CubeSAT HTP Innovative Propulsion System (CHIPS)

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Prepared by:	S. Calatafimi, Researcher	E. Puccinelli, Researcher	A. Pasini, Project Manager	
Agreed by:	A. Pasini, Project Manager		Approved by:	A. Pasini, Project Manager

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Authors	Organization	Address
Stefano Calatafimi; Elia Puccinelli; Angelo Pasini	University of Pisa Department of Civil and Industrial Engineering	Largo Lucio Lazzarino, 2 56122, Pisa, Italy

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Thomas Searle	ESTEC - European Space Research and Technology Centre	4000132061/20/NL/RA	Keplerlaan 1 - P.O. Box 299 NL-2200 AG Noordwijk ZH, The Netherlands

Abstract

This document represents the CHIPS project Executive Summary Report that concisely summarises the findings of the Contract.

Keywords

CubeSat; Green Propellant; Hydrogen Peroxide; Monopropellant; Chemical Propulsion; 3U; Test Rig

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List of Acronyms

Acronym / Abbreviations	Meaning
COTS	Component-Off-The-Shelf
HTP	High Test Peroxide
SPF	Small Plasma Facility
TRL	Technology Readiness Level

Nomenclature

Symbol	Quantity	Unit
T_{on}	Valve Opening Time	s
p_{in}	Thruster Inlet Pressure	bar
I_{sp}	Specific Impulse	s
c^*	Characteristic Velocity	m/s

1 Introduction

CubeSAT HTP Innovative Propulsion System (CHIPS) aims to design, manufacture and test a chemical propulsion system for CubeSat that uses hydrogen peroxide (H_2O_2) as Propellant. This propulsion system wants to be capable of offering propulsive capabilities in a wide range of scenarios and to different payloads as requested by the Agency.

1.1 Scope of the Document

This document represents the Executive Summary Report that concisely summarizes the findings of the CHIPS project funded by the European Space Agency.

2 References

Applicable Documents

[AD 1]	CubeSAT HTP Innovative Propulsion System (CHIPS) Detailed Proposal AO N. 1-10056, Issue 1.0, 15/11/2019
[AD 2]	Statement of Work ESA-TRP-TECMPE-SOW-015295, issue 1, revision 0, issued on 25th September 2019 (Appendix 1 to AO/1-10056/19/NL/RA)
[AD 3]	CHIPS Minutes of Meeting, UNIPI-CHIPS-MN-0, 09/07/2020
[AD 4]	CHIPS Answer to Negotiation Points, UNPDICI_CHP_NPN, Issue 2.1, 09/07/2020
[AD 5]	CHIPS Minutes of Meeting, UNIPI-CHIPS-MN-1, 15/03/2021

Reference Documents

[RD 1]	SP-01 System Requirements Specification, Issue 3.0, 29/03/2022
[RD 2]	SP-02: Major subsystems and critical equipment/components: requirements specifications and potential suppliers Issue3.0, 29/03/2022
[RD 3]	TN-01: System Design Justification File, Issue 2.0, 29/03/2022
[RD 4]	TN-02: Manufacturing, Assembly, Integration (MAI) Plan, issue1.0, 26/04/2022
[RD 5]	TN-03: Interface Control Document, issue1.0, 26/04/2022
[RD 6]	HW-UM: User Manual, issue1.0, 26/04/2022
[RD 7]	TP-01: Test Plan, issue2.0, 29/03/2022
[RD 8]	VCD: Verification Control Document, issue1.0, 29/03/2022
[RD 9]	TP-02: Test Procedure, issue1.0, 09/09/2022
[RD 10]	TR-01: Test Report, issue1.0, 23/01/2023
[RD 11]	FR: Final Report, issue1.0, 27/02/2023

3 Background and Scenario

Nowadays, CubeSats have become significant small satellite players in the space industry, thanks to their standard unit size, simplicity, and low cost. Their applications range from earth observation to scientific, technology demonstration, and communications missions. Moreover, the increasing trend to consider CubeSats for LEO orbits and mega-constellations has led to the need to provide this class of small satellites of propulsion system to enable their orbit maneuverability. Today, only a few nearly off-the-shelf European propulsion solutions exist fostering the need for research activities on new propulsion systems solutions. In this context, the European Space Agency (ESA) launched a call named "Innovative Propulsion System for CubeSats and MicroSats". The aim of this call is to identify the most promising European Propulsion Systems for CubeSats and MicroSats currently available at the technology concept level and assess its TRLs through developments and testing activities. The University of Pisa participated in this ESA call with the CHIPS project (CubeSat HTP Innovative Propulsion System), proposing a chemical monopropellant propulsion system for CubeSats that uses high-performance hydrogen peroxide (HTP) to 98% wt. as the propellant. Compared to electric propulsion systems, chemical ones have the advantage of providing a high thrust-to-weight ratio. This advantage allows the ability to enable impulsive maneuvers as well as attitude control. Moreover, chemical propulsion systems typically require low power consumption contrary to electric solutions. CubeSats present severe constraints in terms of power, volume, mass, and costs. Therefore, a chemical propulsion system represents an optimal solution to provide the maneuverable capability to this class of satellites.

4 Tasks and Outline of the Project

The aim of the ESA Invitation To Tender on which is funded the CHIPS project is to allow the Agency to identify the most promising European Propulsion System for CubeSATs and/or MicroSATs currently available at technology concept level and assess its TRLs through developments and testing activities, with the ultimate objective to minimize development risks before entering qualification, production and commercialisation phases. Throughout the execution of the activity, the Agency aims to boost the propulsion system Technology Readiness Level (TRL) to a level of ≥ 3 (analytical and experimental critical function and/or characteristic proof-of-concept). At completion of this activity the propulsion system shall:

- be complete in all its components
- be adaptable and scalable
- be designed to enable high level of integration
- respond to demanding satellite mass, volume and power constraints of a ≤ 16U CubeSATs (≤ 30 kg)
- deliver a thrust of ≤ 0.5N
- have a maximum weight of 10 kg if to be considered for MicroSATs

- have a target recurrent prize of <50k€ for CubeSATs and of <100k€ for MicroSATs,
- have a target delivery time of less than 6 months from ordering.

The propulsion system shall be subjected to test in order to confirm and/or increase their system TRL. The propulsion system shall be assessed in terms of performances, limitations and criticalities, at the ESA Propulsion Laboratory (EPL) in a dedicated facility or in another equivalent facility.

5 Propulsion System Design

5.1 CHIPS Flight Configuration Components

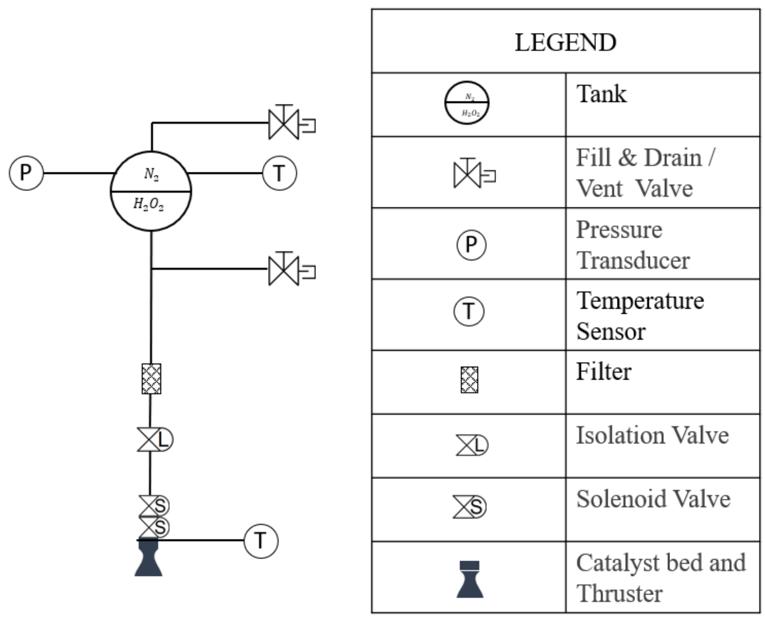

Figure 5.1:Schematic Representation of CHIPS Propulsion System

The CHIPS propulsion system is composed of one tank, two fill and drain valves, one filter, one isolation valve, two solenoid valves, one thruster, one pressure transducer, and two temperature sensors. The model philosophy adopted for the propulsion system was the Engineering Breadboard model to reach the desired TRL. The development of such a model permits to use COTS products that are not qualified for space applications. However, a custom solution was needed for the thruster. Therefore, a detailed R&D activity was focused on the thruster designs.

5.2 CHIPS Engineering Model

This model takes the form of the flight model's propulsion system: a tank connected to a square plate on which the feed line and propulsion system are mounted. However, substantial differences in many components are inserted among the two models. These differences arise for some reasons:

1. safety to maintain during the test
2. possibility of filling and emptying the system several times during the tests
3. development times and costs of some components

In particular, further sensors, a burst disk, draining and purging solenoidal valves with the respective fitting and tubes connected to the feed line of the propulsion system are included in the model. The filling valves and the tank were changed with more suitable COTS products, even if they do not fully satisfy the CHIPS requirements because the ones selected for the flight model present some cost and delivery time related issues.

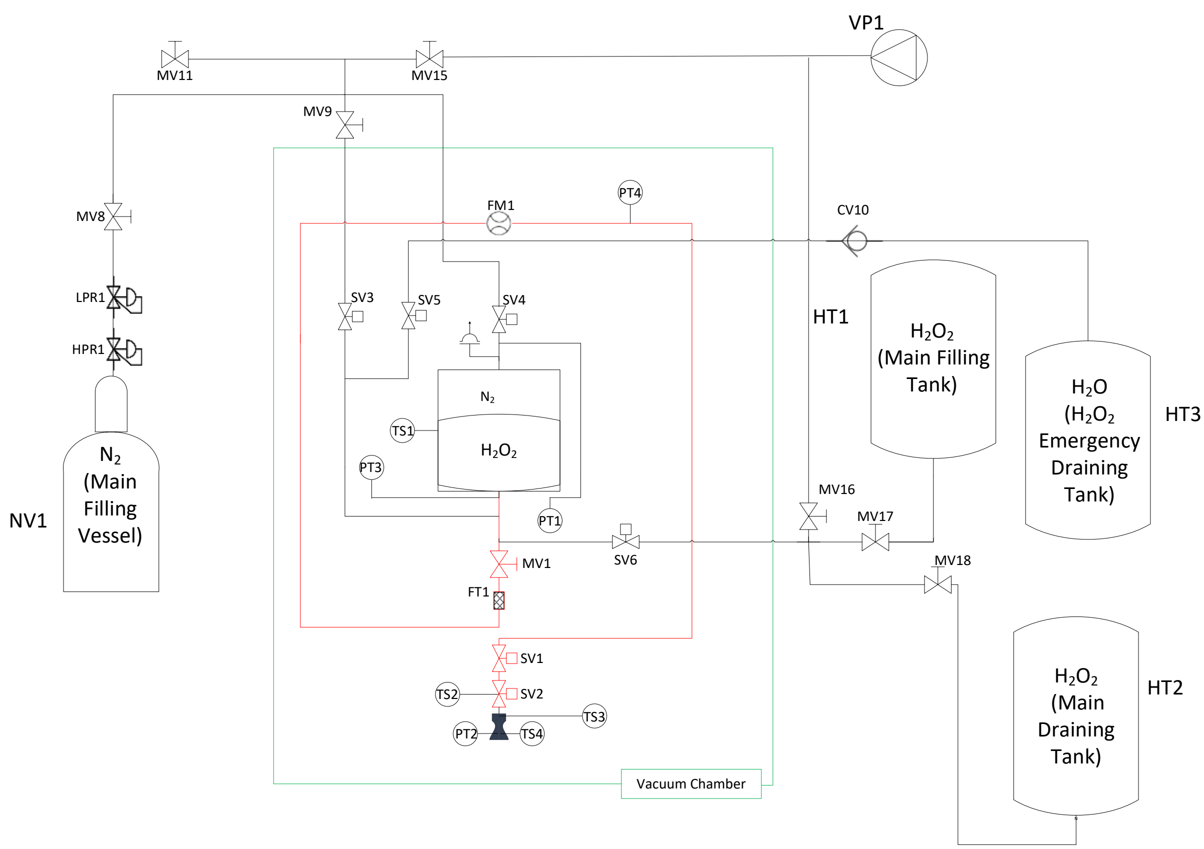

Figure 5.2: : CHIPS Engineering Model Schematic

6 Test Campaign and Test Facility

The aim of the CHIPS project test campaign is to verify that the propulsion system satisfies the fixed requirements and achieves TRL ≥ 3. For this reason, tests in atmospheric and vacuum conditions at component level and overall system level were proposed. The main tests performed during the CHIPS project are indicated in Table 6.1, and a specific ID is associated to each of them.

Table 6.1: Tests to be performed in the Frame of CHIPS Project

Test ID	CHIPS Test
TEST-ATM-01	Tank Leakage
TEST-ATM-02	Tank Proof Pressure
TEST-ATM-03	Tank Pressure Cycling
TEST-ATM-04	Tank Burst Pressure
TEST-ATM-05	Propulsion System Performance in Atmosphere
TEST-VAC-01	Propulsion System Performance in Vacuum

The tests reported in Table 6.1 are separated in three different groups, as illustrated in Figure 6.1. These groups of tests, besides being carried out in different conditions and on different levels, were also carried out in different time intervals. The first group of tests included the experiments done at the component level and in the atmosphere. The second group consisted in the tests carried out at the total system level and in the atmosphere, and the third group included the tests on the total system performed in vacuum. Therefore, the three groups of tests are identified as:

- Group I:
    - TEST-ATM-01
    - TEST-ATM-02
    - TEST-ATM-03
    - TEST-ATM-04
- Group II:
    - TEST-ATM-05
- Group III:
    - TEST-VAC-01

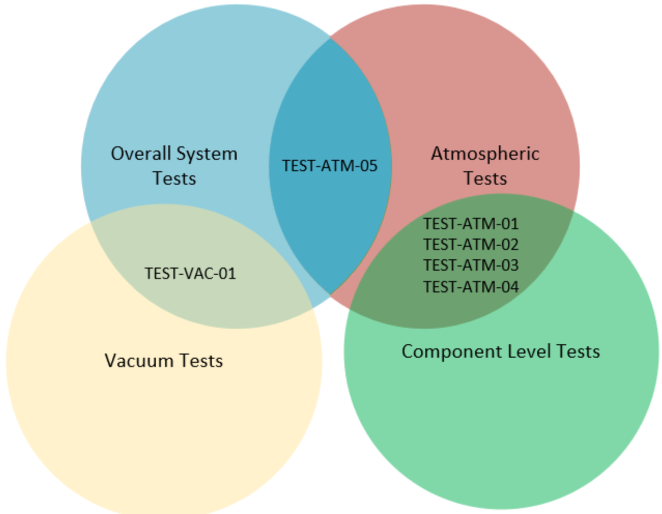

Figure 6.1: CHIPS Test Groups Subdivision

A newly developed thrust balance capable to host an entire 3U CubeSat (Figure 6.2) was built in the frame of the CHIPS project and used during both the atmospheric and vacuum firing tests to simulate the performance given by the propulsion system when mounted on the target satellite.

The UniPi test facility has been used for the tests of the CHIPS propulsion system in atmospheric conditions.

Figure 6.2: CHIPS Thrust Balance

The selected vacuum chamber for the vacuum test campaign of CHIPS project is the Small Plasma Facility (Figure 6.3). SPF consists of a 3.35 x Ø2 meter main chamber with a 1 x Ø1 meter hatch. CHIPS vacuum tests were conducted in the hatch. These dimensions were suitable for inserting in the chamber the thrust balance on which the 3U CubeSat envelope containing the whole propulsion system will be mounted for testing, as visible in Figure 6.4. A new vacuum pump (Figure 6.5) was used to reach in few minutes the level of vacuum required by the experiment (0.1 mbar) and the walls of the chamber were covered with aluminum layers to protect the graphite from the hydrogen peroxide eventually dropped out from the system (Figure 6.6).

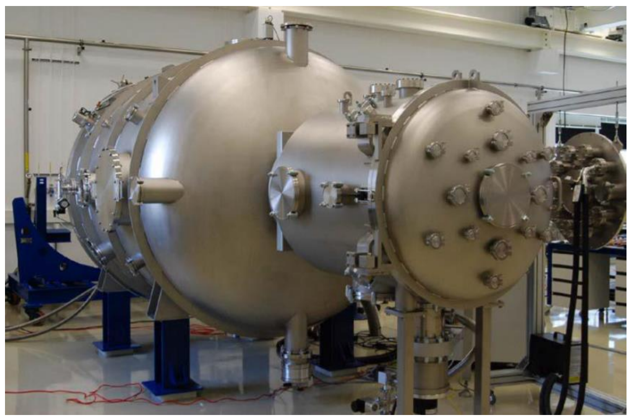

Figure 6.3: Small Plasma Test Facility at ESA/ESTEC

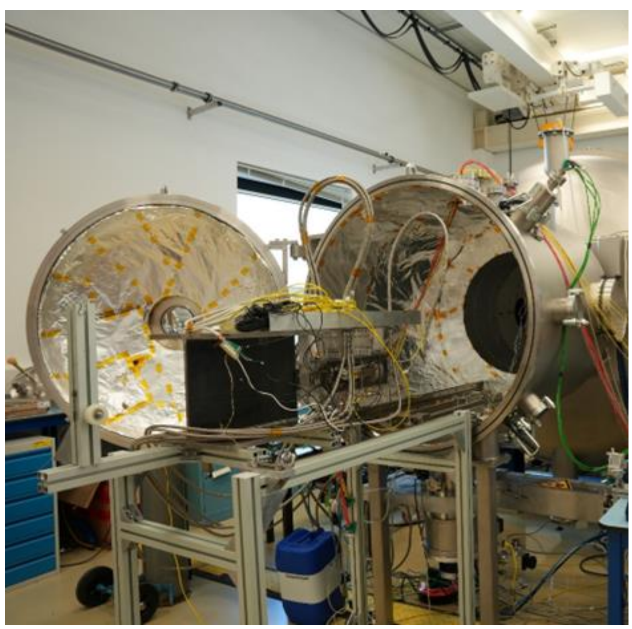

Figure 6.4: Insertion of CHIPS inside the Vacuum Chamber Hatch

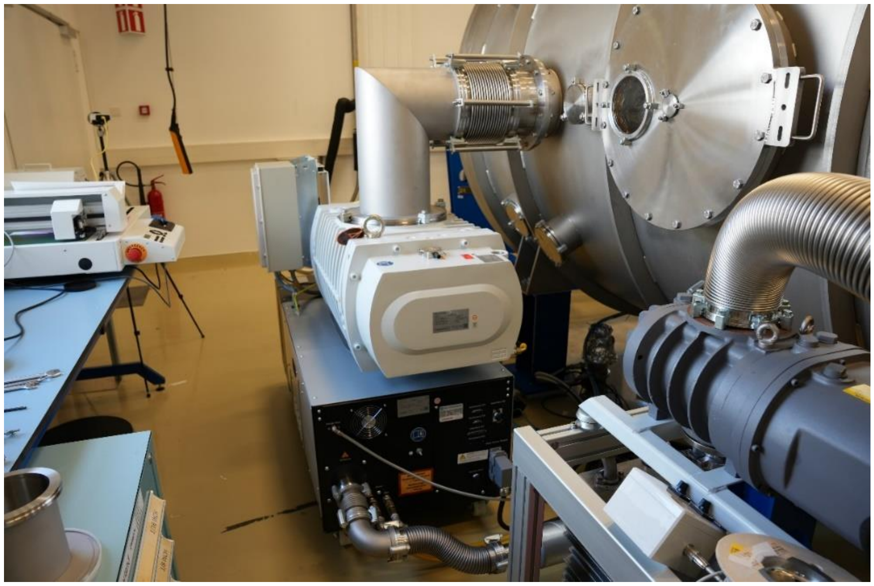

Figure 6.5: New Vacuum Pump Used in the Frame of CHIPS Project

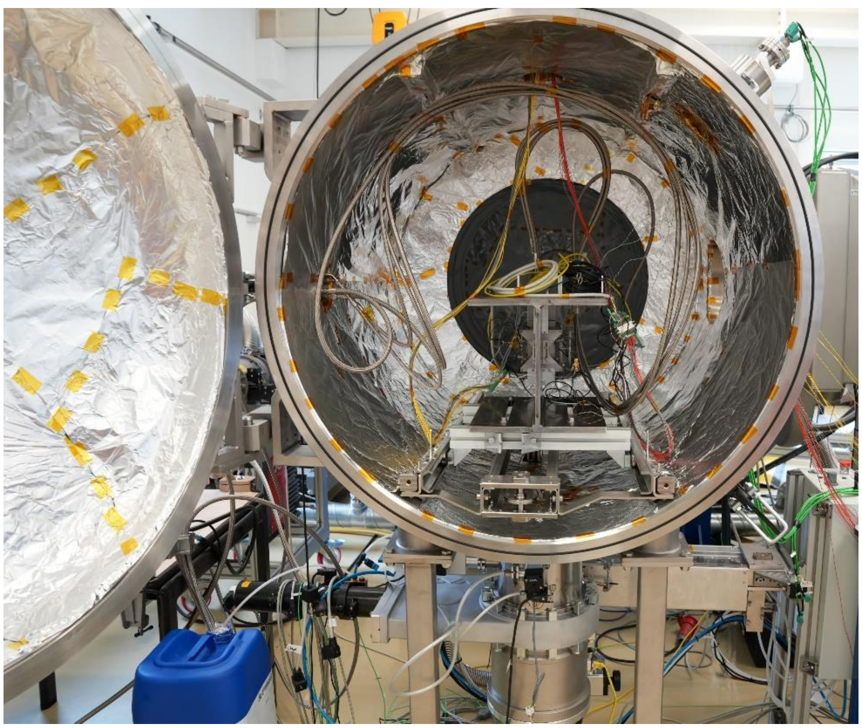

Figure 6.6: Covering of the Vacuum Chamber Walls with the Propulsion System Inserted

During the firing tests the following matrix agreed with ESA was followed to verify most of the imposed requirements:

Repeat the following process for four times (all the pulses will have a duty cycle of 1 s and a t_{on} as specified in the list below, the toff will be adjusted as consequence): • First cold start and firing for 80 s • Hot start and firing in pulse mode with t_{on}=25 ms for 80 times • Hot start and firing in pulse mode with t_{on}=50 ms for 80 times • Hot start and firing in pulse mode with t_{on}=100 ms for 80 times • Hot start and firing in pulse mode with t_{on}=200 ms for 80 times • Hot start and firing in pulse mode with t_{on}=300 ms for 80 times • Hot start and firing in pulse mode with t_{on}=400 ms for 20 times • Hot start and firing in pulse mode with t_{on}=500 ms for 20 times • Hot start and firing in pulse mode with t_{on}=600 ms for 20 times • Hot start and firing in pulse mode with t_{on}=700 ms for 20 times • Hot start and firing in pulse mode with t_{on}=800 ms for 20 times • Hot start and firing in pulse mode with t_{on}=900 ms for 20 times Wait until catalytic bed temperature decreases to the value required by cold start • Repeat cold starts and firing for 1 s until 100 cold restarts are reached • Final continuative firing will be performed until emptying of the tank (for at least 2000 s)

7 Experimental Results

The main achievements obtained during the firing test campaigns are summarized in the following tables. They report the performance obtained with the nominal design of the thruster during continuous firings and pulsed firings both in atmosphere and vacuum conditions.

Table 7.1: Atmospheric Continuous Firing

Parameter	Value	Threshold Value
F (N)	0.3 (s.l.)	≤ 0.5
Isp (s)	80 (s.l.)	160
Rise-time (ms)	<100	150
Thrust Roughness	<3.5%	±5% at 2σ
η_{c^*} (c*-efficiency)	0.9	0.9

Table 7.2: Atmospheric Pulsed Firings

T_{on} (ms)	N° Pulses	p_{in} (bar)	F (N)	Impulse Bit (Ns)
900 (first series)	20	20	0.3 (s.l.)	0.26
900 (second series)	20	16	0.19 (s.l.)	0.22
800 (first series)	20	19	0.3 (s.l.)	0.23
800 (second series)	20	Not completed due to catalyst degradation		
700 (first series)	20	19	0.27 (s.l.)	0.19
600 (first series)	20	18	0.27 (s.l.)	0.15
500 (first series)	20	18	0.25 (s.l.)	0.12
400 (first series)	20	18	0.25 (s.l.)	0.11
300 (first series)	80	17	0.23 (s.l.)	0.077
200 (first series)	80	17	0.23 (s.l.)	0.05
100 (first series)	80	17	0.22 (s.l.)	0.025
50 (first series)	80	16	0.2 (s.l.)	0.016
25 (first series)	80	16	0.15 (s.l.)	0.010
25 (second series)	80	16	0.13 (s.l.)	0.015

Table 7.3: Vacuum Continuous Firing

Parameter	Value	Threshold Value
F (N)	0.4	≤ 0.5
Isp (s)	160	160
Rise-time (ms)	<100	150
Thrust Roughness	<3%	±5% at 2σ
η_{c^*} (c*-efficiency)	0.9	0.9

Table 7.4: Vacuum Pulsed Firings

T_{on} (ms)	N° Pulses	p_{in} (bar)	F(N)	Impulse Bit (Ns)
900 (first series)	20	17	0.5	0.48
900 (second series)	20	14	0.4	0.36
800 (first series)	20	17	0.5	0.43
800 (second series)	20	14	0.35	0.3
700 (first series)	20	17	0.5	0.37
700 (second series)	20	13.5	0.35	0.27
600 (first series)	20	16.5	0.5	0.32
500 (first series)	20	16.5	0.45	0.26
500 (second series)	20	14.5	0.25	0.1
400 (first series)	20	16	0.45	0.21
400 (second series)	20	14	0.25	0.13
300 (first series)	80	16	0.4	0.16
300 (second series)	80	14	0.3	0.13
200 (first series)	80	15.5	0.4	0.11
200 (second series)	80	14.5	0.05	0.005
100 (first series)	80	15.5	0.4	0.065
100 (second series)	80	14	0.05	0.005
50 (first series)	80	16	0.2	0.02
50 (second series)	80	14	0.07	0.005
25 (first series)	80	16	0.2	0.02
25 (second series)	80	14	0.05	0.01

The tables above show that the propulsion system satisfied most of the imposed performance requirements. The only requirements not yet verified are the ones related to the total cycles, total number of cold restarts, longest burn and total throughput, since the proposed test matrix was not completed during the test campaign due to the use of a tank with a propellant volume lower than the estimated one. Furthermore, an instability developed inside the decomposition chamber during the vacuum test campaign, as visible in Figure 7.1. Various strategies and catalytic bed configurations were adopted to dump this instability, however the instability remained for the entire duration of the test campaign.

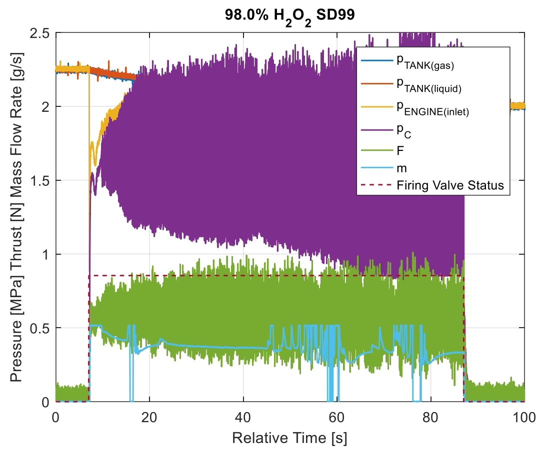

Figure 7.1: Developed Instability inside the Decomposition Chamber

8 Conclusions and Future Recommendations

The newly proposed propulsion system was able to satisfy most of the imposed requirements during the test campaign. In particular, the specific impulse of 160 s, the generated thrust lower than 0.5 N, the minimum impulse bit of 0.025 mNs and the quick response time lower than 50 ms demonstrate the magnitude of the CHIPS potential. The reached TRL value after this test campaign is between 4 and 5. Further developments and tests are necessary to increase the technology readiness of CHIPS making it a valid competitor of the toxic hydrazine thrusters present on the market. The next steps for a future progress of this propulsion system are:

- The instability will be studied in details and the CHIPS design modified accordingly
- The design and development of the innovative cuboidal tank proposed at the beginning of the project
- The modifications to the Engineering Model to make it closer to the Flight Model