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ReFEx: Reusability Flight Experiment - Development of a cold-gas RCS using off-the-shelf components

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Abstract

This paper presents an overview of the development done on a custom Reaction control system (RCS) for the upcoming launch of the Reusability Flight Experiment (ReFEx). The RCS is needed for the de-spin and attitude control of the vehicle during the flight phase in the thermosphere and until the aerodynamic control surfaces can take over control of the vehicle during re-entry. The dimensioning and design of the system are explained with regards to the architecture and the picking of commercial off-the-shelf components (COTS) to form the system. The testing done consecutively is presented with the system performance characterization of its behavior.

1. Introduction

Reusable launch vehicles (RLV) have established themselves increasingly in research and development activities concerning future launch vehicles. First stages may perform Return to Launch Site (RTLS) or downrange landing maneuvers at moderate separation speeds, but propulsive solutions necessitate increasingly large stages if they are designed for higher staging velocities.[6] The study for future Reusable Launch Vehicles (RLV) at the German Aerospace Center (DLR) currently involves the development of the Reusability Flight Experiment (ReFEx). It was first presented at the EUCASS 2017 and is a sub-scale demonstrator representing a winged first stage of a RLV.[5,7,10] It is based on experiments such as SHEFEX II and has concluded phase C with the CDR in November 2021. The winged concept aims to dissipate kinetic energy during re-entry through aerodynamic means, rather than additionally carried propellant, and therefore save weight on the stage. Key technologies that are to be demonstrated on this vehicle are the aerodynamically stable flight through many flow regimes by the Guidance, Navigation and Control (GNC) subsystem, working with a closed loop control algorithm utilizing pre- and on-board generated and optimized trajectories, as well as the steady transition between extra- and intra-atmospheric flight and advanced health monitoring of the vehicle.[8] The project is undertaken by a small integrated team at the DLR on a limited budget with in-house manufacturing and testing capabilities.[8] The experiment is approaching flight-readiness with the launch scheduled in 2024 from the Koonibba Test Range (KTR) in Southern Australia using a Brazilian VSB-30 sounding rocket. The available VSB-30 sounding rocket is passively spin stabilized to compensate thrust inaccuracies and decrease the dispersion at stage separation, stage impact and for the experiment flight trajectory. The launcher deploys the experiment of 400 kg into the low-pressure thermosphere with an Apogee of approximately 130 km. An initial de-spin of the payload is performed at 79 s into the flight utilizing a Yo-Yo system. Because of the then still left over spin rate and the necessity for attitude control during the re-entry preparation flight phase the deployment of a thruster system is necessary on the experiment.[1] A general overview of the architecture, interfaces and the placement inside ReFEx is given by Bauer et al.[1] The following chapters provide a summary of the design and development of the ReFEx RCS, as well as an overview over the testing involved in the development and its results.

2. System design

2.1 Development approach

The mission constraints and requirements for the RCS are set and induced by the requirements and aims for ReFEx and will be introduced in the following as appropriate. One of the main constraints driving the RCS development is the

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budget and the resulting necessary cost optimization. An internal development promised to be cost efficient because of the utilization of commercial off-the-shelf (COTS) components, rather than space certified components with flight heritage. The system development within the DLR also promised to be more agile to respond to the development of the overall experiment and achieve a better integration of the system within the Guidance, Navigation and Control (GNC) subsystem and its development.

2.2 Mission, RCS deployment and operation

The full ReFEx mission design, flight profile, markers and further information is laid out by Bauer et al.[1] as well as in other publications about ReFEx.[4–11] The following discusses the relevant points for the RCS.

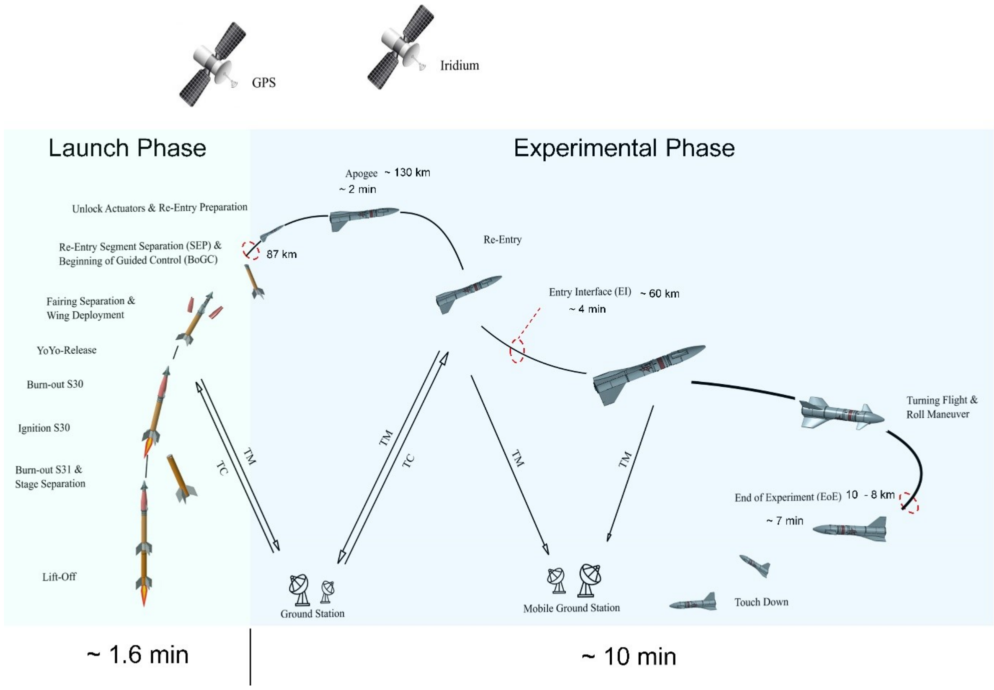

Figure 1: ReFEx mission sequence and flight events[9]

The RCS is powered on in advance and during the entire flight, as the sensor data from the internal pressure and temperature sensors is read and sent as telemetry to the ground stations and launch control. The RCS status being nominal with regards to the read sensor data is one of the requirements for the launch go-ahead. While the Guidance and Control (G&C) subsystem[5] operates throughout the entire launch as well, its commands are only passed onto the RCS system by the interfacing function and port onboard the Guidance & Control Computer (GCC) once the RCS is in the "armed" state in flight at "Unlock Actuators & Re-Entry Preparation" just after the re-entry segment separation. From there the commands from the G&C are transferred into valve actuations within the RCS and the attitude of the segment can be controlled. There are five modes during which the RCS is commanded to execute certain maneuvers during the flight:

- Rate damping mode: RCS reduces left over angular rates of the re-entry segment after yo-yo de-spin to $|\vec{\omega}| < 1°/s$ within 20 s
- Sun acquisition mode: RCS repoints the vehicle to align x-axis with approximated horizon and perpendicular to the sun vector
- Sun scanning mode: RCS slowly rolls the vehicle at a target rate of 2.4°/s to achieve sun measurement with multiple sun sensors
- Entry attitude acquisition mode: RCS repoints vehicle to predefined attack, sideslip and bank angle for atmospheric entry
- Guided entry exoatmospheric mode: RCS follows commands to track a calculated trajectory

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When the dynamic pressure in atmospheric re-entry exceeds 1000 Pa the pressure becomes high enough for the aerodynamic actuators to take over the control with sufficient control authority. The control and actuations are transitioned during this cross-over with simultaneous operation of both actuation systems.

2.3 System architecture

Some of the initial development and conceptual studies were done in a Master's thesis by Lungmuß in 2017.[3] The aim of the work was the design of the system and the selection of the needed components. This also included a cost estimate for the RCS hardware, which was utilized for the eventual decision on the further internal development, laid out in section 2.1. The study by Lungmuß suggests to use two separate systems for the best propellant efficiency. One system with a thrust of 5 N per thruster would be used during exo-atmospheric flight and be mounted within and on the Launch Vehicle Adapter (LVA), while the other system with 60 N per thruster could be used for the transitioning period into intra-atmospheric flight, having first separated the LVA with the low-thrust system. This suggestion was also influenced by the initial plan to include a recovery system in the very back of the re-entry segment including a parachute, not leaving much space at the very back of the vehicle for the implementation of an RCS with an optimal lever arm for pitch and yaw nozzles. The recovery system is eliminated early on in the development though, due to volume considerations and since all flight mission goals will be met by that point. An additional goal is to recover ReFEx after landing for post flight analysis.[8] With the parachute eliminated and space at the very back of the vehicle, it was decided to incorporate a single RCS system there. The nozzles for each thrust direction will thus be mounted onto the back plate of the re-entry segment as displayed in Figure 2 and Figure 5, not being contained directly in the supersonic flow regimes during re-entry, which would cause large local disturbances in the flow. The RCS placement within the re-entry segment and the RCS itself are displayed in Figure 2.

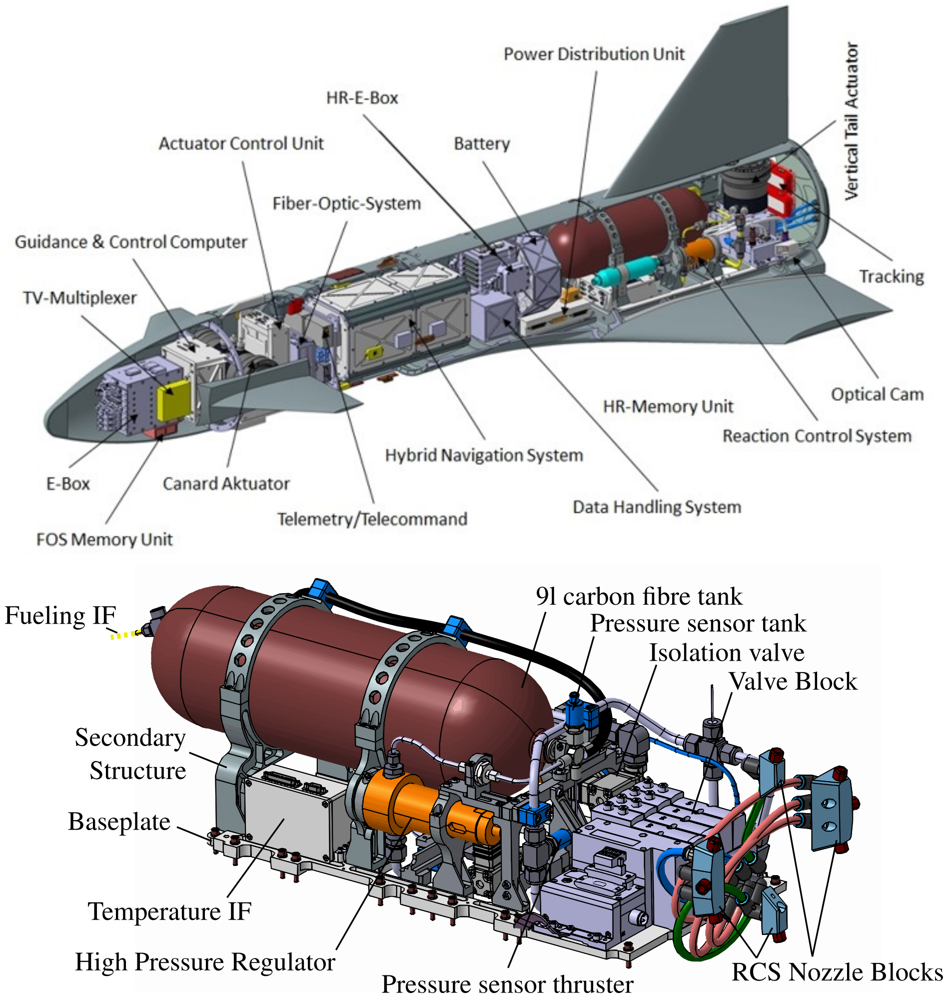

Figure 2: ReFEx re-entry segment[1] and RCS subsystem

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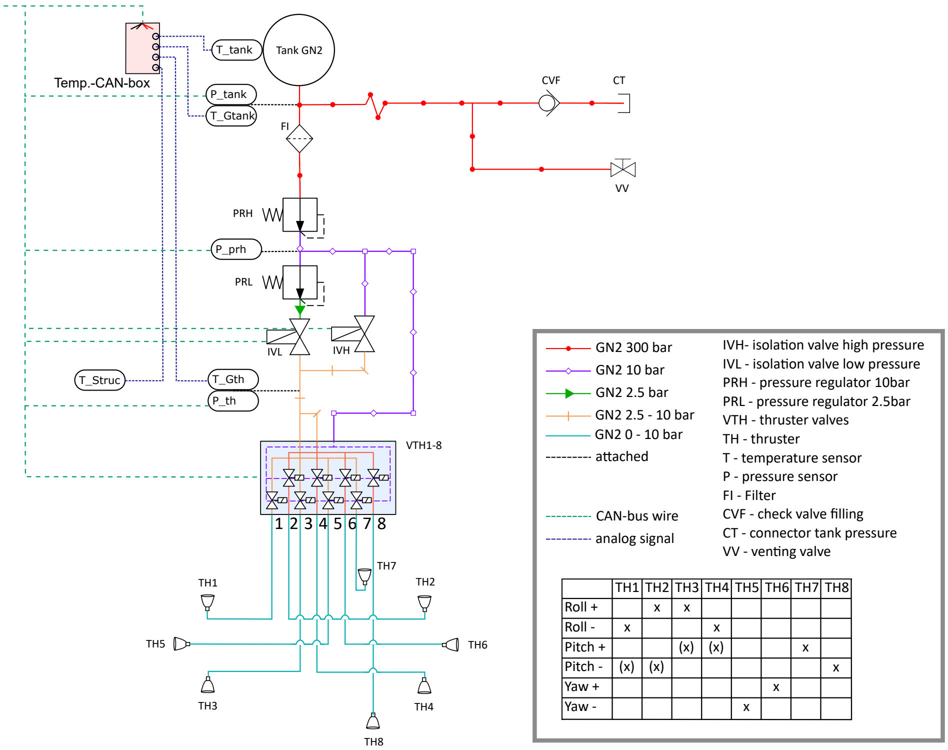
The separate systems with low and high thrust were though considered for a good maneuvering accuracy during the exo-atmospheric flight phase and sufficient control authority during the phases with increasing disturbance torques at atmospheric entry respectively. In order to have differing thrust levels available on the designed system two pressure regulators are integrated into the design with one tank. The pressure level created behind each regulator can be applied to the thrusters through the usage if two isolation valves. The selected absolute pressures are 10 and 2.5 bar. The usage of individual thruster valves would make application of these right before the nozzles possible. However due to cost and space saving measures it is decided to use a valve block with essentially one input and an output for each thruster. The effect of the volume created between each valve and thruster is surveyed in section 3.2.2.



	TH1	TH2	TH3	TH4	TH5	TH6	TH7	TH8
Roll +		x	x					
Roll -	x			x				
Pitch +			(x)	(x)			x	
Pitch -	(x)	(x)						x
Yaw +						x		
Yaw -					x			

Figure 3: ReFEx RCS fluid schematic

2.4 Dimensioning and Component selection

Essential for the dimensioning and selection of the remaining system components is the nozzle. A single custom nozzle is used for all thrusters. Weight of these small nozzles is of no consideration, with the overall weight and center of mass balance needing additional mass at the back of the vehicle anyway. The nozzles and their mounting blocks are therefore custom machined from stainless steel. While also the length of the radially pointing nozzles is not significant, only contributing to an increase in weight, the nozzle exit diameter needs to be chosen complying with axial space restrictions on the aft plate and not cause overexpansion and potential flow separation at the ambient pressures, where the RCS is to be active. These restrictions lead to an early fix of the nozzle to an expansion ratio of 10 with a throat diameter of 3 mm and a conical exit geometry with a half angle of 15°. The conical shape is decided upon, because of its relative ease to manufacture this nozzle geometry, the non-necessity of having a short nozzle and the exit momentum loss through the divergent flow at that expansion ratio only being estimated at $\approx 0.2\%$.[12] The nozzle size is decided upon iteratively, considering the vehicle's moment of inertia, a rough mission architecture (de-spin, re-orientation, limit cycle) and the demands to the RCS during the exo-atmospheric phase. An OpenFOAM simulation of the nozzle is conducted to ensure proper behavior. The propellants of choice are analyzed and evaluated by Lungmuß.[3] While the efficiency and specific impulse of the thrusters is important, so is the usage of the limited volume for a tank within the vehicle and the total impulse. It is decided to utilize nitrogen gas, as it is inert, supplies good specific and total impulse and is cheap to procure. With the 10 bar chamber pressure applied at an ambient 140 Pa this results in an ideal specific impulse I_{sp} of 73.1 s and thrust of 11.6 N. The lower pressure of 2.5 bar can ideally achieve an I_{sp} of 72.9 s and a thrust level of 2.9 N. The 140 Pa ambient pressure for the calculation are approximately the average pressure at which the system is tested in the vacuum chamber and is coincidentally also around the highest pressure to which the

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RCS operates during flight. With the thruster positions as given in Figure 5, this results in a torque in each axis of $\mathbf{M} = [2.87, (11.83 \vee 36.10), 11.80]\,\mathrm{N\,m}$ on high pressure/thrust mode and $\mathbf{M} = [0.72, (2.96 \vee 9.00), 2.94]\,\mathrm{N\,m}$ on low pressure/thrust mode. The pitch direction is originally designed without thrusters 7 and 8, but because of redundancy and control authority necessity in the design the pitch axis includes the option to use either to use the one central thruster or all three in up/down direction, dependent on the mode needs. The thruster-direction matrix is displayed in Figure 5 as well. The thrusters are mounted on the aft-plate interfacing blocks at an angle of 15° to the plate, since the plate includes a raised edge. The 3.4% loss of torques from that angle aims to eliminate thrust diversion and losses due to the thrusters being pointed directly at the edge. With the thrusters sorted out the rest of the system can be designed and picked out in order to comply with the thrusters' design points and with the mission demands. This includes mainly the tank and pressure regulators, but also the valves and other appliances. A fluid schematic of the entire system is displayed in Figure 3. In order to estimate the total fuel demand of the mission the aforementioned nozzle iteration also includes the calculation of the needed propellant for the rough mission architecture and an evaluation of the margins with input of a stored volume at a starting pressure. The analysis of the needed propellant and possible tanks for the RCS converges on the usage of a 9 L pressurized gas composite tank. The tank has a specified working pressure up to 300 bar and is tested between −50°C and +60°C also retaining functionality for small time frames above even 177°C. The pressure regulators need to convert the applied pressures at their entries to the required pressure levels at the thrusters. If pressure regulators are undersized they cannot keep the chamber pressure on the thrusters at or around the designed level when one or more thrusters are open, though they are not the only source of flow resistance in the designed system (valves, filter, pipes, manifolds). In the early design two buffer tanks were also envisaged, but dropped during testing as described further in section 3.2.1. In order to pick out pressure regulators with a sufficiently high flow coefficient, among other performance questions, a 1D simulation is carried out utilizing EcosimPro's European Space Propulsion System Simulation (ESPSS) Library. The model schematic representing the RCS is displayed in Figure 4.

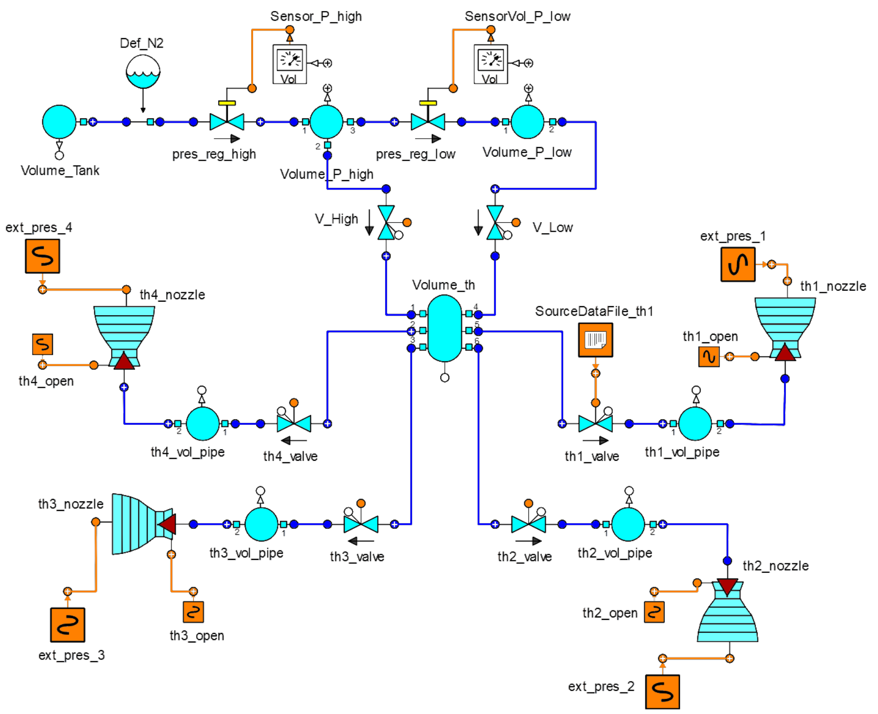

Figure 4: EcosimPro model for simulating the RCS

With mission firing profiles for the thrusters not available during initial development and the idealized propellant demand already roughly being determined, the main goal for the simulation is to evaluate the pressure levels within the system during thruster firings. Therefore, minimum impulse bit and longer activations are simulated. Based on the simulated pressure levels, two on-hand pressure regulators are used for the first physical tests. The valves needed in the RCS setup are selected considering the aims for a minimal pressure loss in the open state, a default closed state, a controllability via a CANopen bus line supplying 24 VDC, vacuum operability and a resistance against the physical loads at vehicle launch. For the isolation valves two industrial DN10 solenoid valves are picked, which are installed with a CAN driver operating the valves according to the supplied digital signal. For the thruster valves it is decided to utilize an industrial valve block platform to minimize the used-up space, wiring and cost. Because the spatial separation

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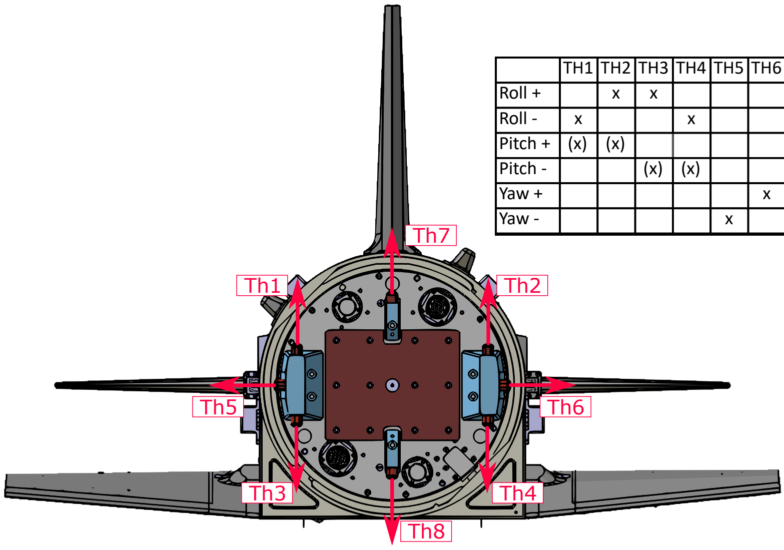
of the thruster valves from the nozzles was of a concern, tests are conducted to investigate whether the intermediate tube volume has a significant effect on the thrust levels. These tests are laid out in section 3.2.2. The tubing utilized for connecting all components mainly consists of 6 or 12 mm steel tubing connected via compression fittings and thread adapters for a flexible design and easy self-assembly. For the up to 300 bar pressurized filling line reaching into the forward part of the vehicle also an aramid braided, polymer hose is used. For applications with lower applied pressures levels where flexible tubes are needed, eg. from the thruster valves to the aft plate feedthroughs, polyamide tubes are used.



	TH1	TH2	TH3	TH4	TH5	TH6	TH7	TH8
Roll +		x	x					
Roll -	x			x				
Pitch +	(x)	(x)					x	
Pitch -			(x)	(x)				x
Yaw +						x		
Yaw -					x			

Figure 5: RCS thruster configuration on aft plate

3. Testing

The Assembly, Integration and Testing (AIT) campaign for the ReFEx RCS is split into four steps of testing on different setups and system readiness levels. The program is displayed in Table 1. The first stage involves the unit tests, where the picked-out components are tested individually where necessary in order to validate their operability under load where this cannot be ensured from specifications or heritage. The next step is the assembly of the Breadboard Model (BBM), where the components and system layout are tested in an easily adaptable setup electronically and fluidically and where the baseline system performance characteristics are determined. The third step is the assembly and test of the Structural Test Model (STM), which in the case of the RCS also resembles the Engineering and Qualification Model (EQM) referenced by Rickmers et al.[8,9] The fully functional and representative system is therein qualified according to the mechanical requirements and the propulsion and fluid aspects are characterized further and definitively. The Protoflight Model (PFM) is finally built up in the same way to be tested against acceptance criteria. The PFM becomes the Flight Model (FM) once the completed system is verified. The main difference in this model philosophy to other developed ReFEx subsystems is that the STM and EQM are the same model. The COTS components with the finalization of the system layout and design after the BBM allow for the build-up of the complex model in its final architectural and functional state.

3.1 Unit testing

For the thruster valves and pressure regulators, intended for use in the ReFEx RCS, functionality under the mechanical loads could not be ensured in advance. Therefore, before basing the entire system around them, they were individually tested on an in-house shaker table. Qualification loads resembling the VSB-30 rocket launch vibrations were applied, as well as the nominal operating input pressures. With a pressure sensor in the output line it could thus be determined that the individually tested thruster valve had no anomalies during or after the vibrations. The pressure regulators also had no opening anomalies, where their integrated spring would be excited enough by the accelerations that the forward pressure would be opened to the back pressure and the output pressure would rise above the set pressure. The high-pressure regulator designated for regulating from the tank pressure to 10 bar and the low-pressure regulator for the 10 bar to 2.5 bar were both able to supply and limit their output pressure. Unlike the tests of the valve (see Figure 6),

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Table 1: Tests to be conducted (T: Test, I: inspection, A: Acceptance, Q: Qualification)

Requirement group	Test	Stage			
		Unit	BBM	EQM	PFM
Propulsion	Thrust level and orientation		T	(T)	
	Minimum impulse bit		T	(T)	
	Impulse reproducibility		T	(T)	
	Total impulse			T	
	Cycle life		(T)	T	
	Mission life			T	T
	Plume effects		T		
	Pressure regulator	T			
Fluid	NDI		I		I
	Leakage		T		T
Mechanical	Vibration	Q		Q	A
	Shock	Q		Q	
EMV	EMV				T
Thermal	Vacuum / thermal balance				A
Functional	Functional checkout wth. GNC		T		T
	Thruster alignment				T

the unit tests for the pressure regulators were carried out after the BBM tests, so that the components switched out during the BBM tests did not need re-testing on the shaker, though this would have caused delays were the tests not successful.

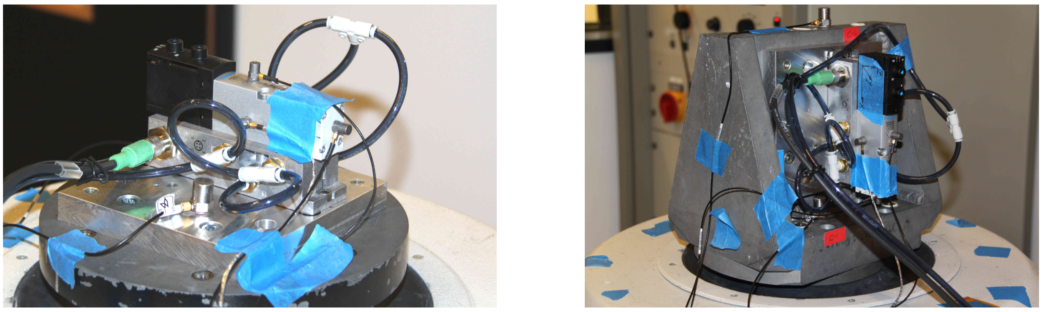

Figure 6: Single thruster valve shaker test setup (two of the axes)

3.2 BBM Testing

The Breadboard Model tests are conducted to determine the reaction control system's performance right after procurement of the considered components. The aim is to identify and improve potential issues where the system and its performance can be further ensured and improved before the system is integrated as the EQM. The breadboard setup is displayed in Figure 7 and is equivalent to the schematic in Figure 3. The fluid setup as displayed is supplied with nitrogen gas. Gas from a bundle of gas cylinders up to 200 bar is in different cases either reduced to a constant testing pressure or pressurized further in a pneumatic compressor stage up to the needed 300 bar for testing the storage in the first stage of the model. The gas is supplied to the high-pressure regulator to be regulated down to constant 10 bar pressure. This pressure is applied to the thruster valve block at the pilot pressure supply inlet inside the vacuum chamber. The valve block is operated inside the vacuum chamber from the beginning in order to minimize the distance from the valve block outlets to the test nozzle. The 10 bar are also applied to the low-pressure regulator. The output 2.5 bar or the 10 bar pressure level can then be applied to the thruster valves by opening either of the two isolation

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valves. The output of the thruster valve block is connected to the aft-plate mockup with the thruster mount blocks. The mock-up plate is mounted on 3D load cell to measure the thrust performance. Pressure sensors for the BBM are inserted to measure the tank/inlet pressure, pre-thruster valve pressure and the pressure between the thruster valves and the thruster nozzle block in the early cases.

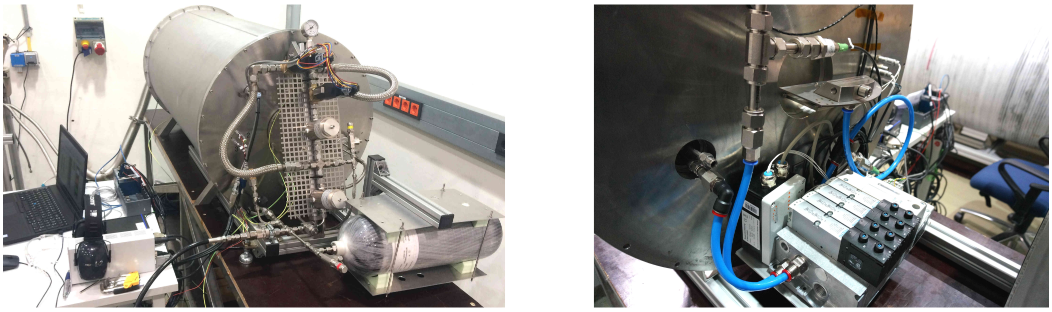

Figure 7: BBM (outside & inside the vacuum chamber)

3.2.1 High pressure regulator

During the initial RCS testing with the BBM it is noticed that the high pressure regulator seemed to bottleneck the RCS performance severely. Figure 8 shows thrust measurements of 200 ms, single nozzle thrust bursts together with the recorded pressure data. From the graph it is evident that the initial pressure level of 10 bar cannot be held and falls off with the ongoing firing. The measured force behaves accordingly. Such a pressure drop was not simulated with the specified flow coefficient of $C_V = 0.5$ for the pressure regulator. Both high and low pressure regulators have an aluminium casing, but in order to improve the performance of the system a pressure regulator with a higher flow coefficient of $C_V = 2.0$ and a heavier brass (later steel) casing was chosen. This pressure regulator is used hereinafter. The initially envisaged buffer tanks can reduce the pressure regulator effect, but they are decided against for reasons of thrust consistency and space management.

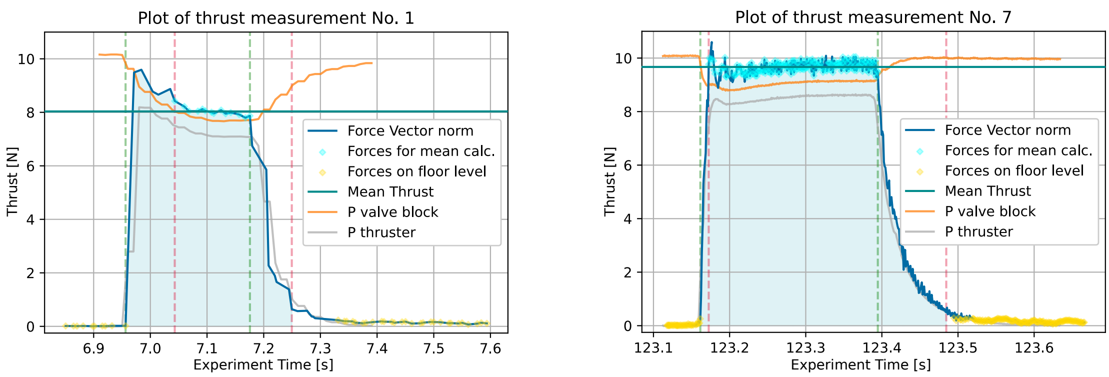

Figure 8: Thrust measurements with initial (l) and new (r) pressure regulator (10 bar to vacuum)

3.2.2 Thruster tube length

The usage of the valve block for the thruster activations and the vehicle actuations is chosen to decrease cost, complexity, volume and weight for the RCS system setup. The separation of the valves from the nozzles creates a volume within the connecting tube, which could have an effect on the thruster performance characteristics. This is thus investigated within some tests conducted at ambient pressure. Tube lengths of 130, 365 and 790 mm are investigated. The force data created by the 130 mm tube is incoherent with the other tubes, most likely due to bracing and preloading of the load cell by the stiff tube, so it is not considered. The thrust performances for the 365 and 790 mm tubes lined up with the previous results. Two representative plots of thrust measurements are displayed in Figure 9. The rise and fall times to and from the recorded thrust level vary according to the intermediate volume and are marked with vertical lines. From all test results it is therefore concluded that transient effects for switching on and off the thrusters are influenced by the tube length. The thrust and impulse measurements for the 200ms test firings though spread around the same

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value, varying through tube installation iterations. Thus, the tube lengths for all thrusters shall be executed around the same length, so that the transient behavior can be accounted for by the controller.

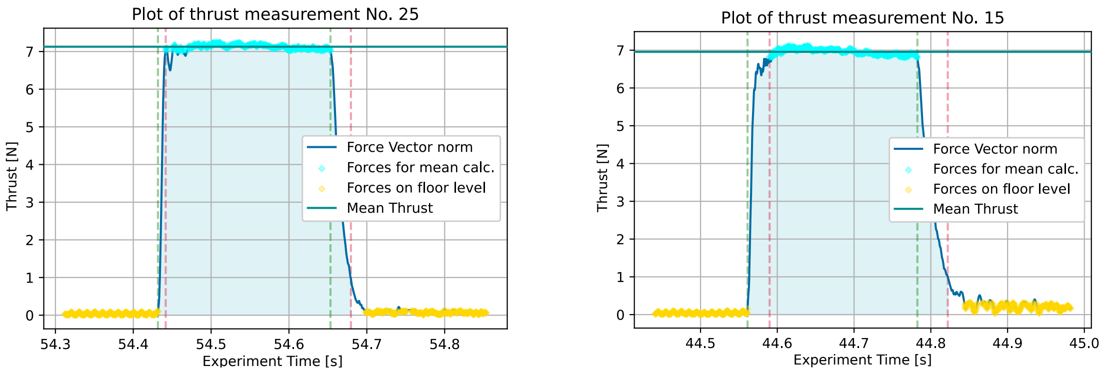

Figure 9: Thrust measurements with 365mm (l) and 790mm (r) tubes (10 bar to atmospheric pressure)

3.2.3 System Delays

The measurement of thrust cycle characteristics is largely tested with the EQM. The representative physical form of the actual system and the operation of the system within the vacuum provide more accurate data for the eventual FM and the control algorithm design. Software changes were made between the BBM and EQM, having to incorporate the entire data stream into the CAN bus interface. This means that control and measurement data within the BBM testing could be recorded synchronously at 1000 Hz. The CAN bus implementation for the EQM test rig though only allows the recording of synchronous data at up to 100 Hz. This means that the data from the BBM tests is in this test case more suited to be used for analysis of the system behavior with regards to the delays between when a command is issued and when it takes effect. An in-depth explanation on the behavior of thrust pulses is given by Brown [2, 4.4.1.2]. Data from the BBM tests is processed and a test series for each of the thruster pressures operating at 2.5 bar and 10 bar is displayed with the results in Figure 10. The opening and closing delay results are used to build an accurate software simulation model of the RCS that is used in the loop with the GNC simulation to further the control development.[11]

3.3 EQM Testing

With the verification of the system components and the outlook of the to be expected performance and behavior the system is integrated into it's final structure. The RCS EQM consists entirely of flight equal hardware, including the pressure regulators, valves, tubes, tubing shapes, electronics and structural parts. The built up EQM can therefore be used to determine the flight-equivalent system performance, which is then further communicated. For performance assurance, some of the testing done with the BBM is rerun with the EQM. As displayed in Table 1, the EQM testing therefore comprises measurement of the thrust and impulse levels, total impulse, the thrust cycles and the mission life. These tests and their respective results are laid out in sections 3.3.1 to 3.3.3.

3.3.1 Thrust, Impulse and Cycles

The first tests are carried out to analyze individual thrust bursts. Parameters are changed in order to gather data for the differing operational conditions through a set of 30 200 ms bursts. The 790 mm tube is used for connecting the thruster valve block to the measured thruster on the load cell. The changed parameters through the tests include the thrust pressure levels and the number of thrusters opened at once. The testing is carried out with the setup displayed in Figure 11. All components are within the vacuum of the chamber during the section 3.3.1 tests. The pressure regulators keep their set pressure in relation to the respective ambient pressure, which results in a change of their absolute output pressure. While the pressure regulators were set to output the demanded 10 and 2.5 bara during the BBM testing, when vacuum is applied the output pressures are reduced by 1 atm each. This is counteracted by setting the low-pressure regulator to 2.5 bara + 1 atm of output pressure. The high-pressure regulator is though kept at the initial level, since the allowed rating for the connected valve block's pilot pressure is specified to within 3 - 10 bar, which would be exceeded by setting it to 10 bara + 1 atm initially. The recorded thrust bursts were analyzed to record their mean thrust level, the effective impulse and the burst cycle behavior. The mean thrust is determined by filtering the data above a set threshold through an iterative z-score exclusion. This data is marked as "Forces for mean calc." within the thrust measurement plots in Figure 9, 10 and 12. Concurrently this data is also used for determining rise and fall times of the thrust. These

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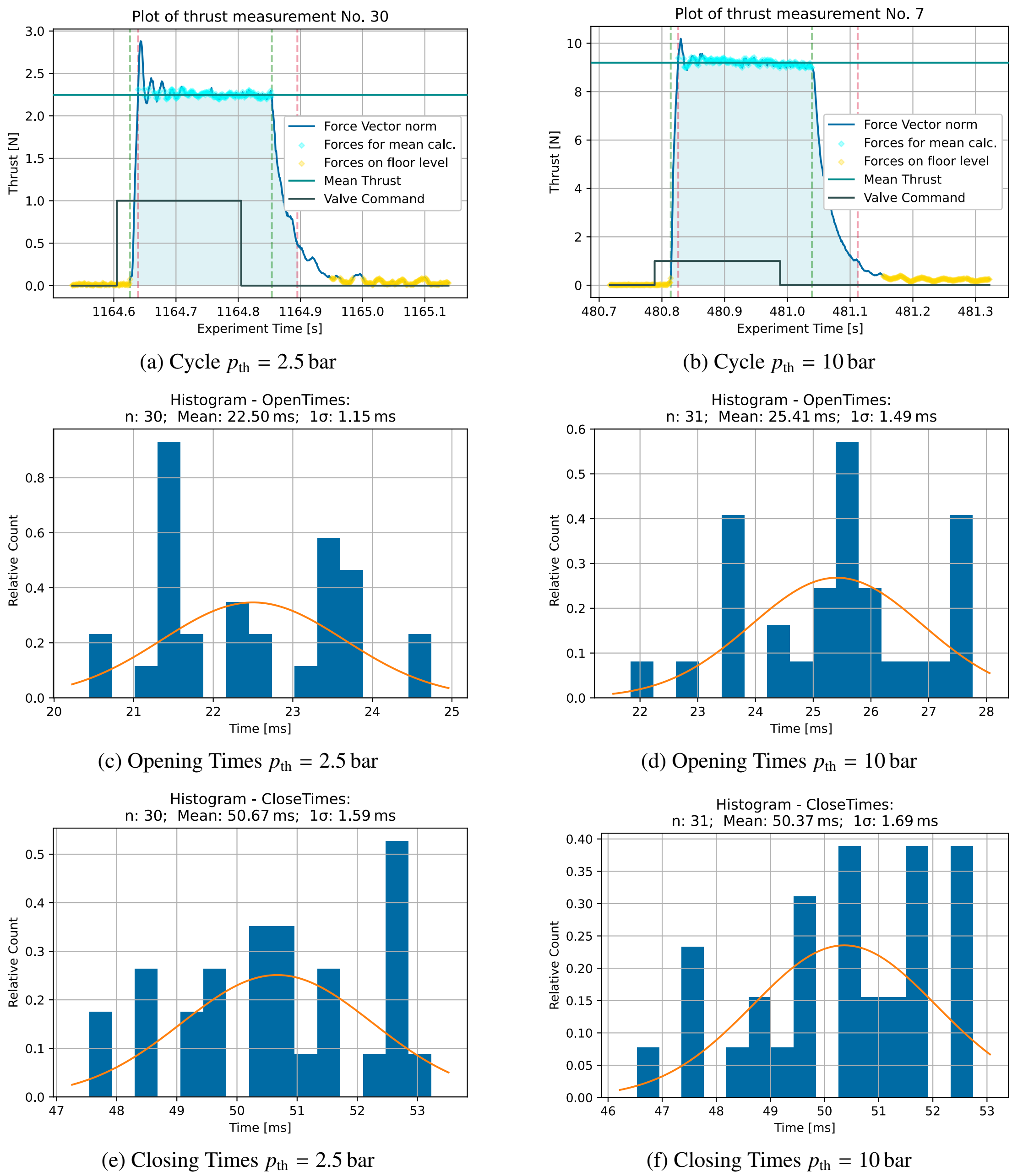

(a) Cycle p_{th} = 2.5 bar

(b) Cycle p_{th} = 10 bar

(c) Opening Times p_{th} = 2.5 bar

(d) Opening Times p_{th} = 10 bar

(e) Closing Times p_{th} = 2.5 bar

(f) Closing Times p_{th} = 10 bar

Figure 10: Thrust cycle results for RCS BBM at ambient (pressure regulators set to 2.5 bar and 10 bar at ambient)

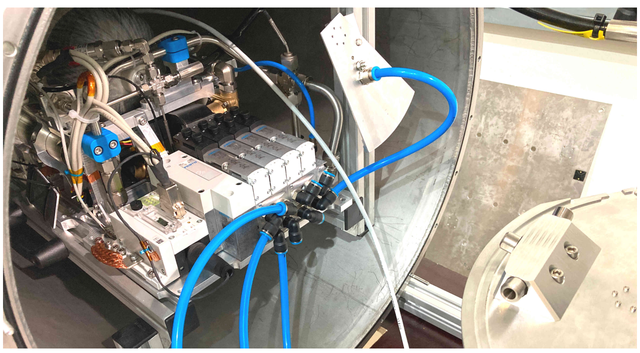

Figure 11: EQM (entirely inside the vacuum chamber)

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times are defined in the following way so that they can be compared eg. to simulator results and not in the way that Brown defines them [2, 4.4.1.2]. The specified marks are highlighted by dashed green and red vertical lines eg. in Figure 12a. To determine the start of the thrust rise the data is also filtered through z-score exclusion to determine the floor level of noise and recognize the point where the thrust rises above this level. The time between this point and the first data point for the mean thrust is determined to be the rise time. The time between the last considered point for the mean thrust and the point where the thrust drops under 0.5/1 N respectively is determined to be the fall-off time of the thrust. The latter point is chosen since a threshold closer to zero is more heavily influenced by the random oscillations in the measurement that are picked up after thrust cycles. The results for the thrust, impulse and cycle behavior from two 2400 Hz measurement series are displayed in Figure 12.

Also determined were the thrust deratings from having multiple thrusters opened at once, as can happen when a roll command is issued or several axis are being actuated at the same time. This increase in propellant demand leads to a higher flow through the respective pressure regulators and thus an attenuated output pressure and chamber pressure for each thruster. To determine the multi-thruster derating factors for the two pressure levels multiple series of thrust cycles with alternating numbers of activating thrusters are conducted. From the collected data the mean thrust for the different numbers of simultaneous thruster activations are determined. The derating graphs for the two pressure levels are displayed in Figure 13. The derating factors are summarized in Table 2 for the high-pressure (HP) and low-pressure (LP) modes, which are used in the simulated RCS model for an accurate performance representation. In this case, with multiple thrusters affecting the force measurement, only the thrust values in the x-direction are used for the data processing. Only one thruster is fired in this direction. Disturbances and mounting inaccuracies skew the results to a degree in this case. Otherwise the thrust vector was determined, where only one thruster is measured in the other tests.

Table 2: Thrust derating factors - firing multiple thrusters at once

Thrusters	HP	LP
1	1	1
2	0.938	0.851
3	0.897	0.711
4	0.749	0.605

3.3.2 Total Impulse

The total impulse of the system is calculated first theoretically during the initial dimensioning of the RCS mentioned in section 2.4. The total real and effective impulse can be determined through the filling pressure of the RCS tank, the measurement of the thrust and the determination of the mass flow and specific impulse. In compliance with the RCS test matrix in Table 1, a series of dedicated tests for the determination of the total impulse are also carried out with the EQM. To achieve this thrust cycles within the vacuum chamber are carried out until the pressure regulators can no longer supply their set output pressures. This point of insufficient tank pressure to keep the performance was identified to be around the time when the tank hits pressures below 15 bar. Below this fill pressure the thruster chamber pressure seems to not be held up during firing due to the thrust dropping off increasingly with the further falling tank pressure. In the flight experiment this would be the point where the RCS is to be considered insufficiently fueled for further operation, since the design envelope of the controller around the RCS performance is being left. Since the pressure regulator dimensioning notes from the manufacturer specify a proportional flow resistance up to the input pressure being twice the output pressure, this is given a slightly bigger margin and is set to 20 bar.

The experiments are conducted from the full 300 bar tank until the tank within the vacuum chamber is empty. After each thrust cycle the vacuum pressure within the chamber rises and there needs to be a delay until the pressure inside the chamber returns to the initial level and further test firings are issued. The vacuum chamber pressure during tests is recorded in the order of magnitude of ≈100 Pa dependent on the thrust commands issued. The entirety of the thrust cycles with altered firing durations and different thruster pressures are recorded over an average time of 14 h. Due to the recording of thrust data at 2400 Hz creating too much data over the conducted test time to handle, only the first couple of thrust cycles are measured at this data rate for an accurate impulse determination for these cycles. The entirety of the thrust data is recorded at 100 Hz as explained in section 3.2.3. The recorded and determined impulses, cycle numbers and resulting total impulse estimations are displayed in Table 3.

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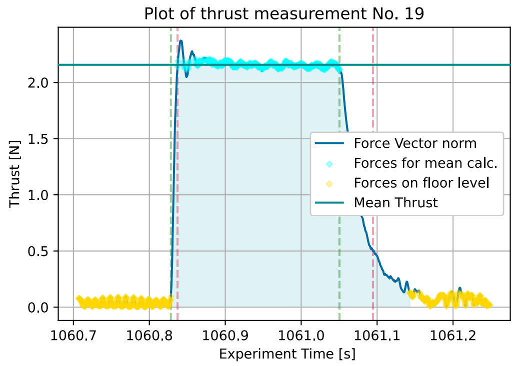
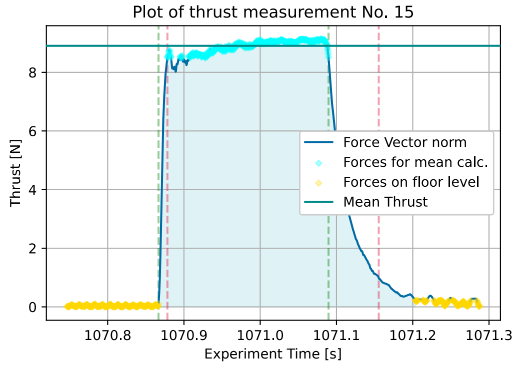
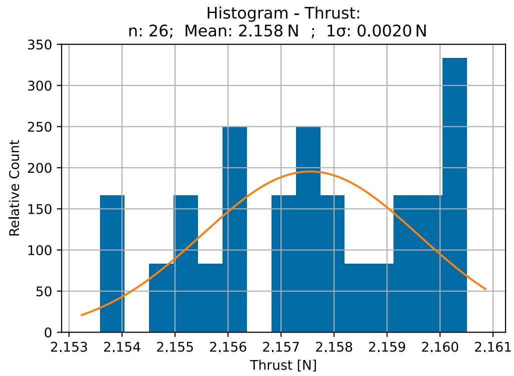


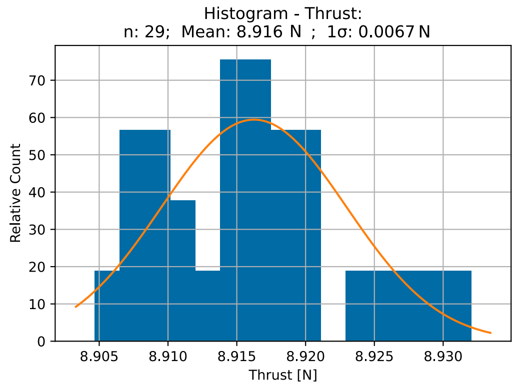
(a) Cycle $p_{\mathrm{th}} = 3.5\,\mathrm{bar} - 1\,\mathrm{atm}$



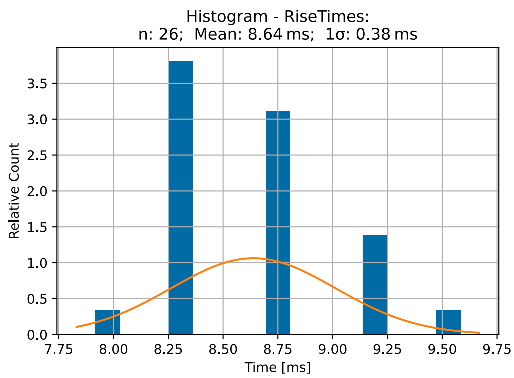
(b) Cycle $p_{\mathrm{th}} = 10\,\mathrm{bar} - 1\,\mathrm{atm}$



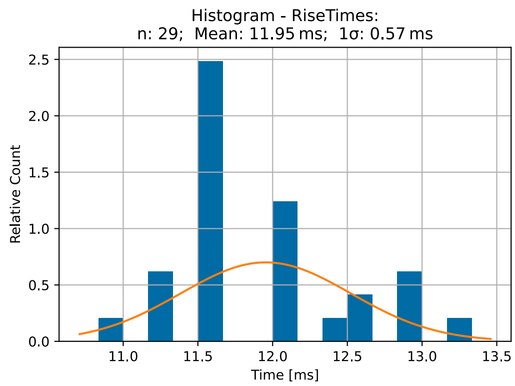
(c) Thrusts $p_{\mathrm{th}} = 3.5\,\mathrm{bar} - 1\,\mathrm{atm}$



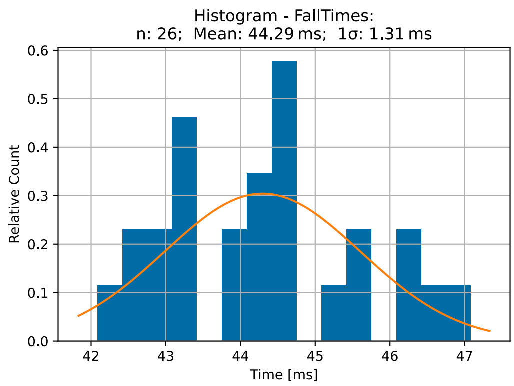
(d) Thrusts $p_{\mathrm{th}} = 10\,\mathrm{bar} - 1\,\mathrm{atm}$



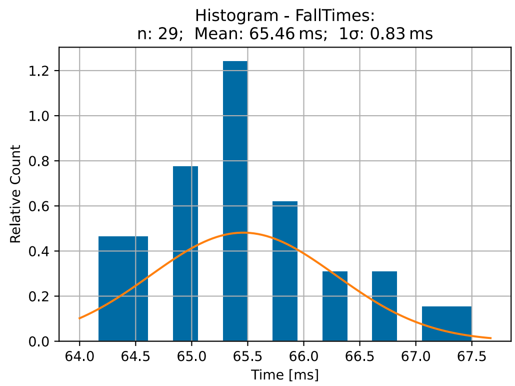
(e) Rise Times $p_{\mathrm{th}} = 3.5\,\mathrm{bar} - 1\,\mathrm{atm}$



(f) Rise Times $p_{\mathrm{th}} = 10\,\mathrm{bar} - 1\,\mathrm{atm}$



(g) Fall Times $p_{\mathrm{th}} = 3.5\,\mathrm{bar} - 1\,\mathrm{atm}$



(h) Fall Times $p_{\mathrm{th}} = 10\,\mathrm{bar} - 1\,\mathrm{atm}$

Figure 12: Thrust cycle results for RCS EQM in vacuum (pressure regulators set to 3.5 bar and 10 bar at ambient)

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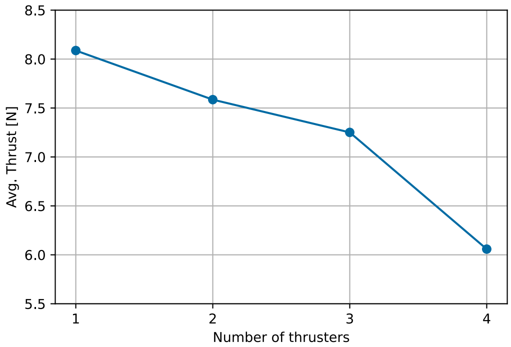
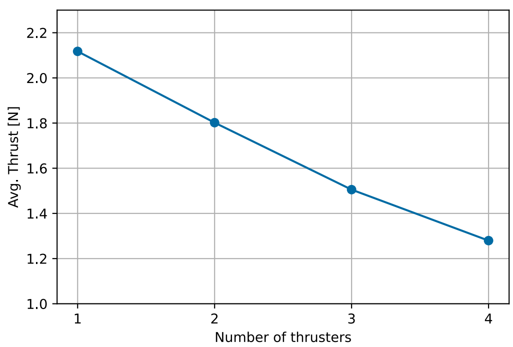


(a) Avg. thrusts at p_{th} = 10 bar − 1 atm



(b) Avg. thrusts at p_{th} = 3.5 bar − 1 atm

Figure 13: Thrust cycle derating results for EQM in vacuum

Table 3: Total impulse estimations as determined from the dedicated tests

Test	Pressure	Cycle open [ms]	Impulse per cycle [Ns]	Cycles to 15 bar	Total Impulse [Ns]
1	HP	200	1.941	883	1714.529
2	HP	300	2.911	556	1618.712
3	LP	1000	2.271	721	1637.342

The differing results can be explained in part by the isolation valve being constantly on during the first experiment which resulted in a significant, constant heat input into the setup in the vacuum over the experiment duration. In the experiments 2 and 3 the isolation valve was switched off in between cycles to eliminate the thermal influence. Also, the first experiment was filled and topped up a few times to start the experiment at room temperature. The latter experiments were started with more proximity to the main filling of the system, which meant a higher starting temperature that resulted in less propellant mass being loaded at the starting pressure.

3.3.3 Mission Life

For the mission life tests a preliminary simulated thruster firing profile is translated into timed firing commands for the RCS testing setup. The mission simulation profile is consequently executed with minor modifications for the pressure level switching points in the firing profile. The tests were carried out to check if the high fluctuation of switching different valves would cause any problems. No problems during the test were recorded. The receding tank pressure during one of the tests is displayed in Figure 14.

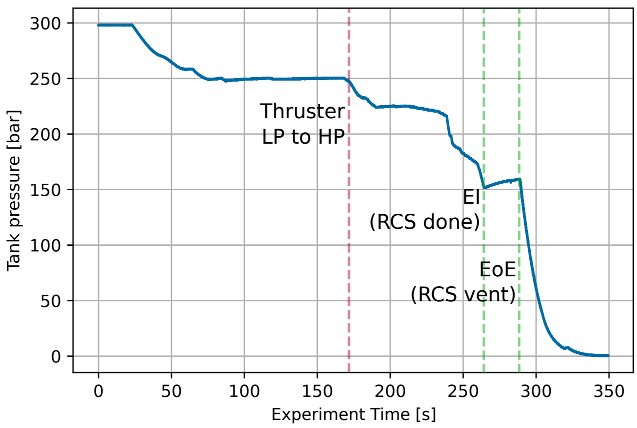


Figure 14: Tank pressure development with thruster firings based on simulated course of events

The mission life firing profile ends at 265 s into the displayed experiment. It is decided to passivate the RCS after the End of Experiment (EoE) (see Figure 1). In order to accomplish this all valves are opened after the declaration of the EoE at the high pressure level to vent the remaining propellant in time for the landing. The thrusters all being opened

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at once should cancel out any turning moment on the vehicle. If there is one or more thruster failures the aerodynamic control surfaces have the control authority to cancel out thrust imbalances. A thruster failure could appear if a thruster module on the valve block fails or a connecting tube melts due to the re-entry temperatures.

4. Conclusion and Outlook

The ReFEx mission and the resulting demands on the developed RCS are presented. The process of dimensioning and designing the system in architecture and detail is laid out in the sequential sections. The applied testing methodology is presented and the resulting findings and system refinements are presented and discussed. Graphs and tables show the measured system performance and detail the found behavioral features.

In the further development and testing of the RCS the EQM will be subject to the qualification mechanical tests that are to be performed on the ReFEx launch segment STM during Q3 2023. This will conclude the testing with the RCS EQM. For the subsequent build of the RCS PFM components have been and are being sourced in order to be able begin the RCS PFM tests in close succession of the mechanical testing in Q4 2023. Additionally, the testing results are continuously being shared and interpreted with the colleagues working on the GNC, as the controller requires characterization of the RCS performance for its best utilization. This is described further by Robens et al.[11] Further testing with the new PFM and the existing testing hardware and software infrastructure will prove to generate quick performance comparisons to the EQM. The in-depth dimensioning process, including applied estimations and simulations, as well as the in-depth performance analysis with more comparisons between the tests is planned for future publications.

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