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Development of the Liquid Green Propellants at the Lukasiewicz-Institute of Aviation

Paweł Stężycki [1], Piotr Wolański [2],*

** Corresponding author*
[1] Łukasiewicz – Institute of Aviation, Al. Krakowska 110/114, 02-256 Warsaw, Poland,
pawel.stezycki@ilot.lukasiewicz.gov.pl
[2] Łukasiewicz – Institute of Aviation, Al. Krakowska 110/114, 02-256 Warsaw, Poland,
piotr.wolanski@ilot.lukasiewicz.gov.pl

Abstract

In Europe, but also in many other countries initiative to replace toxic and corrosive rocket propellants based on hydrazine fuels and nitrogen tetroxide oxidizers with green propellants was undertaken. One of possible substitution of toxic and corrosive propellants are propellants based on highly concentrated hydrogen peroxide. In the Institute of Aviation in Warsaw a new and very effective technology of purifying industrial grade hydrogen peroxide was developed. Highly concentrated hydrogen peroxide up to 98%, or called as HTP (High Test Peroxide) can be very effectively used both as monopropellant or as an oxidizer for hybrid or bipropellant rocket engines.

Complex research on all aspects leading to development of different ways of decomposition of the HTP, such as selection of the most effective catalysts as well as ways of development of thermal decomposition system were carried out. This led to development of small monopropellants green rocket engines based on HTP at the Institute of Aviation. Additionally research to develop effective bipropellant rocket engines for application in satellites propulsion platforms as well as in the last stages of small satellites launchers is discussed. Biggest effort is however focused on development of hypergolic propellants which will provide not only similar performance to recently used toxic propellants but also will be self-ignitable, so it could be used to design very reliable propulsion system. Finally development of efficient hybrid rocket engine based on HTP and its application as a main propulsion system of the probing rocket “Bursztyn”, which was successfully launched last year, will be presented too.

1. Introduction

Today majority of storable and hypergolic propellants are based on Nitrogen Tetroxide (NTO) and its derivatives as oxidizers, hydrazine and its derivatives as fuels. However, at the beginning of development of a storable rocket propellants, especially in the USSR, nitric acid was also often used as an oxidizer, mostly for military rocket applications. But today the use of the Nitric Acid, is already abounded and it is no longer used in recently developed propulsion systems. Combinations of the NTO with hydrazine and its derivatives propellants which are storable for long time and additionally have hypergolic properties are still commonly used in many rockets and spacecrafts. Such combination guarantee reliable self-ignition and possibility to store it on the ground and on board of rockets and spacecraft for a very long time. The most popular oxidizer is NTO sometimes used with addition of nitric oxide, NO, and such combination is called MON. This combination is used in a deep space mission of spacecrafts for attitude control and small trajectory correction, to lower freezing point of the NTO, but with penalty of increasing vapor pressure. As it was already mentioned, basic fuel for such oxidizers are hydrazine and hydrazine related combinations such as Unsymmetric dimethylhydrazine (UDMH), (CH3)2N2H2), Monomethylhydrazine (MMH), (CH3)HN2H2), or Aerozine-50 (50% UDMH, 50% hydrazine). Because those propellants can be stored for a relatively long time they were and are still used in some ballistic missiles as well as for manned missions for orientation and trajectories maneuvers/corrections. NTO with Aerozine 50 was used in Apollo program for Service and Lunar Module propulsion systems. NTO and MMH power Space Shuttle orbiter's orbital maneuvering system (OMS) engines and Reaction control system (RCS) thrusters. Also SpaceX's Draco and Super Draco engines for the Dragon spacecraft are still using the same propulsion system. To summarize storable propellants based on NTO and hydrazine, as well as hydrazine derivatives are still used by the intercontinental ballistic missiles and most spacecraft, including crewed vehicles, planetary probes, and satellites, where storing of the cryogenic propellants over extended periods is unfeasible. So, because of this, mixtures of hydrazine or its derivatives in combination with nitrogen oxides are generally used for

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such applications as most reliable propellants, but they are corrosive, toxic and carcinogenic. In addition handling of those propellants require special protection measure for ground crews operation teams [1-3].

Fig. 1. Europe's 13th Galileo satellite was fueled with hydrazine on 5 May 2016 inside the S3B payload preparation facility of Europe's Spaceport in French Guiana. Credit: ESA-CNES-Arianespace/Optique video du CSG – S Martin. https://phys.org/news/2016-05-galileo-satellites-fuelled-flight.html

For this reason ESA as well as now some USA initiative space ventures such as some crew vehicles Dream Chaser and Space Ship Two plan to use rockets with non-toxic fuel and oxidizer combinations. Due to this problems in Europe a new initiative to eliminate toxic and corrosive propellants was introduced and development of the new substitutions for those propellants was started. The green propellants must be non-toxic and easily handling and stored on rocket tanks as well as on spacecrafts, satellites and deep space probes. Additionally it have to demonstrate comparable performance as recently used toxic and corrosive propellants. This concerns both mono as well bipropellants. The detailed analyzes of possible green propellants is presented by Mayer and Wieling [4] as well as other [5-6]. Substitution of hydrazine or its derivatives by non-reacting liquid, as propane, did not results with higher performance but can but use in a very small satiates, as CubeSat, and offer simple design and operation. More advance solution could be "water", which on board of satellites, spacecrafts and even Space Station, could be decomposed by electrolyze into hydrogen and oxygen and those gases could be used as a very efficient propellants for the propulsion system. However, such approach require to use sophisticated electrolyze system and supply of the electrical energy from the solar cells, storage of gaseous hydrogen and oxygen and then supply such gases to the small thrusters. Another solution, already tested by NASA, is an energetic ionic liquid. The Ionic liquids are salt compounds in a liquid form whose molecules have either a positive or negative charge, which bonds them together more tightly and makes the liquid more stable. Most promising are HydroxylAmmonium Nitrate (HAN) and Ammonium DiNitramide (ADN). They can be dissolved in water to form a liquid monopropellant or a liquid oxidizer in a bipropellant system [4-6]. The Green Propellant Infusion Mission (GPIM) was a NASA technology demonstrator project that tested a less toxic and higher performance/efficiency chemical propellant for next-generation launch vehicles and CubeSat spacecraft. The propellant for this mission is HAN (NH_3OHNO_3) fuel/oxidizer blend, and preliminary data indicates that it offers nearly 50% higher performance for a given propellant tank volume compared to a conventional monopropellant hydrazine system [6]. However, in our opinion, is the possibility of use Highly Concentrated Hydrogen Peroxide, commonly called HTP, both as monopropellant and oxidizer for the bi-propellants systems is also very promising solution. In this paper a detailed description of purifying technology to obtain HTP, analyses of developed green liquid propellants based on the HTP as well as the tests of all kinds of engines/rockets using such green propellants is presented.

2. Hydrogen Peroxide

Hydrogen peroxide (H_2O_2) is a well-known as monopropellant as well as oxidizer for the rocket propellants. In concentration of 70-87% it was used by Germans during WWII and in USA for rocket application in the X-1 and X-15 research aircrafts [1,2]. Hydrogen peroxide can be decomposed into water (steam) and oxygen. During decomposition significant amount of heat is release, so HTP can be used as monopropellant. HTP, with concentration up to 98%, is second after oxygen in oxidizing ability, but unlike liquid oxygen can be stored for a long time in rockets/spacecraft's/satellite's tanks. So it is a very good candidate for oxidizer for a green storable propellants. Also

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vapors of HTP are not toxic and handling of 98% HTP do not required such safety measures as for hydrazine or nitrogen tetroxide [7,8]. Safe handling of the 98% HTP is relatively simple and is show in Fig.2.

Fig. 2. Safe handling of 98% HTP at the laboratory of the Institute of Aviation in Warsaw.

At the Institute of Aviation in Warsaw the new and highly effective method was develop for purifying industrial grade of hydrogen peroxide to concentration of 99,99% of purity, but the installation is commonly used for obtaining of the 98% HTP.

Properties of the HTP is given below:

- High density, 1442 kg/m3 @ 150C,
- High adiabatic temperature of decomposition, 978 ^{0}C,
- High concentration of energy, 1kg@HTP -> ~2850kJ,
- Catalytic decomposition of 1kg HTP results in 4500 liters of gas (47% oxygen, 53% of water vapor),
- Stable, transparent liquid,
- Easy and safe for storage.

At the Space Technologies Division of the Lukasiewicz – Institute of Aviation crucial achievement is the development and commercialization of the method for preparing hydrogen peroxide, in particular High-Test Peroxide – HTP, which is utilized in a wide range of industries. Institute of Aviation holds the European Patent for this technology with concentrations up to 99.99% can be obtained. [9].

Fig.3. Laboratory test stend for purification on comercial H_2O_2 to the purity of 99,99% [9].

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Research conducted on applications of green propellants for rocket propulsion were already made at the Institute of Aviation based on HTP with liquid fuels (bipropellants engines) as well as with solids (hybrid engines). Details can be found below.

3. Green Propellants

For small rocket engines, as it was already mentioned above, one possible replacement for toxic and corrosive propellants based on hydrazine and nitrogen tetroxide is the highly concentrated hydrogen peroxide (HTP). HTP is not only very effective oxidizer but also can be used as monopropellant. Limited applications as propellants of HTP (with concentration of 87%) were initiated by Germans during II Word War for auxiliary propulsion systems. Later there were a few initiatives to apply it as oxidizer for the bipropellant relatively large liquid rocket engines. So far, rocket engines using HTP and kerosene have been used in British Black Arrow launcher, but also Glushko bureau designed the RD-161P engine which was proposed for the Soyuz 3M rocket. Most of those engines used HTP as oxidizer with kerosene (RP-1) as fuel. In the Table 2 parameters of a few rocket engines using kerosene and $H_2O_2$are shown - some were built in the 1950s, some were considered (a study or a prototype) in the 1990s. HTP was commonly used to drive rocket propellants pomp and for the reaction control system (RCS) –e.g. in the X-15 rocket plane for maneuvering in the low-pressure/density environment.

Eng-engineslink	**Thrust(vac)-kN**		**Isp-sec**	**Isp (sealevel)-sec**	**Designed for**	**Status**
RD-161P	24.50		319		Upper Stages	Developed 1993
JP-5/H2O2	63.00		335		First Stages	Study, USAF, 1993
Gamma 2	68.20		265	251	Upper Stages	Out of Production/Black Arrow
BA-44	196.00		300		Upper Stages	Development
Gamma 8	234.80		265	251	First Stages	Out of Production/Black Arrow
BA-810	3,600.00		282		Upper Stages	Development
BA-3200	14,100.00		259		First Stages	Development

Table 1. Large rocket engines using HTP-kerosene as propellants.

Applications of HTP to large rocket engines used in launchers was not competitive with liquid oxygen which is commonly used in rocket launchers as a best liquid oxidizer with such fuels as: liquid hydrogen, kerosene and liquid methane (recently under development). But such combination of propellants is only possible for low storage time in rocket’s tanks, since liquid oxygen as well as liquid hydrogen or liquid methane can be only stored in rocket tanks for hours, but not for months or years as it is required for engines used in long duration missions.

4. Development of the green propulsion systems.

Lukasiewicz - Institute of Aviation is capable of designing, manufacturing and testing rocket propulsion components and systems utilizing HTP. Dedicated laboratories of Propellants, Catalysts and Space Propulsion are part of the existing infrastructure. Tests of engines of trust ranging from mN up to 15 kN are possible in-house and up to 100 kN using facilities of IoA’s Partners. Institute of Aviation has wide experience in development of monopropellant thrusters, bipropellant liquid rocket engines, as well as hybrid green propulsion systems.

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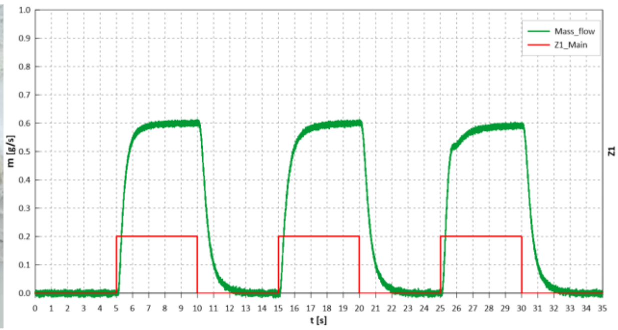
a)



b)

c)

Fig. 4. Monopropellant engine working on HTP: a-picture of the engine, b-recorded trust during pulse operation, c-view of the engine test on the test stand [9-11].

One of possible application of the green propellants are the monopropellant engines for small satellites. They main application is Attitude Control System as well as a small orbit correction. Required trust of such engines is usually less than one Newton but they have to operate for many cycles during useful live of the satellite. Picture of such engine developed at the Institute is shown in the Fig.4. But beside producing necessary impulse also effective work of catalyst should be guaranteed for a many cycles and catalyst should not be damaged during cold start. Thus to prevent this special devoted research were carried out in our Institute to develop catalyst resistible to degradation [12-17].To guarantee effective use of the HTP in propulsion system extensive research of the selection of the catalysts were conducted [18]. This allow the quick engine start and guarantee the longer operation time for the catalyst and the engine, especially for application to the Attitude Control propulsion system and engines designed for orbital maneuvers during injection of satellite to the designed orbit or during mission designed for space debris removal, which will need extensive maneuverability of such spacecrafts in orbit.

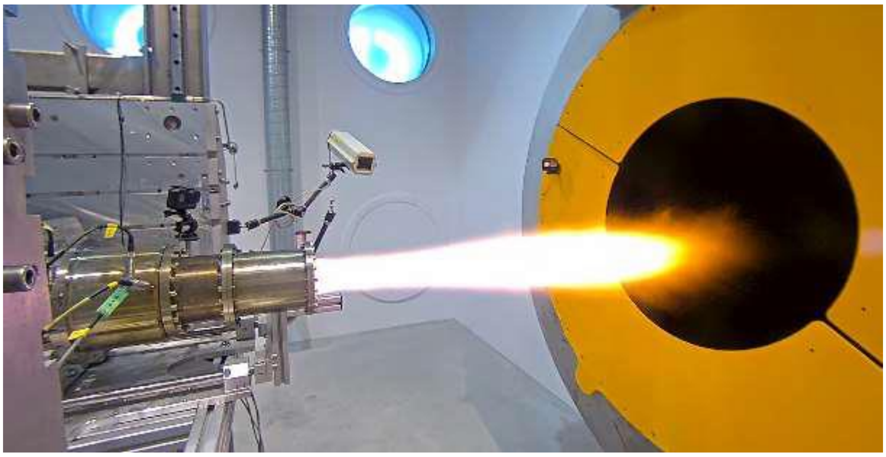


Fig.5. Laboratory test of the monopropellant throttleable green rocket engine with designated 110-10% thrust control system.

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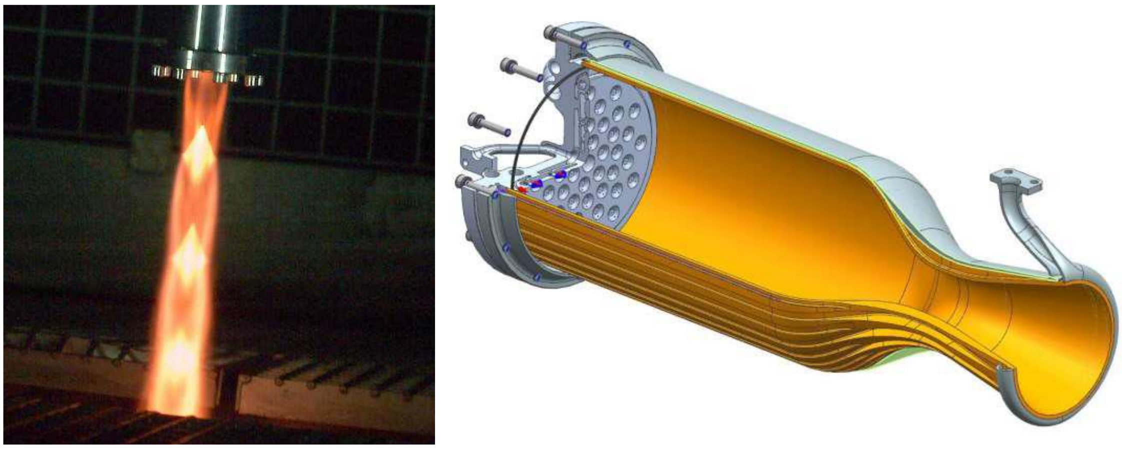
The new monopropellant engine was also designed for testing method of large rocket boosters recover and soft landing. Such research is carried out with cooperation with CNES (Frog Project). Picture of such engine during evaluation tests is presented in Fig.5.[19,20].
More advance research is now focused on the development of hypergolic green propellants based on HTP which may be used to supply rocket engines of last stages of small satellite launchers as well for orbital maneuvers system of larger satellites, especially for future debris removal from orbit. Such propulsion system will guarantee similar performance as recently use propellant based on NTO and hydrazine or its derivatives. Crucial requirement for such engines is necessity to have the ignition delay very short to prevent accumulation of propellants in combustion chamber before ignition and provide a smooth and reliable operation of such engine. To select a most suitable additive to the liquid fuel used in such engine, nearly hundred different additives were tested and the best one was selected for future use. The picture of test of such hypergolic green propellant in laboratory conditions is shown in Fig.6a., and design of the rocket engine working on such propellants, partially manufactured using additive technology is depictured in Fig.6b. [9,19]
Another tested application of the green propellants based on the HTP were development of the large hybrid rocket engine to power suborbital rocket "Bursztyn" [21-23]. This rocket was designed to carry experimental research up to the altitude of 100km, as well as to provide a platform for the microgravity experiments. The engine produce the trust of 15 kN and works for more than 42 s [22]. The rocket "Bursztyn" use two solid rocket booster to accelerate to about 2M velocity, but the main hybrid engine use the HTPB as a fuel and HTP as oxidizer. Such combination will provide sufficient thrust to accelerate rocket to climb to altitude of about 100 km [23-26]. Picture of the test of such hybrid engine in the laboratory conditions is shown in Fig. 7.



a) b)

Fig.6. Bipropellant rocket engines utilizing hypergolic green propellants base on HTP: a- green reignitable storable bipropellant systems with 3-8 kN of thrust in vacuum, b- design of the engine based on additive manufacturing for hypergolic green propellants[9,19].

DOI: 10.13009/EUCASS2023-373

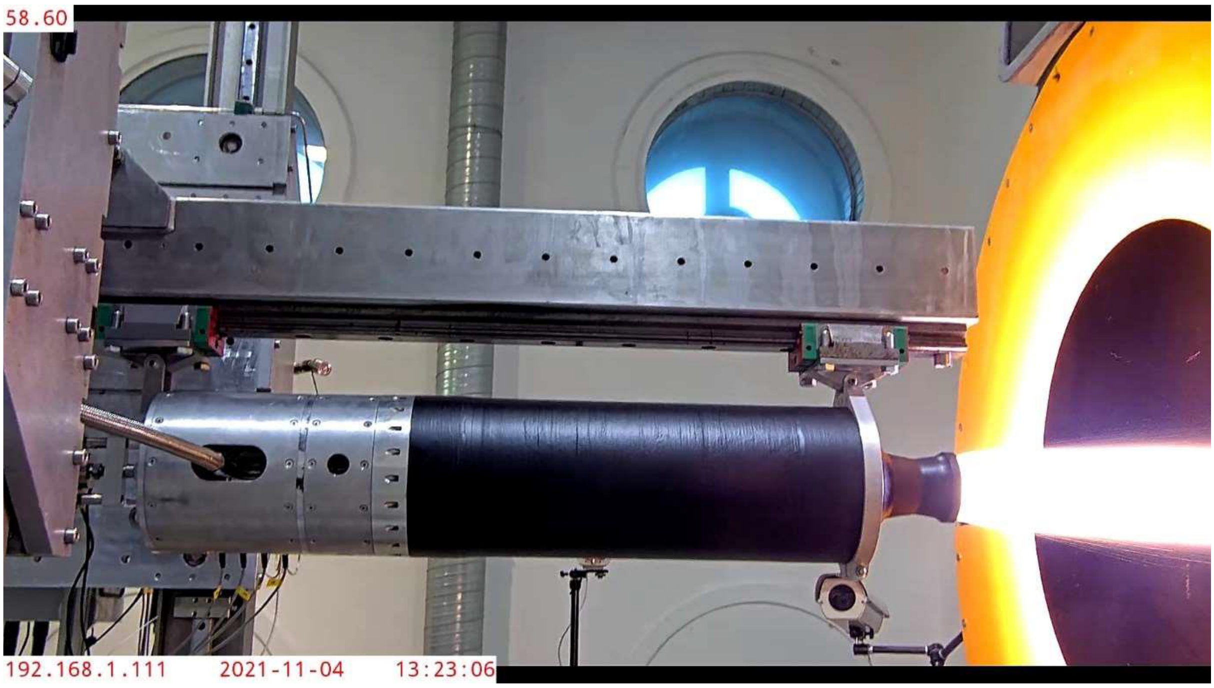


Fig. 7. Laboratory test of hybrid green rocket engine designated for suborbital Bursztyn rocket.

In fig. 8a initial stage of test launch of the Burstyn rocket is presented while in Fig.8b the rocket just before leaving launch pod. In both pictures it is clearly seen exhaust plums from hybrid engine and as well as from the boosters. Plume from the hybrid engine is visible just at the end of the engine's nozzle, while plums from the boosters, which are working on solid propellants, are only seen in some distant from the nozzles, when rich in fuel products start to afterburning with surrounding air.

a)

DOI: 10.13009/EUCASS2023-373

b)

Fig. 8. Test launch of the "Bursztyn" rocket with main hybrid engine working on green propellants: a- initial stage just after ignition of both booster and main hybrid rocket engine, b- accelerated rocket on the launch pod [26].

5. Summary and conclusions

In the Lukasiewicz – Institute of Aviation complex research devoted to development of the Green Propellants were conducted. First of all a new and very effective method of the purifying hydrogen peroxide to the HTP was developed and commercialized. For laboratory tests purifying method of obtaining 99,99% of hydrogen peroxide purity was developed, but for applications 98% H_2O_2 is commonly used. Special engines utilizing HTP were developed, ranging from mN up to 15KN of trust and with applications to small satellites Attitude Control System, throttleable engines for testing technology of recover of the booster of large launcher for its reusability, engines for small orbit corrections and in orbit maneuvers, bipropellant hypergolic engines for upper stage of small satellite launcher and the large hybrid engine for suborbital rocket. All conducted research demonstrated possibility of effective replacement of currently use propulsion systems with a newly developed green propulsion systems based on HTP. So those research open applications of green propellants for different kinds of rocket and space propulsion systems.

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