– PULCHER –
PULSED CHEMICAL ROCKET WITH GREEN HIGH PERFORMANCE PROPELLANTS

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Final Report

FINAL PUBLISHABLE SUMMARY REPORT

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ABSTRACT

This document is the final publishable summary report which includes: an executive summary, a summary description of project context and objectives, a description of the main S&T results, the potential impact and the main dissemination activities and exploitation of results/foregrounds.

KEY WORDS PulCheR, Chemical Propulsion, Green Propellants, Final Report

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PP	Restricted to other programme participants (including the Commission Services)	
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CO	Confidential, only for members of the consortium (including the Commission Services)	

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List of acronyms and abbreviations

Acronym / Abbreviation	Meaning
AD	Applicable Document
ADR	Active Debris Removal
BET	Brauner – Emmett – Teller
BOL	Begin Of Life
CDR	Critical Design Review
COTS	Consumer Off-the-Shelf
DMS	Document Management System
EDS	Energy Dispersive X-Ray Spectroscopy
EOL	End of Life
EC	European Committee
EU	European Union
GA	Grant Agreement
HTP	High Test Peroxide
IDT	Ignition Delay Time
IPR	Intellectual Property Rights
LPG	Liquefied Petroleum Gas
MAIT	Manufacturing, Assembly, Integration and Test
MEA	Monoethilamine
NA or N/A	Not Applicable, Not Available
NCR	Non-Conformance Report
PDRE	Pulse Detonation Rocket Engine
PRM	Periodic Review Meeting
PWM	Pulse Width Modulation
RCS	Reaction Control System
REA	Research Executive Agency
S&T	Scientific and Technical
SEM	Scanning Electron Microscopy
TRL	Technology Readiness Level
WP	Work Package

1 Introduction

This document is the final publishable summary report of the “PulCheR - Pulsed Chemical Rocket with Green High Performance Propellants project (Grant Agreement n° 313271). It includes: an executive summary, a summary description of project context and objectives, a description of the main S&T results, the potential impact (including socio-economic impact of the project) and the main dissemination activities and exploitation of results/foregrounds.

2 References

2.1 Applicable Documents

The following documents, at the latest issue in effect at the date of this specification where not otherwise specified, are applicable. They are referred to within this document as AD*xx*, where *xx* is the identification number in the following list.

AD	Document Identification	Is (Date)	Title
01	GA 313271	13/12/2012	Grant Agreement Number 313271 – PulCheR – Pulsed Chemical Rocket with Green High Performance Propellants
02	D210.211	i1r1 (07/05/2013)	State of the Art Review
03	D210.212	i1r4 (30/07/2013)	PulCheR Propulsion System Requirements
04	D220.221	i1r1 (26/09/2013)	Thruster Modelization and Preliminary Analysis
05	D230.231	i1r2 (23/09/2013)	Propellants Analysis and Trade-Off
06	D240.241	i1r2 (03/09/2013)	Materials Analysis and Trade-Off
07	D250.251	i1r1 (26/09/2013)	Valves Study and Trade-Off
08	D250.252	i1r1 (16/09/2013)	Injectors Study and Trade-Off
09	D260.261	i1r2 (12/11/2013)	Tanks Study and Trade-Off
10	D270.271	i1r3 (18/07/2013)	Catalysts Analysis and Trade-Off
11	D311.311	i1r1 (28/01/2014)	PulCheR Preliminary Design
12	D313.312	i1r1 (17/12/2013)	Preliminary Test Plan
13	D321.321	i1r1 (23/12/2013)	Propellants Testing Report
14	D322.322	i1r3 (11/11/2014)	Combustion Chamber Materials Test Report
15	D323.323	i1r2 (18/06/2014)	Firing Valve Testing Report
16	D323.324	i1r3 (24/07/2014)	Injectors Testing Report
17	D324.325	i1r2 (18/08/2014)	Tanks Testing Report
18	D325.326	i1r0 (29/05/2014)	Catalysts Testing Report
19	D326.327	i1r0 (10/06/2014)	Thruster Demonstrators Test Report
20	D331.331	i3r0 (24/09/2015)	PulCheR Propulsion System Design
21	D332.332	i2r0 (22/09/2015)	PulCheR Test Bench Design
22	D332.334	i1r0 (11/12/2014)	Manufacturing and Procurement Flow Chart
23	D333.333	i2r2 (21/09/2015)	PulCheR Test Plan
24	D415.411	i2r0 (04/02/2016)	Manufacturing and Procurement Report Monopropellant
25	D423.423	i1r0 (29/12/2015)	Assembly and Integration Report Monopropellant
26	D430.431	i1r0 (29/12/2015)	Test Procedures Monopropellant
27	D430.432	i1r0 (29/12/2015)	Test Results Monopropellant
28	D513.511	i2r0 (03/02/2016)	Manufacturing and Procurement Report Bipropellant
29	D523.523	i2r0 (01/02/2016)	Assembly and Integration Report Bipropellant
30	D530.531	i2r0 (03/02/2016)	Test Procedures Bipropellant
31	D530.532	i2r2 (26/02/2016)	Test Results Bipropellant
32	D610.611	i2r1 (26/02/2016)	Post Test Review and Analysis
33	D620.621	i2r0 (04/02/2016)	Road Map and Future Developments

34	D630.631	i2r0 (04/02/2016)	Exploitation of PulCheR Concept
35	PULCH-1-FPR	i1r0 (07/03/2014)	First Periodic Report
36	PulCheR_Review_Report100150186_20140327_000914_CET	(26/03/2014)	Review Report (First Period: 01/01/2013 to 31/12/2013)
37	PULCH-1-SPR	i1r0 (27/02/2015)	Second Periodic Report
38	PulCheR_Review_Report100155148_20150526_1133033_CET	(15/05/2015)	Review Report (Second Period: 01/01/2014 to 31/12/2014)
39	PULCH-1-TPR	i1r1 (29/02/2016)	Third Periodic Report

2.2 Reference Documents

Reference
N/A

3 Executive summary

PulCheR (Pulsed Chemical Rocket with Green High Performance Propellants) is a new propulsion concept 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. At each pulse, pressurization of the combustion chamber gases takes place due to the decomposition or combustion reaction, and the final pressure is much higher than the one at which the propellants are stored. The weight of the feeding system is significantly reduced because the propellants are fed at low pressure. The feed pressure becomes independent on the chamber pressure and the performance degradation typical of the blow down mode in monopropellant thrusters can be drastically reduced. Finally, pulse mode greatly simplifies the throttling of the thrust.

The PulCheR project aims at demonstrating the feasibility of this 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 North-South / East-West station keeping, 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 has been investigated both in mono and bipropellant configurations at breadboard level through the design, realization and testing of a platform of the overall propulsion system. High performance green propellants have been selected for the experimental campaign in order to further investigate possible candidates for substituting current toxic propellants.

During steady-state tests, high grade hydrogen peroxide (98% by weight) proved to be a very good candidate for substituting hydrazine, even with conventional feeding system, for monopropellant system characterized by short enough mission times and not so severe specific impulse requirements. Moreover, the monopropellant thruster exploiting the PulCheR concept was successfully tested and the feasibility of the new propulsion concept was demonstrated with only some minor concerns regarding the propulsive performance that was able to fulfill the requirements only in some cases.

Even if the selected innovative bipropellant combination of propyne and hydrogen peroxide proved to be not hypergolic, these green propellants showed propulsive performance comparable to the current toxic bipropellant combinations. Further improvements of the ignition system based on a catalytic bed will allow for a possible application of these propellants in future missions. Moreover, in the framework of the project, a wide screening of hypergolic combinations with HTP has been carried out. Some fuels have been identified as hypergolic with HTP after their mixing with metal transition salts and metal hydrides. In particular, impinging tests of MEA+7% $NaBH_4$ with HTP have shown that repeatable and very stable hypergolic ignition is possible, even for long time injections (at least 5 s). Therefore, this combination has been identified as a promising candidate to exploit the PulCheR concept in green bipropellant system.

Finally, even if the effort in the development of innovative materials for combustion chamber (such as SiC/Mo and ZrO_2/Mo multilayer system) has resulted in the failure of all the tested samples, the chambers debris showed no melting of the materials, thus confirming the goodness of the selected materials whose manufacturing process and technology still needs to be improved for avoiding micro-cracks that were probably the main reasons of their failures.

New frontiers of research have been opened by PulCheR for virtually all the propulsion system components, due to the new concepts developed for the thrust generation (pulsed operation) and for the feeding system. Moreover, new avenues of research have been opened also in the field of high performance green propellants, with the identification of effective substitutes for the hydrazine and its by-products as space propellants.

4 Project context and the main objectives

PulCheR (Pulsed Chemical Rocket with Green High Performance Propellants) is a new propulsion concept 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 radical innovation introduced by PulCheR is the elimination of any external pressurizing system even if the thruster works at high pressure inside the combustion chamber. At each pulse, pressurization of the combustion chamber gases takes place due to the decomposition or combustion reaction, and the final pressure is much higher than the one at which the propellants are stored. The weight of the feeding system is significantly reduced because the propellants are fed at low pressure, and there is no need for turbopumps, high pressure propellant tanks or gas vessels. The feed pressure becomes independent on the chamber pressure and the performance degradation typical of the blow down mode in monopropellant thrusters can be drastically reduced.

The 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;
- 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. The breadboard will include two thrusters prototypes:

- one monopropellant thruster within the thrust range of 1-5 N (powered by high grade hydrogen peroxide);
- one bipropellant thruster within the thrust range of 10-100 N (powered by high grade hydrogen peroxide and propyne).

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), propellant lines, firing valves and thrust chambers.

Throughout the project, the main performance/research indicators will be:

- the demonstration of the feasibility of the PulCheR concept: the feasibility of generating thrust by means of a system characterized by propellants feeding at low pressure and high frequency pulses will be performed at breadboard level and will consist in the experimental measurement of the thrust generated by the propulsive system;

- the assessment of high performance green propellants combination: hypergolic test will be performed on the selected propellants combination and their propulsive performance will be assessed in steady-state tests (e.g. experimental measurement of the specific impulse);
- the assessment of propulsive performance (see target values above) of the PulcheR system: the propulsive performance will be experimentally assessed at breadboard level both for mono and bi-propellant thrusters;
- the dry-mass reduction of the overall propulsive system: the target values of the dry-mass reduction of the overall propulsive system can be stated as follows:
    - -dry-mass/overall propulsive mass ratio for the monopropellant thruster: from 9.2% to less than 4.5%;
    - -dry-mass/overall propulsive mass ratio for the bipropellant thruster: from 8.7% to less than 5.0%.

5 Main scientific and technical results/foregrounds

5.1 Preliminary studies about the PulCheR concept

A set of studies on the most important aspects of the PulCheR concept including the propulsion systems, thrusters, propellants, combustion chamber materials, valves, injectors, tanks and catalysts have been performed in the framework of the Preliminary Studies work package (WP200).

Accurate literature reviews have been carried out for identifying a set of suitable solutions to be analyzed during the successive design phase. A detailed literature review aimed at defining the present state-of-the-art of propulsion systems and concepts based on similar characteristics to the intended ones for the PulCheR project has been carried out.

The first phase of the literature review has been focused on the research in the open literature of developed or intended propulsion systems based on one or more concepts of the PulCheR system or at least on similar principles. Moreover, the literature review has been aimed at analysing the models used to predict their intended propulsive performance in order to identify possible analytical tools for the modelling of the PulCheR system and at assessing the actual performance of the tested concepts, the main criticalities encountered during the experiments and their eventual space applications. The PulCheR propulsion system relies on three main concepts closely related to each other: propellant(s) feeding at low pressure, high frequency pulses and quasi-constant volume combustion. The thrust is generated by means of high frequency pulses obtained by strong pressure oscillations in the combustion chamber. The propellants are fed in the combustion chamber at low pressure while the pressure peak is the result of quasi-constant volume combustion. Finally, the thrust is obtained by accelerating the combustion products through a nozzle during the blowdown of the combustion chamber. In general, rocket engines can be classified according to two possible modes of operation: the steady state combustion mode (or quasi-steady mode) and the intermittent or unsteady combustion mode. Three main categories of chemical rockets mainly based on pulse mode operation have been identified in open literature and detailed in AD2: pulse detonation rocket engine (PDRE); pulse rocket engine with movable injectors; rocket engine with constant volume pulse combustor.

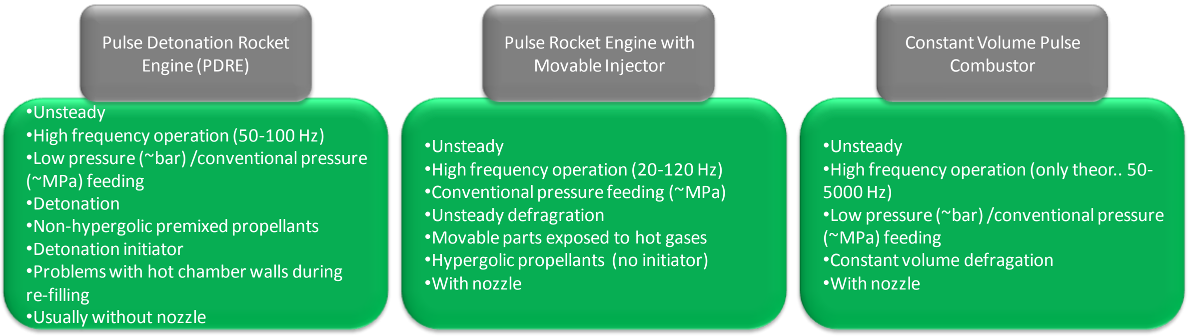


Figure 5.1 Main characteristics of the reviewed pulse rocket engines.

With respect to conventional constant pressure rocket engines, the intermittent or unsteady combustion mode allows for the reduction of the feed pressure and the increasing of the chamber pressure. A reduced feed pressure may imply the reduction or elimination of pumps and/or compressors and therefore the reduction of the overall weight of the propulsion system. Higher chamber pressures may improve the specific impulse or result in smaller and lighter thrusters. Among the engines reviewed in the literature survey, 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. Moreover 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 second phase of the literature overview has been dedicated to the identification of the present state-of-the-art of propulsion systems currently used in the space applications for which PulCheR is intended (essentially in-space applications as North-South / East-West station keeping, orbit transfer, attitude control, docking/rendez-vouz, orbital re-phasing, de-orbiting etc.). For both monopropellant and bipropellant propulsion subsystems, a detailed functional description of the main components (e.g. propellant tank, typical thrusters, latch valves, fill and drain valves, filters, pressure transducer, tubing) has been provided together with the typical system performance, the typical applications, some reference missions, the mass budget and some alternative system configurations (see AD02).

The definition of a set of reduced-order models for the preliminary analysis of the PulCheR propulsion system has been carried out starting from the models found in the open literature and relating to the constant volume pulse combustor. The preliminary analysis has been performed by a simplified thermochemical model for the assessment of adiabatic combustion, a simplified 1D gasdynamic model for propulsive performance assessment and a simplified 0D dynamic model for pressure evolution inside the combustion chamber (details in AD04). The preliminary analysis started with the thrusters operating in the PulCheR mode with rocket grade hydrogen peroxide (monopropellant thruster) and propyne + rocket grade hydrogen peroxide (bipropellant thruster) as propellants. This reduced order analysis allowed for obtaining some specific operational ranges of the main physical quantities needed for drawing the PulCheR system requirements as the chamber pressure, propellants mass flow rates, chamber temperature and thrust time evolutions during the pulsed operation together with the expected performance (mainly the specific impulse).

The definition of the requirements for the PulCheR propulsion system has not been trivial since a lot of aspects must be considered in this phase. It has been decided to approach the problem considering the possible requirements for the PulCheR propulsion system at TRL 8-9 (flight model) and extracting from those the PulCheR breadboard requirements. Mean thrusts of 1 N and of 10 N have been selected respectively for the monopropellant and the bipropellant thrusters. 98% rocket grade hydrogen peroxide and the combination of 98% rocket grade hydrogen peroxide and propyne have been identified and preliminarily considered as propellants.

Potentially promising propellants for the PulCheR concept have been identified, their market availability has been assessed and a preliminary performance analysis and trade-off of the identified propellants have been performed. In particular 98% HTP and the combination of 98% HTP and propyne have been confirmed as very promising solutions for high performance green pulsed chemical rockets.

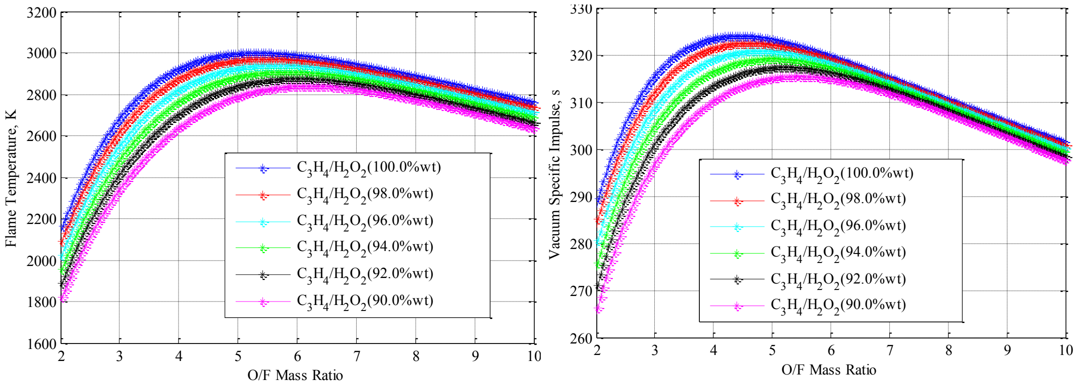


Figure 5.2 Adiabatic flame temperature (left) and actual vacuum specific impulse of the combustion of hydrogen peroxide and propyne as a function of the oxidizer/fuel mass ratio for different H_2O_2 concentrations.

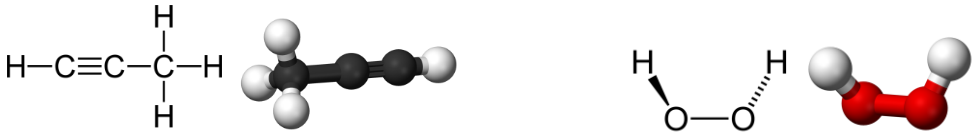


Figure 5.3 Structural formulas of methylacetylene (left) and hydrogen peroxide (right).

The potentially promising materials for the combustion chamber of the PulCheR bipropellant thruster have been identified and a preliminary analysis and trade-off of the identified materials have been performed. As preliminary conclusions, the development of a radiation-cooled combustion chamber made of a coated Cf/SiC has been identified and as a fallback position, it has been recommended to use either a film-cooled chamber made of a refractory alloy.

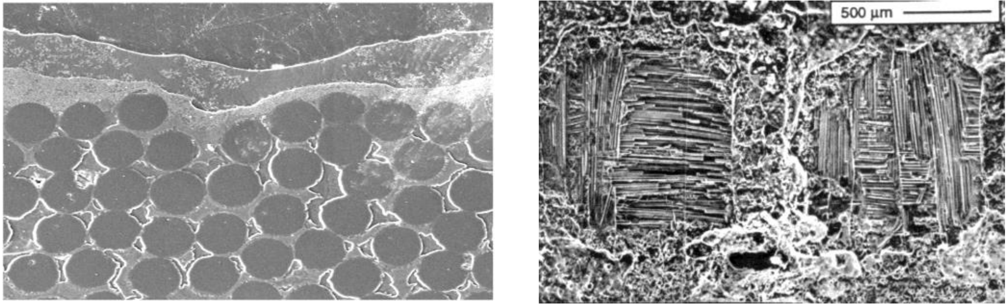


Figure 5.4 Examples of the microstructure of a 2D C/C (left) and a 3D SiC/SiC (right).

The existing firing valve and injector concepts adaptable to PulCheR have been reviewed and a preliminary study and trade-off of them have been carried out. The challenging requirements to be met by the firing valves have been identified in the very fast response time (< 1.3 ms) and the compatibility with the propellants (in particular H_2O_2). The main challenge for the injectors has been to adapt existing concepts (always based on steady state performance) to the unsteady operation of the PulCheR engine: the only reliable re-design process must be performed relying on an intensive experimentation. The pintle injector (automotive-like) has been identified as an alternative to the standard injectors solution (impinging or coaxial).

Existing tank concepts adaptable to PulCheR have been identified and traded-off. Due to the nature of the propellants (in particular for the oxidizer, rocket grade hydrogen peroxide) the main technological issue was identified in the materials compatibility since the PulCheR tank requirements in terms of pressure, capacity and mass flow rate can be easily met. Three ways of possible development have been identified: the first one is based on an existing tank shell design made in a compatible material such as aluminum alloy, stainless steel or composite (a material with structural characteristics which can sustain the mechanical functions); another development can be performed by using an existing qualified tank made in titanium and internally applying a thin layer of compatible materials; a completely new, unconventional custom-designed tank by using for example an unpressurised and flexible bladder associated with a flattening system.

Finally, the potential solutions for the catalysts to be used in the PulCheR concept (monopropellant thruster) have been analyzed and their feasibility has been assessed. Concerning the carriers, the results of the performed trade-off analysis revealed that the most interesting materials to test are: compact alumina; silicon carbide; silica. In particular, compact alumina (α-Al_2O_3) resulted the most versatile carrier. Silicon carbide (SiC) has an exceptional thermo-mechanical resistance but a very limited grafting capability making the deposition of the active species very hard. Concerning the catalytic elements, the developing activity has been mainly focused on platinum (the first choice) and manganese oxides. Moreover, cerium in combination either with platinum or with manganese and calcium in combination with manganese has been identified for further investigations.

5.2 Design of the PulCheR system

The results of the Preliminary Studies have been used as starting point for the System Design activities (WP300: System Design). The activities have been divided into three main phases: the Preliminary Design, the Components Testing and the Detailed Design.

The Preliminary Design of both the PulCheR monopropellant and bipropellant prototypes has been carried out at a breadboard level, with the aim of demonstrating the PulCheR propulsion concept in safety conditions. As baseline solution, the shower head injection philosophy has been used for the monopropellant thruster prototype. A back-up solution is represented by a pintle injection (automotive-like) able to distribute in a uniform way the hydrogen peroxide on the frontal area of the catalyst bed at high frequency. As baseline solution, the coaxial injection philosophy has been used for the bipropellant thruster prototype. A back-up solution has been represented by pintle injectors (automotive-like) able to inject the propellants at high frequency. The preliminary design of the bipropellant thruster has taken into account also the issue of interfacing a C/SiC combustion chamber with a metallic injector flange. The assumption of hypergolic propellants has been done since no experimental data were available until then. All the components of the PulCheR propulsion system have been preliminarily defined and selected and the preliminary design of the complete propulsion system in its monopropellant and bipropellant configurations has been carried out.

The preliminary design of the test bench for the PulCheR thruster demonstrator at a breadboard level has highlighted the issue of the correct measurement of the propellants mass flow rate. Nevertheless some solutions have been identified and proposed. The modularity has been one of the main guidelines of the test bench preliminary design. The feeding line of the monopropellant test bench has been conceived to be used also as the oxidizer feeding line of the bipropellant test bench.

Remotely controllable electro-pneumatic valves have been preliminarily selected for the test bench in order to increase the safety during the testing phase. Off-the-shelf industrial firing valves have been preliminary selected for the test bench. Indication about a possible MOOG firing valve has been provided as well. The preliminary design of the test bench for the tests on the monopropellant propulsion system as well as the modifications, needed for upgrading it to the bipropellant case, have been defined. Concerning the test campaign, it is worth noticing that the thruster in PulCheR configuration (both monopropellant and bipropellant) generates the thrust in unsteady conditions (typical pulse frequency is of 15 Hz and the injection time lasts a few milliseconds). Therefore, the mass flow rate entering the engine is, in general, different from the mass flow rate exiting the nozzle. The punctual mass flow rate used to compute the specific impulse refers to the exiting mass flow rate. Actually, there is no way to obtain a direct and punctual measurement of the exiting mass flow rate. Consequently, the correct way to compute the average specific impulse of the PulCheR thruster is through the measurement of the amount of propellants elaborated by the thruster during the generation of the thrust. The typical response time of pressure transducers and load cells allows for an accurate measurement of the time-evolutions of the thrust and the combustion chamber pressure. Since the typical response time of a thermocouple is in the order of fractions of second, the temperature efficiency that can be computed is approximated and refers to an average value of the overall firing.

According to previous remarks, a preliminary Test Plan for the testing activities of the propulsion system in both its configurations has been drawn. Moreover a detailed Test Plan for the dedicated test activities on the propulsion system components foreseen in the Components Testing phase has been prepared.

According to the outcomes of Preliminary Studies, propyne has been chosen as the fuel candidate for the PulCheR propulsion system. For this reason, it has been decided to concentrate the efforts of the components testing activities in conducting fire tests with propyne and 98% HTP. The main aim of the planned tests was to understand and analyze the hypergolicity properties of this propellants combination. Since propyne is stored at ambient temperature in saturated conditions (vapor pressure of 5.1 bar @ 20 °C), the simple drop tests method cannot be exploited. It has been decided to perform hot fire tests using head of injectors with 4 on 1 injector pattern. The research on the auto ignition phenomenon mainly based on the pressure measurements in the test chamber by fast pressure transducers and measurements of infrared waves occurred at contact point between reactants by photocells during fully work cycle. The test stand consists of the head of injector, combustion chamber, feeding lines for fuel and oxidizer, vacuum pumps, solenoid valves and sensors. The measurement system allows for analyzing the auto ignition time delay, nevertheless it was not observed during all firing tests. All hot fire tests were conducted for different conditions in the combustion chamber, starting from 3 bar of pressure with nitrogen atmosphere and finishing with tests in vacuum conditions. The test campaign has been carried out according to the Test Plan included in AD12. The obtained results have revealed that the chosen propellants combination is not hypergolic at all tested conditions, included and described in the Test Plan. Moreover, works included tests of the injectors with catalytic inserts (carrier: α-Al_2O_3; active phase: MnO_x, at different percentages). Also in these cases the hypergolic phenomenon was not observed. From this reason it has been decided to apply a new approach to the fuel preparation, doping it for obtaining a hypergolic combination with 98% HTP. The liquid propyne was mixed with ferric(III) chloride leading to homogenous mixture. Such mixture including 10% by mass of $FeCl_3$ has been quasi-hypergolic with HTP. The IDT was observed in the range of 40 ms – 255 ms. Nevertheless such prepared fuel is not so suitable for space application due to the difficulties during handling and filling into the feed system. Additional drop tests have been performed to select other fuel candidates. During these tests the ethanolamine and propargyl alcohol have been mixed with ferric chloride and copper chloride. The average IDT for ethanolamine was on the level of 31.1 ms in the range of 20 ms – 44 ms and for propargyl alcohol on the level of 35 ms in the range of 30 ms – 40 ms. Nevertheless propargyl alcohol mixed with $FeCl_3$ below 5% by mass is unstable and in contact with HTP can pass to strong detonation.

Concerning the propellants production, Institute of Aviation’s capability of in-house production of 98% HTP has been confirmed on the level of some liters per week (2-3 liters). On the other side, propyne could not be produced in-house by IoA. Nevertheless a series of suppliers have been identified and contacted.

The development of the combustion chamber materials has been focused on the design and testing of a plasma-spraying technique for building a multilayered ZrO_2/Mo alloy-based structure. The material has been produced and tested satisfactorily. In addition, the material has been produced in the shape of the preliminary design of the bi-prop chamber using a mandrel, adhering approximately to the specifications (Figure 5.5). An alternative material for the bi-prop combustion chamber was also produced of SiC (starting with SiSiC via a modified slip-casting process and converting to mostly SiC) and a final shape chamber was produced as shown in Figure 5.5.

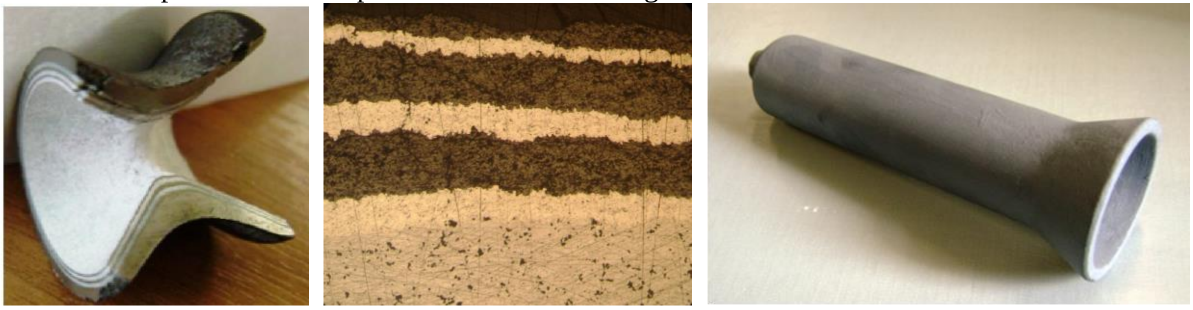


Figure 5.5 Cross section of the ZrO_2/Mo alloy multilayer material at the region of the throat (left). White areas (dark in the optical micrographs in the middle) are the ZrO_2 layers. A SiC chamber (without Mo coating) produced by a modified slip-casting process (right).

Some high temperature shock tests on semi-finished chambers in the cylindrical furnace have been performed, as shown in Figure 5.6. The high temperature (up to 3000°C) was provided by an oxyacetylene torch directly into the chamber. Both preheating (up to 1000°C) and cold-start tests were carried out in air. The SiC-based chamber showed no degradation after thermal shock tests. Tests have been performed also with a multilayered ZrO_2-based combustion chambers.

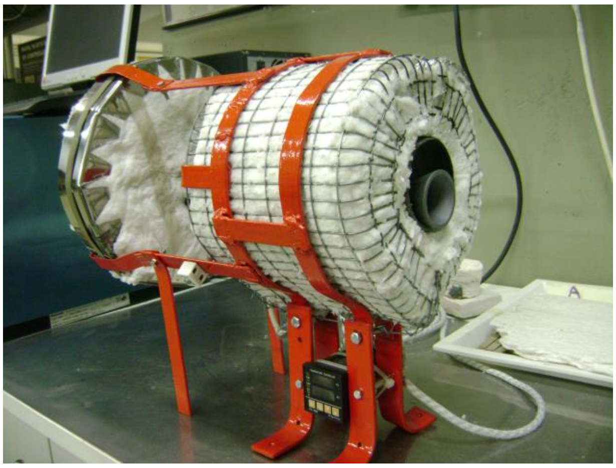


Figure 5.6 The cylindrical furnace built for 3000°C thermal shock tests in air with a SiC chamber in position. The thermal shock is applied by an oxyacetylene torch (not shown) from the right and the flame is directed at the throat or the chamber.

The selection of the firing valves has started from two candidate valves that have been procured for the component testing phase (see Figure 5.7). Both valves are off-the-shelf fully space-qualified designs with performance approaching that required by the present program. Both valves are in line solenoid actuated valves with suspended armature, with response times in the millisecond range. To be compliant with the requirements, the response of the valves has been accelerated by applying higher than nominal voltage in order to short the inductive phase of operation.

Figure 5.7 Candidate Firing Valves (left). Moog 52-204B thruster valve shown integrated with Thruster (right).

Methodology to test candidate valves has been established (see also AD7). Performance has been characterized by test by capturing fluid exiting the valve and weighing or performing a volumetric measurement of the produced sample. Equipment to perform testing on candidate valves has been developed. Primary effort was on the valve driver circuit to enable PWM control of the valve with high voltages and this was achieved by implementing a FET driver. Other equipment is fairly standard and considered normal work. The dose size requirement was demonstrated for both valves experimentally for the case of 30 doses per second, and doses representative for the monopropellant valve (18 mg/dose) and the bipropellant fuel valve (36.8 mg/dose) were successfully tested. However, the dose performance for the bipropellant oxidizer valve (175.5 mg/dose) could not be achieved in test.

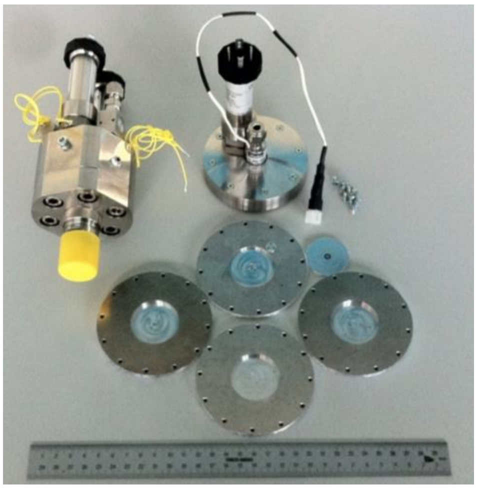


Figure 5.8 Injectors and Bulkheads (left – bipropellant, right – monopropellant).

For this particular valve, Bradford investigated alternative valves which could be made available, and finally identified another model Moog USA solenoid valve (p/n 52-204B) of which two valves were assembled and made available for test in the first quarter of 2015. It is noted that an export license was to be granted by the US Government before this valve could be shipped to Bradford.

The injector head concept chosen for the monopropellant has been the classic showerhead distribution. Moreover, four designs with different bore distributions were developed. The most driving parameter in the design was the dribbling or dead volume within the injector geometry since the mass bits to be output through the bores are very small, leading to strong transient effects. After the tests, the best results have been obtained by the ideal showerhead configuration (maximum spacing between bores aiming for maximum distribution) and the equally distributed showerhead (named also Christmas tree) aiming at having a simultaneous injection in all bores.

The concept for the bipropellant injector was an external mixture shear coaxial injector with a flashing fuel in the core and an oxidizer liquid blast flow on the sleeve. Different geometries and area ratios have been implemented in the test bench. During the tests, the main issue with the bipropellant injector has been a large dribbling volume due to the bulkhead on the injector head. Figure 5.8 shows the injectors used in the test campaign.

Concerning the tanks, a detailed technical specification was established for the tank BBM derived from the subsystem requirement. Major aerospace and chemical tank's suppliers were evaluated (ATK, Astrium, MT Aerospace, Keystone, Arde, Moog, Cobham, MHI, IHI, Air Liquide, Evonik, Solvay…). The important outcomes of the materials compatibility assessment were introduced at same time in the evaluation of the different tank's concepts and suppliers, thus allowing for eliminating potential candidates due to material compatibility issue with HTP. In the beginning, a first supplier was identified that proposed a pressurized tank made in aluminum 2195 and with elastomeric FFKM high grade diaphragm. Due to the relative high percentage of copper in the aluminum 2195, there was a risk of compatibility issue with HTP. It was then evaluated to change the 2195 aluminum by 6061 anodized or 1xxx series aluminum, but this associated cost and schedule impacts were too important.

Finally, an off-the-shelf tank, previously developed for another EU project and fully compatible with 87.5% HTP (AISI 316L shell / FKM bladder), was identified for procuring for the PulCheR test bench.

For a preliminary screening of the catalysts, small quantities of different catalytic systems (about 10 g of each catalyst) have been produced by the Department of Chemistry and Industrial Chemistry of the University of Pisa (DCCI). In order to compare the activity test results, according to the Test Plan (see AD12), carriers with the same pellets dimension (mean diameter of about 0.6 mm) have been used for all the catalyst samples prepared. The carrier chosen as reference was the alpha-alumina sphere with a diameter of 0.6 mm, a surface area of 7 m^2/g and a packing density of 1.27 g/ml. Since one of the main objectives for the catalyst development identified in the test plan was to reduce the pellets size w.r.t. 0.6 mm in order to have more active catalytic surface in the small catalytic bed for the PulCheR monopropellant prototype, some alumina samples of 0.4 mm and 0.35-0.25 mm particles size have been procured. Once the catalytic activity tests were completed and the more active catalysts were identified, then the catalyst carriers of smaller sizes were used to scaling their dimension.

The catalytic activity tests on the developed catalysts have been carried out using the small test facility available in the Chemical Propulsion Laboratory at Sitael S.p.A., the constant pressure test reactor (see Figure 5.9). The test bench consists of a 250 ml reaction flask contained in a glass vessel with a volume of about 2 litres. Before each test, a known volume (1 ml) of catalyst is put in the reaction flask; successively, a given quantity (5 ml) of hydrogen peroxide is added. Two thermocouples are used for measuring the temperatures of the reacting liquid hydrogen peroxide solution and of the reaction gases in the vessel. Catalyst activity experiments have been carried out using 30% hydrogen peroxide solution (PERDROGEN by Sigma-Aldrich). For each catalyst sample, a series of consecutive tests (50) has been carried out in order to investigate the repeatability of the results and the poisoning or degradation of the catalyst sample (e.g. catalyst species leaching). The time needed (t_{max}) for the liquid to reach the peak temperature has been used as a quantitative assessment of the decomposition activity, the susceptibility to poisoning and the repeatability of the catalysts. The average t_{max} values of each activity test campaign were calculated to easily assess the best catalytic activity.

All Mn-catalysts showed a low catalytic activity. On the contrary Pt-catalysts resulted very active. Detailed SEM-EDS (Scanning Electron Microscopy - Energy Dispersive X-ray Spectroscopy) examinations have been performed on the catalyst samples after and before the activity tests with 30% hydrogen peroxide, in order to measure morphological and chemical composition on the fresh catalyst samples and the variations on the catalyst surface after the H_2O_2 decomposition at the end of the catalytic activity tests. Moreover, BET surface area measurements of the carriers have been usually performed before and after the deposition of the catalytic materials.

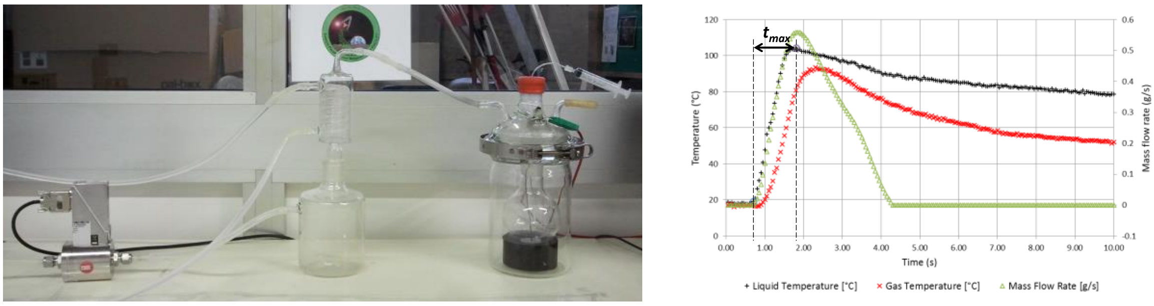
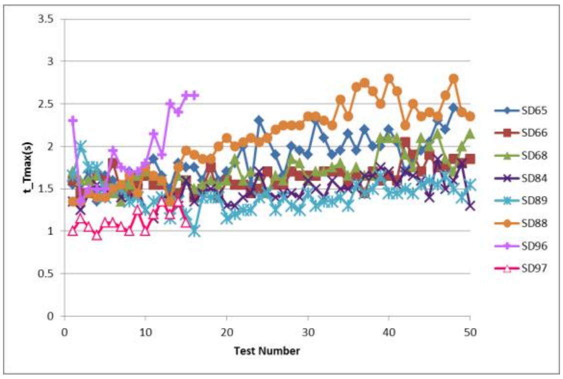


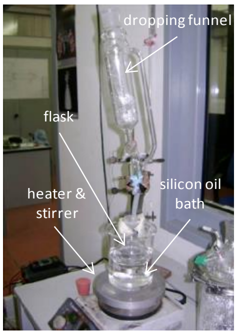
Figure 5.9 Sitael's test bench for evaluating the catalytic activity of different materials/catalysts (left). Example of data acquired during a catalytic activity test (left): liquid temperature (black +), gas temperature (red x) and mass flow rate (green Δ).



Catalyst ID code	*t_{max} (s)*
SD-65-400	1.88
SD-66-400	1.62
SD-68	1.72
SD-84	1.49
SD-88	2.09
SD-89	1.42
SD-96	1.95
SD-97	1.12

Figure 5.10 Results of catalytic activity test campaigns (left) and average t_{max} values (right) of Pt-catalysts with 0.6 mm of size.

The thermo-mechanical resistance of the most active catalysts was evaluated dropping 98% H_2O_2 solution on the catalyst samples in a dedicated experimental setup (see Figure 5.11). A sample of 100 pellets of each catalyst was inserted in the reaction flask and 5 ml of 98% hydrogen peroxide solution were dropped on it by means of the drop funnel set for delivering to the catalyst sample a repeatable stream of hydrogen peroxide droplets, at a rate of about one per second. After the conclusion of the test, the intact spheres were counted by visual inspection and photographic pictures; the ratio of the number of intact/initial spheres for each catalyst has been used as a parameter for evaluating the thermal shock resistance of the catalysts.



	T_i = 20 °C	*T_i = 100 °C*	*T_i = 200 °C*
Catalyst ID code	**intact pellets/ initial pellets**		
SD84	100/100	100/100	100/100
SD89	100/100	100/100	100/100
SD88	100/100	100/100	100/100
SD97	100/100	100/100	100/100
SD99	100/100	100/100	100/100
SD94	100/100	100/100	100/100
SD2-3	93/100	87/100	87/100
SD2-4	90/100	89/100	89/100

Figure 5.11 Picture of the experimental setup used for the thermo-mechanical resistance tests on the catalysts (left) and results of dropping tests with 98% H_2O_2 (right).

The dropping tests were performed at different initial temperature of the catalysts (such as at 20 °C, 100 °C and 200 °C) in order to virtually reconstruct two typical operational conditions in terms of thermal shock, a "cold start" firing and a "hot start" firing. The results of dropping tests with 98% H_2O_2 carried out on the most active catalysts, confirmed the excellent thermo-mechanical resistance of α-Al_2O_3. SEM examinations revealed a beginning of carrier's breaking for catalysts prepared using α-Al_2O_3 with high packing density (1.27 g/ml) whereas no damages were observed for catalysts prepared using α-Al_2O_3 with lower packing density (0.71 and 0.75 g/ml).

Finally, in order to have relevant experimental data to compare the actual propulsive performance of the thrusters exploiting the PulCheR concept with the one achievable with a conventional propulsion system, the assessment of the propulsive performance of the new selected green propellants has been carried out in two stationary thruster demonstrators (a monopropellant and a bipropellant one). In particular, a set of stationary (non-pulsed) tests on the two demonstrators have been performed with the aim of measuring experimentally the actual specific impulse.

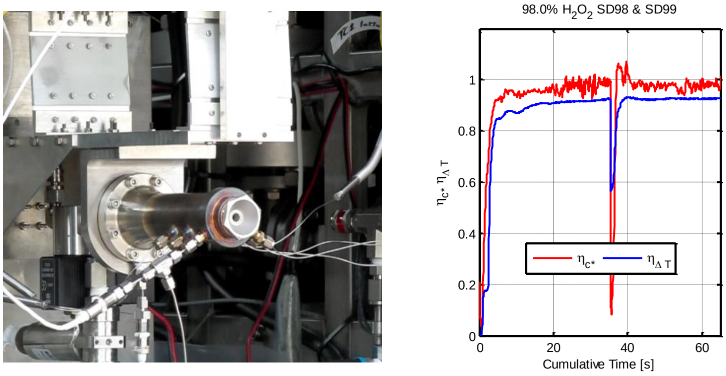


Figure 5.12 Picture of Sitael's hydrogen peroxide monopropellant thruster (left) and comparison between c* and temperature efficiencies as functions of the Cumulative Time (right).

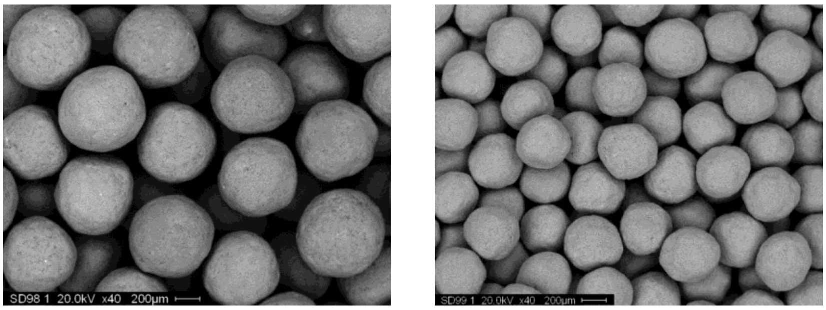


Figure 5.13 SEM pictures of the SD98 (left) and SD99 (right) catalyst samples.

The testing for the monopropellant system has been performed on a thruster prototype already used at Sitael in previous activities and, conveniently, adapted in order to be used with the selected catalysts. The test bench setup used has been the one already present at Sitael. The tests performed on the monopropellant thruster prototype have shown the great capability of the selected catalysts (prepared by DCCI) of decomposing 98% hydrogen peroxide (provided by Institute of Aviation) without the arising of effects like the poisoning or the leaching of the catalysts. The decomposition efficiencies of the SD98 and SD99 catalysts have been higher than 98% for the temperature efficiency and higher than 95% for the characteristic velocity efficiency, whereas no significant pressure drop across the catalytic bed has been recorded, thus revealing good thermo-mechanical resistance of the catalysts pellets. The thrust profile recorded for the thrusters has been particularly smooth and has shown better response time w.r.t. the previous test campaigns on the same prototype. The specific impulse experimentally assessed and conveniently extrapolated for vacuum operation has exceeded the target value for the PulCheR project (expected to be around 185 s).

As in the case of the monopropellant, the challenge for the PulCheR concept for a bipropellat thruster is the achievement of a high frequency pulse mode which could allow for a reduction of the propellants feeding pressure with a resulting reduction of the propulsion system weight without significantly affecting the propulsive performance. Indeed, in the case of the bipropellant, the PulCheR concept could be exploitable already with the actual toxic hypergolic propellants, but one of the goal of the project has been the identification of a possible hypergolic mixture of "green" propellants. The "green" propellants initially identified have been 98% HTP and propyne. From a literature survey performed at the beginning of the project, the selected propellants have shown the possibility of reaching very high combustion temperature with relatively low weight by-products. The most interesting aspect of this mixture has been their possible hypergolicity as reported in literature, even if no experimental evidence has been given. So the efforts have been concentrated on testing their hypergolicity, their compatibility with common structural materials and the development of materials

capable of sustaining the very high combustion temperature which almost reaches 3000 K. The interest in these propellants has been driven by the very high expected specific impulse (higher than 320 s in vacuum and with an expansion ratio of 330).
The first testing has been the experimental characterization of all the new components specifically purchased for the bipropellant tests (turbine flowmeter for fuel line, both the cavitating venturis for fuel and oxidizer lines, the injectors for oxidizer and fuel injection in the combustion chamber). Some tests on the injectors have been performed with simulant fluids (water for HTP and LPG for propyne) in order to better characterize the injection pattern. Some further tests on the ignitability have been then performed with the actual propellants and with the thruster manifold in order to confirm, first, the non-hypergolicity of the propellants themselves and then to characterize their ignition by means of either a spark plug or by staged combustion (ignition of propyne by heat released by HTP decomposition through a catalytic bed). Some injectors have then been selected for the tests with the combustion chamber. The tests have been almost exclusively performed with the TZM combustion chamber. Some previous experiments with the Silicon Nitride combustion chamber have shown its too high fragility. The tests performed on the bipropellant thruster have been successfully completed. Among the different configurations tested, the most successful has been the one with the staged combustion (see Figure 5.14): the injection and subsequent decomposition of HTP through a catalytic bed with significant heat release have proven that HTP decomposition by-products can almost instantly react with propyne. Such an ignition has allowed for assessing the thrust performance of the selected propellants and the expected performance has been confirmed. Some of these experimental and extrapolated data are summarized in Table 5.1.

Figure 5.14 On the left the bipropellant setup used for the tests with the metallic (TZM) combustion chamber. On the right a picture during the thruster firing.

In particular the specific impulse, extrapolated in vacuum with an aspect ratio of 330, has attested on 324 s and the characteristic velocity has exceeded 95% of the ideal value, thus confirming the very good combustion process.

c^*_{theo}	η_{c^*}	A_e/A_t	$C_{F\,theo\,(Vacuum)}$	η_{C_F}	$I_{sp\,ext\,(Vacuum)}$
[m/s]	[--]	[--]	[--]	[--]	[s]
1675	≥ 0.95	2.25	1.49	0.98	~ 239
		100	1.96		~ 314
		330	2.03		~ 324

Table 5.1 Theoretical values and efficiencies used for extrapolating the vacuum specific impulse.

Indeed the tests performed on the HTP + propyne have demonstrated that the PulCheR concept cannot be exploited by this way, because hypergolic propellants are necessary in order to exploit the high frequency pulse mode. Nevertheless the selected propellants have shown very interesting propulsive performance which could be even improved in terms of rise time by a proper design of the thruster.

As a consequence of the good results obtained during the Components Testing Phase, the Detailed Design of the monopropellant PulCheR system has been smoothly carried out in all its parts, such as the Propulsion System itself, the corresponding Test Bench and the corresponding Test Plan.

Concerning the bipropellant side, some issues have been arisen mainly due to the lack of hypergolicity of the combination of the selected propellants (such as propyne and hydrogen peroxide). As a main outcome of the PRM2 held in Brussels, a recovery plan for the bipropellant system was agreed with the ESA Reviewer and the Project Officer. The redefined objectives of the bipropellant part of the PulCheR project became:

- design, manufacturing and testing of a Reaction Control Thruster powered by hydrogen peroxide and propyne with conventional pressurization system (no PulCheR concept) and a thrust level of 20 N;
- testing of an injection system for the hypergolic propellants identified by Institute of Aviation (i.e. MEA doped with suitable catalysts and hydrogen peroxide).

As a result of the PulCheR recovery plan, the pulsed concept was no longer applicable to the bipropellant thruster. As a consequence, the test plan for the valves was amended to accommodate for these changes by testing the valves in representative steady state flow rate conditions and flow and pressure drop testing of the two bipropellant valves was performed. For the set of two bipropellant valves a laboratory style valve driver was build, providing a high voltage needed to open the valves, before leveling off to a lower keep-open voltage, reducing thermal loads on the opening coil.

5.3 Main results on the PulCheR monopropellant system

The detailed design of the PulCheR monopropellant propulsion system has been based on the outcomes coming from the thruster modelization and preliminary analysis and from the results of the components testing activities. In particular the results have been used for both the design of the fluidic lines and the thruster. Indeed the use of 98% HTP is very critical for the compatibility with many metals and care must be taken for the choice of the wetted materials.

Therefore, the design of the test bench for managing HTP has been driven by material compatibility with HTP and by the need for reducing the firing line as much as possible in order to reduce the effect of the firing line dynamics on the thruster operation. The tank used for storing HTP has been procured by Thales Alenia Space, which has identified a suitable tank, whose seals materials are compatible with hydrogen peroxide. All the fluidic lines have been manufactured with COTS components. The test bench includes also a thrust balance, specifically designed to allow the assessment of the thrust in pulse mode. The thrust balance and the supporting structure for the fluidic lines have been also split in order to avoid the influence of the structural dynamics on the thrust assessment. Some pictures of the test bench are shown in the following Figure 5.15.

Figure 5.15 The fluidic line supporting structure (on the left) and the thrust balance (on the right) specifically designed for assessing the propulsive performance of the PulCheR monopropellant propulsion system.

Along the test bench a series of fast pressure transducers, thermocouples and a turbine flow meter are placed in order to monitor the status of the propellant during either the management or the firing phase.

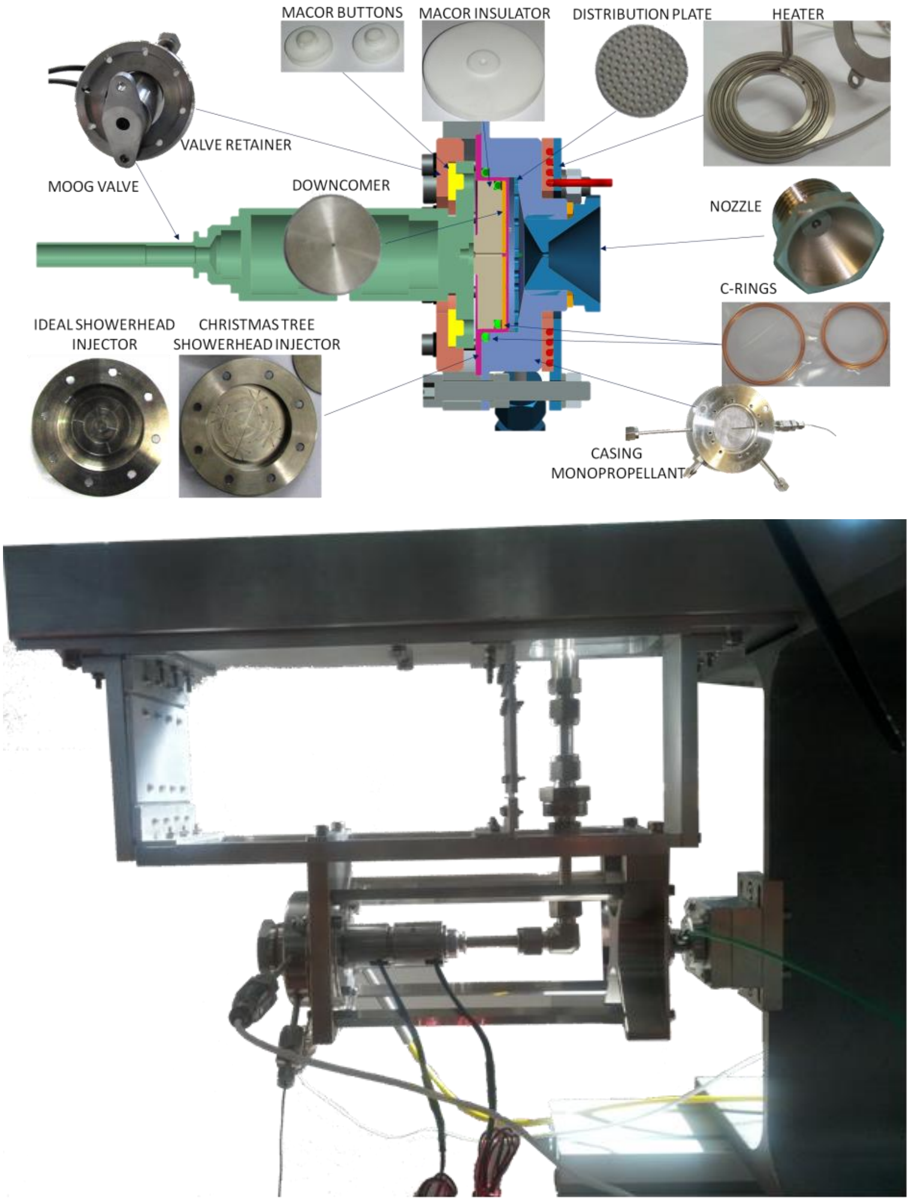


Figure 5.16 On the top a 3D CAD rendering of the PulCheR monopropellant thruster together with the several components. On the bottom the PulCheR monopropellant thrusters assembled on the thrust balance.

The design of the thruster has been very different with respect to the usual ones. In particular the biggest difference is the absence of a stand-off for the firing valve. This has been done in order to reduce as much as possible the dead volume between the valve and the catalytic bed. The valve is thus packed between insulating elements which are used to avoid the valves overheating. The aspect ratio of the catalytic bed is also different w.r.t. usual configurations: the catalytic bed diameter is much bigger than its length. This configuration, in turn, has driven to the design of the injector with two different configurations: a common one (ideal showerhead) and a new showerhead injector (named Christmas tree showerhead) with special holes pattern which allows a fast and simultaneous response of all the bores. The thruster has been designed as a prototype for exploring the feasibility of the PulCheR concept and so a series of pressure transducers and thermocouples have been used to monitor the thuster physical parameters. Some pictures of the thruster and its main components are shown in the Figure 5.16.

During the following tests campaign a lot of experiments have been carried out, for a total amount of 182 firings and a cumulative firing time of 1820 s. Two catalysts with different typical size have been integrated and tested in the PulCheR Monopropellant. Concerning the catalytic bed arrangement, two catalytic bed lengths have been investigated:

- 1.5 mm;
- 3.0 mm.

During the experiments, the value of the opening time of the firing valve (t_{ON}) has ranged from 2.4 ms up to 11 ms. The thruster has been operated starting from a minimum pulse frequency of 5 Hz up to a maximum pulse frequency of 75 Hz. According to the Test Plan, the tests have been performed at the BOL pressure (10 bar) and at the EOL pressure (5 bar). Moreover, the engine has been operated also at 15 bar tank pressure in some specific operating conditions.

The typical dynamics of the combustion chamber of the PulCheR concept has been obtained in some configurations. The dynamics of the feeding system is almost fully compliant with the PulCheR concept up to the firing valve. The firing valve proved to fulfil the requirements of the PulCheR system. Therefore, the selected off-the-shelf firing valve can reach the target requirements for the PulCheR concept. In some configurations, the typical dynamics of the PulCheR concept has not been achieved and it can be tentatively attributed to the catalyst, less active than expected, or to the dead volume inside the injection system. Some plots of the firings are shown in Figure 5.17. The plots clearly show that sometimes the PulCheR behaviour has been achieved, whereas the change in some of the driving parameters (t_{on}, pulse frequency, catalyst and catalytic bed length) can cause the behaviour to totally differ from the expectations.

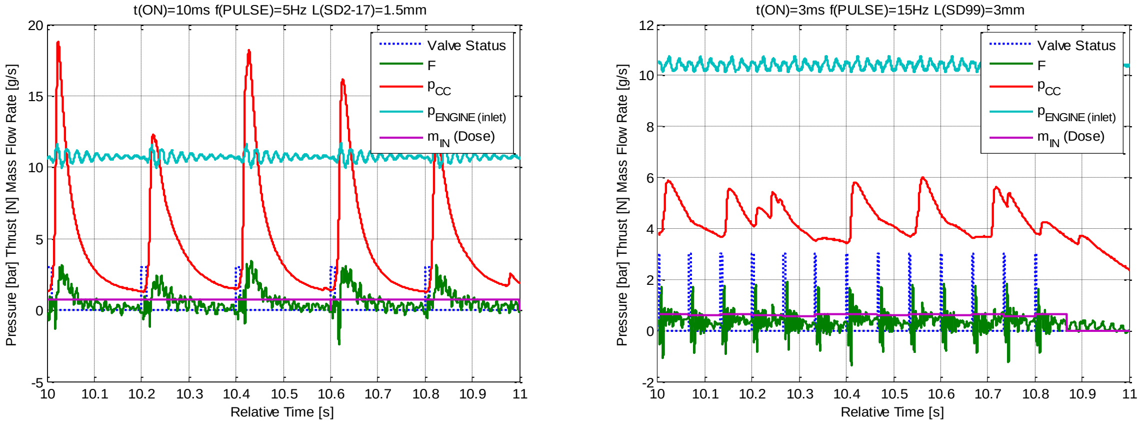


Figure 5.17 Some plots of the PulCheR monopropellant thruster at work. On the left a firing which resembles the PulCheR concept. On the right a firing which completely differs from the PulCheR concept.

The preceding tests campaign has clearly shown the feasibility of generating thrust by means of a system characterized by propellants feeding at low pressure and high frequency pulses. The specific impulse reached during the experiments, unfortunately, has not reached all the times the target value extrapolated in vacuum (185 s), even if in one case it has exceeded that value. Nevertheless the throttling level reached (higher than 5:1) has been astonishing and very easily achievable by means of just changing the pulse frequency.

The catalytic beds used during the experimental activity on the PulCheR monopropellant thruster have been chemically analysed by the Department of Chemistry and Industrial Chemistry of the University of Pisa in order to get information about the catalyst status, its poisoning and leaching. Some SEM images are shown in Figure 5.18. From the analyses, the catalyst has shown no leaching, but in all the cases the strong pulse mode has cause a breakage in the carriers. The catalyst is one of the crucial elements to be focused on, especially for the development of a strong enough carrier in terms of thermo-mechanical properties. Nevertheless the road taken is the right one and the PulCheR concept for green propellants seems feasible for real applications.

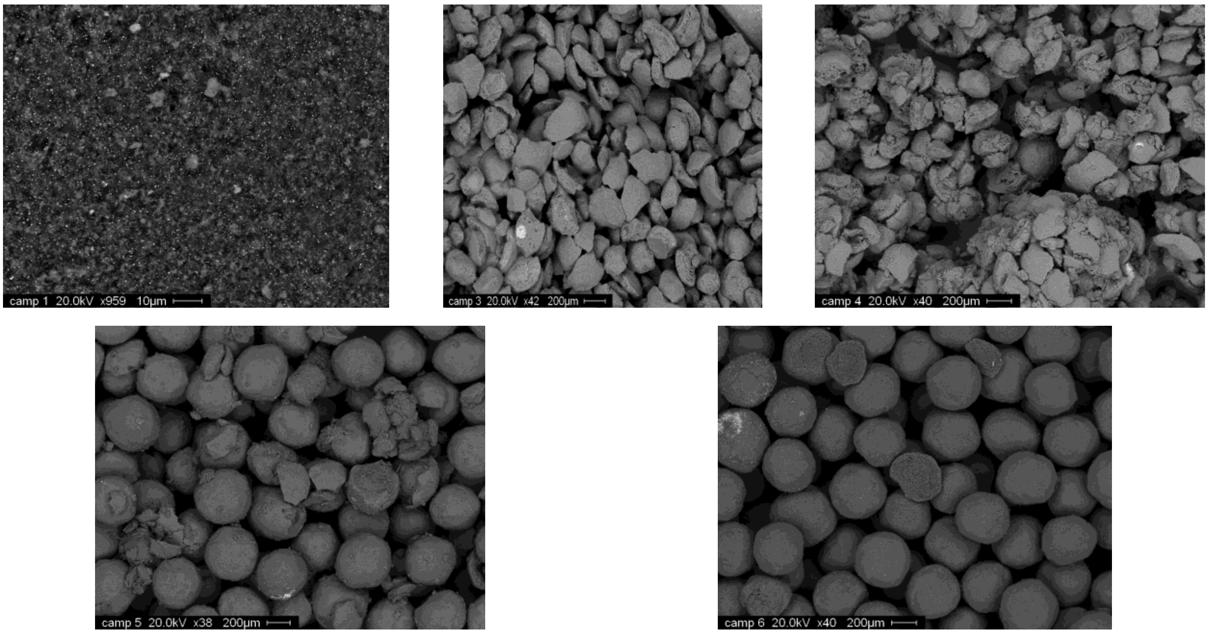


Figure 5.18 Some SEM images of the catalysts samples used in the experimental campaign with 98% HTP performed with the PulCheR monopropellant thruster.

5.4 Main results on the bipropellant system

As a consequence of the proof of non hypergolicity of hydrogen peroxide and propyne, two directions have been chosen for the development of the bipropellant side of the project. Institute of Aviation has been put in charge of the identification of some “green” fuels which are hypergolic with 98% HTP and, therefore, suitable for the PulCheR mode operation, whereas the development of the thruster driven by HTP and propyne has been further continued in order to improve the response time and the development of the materials for sustaining the hot temperatures inside the combustion chamber in such a way to be compliant with the typical requirements of a Reaction Control Thruster.

The Reaction Control Thruster powered by hydrogen peroxide and propyne was designed and successfully tested on the suitably designed bipropellant test bench (WP500 M.A.I.T. Bipropellant). Unfortunately, the premature failures of the combustion chambers developed in the framework of the PulCheR project by Demokritos, based on SiC and ZrO_2 innovative materials, did not allow to complete the Test Plan foreseen for the bipropellant system. However, the experimental results further confirmed the high propulsive performance of the selected propellants combinations. Moreover, the injection system for hypergolic combination with hydrogen peroxide was successfully tested by Institute of Aviation. In particular, MEA+$NaBH_4$ was identified as the best fuel and recommended to be used for the PulCheR concept. The main results can be summarized as follows.

Without a fast rise time, the bipropellant thruster with HTP and propyne would not be of interest for space propulsion. In order to pursue this goal, a 1 N HTP monopropellant thruster has been specifically designed as a test bench for enhancing response time and lifetime of the catalyst (see Figure 5.19). The thruster has been designed as a classical monopropellant thruster with a stand-off configuration and the propulsive performance has been assessed. Particular interest has been devoted to the assessment of the rise time and the lifetime.

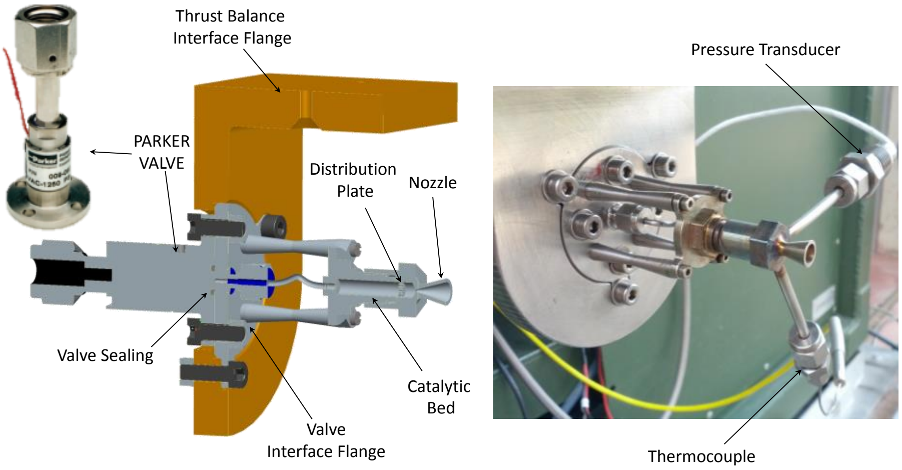


Figure 5.19 The 1 N HTP monopropellant thruster. On the left a 3D cad rendering. On the right the thruster during the test campaign.

The results of the experiments (some of those are shown in Figure 5.20) are very promising. The design of the catalytic bed allows a thruster rise time lower than 100 ms and the steady state time is reached very fast also in pulse mode. The cumulative firing time has overcome 500 s. The post-test analyses performed on the catalyst have clearly pointed out the very good performance of the catalyst, with no leaching and no pellets breakage. Given the limited time for the development of the catalyst during the project, a TRL 4 can be considered as achieved.

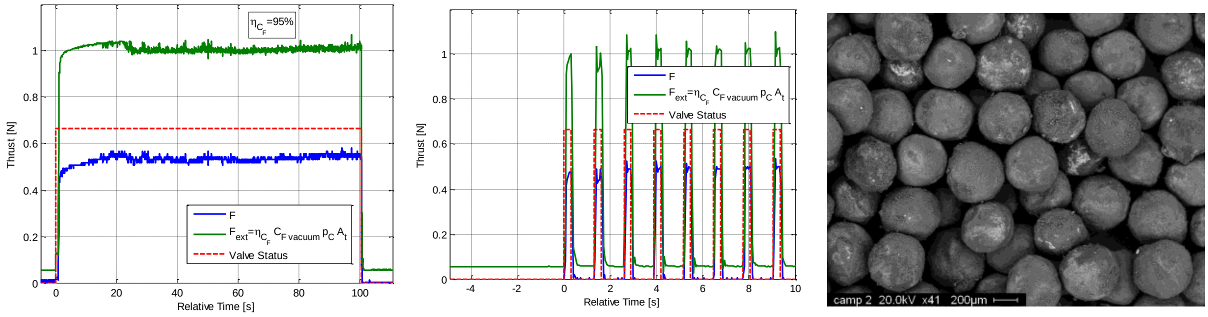


Figure 5.20 Examples of thrust performance of the 1 N HTP monopropellant thruster in steady-state conditions (on the left) and in pulse mode (on the mid). A SEM image of the catalyst after the firing tests (on the right).

By exploiting the outcomes of the test campaign on the 1 N HTP monopropellant engine, the bipropellant thruster with HTP and propyne has been so re-designed. New targets with respect to the beginning have been set for the bipropellant thruster. In particular the thruster has been designed in order to behave as a reaction control thruster with conventional feeding pressure and with the possibility of both exploiting the steady-state and the pulse mode operations. The main characteristics of this new thruster are:

- type of thruster: Reaction Control Thruster
- thrust level: 20 N
- selected propellants: C_3H_4+H_2O_2

- no PulCheR concept (low feeding pressure, high frequency pulses);
- conventional feeding pressure level;
- steady state operation with high specific impulse (target value I_{sp} vacuum>290 s);
- pulse mode operation with high frequency pulses (target value I_{sp} vacuum>245 s);
- desired target single burn time: > 15 hour (in the test the bipropellant engine will be tested only for a t_{ON} > 25 s that will assure to reach the steady-state condition of the temperature of the material of the radiative thrust chamber).
- "staged" combustion with first injection of HTP through a catalytic bed and successive injection of propyne for reaction with hydrogen peroxide decomposition by-products.

Given the research level of the project, many of the components used for the thruster working and its monitoring have been taken from the market. In particular the firing valves have been chosen by Moog-Bradford among the firing valves already used in the space market. Indeed the Moog 52-204B solenoid valves have been chosen as both the oxidizer and the fuel firing valves. These valves have been tested and they have resulted to be compliant with the requirements and with the selected propellants even if with some concerns for long time exposure to HTP. Some tests performed on the wetted material of the monopropellant valve (the same material is used for the bipropellant valves) have been performed at Institute of Aviation and they have demonstrated the good compatibility with HTP for short term period.

In order to test the thruster, a specific test bench has been designed. In particular the test bench is partly the same already used in the PulCheR monopropellant thruster with the addition of a bench for supporting the feeding line for the fuel. The two benches have been designed to store the propellants, to safely manage them during all the working phases, and to monitor their status by means of pressure transducers, thermocouples and turbine flowmeters. The test bench includes also the thrust balance, specifically designed and equipped with a load cell for assessing the pulse mode behavior foreseen for the PulCheR concept (see Figure 5.21).

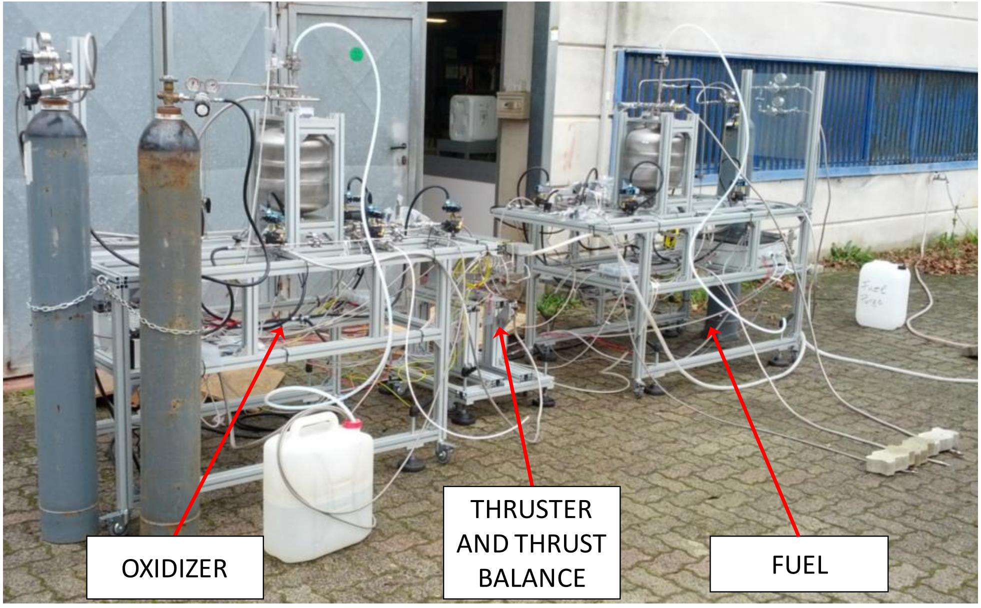


Figure 5.21 The test bench for the bipropellant thrusters.

Given the very high temperature expected for propellants combustion and the very low limit temperature for the firing valves, a stand-off configuration has been used for both the firing valves. Nevertheless, the design of the thruster has been focused on the reactivity of the system in order to exploit also the pulse mode. In pursuing this goal some aspects have been considered:

- specific design of the catalytic bed;

- integration of a bed heater;
- specific design of the combustion chamber, in particular the characteristic length of the chamber has been reduced w.r.t. the one tested in the thruster prototype;
- reduction as much as possible of the propellants feeding lines from the firing valves to the combustion chamber;
- possibility to change the propellants injector;
- limit the suspended mass in order to avoid an error measurement in the thrust assessment due to the vibration frequency of the thrust balance structure.

A cut-out rendering of the bipropellant thruster is shown in Figure 5.22 together with a picture of the real thruster assembled on the thrust balance.

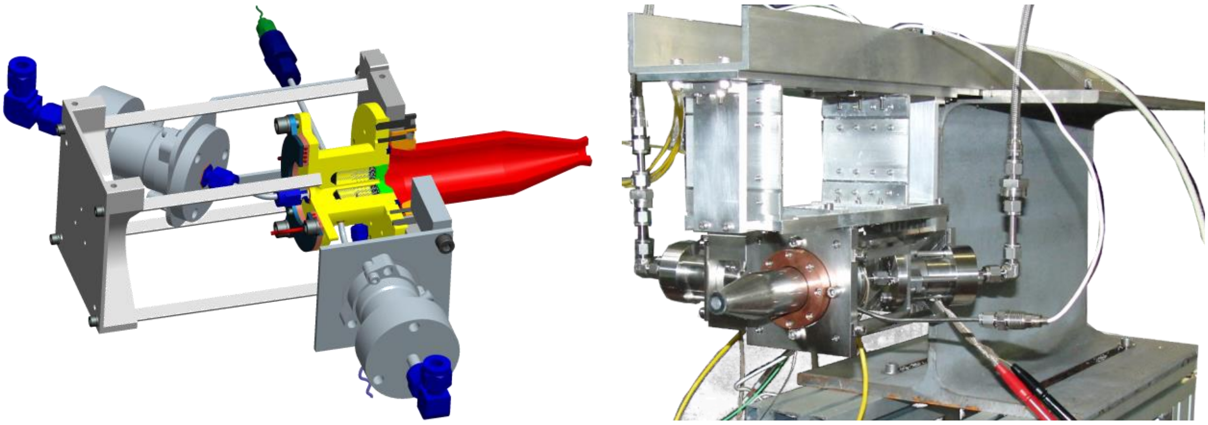


Figure 5.22 On the left a 3D rendering of the thruster. On the right the bipropellant thruster assembled on the thrust balance.

The tests on the new bipropellant thruster have been performed by using the combustion chambers developed by Demokritos in the framework of the PulCheR project. Two types of combustion chambers have been manufactured and their pictures are reported in Figure 5.23.

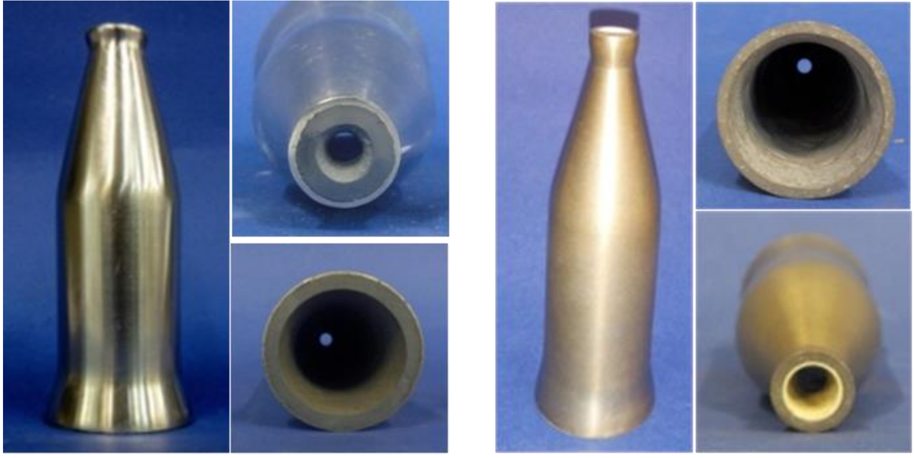


Figure 5.23 The two types of combustion chambers developed and manufactured by Demokritos. On the left the SiC-based combustion chamber with the outer layer made of Molybdenum. On the right the ZrO_2-based multilayer material.

Unfortunately all the tested combustion chambers, for a total amount of 4 samples, have registered a failure with either a final explosion of the chamber or the expulsion of part of it after, at most, a few seconds (less than 5 s) from mixture ignition. Some pictures of the firing tests are shown hereafter (Figure 5.24) together with the final picture after the failure.

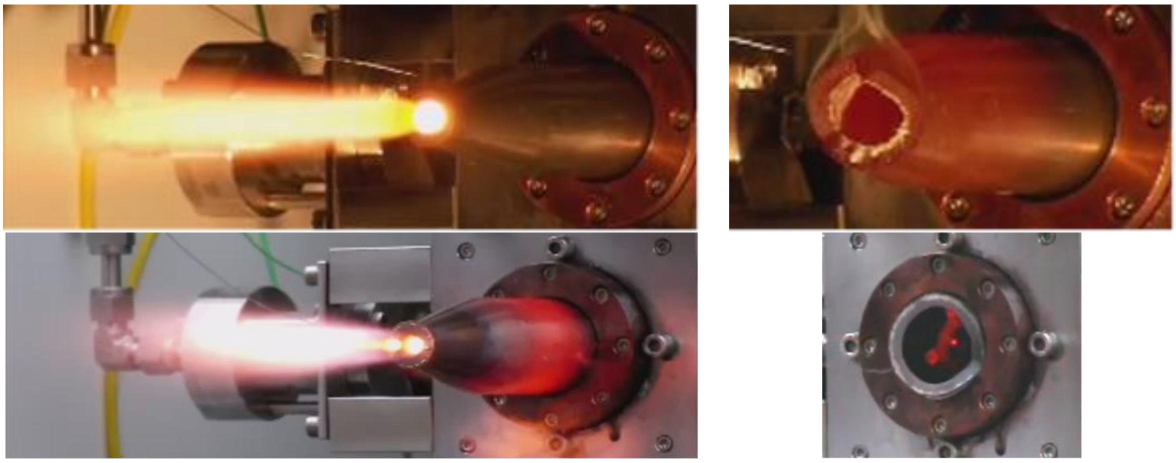


Figure 5.24 Some pictures of the firing tests performed on the bipropellant thrusters. On the top the ZrO_2-based multilayer combustion chamber. On the bottom the SiC-based combustion chamber.

Despite the combustion chambers failures, the propulsive performance registered during the tests has been as expected for the combination of HTP and propyne. Once propyne is injected, the combustion is effective almost immediately (a few milliseconds for rise time), whereas the steady-state of the monopropellant mode is reached in cold conditions after almost 900 ms due to the large combustion chamber after the catalytic bed. Even if the value of the transient for the monopropellant mode is still high, an improvement can be still achieved by some changes of the catalytic bed. Concerning the combustion chamber materials, a deep failure analysis has shown the key points which have to be improved. In particular, some cracks seem to be the probable origin of the chambers failures. They have been probably caused by the chamber docking system or they have been present since their manufacturing. Nonetheless the chambers debris have shown no melting of the material, thus confirming the goodness of the selected material, whose manufacturing process and technology still needs to be improved for avoiding these micro-cracks and for a better respect of the design characteristics. Indeed, one of the crucial points arisen during the manufacturing of these chambers is the difficulty in shaping the ceramic materials for very small radii, as those present in the nozzle throat.

At the same time Institute of Aviation has investigated in depth hypergolic combinations with HTP. In particular some fuels have been identified as hypergolic with HTP after their mixing with metal transition salts and metal hydrides, even if the ignition delay time (IDT) of the reaction can be widely spread. Institute of Aviation has prepared and tested more than 80 samples of fuels by using 24 types of catalyst additives and 4 types of hydride additives (some samples of fuels are shown in Figure 5.25).

Figure 5.25 Some samples of fuels mixed with either catalyst additives or chemically active hydrides.

The assessment of the IDT of the reaction between the prepared fuels and HTP has been performed by drop tests (Figure 5.26).

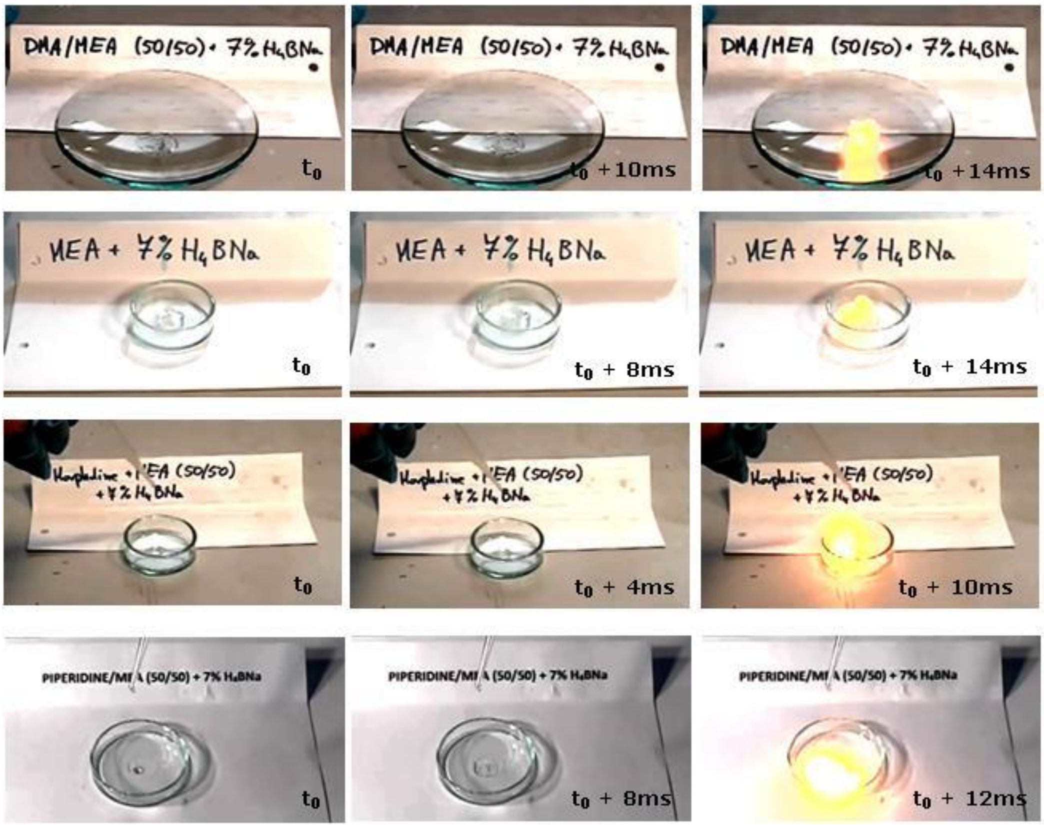


Figure 5.26 Drop tests of the fuels promoted by hydride additives on HTP.

From this tests, two selected candidates (MEA+4% $CuCl_2$ and MEA + 7% $NaBH_4$) have been subjected to further investigations, using pressurized injection system. These fuels are both made of ethanoloamine (MEA) doped with either a catalyst for HTP ($CuCl_2$) or a reacting agent for HTP ($NaBH_4$). Ignition delay time for the former combination has showed repeatable values in the range 10-16 ms, whereas the latter combination has shown an IDT of about 6-16 ms.

The impinging tests of MEA mixed with 4%$CuCl_2$ in contact with HTP have shown that fast, reliable and safe ignition is not possible. Two sizes of injectors have been used and almost all the performed tests have indicated that stable and repeatable, hypergolic ignition is not possible.

Impinging tests of MEA+7% $NaBH_4$ with HTP have shown that repeatable and very stable hypergolic ignition is possible, even for long time injections (at least 5 s), as shown in the pictures of Figure 5.27.

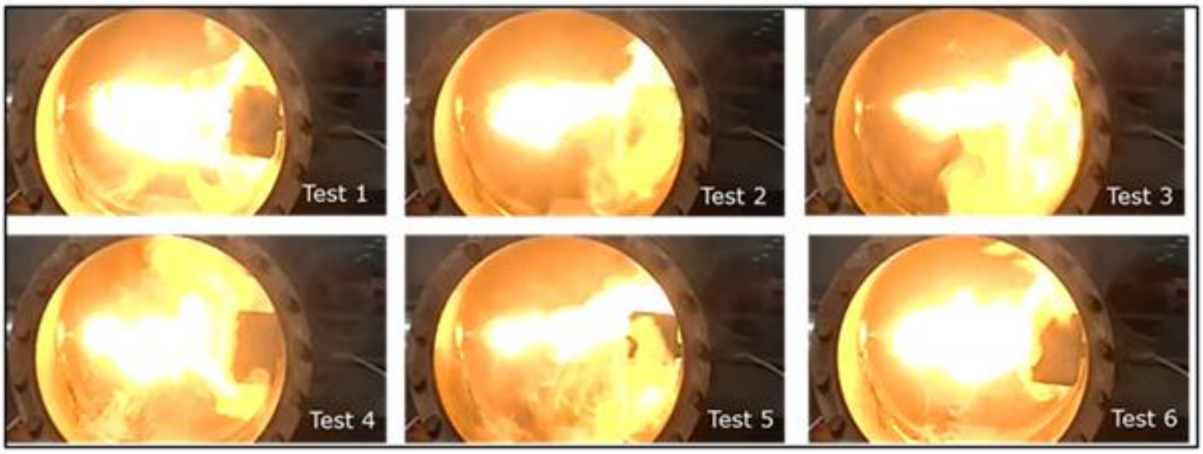


Figure 5.27 Long combustion tests of MEA/7% $NaBH_4$ + HTP.

5.5 Conclusion

All the main results of the PulCheR Project have been critically analyzed according to the main performance/research indicators previously identified for the PulCheR Project:

- the feasibility of the PulCheR concept has been demonstrated through the test campaign performed on the PulCheR monopropellant thruster even if with some issues on some points;
- concerning the assessment of high performance green propellants combination, the selected green propellants for both the monopropellant and bipropellant configurations have been able to exceed the target values in terms of specific impulse;
- the throttling level for the PulCheR monopropellant thruster has been higher than 5:1 while the target value for the MIB has been partially achieved because of low propulsive performance.
- the selected materials for the combustion chambers have prematurely failed during the experiments. However, the main reasons of these failures have been identified together with some possible solutions.

For both the PulCheR monopropellant and bipropellant thrusters, the foreseen roadmap has been clearly defined in a two steps development: a short term (0 – 2 years) and a middle term (2 – 5 years) phase. In the short term phase, the attention has been directed towards the identification of the materials compatibility, the choice of the farther fluidic components and the optimization of some components design (such as the tank and the thruster), necessary for reaching a higher TRL propulsion system, by increasing the lifetime and the operating requirements for a flight type thruster. For the middle term phase, the identified targets for both the monopropellant and the bipropellant thrusters have been the same and, specifically, they have been the winning of bids for demonstration missions, the detailed design of a propulsion system flight type (CDR status) and the final qualification. HTP short storability has been identified as one of the biggest issues to be resolved. The life of fast moving valve (firing valve) is also a big issue for PulCheR system to be used in space propulsion system.

6 Potential impact

The testing and validation of the prototypes developed in the framework of PulCheR will bring up a radical change in the idea and concept of the propulsion systems for space applications. New frontiers of research will be opened for virtually all the propulsion system components, due to the new concepts developed for the thrust generation (pulsed operation) and for the feeding system. New avenues of research will be opened by PulCheR also in the field of high performance green propellants, with identification of potential applications of new propellants (e.g., the propyne). In the PulCheR concept, due to the elimination of any pressurization system external to the thruster, it will be possible to achieve higher combustion chamber pressures w.r.t. the present state-of-the-art, with possible improvements in the propulsive performance. The thruster design will become independent on the feeding system characteristics (as, for instance, the tanks size), thus giving the possibility to employ the same thruster for significantly different applications without any particular design modifications; the consequent design simplifications would be greatly helpful, especially in the future research for re-usable vehicles. With a sufficiently elevated pulse frequency, the generated thrust will be practically continuous even under pulsed operation conditions. In this case, thrusters based on the PulCheR concept are likely to be used also in all the missions for which continuous thrust is required (launch, lift-off, landing), thus extending its intrinsic advantages (smaller weight, good performance even with “green” propellants, components reduction) to these missions.

The PulCheR consortium gathers partners from 6 different EU countries (Italy, France, Germany, Netherlands, Poland, and Greece) plus 2 non-EU space powers (United States and Japan). The internationality of the consortium is therefore clearly evident and the project is expected to build up strong research alliances, both inside and outside Europe, which will most probably continue to be in-force after its conclusion. The borderline characteristics of the PulCheR concept and its potential enormous impacts on the space propulsion sector in case it is successfully validated do not consent to carry out the project simply at local level. PulCheR is a project concerned with all the main components of a typical propulsion system for space applications, and an effort has therefore been necessary to gather the available expertise throughout all countries inside (and even outside) Europe.

In addition, the exploitation of project results is expected to be much more effective if the “global” market (not just the local one at the level of one single European country) is addressed.

One of the most important expected impacts of PulCheR will be the identification of effective substitutes for the hydrazine and its by-products as space propellants. A significant enforcement of this impact will be represented by the necessity of the space industry to take in due account the recent amendments to the EC REACH (Registration, Evaluation, Authorization and Restriction of Chemicals), in which hydrazine and dimethyl hydrazine have been identified as potential carcinogens and a reduction of their industrial use has been firmly requested.

The steps needed to bring about these impacts are:

- demonstration of feasibility of the PulCheR concept;
- selection, trade-off and characterization of high performance green propellants;
- further improvement of the TRL of the PulCheR propulsion system (after the conclusion of the project) up to flight qualification;
- application of the PulCheR propulsion system in small satellites or other vehicles in space;
- application of the PulCheR concept in vehicles requiring continuous thrust (launch, lift-off, landing).

7 Main dissemination activities

In order to guarantee the internal circulation of information inside the Consortium (and, to a certain extent, between the Coordinator and REA) a password-protected Document Management System (DMS), set-up by the Coordinator at the beginning of the project (see AD35), has been extensively used during the project for sharing documents, deliverables drafts and storing the final version of the documents.

According to the dissemination plan, the external circulation of information on the PulCheR project has been ensured via a number of different communication tools.

First of all, the official website dedicated to the PulCheR project, designed by the Coordinator in the first part of the first reporting period (see AD35), has been periodically updated by the Coordinator during the course of the project. The PulCheR website is available online at http://www.alta-space.com/pulcher and it is the first entry on the Google search engine when "Pulcher FP7" string is inserted. The official webpage reports project information not protected by IPR or deemed confidential.

PULCHER PDR1 MILESTONE ACHIEVED

24 Jan
Posted by: lucio
Category: General

The first Preliminary Design Review meeting has been successufully held on January 23rd.

More →

PULCHER ON THE 5TH CALL BROCHURE 'BEYOND THE SKY'

11 Nov
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The 5 th call brochure ' Beyond the Sky 'is now available .

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Page 1 of 4 > >>

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The PulCheR (Pulsed Chemical Rocket with Green High Performance Propellants) project, funded by the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n°313271, officially started as of January 1st, 2013.

PulCheR is a new propulsion concept 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.

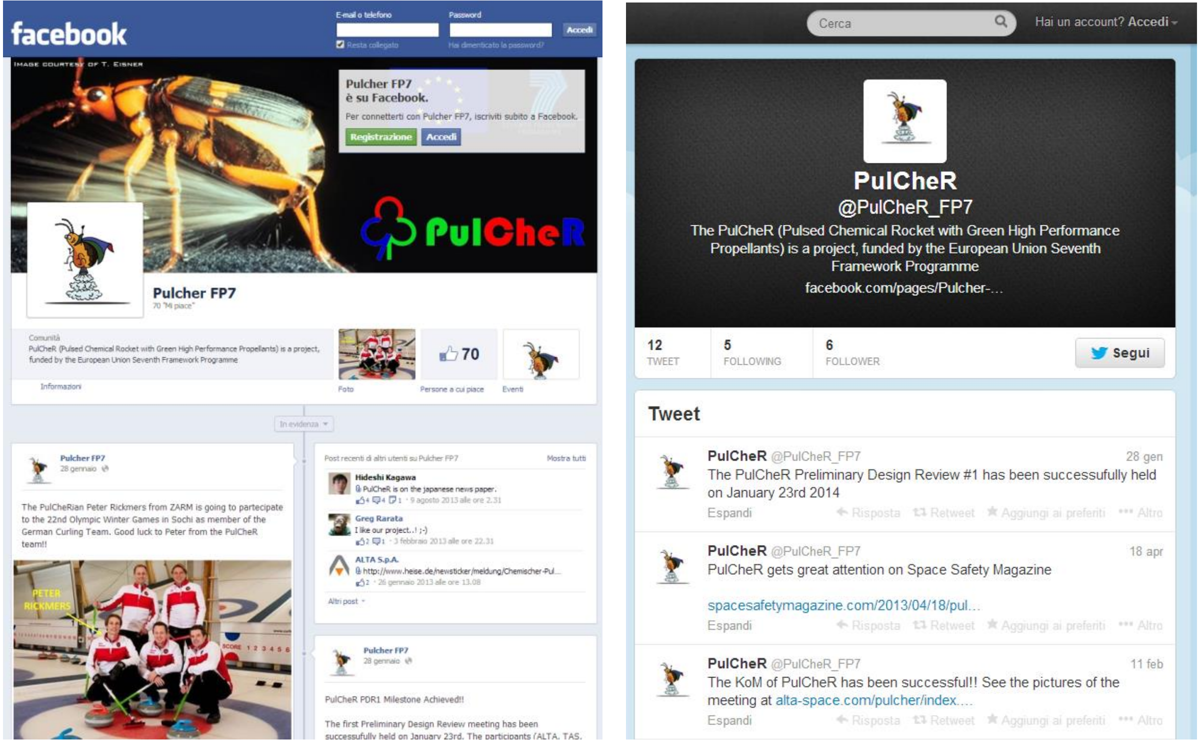
Next page: Objectives

PulCheR (Pulsed Chemical Rocket with Green High Performance Propellants) is a project funded by the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n°313271.

The PulCheR Mascotte has been created by Valentina Berti.

Figure 7.1 PulCheR website HOME page.

In addition to the PulcheR website, a dedicated web page has been created on the two major social networks, such as Twitter (https://twitter.com/PulCheR_FP7) and Facebook (https://www.facebook.com/pages/Pulcher-FP7). The Facebook web page has been periodically updated by the Coordinator whereas it has been decided not to update the Twitter one due to the minor impact of this social network. It is worth noticing that the PulCheR Facebook page is the third entry on the Google search engine when "Pulcher FP7" string is inserted. The content of the Facebook webpage is less formal than the official PulCheR website. The PulCheR website is promoted through the Facebook web page and vice versa.



Pulcher FP7
è su Facebook.
Per connetterti con Pulcher FP7, iscriviti subito a Facebook.

Pulcher FP7
70 "Mi piace"

Comunità
PulCheR (Pulsed Chemical Rocket with Green High Performance Propellants) is a project, funded by the European Union Seventh Framework Programme

70

Pulcher FP7
28 gennaio

The PulCheRian Peter Rickmers from ZARM is going to partecipate to the 22nd Olympic Winter Games in Sochi as member of the German Curling Team. Good luck to Peter from the PulCheR team!!

Post recenti di altri utenti su Pulcher FP7

Hideshi Kagawa
PulCheR is on the japanese news paper.
4 4 1 · 9 agosto 2013 alle ore 2.31

Greg Rarata
I like our project..! ;-)
2 1 · 3 febbraio 2013 alle ore 22.31

ALTA S.p.A.
http://www.heise.de/newsticker/meldung/Chemischer-Pul...
2 · 26 gennaio 2013 alle ore 13.08

Pulcher FP7
28 gennaio

PulCheR PDR1 Milestone Achieved!!

The first Preliminary Design Review meeting has been successfully held on January 23rd. The participants (ALTA, TAS,

PulCheR
@PulCheR_FP7
The PulCheR (Pulsed Chemical Rocket with Green High Performance Propellants) is a project, funded by the European Union Seventh Framework Programme
facebook.com/pages/Pulcher-...

12 TWEET | 5 FOLLOWING | 6 FOLLOWER

Tweet

PulCheR @PulCheR_FP7 28 gen
The PulCheR Preliminary Design Review #1 has been successfully held on January 23rd 2014

PulCheR @PulCheR_FP7 18 apr
PulCheR gets great attention on Space Safety Magazine
spacesafetymagazine.com/2013/04/18/pul...

PulCheR @PulCheR_FP7 11 feb
The KoM of PulCheR has been successful!! See the pictures of the meeting at alta-space.com/pulcher/index....

Figure 7.2 Screenshots of the PulCheR Facebook (left) and Twitter (right) web pages.

According to the dissemination plan, three dedicated workshops on the PulCheR project have been held in the framework of the PulCheR project.

The first PulCheR workshop was organised in conjunction with the VIII International Scientific Conference "Development Trends in Space Propulsion Systems" (Institute of Aviation, Warsaw, October 18th, 2013) and it consisted of one plenary session with high-level speakers from members of the PulCheR project and a posters session. During the oral session the Coordinator (SITAEL) and the partners attending the workshop (TAS, JAXA, IoA and ZARM) presented the project, its main objectives, its current status, the PulCheR Consortium and the tasks sharing among the partners, the impact of REACH Legislation concerning Hydrazine on the European Space Industry and the dissemination activities planned for the incoming future. DCCI and DEMOKRITOS, even if not attended the workshop, contributed to the oral session by sending a video message. Seven posters have been presented to the posters session by SITAEL, TAS, JAXA, IoA, DEMOKRITOS, ZARM and DCCI.

The second workshop consisted in the presentation of the project in occasion of the European Space Expo held in Genoa (Italy) from October 24th to November 2nd 2014. During the workshop the PulCheR official brochures and the PulCheR stickers have been distributed.

The final close-out workshop was finally held on the 7th of September 2015, in occasion of the 5th CEAS Air & Space Conference in Delft (The Netherlands). The oral plenary session with high-level speakers from members of the PulCheR project (SITAEL, JAXA, ZARM) was supported also by a posters session by JAXA, ZARM, TAS, DEMOKRITOS and DCCI.

Concerning the scientific publications (see LIST OF SCIENTIFIC PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES in Section 4.2 of the Final Report), all along the project fourteen papers have been prepared and presented to scientific international conferences. In particular, the papers presented have been: one to the Joint Propulsion Conference 2013, and one to the VIII Development Trends in Space Propulsion Systems Conference 2013, three to the Space Propulsion Conference 2014, one to the METECH 2014, five the Joint Propulsion Conference 2015, two papers to the 5th CEAS Air & Space Conference 2015 and one at the IAC 2015. Moreover, one paper has been accepted for publication in the AIAA Journal of Propulsion and Power (03/02/2015).

In addition to the PulCheR project logo it has been decided to create also an official mascot, named PulCheR. It has been conceived by SITAEL's team but it has been first drawn and then manufactured in Fimo polymer clay (see Figure 7.3) by two supporters of the project (Miss Valentina Berti and Miss Eleonora Torre). The mascot is a funny representation of a bombardier beetle, the insect whose defence mechanism inspired the project. It is intended as a comic superhero, with a cloak coloured green-blue-red, the same colours of the PulCheR logo, and propelled by a pulsating chemical thruster.

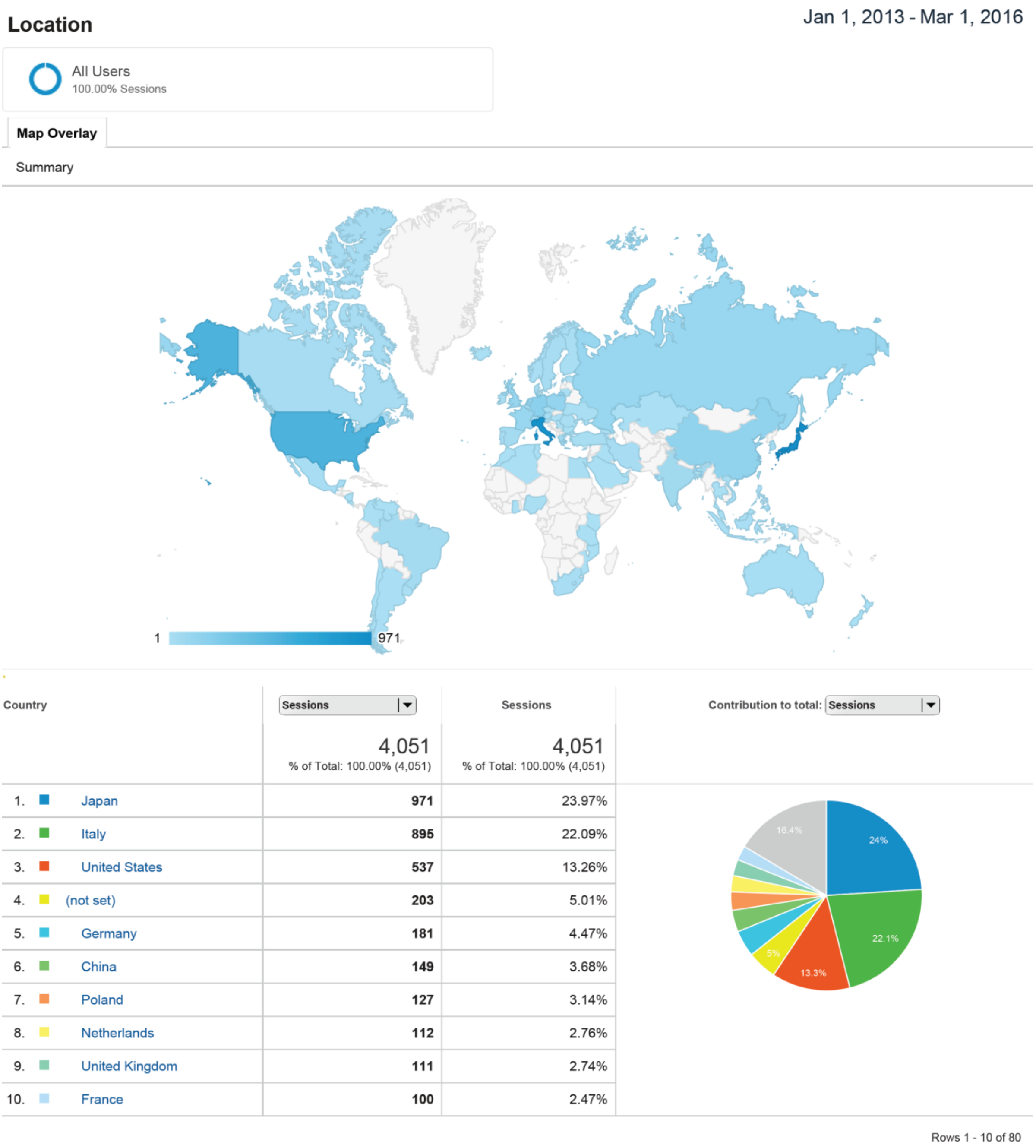
Figure 7.3 The PulCheR mascot: a drawing (left) and a model in Fimo (right).

During the course of the project, especially in its first part with the aim of promoting the kick-off of the activities, the dissemination involved also mass-media such as newspapers and magazines, and TV/radio broadcast shows (intended for scientific divulgation).

Moreover a series of news and short articles on the PulCheR project has been promoted on the web pages of the partners participating to the Consortium. All these dissemination activities are summarised in the table named LIST OF DISSEMINATION ACTIVITIES in Section 4.2 of the Final Report.

Finally, the web site address has been reported on the official brochures and on the posters produced during the dissemination activities. The web site address has been reported on the official PulCheR stickers distributed at the Space Propulsion Conference 2014 and at the European Space Expo 2014. The QR-code of the PulCheR website has been created and inserted into the produced brochures, posters and stickers.

Figure 7.4 QR-Code for redirecting to the PulCheR website.



Location

Jan 1, 2013 - Mar 1, 2016

All Users
100.00% Sessions

Map Overlay

Summary

Country	Sessions	Sessions	Contribution to total: Sessions
	4,051 % of Total: 100.00% (4,051)	4,051 % of Total: 100.00% (4,051)	
1. 🟦 Japan	**971**	23.97%	
2. 🟩 Italy	**895**	22.09%	
3. 🟥 United States	**537**	13.26%	
4. 🟨 (not set)	**203**	5.01%	
5. 🟦 Germany	**181**	4.47%	
6. 🟩 China	**149**	3.68%	
7. 🟧 Poland	**127**	3.14%	
8. 🟨 Netherlands	**112**	2.76%	
9. 🟩 United Kingdom	**111**	2.74%	
10. 🟦 France	**100**	2.47%	

Rows 1 - 10 of 80

Figure 7.5 Worldwide distribution of the connection sessions to PulCheR website.

Figure 7.6 PulCheRians...

8 Exploitation of results

During the three years of the project, a lot of tests have been performed. The research activities have focused on the development of a new propulsion concept (PulCheR) for both monopropellant and bipropellant thrusters. The concept exploits the unsteady pulse mode in order to reduce the thruster feeding pressure. One of the crucial points of the project has also involved the identification and use of “green” propellants which will be able to substitute actual toxic propellants. In particular for the monopropellant thruster, hydrogen peroxide at high concentration (> 98% by weigth) has been selected as propellant, whereas for the bipropellant thruster the combination of hydrogen peroxide and propyne has been selected.

Some of the most interesting results of the project for the space propulsion application are the following:

- HTP monopropellant thruster can be considered for compact systems, but they are not the optimum for high ΔV missions, because of resulting propellant mass penalty;
- HTP can be stored only for a limited period, but its use is so limited to short term missions;
- HTP monopropellant system can be used in fine attitude control applications;
- HTP and propyne are not hypergolic but they can be effectively ignited by staged combustion;
- high exhibited specific impulse for propyne/HTP combination can be seriously considered for compact systems and for high ΔV missions;
- some alternative fuels to propyne have been found hypergolic with HTP, in particular ethanoloamine (MEA) seems the most promising choice;
- bipropellant system with the selected propellants can be used just for short term missions because of HTP storability issues.

A survey of the future and on-going missions in Europe and in Japan has been performed by Thales Alenia Space and JAXA. The comparison between the missions requirements and the characteristics of the PulCheR monopropellant thruster and the bipropellant thruster has allowed to identify some of their possible applications.

The on-going missions are mostly concentrated in some areas:

- launchers;
- earth observation;
- space exploration & observation;
- telecommunication;
- carrier & cargo;
- other (experiments in space…).

Most of the on-going and future missions are designed for in-flight lifetime of at least 5 years, which could be jeopardized by long term HTP storability issue.

However, the following missions can be considered:

- launchers and carrier & cargo missions are well suited because their required in-flight lifetime is much less than 5 years (less than 1 year);
- landers to solar system planets can also be considered if the crew time is typically less than 1 year;
- private business and market for human spaceflight (space tourism) and cargo.

Possible missions for the PulCheR monopropellant system require limited in-flight lifetime and ΔV.

Some possible applications in the European frame are the attitude control system for Ariane 6 and Vega C as well as the reaction control system for PRIDE. Other applications can be in ADR (Active Debris Removal) and the RCS for the braking manoeuvres of landers on solar system planets.

The main features of the mentioned missions are summarized in the following Table 5.1.

<table>
<tr><th colspan="2">Ariane 6</th></tr>
<tr><td></td><td>Ariane 6 launcher is now under development as Europe’s new heavy-class launcher with a first launch scheduled in 2020.
The targeted payload performance of Ariane 6 is over 4.5 tons for polar/Sun-synchronous orbit missions at 800 km altitude. Ariane 6 can lift a payload mass of 5–10.5 tons in equivalent geostationary transfer orbit.
The Attitude Control System (ACS) is planned to use storable monopropellant propulsion system. Although hydrazine is a strong candidate for the propellant, green propellant also would be applicable because of REACH regulation.</td></tr>
<tr><th colspan="2">VEGA C</th></tr>
<tr><td></td><td>Vega is Europe’s small launcher with a current payload performance of 1.5 tons for circular orbit, 90°inclination, 700 km.
A more powerful version of the Vega launcher is in development, the Vega C.
As for Ariane 6, VEGA will favour monopropellant propulsion systems for attitude control, with great emphasize for green propellants.</td></tr>
<tr><th colspan="2">PRIDE</th></tr>
<tr><td></td><td>PRIDE is ESA’s Programme for Reusable In-orbit Demonstrator in Europe.
It is aimed to improve European know-how in critical re-entry technologies domain, focusing on system and technology performance verification in all flight conditions. This will be achieved through an end-to-end European orbital mission with landing on a conventional runway.
RCS using monopropellant propulsion system should be considered. Moreover, the demonstration purpose of PRIDE makes it suitable for new green propellant in-flight demonstration.</td></tr>
<tr><th colspan="2">ADR (Active Debris Removal) for low Earth orbit</th></tr>
<tr><td></td><td>ESA is actively pursuing technologies and systems for space debris removal in the critical LEO area under its Clean Space initiative. One of the activities is aimed to develop systems for de-orbiting debris that can be allowed to re-enter in an uncontrolled manner.
The short-term goal and main driver for the current technology developments is to achieve sufficient TRL on required technologies to support a potential de-orbit mission to remove a large and strategically chosen piece of debris.
Monopropellant propulsion systems with green propellant are considered.</td></tr>
</table>

Table 8.1 Some of the european missions which can be exploited by PulCheR concept thrusters.

Both Ariane 6 and VEGA C programs for sure will favor mature technologies because of their short-term schedules, so PulCheR propulsion system will not be considered for these applications in a short-term period.

Some applications in the Japanese market could be envisaged in the Lunar Landing mission, given the throttling capability for the PulCheR thrusters, the low time mission and the transparent plume for the HTP decomposition by-products which is compatible with some optical instrumentations.

For bipropellant thrusters with “staged” combustion the possible market concerns the huge satellites which require controlled re-entry for deorbiting as well as high thrust for orbit transfer. For huge satellites, attitude control could be provided by HTP monopropellant thrusters as well.

Some on-going programs in Europe have been initiated such as EASE (CNES) and Space Tug (ESA) programs, but they are currently considering electric propulsion system rather than chemical propulsion systems. On the Japanese side, some missions could be achieved with the “dual” mode thruster, like the H-II transfer vehicle (HTV) which could exploit the PulCheR thruster modulation for a fine control during the necessary rendez-vous maneuver around the ISS as well as the high I_{sp} for more payload mass.

Even if the PulCheR concept could be exploited in some future missions, some issues must be solved before it can be used in real space applications. A list of the main issues to be faced is summarized in Table 8.2.

Issues	Details
Cost reduction	The costs of space qualified components (e.g. valve, tank…) are too high for small satellite users. Cost reduction is needed if PulCheR propulsion system is used on small satellites
Thrust level	Thrusters of each thrust levels should be developed. - 50N class thrusters are usually used in Japanese launch vehicles - 1N, 4N, and 20N class thrusters are usually used in LEO satellites
Heat soak back	In low frequency pulse mode, heat soak back issue is concerned, because the length between valve and chamber in PulCheR thrusters are shorter than that of the conventional hydrazine thruster
Repeatability	Repeatability of each impulse bit is important for fine satellite control
Utility maximization of low pressure feed system	PulCheR's low pressure feed system seems big advantage compared to the conventional thrusters. This advantage should be exploited by using: - COTS for fuel tank and feed line - Aluminum tank may be applicable. (It melts by re-entry.)
Storability of HTP	Long term storability of HTP should be assessed and guaranteed for long term missions
Plume assessments	The plume of hydrogen peroxide itself is clean and very interesting for applications on scientific satellites. However, the following assessments should be conducted: -The effect of HTP's stabilizers on plume -The effect of MEA's sensitizer on plume -The plume assessment of HTP and propyne (or MEA) combustion.
Life of firing valve	Fast moving valve seems to be a critical component for thruster's life (the life in the case of high-frequency mode is probably much shorter than in the case of normal use)
Life of Catalyst	High-frequency pulse operation seems tough condition for catalyst
PulCheR concept for bipropellant	High-frequency pulse operation should be achieved also in bipropellant system

Table 8.2 Main issues to be faced by the PulCheR concept to be exploited in real space applications.