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From Lampoldshausen to Orbit: DLR Spin-off GreenDelta and the Development Status of Green Propellant Thrusters Based on H_2O_2 and N_2O

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ABSTRACT

The German Aerospace Center's Institute of Space Propulsion in Lampoldshausen has more than a decade of experience in green propellant research and green propulsion hardware development. In the frame of internal research projects as well as ESA and third-party projects DLR employees gained a deep and extensive knowledge of propulsion hardware. Based on this knowledge, thrusters and propulsion hardware were developed in-house and the TRL was increased step by step. Currently, the two most promising technologies are: the HyNOx bipropellant technology, based on nitrous oxide and hydrocarbon fuels, as well as the hypergolic HIP_11 technology. The HyNOx bipropellant offers a high I_{sp}, non-toxic components, self-pressurized propulsion systems, easy handling and very low cost. HIP_11 is a patented, hypergolic combination based on hydrogen peroxide and ionic liquid fuels, which offers a comparable I_{sp}, significantly reduced costs, and easy to handle propellants. To commercialize the two propulsion technologies, a DLR spin-off called GreenDelta will be founded in summer 2023. The preparation of the spin-off is currently funded by the Helmholtz Association and DLR. This paper gives an overview on the development of the two technologies and their development status. First thrusters from GreenDelta will be commercially available at Q4 2023.

INTRODUCTION

The propulsion system of a spacecraft is essential for the success of many missions. State of the art propellants, such as hydrazine-based fuels or oxidizers based on oxides of nitrogen, typically used in chemical propulsion systems are highly toxic. Hence, they pose a danger to the personnel who have to handle these propellants during different stages of the preparation of a mission. For safe handling, the personnel have to wear so-called SCAPE suits, which leads to time consuming procedures and high costs. In Europe, hydrazine is subjected to the REACH regulation. In 2011 it was added to the candidate list as substance of very high concern [1]. In a further step, the use of this substance could be banned in Europe. To overcome the danger for the personnel and the environment, to avoid costly handling activities and to anticipate potential political restrictions regarding conventional propellants, several alternative, so-called green propellants were developed in the last decades.

Several approaches exist to substitute conventional toxic propellants and first solutions are already proven in space. One alternative to hydrazine are fuels blends, containing an energetic compound dissolved in a fuel and water. Examples are LMP103s, ASCENT (formerly AFM-315E) or SHP163, propellant blends based on the so called energetic ionic liquids ammonium dinitramide (AND) or hydroxylammonium nitrate (HAN). These fuel blends offer a higher performance compared to hydrazine as a monopropellant, but require costly, very temperature resistant materials and expensive catalysts. Further scaling of thrusters operating with ADN or HAN seems to be a challenging task.

Regarding bipropellants, green solutions require an alternative oxidizer to the commonly used dinitrogen tetroxide (NTO). But liquid storable oxidizers for space propulsion applications are rare. Possible options are highly concentrated hydrogen peroxide (H_2O_2) or nitrous oxide (N_2O). Hydrogen peroxide is a widely used substance in a variety of industrial applications. It decomposes into water and oxygen. The toxicity is several classes lower compared to the conventional oxidizer NTO. Nitrous oxide is non-toxic, but has a high vapor pressure and thus needs to be pressurized above 50 bar to stay in liquid phase at ambient temperature.

DLR's Institute of Space Propulsion in Lampoldshausen works on green propellants for space propulsion for more than a decade [2, 3]. The satellite and orbital propulsion department has experience in testing ammonium dinitramide fuel blends [4–7], nitromethane-based propellants [8, 9], hydrogen peroxide [10, 11], nitrous oxide based monopropellant blends and nitrous oxide based bipropellants [12–16].

Based on many years of research, two green propellant solutions proved their potential to substitute the conventional toxic propellants. Now, they have reached a maturity, where first products can be developed. To commercialize the research and transfer products into the market, the DLR employees Lukas Werling and Felix Lauck are founding the spin-off company GreenDelta. The products of GreenDelta will be based on the HyNOx and HIP_11 propulsion technologies. HyNOx stands for hydrocarbons with nitrous oxide. This technology offers a high specific impulse (up to 300 s), non-toxic components, self-pressurized propulsion systems, easy handling and low cost. Initial products are bipropellant thrusters between 1 and 200 N of thrust and associated propulsion systems. HIP_11 is a patented hypergolic propellant with hydrogen peroxide as oxidizer and an ionic liquid based fuel. This technology features low toxic components, hypergolic ignition, comparable performance to conventional hypergolic propellants, reduced costs for handling, operation, and testing. Currently, a 200 N class thruster is under development.

PROPELLANT AND PROPULSION SYSTEM DEVELOPMENT

Development of the HyNOx technology

In 2014 the development of the HyNOx propulsion technology started at DLR. The HyNOx propellant uses nitrous oxide as oxidizer and a light hydrocarbon as fuel. As mentioned, nitrous oxide has a vapor pressure of approximately 50 bar at ambient temperature. Due to this high vapor pressure, N_2O can be used in a self-pressurizing propulsion system without the need of an external pressurization system or infrastructure. Light hydrocarbons, such as ethane (C_2H_6) or ethylene (C_2H_4) have vapor pressures of a similar level. Therefore, they are suitable to be used as self-pressurized fuels together with nitrous oxide. This principle allows simplicity and reduced costs since no additional components for a pressurization and its control are needed. Further, nitrous oxide, ethane or ethylene are widely available substances, which are applied in several industrial processes and therefore low cost.

The initial investigation on HyNOx were focused on premixed oxidizer-fuel blends. These fuel blends offer the same system simplicity as a monopropellant, but provide the performance of a bipropellant. However, a main challenge of fuel and oxidizer mixtures are their sensitivity and the possibility of ignition if sufficient energy is available. Moreover, a flame can propagate upstream the injector and lead to an ignition of the propellant in the feeding system. Such a flashback must be avoided in any case. Extensive research was conducted on flame arresters, assuring the quenching of the flame and hindering it entering the feeding system [17]. Another challenge of HyNOx propellants is the high combustion temperature and the provision of sufficient cooling [12]. Research on the performance of a mixture of nitrous oxide and ethylene and ethane was conducted [15]. In the frame of an ESA project, firings with a battleship thruster fed from a liquid premixed propellant reservoir were demonstrated [16, 18].

Based on the experience with nitrous oxide fuel blends, research in nitrous oxide bipropellants was also conducted. Here, ethane was chosen as fuel. The developments focused on the regenerative cooling concepts, optimization of injector geometries and combustion chamber geometries. In an iterative process several demonstrators were tested and the TRL was increased. Now, a 22 N and a 1 N thruster reached a level of maturity, which makes them attractive to the market. In the following section some key achievements of the current demonstrators are presented.

Development of the HIP_11 technology

In the frame of a PhD project, novel hypergolic fuels with highly concentrated hydrogen peroxide were investigated. A screening for suitable fuel candidates was performed, focusing on commercially available room temperature ionic liquids [19]. This kind of substances are salts with a melting point below room temperature. Due to the composition of anions and cations, ionic liquids do not have a vapor phase at ambient temperature. This significantly facilitates handling compared to conventional propellants. Based on the screening, a selection of promising ionic liquid was made. These ionic liquids were tested on their hypergolic performance in a so-called lab-scale drop test [19–22]. This procedure allows the initial evaluation of a hypergolic behavior of two substances. After several fuel candidates were identified in the drop tests, the ignition under more relevant conditions using injectors was studied [23, 24]. The most promising fuel candidate was successfully hot fired in a battleship thruster [11]. Further achievements will be presented in the next section.

STATUS OF THE DEVELOPMENT

HyNOx 22 N Thruster

Figure 1 shows a prototype of the HyNOx 22 N thruster. The used propellant combination is nitrous oxide and ethane. The thruster is additively manufactured and features a regenerative cooling concept. This allows steady state firings and short repeatable pulsing. Ignition is achieved with a glow plug. The thruster is designed to operate under a wide range of operating conditions, resulting in a throttle range of 35%-200%.

Figure 2 shows the 22 N HyNOx thruster firing at atmospheric conditions.

Figure 1: HyNOx 22N Thruster

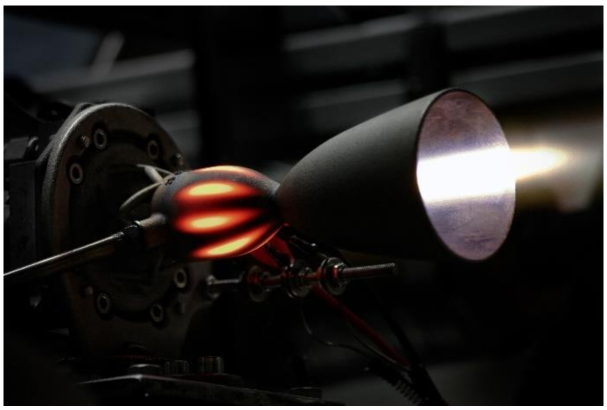

Figure 2: HyNOx 22 N thruster, atmospheric firing

Hot fires longer than 7 s resulted in a combustion efficiency of more than 95%. Based on the atmospheric testing, the vacuum specific impulse and thrust were calculated using the determined combustion efficiency and the thrust coefficient calculated with NASA CEA assuming a frozen flow at the throat and 2% nozzle losses. The average I_{sp} thus is 290s at a thrust of 22N, see Figure 3.

Figure 4 shows the temperature profile of the thruster during an atmospheric firing. The thruster was operated for 900 s and established a thermal steady state operation approximately after 40 s.

Furthermore, the operation under thermal steady-state conditions for a wide range of mixture ratios (6 – 20) and thrust levels (14-30 N) was successfully demonstrated under atmospheric conditions. With the 22 N HyNOx thruster a cumulated on-time of more than 1 hour and more than 20 kg of propellant throughput was demonstrated. Table 1 summarizes the thruster's performance.

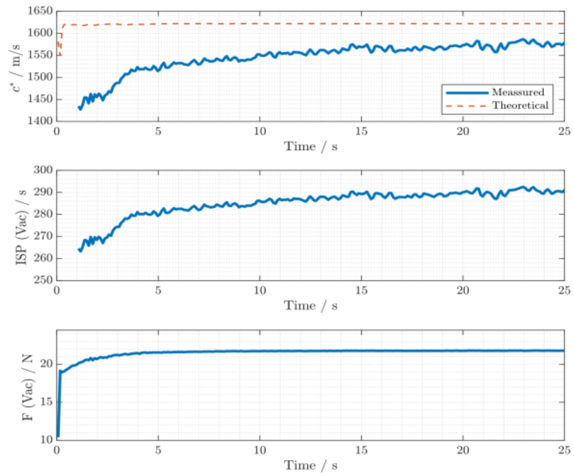

Figure 3: Efficiency Characteristics at Nominal Operating Conditions

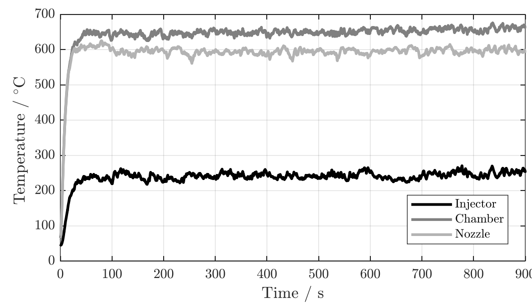

Figure 4: Steady-State Operation of 22 N Thruster

Within the scope of an ESA program, further testing of steady-state operation under vacuum conditions is currently ongoing. Figure 5 shows a vacuum firing of the 22N thruster. Thermal Steady state operation was demonstrated at 18 N of thrust. Thrust measurements during the vacuum tests confirm the I_{sp} calculations from the atmospheric testing.

Moreover, pulse mode capability was demonstrated under atmospheric conditions and in vacuum. The minimum On-time is 75 ms, with a total impulse bit lower than 1 Ns.

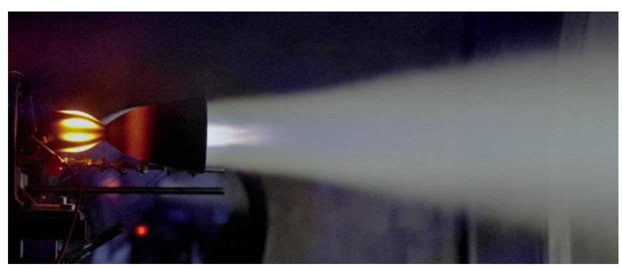

Figure 5: Steady-State Operation of HyNOX-22 in Vacuum Chamber

Table 1 HyNOx 22N Operation Characteristics

	Value	Status
Thrust (nominal)	22 N	
Thrust Range	44 – 7.7 N	qualification target
Specific Impulse (nominal)	290 s	calculated (from measured combustion efficiency)
Chamber Pressure (nominal)	6 bar	demonstrated
Minimum Impulse Bit	< 1 Ns	demonstrated
Single pulse firing time	>15 minutes	demonstrated
Propellant Throughput	20 kg	demonstrated
Cumulated on-time	> 60 minutes	demonstrated
Nozzle Expansion Ratio	100:1	adjustable
Maximum Pulse Frequency	5 Hz	demonstrated

Figure 6: HyNOx 1N Thruster

HyNOx 1N

Figure 6 shows the operation of a 1 N HyNOx thruster at ambient pressure. The thruster is also additively manufactured and features a regenerative cooling. In atmospheric tests, steady state and pulse mode operation were demonstrated. The thruster has a nominal chamber pressure of 7 bar. Operation was demonstrated with throttling between 30 and 120 %. Repeatable pulses with a minimum impulse bit of 0.1 Ns were verified.

Figure 7 shows a 60 s test run where the thruster reaches thermal steady state operation under vacuum conditions. The chamber pressure is 7 bar at a thrust of 0.83N. The temperature shown in Figure 7 is measured at the divergent part of the combustion chamber. The curve shows that the temperature is steady at a value of about 830°C. The demonstrated I_{sp} efficiency for the steady state operation is 90 %. To the authors knowledge, the thermal steady state operation of a 1 N bipropellant thruster with regenerative cooling is a unique achievement.

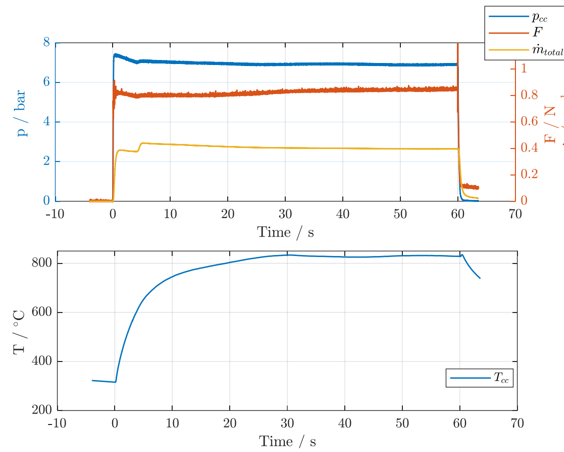

Figure 7: Steady-State Operation of HyNOx 1N Thruster in Vacuum

Table 2 HyNOx 1N Operation Characteristics

	Value	Status
Thrust (nominal)	1 N	
Thrust Range	0.3 – 1.2 N	qualification target
Specific Impulse (nominal)	up to 270 s	calculated (from measured combustion efficiency)
Chamber Pressure (nominal)	7 bar	demonstrated
Minimum Impulse Bit (Hot Gas)	< 0.1 Ns	demonstrated
Single pulse firing time	1 minute (vac) 3 minutes (atmospheric)	demonstrated
Propellant Throughput	1 kg	demonstrated
Cumulated on-time	> 40 minutes	demonstrated
Nozzle Expansion Ratio	100:1	adjustable
Maximum Pulse Frequency	5 Hz	demonstrated

A new iteration of the thruster is expected to increase the performance, and should allow operation at a mixture ratio with a higher I_{sp}.

Apart from the shown hardware, a 200 N HyNOx thruster is currently under development and will be tested in the second half of 2023. Moreover, the complete propulsion system is currently developed and will be offered by GreenDelta.

Demonstration HIP

The HIP_11 propellant is based on an ionic liquid fuel and highly concentrated hydrogen peroxide (up to 98%). The theoretical performance of the propellant is 315s (NASA CEA, chamber pressure 10.35 bar, expansion ratio 330, frozen at throat). This is 5% less than the conventional combination MMH/NTO at the same conditions (334s). On the other hand, the density specific Isp of HIP_11 is about 10% higher than the conventional one.

After the identification of a suitable hypergolic fuel candidates, tests with a 40N battleship thruster are used to evaluate the performance of the HIP_11 propellant. The design of the thruster is described in [11].

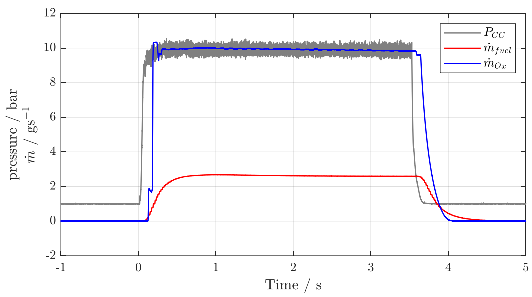

Figure 8: HIP_11 Test Run

Figure 8 shows the pressures and mass flows during a test run with the HIP_11 battleship thruster. As propellant, the ionic liquid with a copper additive is used with 97 % hydrogen peroxide. At 0 s fuel and oxidizer valve are commanded to open. The firing time was 3.5 s. The supply pressure was set to achieve a nominal chamber pressure of about 10 bar at an O/F of 3.8. After the valves open, smooth pressure rise inside the combustion chamber can be observed. The pressure increases to a steady level of about 9.9 bar. The following values are analyzed in the window from second 3 to 3.5. In this window, the mean values of the signal are calculated for the analysis. The combustion chamber pressure in the analysis window is 9.9 bar. The corresponding mass flows in the steady phase of the test run are 9.8 g/s for the oxidizer and 2.6 g/s for the fuel, which results in an O/F of 3.8. The calculated c* for this test is 1492.3 m/s. The c* efficiency of this test compared to the theoretical c* value calculated with the actual operating condition is 94.4%. The chamber pressure fluctuation assessed with the root-mean-square is 0.2 bar. Figure 9 shows a snapshot of the firing.

With the demonstrator, combustion efficiencies up to 96 % were demonstrated. Further, steady state operation up to 5s and reliable pulsing down to 50 ms ON time confirmed. The ignition in vacuum condition was validated as well. Currently, the development of a 200N HIP_11 thrusters in ongoing.

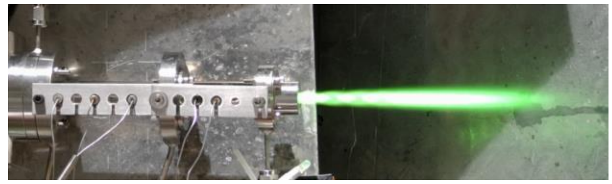

Figure 9: HIP_11 Hot Firing

CONCLUSION

Initial system studies were performed to investigate the performance and suitability of our solutions [25]. The HyNOx technology is a low-cost solution best suitable for spacecraft masses below 500 kg. The HIP_11 technology is a highly reliable solution and has advantages for lager spacecrafts with masses in the order of several 100 kg and above.

First HyNOx products will be available Q4 2023 and an in-orbit demonstration for 2024 is foreseen. End of 2024 first HIP_11 products will become available and an in-orbit demonstration is aimed in 2025.

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