Aperture Valve for the Mars Organic Molecule Analyzer (MOMA)

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Abstract

NASA's participation in the multi-nation ExoMars 2018 Rover mission includes a critical astrobiology Mass Spectrometer Instrument on the Rover called the Mars Organic Molecule Analyzer (MOMA). The Aperture Valve is a critical electromechanical valve used by the Mass Spectrometer to facilitate the transfer of ions from Martian soil to the Mass Spectrometer for analysis. The MOMA Aperture Valve development program will be discussed in terms of the Initial valve design and subsequent improvements that resulted from prototype testing. The Initial Aperture Valve concept seemed promising, based on calculations and perceived merits. However, performance results of this design were disappointing, due to delamination of TiN and DLC coatings applied to the Titanium base metals, causing debris from the coatings to seize the valve. While peer reviews and design trade studies are important forums to vet a concept design, results from testing should not be underestimated.

Despite the lack of development progress to meet requirements, valuable information from weakness discovered in the Initial Valve design was used to develop a second, more robust Aperture valve. Based on a check-ball design, the ETU /flight valve design resulted in significantly less surface area to create the seal. Moreover, PVD coatings were eliminated in favor of hardened, nonmagnetic corrosion resistant alloys. Test results were impressive, with the valve achieving five orders of magnitude better sealing leak rate over end of life requirements. Cycle life was equally impressive, achieving 280,000 cycles without failure.

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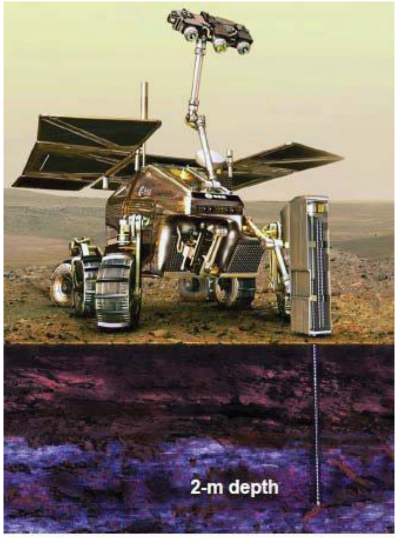
Introduction

By studying organic molecules (the chemical building blocks of life as we know it), MOMA is designed to help answer questions about whether life existed on Mars, as well as its potential origin, evolution, and distribution on the Red Planet. The MOMA Instrument is principally a mass spectrometer used to detect the masses and relative concentrations of atoms and molecules in a substance. MOMA is designed to analyze the types and amounts of chemicals that make up organic and inorganic compounds found in rock and soil samples on Mars. The instrument will address a top science goal seeking the signs of past or present life on Mars. Since the surface of Mars is bathed in ultraviolet and cosmic radiation, complex organics in the uppermost surface layers could be degraded. The 2018 Rover will be equipped with a drill to obtain samples from as deep as 2 meters in the hope that organics at that depth would still be viable. Core samples of Martian soil will be ablated by a UV laser, producing ions which pass thru the Aperture Valve and are subsequently trapped and analyzed by the Mass Spectrometer to determine the molecular composition of the ion, which then determines the molecular composition of the sample.



The MOMA Mass Spectrometer illustrated in figure 1. Principle components are the Mass Spectrometer Housing, 266nm UV Laser Head and Aperture Valve. The Martian sample is moved to the Ultra-clean zone directly below the Aperture Valve. A laser mounted onto the Mass Spectrometer Housing creates a focused beam of energy which oblates the soil and ionizes soil particles. The valve opens, allowing ions to flow into the Mass Spectrometer, then quickly closes. Ions are trapped by a Linear Ion Trap, scanned for molecular composition, then ejected.

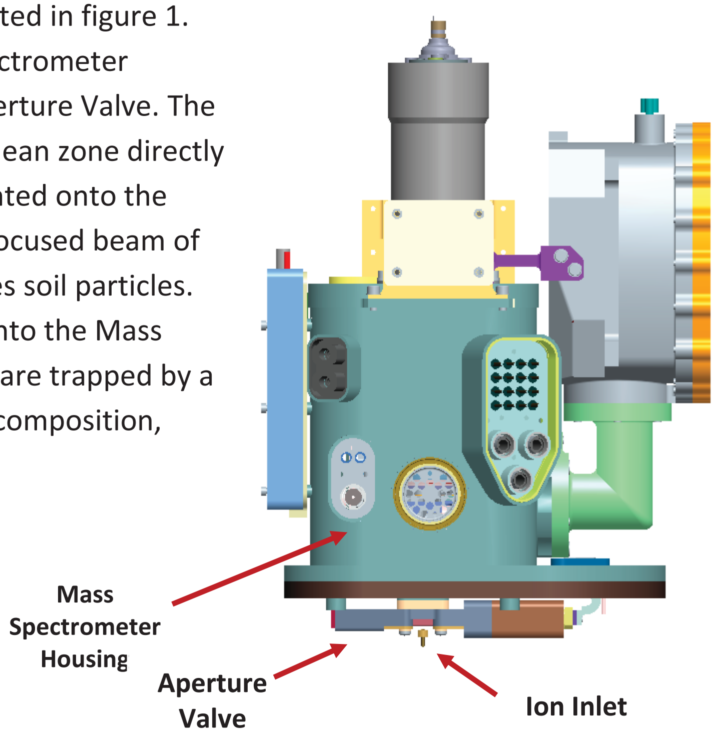


Figure 1- MOMA Mass Spectrometer with Aperture Valve

Initial Aperture Valve Design

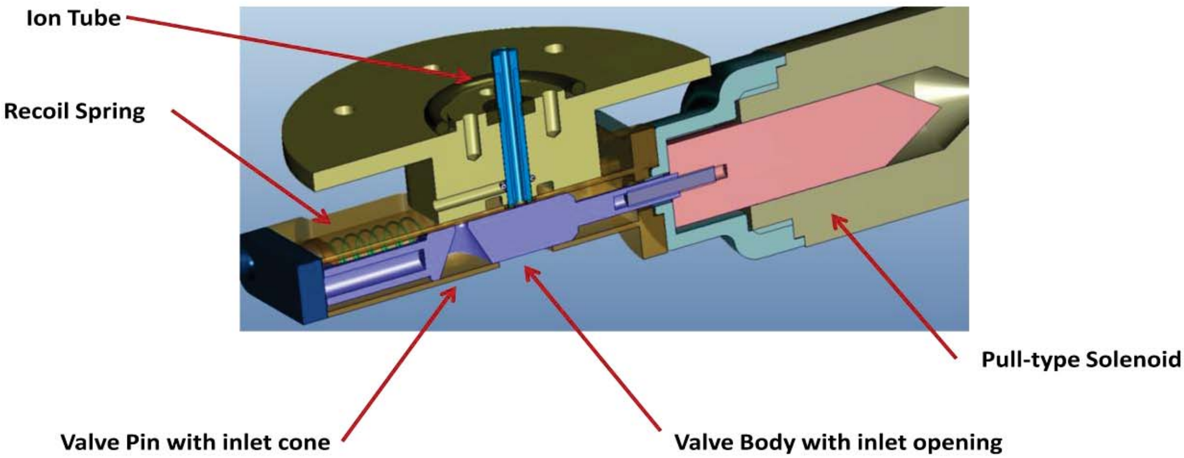


Figure 2- Aperture Valve early design

Over 125 requirements for the valve were levied, which were then ranked according to importance and distilled down to the 25 top "driving' requirements. The initial Aperture Valve design is illustrated in figure 2. Sealing the inlet was accomplished by means of a Sliding Pin, which operated to open and close off the Ion Tube. A solenoid was connected to the sliding pin connected to a pull-type solenoid, which when energized, pulled the Pin to the open position, allowing ions to travel from a Martian sample below the valve, up the inlet cone and thru the hole at the base of the cone. After power to the solenoid was removed, the solenoid rapidly closed from stored energy in a recoil spring. Close tolerance between the sliding Pin and Valve Body produced a pressure leak rate consistent with the requirement of 10E-3 cc/sec He for beginning of life and 10E-2 cc/sec He, end of life, which was defined as 125,000 actuation cycles.

Requirement	
Pressure leak rate	10E-3 cc/sec He
Operational cycle life	125,000 cycles
Operational temperature	-20°C to 50°C
Valve open/close time	<50ms
Mass	90grams
Failure Mode	Fail closed
Power	5 watts
Material limitations	Non-magnetic

To meet operational and performance requirements, materials for Aperture Valve components were comprised of Titanium 6AL-4V. Titanium is well known material of choice for aerospace design with benefits including: high strength-to-weight ratio, corrosion resistance and non-magnetic. Coatings applied to the Titanium were added for surface hardness, lower coefficient of friction and prevented galling between the Sliding Pin and Valve body. The choice of coatings on these parts and application of the coatings to the Titanium base metal would prove problematic. Figure 3 illustrates two versions of the Initial

Valve design. Both feature the same mechanical sliding pin type concept. Clearance between the outside diameter of the Sliding Pin and bore hole within the Valve body were tightly controlled to .0002" clearance. The valve body was coated with Titanium Nitride (TiN) by means of physical vapor deposition or PVD, a process of sublimating pure titanium with nitrogen in a high energy, vacuum oven. The result is an extremely hard, thin, gold colored film, commonly found on tool bits. The sliding pin was coated with Diamond-Like-Carbon (DLC), another PVD coating having a desirable combination of a low coefficient of friction and high micro hardness. In general, PVD coatings have a micro-hardness greater than 80Rc, well above the hardness of tool steel. Both coatings were applied at 2.5 micron (.0001in.) thickness.

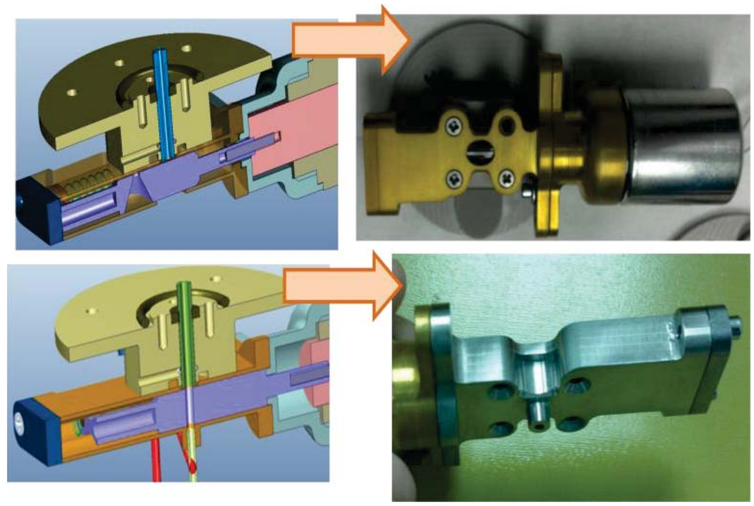


Figure 3- variations of coated valves

Problems with TiN and DLC Coatings

Traditionally, the largest inherent problem with ceramic based coatings such as TiN and DLC has been the issue of adhesion: typically the higher the diamond percentage in a DLC film, the harder the DLC film but the higher the compressive stress within that film. In extreme cases, such stresses can create unstable interfaces (i.e adhesion and/or cohesion issues) and the film may become prone to delamination.

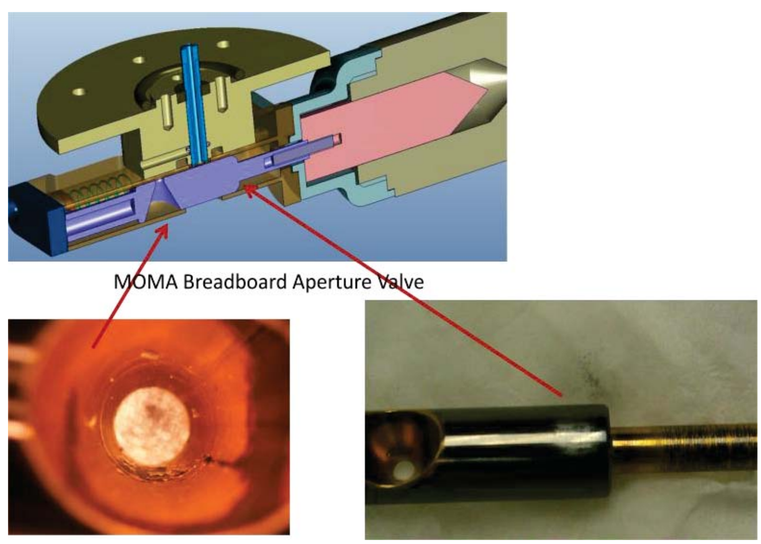


Figure 4- Coating delamination on valve parts

Figure 4 illustrates the results of Aperture Valve testing after less than 100 actuations. Figure 4 (left) illustrates the bore of the valve body coated with TiN. Flaking of gold colored material inside the bore and complete film separation from the base substrate is evident. From our experience, the PVD process used to apply TiN onto internal cavities and bore holes does not produce acceptable adhesion of the TiN film. It is not clear whether additional factors associated with substrate preparation within the bore were contributing factors. Figure 4 (right) illustrates excessive wear of DLC coating on the sliding Pin. This was probably the result of delaminated TiN flakes abrading the DLC surface. TiN on the cone and smaller shaft feature on the Sliding Pin were requested by the science team. While monolithic coatings are most common, multi-layer PVD coatings are applied with acceptable results, depending on number of layers, layer thickness, hardness of the coatings, etc. In this case, TiN was applied over the DLC coating with poor results, as flaking was evidenced here as well.

In the laboratory, the assembled valve initially operated well, meeting open and close times of <50ms per the requirement. Leak rate on the valve was also initially within requirement of 1E-3 cc/sec He. After less than 100 open-close cycles however, there was a notable sticking of the sliding pin; the solenoid could quickly open the valve, however the recoil spring could not return the pin quickly due to particulates generated from TiN fragments. Finally, the valve pin ceased to open or close, overwhelmed by friction between sliding surfaces. Moreover, scratches on the sliding surfaces prevented the valve from being refurbished resulting in a failure. The valve test chamber is illustrated in figure 5. Valve operates at 5-7 torr (Mars ambient pressure) in a CO_2 environment. Upper Chamber (not shown) operates at 1E-6 torr. Physical dimensions of the Initial Valve are 98mm x 20mm x 20mm (LxWxH)

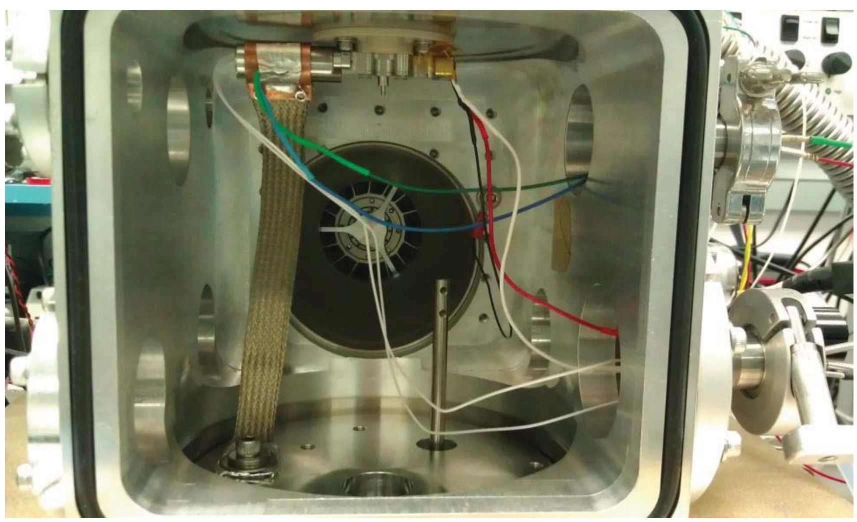


Figure 5- Aperture Valve test chamber

ETU /Flight Aperture Valve design

The second generation Aperture Valve for ETU and Flight was designed to specifically avoid the issues associated with PVD coatings and the Sliding Pin sealing concept requiring .0002 in. clearance to the Valve body bore to create the seal. While the previous design was based on creating hard, durable sliding surfaces between the Sliding Pin and Valve Body to minimize friction and particulate wear, the Initial Aperture Valve never achieved more than 1200 cycles before failing due to particulates. Obviously, the Initial Valve design could not meet the open-close requirement of 125,000 cycles. Therefore, another valve design was developed which specifically avoided the design weaknesses described. Figure 6 illustrates the improved valve design. Common features to the Initial Valve include a pull-type solenoid, sliding carrier (not pin), valve body and recoil spring. Figure 6a illustrates the principle components of the new valve design.

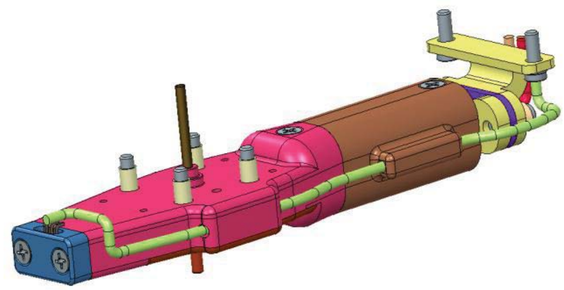


Figure 6- ETU /Flight Aperture Valve

The innovation in the design may be found in the method of sealing the valve open and closed, similar to a check-ball design, whereby a ball fits into a spherical seat to create the seal. In this design, the ball is placed into a socket forcing the ball onto the seat by a small spring. A sliding Carrier containing the ball assembly translates to the right when pulled by the solenoid. Translation of the Carrier forces the ball out of the valve seat and into the Carrier. A hard stop prevents further motion of the Carrier, allowing a hole in the carrier to provide an open path for ions to travel thru the valve and up the inlet tube. When power to the solenoid is removed, the recoil spring sends the Carrier back, returning the ball to the valve seat to complete the seal.

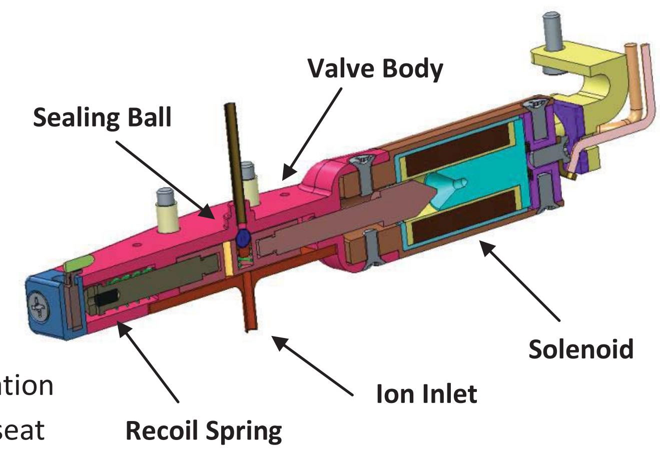


Figure 6a- ETU /Flight Valve Section

Results of ETU /Flight Aperture Valve Testing

The ETU /Flight Aperture Valve design exceeded expectations for sealing and performance. The valve seat design was unique for this application and routinely achieved sealing leak rates as high as <E-9 cc/sec He. In fact, 5E-9 cc/sec. in Helium was measured even after 125,000 cycles.

Closure times also exceeded requirements; open and closure times of <50ms (each way) were observed with an typical time of 26ms. The ETU /Flight Aperture Valve design proved superior to the original valve in meeting or exceeding design requirements. Tests were conducted on valve endurance beyond requirements, finding a small reduction in sealing leak rate after 250,000 cycles. Additional testing was subsequently performed on the same valve to assess endurance when contaminates were introduced into the test chamber environment. Mars regolith, an earth-based concoction of materials to simulate a typical Martian bedrock soil was used for the test. The test valve was run again for an additional 30,000 cycles in the contamination environment without failure. Leak rate was measured at 2E-8cc/sec He, approximately 5 orders of magnitude higher than the end of life requirement (1E-3 cc/sec He EOL spec vs. 2E-8 cc/sec He on test valve).

Conclusion

The MOMA Aperture Valve development program was briefly discussed in terms of design improvements resulting from prototype test results. The Initial Valve design was based on over 125 requirements which were distilled down to the top 25 “driving” design requirements. The Initial Aperture Valve concept seemed promising, based on calculations and perceived merits. However, performance results of this design were disappointing, due to delamination of TiN and DLC coatings applied to the Titanium base metals, causing debris from the coatings to seize the valve.

Despite the loss, valuable information from weakness discovered in the Initial Valve design was used to develop a second, more robust Aperture valve. Based on a check-ball design, the ETU /flight valve design resulted in significantly less surface area to create the seal. Moreover, PVD coatings were eliminated in favor of hardened, nonmagnetic corrosion resistant alloys. Test results were impressive, with the valve achieving five orders of magnitude better sealing leak rate over end of life requirements. Cycle life was equally impressive, achieving 280,000 cycles without failure. Due to schedule constraints, the ETU/ flight valve was never tested to actual end of life, however, it is estimated that the valve could achieve 500,000 cycles, due to the relatively few particulates discovered during post-test inspection of valve components.

Acknowledgements

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