PULCHER – PULSED CHEMICAL ROCKET WITH GREEN HIGH PERFORMANCE PROPELLANTS: PROJECT OVERVIEW

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Abstract:

PulCheR is a research project co-funded by the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n°313271, officially started as of January 1st, 2013. The project is mainly aimed at demonstrating the feasibility of a pulsed propulsion system in which the propellants are fed in the combustion chamber at low pressure and the thrust is generated by means of high frequency pulses, reproducing the defence mechanism of a notable insect: the bombardier beetle. The suitable design of the feeding lines, comprehensive of the injectors, allows the low pressure injection of the correct amount of propellants into the combustion chamber: the decomposition or combustion reaction increase the chamber pressure that rises to values much higher than the one at which the propellants are stored, exploiting the advantages of quasi constant volume combustion. The combustion products are accelerated through a convergent-divergent nozzle generating the thrust pulse and once the pressure inside the combustion chamber decreases under the injection pressure, the cycle can be repeated. The feasibility of this new propulsion concept will be investigated at breadboard level in both mono and bipropellant configurations through the design, realization and testing of a platform of the overall propulsion system including all its main components. In addition, the concept will be investigated using green propellants with potential similar performance to the current state-of-the-art for monopropellant and bipropellant thrusters. The present paper aims at presenting the main objectives and the current status of the PulCheR project.

Key words: Pulsed Chemical Rocket, Green Propellants, High Frequency Pulses, Biomimetic

1. INTRODUCTION

The PulCheR (Pulsed Chemical Rocket with Green High Performance Propellants) project, co-funded by the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n°313271, officially started as of January 1st, 2013. More in detail, the project has been proposed in response of the *fifth space call* (FP7-SPACE-2012-1), activity/area 9*.2.2 Strengthening the foundation of Space science and technology/ Research to support space transportation and key technologies*, topics called *Key technologies for in-space activities* (SPA.2012.2.2-02), under the *Collaborative Projects* funding scheme. The call recurrently insisted on the expected innovation aspects with great emphasis on the need to pursue radical innovation which may then lead to "disruptive technologies" rather than activities for improving existing technologies. In this perspective, the proposed project should have addressed research topics with a clear long term vision, far beyond the state of the art, by engaging with high-risk ideas rather than the refinement of current approaches, requiring the development of components with highly advanced performances well beyond current available specifications as well as new system concepts, thus providing a wide range of research opportunities for space industry to engage in. In the light of these requirements, the PulCheR project has been proposed and positively evaluated by the European Commission.

The project is mainly aimed at demonstrating the feasibility of a pulsed propulsion system (see Pasini et al., 2013) in which the propellants are fed in the combustion chamber at low pressure and the thrust is generated by means of high frequency pulses, reproducing the defence mechanism against predators of a notable insect: the bombardier beetle (see Aneshansley & Eisner, 1969, Eisner & Aneshansley, 1999, and Beheshti & McIntosh, 2007).

When threatened, this insect ejects a hot stream of liquid chemicals onto its aggressor accompanied by a loud popping sound (see Fig. 1). The chemicals, hydroquinones and hydrogen peroxide, are secreted by a pair of glands. Each gland consists of a reservoir (collecting vesicle) and a reaction chamber (explosion chamber) connected by a valve. The reaction chamber is connected to the outside world via a nozzle and an exit valve. The reservoir contains an aqueous solution of hydroquinones and hydrogen peroxide. The beetle uses its muscles for opening the one-way connecting valve, forcing chemicals into the reaction chamber (low pressure feeding). Once in the reaction chamber, the enzyme catalysts (catalase and peroxidase) are introduced through the chamber walls. Extremely fast reactions occur and result in free oxygen, generating enough heat to bring the liquid to the boiling point. The temperature and pressure reach respectively 105 °C and 1.1 bar. The valve to the reservoir closes due to the pressure of the released gasses and the liquid is expelled explosively through the nozzle and exit valve at the tip of the abdomen. The flow of reactants into the reaction chamber and subsequent ejection to the atmosphere occurs cyclically at a rate of about 500 times per second and with the total pulsation period lasting for only a fraction of a second.

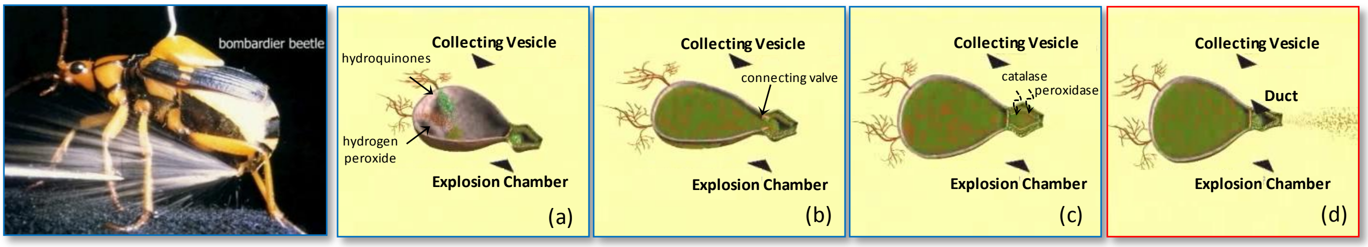


Fig. 1. The African bombardier beetle (*Stenaptinus Insignis*, left) and its defence mechanism (right)

The main events occurring during the discharge of the defence mechanism of the bombardier beetle can be summarised as follows:

1. hydrogen peroxide and hydroquinones water solutions are stored at low pressure into the collecting vesicle (Fig. 1-a);
2. the beetle uses its muscles to open the connecting valve, forcing chemicals into the explosion chamber (low pressure feeding, see Fig. 1-b);
3. the chemical reacts with the catalysts and the liquid chemicals in the reaction chamber and reaches a temperature of more than 105 °C (see Fig. 1-c);
4. the release of gases and the increase in temperature cause an increase in pressure that, in turn, causes the connecting valve to close;
5. when pressure reaches 1.1 bar, the exit valve opens and the gases rapidly expand (see Fig. 1-b);
6. the pressure stays high until the end of the discharge, when the pressure rapidly drops;
7. this pressure drop forces the exit valve to close and opens the connecting valve, thus continuing the cycle until the beetle relaxes its muscles.

The PulCheR propulsion system concept is intended to mimic the defence mechanism of the bombardier beetle for generating an efficient thrust by high frequency pulses, borrowing by nature the concepts of low pressure feeding of propellants, quasi-constant volume combustion and high frequency pulses.

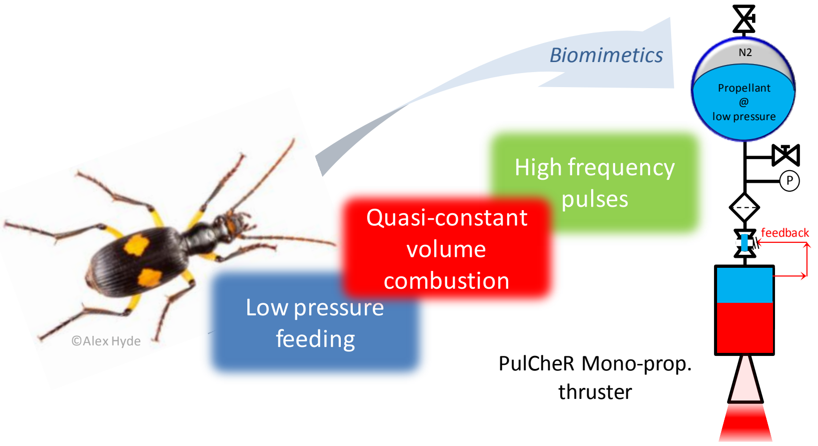


Fig. 2. PulCheR: a bio-inspired project

In particular, following the parallelism with the defence mechanism of the bombardier beetle, the PulCheR propulsion system operation can be summarised in the following way:

1. the propellant (for the monopropellant concept) or propellants (for the bipropellant) is/are stored at low pressure (e.g. 5-10 bar);
2. after the opening of the valves, the propellant/s is/are fed to the chamber at low pressure: the delays in decomposition (for the monopropellant) or mixing-ignition-combustion (for the bipropellant) allow for feeding propellant/s into the catalytic bed/combustion chamber;
3. decomposition/combustion occurs, increasing chamber pressure and mixture temperature;
4. this pressure and temperature increase causes the firing valves to close;
5. the gases rapidly expand through the nozzle and a thrust pulse is generated;
6. the pressure stays high until the end of the discharge, when the pressure rapidly drops under a threshold limit;
7. this pressure drop opens the firing valve, thus continuing the cycle.

In current liquid rocket engines for in-space manoeuvres, in both monopropellant or bipropellant configurations, the feeding system provides the propellants at a pressure that allows them to be injected into the thrust chamber by means of pressurized systems such as direct gas pressurization, flexible bags within tanks or piston pressurization. Usually the monopropellant propulsion subsystems use a blow-down type feeding with a Begin of Life (BoL) pressure of about 23 bar. During the operation, the pressure inside the tank decreases down to about 5.5 bar and, as a direct consequence, both thrust and specific impulse deteriorates. As an example, the blow-down effect for a 1N hydrazine decreases the steady state thrust and the specific impulse respectively from 1 N to 0.3 N and from 226 s to 210 s.

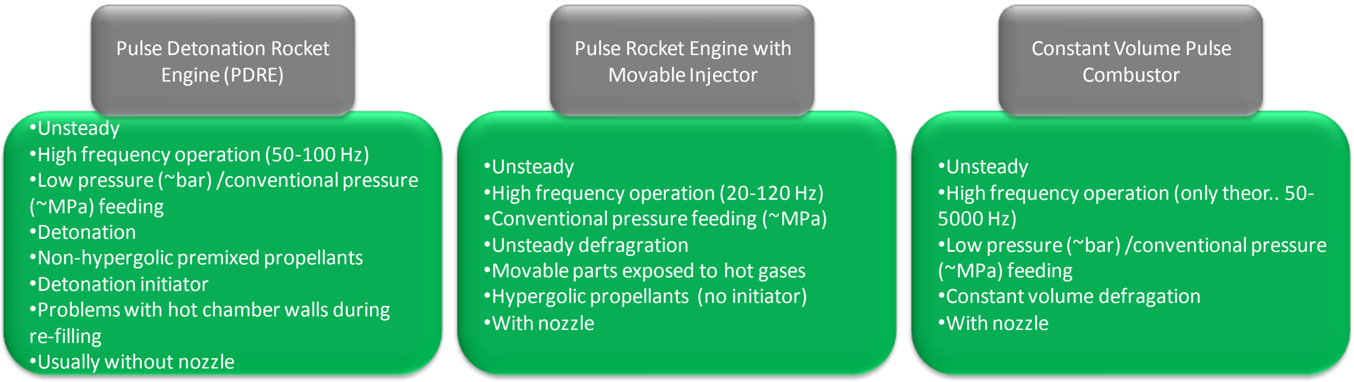
For more complex configurations employing both a bipropellant Large Apogee Engine (LAE) and several bipropellant Reaction Control Thrusters (RCT), oxidizer and fuel are stored in two, identical, propellant tanks. Each tank incorporates a Propellant Management Device (PMD) to deliver gas-free propellant to the main engine and thrusters units. The propellant system is pressurised using Helium gas, stored in high pressure tanks (pressure up to 275 bar). The pressure in the propellant tanks is controlled by a pressure regulator, which reduces the pressure in the gas system from storage pressure to regulated pressure and maintains this pressure during the transfer phase (operation of the LAE). Once the final orbit is reached, the high pressure system is isolated from the propellant system and from this moment until the End of Life (EoL), operates in blow-down mode (i.e. continuous reduction of the pressure in the main tanks, as propellant is consumed).

Even if the engine can be operated in pulse mode, the feed system is currently designed in order to guarantee the nominal steady state operation and, consequently, the nominal feed pressure should be higher than the expected one inside the combustion chamber due to pressure losses inside pipelines, valves and injectors. Except for the propellant itself, most of the weight of the propulsive system consists in the pressurizing system.

Monopropellant systems use propellants which are able to release much heat during their decomposition when in contact with some catalytic substances. The most typically used propellant, to this respect, is hydrazine and typically its catalyst is iridium on alumina. Hydrazine is a liquid propellant, highly toxic and nowadays recognized as carcinogenic. Bipropellants use an oxidizer and a fuel as propellants. Present fuels are typically hydrazine and its by-products (Monomethylhydrazine, MMH, Usymmetrical dimethylhydrazine, UDMH) whereas Nitogen Tetraoxide (NTO) and Mixed Oxides of Nitrogen (MON) are commonly used as oxidizers. These bipropellant combinations are hypergolic and have excellent performance (specific impulse ranging from 285 s to 325 s depending on the thrust size).

On the basis of the operational mode, in general the combustion process inside the rocket engines can be classified as steady state combustion (or quasi-steady) and intermittent or unsteady combustion. In the first case, the combustion process is continuous and occurs by deflagration: in this case the flame speed propagates into the fuel-oxidizer mixture at a typical rate of few meters per second. The slow chemical reaction times constrain these engines to constant pressure heat addition, and as a result, limit their efficiency. Contrary, in the devices operated by intermittent mode, combustion occurs in a discrete repetitive manner governed by fuel/oxidizer flame speeds and combustion chamber characteristics. Unsteady propulsion system can be based on either deflagration combustion or on detonation combustion. Typical flame front velocities in detonation combustion are in the order of thousand meters per second, making the detonation process thermodynamically closer to a constant volume process (instead of a constant pressure process as deflagration). Three principal categories of chemical rockets mainly based on pulse mode operation have been identified in open literature: pulse detonation rocket engine (PDRE), pulse rocket engine with movable injectors, rocket engine with constant volume pulse combustor.

Pulse detonation rocket engines (PDRE) detonate combustible propellant mixture to produce high chamber pressures and thrust (see Bratkovitch et al., 1997, Damphouse, 2001, and Coleman, 2001). To obtain high pulse frequency and quasi-steady thrust, some PDRE designs include multiple detonation chambers. The combustion cycle of the PDRE involves the cyclical loading, detonating, and purging of a long, typically cylindrical detonation tube that is closed on one end and open on the other. Once the fuel/oxidizer mixture is injected into the tube at or near the closed end, the fast-acting propellant injection valves close to seal the detonation chamber and detonation is initiated near the closed end. The detonation wave passes through the detonation chamber at supersonic velocities, igniting the propellants and elevating the upstream pressure to several times (6-12 times) that of the initial fill pressure. Once the detonation wave reaches the open end of the tube, the pressure differential causes rarefaction waves to progress toward the closed end and the burned products are expelled. After the products are expelled, a new fuel/oxidizer charge is injected and the process is repeated.



Pulse Detonation Rocket Engine (PDRE)

- Unsteady
- High frequency operation (50-100 Hz)
- Low pressure (~bar) /conventional pressure (~MPa) feeding
- Detonation
- Non-hypergolic premixed propellants
- Detonation initiator
- Problems with hot chamber walls during re-filling
- Usually without nozzle

Pulse Rocket Engine with Movable Injector

- Unsteady
- High frequency operation (20-120 Hz)
- Conventional pressure feeding (~MPa)
- Unsteady defragration
- Movable parts exposed to hot gases
- Hypergolic propellants (no initiator)
- With nozzle

Constant Volume Pulse Combustor

- Unsteady
- High frequency operation (only theor.. 50-5000 Hz)
- Low pressure (~bar) /conventional pressure (~MPa) feeding
- Constant volume defragation
- With nozzle

Fig. 3. Main characteristics of the reviewed pulse rocket engines

In the nineties, SEP division of SNECMA carried out an experimental program based on the use of a new concept of Pulse Rocket Engine in the frame of the development of miniaturized technologies for space application (Koppel et al., 1999, Koppel & Maine, 1998/1999). This promising thruster concept leads to reach a very high propellant and combustion pressure (~100 MPa) with only a conventional propellant feed pressure (~2 MPa). Those very high pressures allow to really minimize the dimensions of the thruster. The concept is based on the use of a differential piston to self-pressurize the liquid propellant, that piston being driven directly by the combustion pressure. Pulses automatically generated by the thruster produce the thrust. More recently, Qin et al. (2009) developed lumped parameter models of the extruding room and the combustion chamber and one dimensional unsteady flow model of the nozzle in order to understand the operating characteristics of a novel rocket engine based on the same concept proposed by Koppel & Gallier (1999).

Only laboratory-scale prototypes of PDREs and pulse rocket engines with movable injectors have been tested, but there has not been any flight test for these types of rockets. The propulsive performance obtained from the available experimental data is still far from the promising theoretical one. At this stage, test campaigns have mainly focused on the feasibility demonstration of the concepts.

Talley & Coy (2000 and 2002) explored theoretically the constant volume limit of pulsed propulsion, where the combustion chamber was approximated as being time-varying but spatially uniform, while the nozzle flow was approximated as being one dimensional but quasi-steady. The constant volume limit was explored for the isentropic blow down of a constant specific heat ratio ideal gas for fixed expansion ratios and for variable expansion ratios which were adjusted to match the pressure ratio at all times. The constant volume limit of pulsed propulsion refers to a limiting case for pulsed propulsion cycles which is approached when blow down times become much longer than characteristic wave transit times in the combustion chamber. The results obtained by the authors rely on the assumption that the heat release process completely consumes the propellant and occurs without change in mass in the combustion chamber either because the injection and reaction rates are much faster than the rate of mass flow out of the nozzle, or because a hot-gas valve is located in the exit stream, as proposed in some recent patents (DiSalvo et al., 2009). In a more recent paper Edward B. Coy (2003) extended the analysis by considering finite-rate processes such as heat release, injection and blow-down, and inefficiencies associated with incomplete combustion. The rocket engine with constant volume pulse combustor, which seems to be the most similar configuration to the PulCheR system, has been only theoretically analysed with simplified approaches.

The PulCheR system introduces radical innovations for the propellants feeding system, the thrust generation mechanism and the employed new combination of propellants as better discussed in the next sections.

2. PULCHER ADVANTAGES AND TECHNOLOGICAL CHALLENGES

The radical innovation introduced by the PulCheR propulsion system concept is the simplification and in some cases the elimination of a pressurizing system external to the thruster that allows the liquid rocket engine to work at high pressure inside the combustion chamber. In each pulse, the pressurization of the combustion chamber takes place due to the decomposition/combustion reaction and the chamber pressure can reach levels much higher than the ones at which the propellants are stored without any increase in the overall weight of the feeding system. Moreover, the weight of the feeding system can be significantly reduced because the feeding of the propellants is performed at low pressure and, consequently, there is no need for turbopumps, high pressure gas vessels and high pressure propellant tanks. Thus, the feed pressure becomes independent on the chamber pressure and the performance degradation of blow down mode typical of monopropellant thrusters can be avoided.

Therefore, the overall propulsion system is greatly simplified in turn of increased reliability and decreased weight.

Furthermore, the engine always works under transient conditions, with high frequency pulses that allow for a very fine control of the minimum impulse bit (MIB), particularly suitable for specific in-orbit missions such as fine attitude control, reaction control and dockings.

Even more, the time averaged thrust generated by the high frequency pulses can be simply modulated only by changing the threshold limit of the pressure at which the firing valves re-open. In fact, the thrust pulse is directly correlated to the amount of propellants elaborated in each pulse which, in turn, is controlled by the threshold pressure at which the cycle re-starts.

As an added value, the new propulsion concept will be investigated using green propellants for both mono and bipropellant configurations. Since hydrazine has been identified as a substance of very high concern by the European Chemicals Agency (ECHA, 2011), the issue of finding effective alternatives to the state-of-the-art propellants combinations (hydrazine or its derivatives, such as MMH and UDMH, in combination with NTO or MON in case of bi-propellant engines) cannot be postponed anymore. A preliminary assessment study for the PulCheR propellants has identified in the high grade hydrogen peroxide a valid alternative for monopropellant applications and in the combination of hydrogen peroxide and a light unsaturated hydrocarbon, the propyne, a possible combination for obtaining a propulsive performance analogous to the current state-of-the-art for future green bipropellant thrusters (Valentian et al., 2004, and Briggs & Milthorpe, 2007).

Moreover, fuels with a quite high value of the vapour pressure at ambient temperature, such as propyne, are suitable for the self-pressurization of the fuel and oxidizer tanks thus providing further advantages in terms of weight reduction and system simplification.

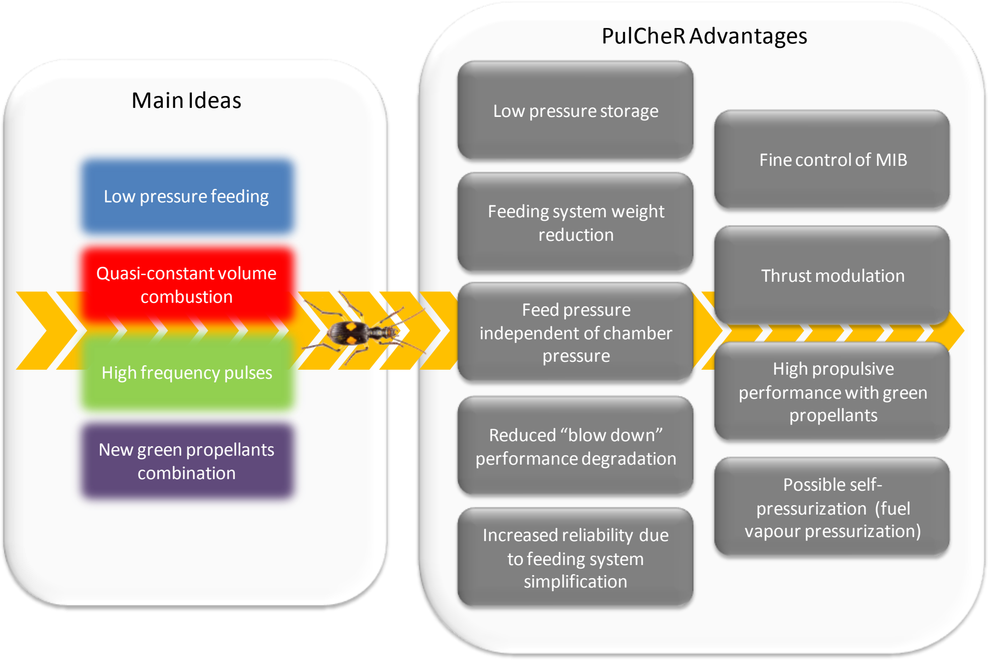


Fig. 4. Main ideas behind the PulCheR project and its main advantages

2.1. Mass Reduction and Cost Savings

In the light of a flight architecture based on the PulCheR system, a series of simplifications are expected concerning the propulsion sub-system. The following table reports the main simplifications for both the monopropellant and bipropellant PulCheR configurations.

Tab. 1. Main simplifications to the propulsion subsystem introduced by the PulCheR concept

Monopropellant System	Bipropellant System
Low pressure inside tanks and feeding lines	Low pressure inside tanks and feed lines
Weight reduction due to lower pressure inside the tank and feed lines	No tanks needed for the pressurant
Possibility of eliminating the external pressurant for propellants with high vapour pressure	Weight reduction due to lower pressure inside the tank and feed lines
	Possibility of eliminating the external pressurant for propellants with high vapour pressure
	Reduction of the number of valves and no need for a pressure regulator

The elimination of the heavy tanks for the pressurant gases and the reduction of the storage pressures for propellants lead to a much simpler and safer system. The use of high vapour pressure propellants can further simplify the system by giving the possibility of self pressurization of the propellants. These aspects contribute to make the propulsion system based on the PulCheR concept more reliable than the presently used ones.

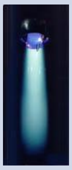
A quantitative comparison between the mass and cost budget of propulsion systems used in current space vehicles and systems based on the PulCheR concept has been performed for a satellite based on a bipropellant propulsion system and for a satellite based on a monopropellant one (see Tab. 2 and Tab. 4). The comparison has been based on the assumption that same propellants are used by PulCheR and the current technology, in order to highlight the effects of the new propulsion system concept without taking into account those related to the propellant choice.

Tab. 2. Main characteristics of the ARTEMIS satellite (from http://www.astrium.eads.net) the main assumptions for the mass budget estimation in the bi-propellant configuration

Artemis / 2001 - 029A	
Category	Telecom Technology
Operator	ESA
Orbit	GEO
Sat position	21.5° E
Launch mass	3100 kg
Design life	10 years
Launcher	Ariane 5
Satellite / Bus	Italsat Bus
Manufacturer	Alenia Spazio SpA

Assumptions
Same propellants are used by PulCheR and the current technology (for highlighting only the effects of the new propulsion system concept)
Unified Propulsion System (U.P.S., by Thales Alenia Space) configuration
Same weight for pipes, transducers, filters, electric propulsion system, etc.
3 Helium tanks, 51 dm^3 each
Fuel and oxidizer tanks new BOL pressure: 5 bar (EOL pressure: 1.25 bar)
Fuel and oxidizer tanks new burst pressure: 10 bar
New spherical tanks, SF=2, Aluminum Alloy
Additional new tank weight for bladders: 2 kg each

Propulsion System (EADS Astrium)
1 x 400 N thruster (N2O4 / MMH), S400-01
16 x 10 N thruster (N2O4 / MMH), S10-13
2 x surface-tension tank, OST 22/1
2 x 15 mN ion thruster (Xenon), RIT 10



The bipropellant system configuration by Thales Alenia Space has been assumed as the reference propulsion subsystem to assess the improvements potentially brought up by the PulCheR concept. The main assumptions taken for computing the new mass budget are reported in Tab. 2. Since the propellant selected for the mass budget estimation do not allow for a self-pressurized configuration, diaphragm tanks in blow-down mode have been considered. The estimated weight of the bladders is 2 kg and the pressurant Helium mass is 0.25 kg. The estimated propulsion system dry mass, in case the PulCheR concept is used, is about 43.13 kg (or 27%) lighter than in the presently used baseline configuration, as shown in the following mass budget table (Tab. 3).

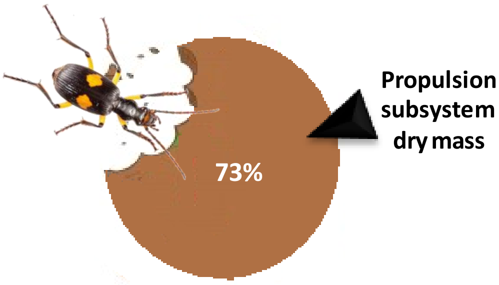


Fig. 5. Estimated mass saving due to the application of the PulCheR concept to a bipropellant propulsion system

The components leading to a higher percentage mass saving are clearly the tanks, due to both the elimination of the tanks for the external pressurant. Little mass savings are also due to the Helium mass reduction (Helium is still used as pressurant) and to the reduction in the number of valves. The tank mass of the new system results higher that the current configuration due to an increased tank volume that is needed for the assumption of blow-down operation via a diaphragm tank. These mass savings are quite significant, considering that for the ARTEMIS satellite they lead to a Δv gain of 44 m/s by using the same boarded propellant mass and payload mass (approximately equal to the necessary Δv amount for one year station-keeping manoeuvres).

Tab. 3. Comparison between the mass budget of the current UPS-like propulsion sub-system (ARTEMIS reference satellite) and the PulCheR configuration

	Current Configuration			**PulCheR Configuration**		
Item	*n°*	*unit weight [kg]*	*total weight [kg]*	*n°*	*unit weight [kg]*	*total weight [kg]*
HP pressurant tank	3	16.15	48.45	0	16.15	0
Helium mass	3	2.3	6.9	1	0.25	0.25
HP pressure regulator	1	1.14	1.14	0	1.14	0
Helium check valve	2	0.08	0.16	0	0.08	0
Helium filter	1	0.09	0.09	0	0.09	0
Helium F&D valve	7	0.07	0.49	0	0.07	0
Helium pyro valve	5	0.13	0.65	0	0.13	0
Helium pressure transducer	1	0.22	0.22	0	0.22	0
Propellant tank	2	36	72	2	43.36	86.72
Propellant filter	2	0.16	0.32	2	0.16	0.32
Propellant F&D valve	4	0.15	0.6	4	0.15	0.6
Propellant pyro valve	4	0.14	0.56	4	0.14	0.56
Propellant pressure transducer	4	0.22	0.88	4	0.22	0.88
Tubing	1	3	3	1	3	3
400 N thruster	1	4.3	4.3	1	4.3	4.3
Main engine bracket	1	4.8	4.8	1	4.8	4.8
10 N thruster	16	0.65	10.4	16	0.65	10.4
Others (mounting parts, etc.)	1	6.21	6.21	1	6.21	6.21
Total dry mass			***161.17***			***118.04***
Propellants	1	1538	1538	1	1538	1538
Total			*1699.17*			*1656.04*

As a reference case for the typical thrust levels of a monopropellant system, the GLOBALSTAR satellite propulsion system has been considered (see Tab. 4). The monopropellant propulsion system configuration by Thales Alenia Space has been assumed as the reference propulsion subsystem to assess the improvements potentially brought up by the PulCheR. The main assumptions taken for computing the new mass budget are reported in Tab. 4.

The estimated propulsion system dry mass, in case PulCheR concept is used, is about 4,35 kg (or 35%) lighter than in the presently used baseline configuration, as it is shown by the mass budget calculations in Tab. 5. The monopropellant systems are simpler, with less components with respect to bipropellant ones. So the mass savings in case the PulCheR concept is used are less significant than for the bipropellant case, and are almost totally due to tanks mass reduction.

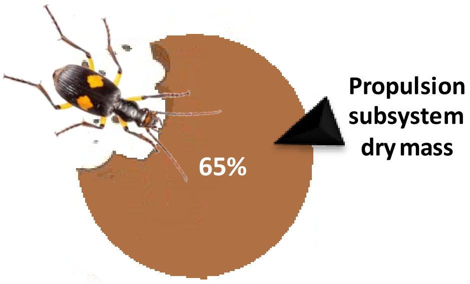


Fig. 6. Estimated mass saving due to the application of the PulCheR concept to a monopropellant propulsion system

Tab. 4. Main characteristics of the GLOBALSTAR satellite (from http://www.astrium.eads.net) the main assumptions for the mass budget estimation in the monopropellant configuration

Assumptions

Globalstar 1998 - 2000	
Category	Commercial Telecom
Operator	Globalstar Telecom. Ltd.
Orbit	MEO
Sat position	1236 km x 1410 km
Launch mass	450 kg
Design life	7 yr
Launcher	See table next page
Satellite / Bus	LS 400 (Loral)
Manufacturer	Alenia Spazio

Same propellants are used by PulCheR and the current technology (for highlighting only the effects of the new propulsion system concept)

Monopropellant Propulsion System (M.P.S., by Thales Alenia Space) configuration

Same weight for pipes, transducers, filters, etc.

Blow down mode

New pressurization: 5 bar @ BOL

Propulsion System (EADS Astrium)
5 x 1 N thruster (Hydrazine), CHT 1
1 x surface-tension tank, OST 31/0

Tab. 5. Comparison between the mass budget of the current MPS-like propulsion sub-system (GLOBALSTAR reference satellite) and the PulCheR configuration

	Current Configuration			**PulCheR Configuration**		
Item	*n°*	*unit weight [kg]*	*total weight [kg]*	*n°*	*unit weight [kg]*	*total weight [kg]*
Propellant tank	1	6.4	6.4	1	2.13	2.13
Propellant filter	1	1	1	1	1	1
Propellant F&D valve	1	0.05	0.05	1	0.05	0.05
Latch valve	2	0.37	0.74	2	0.37	0.74
Pipework	1	2	2	1	2	2
Pressurant F&D valve	1	0.05	0.05	1	0.05	0.05
Helium mass	1	0.1	0.1	1	0.02	0.02
1 N thruster	5	0.29	1.45	5	0.29	1.45
Others (mounting parts, etc.)	1	0.55	0.55	1	0.55	0.55
Total dry mass			***12.34***			***7.99***
Propellants	1	79.64	79.64	1	79.64	79.64
Total			*91.98*			*87.63*

The costs saving analyses due to these estimated mass reductions have been performed considering both a heavy launch vehicle, the European ARIANE5G, and an intermediate launch vehicle, the Russian SOYUZ. General data about the ARIANE 5G and SOYUZ are reported in Tab. 6 and the costs saving estimation is reported in Tab. 7. As shown by the table, a significant cost saving for launched satellite (up to 1.05 M$ for the bipropellant case using the ARIANE 5G launcher and 120 k$ for the monopropellant using the SOYUZ launcher) can be expected in case a propulsion system based on the PulCheR concept is used.

Tab. 6. ARIANE 5G and SOYUZ payload capacities and payload costs per kg (data from Futron Corporation, 2002)

	ARIANE 5G 	SOYUZ 
Country/Region of origin	EUROPE	RUSSIA
LEO capacity (kg)	18’000	7’000
GTO capacity (kg)	6’800	1’350
Estimated launch price (2000 US $)	165’000’000	37’500’000
Estimated LEO payload cost per kg ($)	9’167	5’357
Estimated GTO payload cost per kg ($)	24’265	27’778

Tab. 7. Costs savings for launching into LEO and GTO the references study cases based on the PulCheR configuration

	Cost Savings ($)			
	Mono-Propellant		Bi-propellant	
	ARIANE 5	*SOYUZ*	*ARIANE 5*	*SOYUZ*
LEO	39'876	23'303	395'373	231'047
GTO	105'553	120'834	1'046'549	out of capacity

2.2. Green Propellants

In 2011, REACH (Registration, Evaluation, Authorisation and Restriction of CHemical substances, the European Community Regulation on chemicals and their safe use) added Hydrazine (N_2H_4) to the candidate list of Substances of Very High Concern (SVHC), the main consequence being that the use hydrazine may be phased out prior the end of this decade for non-essential use. This is the why because aerospace industry is currently strongly interested in finding different chemicals (possibly “green”) which can substitute hydrazine. In this context, one additional added value of the PulCheR project is the research and application of new propellants in order to replace hydrazine and its by-products, which are highly toxic and carcinogenic, with propellants of easier and less hazardous handling, but ensuring comparable propulsive performance.

Rocket grade hydrogen peroxide has been selected for the monopropellant system whereas the combination of rocket grade hydrogen peroxide and propyne (C_3H_4) has been traded-off as one of the most interesting solution for the bipropellant configuration, expecially due to some interesting peculiar characteristics of propyne (in particular its moderate vapour pressure (5.1 bar at 20 °C), which could be interesting for its use for self-pressurized systems).

Hydrogen peroxide is a high density liquid having the characteristic of being able to decompose exothermically into water (steam) and oxygen according to the reaction:

$$H_2O_2(l) \rightarrow H_2O(g) + \tfrac{1}{2}O_2(g)$$

The temperature of the resulting steam/oxygen mixture depends on the hydrogen peroxide concentration. When the concentration of hydrogen peroxide is higher than about 67% by weight, the generated heat is sufficient to evaporate 100% of the water. Tab. 8 reports the adiabatic decomposition temperature, the theoretical characteristic velocity and the mean molecular weight of the decomposition products of hydrogen peroxide water solutions at different concentration. The adiabatic decomposition temperature increases with the hydrogen peroxide concentration. The relative low decomposition temperature allows for avoiding the necessity of active cooling system. The mean molecular weight of the products is relative low and slightly increases with the concentration of hydrogen peroxide due to the bigger amount of molecular oxygen in the decomposition products when the concentration is higher.

Tab. 8. Hydrogen peroxide decomposition temperatures and characteristic velocities

H_2O_2 concentration [wt. %]	Decomposition Temperature [°C]	Characteristic Velocity, c* [m/s]	Molecular Mass [kg/kmol]
90	758	943	22.11
92	808	963	22.22
94	857	984	22.34
96	906	1004	22.45
98	955	1021	22.57
100	1006	1040	22.70

The effectiveness of the decomposition process mainly depends on the catalytic bed properties and is usually assessed by means of the characteristic velocity efficiency. In general, this efficiency can be very high, 99%.

In order to asses the attainable specific impulse usig rocket grade hydrogen peroxide as propellant, a series of computation has been performed changing the nozzle expansion ratio in the range 20-90 in order to avoid the possibility of condensation of steam inside the nozzle. Fig. 7 reports the vaccum specific impulse and the vacuum density specific impulse as a function of the hydrogen peroxide mass concentration, computed for a 1N thruster with 20 bar of chamber pressure. The red curves refer to the actual values obtained assuming a c* efficiency of 99% and a C_F efficiency of 97% according to the following relation:

$$I_{sp} = I_{sp}^{theo}\eta_{c^*}\eta_{C_F} \quad \text{and} \quad I_d = I_{sp}\rho_P$$

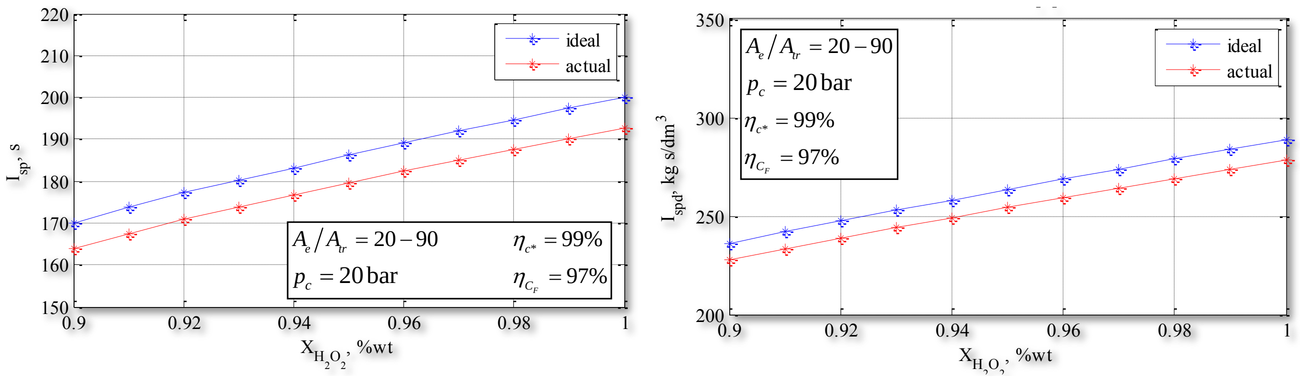


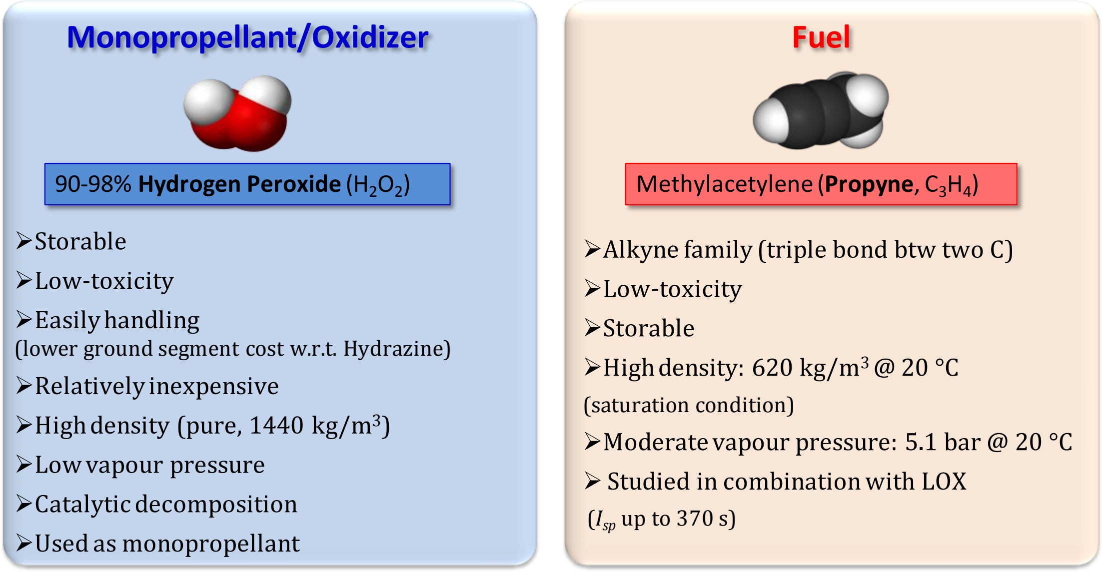
Fig. 7. Vacuum specific impulse (left) and vacuum density specific impulse (right) as a function of H_2O_2 mass concentration (η_{c^*}=99% and η_{CF}=97%)

98% HTP (High Test Peroxide) allows for an estimated actual vacuum specific impulse of 187.5 s that is about 10.7% lower that the typical performance of a 1N hydrazine thruster at the End of Life (blow-down mode, steady state operation). Due to the high density of 98 % HTP (1431 kg/m³ @ 25°C), the actual value of the estimated vacuum density specific impulse is 268 kg s/dm³, that is higher than for the hydrazine case (ranging from 214 to 230.5 kg s/dm³).

Concerning the bipropellant configuration, the propulsive performance of the new combination of propellants has been evaluated in steady-state conditions for a nominal chamber pressure of 10 bar and a nozzle expansion ratio of 330. This selection of the operational parameters allows to compare the expected propulsive performance of the combination hydrogen peroxide-propyne with the current state-of-the-art, represented in this case by the 400N bipropellant thruster model S400-15, produced by EADS Astrium (see Tab. 10).

The preliminary thermochemical analysis has been performed by means of the Cantera toolbox for Matlab. The estimated adiabatic flame temperature and mean molecular mass of the combustion products for various hydrogen peroxide concentrations are reported in Fig. 8. The maximum combustion temperature of a usual combination of propellants based on hydrazine by-products, MMH-MON (3455 K), is higher than the possible one achievable by hydrogen peroxide and propyne. However, the estimation of the vacuum specific impulse and density impulse with an assessment of the C-star and thrust efficiency for the new combination of propellants (0.95 and 0.98, respectively), reported in Fig. 9, shows that they can be comparable to the values obtained for MMH-MON (about 321 s for the vacuum specific impulse and 366 kg s/l for the vacuum density impulse), for H_2O_2 concentrations higher than about 97-98%.

Tab. 9 Main characteristics of the "green" propellants selected for the PulCheR project



Monopropellant/Oxidizer	Fuel
90-98% **Hydrogen Peroxide** (H_2O_2)	Methylacetylene (**Propyne**, C_3H_4)
➢Storable ➢Low-toxicity ➢Easily handling (lower ground segment cost w.r.t. Hydrazine) ➢Relatively inexpensive ➢High density (pure, 1440 kg/m^3) ➢Low vapour pressure ➢Catalytic decomposition ➢Used as monopropellant	➢Alkyne family (triple bond btw two C) ➢Low-toxicity ➢Storable ➢High density: 620 kg/m^3 @ 20 °C (saturation condition) ➢Moderate vapour pressure: 5.1 bar @ 20 °C ➢ Studied in combination with LOX (I_{sp} up to 370 s)

Tab. 10. Characteristics of the baseline bipropellant thruster S400-15 produced by EADS Astrium (Astrium, 2012)

Engine Model S 400-15	
Propellants	MMH/N_2O_4 (MON-1, MON-2)
Nominal Mixture Ratio	1.65
Nominal Specific Impulse	321 s
Nominal Density Impulse	366 kg s/l
Nominal Chamber Pressure	10 bar
Nozzle Expansion Ratio	330
Nominal Thrust	425 N

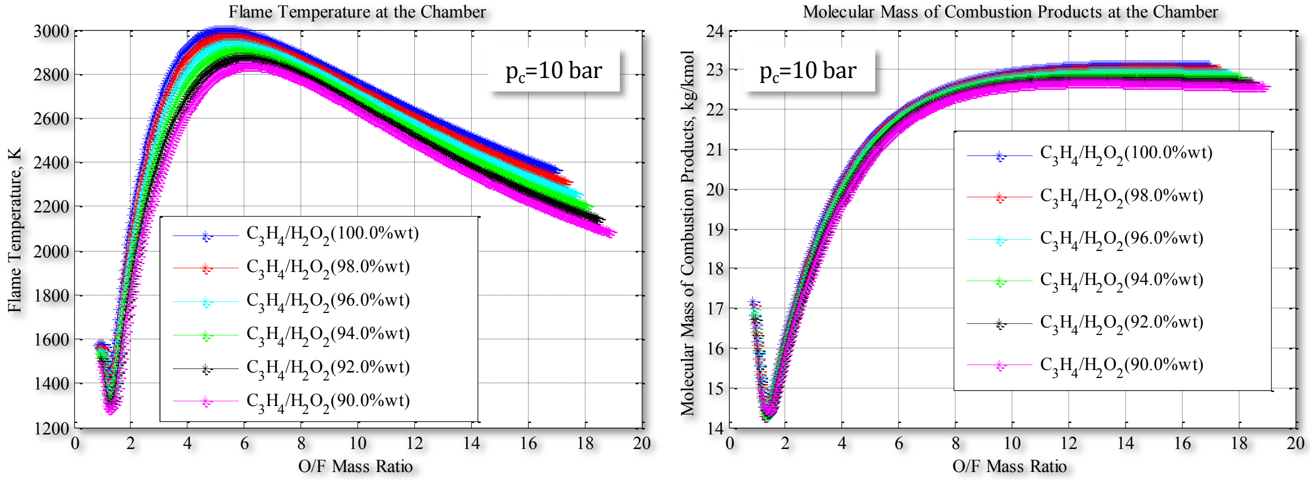


Fig. 8. Estimated flame temperature and molecular mass of the combustion products for the hydrogen peroxide-propyne bipropellant combination.

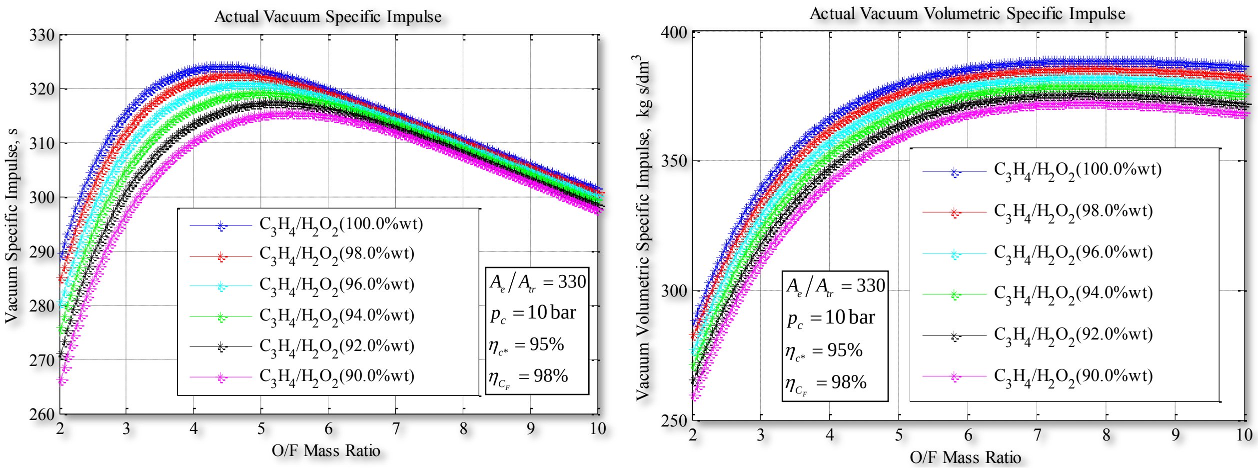


Fig. 9. Estimated vacuum specific impulse (left) and vacuum density impulse (right) for the hydrogen peroxide-propyne combination

These results show that, in terms of specific impulse and density specific impulse, hydrogen peroxide and propyne are a valid alternative to the currently used MMH-MON combination (baseline propellants).

Hydrogen peroxide and propyne can therefore be considered high performance propellants, able to provide a specific impulse comparable to the currently used ones (as MMH-MON) but, additionally, they are considered "green" due to their non-toxicity.

2.3. Thrust Generation by High Frequency Pulses

The pulsed mode operation is intrinsic in the PulCheR concept, for both the monopropellant and bipropellant case. As previously described, operation in pulsed mode is already employed by chemical propulsion thrusters but only for short time intervals and for typical times that allow the thruster to work in a quasi-steady operation mode. In the PulCheR concept, the thruster always operates in unsteady condition, generating the thrust by means of high frequency pulses.

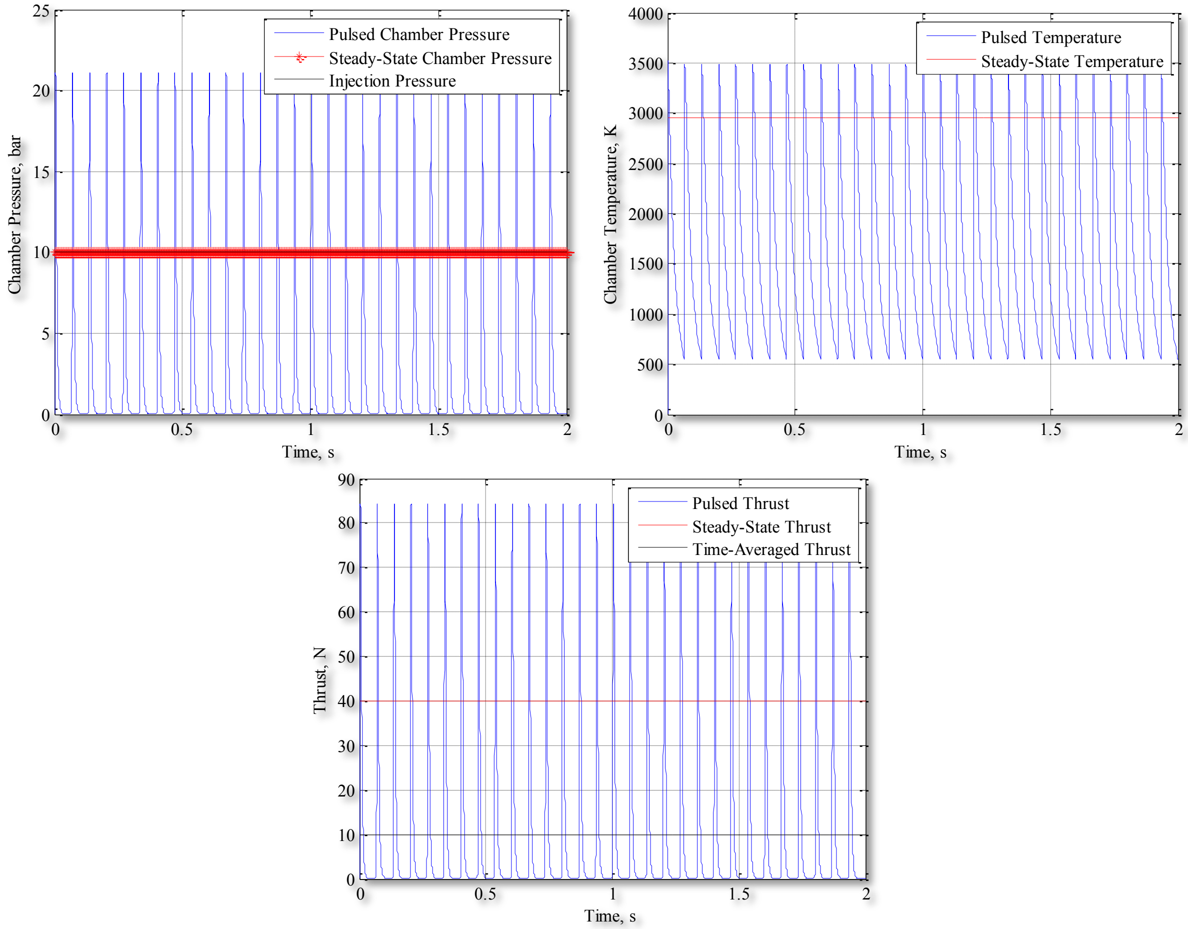


Fig. 10. Chamber pressure, chamber temperature and thrust as functions of time, estimated by a preliminary analysis of the PulCheR concept (bipropellant configuration, 98% HTP/propyne, O/F ratio: 4.765, design mean chamber pressure: 10 bar, injection pressure: 10 bar, design mean thrust: 10 N, expansion ratio: 330 pulses frequency: 15 Hz)

Fig. 10 shows the behaviour of a typical pulse for the bipropellant case, together with a comparison to the steady state case. The reported data are the result of an analysis of the dynamics of the combustion chamber performed with a lumped-parameter method (zero-dimensional analysis) of the reacting gases within the chamber coupled with the unsteady Bernoulli equation for the liquid propellants inside the feed system. The employed system of governing equations is not reported here because the detail analysis of this aspect is beyond the scope of this paper.

The PulCheR concept shows significant combustion pressure and temperature peaks, well higher than steady-state ones. The chamber pressure peaks are due to the injection of a higher mass than that which can be expelled through the nozzle. The temperature peaks are higher than the evaluated flame temperature of hydrogen peroxide and propyne, due to the presence of compression effects.

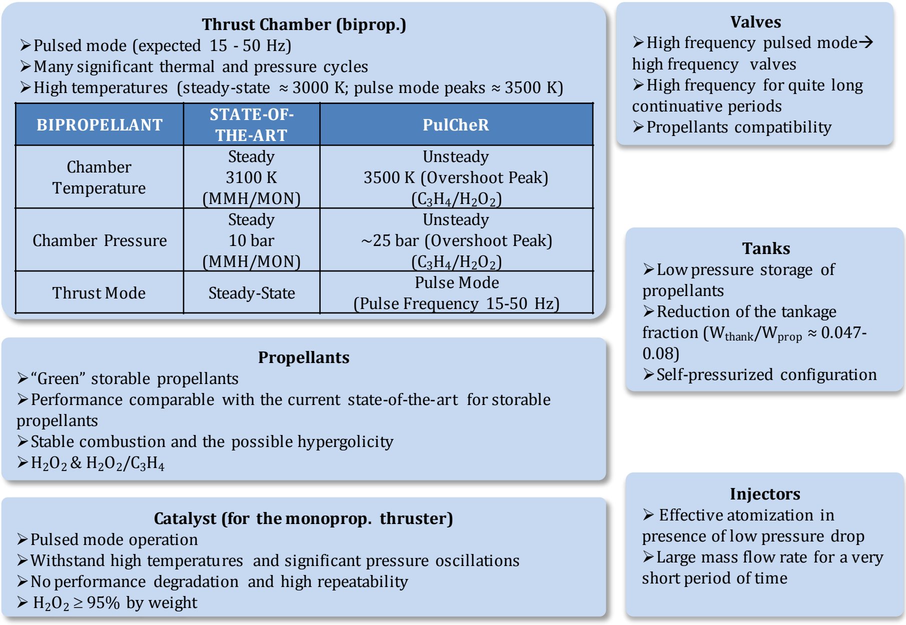
The mass flow peaks (here not reported) are extremely high with respect to the steady-state conditions: this is due to the need of introducing the right amount of propellants in a very short time compatible with the injection into the combustion chamber at low pressure. However, the pulse mode propulsive performance in terms of specific impulse is of the same order of the steady-state case.

Therefore, the combustion chamber is subjected to many significant thermal and pressure cycles per seconds. Moreover, the flame temperature foreseen for the selected green bipropellant combination, such as high grade hydrogen peroxide and propyne, can reach 2960 K in steady-state condition and even higher values in pulse mode operation due to the unsteady compression (temperature peaks can reach almost 3500 K). Current bipropellant thrust chambers are radiation-cooled and the PulCheR bipropellant thruster will probably employ this type of technology. Therefore, the combustion chamber will be subjected to important stresses and possible creep. Materials presently used for radiation cooled combustion chambers have to be tested in order to assess their capability to sustain important stresses due to the particular environment inside the combustion chamber. New materials have eventually to be chosen and tested for fitting these particular environmental conditions.

2.4. Main Technological Challenges

PulCheR is a very challenging project that requires the development of components with highly advanced performances well beyond current available specifications, plenty in agreement with the request of the call. The main criticalities involve the following main components (see also Fig. 11):

- Thrust chamber (it has to sustain high frequency thermo-mechanical cycles);
- Firing valves (the valves have to meet very demanding requirements concerning their response time, that is in the order of few milliseconds);
- Injectors (they have to guarantee a large amount of atomised propellant in a very short period and with a moderate value of available pressure drop);
- Tanks (novel solutions for low pressure storage, reducing tankage fraction and allowing self-pressurised configurations);
- Catalyst (it has to be efficient in the pulse mode operation and sustain high frequency thermo-mechanical cycles);
- Propellants (they have to be "green", possibly hypergolic and with performance comparable to the current state-of-the-art for storable propellants)



Thrust Chamber (biprop.)

➢Pulsed mode (expected 15 - 50 Hz)
➢Many significant thermal and pressure cycles
➢High temperatures (steady-state ≈ 3000 K; pulse mode peaks ≈ 3500 K)

BIPROPELLANT	STATE-OF-THE-ART	PulCheR
Chamber Temperature	Steady 3100 K (MMH/MON)	Unsteady 3500 K (Overshoot Peak) (C_3H_4/H_2O_2)
Chamber Pressure	Steady 10 bar (MMH/MON)	Unsteady ~25 bar (Overshoot Peak) (C_3H_4/H_2O_2)
Thrust Mode	Steady-State	Pulse Mode (Pulse Frequency 15-50 Hz)

Valves

➢High frequency pulsed mode→ high frequency valves
➢High frequency for quite long continuative periods
➢Propellants compatibility

Tanks

➢Low pressure storage of propellants
➢Reduction of the tankage fraction ($W_{thank}/W_{prop} \approx 0.047$-0.08)
➢Self-pressurized configuration

Propellants

➢"Green" storable propellants
➢Performance comparable with the current state-of-the-art for storable propellants
➢Stable combustion and the possible hypergolicity
➢H_2O_2 & H_2O_2/C_3H_4

Catalyst (for the monoprop. thruster)

➢Pulsed mode operation
➢Withstand high temperatures and significant pressure oscillations
➢No performance degradation and high repeatability
➢ $H_2O_2 \geq 95\%$ by weight

Injectors

➢ Effective atomization in presence of low pressure drop
➢Large mass flow rate for a very short period of time

Fig. 11. Main components and technological challenges for meeting the PulCheR requirements

3. PROJECT SCOPE AND ORGANIZATION

PulCheR project aims at demonstrating the feasibility of a new propulsion concept that can substitute today's propulsion system for accessing space. The new propulsion system can be employed for low orbital flight and beyond and subsequent re-entry, allowing also for re-usable vehicles. It can be used in satellites or space ships to carry out typical manoeuvres around a planet or during interplanetary missions as station keeping (North-South / East-West), low orbit flight, orbital re-phasing, de-orbiting, docking / rendez-vouz, re-entry, attitude control and orbit transfer.

The feasibility of the new propulsion concept will be investigated both in mono and bipropellant configurations at breadboard level through the design, realization and testing of a platform of the overall propulsion system that will include all its main components. Except for the transducers used for assessing the propulsive performance, the platform of the propulsion system will certainly include:

- one monopropellant thruster within the thrust range of 1-5 N (powered by high grade hydrogen peroxide);
- one firing valve for the monopropellant thruster;
- one bipropellant thruster within the thrust range of 10-100 N (powered by high grade hydrogen peroxide and propyne);
- two firing valves for the bipropellant thruster;
- one fuel tank with an estimated volume of 5 litres;
- one oxidizer tank with an estimated volume of 5 litres;
- the requested fluidic lines.

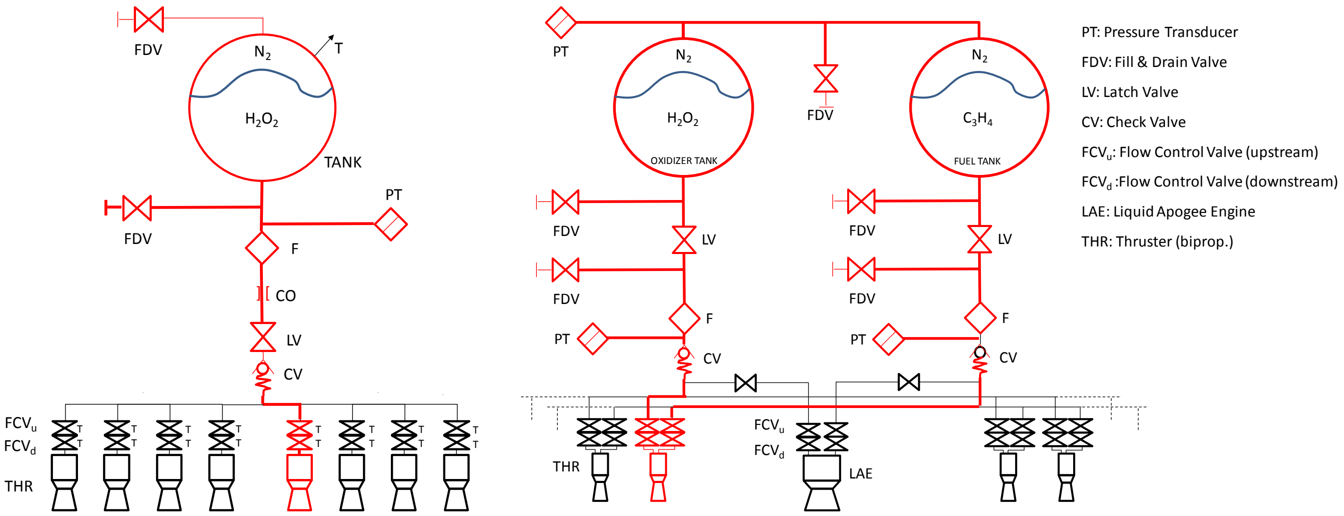


Fig. 12. Monopropellant (left) and bipropellant (right) PulCheR propulsion system layout configuration (in red the main configuration that will be tested at a breadboard level)

The test campaign will experimentally investigate the propulsive performance of both the thrusters by particularly focusing on the specific impulse, minimum impulse bit and thrust modulation in order to compare them with the current state-of-the-art. The target values of the propulsive performance, the achievement of which will represent the main objective of the entire PulCheR project, can be stated as follows:

- vacuum specific impulse for the monopropellant thruster: >185 s;
- vacuum specific impulse for the bipropellant thruster: >320 s;
- minimum impulse bit for the monopropellant thruster: <0.02 Ns;
- thrust throttling level for the bipropellant thruster: 5:1.

Moreover, particular attention will be paid on the weight variation introduced by the new propulsion concept on specific components such as tanks (tankage fraction), firing valves and thrust chambers.

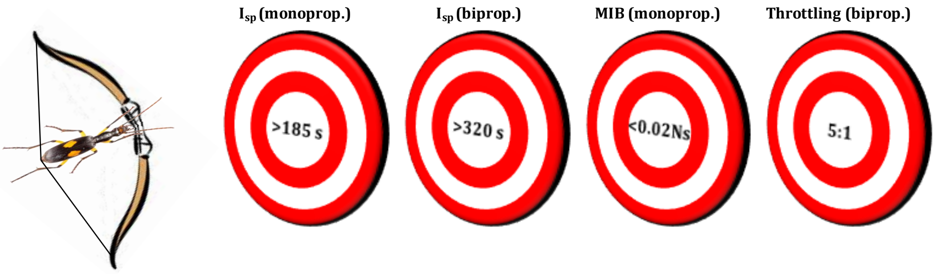


Fig. 13. Main target values of the PulCheR performance

The project aims to increase the Technological Readiness Level of the PulCheR propulsion system from TRL-3 (analytical & experimental critical function and/or characteristic proof-of-concept) to TRL-4 (component and/or breadboard validation in laboratory environment).

The PulCheR project scheduled duration is 36 months and the project starting date has been January 1st, 2013. The overall work plan for PulCheR is summarized in Fig. 14.

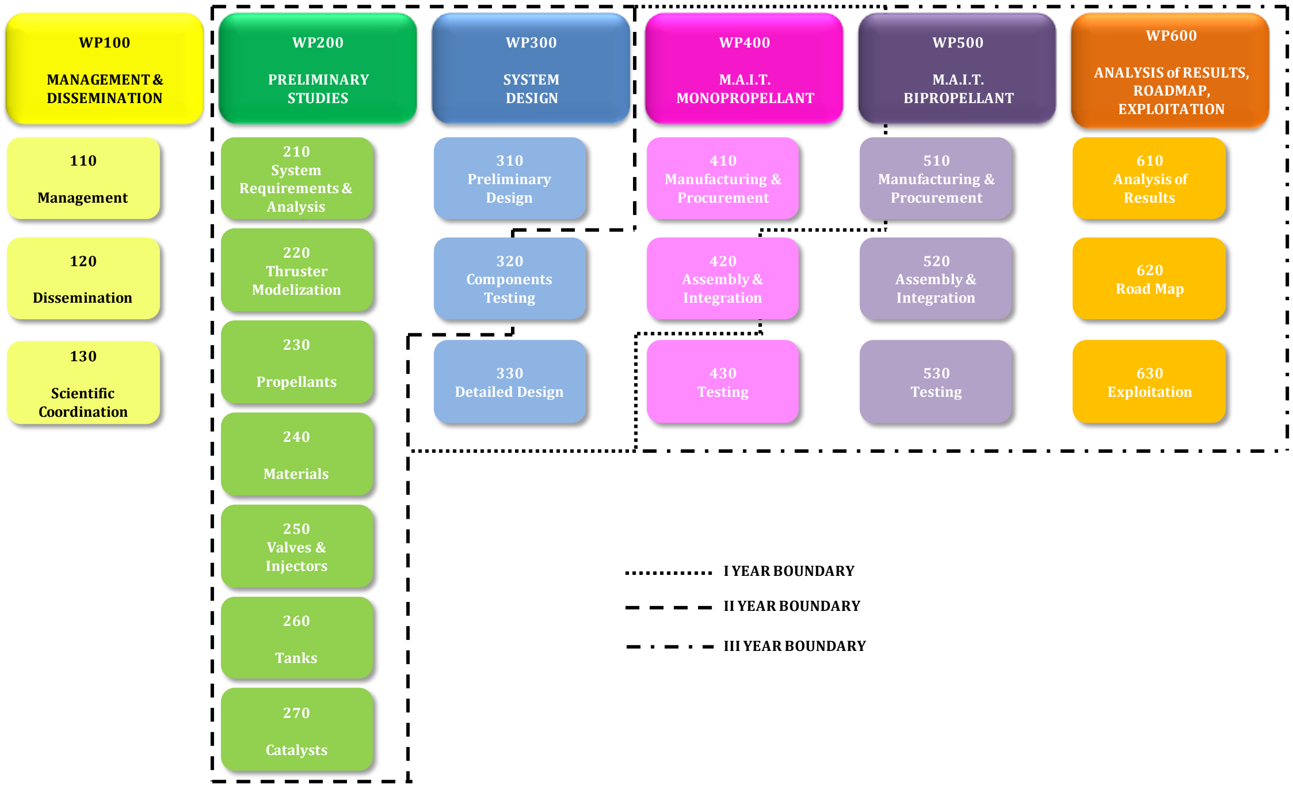


Fig. 14. PulCheR Work Breakdown Structure

WP100 (Management & Dissemination) is spread over the entire project duration (36 months) in order to ensure a continuous and effective management of the project, as well as a wide dissemination of all the project results. A dedicated work package will deal with the scientific coordination of the project.

The WP200 (Preliminary Studies), with a duration of 6 months, has been recently completed. It was devoted to a set of studies on the most important aspects of the PulCheR concept including the thruster, the propellants, the tanks, valves and injectors and the combustion chamber materials. Accurate literature reviews has been performed in order to identify a set of suitable solutions to be analyzed during the successive design phase. Appropriate reduced-order analytical models for the prediction of the propulsion system characteristics and performance have been developed and they will be used for preliminary design phase. At the same time, the system requirements for potential application of the PulCheR concept in actual future space vehicles or missions have been preliminarily defined.

The WP300 (System Design), recently kicked-off, will last for 12 months and will include the design of two different PulCheR propulsion system prototypes: a monopropellant and a bipropellant one. A preliminary design of the prototypes and the test bench in which they will be tested (including the corresponding Test Plan) will be first prepared, including in particular a trade-off of the different solutions identified during the preliminary studies phase, in order to select the most promising ones. Successively, a set of dedicated first-level test activities will be performed on the most critical propulsion system components (thruster, catalysts, tanks, valves, injectors, combustion chamber, propellants) in order to investigate the selected solutions and to refine the indications provided by the preliminary design. A detailed design of the two prototypes, based on the outcomes of this components testing campaign, will be then prepared and discussed.

The WP400 (M.A.I.T. Monopropellant) and WP500 (M.A.I.T. Bipropellant) will be dedicated to the manufacturing and assembly of the two PulCheR propulsion system prototypes (the monopropellant and the bipropellant one), their integration in the test bench and their testing according to the previously established Test Plan. Both Work Packages will last for a total of 10 months, but they will be slightly overlapping: in particular, the manufacturing and procurement of the components for the bipropellant propulsion system will start immediately after the one for the monopropellant, and will be carried out in parallel with the assembly, integration and testing of the monopropellant itself. Both test campaigns will start with a Test Readiness Review meeting and will end up with a Post Test Review meeting.

Finally, the WP600 (Analysis of Results, Road Map & Exploitation) will be devoted to a detailed analysis of the results obtained by the test campaign. The perspectives for any future exploitation of the project results will be carefully studied and presented, also by means of Road Maps prepared by all the components of the consortium. This Work Package will have a total duration of 8 months and will start immediately after the end of the first test campaign on the monopropellant propulsion system.

The PulCheR project is carried out by the PulCheR Consortium, composed by nine leading companies in space technologies as reported in the following table.

Tab. 11. PulCheR consortium

PulCheR Consortium
Alta S.p.A., Italy (project coordinator)
Thales Alenia Space France, France
Moog Inc Corporation, USA
Japan Aerospace Exploration Agency, Japan
Bradford Engineering B.V., The Netherlands
National Center for Scientific Research "Demokritos", Greece
Institute of Aviation, Poland
Universität Bremen (ZARM), Germany
Università di Pisa (DCCI), Italy

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