PROPELLANT MANAGEMENT UNITS FOR ELECTRIC PROPULSION THRUSTERS IN SERIES PRODUCTION AND IN UPDATE FOR NEW APPLICATIONS

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ABSTRACT:

Over the last decade, AST Advanced Space Technologies GmbH (AST) has developed highly integrated fluid management devices for space propulsion systems. Today, over 400 units are flying in orbit with millions of flight hours in-orbit proving the robustness of the design and the chosen production approach.

The product with most flight heritage is the High-Pressure Flow Control Unit operating on LEO spacecrafts in a large constellation. For this AST has established an integrated production line to manufacture up to 600 units per year. This running production line uses qualified processes and inhouse-developed test-means that are confirmed by successful production of 600+ flight units.

In parallel to the serial production, new products are developed to meet specific thruster and customer requirements. An example of this is ESA's MSR-ERO mission for which AST is currently developing fully redundant pressure regulators and flow controllers. In order to maintain the majority of the previous design heritage, the building-block concept of AST's pressure regulators and flow controllers is used vastly.

This paper shows the typical types of building blocks, their example applications and the status of qualification and industrialization.

Based on the building-block elements, propulsion architectures can be defined that are meeting mission requirements at minimum integration efforts on spacecraft level.

The need for operation with even higher-pressures and operation with other media like Krypton has been expressed by customers. This has resulted in a development activity recently started in cooperation with ESA. In this, the HPFCU design will be optimized to comply with MEOP inlet pressures above 300bar and maintaining a constant, low-pressure massflow with fixed split-ratio to two outlet ports. This paper outlines the qualification plan for the upgraded High-Pressure Flow Control Unit and present the status of the unique GSE development for lifetime and acceptance testing.

1. INTRODUCTION TO AST'S FLUID SMD DESIGN PRINCIPLE

Willing to answer the growing request for production of high-quality space products in large quantities at significantly reduced cost, AST's designers challenged the classical design concept of integrating discrete components onto a spacecraft or an assembly. The aim was to reduce number of interfaces and AIT efforts on spacecraft level and the result was a design approach where fluidic functions are combined in a single unit. Just like in electronics design where surface mounted devices (SMD) are integrated on printed circuit boards (PCB), AST's fluidic components are placed on a flow path board (FPB), which has the role of the PCB. It is a multilayer stack of plates with integrated flow channels. The stack is welded by a diffusion bonding process forming a solid and vacuum tight piece of metal with integrated channels. Like in the PCB the channels form a 3D-fluidic network. Components are directly placed and welded into cut-outs on top of the FPB. The FPB and all of the components' weld interfaces are made of stainless steel 316L.

With the multitude of product designs generated over the last ten years, AST has gained vast experience of the critical processes which allow to continuously improve the functions and performances of its products. Based on the fluid SMD design principle, new products can be designed and built for test in short timeframes.

2. BUILDING BLOCK ELEMENTS OF AST'S PROPELLANT MANAGEMENT DEVICES

The building block elements carry individual functions which can be arranged to customer needs. By reusing the same (or similar) component design on different products, a high level of flexibility in design at low individual effort can be achieved. Most elements are interchangeable such that a high stability of a series-production is maintained. The building-block elements can be produced in large quantities which allows for economies of scale over several products.

The main elements of AST's products are:

- **Flow Path Board (FPB):** main board which fluidically connects all welded parts and contains flow restrictors
- **Inlet / Outlet Tube Stub:** interconnects S/C pipework with FPB; equipped with 5µm filter mesh (11µm filtration rate)
- **High-Pressure / Low-Pressure Valve:** used for propellant isolation or massflow/pressure control
- **High-/Low Pressure Sensor:** used for pressure measurement as input to closed-loop control of outlet pressure/massflow
- **Intermediate Plenum:** allows for intermediate expansion of small quantities of gas to reduce pressure or flattening pressure-ripples
- **Harness:** interconnects valves and sensor heads to S/C electrical infrastructure; may be equipped with connector

Figure 1: typical building block elements of AST's fluidic management devices (center: Fluidic-Path-Board, FPB)

3. ELECTRONIC PRESSURE REGULATOR

Based on the Building Block Elements, several functions can be combined and integrated as a single unit. One readily available and customizable product is the Electronic Pressure Regulator (EPR) which is qualified in several configurations for specific requirements. Design details have been published in [1].
The assembly of fluidic components follows a multi-stage pressure regulation concept where a sequential step-down of inlet pressure is achieved (see flow schematic of the EPR below).

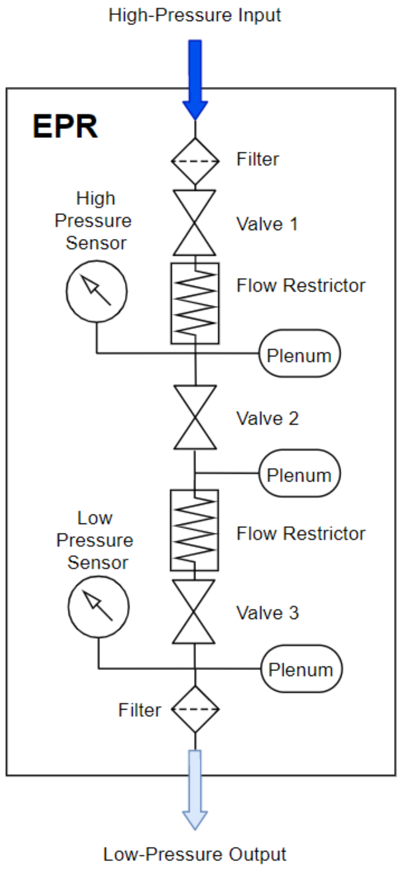

Figure 2: Flow Schematic of AST's Electronic Pressure Regulator

The final, integrated product shows a high-density of functions integrated in a single unit (see figure below). The footprint of the assembled EPR is the one of a state-of the art smartphone, while its mass is less than 900g. The driver electronics are typically part of the customer's power electronics. Yet, based on extensive EGSE design at AST, a stand-alone flight-design of a driver circuit is currently under development. That will allow the EPR being a true stand-alone component of an integrated propulsion system onboard of future spacecrafts.

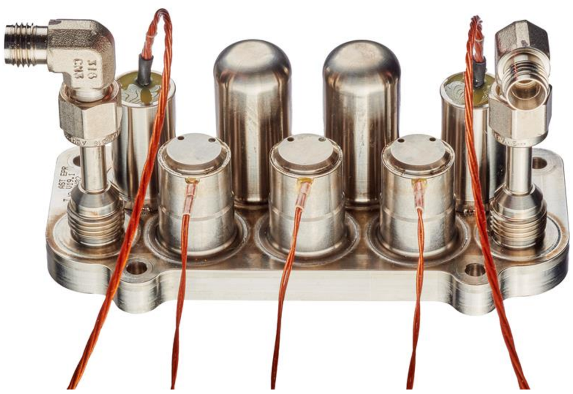

Figure 3: AST's Electronic Pressure Regulator

The EPR has been qualified to operate with inlet pressures up to 300 bar. Its operation allows a tank pressure drop down to about 5 bar while maintaining a low-ripple pressure output to the downstream components. As an all-welded design, the external leakage is minimum and the internal leakage is only determined by the individual leakage of the three valves placed in series.

Table 1: EPR Performance Characteristics

Operating Media	*GN2, GXe, GKr*
Operating Pressure	*5 to 300 bar*
Outlet Pressure	*1 to 5 bar*
Internal Leackage	*< 10-5 sccs GHe*
External Leackage	*< 10-8 sccs GHe*
Max Flow Rates	*> 250 mg/s (coarse mode)* *> 50 mg/s (fine mode)*
Pressure ripple	*< 20 mbar (fine mode)*
Proof / Burst Pressure	*1.5 / 2.5 x MEOP*
Mass	*0.65 kg*
Op.Temp.Range	*-20°C up to 65°C*

4. LOW-PRESSURE FLOW CONTROL UNIT

Coming from a pressure regulator, the propellant flow needs to be controlled such that specific quantities of propellant are delivered to the thruster's ionizing vessel and neutralizer / hollow cathode. For some thrusters, even a third propellant flow line is required. For that the thruster and neutralizer work in known and well-selected regimes, the massflow needs to be controlled in very fine manner with a minimum in flow ripples and flow uncertainties. Especially scientific missions demand for large operational thrust range and operational flexibility.
This wide span of performance driving requirements (high flow accuracy and large throttle range) can only be achieved through an active massflow control. With its miniature low-pressure valves, AST has designed a miniature Flow Control Unit which provide highly agile and accurate massflow control on a very small footprint. Details of the design have been published in [2].
Depending on the mission needs, and by using AST's building block elements, an open-loop or a close-loop configuration of the Low-Pressure Flow Control Unit can be designed. The flow schematic of an open-loop and closed-loop LP-FCU can be seen below.

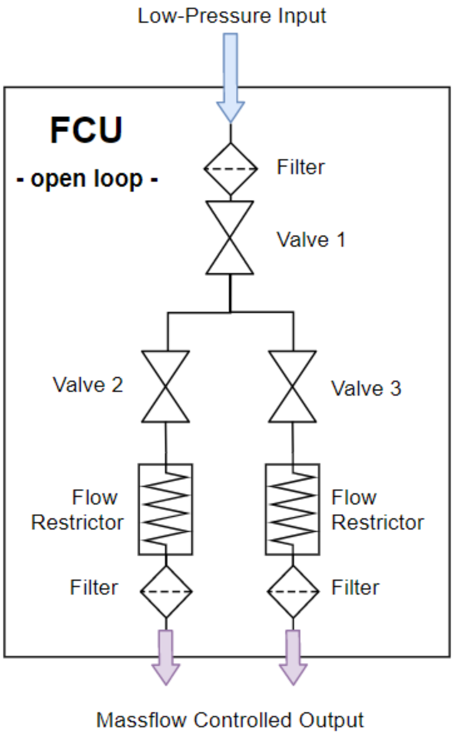

Figure 2: Flow Schematic of an open-loop Low-Pressure Flow Control Unit

Figure 3: As-build configuration of an open-loop Low-Pressure Flow Control Unit

Due to the lower operating pressure, the FPB can be sized in smaller dimensions. With the miniature, low-pressure valves placed on the FPB, the complete footprint can be kept to a minimum (smaller than a credit card) while maintaining a very fine massflow control.
By adding AST's pressure sensors and intermediate plenums, the pressure upstream the regulation valves can be measured. That sensing signal is then used in the closed-loop control algorithm to orchestra the operation of the valves.
Within limits, the FCUs can be operated in a narrow

temperature band maintaining its control functions. For operation in larger environmental temperature ranges, the FCUs can be equipped with thermal control hardware that maintains the unit at a defined temperature level.

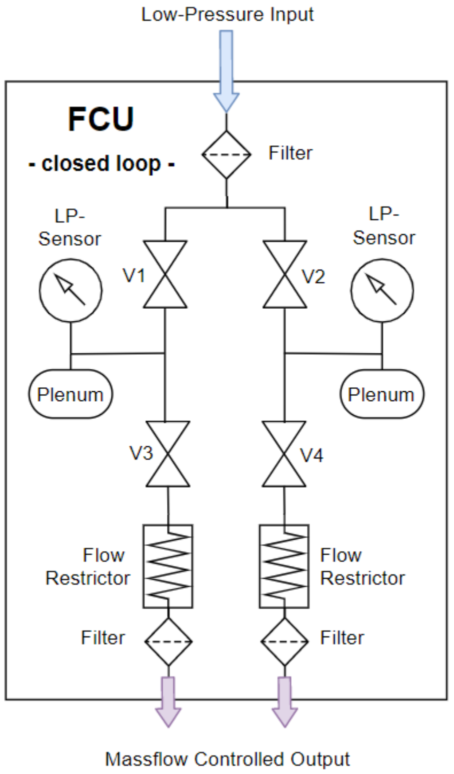

Figure 4: Flow Schematic of a closed-loop Low-Pressure Flow Control Unit

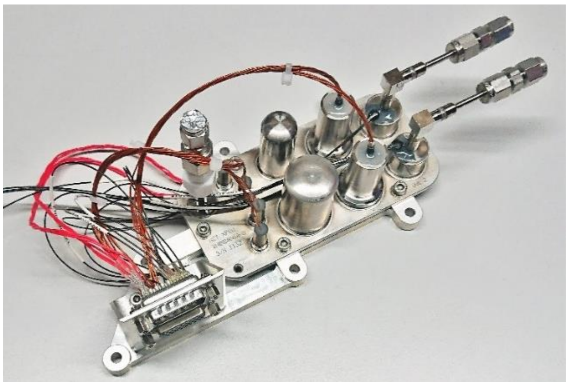

Figure 5: As-build configuration of a closed-loop Low-Pressure Flow Control Unit

The design concept of the FCU is the same as for the EPR. A flat Fluid Path Board is populated with surface mounted fluidic elements (valves, volumes, sensors, fluidic connections). As an all-welded design, the external leak rate is very low. The back-pressure generated by a flow-restricting thruster is to be known for accurate flow-control. This can be determined in a coupling-test and operational parameters of the FCU can be optimized (even in orbit). Through that design and operational approach, a large variety of thrusters operating under very different conditions can be served.

Table 2: LP-FCU Performance Characteristics

Operating Media	*GXe (GKr, GN2, GHe)*
Operating Pressure	*2 bar (0.5 – 8bar)*
Back-Pressure	*Selectable 0.3 … 0.8bar*
Internal Leackage	*< 10-5 sccs GHe*
External Leackage	*< 10-8 sccs GHe*
Flow Rates	*Selectable e.g.* *0.15 m g/s - 10 m g/s*
Flow ripple	*< 1%*
Proof / Burst Pressure	*1.5 / 4 x MEOP*
Mass	*<0.07 kg (open-loop FCU)* *<0.70 kg (closed-loop FCU)*
Operating Temperature Range	*-20°C up to 65°C*

5. HIGH-PRESSURE FLOW CONTROL UNIT

For propulsion systems that envisage use of only one or two thrusters onboard, operating in single or dual operation mode, the functions of an EPR and a FCU can be combined. AST has developed a high-pressure flow control unit (HP-FCU), also known as "RADICAL". The concept is based on an easily adaptable, but fixed, split ratio with a single operating point (slightly adjustable in flight). The high-pressure inlet is converted to a defined outlet flow by two binary operating solenoid valves and a fluidic low-pass filter. Furthermore, the included high-pressure sensor allows gauging of the tank pressure. The two vales form a double redundancy for pressure leak tightness. Its simplicity in electric control and mechanical dimension allows easy integration in the satellite system and setup. This highly integrated design has been chosen to provide propellant to propulsion thrusters onboard several hundred satellites of the OneWeb constellation.

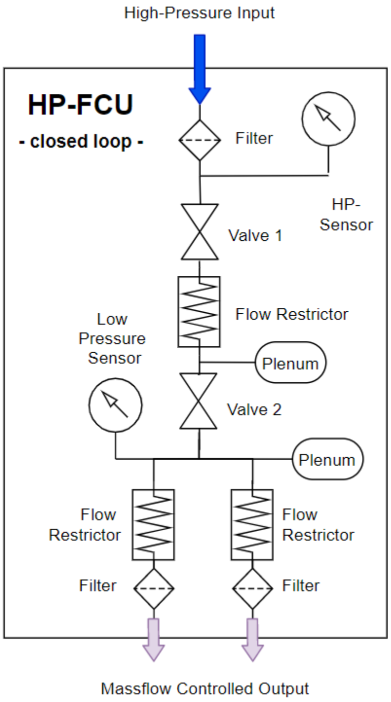

Figure 6: Flow Schematic of the High-Pressure Flow Control Unit

Figure 7: Integrated Configuration of AST's High-Pressure Flow Control Unit

Also, for this high-pressure FCU, the back-pressure downstream of the unit is a result of the thruster's fluidic resistance. The FCU's internals and operational parameters can be adopted to reflect that additional flow-restrictor in the overall fluidic network.
The unit has been qualified for burst pressures up to 600 bar and is testes to acceptance pressures of 225bar. After exposure to this acceptance pressure, the unit is tested to be fully operational an in compliance to performance requirements. This high-pressure design has a dimensional footprint similar to the one of a modern smartphone.
By design-choice, the overall flow-rate regime can be selected and the flow-splitting ratio between both outlets can be defined. During operation, these choices determine the global operation point of the unit, while the internal pressure setpoint can be modified by operational parameters such that the overall massflow can be varied within limits.

Table 3: HP-FCU Performance Characteristics

Operating Media	*GXe*
Operating Pressure	*2 to 150 bar*
Back-Pressure	*Selectable 0.3 … 0.8bar*
Internal Leackage	*< 10-5 sccs GHe*
External Leackage	*< 10-8 sccs GHe*
Flow Rates	*Selectable e.g. 1.5 mg/s*
Flow Split Ratio (anode – cathode)	*Selectable (typically 10 / 1)*
Flow ripple	*< 1%*
Proof / Burst Pressure	*1.5 / 4 x MEOP*
Mass	*< 0.900 kg*
Operating Temperature Range	*-20°C up to 65°C*

6. SUCCESSFUL DEMONSTRATION THROUGH COUPLING TESTS

In frame of European Commission partnership projects (EPIC) coupling tests were conducted successfully with multiple thrusters. EPR+LP-FCU and HP-FCU configurations have been tested in multiple different setups since 2017 with Hall-Effect Thrusters, Gridded Ion Engines, HEMP Thrusters and Helicon Plasma Thrusters.
The thrusters power range from few hundreds of Watts to 20kW – with similar range in required massflows. In nearly all cases, AST's fluidic devices were integrated into the overall test setup and performed as expected from day-one. The possibility to adopt the design and its operational parameters makes it easy to comply with many different thruster needs.

7. FLUIDIC MANAGEMENT FOR ELECTRIC PROPULSION SYSTEMS

The fluidic equipment developed and qualified at AST, allow propulsion system architects to define customized propulsion solutions based on industrialized space-products. By complementing with stand-alone Fill-and Drain valves, stand-alone pressure sensors, stand-alone isolation valves and cold-gas thruster, all concepts for electric propulsion systems can be supported. This gives a large degree of design freedom to the spacecraft designers and mission architects. The following gives examples of some architectural choices.
A classical system concept is consisting of the AST Electric Pressure Regulator (EPR) and an closed loop Flow Control Unit (FCU) that can be chosen for a multi-thruster mission. With the EPR providing sufficient massflow at a controlled outlet pressure,

also high-massflow devices like cold-gas thruster can be embarked. Thanks to the controlled pressure inlet, these thrusters can generate very distinct thrust and with its very fast control valves, fine attitude control of spacecrafts is possible when the EP thrusters cannot/shall not operate.

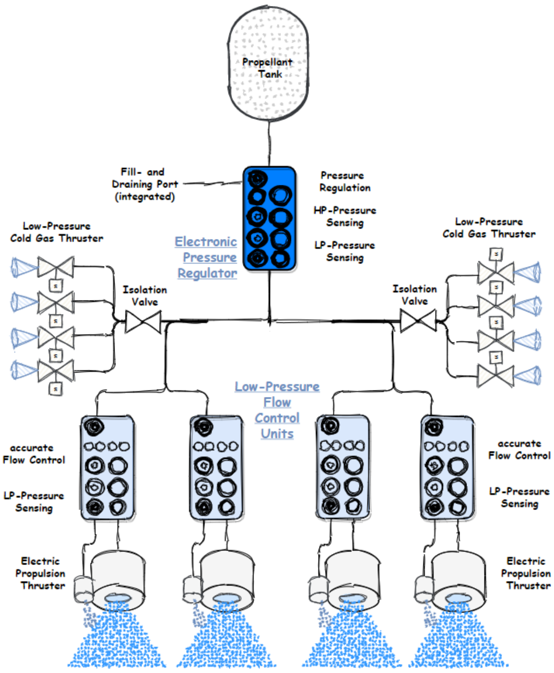

Figure 8: Example of a fluidic architecture using EPR and FCU for mult-thruster operation

Another EP-system option is based on the combination of EPR and FCU in one device. As described above, the High-Pressure FCU can add value to low-cost missions which typically operate one or two thrusters at a specific operation point. Due to the high degree of functions-integration this concept eases AIT efforts. Only few components need to be integrated and tested on S/C level.
Due to its clear design-focus on massflow control for a single EP thruster, the HP-FCU cannot support low-pressure coldgas thruster. Instead, it is proposed to use High-Pressure Cold Gas Thruster. These operate in blow-down mode as they are connected via high-pressure lines to the propellant tank. With the fast valve response, these thrusters allow to generate fine impulses for coarse attitude control (e.g. for de-tumbling and safe-mode) and with longer firing also for fast (high-thrust) collision avoidance manoeuvres.

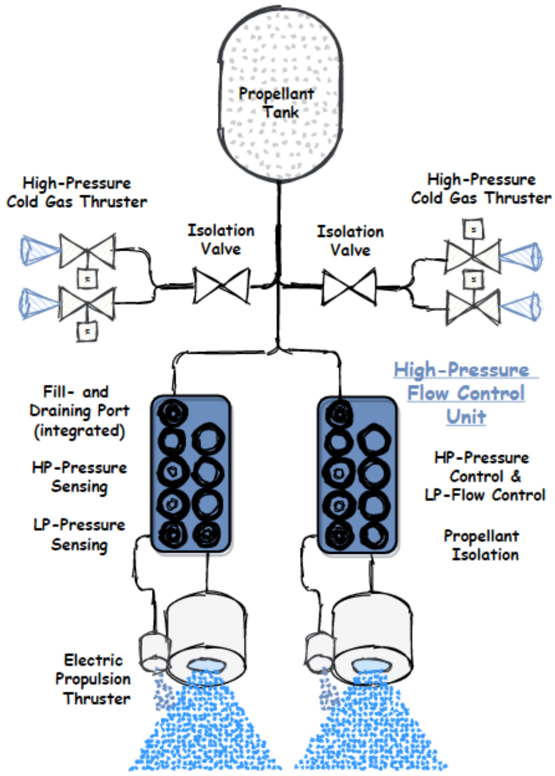

Figure 9: Example of a fluidic architecture using HP-FCU for single or dual-thruster operation

An example of an implementation of the highly integrated fluidic management for a single-thruster EP subsystem is shown the figure below. The whole fluidic management of the EP system is done by the one HP-FCU – no further devices needed.

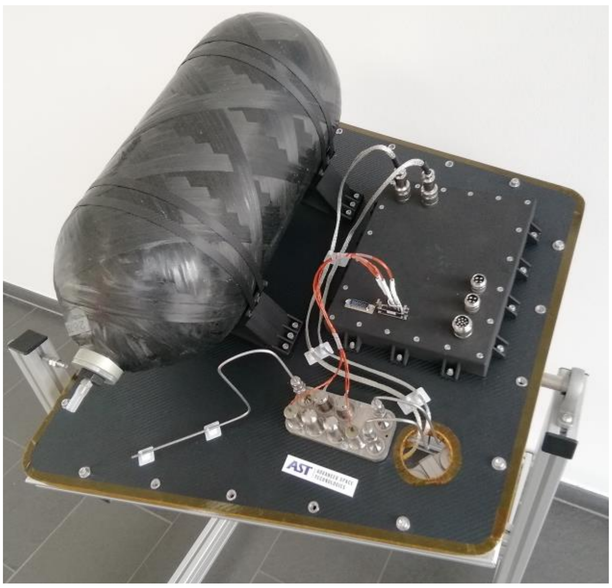

Figure 10: Example of an accommodation of the High-Pressure Flow-Control (stainless steel element on bottom) on a small-satellite panel; the EP thruster is placed on the back-side;

8. FLUIDIC MANAGEMENT FOR COLDGAS PROPULSION SYSTEMS

By embarking an Electronic Pressure Regulator and a series of cold-gas thruster, the simplest concept of a satellite propulsion system can be realized. As the EPR is equipped with upstream high-pressure sensor for propellant gauging and optionally also with a fill-and drain valve, the fluidic concept of such system is even further simplified and integration-efforts on a spacecraft are minimized.

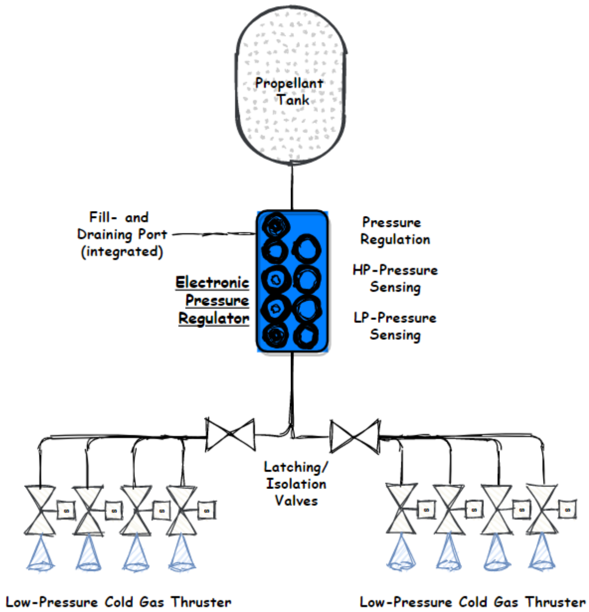

Figure 11: Flow Schematic of an Integrated Cold Gas Propulsion System

The coldgas thruster for such a solution is currently under development at AST. It is based on AST's flight heritage coldgas thruster design (see [3]) and sized to provide a nominal thrust level of about 50mN at less than 2bar inlet pressure.

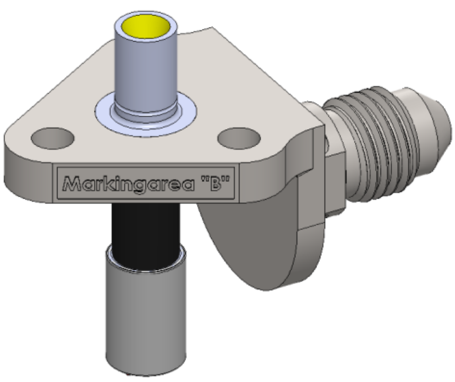

Figure 12: CAD drawing of AST's low-pressure coldgas thruster

9. ONGOING DEVELOPMENTS AND CUSTOMIZATION

Due to the continuously increasing procurement prices for Xenon, the market demand for a Krypton-based electric propulsion system is increasing. AST has therefore started the delta-development of its High-Pressure Flow Control Unit – supported by an ARTES C&G program. Within this 2-year activity, AST aims to adopt the design becoming compatible to the future technical needs and to qualify the upgraded design up until flight readiness.

Table 4: Tasks and Challenges for Delta-Development

High-Pressure operation at 300bar MEOP	*Defines maximum design pressures for the assembly and the individual components; also defines acceptance and qualification test efforts (proof pressure > 450bar)*
Operational Fluid: Krypton	*Longterm operation / total throughput capability with Krypton has to be demonstrated by test*
Total Throughput	*Capability of valves operational cycles and FCU output performance is to be demonstrated by endurance test*

While the fluidic architecture of the HP-FCU remains the same, design adaptations of individual components are considered necessary to account for the much higher operation and proof pressures. Plastic deformation at 450bar proof pressure is to be avoided/reduced which is why especially the FPB design will be optimized for that aspect without adding mass.

The overall delta-development and qualification program foresees as program logic as shown in the flow-chart below. After design has been frozen, qualification hardware will be built and tested to show compliance the requirements.

One major challenge is the availability of adequate test means. The test equipment available for verifying workmanship in series production at AST is currently defined to operate pressures up to 150bar MEOP. Higher pressures operation requires upgraded test-stands and the provision of highly pressurized gasses. A pressure compressor-system is currently under development which will be used to allow for acceptance and qualification tests at more than 300bar Krypton pressure (while supply and stock pressures are typically below 200bar). In order to maintain the cleanliness of the products under test, the compressor cannot be a conventional type but has to be completely free from oil or other contaminants. AST will be ready to validate the new compressor design in frame of the first HP-FCU article tests planned for summer 2022.

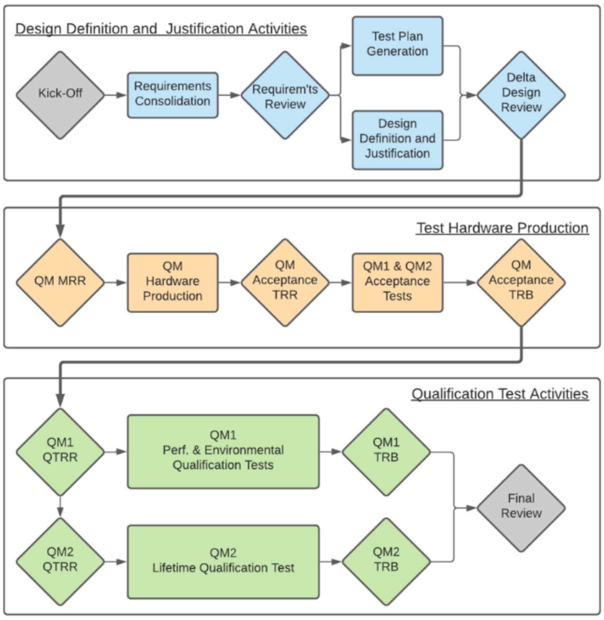

Figure 13: Development logic for adaptation of the High Pressure Flow Control Unit design

The envisaged performances of the upgraded High-Pressure Flow Control Unit are listed in Table 5 below. These are based on experience with AST's flight heritage design and new customer requirements for enlarged operational range.
The design upgrade will allow for customized configurations. Following standard design options exist for the HP-FCU:

- Integrated Fill- and Drain Valve
- Selectable nominal outlet massflows
- One or two outlet ports
- Tube-Stubs with weld interface or screwed (AN) connections
- Optimized for high-throughput or low-massflow ripple
- Thermal hardware selection and integration

Thanks to the building block elements of AST's fluidic products, a large range of customized product configurations can be offered while maintaining a high level of design-synergies that also results in standardized processes and test approach. The fully industrialized approach allows to reflect customer specific needs at high cost-effectiveness. With the production line established at AST (see [4]), a high production rate can be achieved allowing about 600 units to be delivered per year. This allows for economies of scale, thus low unit prices in a reliable high-pace production.

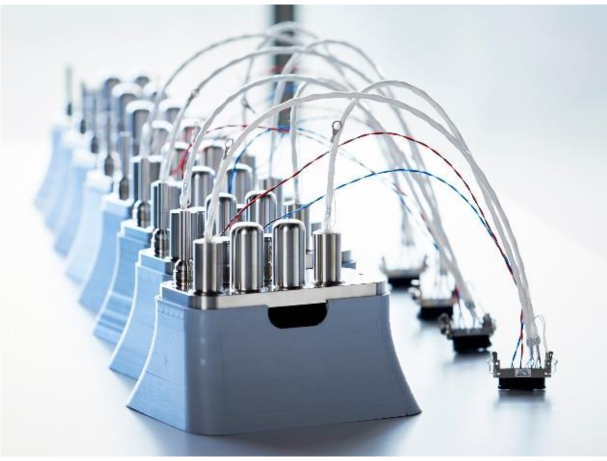

Figure 14: Heritage HP-FCU's produced in large quantities at AST

10. REFERENCES

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Table 5: Envisaged Performances of upgraded HP-FCU currently under development at AST

Parameter	Value	Remark
Inlet pressure MEOP, Kr	>300 bar	
Inlet Pressure EOL, Kr	2 bar	Flow dependent
Proof pressure	1.5 x MEOP	Design value > 450 bar
Low pressure line MEOP	1/5 bar	Limited by LP sensor
Low pressure lines proof pressure	7 bar	Limited by LP sensor
Burst pressure	2.5 x MEOP	Design value > 750 bar
Nominal anode flow	1.5 mg/s Xe	selectable
Nominal cathode flow	10% of anode flow	selectable
Throttle range	-25% to +50%	
Propellant throughput capability	>50 kg	Depends on flow level
Regulation precision	better 1%	Depending on electronics and control loop
Output flow ripple	< +/-2.5%	Depending on electronics bandwidth and line volume
Flow response time	up <5 s down<20s	to achieve 95% of a full scale step at line outlet port (e.g. during start up).
Internal leakage	< 1*10-5 sccs GHe	
External leakage	< 1*10-8 sccs GHe	
Thermal range non-op	-20°C to +80°C	incl. qualification margin
Thermal range op	+25°C to +65°C	full performance
Thermal range op (cold start)	-10°C to +65°C	limited performance
Mass	< 900 g	w/o harness