

Miniaturized Single-Shot Valve and its Application to the ExoMars Pasteur Payload

Pierre Muller*, Hartmut Henkel* and Sabine Klinkner*

Abstract

Hermetically sealing a gas tank and opening it into tubing under telecommand control is a function required in various space instruments. There are a number of space valves that are power saving, withstand vibration, and do not contaminate the gas. But none of them combines these features with low mass and the ability to withstand temperatures of 130°C during the sterilization process mandatory for planetary missions.

In this paper, a novel miniature valve is presented, which is particularly adapted to space applications. It is electrically actuated, utilizing a bimetallic snap-disc that pierces a metallic membrane by a needle pin, thereby opening the valve. The design of this single-shot valve is such that it allows it to withstand a temperature of 130°C and a pressure of 50 bars. The valve is also lightweight (6.62 g) and it requires only 9 W to operate.

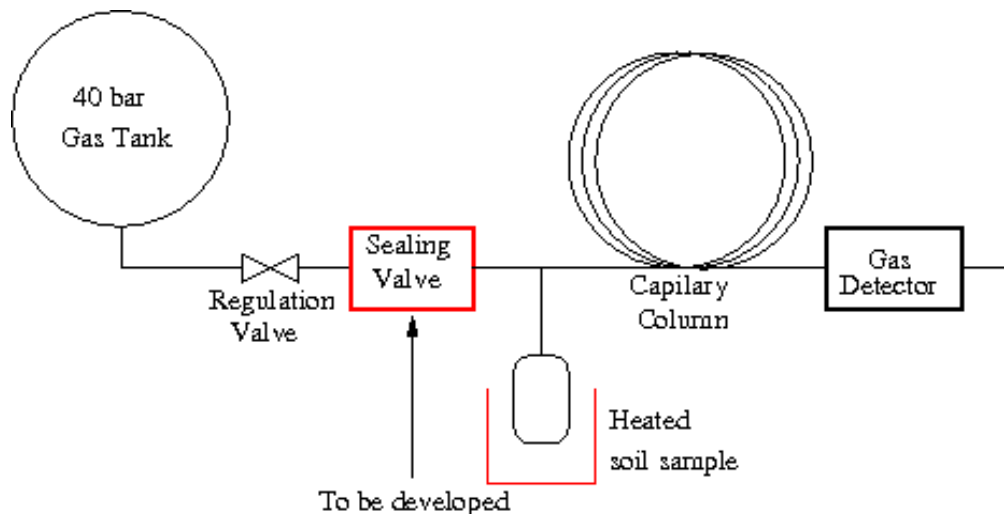


Figure 1. Schematic of a gas chromatograph (MOMA design).

Introduction

How to hermetically seal a high pressure tank and remotely open it in a reliable manner? This technical question arose within the development of the gas chromatograph of the Martian Organic Molecular Analyzer (MOMA), a space instrument part of the ExoMars Pasteur Payload. Onboard is a gas tank, since gas is needed to carry the substances in the chromatographic columns. After assessing the existing valves, the conclusion was drawn that none of these valves was perfectly adapted to the purpose described above.

* von Hoerner & Sulger GmbH, Schwetzingen, Germany

Therefore other solutions were considered. A self-opening valve consists of two main elements: the sealing element, and an actuator. All combinations of existing sealing elements and actuator were listed, and it appeared that sealing valves is a field that requires more exploration. Who has ever built a sealing valve with a piezoelectric actuator? To the current knowledge this has never been done. This seems also the case for a valve working with a bimetallic snap-disc.

This paper first explains the motivation of this development, in particular the function the valve has to fulfill in the MOMA gas chromatograph. After this, the basic design and the refined design of the valve are developed. Finally, the valve was tested and the design reviewed.

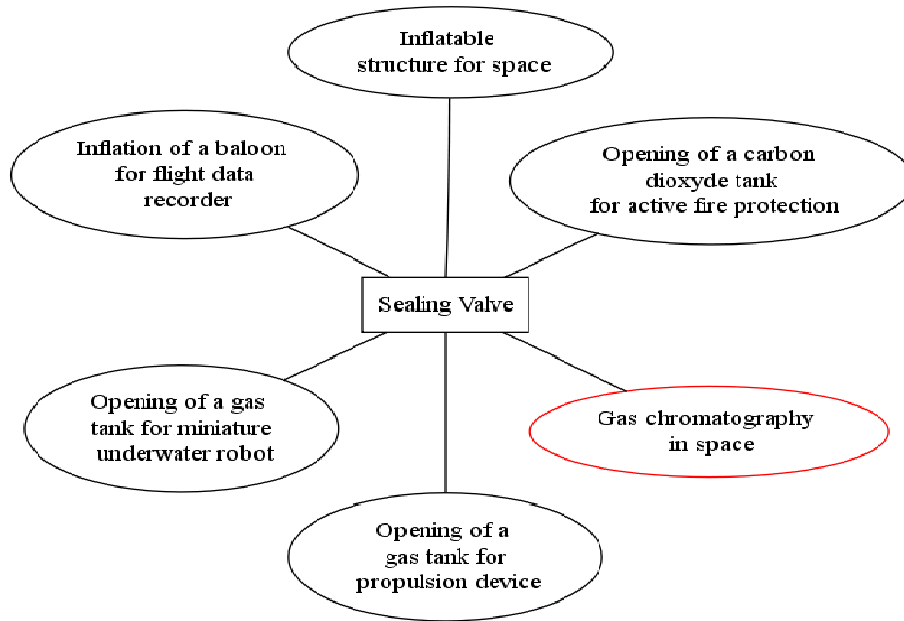


Figure 2. Diagram of the applications of the valve.

Purpose

MOMA is a project of the Max Planck Institute for Solar System Research and the Laboratoire Atmospheres, Milieux, Observations Spatiales. The MOMA objective is the analysis of the Martian soil composition during the ExoMars mission. It consists mainly of a gas chromatograph and a laser spectrometer. The gas chromatograph uses helium to carry the evolved gases from the heated soil sample to the capillary columns, as shown in Figure 1. The speed of the gas flow is regulated by a thermal regulation valve in which the flow is controlled by a sapphire ball compressed to the aperture to a higher or lower level. The compression of the ball is determined by the thermal expansion of the body of the regulation valve, which is heated by a resistor. In this continuous process the regulation valve opens as its temperature is increased. Here a key problem appears, as the entire instrument is heated up during the sterilization process required by the committee on space research for missions to the Martian surface: If no other device is hermetically closing the gas tank during sterilization, it would lose its contents. The main focus of the development presented here is to have a valve that truly hermetically seals the tank, before it is opened by breaking the seal. The initial hermeticity is the key point to select a single-shot valve principle.

The projected valve has to be very lightweight (maximum 10 g), as the mass budget of the scientific instrument is very limited. The flow rate does not need to be very large, as the typical flow rate of helium

in gas chromatography using capillary columns does not exceed 50 ml/min. However the other specifications are quite harsh: the valve has to withstand the gas tank pressure of 50 bar, and a temperature of 130°C (temperature of the sterilization process) should not modify its behavior.

A further purpose of this work is to propose a smaller and more rugged alternative to the existing valves that provide hermetic sealing at pressures in the range of 50 bar. Such valves can have a wide range of applications. Indeed, it can be used in the space industry for deployment of inflatable structures, for opening of a gas tank for an electrostatic ion thruster or other space experiments with gas. On the ground, it can be used for opening a CO₂ tank for active fire protection. A gas tank of an underwater robot could also be opened to bring it at the surface.

Existing Sealing Valves

Having an overview of existing valves was a very helpful step of this work. The focus was placed on single-shot valves, for the reason that it seemed the only reliable way to keep a tank hermetically sealed years after filling. The first encountered single-shot valve was the solenoid valve from the company Industria, France. This valve was already on board the Aerosol Collector Pyrolyzer (a GC-MS) for Huygens, and isolates the gas tank of the COSAC instrument, part of the ESA cometary mission Rosetta. It consists of a quite bulky solenoid actuator and of a thin membrane that obstructs the gas flow and can withstand pressures up to 50 bar. When it is electrically powered, the solenoid displaces a pin that pierces the membrane.

Very original other means to pierce a metallic foil to open a tank were found for space. In the Thermal Evolved Gas Analyzer on-board with the Phoenix Mars mission, the gas tanks are opened with a foil punctured by a wax actuator [1]. Here the device is not suited for the application because typical fusion temperatures of wax are below 130°C. Often used in the space industry is the Pyrovalve, manufactured by Conax, Florida [2]. It has been used for instance in the Titan and Delta II NASA missions. Here, the gas flow is blocked by a ram that is moved downwards by an explosive initiator placed on a tube above. The data sheet claims that the valve does not contaminate the gas and that the operating pressure reaches 647 bar. The reasons why it is not suitable for the application is the maximum storage temperature of only 60°C and its bulky construction.

The Space Science and Technology Department, Rutherford Appleton Laboratory has designed a one-time opening valve for the carrier gas tank of the Ptolemy instrument, a gas chromatograph coupled with a ion trap mass spectrometer built for the Rosetta mission [3]. Using this valve, the tank is normally sealed by a hollow and frangible pillar. A shape memory alloy (SMA, here Nitinol) actuator, having the ability to bend when heated over a certain temperature, is placed near this pillar. To release the gas, a heater outside of the housing elevates the temperature of the nitinol actuator, which bends and breaks the seal. The pressure of the Ptolemy tank is similar to the one of MOMA, and the valve is effective more than 15 years after filling. But also here the low actuation temperature of 76°C prohibits its use for MOMA.

Interesting is also the concept of an alternative to the Pyrovalve [4] which utilizes three burst discs (diaphragms specially designed to burst at a precise pressure difference) to form two chambers. The left chamber is pressurized at the tank initial pressure, while the right chamber is pressurized at the external pressure. A heater is able to elevate the temperature and thus the pressure inside the left chamber. This causes the discs to burst in the succession middle-left-right. This system has apparently not yet been realized.

A further project, launched by NASA aims at finding an alternative to the Pyrovalve. The principle is close to the one of the Ptolemy valve: the actuator is a SMA tube that can be heated from the outside. As the SMA is heated, it recovers its expanded shape, and the evolving force breaks a titanium tube responsible for the gas-tightness. Here the actuation temperature is linked to the used alloy nitinol, and is therefore approximately the same as for the Ptolemy valve. For this reason it cannot be used in MOMA.

On some one-time opening valves, the sealing element is neither broken nor pierced, but melted. The Angström Space Technology Centre has developed a valve made from two silicon discs or wafers forming a filter and a heater [5]. The gas path is obstructed by an indium solder (melting point 156.6°C), that can withstand 100 bar pressure and is melted within 10 s requiring power of 13 W. The silicon element weighs only 0.4 g, but the housing weight amounts to 140 g. The Jet Propulsion Laboratory has also built the micro-machined isolation valve, opening when a doped silicon membrane melts (less than 30 mJ are needed). The Pyrex housing has a burst pressure of about 200 bar. A disadvantage of these valves is that parts from the solder can be released into the carrier gas, although both valve types integrate a filter that captures the larger particles. Another thermally actuated valve using paraffin as seal was developed, but it can be excluded for the MOMA instrument because of the low actuation temperature.

Basic Design

Looking at all these valves increased the motivation to build a new valve. Also, the basics of a sealing valve were retained: it is always a combination of a sealing element and of an actuator. The sealing element can be a frangible pillar, a shaft, a meltable element or a metallic membrane. All possibilities of sealing element are used in single-shot valves. However not all possible actuators have been tried for such an application. Particularly interesting are actuators that are activated by a temperature change. Good examples are the regulation valve of MOMA, the valve with a wax actuator, or the valve with a shape memory alloy. Indeed it only requires a heater, which is a very simple and rugged way to transmit energy. Moreover, the heater can be placed outside the body of the valve, which avoids complications with cables fed through the body of the valve. The only problem with thermal actuation is that the activation temperature has to be above 130°C, temperature of the sterilization process, with a sufficient margin. Ideally, there should exist an activation temperature point, and the actuation should not take place progressively. Which thermal actuator has a well defined actuation temperature? Shape memory alloys are very interesting, and materials that recover their shape at temperature over 150°C were searched. The Company Dynalloy could provide high temperature SMA made of NiTiPt with a recovery temperature of 300°C. But high temperature SMA is still a field of research, and these are very costly elements, only available in the form of wires. A rugged design needs an actuator with a longer heritage. A longer heritage and also high working temperature is given by snap-discs. These are made of two layers of metals foils with different thermal expansion coefficients and bend at a determined temperature. This actuator was favored because it is very easy to fit inside a housing, very light, and does not produce any out-gassing, like thermal actuators based on phase change.

Having chosen the actuator, the sealing element remained to be selected. Also here, the criterion was the reliability. Therefore it was looked for a component that has a broad use and that benefits from wide knowledge. An attractive device on which the design could be based on is called burst disc. It is basically a thin disc of gas-tight material that ruptures at a certain pressure difference between the two sections it separates. These discs are widely used to protect against over-pressures. Similar to the solenoid valve from Industria, a membrane could be punctured by a pin attached to the actuator. The first test showed that the force and the displacement yielded by the bimetallic snap-disc were sufficient to clearly pierce a membrane similar to a burst disc calibrated at 150 bar. The next step was to design the body of the valve with heater, tubes, and adequate pin attached to the snap-disc.

Refined Design

In order to ensure a high reliability, some important design parameters have to be selected carefully. For example the pin has to be fixed in a manner that it cannot accidentally touch the membrane, the membrane and the housing have to be so thick that they withstand the high pressure.

First of all, a housing made of stainless steel was chosen, to be weld-compatible with the 1/16" (1.6 mm) outer diameter tubes used in gas chromatography. As basic shape, a cylinder was chosen, to just fit the dimension of a commercial snap-disc that is 12.7 mm. From the beginning, a configuration was found,

where the snap-disc does not block the flow of gas: the inlet tube and the outlet tubes will be placed at the same side of the housing, the inlet (high pressures) at the side and the outlet with the membrane at the center (See Figure 3). This has also the advantage to let one side free for the placement of the heater. A heater with a diameter 12.7 mm from the manufacturer Minco could be found. It is an ohmic heater that is very thin and lightweight that can heat up to a temperature of 200°C. The cover material of the heater is made of Kapton .Because of its low out-gassing rate and because it remains stable in the temperature range of -273°C to +400 °C, Kapton is a material that is often used in the space industry. The heater has a hole in the middle so that it can be reliably fixed via a screw and a custom-made washer. As shown in Figure 3, the pin is also attached via a hole in the middle of the snap-disc and a washer. The parts are soldered together with a 300°C melting temperature solder. The pin is gold plated and the washer is made of brass, so it can be soldered without any problem.

The snap-disc itself is held in place by the two main parts of the housing that form the volume for the snap-disc where it cannot touch the membrane when it is not actuating. It was also verified by CAD that the pin enters in the membrane with a reasonable margin. The snap-disc is not fully fixed to the body of the valve, but has a little play to let it bend correctly, this also providing thermal expansion. The snap-disc does not separate the inside of the valve into two chambers; a little drilling is in the housing equalizes the pressures. Hence it is ensured that gas pressure cannot activate the snap-disc.

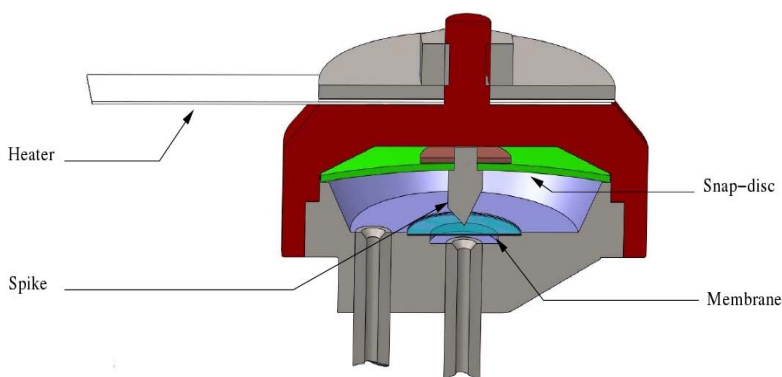


Figure 3. 3D view of the inside of the valve.

The thickness of the housing was determined with a finite element analysis program. The behavior of the housing under a pressure of 50 bars was simulated. Resulting from the analysis, the housing was reinforced at the fixing points of the tubes. This resulted in a mechanical factor of safety using the von Mises yield criterion of 3.34.

All welds were carried out using Nd:YAG Laser technique. The process for welding the membrane to the housing needed some iteration to come to a gas-tight result, but now the process is well determined. Once the valve had been manufactured, the overall gas tightness could be verified, and also that the valve opens when electrically powered.

Design Verification

Testing a single-shot device is a critical issue, because repeatability has to be tested over many valves, and therefore has to be carried out carefully.

A helium leak detector was used to test separately the gas-tightness of the welds for mounting the membrane within the housing. No leak could be detected after one hour at 30 bar inner pressure. The valves were tested in an oven at 130°C and it was observed that the valves were afterwards still gas-tight. The opening test was also successful: in average after 90 s of powering the valve at 9 W, the valve at 30

bar on the inlet opens and bubbles become visible if the outlet is put in water. A test with an open valve was also carried out, in order to observe the hole created by the pin after actuation.

Nevertheless, the valve is still not formally space qualified; this would imply a program with testing of a large amount of valves, including thermal cycling and vibration test.

Conclusion

Bimetallic thermal actuation is a very simple, rugged and widely used principle. However, its use is mainly confined in thermal switches where the force needed is not large. In some application where a small, simple actuator, preferably without harness, is required, a standard snap-disc can be a good choice.

Even though single-shot devices have drawbacks concerning their testing, they provide a considerable advantage concerning their reliability. In the specific case of MOMA where a perfectly hermetical device is required, it is safer to choose a sealing element based on single-shot operation.

The valve built (see Figure 4) has the advantage over the previously foreseen solenoid valve to be lighter by a factor of ten. Space qualification was taken into account from the beginning of the design task, and testing showed high reliability of the device.

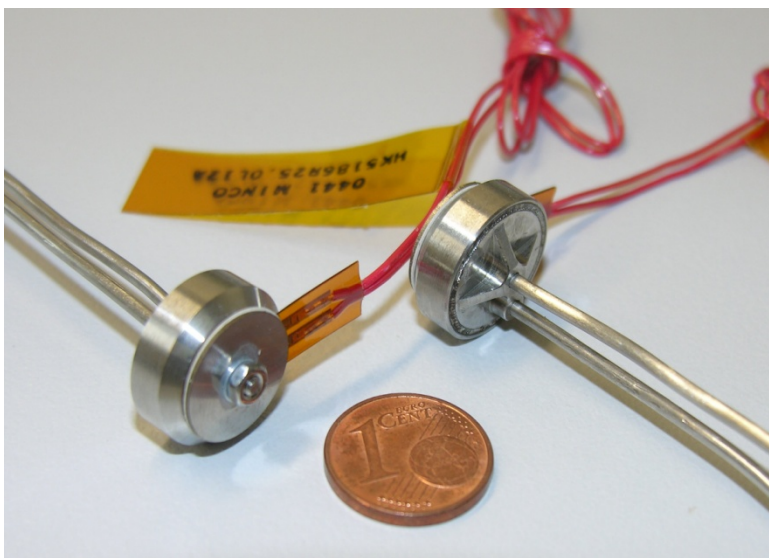


Figure 4. Photo of the manufactured valves.

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