PERFORMANCE AND CAPABILITIES OF THE COMET WATER PROPULSION SYSTEM

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ABSTRACT:

Bradford Space is specialized in the design and development of propulsion systems using non-toxic, so-called 'green', propellants. Water, the ultimate environmentally friendly liquid propellant, is used on one of the newest products that Bradford Space is offering: the Comet propulsion system. This system operates by using one or more propellant tanks holding a phase-changing pressurant on one side of a diaphragm, which pushes the water on the other side of the diaphragm to the thruster. In the thruster, the water is electrically heated and converted into superheated steam before being expelled through a nozzle to generate thrust. Different Comet configurations are available from a 3U CubeSat volume to larger dimensions tailored to specific mission needs.

With over 25 units in orbit and over two dozen more delivered, the design and production has now been fully transferred from the US to Europe. To further characterize and expand the Comet's operational envelope, extensive additional testing has been performed over the last 2 years. This paper summarizes the performance and the capabilities of the Comet water propulsion system.

NOMENCLATURE:

AIT	Assembly, Integration and Test
BSI	Bradford Space Industries
DSI	Deep Space Industries
DSIE	Deep Space Industries Europe
F/D	Fill and Drain
MGSE	Mechanical Ground Support Equipment
TRL	Technology Readiness Level
TVAC	Thermal Vacuum Chamber
ΔV	Change in velocity

1. BACKGROUND

Deep Space Industries (DSI) was founded in 2012 to exploit the resources of the solar system for which deep-space capabilities had to be developed. As part of this goal, water-based space propulsion technology was developed [2], resulting in the electro-thermal thruster used in the Comet propulsion system, which is discussed later in this paper in more detail.

In 2016, DSI established its initial presence in Luxembourg within the framework of the Government's Space Resources Initiative. In 2018 Bradford Space, acquired DSI to expand and diversify its portfolio of products and technologies to remain at the forefront of space exploration and exploitation. Since the acquisition, the Luxembourg-based entity has been rebranded as Bradford Space / Deep Space Industries Europe (DSIE). DSIE is a direct subsidiary of Bradford Space Inc. (formerly Deep Space Industries Inc.) from New York City, New York.

By acquiring DSI, Bradford Space aims to capture the growing microsatellite (10 and 100 kg) market by providing a reliable low-cost green propulsion system, namely the water-based Comet space propulsion system. At present, Bradford Engineering in the Netherlands is manufacturing heritage Comet systems while DSIE is focusing on the transfer and qualification of the existing Comet product line and technology developed by BSI USA to Europe and combine it with the extensive experience of developing space products by Bradford Space.

Flight heritage of the Comet propulsion systems was obtained when three Comet-1000 systems were launched in 2018 on the Hawk satellite constellation. The first satellite with the bigger version of the system, the Comet-8000, was launched in 2019, with several more systems launched in 2021 and 2022. At the time of writing, 25 water-based systems are flying in space and counting.

2. WATER PROPULSION

Bradford Space offers a revolutionizing and launch-safe propulsion system, called Comet, which is an electro-thermal based propulsion system that uses water as a propellant. Water is an excellent green propellant as it is non-toxic, inexpensive, and thermally stable. In addition, the low molecular mass of water and high mass density allows storing the propellant in smaller tanks in comparison to gaseous propellants. The above-mentioned characteristics in turn allow relatively easy transportation and fuelling operations, making a water propulsion system cost effective and a viable option for commercialization and lower turnaround times for commercial spaceports by reducing ground processing and operation time. In addition, a propulsion system using water as a propellant also ensures that safety requirements imposed by the primary payload satellite and the launch site are met in the case of rideshare.

The Comet propulsion system operates by using propellant tank(s) which holds a phase-changing pressurant on one side of a diaphragm. The combination of the pressurant vapor pressure and the diaphragm, a positive expulsion device, forces the propellant on the other side of the diaphragm to the engine. The Comet pressurant is a non-toxic, low-pressure multiphase fluid, whose pressure is controlled by heaters. This pressurant has been chosen based on the suitability of its vapor pressure and temperature curve for the propellant. Therefore, this pressure regulated system avoids high pressure requirements found in "blowdown" propulsion systems. Comet works by introducing liquid water into an electrically heated chamber, which in turn heats the propellant well above its boiling point to create vapor. The superheated water vapor is then expelled through a nozzle, generating thrust.

Ground operations including pressurization and propellant loading is facilitated by two service ports and solenoid valves, one for the pressurant and one for the propellant. Those two valves are only open during fill and drain (F/D) ground operations. Comet includes a third solenoid valve that controls the flow of propellant through the thruster chamber that is used to evaporate and superheat the propellant to the desired temperature.

Comet incorporates a flexible interface suitable for a wide range of spacecraft sizes including CubeSats larger than 6U. The system features an in-flight reprogrammable application software layer, a superheater and a simple, robust and scalable water tank that can readily accommodate different propellant volumes based on customer needs. The Comet has been designed for an electrical interface that can accept a wide range of input voltages, from the lower-end of CubeSat-typical supplies to the standard ~28V battery busses typical of small satellite power systems. Upon request, Comets can be delivered fuelled to the customer taking away the burden of pre-launch fuelling activities.

Currently, two recurring Comet propulsion configurations, the Comet-1000 and Comet-8000, are being manufactured at Bradford Engineering, Netherlands. The naming of the Comet systems is based on total Impulse of the system. The configurations are discussed in detail in the next chapters.

3. COMET-1000

The Comet-1000 propulsion system, as shown in Figure 1, is a very compact solution that fits in a small volume as its dimensions are 10 x 10 x 26 cm. The Comet-1000 is comprised of three primary sub-assemblies namely, the propellant tank, enclosure, and thruster. The propellant tank can load up to 700 grams of propellant and 40 grams of the pressurant while the enclosure of the system holds integrated propellant management and the control unit.

The architecture of the Comet-1000 propulsion system is shown in Figure 2. The propellant management of the system consists of three solenoid valves to control the propellant flow into the thruster assembly and to allow fill and drain of propellant and pressurant, a pressure transducer to allow monitoring of the pressurant pressure, and a filter to block particles from entering the thruster.

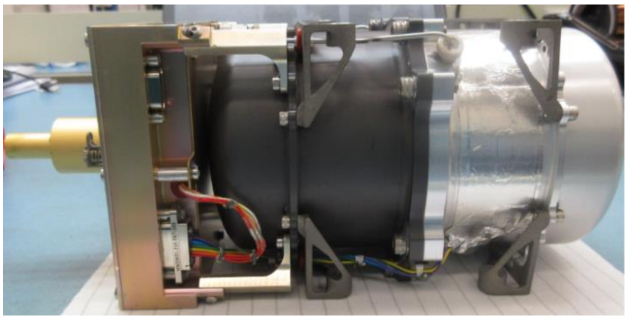

Figure 1: Comet-1000 Propulsion System

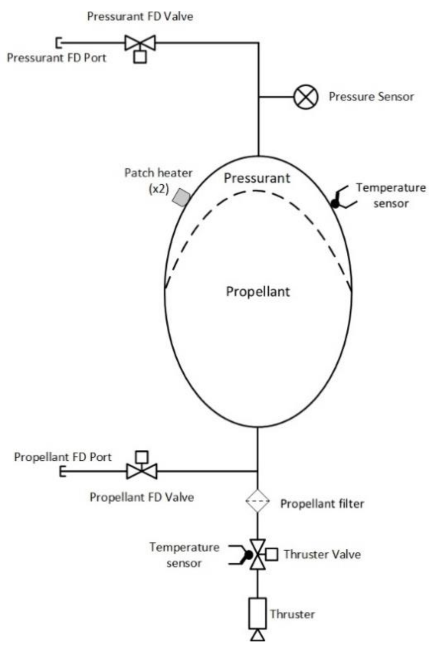

Figure 2: Comet-1000 Propulsion System Architecture.

3.1. Comet Avionics

The Comet avionics interfaces with the bus to collect telemetry and control the thruster during operation. The avionics can accept unregulated power with a voltage between 8.5V and 34V, with power consumption that varies between 0.25W to 25W depending on the operating mode of the thruster. Command and telemetry communications with the Comet microcontroller is over a CAN Bus or RS-485 \ RS-422 asynchronous serial interface, with either option configurable on build. Either transceiver can be configured with an optional termination resistor if required. Bus power and data interface is via a 15pin socket micro-D connector.

The thruster superheater temperature is precisely regulated using a current controlled switch mode regulator during propulsive manoeuvres to maintain thrust repeatability and maximize superheater lifetime. The thrust valve is directly controlled by the microcontroller so the thrust intervals can be precisely timed for accurate and repeatable impulses. Finally, the avionics can also regulate heaters located on the propellant tank to maintain the water in the nominal operating range.

All electronic assemblies are designed and manufactured to be compliant with IPC J-STD-001ES. TVAC tests were performed over a temperature range from 0 °C to 80 °C, assuring that it is fit for flight.

An overview of the Comet-1000 performance is shown in Table 1.

Table 1: COMET-1000 Propulsion System Performance and Electrical Interface

Characteristic	COMET-1000
Thrust	17 mN
Specific Impulse	175 … 185 s
Tank Pressure	3.4 ± 0.3 bar
Warm-up Time	10 minutes
Power Consumption while Thrusting	25 W for < 1 minute 55 W for continuous
Power Consumption when Idle	0.25 W
Input Voltage Range	8.5 … 34 V
Minimum Impulse	< 50 mNs
Operating Temperature Range	+5 °C to +60 °C
Total Impulse	1155 Ns
System Dry Mass	740 g
Propellant Mass	700 g
Physical Layer Interface	RS422/485
Protocol and Command Interface	NSPv4

The Comet-1000 has been successfully tested to the mechanical qualification levels listed below in Table 2.

Table 2: Comet-1000 Qualification Level

Parameter	COMET-1000
Quasi-static loads	60 g
Random vibration	X: 14.88 grms, max 1.47 g^2/Hz Y: 15.9 grms, max 1.06 g^2/Hz Z: 17.78 grms, max 1.52 g^2/Hz
Shock	100 Hz: 30 g 500 Hz: 300 g 1000 Hz: 1000 g 5000 Hz: 2500 g

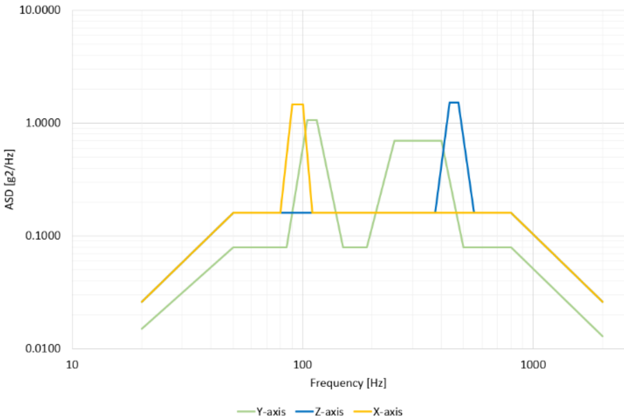

Figure 3: Comet-1000 Demonstrated Random Vibration Qualification Levels

Due to Comet flight heritage, all components of the system are TRL 9. At present, 12 systems have been delivered, 6 COMET-1000 systems are currently operating in space. Currently, up to 6 units are scheduled to be launched in 2022. Commercial customers who have procured and/or launched the COMET propulsion system include SFL.

4. COMET-8000

The Comet-8000 propulsion system is shown in Figure 4, and its system architecture is shown in Figure 5. This configuration consists of two propellant tanks to store 4.6 kg of water. The main mechanical differences between the Comet-8000 and Comet-1000 are larger propellant tank volume, mechanical design, and footprint of the system. The enclosure of the system is similar to the Comet-1000 design with the only difference being the additional fluidic connections from the tank ports to the enclosure. The thruster assembly of the system is the same as in the Comet-1000 system.

Figure 4: Comet-8000 Propulsion System (with MGSE)

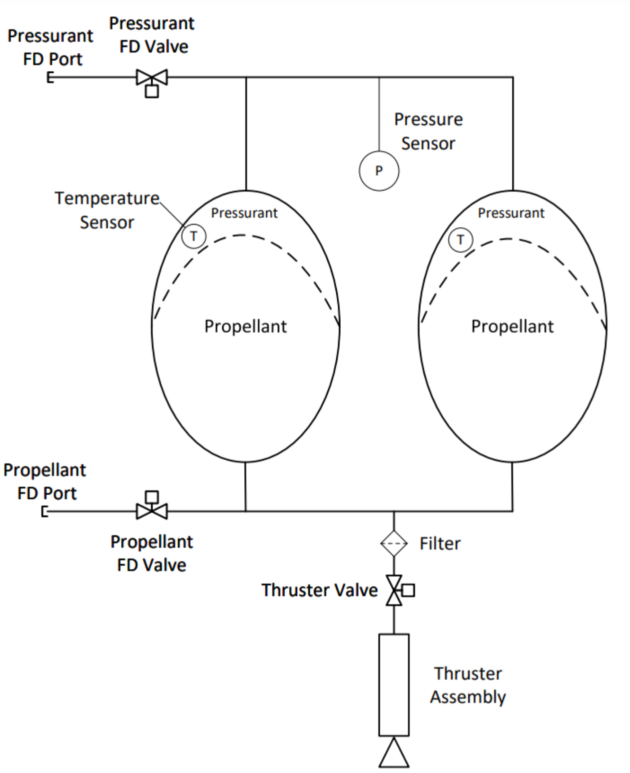

Figure 5: Comet-8000 Propulsion System Architecture

An overview of the Comet-8000 performance is shown in Table 3.

Table 3: COMET-8000 Propulsion System Performance and Electrical Interface

Characteristic	COMET-8000
Thrust	17 mN
Specific Impulse	175 … 185 s
Tank Pressure	3.4 ± 0.3 bar
Warm-up Time	10 minutes
Power Consumption while Thrusting	25 W for < 1 minute 55 W for continuous
Power Consumption when Idle	0.25 W
Input Voltage Range	8.5 … 34 V
Minimum Impulse	< 50 mNs
Operating Temperature Range	+5 °C to +60 °C
Total Impulse	8348 Ns
System Dry Mass	2075 g
Propellant Mass	4600 g
Physical Layer Interface	RS422/485
Protocol and Command Interface	NSPv4

One of the key characteristics of Comet is that it offers constant performance over its lifetime. The performance can be regulated based on customer's requirement by adjusting the tank pressure setpoint. The tank pressure is driven by the temperature of the tank, which is controlled by the tank heaters mounted on the pressurant side of the tank.

An optimal performance i.e., a thrust level of 17 mN and Isp of 180 s is achieved with a tank temperature of 35°C which corresponds to a tank pressure of 3.8 barA (54.5 psia).

The Comet-8000 has been successfully tested to the mechanical qualification levels listed below in Table 4.

Table 4: Comet-8000 Qualification Level

Parameter	COMET-8000
Quasi-static loads	30 g
Random vibration	X, Y, Z: 14.1 grms, max 0.16 g^2/Hz
Shock	100 Hz: 25 g 1000 Hz: 505 g 10000 Hz: 505 g

At present, 28 systems have been delivered, 18 COMET-8000 systems are currently operating in space. Currently, 4 units are scheduled to be launched in 2022.

5. Testing

Each Comet propulsion system built by BSI and the units currently being built at Bradford Engineering undergo an acceptance test campaign including environmental testing, pressure testing, and functional testing.

5.1. Functional Testing

Each Comet system undergoes functional testing before and after vibration testing to ensure the thruster performance requirements remain unaffected after being subjected to mechanical loading. With the exception of vibration testing, all acceptance testing is performed in-house.

With the Comet-1000 system's compact system dimension of 10 x 10 x 26 cm, the system is efficiently tested inside a bell-jar vacuum chamber setup as shown in Figure 6. The vacuum required for hot-fire testing is accomplished using a pre-pump/turbo pump combination to keep the vacuum level less than 1.0E-05 mbar prior to the start of thrusting and maintains it below 1 mbar during the thrusting period. The pumps run continuously during testing. The tank pressure for the test is set to the required on-orbit operational parameters.

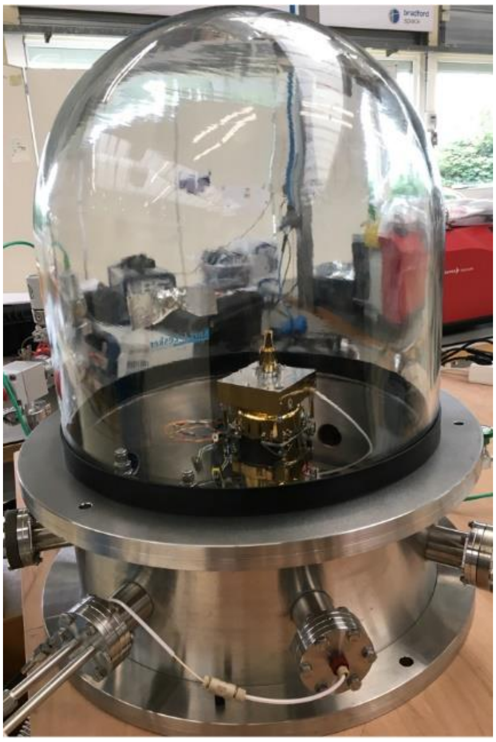

Figure 6: Bell Jar Vacuum Chamber Setup Testing Comet-1000

Comet-8000 system, with dimensions of 44 x 30 x 18 cm, is tested in a larger vacuum chamber test setup as shown in Figure 7.

Figure 7: Functional Test Setup Suitable for Comet-8000 (Vacuum Chamber 700 mm diameter x 700 mm long)

5.2. Vibration Testing

The Comet systems are subjected to environmental testing. The testing includes a low-level sine sweep test, random vibration acceptance test, and low-level sine sweep test. The random vibration acceptance levels correspond to the customer specification. The system is fully fuelled for the vibration testing, and hence, the test and the results are flight representative. Vibration testing is performed to verify workmanship but is often also used by the customer as input for flight acceptance for the launch provider.

Vibration testing is performed at an external facility. The test setup for Comet-8000 vibration testing is shown in Figure 8. The system is mounted onto an interface plate that is in line with the mounting interfaces of the system, which in turn is mounted on an adapter plate that integrates it to the slip table.

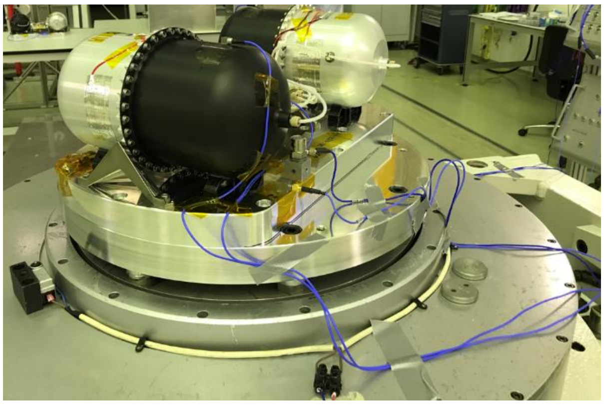

Figure 8: Comet-8000 Vibration Test Setup

For the vibration testing of the Comet-1000 system, the vibration adapter plate allows the mounting of two units. In this way, two units can be vibrated together. This capability significantly reduces cost and overall project timeline.

5.3. Feedthrough Testing

At present, the Comet propulsion system is undergoing a hot firing life testing at Bradford Engineering, the Netherlands, to demonstrate the full feedthrough performance of the Comet-8000 propulsion system. The goal of the test is to complete a total of 700 thrust cycles to validate lifetime operations of the head assembly i.e., the thruster assembly, fluidic management system and the comet avionics. Each thrust cycle consists of 10 minutes preheat period, a thrusting period of 10 minutes, followed by a cool-down period. To facilitate this test, the Comet-8000 system has been disassembled to achieve the desired performance without any hindrance. The head (thruster assembly) is installed inside the vacuum chamber, and the tank is placed outside the chamber to allow continuous monitoring and refilling of propellant. The head and tank are electrically and fluidically connected to replicate the nominal flight conditions. Figure 9 shows the test setup of the life testing.

At the time of writing, the feedthrough performance of a Comet-1000 is successfully covered by this test.

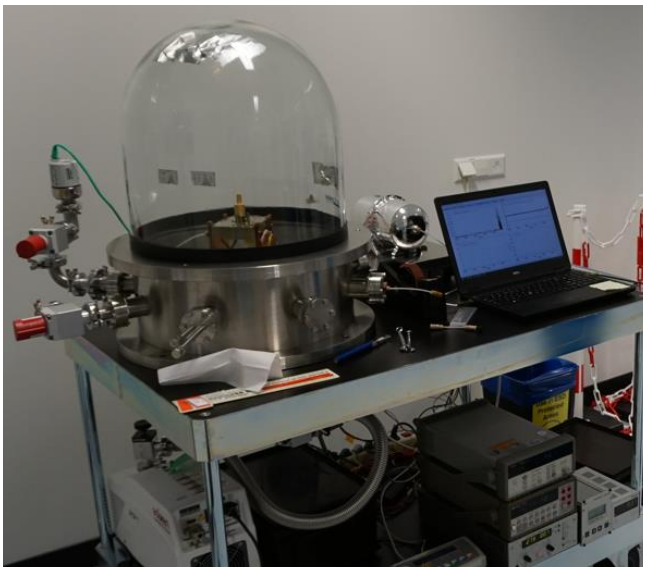

Figure 9: Comet Life Test Set-Up

6. Technology Transfer and Development

With the acquisition of DSI by Bradford Space, the new Comet product line is currently being set up in Luxembourg. This includes all capabilities, resources and existing customer base.

The technical development objective within this technology transfer is to build on the foundations of BSI US to redesign based on lessons learned and to requalify the Comet propulsion system. The new Comet product line includes a new manufacturing facility where all units will be completely built, tested, and manufactured in Luxembourg.

The approach in the Comet redesign process is to make it as adaptable as possible to mission-specific needs, without sacrificing simplicity and robustness. As such, the redesign innovation in Comet is not specifically targeted on generating high specific impulse or thrust, but rather on a balance between several different design considerations to achieve an effective solution that can work in practical implementations for a wide range of customers.

Compatibility and flexibility are new features implemented in the new design, for instance a simple, low weight, robust and scalable propellant tank that gives the ability to fit in different platforms and accommodate different water volumes according to specifics needs. All together with a philosophy design based on intersecting the best combination of cost and effectiveness to allow reduce production costs while increasing reliability, such as used of COTS components with flight heritage and high quality materials.

Similar to its predecessor, the new Comet thruster targets the growing “NewSpace” industry and the nano-microsatellite market. To adapt Comet to a wide range of spacecraft sizes, the new design incorporates a highly flexible interface compatible with CubeSat platforms larger than 3U and with larger nano-microsatellite busses up to 100 kg.
The key steps for the realization of the main technical objectives are listed below.

- Improvements based on lessons learned from the existing Comet technology development process and customer’s in-orbit operations. Lessons learned during all product cycles are captured and applied in the redesign process to identify the main points for improvement and requirements to be further satisfied by the new design. Comet flight heritage provides an unique advantage that competing thrusters do not have, and as such, it plays a valuable factor during the redesign process.

- The existing Comet design has already been qualified and 25 units are currently in flight. Since the new Comet product development incorporates changes in design, manufacturing, materials, parts and processes, a delta-qualification process forms part of its development plan. This new qualification will guarantee the design standards, manufacturing, and qualification status are being reviewed to assess the design against the new set of requirements.

- To increase Comet’s potential of being tailored to a specific mission needs, the new design incorporates a modular architecture. Such that the modular construction will allow for easier scaling performance and specific features needed by the mission.

7. CONCLUSION

The Comet is the only readily available water-based propulsion subsystem that offers a turnkey solution for satellites ranging from CubeSats to SmallSats with a TRL of 9. It has delivered 44 systems to date with currently 25 systems operating in space.

A new Comet product line is being built at DSI Luxembourg where lessons learned from heritage design are incorporated to offer a more performing propulsion system for the microsatellite (10-100 kg) NewSpace market.

8. REFERENCES

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