Challenges and Economic Benefits of Green Propellants for Satellite Propulsion

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Abstract

Satellite market currently faces several new trends that will significantly change today's product portfolio. Besides upcoming mega-constellations and the maturation of electric propulsion several other factors like clean space require a re-definition of propulsion concepts. One aspect of clean space is to use more green / eco-friendly or non-toxic propellants to replace classical toxic hydrazine based systems. The need for nontoxic propellants is increasing not only since classical, hydrazine based propulsion systems are facing legislative regulations but also because non-toxic alternatives can offer significant technical and economical assets. This paper gives an overview on recent trends, requirements and upcoming new technologies with a focus on challenges and economic interests of these green propellants.

1. Introduction

Hydrazine based propulsion systems are state-of-the-art for various applications ranging from launchers to large and small satellites. They have a long and successful heritage and a great variety of space qualified, off-the-shelf components. Hydrazine as a monopropellant and MMH (Monomethyhydrazine) or UDMH (Unsymetric Dimethylhydrazine) as a bipropellant are toxic, carcinogenic and mutagenic. Therefore special precautions have to be taken during all ground and operational phases when Hydrazine or its derivatives are used.

Since Hydrazine was identified as a substance of high concern by the REACh regulation in 2011 there is a threat that these systems might be forbidden in the future [1]. The process is still ongoing but it triggered another progression to investigate attractive new propellants and technologies for the market and fostered the research for non-toxic high performance alternative technologies. In parallel to these developments the global market faces a change due to the further maturation of electric propulsion and due to mega-constellation programs.

This paper focus the replacement of Hydrazine as a monopropellant.

1.1 Market Changes

The classical chemical satellite market is influenced by several external factors that have to be considered when investing in a new propulsion technology:

- "Greening" of classical hydrazine based propulsion systems is recommended and supported by European and national agencies
- The maturation of electrical propulsion systems (EP systems) strongly influence the market because electric Propulsion has about a factor of 10 higher ISP compared to classical chemical systems and the usual propellant, Xenon, is non toxic
- New Requirements like the need to perform active deorbiting impose demands for additional Δv (propellant mass) but also high thrust engines for an active deorbit with given time constraints
- Mega constellations like OneWeb require a significant price reduction that is realized by a different reliability approach vice versa sets new standards for classical satellites
- New and upcoming launchers offer dedicated orbit injection capabilities (direct SSO, direct GEO, ..).
- Small launchers offer direct end orbit injection also for small satellites in the 100kg class

1.2 New Requirements for Propulsion

The market change stimulates changes and evolution in the required propulsion technology that are discussed hereafter:

Electric Propulsion: The following figure shows an example of the mass distribution of a GEO satellite when electric propulsion is used. The significant advantages of launching two satellites by the price of one has the disadvantage that current EP systems are still produced at higher prices and offering only thrust in the mN range. This low thrust means that the duration for orbit rising may be up to several months compared to a few hours for classical chemical systems. However higher thrust is required for specific manoeuvres such as collision avoidance or in an emergency case. As the Δv requirements for these auxiliary manoeuvres are reduced, it is possible to exploit cold gas or monopropellants instead of complex bipropellant systems.

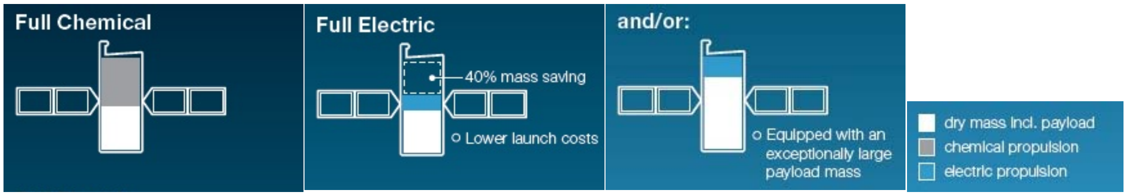

Figure 1: Mass savings for a typical GEO satellite when EP is used

Space Debris Mitigation: In order to avoid a pollution of used/privileged orbits the technologies that are required for space debris mitigation are [2]:

- **Design for Demise:** Aluminium Tanks instead of Titanium Tanks, early breakup Structures
- **Passivation:** Passivation valves; Lifetime extension of pyro valves used at End of Life
- **Deorbit Systems:** active propulsion systems with high Thrust, high Δv capability

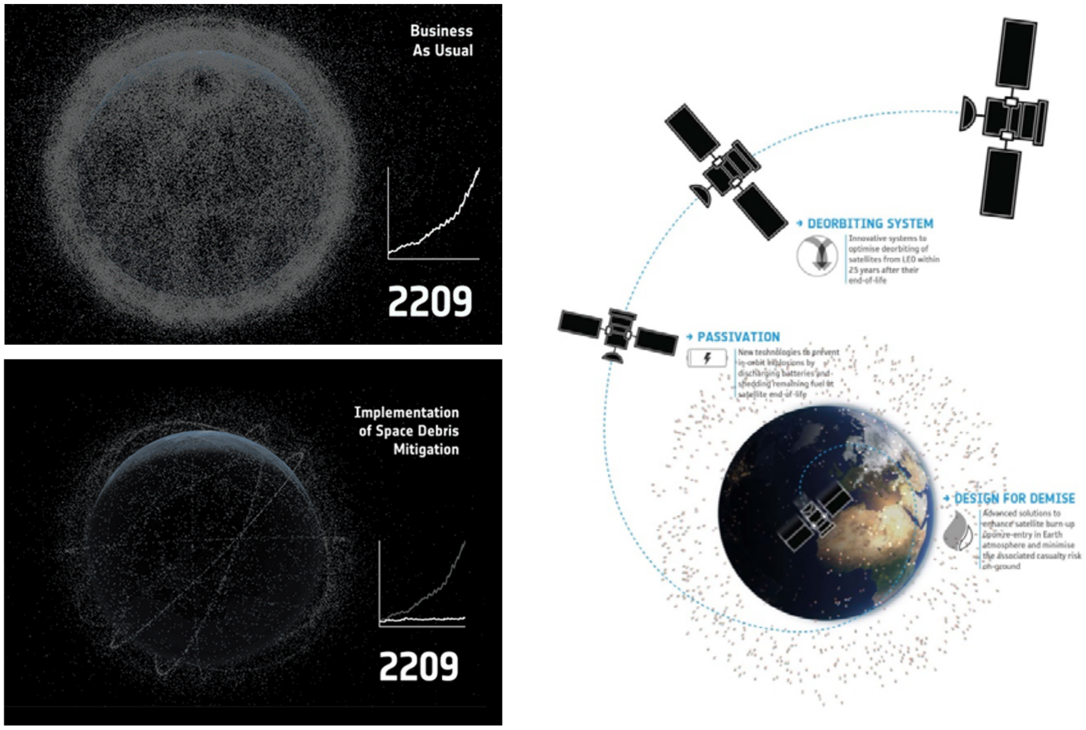

Figure 2: Space debris and ESA Space debris mitigation approach

Mega-constellations: Hundreds of satellites in LEO or MEO orbit require but also allow a significant cost reduction of satellite manufacturing but also requesting low launch cost. In order to allow a deployment in any LEO orbit a high Δv is needed in order to allow the satellite to reach its final orbit. For this purpose low cost EP systems are developed. Once low cost EP systems for small satellites are available they will also take market share from systems that previously used Hydrazine and thus also from green replacement candidates.

2. Green Propulsion Technologies

2.1 Application areas for Classical and Green Technologies

The following figure shows an overview over the application areas for space propulsion, current toxic (in red) and non-toxic (in green) technologies that are used and non-toxic technologies that are currently investigated or under introduction into the market.

The figure also shows that for key applications where today still toxic propellants are in use green technology is already available. Further maturation is necessary to fulfil all the various demands of the different applications and use cases.

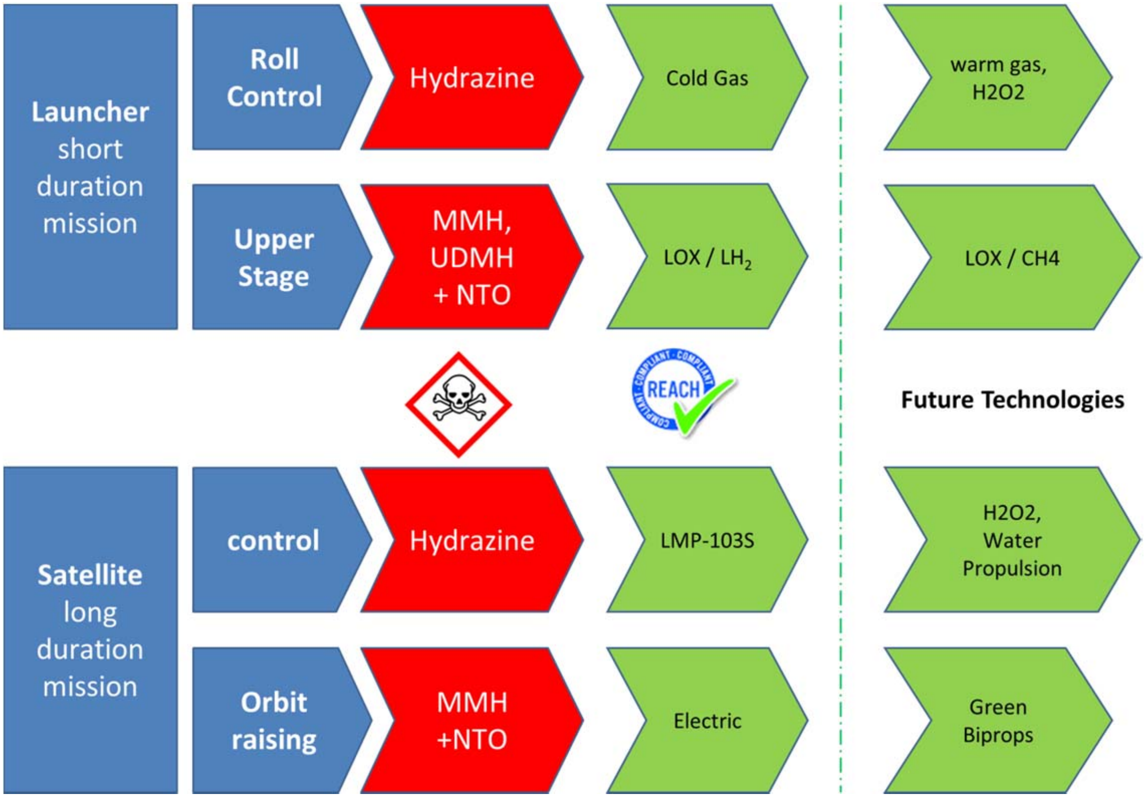

Figure 3: Application areas for space propulsion and technologies that are used

Technologies that are currently investigated at Airbus Safran Launchers (ASL) are described hereafter in more detail.

2.2 ADN Technology

The term “ADN Technology” is used for a liquid monopropellant where solid oxidizer (ADN - Ammonium dinitramide salt) is solved in water and then fuel and stabilizer are added. In the combustion chamber the oxidizer and fuel are burned with subsequent high combustion temperatures. It is considered as non-toxic and air transportable. Typically these propellants have a higher ISP and a higher density compared to Hydrazine. A comparable technology is the HAN technology where HAN (Hydroxylammonium Nitrate) is used as a solid oxidizer, e.g. in the propellant AF-315ME [3].

ECAPS LMP-103S Technology: LMP-103S is a liquid propellant where the solid oxidizer (ADN) is solved in water and Ethanol is used as fuel. The ADN technology is closely linked to the Swedish company ECAPS that developed the propellant LMP-10S and subsequent thrusters which are for the first time used on a commercial mission [4].

Based on these good results LMP-103S technology was selected to be able to offer a green alternative for the Airbus Safran Launchers MYRIADE satellite family. The propellant and the thruster are currently in a qualification phase for the use in European applications.

Airbus Safran Launchers demonstrated that in the mechanical and thermal design of a propulsion system can be made compatible with both Hydrazine and LMP-103S. Therefore with only small impact, the propellant for the propulsion system can be decided at a very late development stage. E.g. for the MYRIADE system only the thrusters needs to be adapted when changing from Hydrazine to LMP-103S.

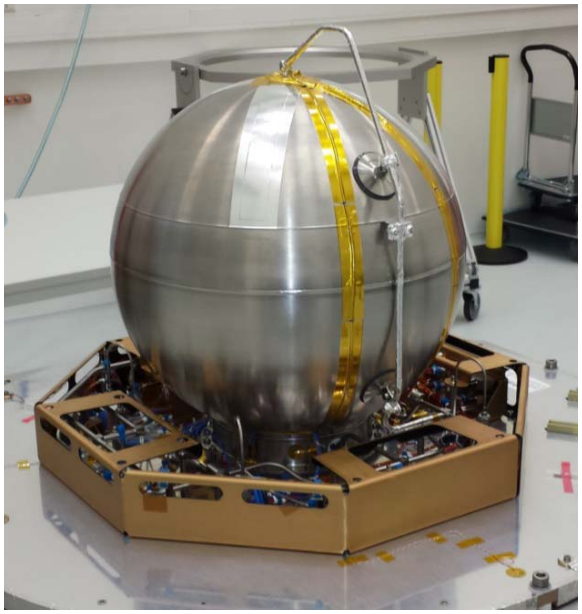

Figure 4 MYRIADE satellite propulsion subsystem for Hydrazine and LMP-103S

Advantage of LMP-103S	Disadvantage of LMP-103S
▪ Non Toxic, non-carcinogenic ▪ Most COTS components can be used ▪ Lower cost of handling ▪ High Density (1250 kg/m³) ▪ Higher performance (235 s) ▪ Allowed to be transported by airplane	▪ Higher cost of propellant and thruster ▪ Preheating of thruster to > 250°C required and has to be controlled ▪ High combustion temperature requires high temperature combustion chamber material ▪ ADN salt itself is a friction sensitive explosive with subsequent handling effort

Table 1 Advantages / Disadvantages of LMP-103S

ADN Technology Evolution - Horizon 2020 project RHEFORM: The current disadvantages of the ADN based propellant technology as required preheating power and expensive combustion chamber material are addressed in the EU Horizon 2020 project RHEFORM. In this project two different ADN based propellants are investigated: FLP-106 and LMP-103S with variations in actual composition (mainly the water content that drives performance and combustion temperature). In the following figure the ISP versus combustion temperature is given and potential combustion chamber materials indicated.

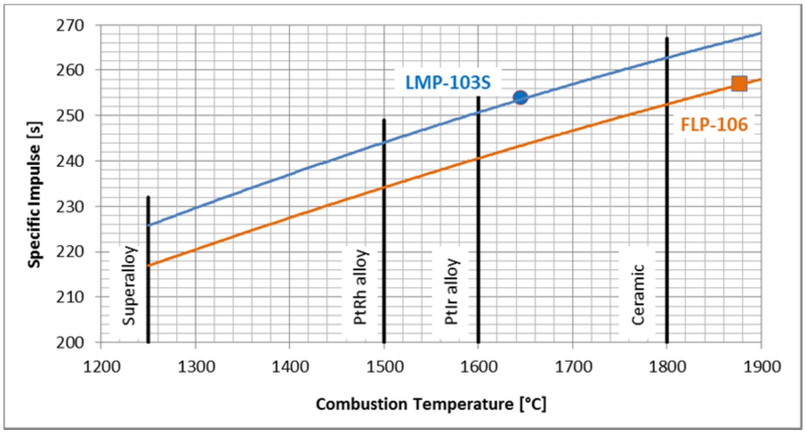

Figure 5 Theoretical ISP of ADN based propellant with variation in water content

The following main targets are followed in the project; first results of this project are presented in [5].

- Adjustment of propellant composition to be compatible with European high temperature chamber material
- Improvement of catalyst in order to reduce preheating power
- Investigate ignition methods to avoid preheating.

2.3 Hydrogen Peroxide

Hydrogen peroxide is a chemical compound with the formula (H_2O_2). In its pure form it is a colourless liquid, slightly more viscous than water. Hydrogen peroxide is a strong oxidizer and is used as a bleaching agent and disinfectant. Concentrated hydrogen peroxide, or 'high-test peroxide' (HTP) is used as a rocket propellant since 1934. Currently HTP is being used on the Sojuz Launcher for the first stage gas generator and on the Sojuz capsule for the reaction control thrusters used during re-entry. In the frame of the H2020 project HYPROGEO the manufacturing and transport of 98% was qualified and this propellant blend is now commercially available on the market [6].

Hydrogen Peroxide was investigated at ASL in the frame of a fully ALM printed thruster [7] and is currently considered as a low cost option for orbital propulsion. It has the following advantages / disadvantages compared to classical Hydrazine:

Advantage of H_2O_2	Disadvantage of H_2O_2
▪ Non Toxic, non-carcinogenic ▪ Cheap, commercially available ▪ Cold start capable (monopropellant with catalyst) ▪ Low decomposition temperature (<1000°C) ➔ conventional materials can be used ▪ High Density (1450 kg/m³) ▪ Can be used as an oxidizer in biprops and pure as monoprop (dual mode system)	▪ **Safety:** Careful handling required (H_2O_2 not as robust / failure tolerant as Hydrazine) ▪ Significant self-decomposition ratio, pressure increase in tanks, venting system required ▪ Not compatible with Titanium (Stainless steel or Aluminum required), limited use of COTS components ▪ Low performance in monoprop mode - max 185s pending on H2O2 concentration

Table 2 Advantages / Disadvantages of Hydrogen Peroxide

2.4 Water Propulsion

Water propulsion is defined as propulsion that uses water as a stored propellant which is decomposed into gaseous Oxygen and Hydrogen via an electrolyser in orbit. These gases are then exothermic combusted for generation of thrust. It is a semi electric propulsion where propellant is generated over a longer time period with low power and is then exploited during short boost.

The operational sequence is the following

(1) After the start the water feed is switched ON: water from the water tank is fed via low pressure into the electrolyzer

(2) GOX and GH2 are produced in the electrolyzer via electric power with a high pressure

(3) After production the propellants are stored in gas tanks ready for use (gas tanks full)

(4) The gases are either used in the thrusters to generate thrust or by a fuel cell to generate electric power when needed

(5) when the gas tanks are empty the process starts again (back to first step)

The following figure shows the generic system layout and the operational sequence:

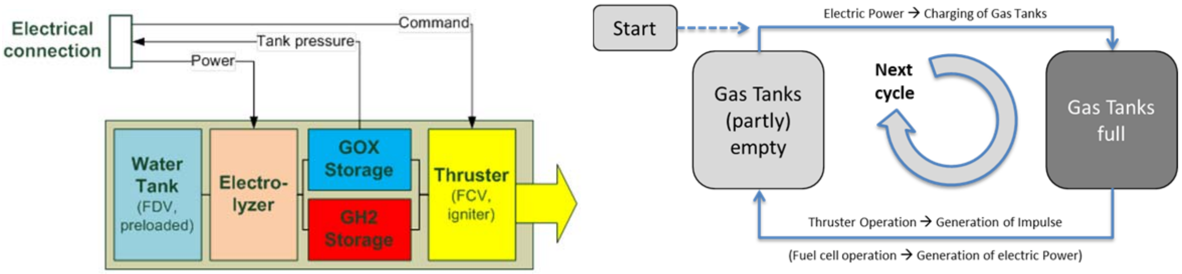

Figure 6 Water Propulsion – functional diagram and operational sequence

ASL development is focusing on electrolyzer and the thruster technology.

- **The Electrolyzer:** development target is a low cost electrolyzer where water at low feed pressure enters on one side and high (50 bar) pressure, dry and phase separated gases are produced under space conditions. Pressure increase is done via electrochemical pumping that does not require moving parts.
- **The Thruster:** development target is a thruster derived from existing European chamber material and passive ignition that operates with stoichiometric produced gases and generates a high specific impulse. The current ASL design consists of a catalytically ignited thruster with a platinum alloy based chamber. Baseline functions have already been demonstrated and the hot firing demonstration test is planned in 2017.

Advantage of Water Propulsion	Disadvantage of Water Propulsion
▪ High performance (ISP > 300s) ▪ Low cost, green propellant without any potential limitations in the future ▪ Can be preloaded at the manufacturer ▪ High gas pressure is generated only when electrical power is applied ▪ If combined with a fuel cell it can even be used as a high effective battery ▪ Existing COTS components can be used	▪ Higher system complexity; additional elements like electrolyzer, electronics, gas tanks needed ▪ GOX / GH2 thruster requires high temperature combustion chamber material ▪ Usage only in cycle mode; limit of individual manoeuvre impulse via gas tank size

Table 3 Advantages / Disadvantages of Water Propulsion

3. Market, Opportunities and Challenges for Green Propulsion to replace Hydrazine

The actual development of green propellants was initially triggered by the REACh threat that the use of Hydrazine may be limited or even forbidden in the future. In the meanwhile, the market changed and additional requirements for the propulsion subsystem arose that can push the introduction of green technologies into the market without a legislative compulsion to do.

The propulsion system requirements driven by the changing **Market** are the following

- More and more customers require explicitly at least a green option for their satellite or launcher (e.g. roll control system for VEGA E)
- The use of electric propulsion on GEO satellites requires small auxiliary propulsion systems
- Clean Space requires high thrust, high performance deorbit thrusters for larger LEO satellites
- Constellations are composed of a high number of satellites with a significantly reduced price.

The **Opportunities** of green propellants are:

- **Lower the total lifecycle cost of operation:** Handling of toxic propellants is expensive: Special precautions have to be taken during every handling step, special facilities and infrastructure have to be maintained, the propellant itself has to be controlled in every step from production, transport, testing, mating with the launcher, use and disposal
- **Increase Flexibility:** Air transport and parallel operation in the cleanrooms during spacecraft propellant loading allows to flexibly adapting the schedule because the operations are shorter and no long preparation has to be planned e.g. when transporting Hydrazine to the launch site. When propellant can be preloaded at the manufacturer site specific propellant transport to and loading at the launch pad can be avoided and thus reduces cost
- **Increase Performance:** With an increased ISP and density more impulse (Δv) can be loaded into the spacecraft. This allows longer mission duration or missions that previously require more complex technologies (e.g. bipropellants). For the same Δv the satellite can be smaller and lighter which allows to transport more satellites during one launch.

The **Challenges** for a new green propellant replacing existing ones are

- Non Toxic, no potential to be affected by REACh in the future
- Safely Space and ground storable
- ISP of 200 sec in monopropellant mode, ideally >250 sec
- ISP of 300+ sec in bipropellant mode, ideally >320 sec
- Passive or hypergolic ignition ideally in cold start
- No operational limitations (unlimited steady state and pulsed mode operation with all combinations of ON / OFF time)
- Compatible with standard construction materials to uses as much as possible COTS components
- Commercially available
- Cheap with a high potential to decrease cost for larger quantities in serial production

4. Economic Benefits

Cost differences and thus economic benefits of green propellants are in the following areas:

- **Propulsion hardware:** suppression of expensive catalysts, exotic chamber materials or additional hardware reduced the cost whereas low cost materials or less components lead to cheaper systems
- **System complexity:** with toxic propellants 3 barriers are required for launch site safety. A thruster flow control valve typically has 2 barriers and the third barrier is realized by a pyrotechnical device or a latch valve. When non-toxic propellants are used a system can be designed with only 2 liquid barriers. System complexity increases when additional components have to be used e.g. if a pressure built up due to self-decomposition has to be considered
- **Propellant:** the cost of propellant for flight but also for ground tests has to be considered especially when a higher amount of propellant is used. Propellant cost can range between nearly zero when water is used up to >1.000 €/kg when ADN based propellants are used
- **Handling during manufacturing, assembly, integration test:** if toxic or explosive propellants are handled this requires certain safety measures for storage, testing and handling of propellant waste. If simulation fluids have to be used during system tests this requires loading, unloading cleaning activities
- **Logistics for propellant transport:** pending on the transport capabilities (ground / air) air transport or no separate transport at all can have benefits over the classical ship / ground route
- **Handling during launch:** this relates to required equipment (protective suits for toxic propellants), potential excluded parallel operation in the clean room during propellant loading or the cost of disposal of contaminated equipment.

The following table compares the different cost factors to a standard Hydrazine monopropellant propulsion system with following ranking:

Slightly more expensive	Significantly more expensive	Slightly less expensive	Significantly less expensive

Cost Factor	LMP-103S	Hydrogen Peroxide	Water Propulsion
Propulsion hardware	Thrusters more expensive	limited COTS hardware available	Higher system cost due to additional components
System complexity	Comparable; additional thruster temperature monitoring is required	comparable; venting to be considered	Significantly higher due to additional electrolyser, gas tanks
Propellant	More expensive	Less expensive	neglectable
Handling during manufacturing, assembly, integration test	Comparable to Hydrazine as propellants are high energetic fuels	Comparable to Hydrazine as propellants are high energetic fuels	Significantly lower
Logistics for propellant transport	Advantages due to possible air transport	Comparable to Hydrazine	No cost at all, propellant is COTS water
Handling during launch	Significant advantage because no scape suit is needed and parallel operation in clean room is allowed	Advantage compared to Hydrazine	No cost at all, propellant is preloaded at manufacturer

Table 2 Cost comparison of various alternative propellant technologies

5. Conclusion

The research on green propellants was intensified since Hydrazine was identified as a substance of high concern in the European REACh regulation. The process to implement Hydrazine in REACh Annex XIV and thus to limit its use in the future is pending. Even without a legislative ban of Hydrazine the new green technologies can offer economic and performance advantages and thus be attractive for entering the market.

Agencies push for an introduction of green technologies whereas commercial customers are more reluctant.

The market itself for orbital propulsion also faces a change due to new requirements and the maturation of electric propulsion. The main substitute technologies that are followed in Europe to replace toxic Hydrazine as a monopropellant (ADN based propellants, high concentrated Hydrogen Peroxide and Water Propulsion) were described and the technical and economic benefits of each technology presented.

As a resume it can be noted that none of the discussed technologies can a serve yet as a full substitute for all applications where currently Hydrazine is used. All green propellants offer a handling cost advantage which has to be traded against the higher system complexity and thus higher hardware cost.

6. Acknowledgements

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