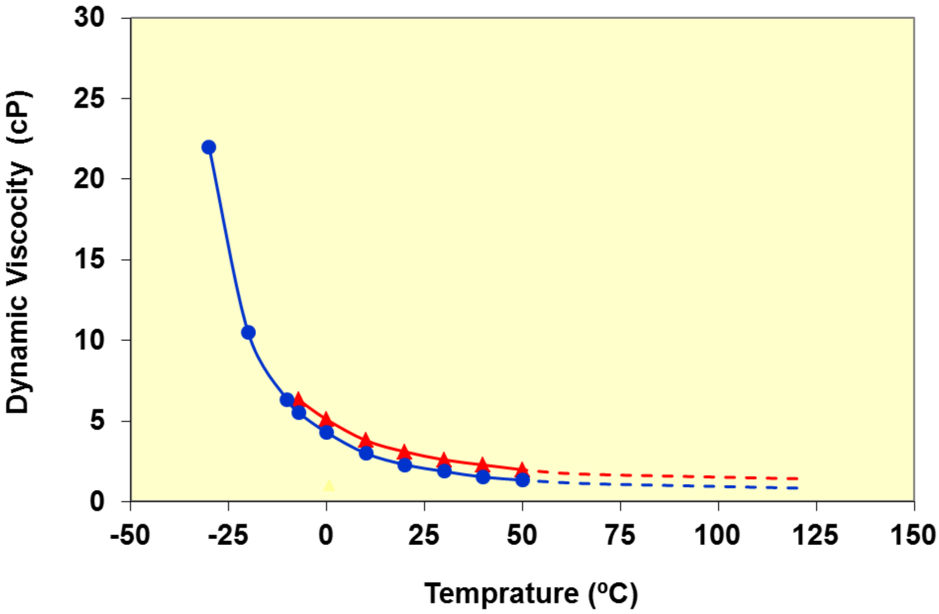

Figure 2. Dynamic Viscosity vs Temperature for LMP-103S and 1127-3

4. Test Stand (TS-2) Description

ECAPS test facility is a “green” test site with minimal emission to the environment. Fueling or any other operation does not require use of SCAPE. The facility is located at Swedish Defence Research Agency – FOI, in Grindsjön, 50 km south of Stockholm. The test equipment is developed, owned and operated by ECAPS. Two vacuum chambers allows for near vacuum testing of the HPGP thrusters; Test stand 1 (TS-1), for 1N–5N thrusters, and Test stand 2 (TS-2), figure 3, for 5N–200N thrusters. TS-1 and TS-2 are equipped with the following features:

- Temperature controlled thrust balance
- Propellant mass flow control gauge for long pulses and continues flow
- Propellant tank mass balance for pulse mode propellant consumption
- Regulated propellant inlet pressure
- Propellant inlet temperature sensor
- Propellant temperature control
- Scanning pyrometer
- FLIR camera
- CCD camera

Figure 3. Test Stand 2 for 5N–220N Thrusters

TS-2 was commissioned in the spring of 2011 and has been used for testing thrusters from 5N up to 220N. It is now fully operational and used to test 200N thrusters in pulse mode with 5s on-time. The test stand is designed so it can be upgraded to a capacity of 500N. The vacuum in TS-2 is achieved by a two stage ejector pump driven by compressed air (26 m^3 at 180 bars). The thruster is acting as an additional first stage i.e. the system with thruster will act as a three stage ejector pump. TS-2 has capacity to keep the vacuum level ≤ 5 mbar at 22N thrust level. The test duration at 22N is up to 1 hour.

5. 22N HPGP Thruster

The design and function of the HPGP thrusters developed for ADN-based monopropellant blends [6] have several similarities with hydrazine thrusters. The Flow Control Valve (FCV) is a solenoid valve with extensive flight heritage. In the HPGP thruster the propellant is thermally and catalytically decomposed and ignited by pre-heated reactor. Preheating is nominal >350ºC. For thermal control the thruster is equipped with heaters and thermocouples.
The HPGP thruster operates at a combustion temperature of 1600˚C (using LMP-103S), which is significantly higher than for a hydrazine thruster. The thrust chamber assembly is therefore made of high temperature resistant materials. ECAPS has also developed and patented a unique high temperature resistant catalyst.

The 22 N HPGP thruster, shown in figure 4, is under development to specific customers applications. It is designed mainly for delta-v manoeuvres requiring continuous and off-modulation firings, with some attitude control capabilities (i.e. pulsed mode firing). The thruster has high specific impulse (using LMP-103S), good response times and stable combustion. The 22N HPGP thrusters have demonstrated steady state specific impulse up to 2500 Ns/kg and density impulse of 3100 N/L, using the monopropellant LMP-103S. The maturity demonstrated is TRL 5. The thruster used for this test campaign has a flange interface between the thrust chamber and injector which makes it modular and suitable for optimizing the reactor and for tests of new propellant blends. It was equipped with a thermocouple placed inside the reactor in order to measure the temperature during firing.

6. Hot Firing tests using 1127-3

The actual combustion properties of propellant blend 1127-3 were evaluated by hot firing tests using the 22 N HPGP thruster at ECAPS test facility. The results from the tests are compared with earlier hot firing of LMP-103S using the same 22 N thruster. The results of the 22 N HPGP thruster firings, comparing LMP-103S with 1127-3, are summarized below. Figure 5 shows hot firing with propellant blend 1127-3. The tests were performed at nominal and low propellant inlet temperatures.

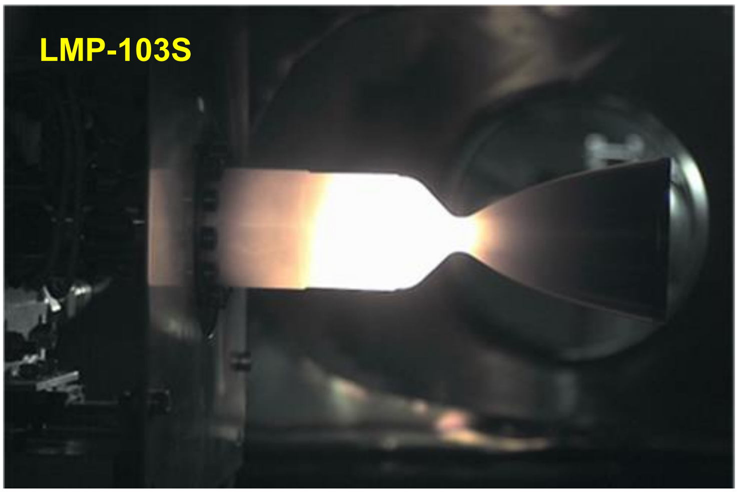

Figure 4. 22 N HPGP Thruster fired with LMP-103S

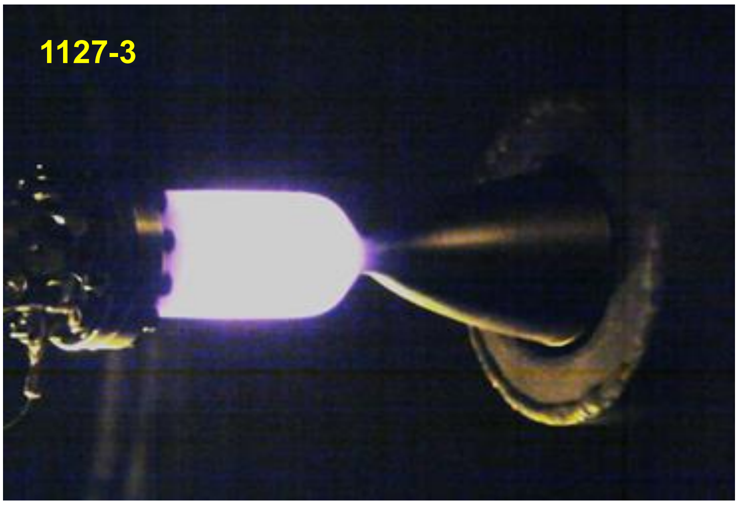

Figure 5. 22 N HPGP Thruster fired with 1127-3

6.1 Single Pulse Firing – Thrust Response

The Ton = 1s single pulse thrust response was compared between 1127-3 and LMP-103S, as shown in figure 6. It was observed that both propellants give the same thrust profile, the same combustion stability, the same response time and centroid delay. The differences are that 1127-3 has slightly lower Isp compared to LMP-103S, but similar to hydrazine.

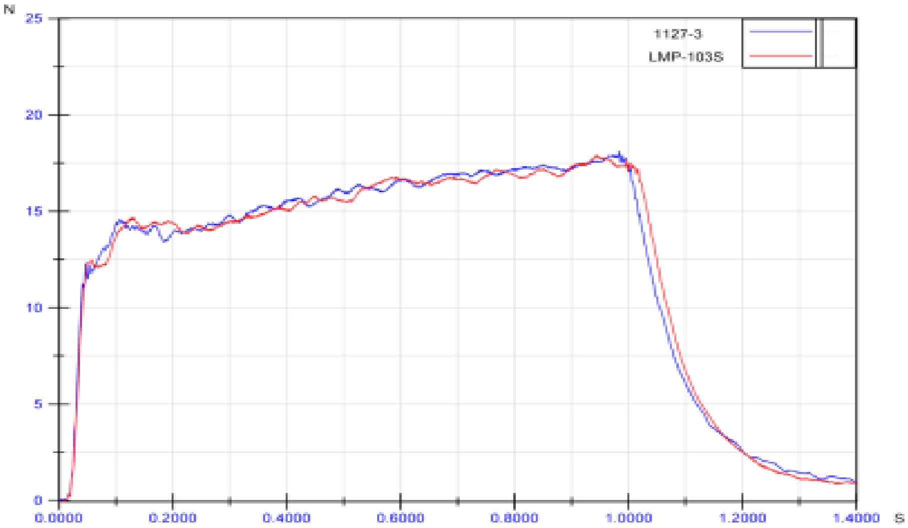

Figure 6. 1 s single pulse firing - thrust response 1127-3 vs. LMP-103S.

6.2 Demonstrated Specific Impulse

Hot firings at 22 bar feed pressure were performed to compare the Isp of 1127-3 with LMP-103S. The Isp (vacuum) after 10 s firing was found to be 2200 Ns/kg for 1127-3 and 2280 Ns/kg for LMP-103S. For the subject single pulse and pressure the demonstrated Isp is about 4% lower for 1127-3 compared to LMP-103S.

6.3 Pulse mode firing

Comparison of pulse mode thrust response between 1127-3 and LMP-103S was made. As indicated in figures 7 and 8, the 22 N HPGP thruster is capable to deliver good pulse mode operation using both LMP-103S and 1127-3.

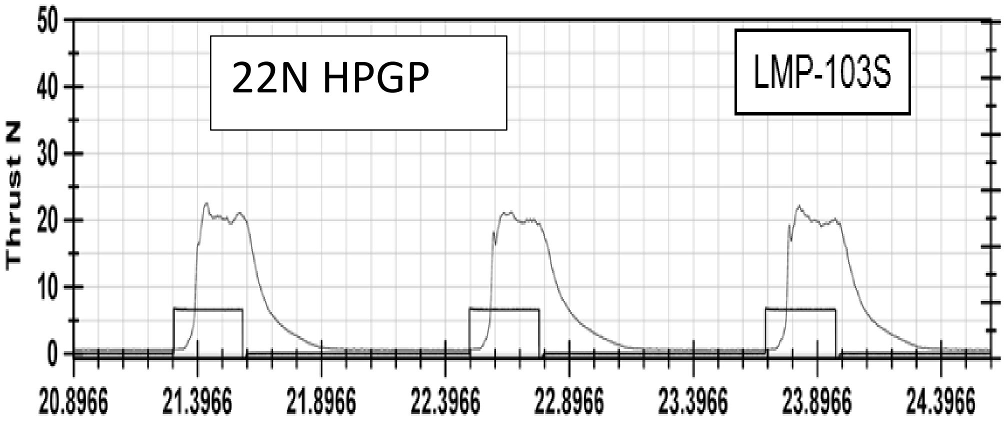

Figure 7. Pulse mode firing - thrust response LMP-103S.

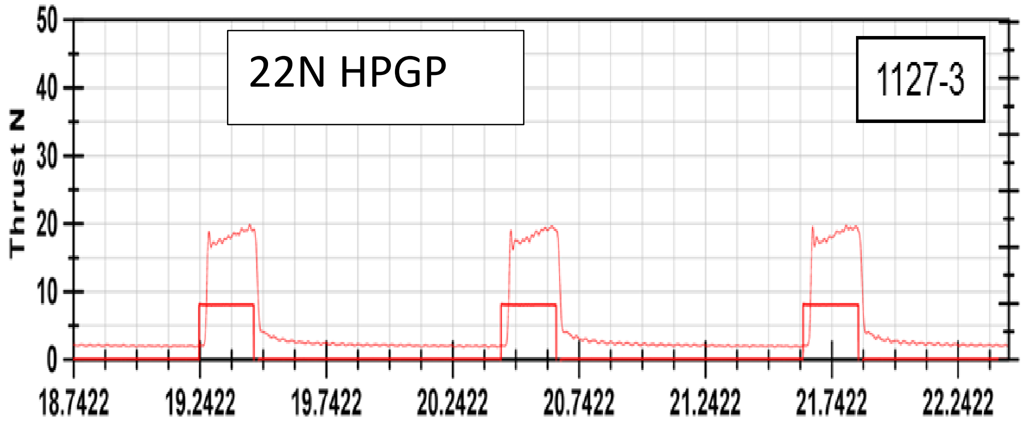

Figure 8. Pulse mode firing - thrust response 1127-3.

6.4 Low propellant feed temperature

The influence of low propellant feed temperature for 1127-3 was tested and firings with Ton = 230 ms and Toff = 1000 ms, with feed temperature at 15°C and -3°C were conducted. Testing at feed temperatures below -3°C was not possible with the current test set-up.

7. Conclusions

A low temperature (LMP-103S derivative) propellant i.e. 1127-3 has been developed and successfully been fired in a 22 N HPGP development thruster. The specific impulse is comparable with hydrazine, and density 20% higher which is of importance for volumetric efficiency. The 1127-3 gives the same thrust profile, the same combustion stability, the same response time and centroid delay as LMP-103S. The 1127-3 blend has a storage temperature about -30ºC, but today the availability fluid components qualified for such low temperature is limited.

The main conclusions from the investigation of propellant blend 1127-3, compared with LMP-103S are:

- Propellant blend 1127-3 becomes saturated with respect to ADN at temperatures below -30°C and slowly starts to re-dissolve at -20°C, while LMP-103S becomes saturated around -7°C and re-dissolve at -5°C.
- The theoretical vacuum specific impulse of 1127-3 is 7 % lower than for LMP-103S, but similar to hydrazine.
- The demonstrated Isp for 1127-3 is about 4% lower than for LMP-103S.
- The sensitivity of 1127-3 to drop-weight impact was found to be less than for LMP-103S, which results in an improvement compared to the already safe handling of LMP-103S.
- The viscosity of 1127-3 is found to be similar to LMP-103S (just slightly lower) in the temperature range of 0 - 50°C, while at lower temperatures (down to -30°C) the viscosity increases rapidly (as it does for most other liquids).
- Both propellants give the same thrust profile, have the same combustion stability, and the same response times and centroid delays for single pulse firing (Ton=1s).
- Thruster firing with 1127-3 feed temperature of -3°C has been demonstrated.

Acknowledgments

The authors wish to acknowledge the support from Astrium, the European Space Agency (ESA) and the Swedish National Space Board (SNSB). The authors also acknowledge the strong support from SSC´s management and the effort of all co-workers from ECAPS, EURENCO Bofors, partners and subcontractors.

References

[1] Sanford Gordon and Bonnie J. McBride "Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications I. Analysis" NASA RP-1311, October 1994.

[2] Gordon, S., McBride, B.J., "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouget Detonations". NASA SP-273, Interim Revision, March 1976.

[3] Anon, "Recommendations on the Transport of Dangerous Goods: Manual of Tests and Criteria", third revised edition, ST/SG/AC.10/11/Rev.3, United Nations 2009.

[4] Anflo, K. and Crowe, B., "Two Years of In-Space Demonstration and Qualification of an ADN-Based Propulsion System on PRISMA", AAAF/ESA/CNES Space Propulsion Conference, Bordeaux, May 7-10, 2012.

[5] Anflo, K., Persson M., Welberg D., Lange M. and Bahu J.-M., "HPGP Thruster Demonstrator Development for A Launcher Upper Stage Reaction Control System", AAAF/ESA/CNES Space Propulsion 2012 Conference, Bordeaux, May 7-10, 2012.

[6] Persson M., Anflo K., Dinardi A., "A Family of Thrusters for ADN-Based Monopropellant LMP-103S" 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 2012, Atlanta, July 29 – August 1, 2012.