Building Blocks for EP Propellant Management Systems

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AST Advanced Space Technologies GmbH has developed a modular set of building blocks for propellant management systems for electric propulsion. These qualified building blocks implement core functions of typical propellant management systems. The use of identical block in different projects leverage scaling effects and provides a fast and cost-effective solution for system implementations ranging from simple LEO constellations to complex planetary missions like mars sample return earth return orbiter (MSR-ERO).

I. Introduction

Since 2011 AST Advanced Space Technologies GmbH develops components and technologies for propellant management systems for electric propulsion. The portfolio comprises pressure sensors, valves, filters, fill & drain valves, etc. With a new developed technology called flow path board (FPB). Components are place onto the FPB like electronics components on a PCB. Due to this similarity the technology is called fluid-SMD.

In the past years, AST further improved the technology by introducing pre-qualified and standardized components and building blocks. With such building blocks more complex systems can be design with low risk and short development times. Beside the technical advantages the building block approach increases the number of identical parts for a highly efficient manufacturing and sourcing strategy. Standard components are on stock available for small quantities FM production and development programs. This reduces lead times significantly.

II. Standardized Components

The lowest level of Building Blocks are standardized components together with their manufacturing and system assembly processes.

The main elements of AST's products are:

A. Flow Path Board

The Flow Path Board acts as structural baseplate and as interconnection layer between other fluidic components. The FPB contains a 3D network of flow channels such that no tubes between components are required. It is possible to integrate flow restrictors directly into the FPB by using channels with small dimensions.

The channels start and end at "ports". At each port, components can be placed and electron beam welded for a robust and leak tight joint.

B. Other Components

Several active and passive components are available to be used with the FPB. The components are design to be placed into the ports of the FPB and welded by electron beam welding.

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- 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
- Fill and Drain Valve: gives access to the high pressure line connected to of the tank

For each component category several subtypes allow optimized system designs. For example the pressure sensor is available in subtypes of 1 bar, 4 bar, 50 bar, 200 bar, and 300 bar full range. The fluidic interfaces can be chosen between straight tube for swaging, straight tube for welding, AN-style fittings, and VCR.

The combination of these components allows the design of pressure or flow control blocks. These blocks are either directly used as subsystem or act as functional building block for more complex systems.

The direct welding of component to the stainless-steel structure of the FPB forms a robust interface that shows a minimal mechanical coupling between individual components. The local environment of a component is mainly independent of the overall subsystem design. For new designs the validation by similarity reduces the effort for mechanical, thermal and lifetime tests. Typically, for a delta design only a function and performance test is required for demonstration.

Figure 1: Typical components of AST's fluidic management devices

(center: Fluidic-Path-Board, FPB)

III. Common Building Blocks and Subsystem

Manufacturing streamlining is a core target of AST’s efforts to reduce cost and production time for space systems. For the FPB a standard size with the footprint of a smart phone has been chosen. While larger FPBs are possible, the standard would provide the best cost efficiency. The standard FPB can have ports for up to 10 components on each side, so 20 components in total. With this number of components, the complexity of most propellant management systems can be mastered. Several standard Building Blocks have been developed and used either stand alone or for more complex systems.

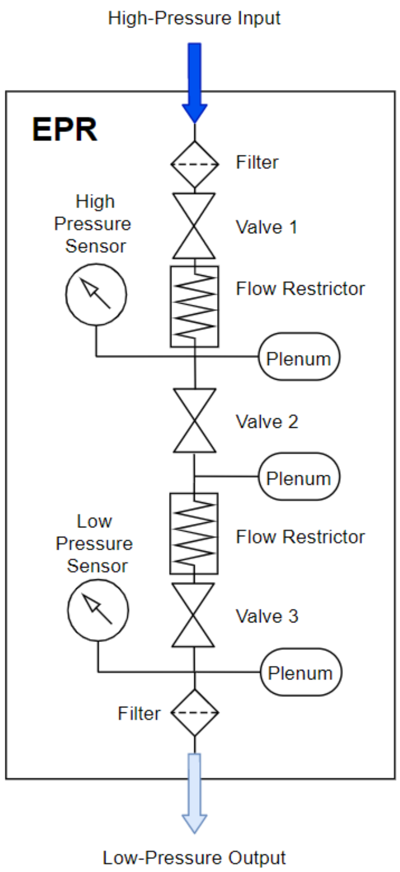
A. Electronic Pressure Regulators

One building block is the Electronic Pressure Regulator (EPR). In its minimum configuration it consists of one FPB, two valves, one low pressure sensor, two volumes and two fluidic connectors. The valves are operated in a Bang-Bang principle to control the pressure in the volumes. The first valve is operated for a short pulse to take a small amount of gas from the inlet (tank) through a restrictor to the intermediate volume. From the intermediate volume the second valve expands the gas via a flow restrictor to the outlet volume. A pressure sensor is connected to the outlet volume to sense the current pressure level. If the pressure drops due to a gas flow through the outlet, the second valve is operated to charge up the outlet volume. In a continuous flow operation the frequency of the outlet recharging depends on the intermediate pressure that drops with time. If the frequency exceeds a certain threshold the first valve is cycled to refill the intermediate volume.

AST has evaluated such Electronic Pressure Regulators for different pressure and flow ranges for applications like electric propulsion, cold gas thruster and re-pressurization units for chemical propulsion.

If a triple barrier in the flow line is required, e.g. to allow the isolation of redundant branches, a third valve is placed in the inlet.

To finalize the design of the EPR, also a high pressure sensor can be integrated to have all functions of a pressure regulation system including tank monitoring in one unit.



Typical Performance Characteristics of an EPR

Operating Media	*GN2, GXe, GKr*
Operating Pressure	*5 to 300 bar*
Outlet Pressure	*1 to 5 bar*
Internal Leakage	*< 10-5 sccs GHe*
External Leakage	*< 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*

Figure 2: Flow Schematic and Performance Characteristics of AST's Electronic Pressure Regulator (2 valves)

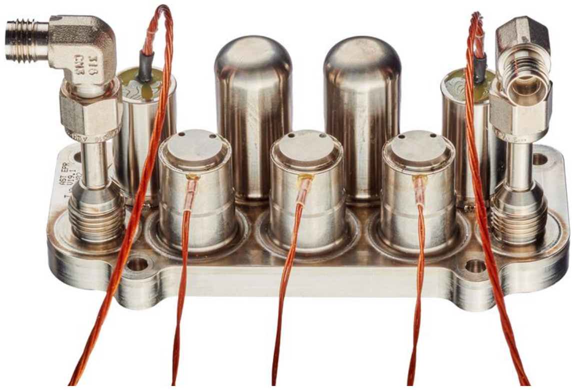
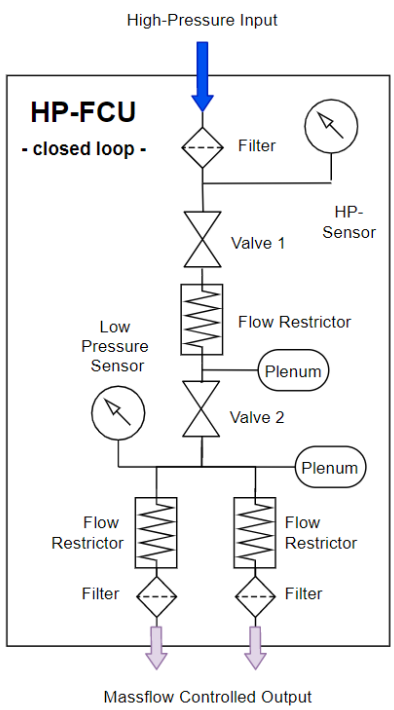


Figure 3: AST's Electronic Pressure Regulator (3 valves)

B. High Pressure Flow Control Unit

Directly derived from the Electronic Pressure Regulator AST offers a High Pressure Flow Control Unit (HPFCU). It uses the same components, methods and the core design of the EPR. In difference to the EPR the outlet flow line splits into two lines. In each line a flow restrictor is integrated before the fluidic connector. This transforms the internally controlled pressure into a flow in dependence of the chosen flow restrictor value. This HPFCU can directly supply a thruster anode and a cathode from the tank without additional components. The HPFCU design has been used in an application as Xenon Feed System for the OneWeb constellation. Figure 6 shows an EP system with integrated HPFCU.



Performance Characteristics of a HPFCU

Operating Media	*GXe, GKr*
Operating Pressure	*2 to 300 bar (150 bar Xe)*
Back-Pressure	*Selectable 0.3 … 0.8 bar*
Internal Leakage	*< 10-5 sccs GHe*
External Leakage	*< 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*

Figure 4: Flow Schematic and Performance Characteristics of a High-Pressure Flow Control Unit

Figure 5: Integrated Configuration of an AST's High-Pressure Flow Control Unit

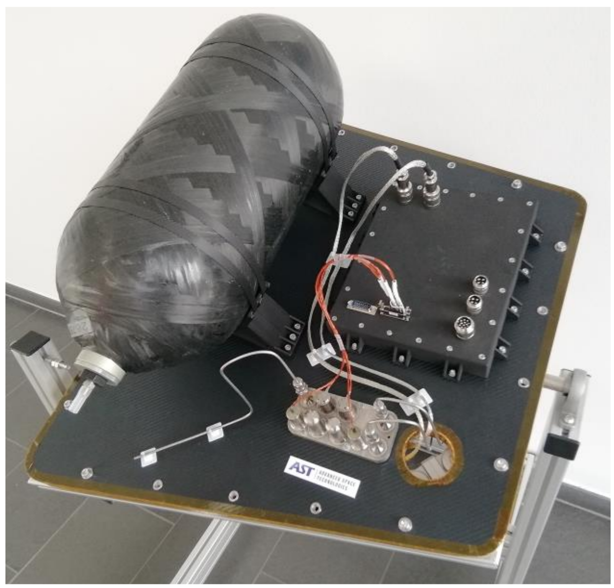
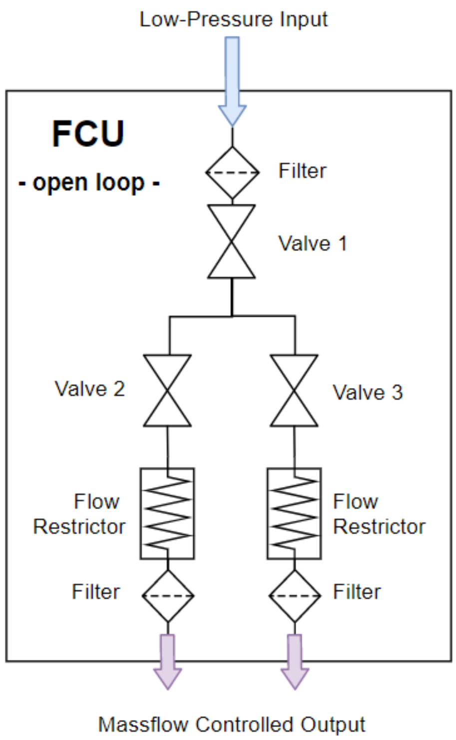


Figure 6: Example of an accommodation of a High-Pressure Flow-Control (stainless steel element on bottom) on a small-satellite panel; the EP thruster is placed on the back-side;

C. Low Pressure Flow Control Unit

While the High Pressure Flow Control Unit is the best selection, if the number of thrusters per satellite is small, a more classic design with EPR and several low pressure flow control units may be of advantage for complex EP systems with several thrusters. AST offers low pressure flow controls (LPFCU) in two different configurations.

The design concept of the LPFCU is the same as for the HPFCU. 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. In general, the operation of AST’s LPFCU is determined and stable, if the environmental conditions and operational parameters are constant. For a controlled EP system, a feedback signal is typically required to close the loop. In the simplest and smallest LPFCU configuration a thruster parameter (e.g. anode current) is used to compensate system drift. This minimum design has only three low pressure valves, the FPB, tube stubs and harness but no pressure sensors. The LPFCU does not use an internal close loop control in this case and is therefore rated as “open loop” device.



Performance Characteristics of a LPFCU

Operating Media	*GXe (GKr, GN2, GHe)*
Operating Pressure	*2 bar (0.5 – 8bar)*
Back-Pressure	*Selectable 0.3 … 0.8bar*
Internal Leakage	*< 10-5 sccs GHe*
External Leakage	*< 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*

Figure 7: Flow Schematic and Performance Characteristics of an open-loop Low-Pressure Flow Control Unit

Figure 8: Open-loop Low-Pressure Flow Control Unit

In EP systems that do not provide an useful feedback signal from the thruster, or systems that require an improved knowledge of the flow, a LPFCU with integrated pressure sensors is offered. The outlet flow is then controlled similar to the HPFCU algorithm without the need of an external parameter.

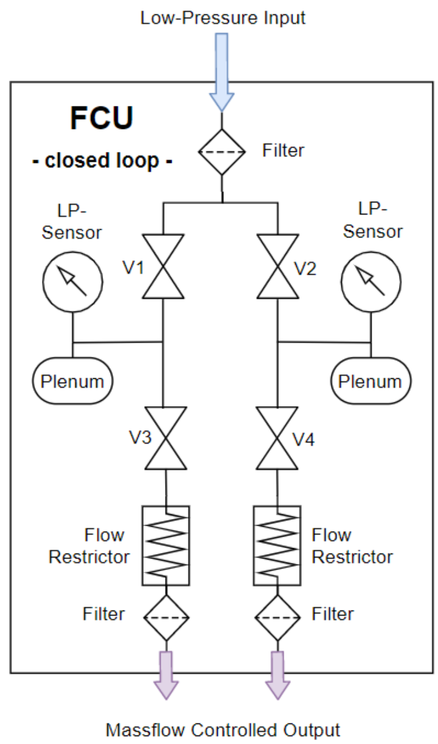


Figure 9: Flow Schematic of a closed-loop Low-Pressure Flow Control Unit

Figure 10: Closed-loop Low-Pressure Flow Control Unit

IV. Complex Systems

If systems get more complex, multiple building blocks can be joint to form a full system. In addition, AST provides components like valves and sensors as stand-alone components and cold gas thrusters to complete the systems.

A. Redundant Pressure Management Subsystem

As one example the pressure reduction and regulation of the Mars Sample Return – Earth Return Orbiter Mission (MSR-ERO) is sketched. Two identical EPR building blocks share one line to the tank. The outlets are feed into a low-pressure volume to eliminate pressure ripple and to damp potential transients from downstream components. The result is a very compact system of two fully redundant branches with the capability of twice the nominal flow rate if both EPR blocks are operated in parallel.

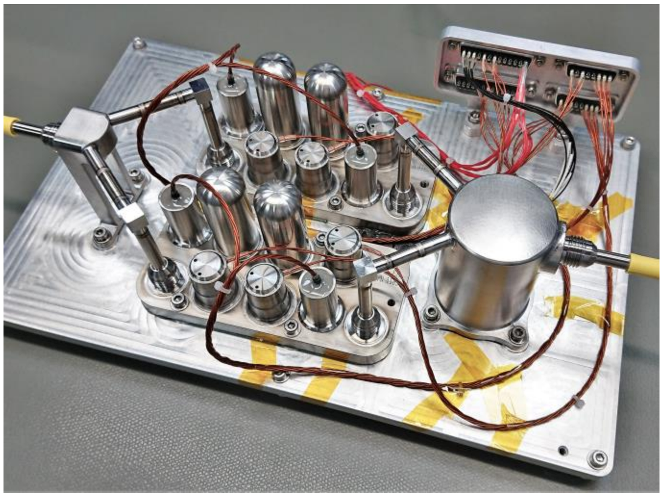


Figure 11: Pressure Regulation System EM for MSR-ERO

B. Simple EP system with Cold Gas Thrusters

The next example shows electric propulsion system for orbit raise with cold gas thrusters for detumbling and safe mode operation. In this example the EP system makes use of two redundant thrusters. It shall be possible to operate both thrusters in parallel for orbit raise and deorbit mission. The propellant management of the EP system consists of two high pressure flow controls directly connected to the propellant tank. The example shows two redundant high pressure cold gas thrusters currently under development at AST. Each branch is isolated by a solenoid.

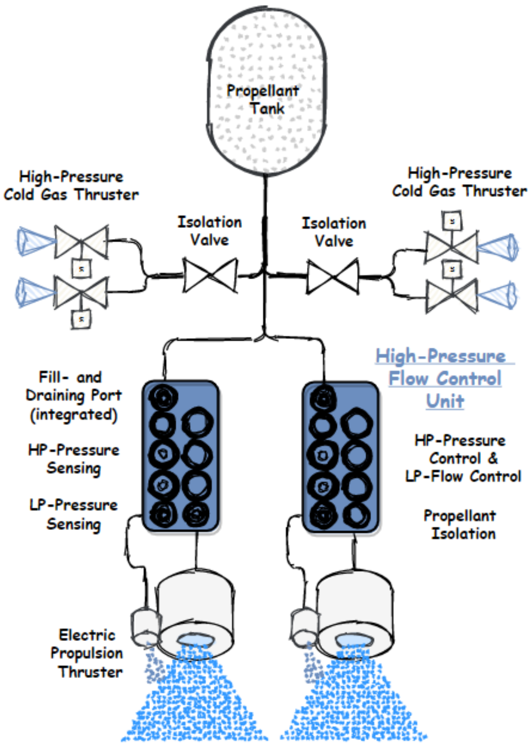


Figure 12: Example of a fluidic architecture using HP-FCU for single or dual-thruster operation

C. Classic EP system

In classic EP system with multiple independently controlled thrusters the functions of pressure reduction and flwo control are separated. The sketch below shows a full system with one electronic pressure regulator block and for low pressure flow control unit blocks. The possibility to integrate a cold gas thruster system is also shown. In this case a low pressure cold gas thruster is proposed. The cold gas thruster branches are fed from the supply line behind the EPR.

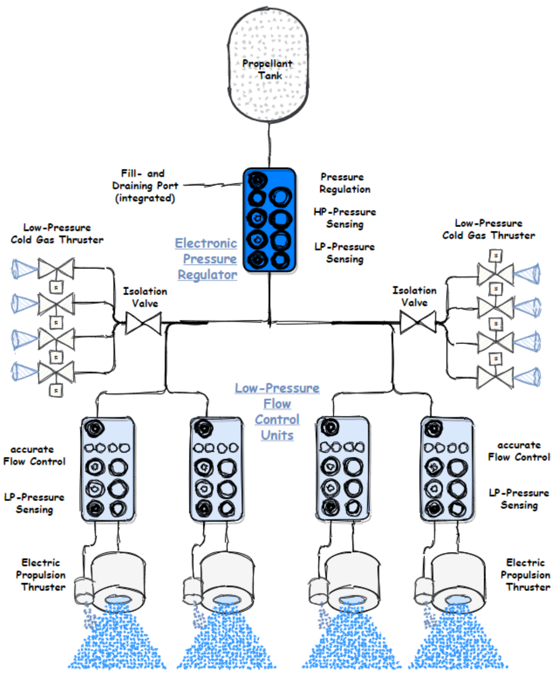


Figure 13: Example of a fluidic architecture using EPR and FCU for mult-thruster operation

V. Advantages of Building Blocks

Technical advantages of AST building blocks like low mass, low volume and reduced AIT work are obvious. Beside these the building block approach shows major advantages in the non-technical field:

- Standardization allows the availability of on stock components instead of long lead items
- Fast development cycles
- Reduced or eliminated non-recurring cost
- Continuity in production with reduced risk of obsolescence, improves quality and long term availability
- Scaling effects for larger quantities of similar standard components
- Reduced recurring cost
- Larger quantities allow statistical methods for quality improvement

VI. Current Usage of AST Building Blocks

AST's propellant management systems and building blocks are currently used in several projects and programs. The larges heritage is with the OneWeb constellation. AST has delivered more than 650 Xenon Feed System based on the HPFCU design. At the time of this paper 428 units have been launched to space and operated. The accumulated in-orbit time exceed 4.3 million hours.

Other building blocks are used on satellites in GEO and LEO. For deep space application a complex system using EPR blocks and LPFCU blocks is currently under development for MSR-ERO.

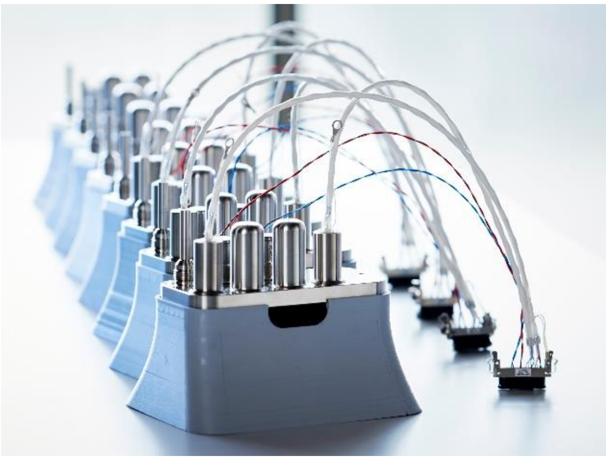


Figure 14: Small production batch of heritage HP-FCU at AST

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