ACHIEVEMENTS OF A HIGH-PRESSURE COLDGAS THRUSTER DEVELOPMENT

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ABSTRACT:

Modern satellite platforms rely on established electric propulsion systems for efficient propellant use. However, these systems provide limited thrust, usually only a few hundred millinewtons, which restricts their use only to long-duration manoeuvres. High-thrust actuators are necessary for detumbling after launcher separation, collision avoidance, orbit insertion, or safe mode. To fulfil this requirement, integrating a cold gas thruster into the onboard infrastructure provides a feasible solution.
AST Advanced Space Technologies GmbH has developed a high-pressure cold gas thruster capable of generating thrust exceeding 2 N using standard gases such as nitrogen, argon, krypton, and xenon. This thruster operates efficiently across a wide pressure range, from a maximum expected operating pressure of 300 bar down to an end-of-life pressure of 1.5 bar, without the need for a pressure regulator.

1. INTRODUCTION

AST Advanced Space Technologies GmbH (AST) has developed a high-pressure cold gas thruster (HP-CGT) capable of providing thrust of well over 2 N using typical gases such as nitrogen, argon, krypton, and xenon. This newly developed thruster operates seamlessly from 300 bar maximum expected operating pressure (MEOP) down to 1.5 bar end-of-life (EoL) without requiring a pressure regulator. The development followed a structured process, including initial requirements identification, design trade-offs, and de-risking tests at the component level, culminating in a baseline design agreed upon during a design review with the European Space Agency (ESA).
Two elegant breadboard (EBB) units were built, and their performance was thoroughly characterised. AST developed a specialized thruster test stand with measurement techniques for high-thrust, high-flow, and high-pressure operations.

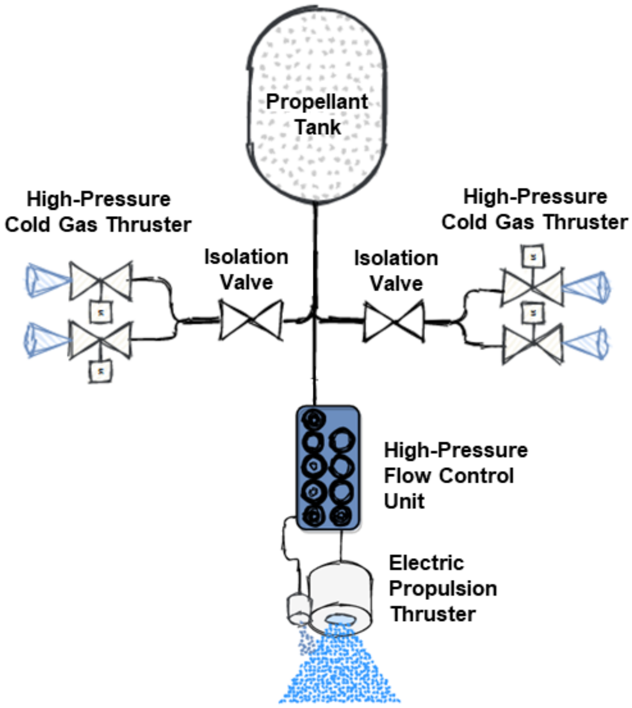

Figure 1. Example of a fluidic architecture which integrates the HP-CGTs

This cold gas thruster serves as a high-thrust extension to existing electric propulsion systems. The schematic illustration in Fig. 1 demonstrates how the HP-CGT system can be integrated into the fluidic architecture of the S/C. It is possible to use the same propellant as the main propulsion system, such as xenon or krypton, which eliminates the need for an additional tank for a different propellant type. An isolation valve provides redundancy by connecting the propellant tank of the main propulsion system to the HP-CGT system. This approach offers several significant advantages. It uses a minimal number of additional components to achieve higher thrust, ensuring high reliability. Additionally, it is a lightweight system that is simple to integrate into existing propulsion systems. This makes the HP-CGT system a highly scalable and low-cost option for high-thrust tasks such as detumbling after launcher separation, collision avoidance, orbit insertion, or safe mode.

2. HP-CGT DESIGN

2.1. Driving requirements

During the design phase of the HP-CGT development, a detailed elaboration of the basic design was carried out. Key design requirements were identified and discussed. The initial requirements were defined by ESA and supplemented by AST. The most important requirements are listed in Tab. 1.

Table 1. Design driving requirements for HP-CGT

Description	Requirement
thrust range	> 2 N of thrust at MEOP in steady-state operation (with xenon)
ISP range	> 25 s of ISP at MEOP > 20 s at 5 bar in steady state operation (with xenon)
Pulsed mode performance	thrust and ISP performance shall be characterised for short on-pulses (10 ms < t < 1000 ms) at distinct operating pressures between MEOP and 1 bar
Performance characterisation	thrust and ISP performance shall be characterised per analysis supported by tests at intermediate operation points

2.2. Design trade-offs

Design trade-offs were analysed in terms of function, performance and complexity, impact on spacecraft, cost, development effort and availability. Considerations were made at component level, e.g. nozzle shape and valve design. Different concepts such as resistojet, augmented CGT and a pure CGT concept were tested and weighed up in terms of a technical compromise (see Fig. 2).

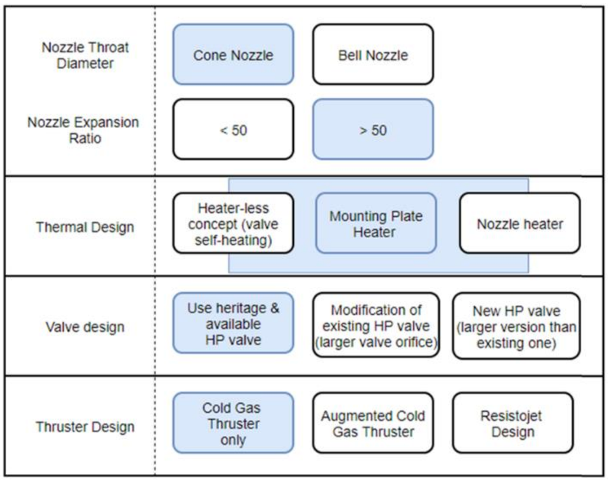

Figure 2. HP-CGT trade-off map

Expertise from other AST´s heritage products played a special role in the design of the HP-CGT. As shown in Fig. 3, the high-pressure valve from AST´s series products was used for the CGT. Manufacturing processes such as electron-beam welding and design experience from the LP-CGT were also utilised.

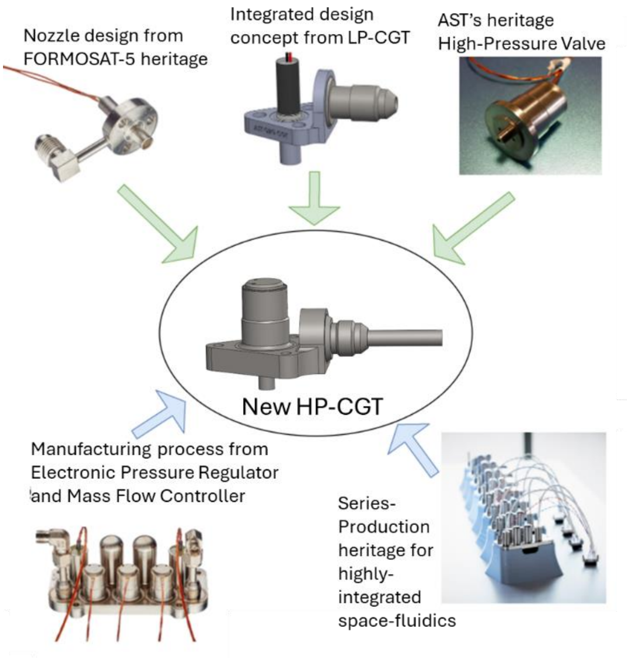

Figure 3. AST expertise incorporated into the design process of the HP-CGT

2.3. Breadboard design definition

Following the design process, a breadboard of the HP-CGT was created. As is typical during the development stage of an EBB, some questions still needed clarification. Therefore, two EBBs were produced in different configurations to compare influencing parameters and improve the success of subsequent characterization tests. One of the uncertainties was the ratio of the nozzle throat diameter to the valve orifice diameter. It is preferable to have larger nozzle throat diameters to achieve higher thrust. If the throat diameter becomes too large compared to the valve orifice, performance could be adversely affected. Additionally, there were concerns that the expansion of the propellant gas, particularly at high inlet pressures of the HP-CGT, could cause the Joule-Thompson effect to cool the elastomer valve seal. This could lead to seal damage at excessively low temperatures or result in thruster clogging. As a result, the two EBBs were built with different nozzle throat diameters. Also, an option to preheat the thruster with a removable aluminium heating block was added to reduce the impact of cooling due to the Joule Thompson effect, if necessary. It should be noted that the aim was not to increase the specific impulse (ISP) with the attachable heater, although an effect on ISP is visible in the subsequent measurements. If the objective is to increase the ISP, a more effective design would be to use an inline heater to preheat the propellant gas like in a resistojet.
As illustrated in Fig. 4, the final design was made to be high pressure compatible using standard AST components and fluidic interfaces joined by electron beam welds to the mounting plate. A photograph of the two thrusters is also shown in Fig. 5.

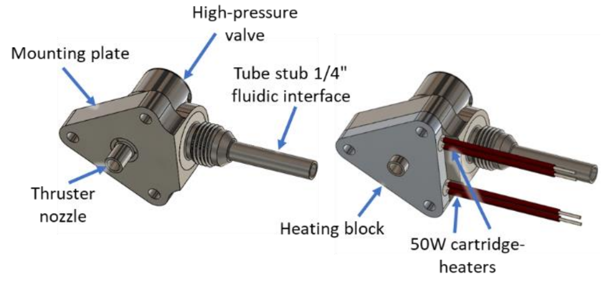

Figure 4. Design of the HP-CGT EBB with a detachable heating block

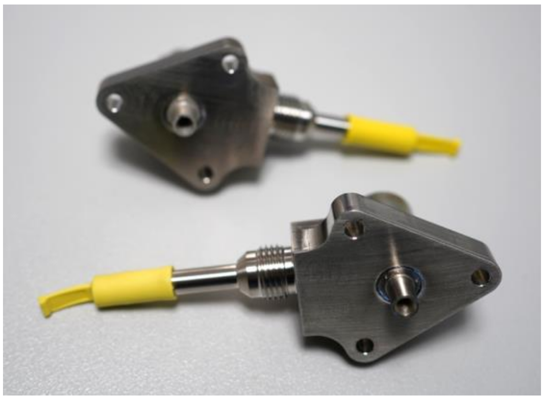

Figure 5. Picture of both HP-CGT EBBs

3. HP-CGT TEST CAMPAIGN

AST developed a methodology and measurement hardware to determine the thrust and ISP at high mass flow and high-pressure conditions. The HP-CGT EBB thruster characterisation tests were performed at AST facilities. The thruster performance was characterised with respect to different gases, inlet pressures, thruster temperature, heating power, and power consumption. Two HP-CGTs with different nozzle diameters were examined with and without heating. Special test methods were developed and verified before subjecting the HP-CGT EBBs to characterisation tests.

3.1. Test setup

AST has defined a unique high pressure, high flow test set-up with direct thrust measurement under vacuum conditions. A sketch of the setup is shown in Fig. 6. The vacuum chamber houses a jig-mounted CGT on a high-precision industrial measuring scale, which was used to record the thrust. The test setup includes the required hardware and software to electronically record data, such as temperature readings at the thruster, inlet and vacuum pressure, mass flow, and thrust measurements. The test-software was specially developed for the HP-CGT tests.

The propellant used for the tests is primarily stored in a one-litre buffer volume. The gas is initially loaded through a gas supply. After propellant loading the buffer volume is then isolated from the gas supply using a shut-off valve before the CGT firing tests. The buffer volume is mounted on a separate measuring scale, enabling the measurement of propellant change in the tank between each firing of the CGTs. This also allows for the determination of the total propellant consumption of a shot.

The propellant line from the vacuum chamber feed-through to the thrust jig has the greatest interfering influence on the measurement of the thrust scale. During thruster firing, the pressure of the propellant inside the line changes, affecting the mechanical rigidity and weight of the line. To minimise the force exerted by the propellant line on the thrust scale, it is mechanically decoupled by a loop in the pipe. The remaining force exerted on the thrust measuring scale is recorded during propellant loading and used in post-processing to estimate this variable of disturbance.

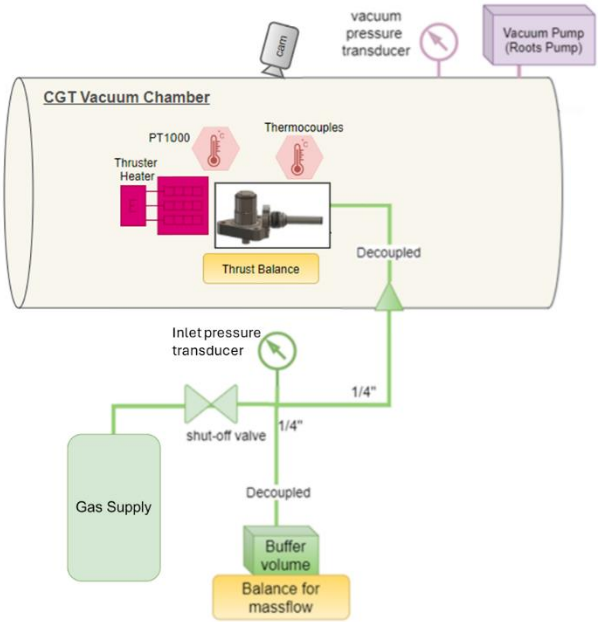

Figure 6. Sketch of the test setup for evaluating thruster performance

3.2. Test measurements methodology

Three different types of tests were carried out:

- Integrity tests
- Continuous firing mode
- Minimum impulse bit (MIB) characterisation

These are discussed below.

<u>Integrity tests</u>

The aim of the integrity test is to evaluate the condition of the HP-CGTs. These tests, including initial inspection, health checks, and proof pressure, were conducted following AST standard procedures, which are not elaborated here.

<u>Continuous firing mode</u>

In continuous firing mode, the thruster is fired continuously for a certain duration, depending on the inlet pressure. The thrust is measured using the thrust measuring scale, and the propellant consumption is determined after firing using the other scale for the ISP calculation. This type of test was performed with the CGT at room temperature or at an elevated

temperature of 60°C using the attached heating block.
The test can be described in more detail as follows. This test mode begins with propellant loading. The propellant from the gas bottle is gradually transferred into the buffer volume. The weight and stiffness of the propellant line to the thruster jig change during loading. To remove the effect of this disturbance variable in post-processing, the change in force on the thrust measuring scale is recorded during propellant loading. The target pressure for nitrogen, argon and krypton has been set at 300 bar, and 186 bar for xenon. It should be noted that gas bottles for xenon and krypton are not commercially available at these pressures. Therefore, an internally developed compressor is used to achieve higher pressures. The compressor hermetically pressurises the gas to the target pressure. For certain types of propellants, particularly xenon, a significant delay occurred until the pressure in the propellant tank has stabilised thermally after compression. By firing the CGTs the fluidic system basically operates in a blow-down mode. The pressure and temperature of the propellant in the tank and the lines will change during firing. This blow-down mode will also occur later in the satellite for CGT operation. However, the satellite will likely have a larger combined tank and line volume compared to the one-litre volume in this setup, resulting in smaller thermodynamic changes for a given CGT firing time during blow-down. To ensure comparability of test results across different fluidic systems, such as those with varying tank sizes, the following measures were taken:

- The CGTs were fired in individual shots, each covering a specific pressure range, rather than from MEOP to EoL pressure in one continuous shot. This approach reduces the change caused by the blow-down mode per shot.
- As the shot progresses, the inlet pressure and therefore the thrust of the CGT decreases. Therefore, arithmetic averages were calculated for thrust, inlet pressure, propellant consumption and ISP per shot.
- Delays were introduced between shots to allow the propellant in the tank and the overall system to thermally stabilise again. This delay was also used to ensure that the background vacuum pressure dropped below 1 mbar.
- CGT firing times varied from 3 s to 60 s. At high inlet pressures, short durations were used and as pressure decreased, firing times became longer. The aim is to keep the firing time short to avoid excessive temperature and thus ISP drops during blowdown. At the same time, the firing duration must be long enough so that the amount of propellant used is large enough to minimise the error of the propellant measurement scale.

For the average thrust T_{avg} all measured values are corrected for the pipework effect and then the arithmetic mean is calculated. The average ISP is then calculated with the shot duration t_{shot} and the consumed propellant mass Δm_{prop}:

$$ISP_{avg} = \frac{T_{avg} \cdot t_{shot}}{\Delta m_{prop} \cdot g_0} \quad \text{Eq.1}$$

<u>Minimum impulse bit characterisation</u>
In this work, the MIB is defined as the smallest impulse that can be generated when the thruster valve operates at its minimum opening time. A reliable minimum CGT-valve opening time of 10 milliseconds was found for the HP-CGT, thus defining the minimum impulse. The MIB level depends on the inlet pressure.
However, the thrust measurement scale is not fast enough to resolve the thrust curve of a single MIB instance. To still gain insight into the magnitude of the MIBs, several thousand were run in rapid succession. At this rate, the thrust scale did not detect individual pulses and dead times and only gave a time averaged value. With this time averaged thrust value $T_{pulse,avg}$ and with the pulse times and cycle count, the average impulse bit can be estimated with:

$$IB_{avg} = \frac{I_{tot}}{n_{cycles}} = T_{pulse,avg} \cdot \left(t_{on} + t_{off}\right) \quad \text{Eq.2}$$

The average MIB of a pulse sequence then becomes:

$$MIB_{avg} = IB_{avg}(\, t_{on} = 10ms) \quad \text{Eq.3}$$

To validate the assumption that the thrust scale outputs the time average of the pulse sequence, previous characterisation tests of the test setup were performed. The duty cycle of the pulse sequence was varied at a constant high frequency, confirming that the output value of the scale has a linear scaling with the duty cycle, at least in the relevant range from a duty cycle of 100 % down to the duty cycle with $t_{on} = 10ms$. Therefore, the output signal can be interpreted as the average of the MIB pulses.

3.3. Test sequence

The test was conducted following a specific sequence of test setup, as shown in Fig. 7. Test results were obtained during post-processing of test data. The characterisation tests involved initial testing with nitrogen to establish the test sequence for thruster firings and confirm the procedure. Subsequently, the characterisation was performed with argon and krypton during multiple thruster firing runs to cover all EBB configurations and test conditions. Finally, the complete characterisation was carried out using xenon gas. In total, the two EBBs underwent over 200 continuous firing tests and several thousand cycles of MIB tests.

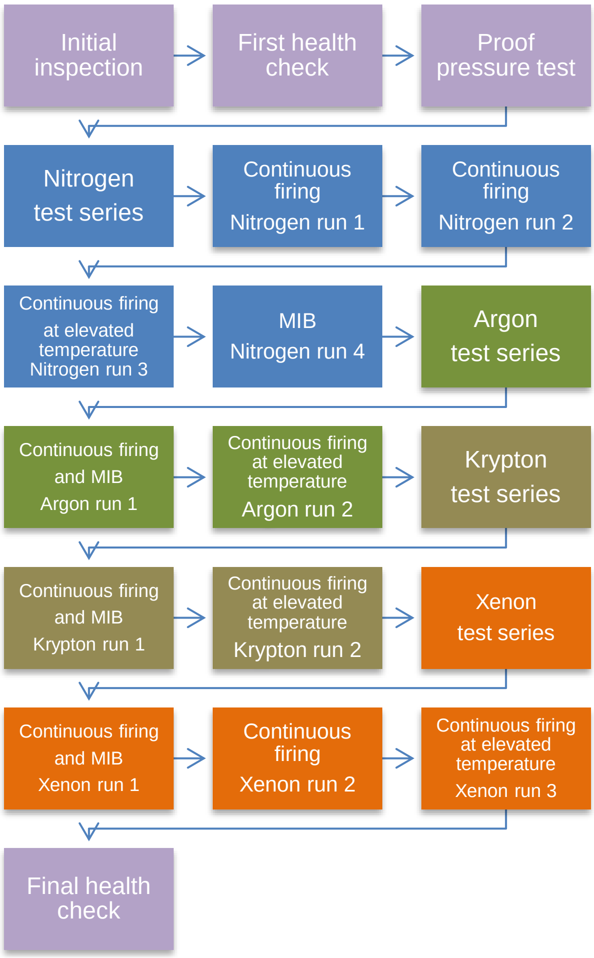

Figure 7. HP-CGT EBB characterisation test sequence

4. TEST RESULTS

This chapter presents and discusses the test results of the HP-CGTs with various gases, temperatures, and pressures.

4.1. Test results of continuous firing

Among all the propellants tested, xenon has the most unique characteristics in terms of ISP and thrust over inlet pressure. Fig. 8 and Fig.9 provide a detailed representation of the thruster performance.

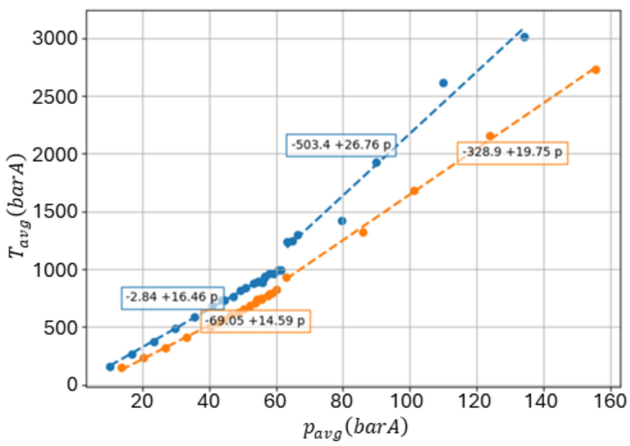

Figure 8. Average thrust of the HP-CGT using xenon propellant. In blue EBB with larger nozzle throat diameter, in orange the EBB with the smaller nozzle.

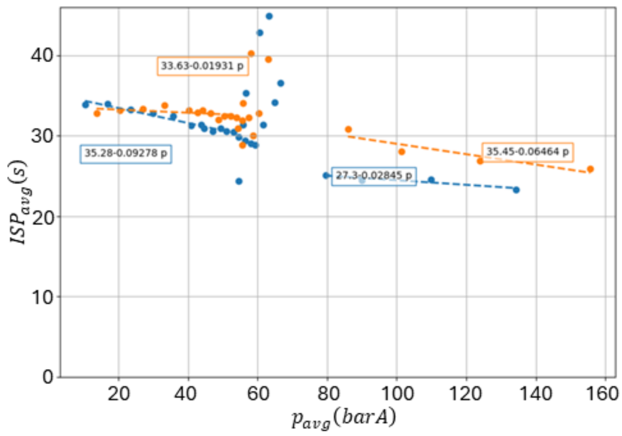

Figure 9. Average ISP of the HP-CGT using xenon propellant. In blue CGT at room temperature, in orange CGT heated to 60°C

Like thrust, the ISP of the HP-CGT when using xenon propellant can also be divided into two regions. A higher ISP of 30 s to 35 s is achieved in the gaseous phase up to 40 bar compared to the supercritical phase with around 25 s from 80 bar upwards. In the pressure range in between of approximately 50 to 80 bar, the ISP measurement with xenon exhibits irregular behaviour compared to other propellants.

In Fig. 10 and Fig. 11 a comparison of the performance of the HP-CGTs with all tested gases is illustrated. Each data point in the graphs represents an individual continuous shot analysed for three average parameters: thrust, ISP, and pressure (refer to section 3.2). In these figures the CGT is shown with the smaller and larger nozzle throat cross-sections, respectively. The diagrams on the left half of each figure display the thrust and ISP in the unheated state, while the right half shows the heated state at 60°C. The specific impulse is higher in the heated state at a higher temperature than in the unheated state. In contrast, the thrust appears to be independent of temperature and linearly proportional to the inlet pressure. Additionally, it is evident that the CGT with the larger nozzle throat cross-section generates more thrust at the same pressure.

<u>Discussion</u>

As per theory [2], the ISP increases with temperature and with a lower molecular mass of the propellant. Consequently, higher ISP values are achieved in the heated state of the CGT and for lighter gases such as nitrogen than in the unheated state and with heavier gases such as krypton.

Xenon propellant displays unique behaviour, with a lower thrust over pressure slope in the gaseous phase below 40-60 bar, but at a higher ISP. Above 60bar, in the supercritical state, a higher thrust slope is obtained, albeit at a lower ISP.

During the phase transition from the supercritical state to the gaseous state in the pressure region in between, irregular ISP measurements occur. It should be noted that the ISP curve in this range is history-dependent, meaning that different values are obtained depending on the exact starting conditions, i.e. temperature and pressure of the fluidic system. After each CGT firing, the inlet conditions are altered due to the blow-down operation, despite the test procedure including a break for thermal equalisation. The time for equalisation was limited, as a complete thermal equilibrium with xenon in this transition state may take several hours to be reached between each shot. The xenon test results obtained in this study are comparable to those achieved by other researchers [1].

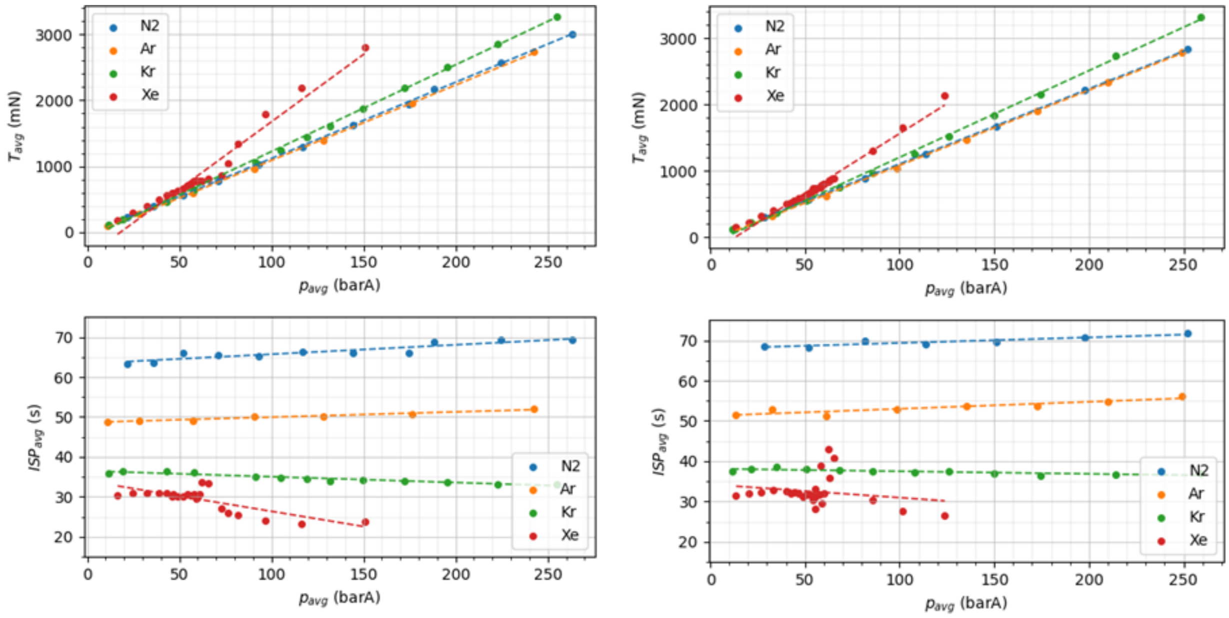

Figure 10. Evaluated results of the performance characterisation of the HP-CGT EBB with the smaller nozzle throat diameter, left at room temperature, right heated with external heater to 60°C

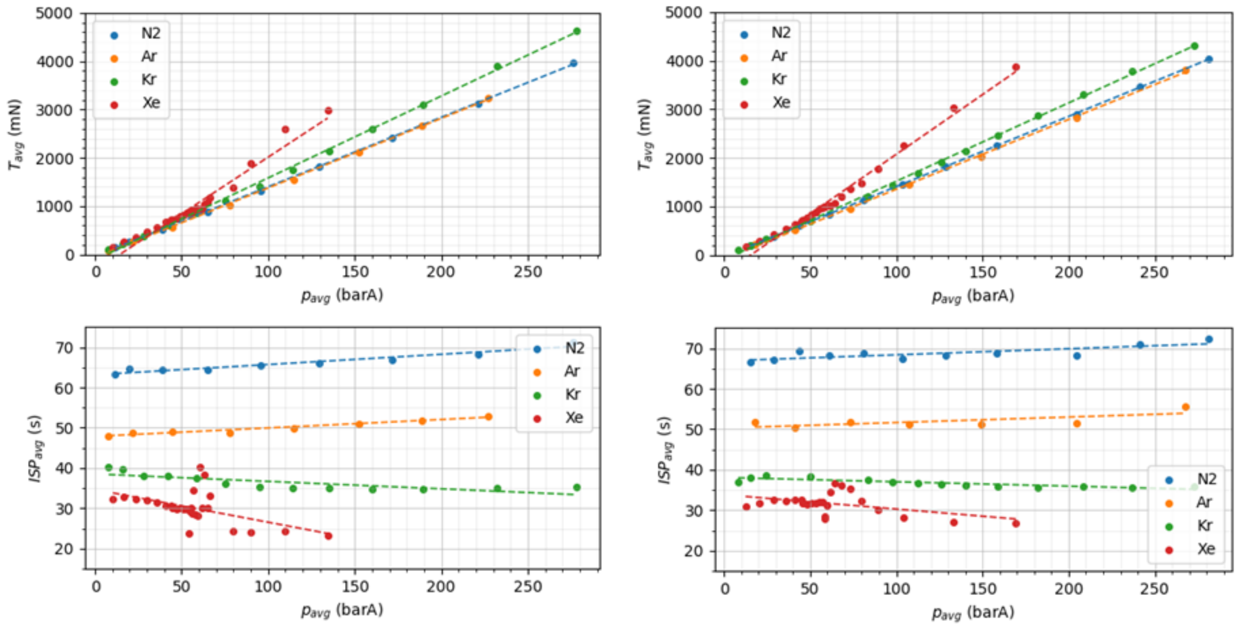

Figure 11. Evaluated results of the performance characterisation of the HP-CGT EBB with the larger nozzle throat diameter, left at room temperature, right heated with external heater to 60°C

4.2. Test results of MIB

The mean ISP of the MIBs is similar to that of continuous firing. Tab. 2 presents the test results for the MIBs. Following the same trend, higher inlet pressures, higher molecular weight propellants and larger nozzle throat diameters will result in higher thrusts for a constant 10 ms turn-on time.

Table 2. Estimated average MIB (at 20°C) of the HP-CGT EBBs, nozzle throat diameter size is given in S (small) and L (large), relative uncertainty for MIB ±6.5% and ±7.8% for ISP

Propellant	Nozzle throat Ø	p_{avg} (bar)	MIB_{avg} (mNs)	ISP_{avg} (s)
Nitrogen	S	33.3	7.07	64.8
	L	33.1	8.14	65.7
Argon	S	34.6	6.94	49.4
	S	70.1	13.9	49.5
	L	35	8.15	49.2
	L	68.2	15.5	47.3
Krypton	S	36.1	5.38	34.9
	S	81.2	17.8	33
	L	37.1	8.1	34.8
	L	68.9	17	35
Xenon	S	38.9	10.6	29.7
	S	67.2	19.3	28
	L	56.4	18.4	26.6
	L	75.8	27.1	21.6

4.3. Xenon plume and ice formation

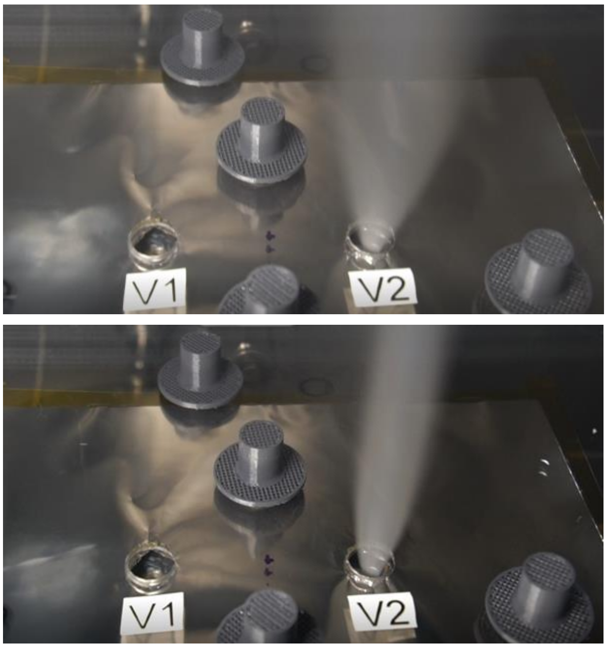

Figure 12. Development of the visible part of the xenon exhaust plume during the firing of the HP-CGT thruster. The upper picture displays the plume immediately after the thruster is started, while the lower picture shows the plume after a few seconds.

Videos were taken of the exhaust plume during firing with xenon from the CGT. An excerpt from the video can be seen in Fig. 12. The visible part of the plume, where xenon is expected to condense into small droplets, constricts over time. An exhaust plume of xenon was particularly visible at high pressures and in the unheated state of the thruster. However, as the pressure decreased the exhaust plume became increasingly transparent, resulting in decreased visibility until it became completely invisible. Ice formation was also observed above the CGT where the viewport of the vacuum chamber is located for thruster observation. During firing, the plume struck the viewport, causing ice to form. After some time, the ice flaked off and fell onto the backsputter shield. It is expected that the ice is composed of xenon rather than water or any other gas species, as the vacuum chamber's background pressure was sufficiently low at the start, and the thruster was operated with high-purity xenon gas.

4.4. Final health checks and summary

No clogging or non-steady mode was observed during the firing of HP-CGTs. The final health check revealed no unexpected degradation for the two HP-CGTs after undergoing a series of tests involving various gas types, temperatures, and pressure conditions. This suggests that xenon ice formation only occurs at the nozzle throat and downstream of it, and that the valve seals were not damaged due to Joule Thompson cooling of the expanding propellant gases.
The technical achievements of the HP-CGT design and test phase are summarised in Tab. 3.

Table 3. Technical achievements of HP-CGT

Parameter	Value	Remark
Propellants	N2, Ar, Kr, Xe	tests performed
Inlet pressure range	186 bar (Xe) 300 bar (other) down to 3 bar	
Thrust	up to 4 N	proportional to inlet pressure
ISP	> 65 s (N2) > 50 s (Ar) > 35 s (Kr) > 25 s (Xe)	depending on inlet pressure and gas temperature
Size	length 93 mm width 43 mm height 44 mm	length with fluidic interface
Mass	< 150 g	without harness
Operational thermal range	-10°C to +65°C	heritage valve temperature range
Minimum valve actuation time	10 ms	typical minimum valve actuation

5. DEVELOPMENT AND QUALIFICATION PLAN

With the positive test results from HP-CGT characterisation test campaign, the suitability of the design for use on future spacecrafts has been proven. Yet, the focus of the Technology Development Element activity was on functional and performance requirements. Aspects like environmental loads, interface definitions and operational constraints are to be accounted for in follow-up activities which shall result in a qualified product. For that, AST had defined a preliminary Design, Development and Verification plan. This defines activities and a sequence of milestones to be passed until flight qualification status is reached (see Fig.13). This sequence follows ECSS standards. The details of the program must be agreed upon with the spacecraft prime.

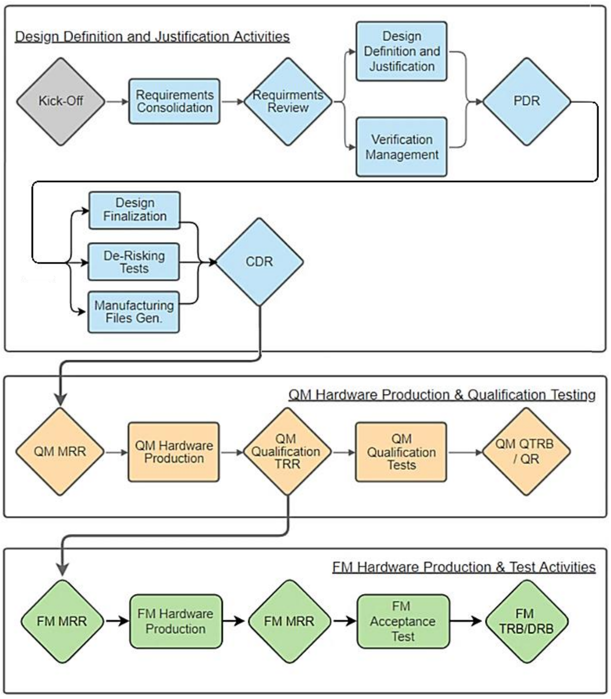

Figure 13. Sequence of major project tasks and milestones

6. SUMMARY AND CONLUSION

The development activity of the High-Pressure Cold Gas Thruster was started in 03/2022 and followed a clear development logic. The requirements initially set by ESA were iterated and completed with supporting functional, performance, environmental and test requirements.

Initial design concepts for the HP-CGT were identified, and trade-offs were made to find an optimal design solution that met the requirements. Lower-level de-risking tests were conducted to support design choices.

Two EBBs were manufactured in a total of four configurations. For their manufacturing, AST's heritage component design and manufacturing processes were used – they are of flight standard to this extend. The direct-driven high-pressure valve which has heritage in many in-flight products was used to build-up the HP-CGT EBBs. The nozzle design was selected to allow maximum available thrust while assuring that pressure-drop appears at the nozzle – not at the valve orifice.

These two test units were then subjected to extensive characterisation testing in AST's test facility. The test setup was tailored to the specific requirements for high mass flows at high pressures with the aim of measuring large thrust ranges. New measurement and test procedures were established and verified as part of the HP-CGT development to ensure that the results are achieved with appropriate measurement uncertainties.

This setup demonstrated that the design of the HP-CGT complies with the specified technical requirements. The overall goal of achieving thrust levels above 2 N at relevant inlet pressure was realized with all gases tested in the characterisation test campaign. The CGT has short operation times of 10 ms, resulting in small Minimum Impulse Bits (MIB).

A development and qualification plan was established to identify residual development needs and propose a qualification approach. It is estimated that the HP-CGT design could be finalized and brought to flight standards for a specific mission within 18 months, with distinct interface and operational requirements. The qualification tasks would verify the flight readiness of the design, with the intention of building flight models from the same qualified design.

The development activity demonstrated that an AST-defined HP-CGT design can effectively fulfil the requirements for high-thrust actuators in upcoming satellites that use gaseous propulsion systems. No obstacles were found that would prevent the finalisation of the design and qualification.

7. ACKNOWLEGEMENTS

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