BIOCONTAINMENT OF MARS SAMPLES RETURNING TO EARTH

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ABSTRACT

In the framework of a potential international Mars Sample Return (MSR) mission, a Bio-Containment system was conceived, designed, breaboarded and deeply investigated by Leonardo S.p.A. (formerly Selex ES) and Eniprogetti (formerly Tecnomare) under European Space Agency development contracts funded by the Mars Robotic Exploration Preparation (MREP) Programme. This paper presents the results achieved in the development phase, started in 2011, and reports the results of several tests performed on the breadboards: indeed, the original Bio-Container System concept has been validated and consolidated through a significant experimental test campaign performed at breadboard level. The proposed next step is the development and test of a more complete and representative Engineering Model of the system.

1. INTRODUCTION AND REQUIREMENTS

The material coming from Mars are full of interesting information to be studied on Earth but could transport some form of bacterial life that might injure the life on our planet. In order to avoid possible cross contamination a bio-sealing/containment barrier is needed.

The bio-containment method described in this paper is based on gaskets and vessels and put in place by mechanisms. Together with the sealing/containment system a monitoring system also is foreseen.

In sequence, the Orbiting sample (OS) coming from Mars, will be captured and introduced into the bio container. Here the OS will be sealed and the chain with Mars broken. Once also the containment is applied, the bio-container will be transferred into the Earth Re-entry Capsule (ERC) and the monitoring system activated. At this point the system is ready for the return flight to Earth. During the flight the monitoring system will verify if the application of the sealing/containment has been done properly and if macroscopic degradation occurred during the return period. If all the monitoring parameters are in line with the expectation, the ERC will be authorized for Earth landing.

The most critical aspects of the project are the requirements referred to planetary protection. A sample return from Mars is considered a planetary protection category V restricted return - no material can be returned from Mars unless safely sealed or sterilized. This lead to one of the most important requirement that heavily drives the design. This requirement states:

- *The bio-container shall ensure that the probability that a single unsterilized particle of > 10 nanometers in diameter is released into the terrestrial biosphere shall be < 10^{-6}*

This is the critical requirement defining both the quality of the required seal and the performance of the gross failure detection and monitoring system.

Other requirements that have impact on the design are referred to redundancies and reliability of the system and they can be reassumed stating that all the elements that have a direct impact on safety need to be double failure tolerant.

To satisfy the requirements the resulting bio-containment system has been based on:

- Two metallic containers one into the other
- First lid of the inner container that represents the first bio barrier (Chain Breaking Lid - CBL).
- Second lid of the inner container that represents the first level of containment
- Lid of the external container that represents the second containment level
- A monitoring system that checks the status of the seals during the return flight to Earth

2. ORIGINAL DESIGN

The image here below shows the whole system:

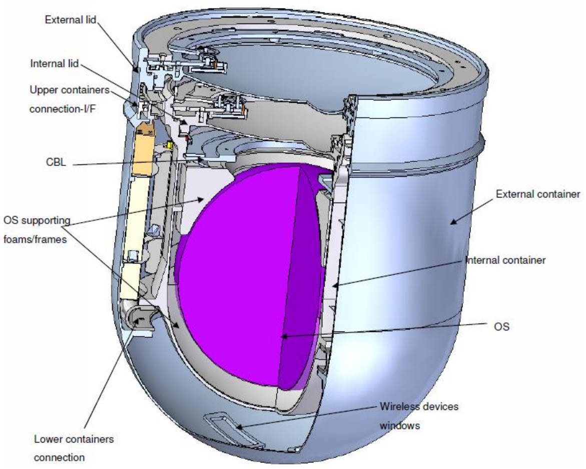


Figure 1: Schematics of the Bio-containment system

Metallic containers

The container consists of two metallic compartments, fixed each other by means of screws. The image here below shows the inner container and the fixing points.

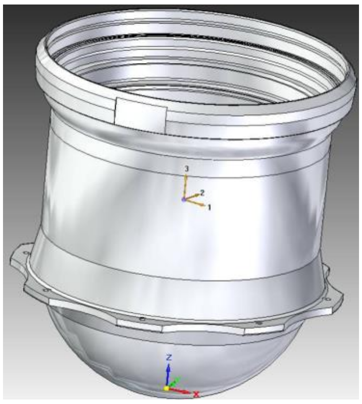


Figure 2: Inner container CAD model

The material of the inner container is aluminium while the external one is in made in titanium. This second material is needed for the wireless data/power exchange between the bio container and the spacecraft (see monitoring system section later on).

The dimensions of the two containers are driven by the diameter of the Orbiting Sample (OS).

On the internal base of the inner container a material (PEEK structure) supporting the OS has been introduced. During insertion of the CBL (see CBL later on), this material will sustain the OS during application of the design pre-load.

From a mechanical point of view the containers have to withstand to the re-entry shock without compromising the containment function: some analysis have been performed to guarantee good margins during sizing.

Chain Breaking Lid

The Chain Breaking Lid (CBL) is the first lid that is introduced into the inner container. It is composed by two half lids equipped with one metal gasket (each).

The CBL has the following main tasks:

- Pre-load the OS into the first container
- Seal the contaminated zone (on both side container and receiving tunnel)
- Sterilise the contaminated line between container and receiving tunnel applying a Self-sustained High-temperature Synthesis (SHS)

The image here below shows a conceptual view of the operations performed to break the chain with Mars.

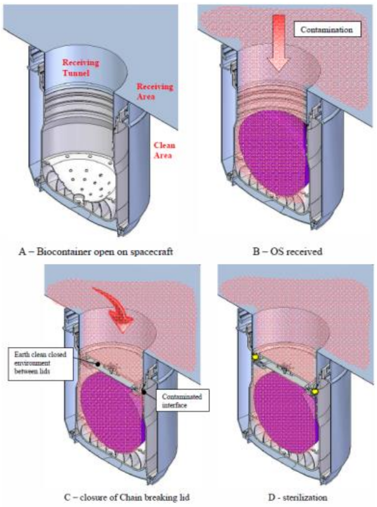


Figure 3: Operations for breaking the chain.

The internal container (position A) is in contact with the receiving tunnel (from where the OS will enter). Once the OS is into the container (position B) the closure of the CBL can be started (the red part in figure IV represents the contaminated zone). When the CBL is in the correct position (C) the SHS is activated using a power source and the contaminated boundary line is sterilized. The SHS technology is based on Nanofoil© where a combination Aluminium and Nickel layers (after the activation) can reach a temperature higher than 500°C. At this point one half of the CBL is attached into the inner container and the other half is attached to the receiving tunnel. The bio container can be removed from the receiving tunnel and positioned in another place for the succeeding operations.

In conclusion breaking the chain with Mars consists in insulating the contaminated zone plus a sterilization of the remaining contaminated line.

From the fixing/sealing point of view, the half lid introduced into the inner container works similar to the other lids described in the next subheading.

Containment lid internal and external container

The function of each lid is to close the respective container. The two lid are practically the same, they offer the same sealing level and use the same concept to assure the closure on the container. The only difference is in the outer diameter. They are equipped with three level of sealing gaskets (see fig.4 here below).

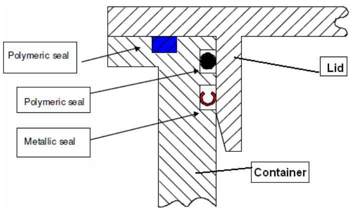


Figure 4: Schematics of the three sealing levels.

The gaskets are of three different materials: one metal spring energized, and two polymeric ones (i.e. Viton, silicone or PEEK). The choice of having different materials for the gaskets has the aim to reduce any possible common failure mode. With respect to the direction of lid insertion into the containers, two of these gaskets are radial while the third is axial.

Once the lid has been positioned into the container and the gaskets have been put in the correct position, the lid needs to be taken in place in order to ensure the correct sealing: the original solution was to fix the lid to the container thanks to two latching blades (see fig.5).

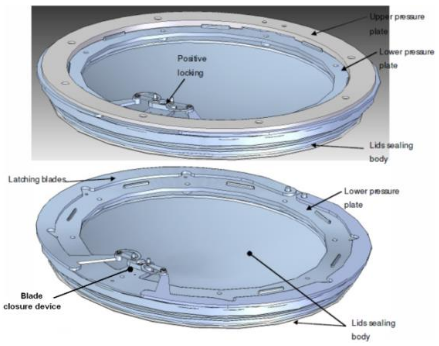


Figure 5: view of the lid.

The positioning of the lid and the closing of the blades is performed by the End Effector described later on.

Monitoring system

The monitoring system is a pressure/temperature based system that will monitor a defined pressure within a well-known volume. The system is positioned between the two containers. For safety and reliability aspects, the monitoring system is presently foreseen in triple redundancy.

The two images here below show the monitoring system alone on the supporting structure and integrated into the bio-container.

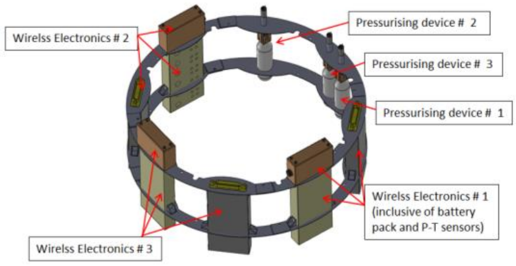


Figure 6: Basic layout of monitoring system components (preliminary).

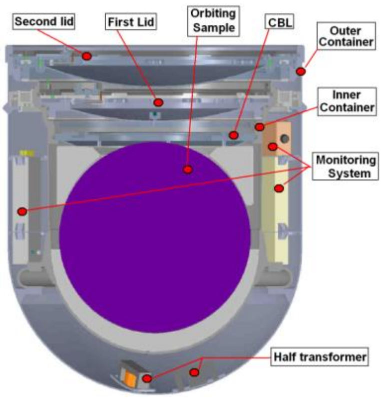


Figure 7: Monitoring system integrated into the bio-container.

It is basically composed by:

- One pressure-temperature sensor from Honeywell
- One pressure sensor from Kulite
- One electronic board
- One battery pack
- One pressurization device
  - Motor-reducer
  - Drilling bit mechanism
  - Miniaturized Argon gas cylinder
  - Hall sensor (and magnet)
- One half transformer for wireless communication

After closure of the lids and positioning of the bio-container into the ERC, the inter-vessel chamber will be pressurized by argon gas. The pressurization is achieved by perforating a miniaturized argon container so to create a pressure in the range of some of hundreds of mbars. This is achieved by a dedicated mechanism, composed by an actuator that perforates an argon container by means of a drilling tip. The energy needed to actuate the motor-reducer is stored in rechargeable batteries.

Once pressurized, the environment evolution and status of the inter-vessels chamber is then monitored by reading the pressure and temperature information from

appropriate P-T transducers. The data collected will be transferred to the ERC via wireless data transmission.
All the monitoring operations to be performed in the bio-container are managed by an external electronics present in the ERC and by a bio-container internal electronics. The exchange of the information between the external and the internal electronic is done via a wireless interface which consists of an electromagnetic coupling between two half transformers faced one to the other and separated by the metallic wall (titanium) of the outer container. Through this wireless communication both power and data will be transmitted.
The use of a wireless device gives the advantages that no additional leak path are present (e.g. via a feed-through), the bio-container can be moved without restrictions coming from an existing harness and the container structural integrity is maximised.
Fig. 8 shows the two halves of transformer (three for redundancy) one into the bio-container and the other into the ERC.

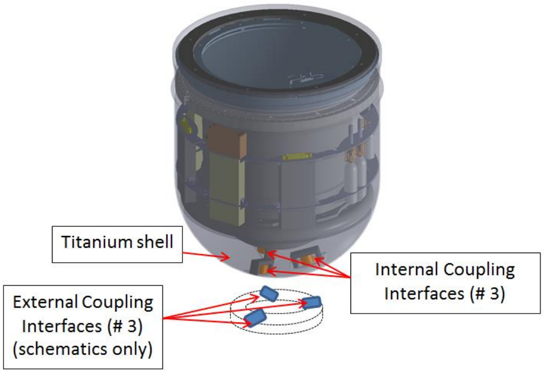


Figure 8: Location of the monitoring system wireless interfaces (preliminary)

Closure mechanisms
In order to close the two lids and the CBL, specific mechanisms are utilised.
Due to the fact that the CBL is positioned in place before the chain breaking operations (contaminated zone) while the other two lids are put in place after the chain breaking (clean zone) the mechanism that close the CBL and the one that close the lids need to be two separate objects.
The mechanism that close the two lids, is a two degrees of freedom effector; the images here below show a 3D cad model (alone and mounted on the container).

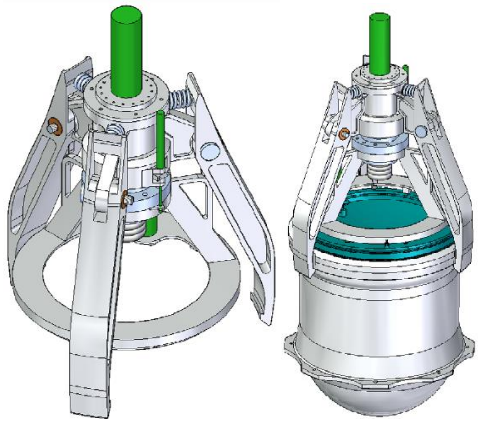


Figure 9: End Effector for lid closure alone (left) and engaged with the inner container

The End Effector is in charge of:

- ✓ Grasp the lid during the movement that position the lid close to the container
- ✓ Insert the lid applying an appropriate amount of force
- ✓ Close the latching blades

Based on the same principle, the closure device for the CBL is here below shown.

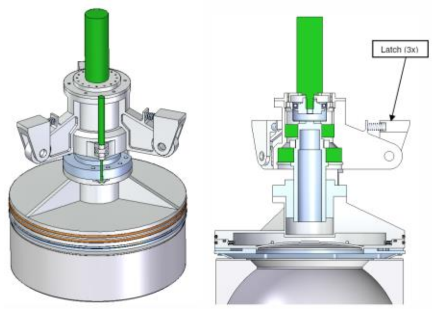


Figure 10: CBL closure device.

In the image can be seen the two half of the CBL and half-sphere that preloads the OS into the container (attached to the half lid that goes into the internal container).
These two closing device (the End effector and the CBL) will be not returned, they will be ejected once the closing operations are finished.

3. BREADBOARDS AND TEST RESULTS FROM THE PREVIOUS PHASE

The first phase of the project consisted in the development of the described design and in an appropriate breadboarding phase, that covered manufacturing and test of the key parts of the system.
The breadboards tested are shown hereafter:

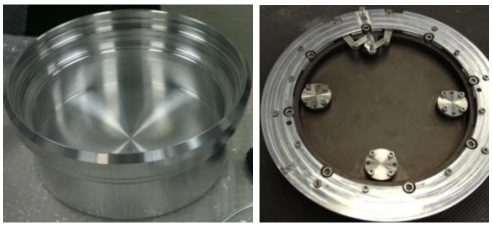


Figure 11: Inner Container (left) and Lid (right)

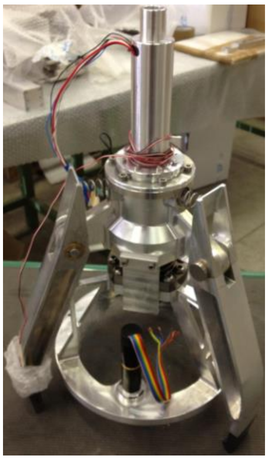


Figure 12: Closing device (End Effector)

The tests performed aimed to:

- Characterize different types of gaskets (Silicone, Viton, Teflon, Metal spring energized radially compressed) in terms of lak rate with respect to helium and in terms of number of particles escaped. This results were used as input parameters in a mathematical model that simulates the whole sealing barriers of the bio-container and propagates their performances.
- Gain confidence with the SHS based on Nanofoil® by means of a mock up representing a '90-degrees sector' of the part to sterilize.
- Verify overall correct performances in terms of pressurization capability, pressure and temperature identification accuracy, electric power and data transfer concerning the monitoring system, of which a complete breadboarding was done.

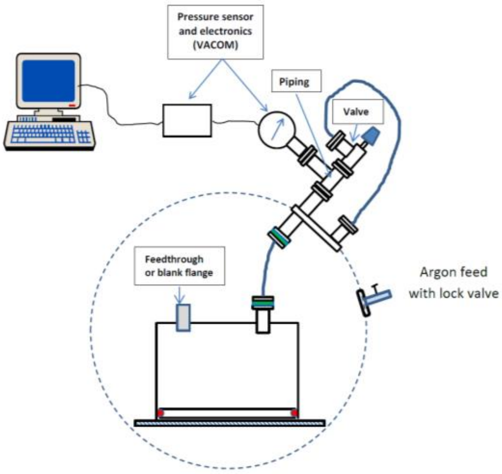
The main outcomes of the first phase were:

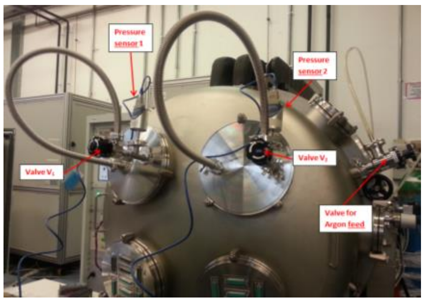
- The EndEffector proved to perform reliably (smooth motion, high force)
- Polymeric seals achieved He leak rate performances in line with nominal values.
- It has *not* been possible to achieve the tightness performances claimed by the manufacturer with the metal seals
- The technology based on Nanofoil needs to achieve reliable measuring of the surface temperatures induced by the very fast combustion process.

4. PURPOSE AND ACTIVITIES OF THE CURRENT PHASE

Starting from the outcomes of the first phase, a second phase of the project was released with the purpose to solve the open issues and consolidate the good results previously obtained.

The most recent activities focused on investigating and testing of gaskets of different types: in this respect, four different polymeric gaskets (Viton, Silicone, EPDM, Teflon) have been tested through a test campaign aiming at subjecting the polymers to an ageing process/performance degradation due to environmental conditions related to the mission scenario (i.e. radiation, vacuum, thermal ageing). In order to perform a representative test in a reduced amount of time, an 'accelerated life test' approach was chosen: in this way, the polymers was subjected to an ageing equivalent to that due to the mission scenario. On the basis of the results obtained in terms of leak rate performances during the first part of the test campaign, the two best candidates (Viton, EPDM) were selected to perform an 'operative' test with the gaskets individually installed in a breadboard of the container and of its lid. The 'operative' test consisted in an accelerated life test in T/V chamber with the closed container pressurized with Argon and the monitoring of the pressure in order to detect possible failure of the sealing. A dedicated setup was conceived to allow the necessary operations:





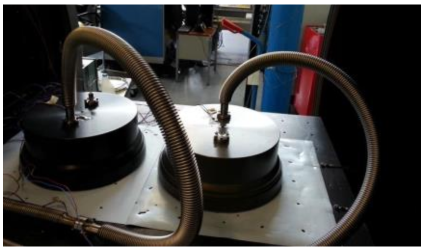


Figure 13: Setup for ‘operative’ test in T/V chamber

The setup architecture allowed to connect/isolate the item under tests to the T/V chamber appropriately, allowing operations such as evacuation and pressurization. Moreover, in order to prevent any leakage inward or outward due to the setup, all connection points were verified in terms of leak rate.
The test campaign led to the selection of two different polymeric gaskets, that proved to be promising both in terms of resistance to representative environmental conditions and in terms of sealing performance. Indeed, both Viton and EPDM showed an excellent behavior both at high (80-92°C) and low temperatures (-35/-55°C). Moreover, in general, considering different conditions (ambient condition, ‘operative’ test conditions, etc.) the leak rate values was maintained in the order of 10^{-9} -10^{-7} mbar*L/s.
To perform these tests, basically the breadboards manufactured in the first phase were used.

Concerning the third seal, of metal type, a thorough experimental investigation was conducted in order to solve the issues faced during the first phase (expected tightness performances not achieved/deformation of the container). The activity finally led to the selection of a configuration based on a metal seal with axial compression, instead of a metal seal radially compressed: indeed, this solution proved to provide the required level of sealing compatibly with a reasonable compression force, without damaging the system (container and lid).
Spring energized metal seals with different stiffness and coating material was considered: in the best cases, the force needed for inserting the metal energized gasket in axial configuration resulted around 50-70KN (against more than 100KN for a radial one), and the performance achieved in terms of leak rate was in the order of 10^{-10} mbar*L/s. To perform the closure operations, a press machine was used instead of the End Effector, that was originally designed for lower force levels.
Instead, the insertion force of the polymeric gaskets was confirmed to be negligible with respect to a metal seal and, in this cases, the closure of the containers was performed by means of the End Effector.
Also the metal seal with axial compression was subjected to an ‘operative’ test in order to verify that the good sealing was maintained under thermal conditions beyond the operative limits: as expected for the metal seal, the tightness performance was not affected by environmental conditions.

Concerning the technology for the sterilization to break the chain with Mars, it was investigated and tested trying to overcome the problems faced in the first phase, such as the need to obtain reliable temperature measurements. A new mock-up was conceived: in addition to thermocouples, it makes use of optical sensors to measure temperature values. Moreover, it allows to vary the thickness of the Nanofoil and the distance between Nanofoil and the surface to heat by radiation in order to select the best values for these parameters. The tests have been carried out for different materials: Aluminium 7075 black anodized, Titanium nitride and Titanium anodized. The results confirmed that Titanium behaves better than Aluminium (probably due to the higher thermal resistance), that the Nanofoil deforms during the reaction and that the correct measurement of the temperature is critical. Based on this, the setup was further modified in order to improve the reliability and repeatability of the results. The tests are currently in progress.

Last but not least, a testing activity was conducted also on the pressure transducers identified for the monitoring system: in particular, a test aiming to verify their performance in terms of long duration stability was performed in a representative environment (T/V chamber filled with few hundreds of mbars of Argon). The accelerated life test approach was used. Both the sensors showed performance in line with what declared by the manufacturer and with what needed.

Figure 14: Honeywell IPT sensor (left) and Kulite transducer (right)

Table 1: Long term stability performance declared by manufacturer

	IPT	KULITE
Long term stability [*mbar / day*]	≤ 9,45E-04	≤ 5,67E-03

Table 2: Measured Long term stability performance

	IPT1	IPT2	KULITE
Long term stability [*mbar / day*]	7,006E-04	9,610E-04	5,811E-04

5. OUTCOMES OF THE CURRENT PHASE

The extensive test campaigns carried out in the current phase consolidated the global architecture of the system proposed in the first phase and the good results obtained on some items (i.e. polymeric seals).

Also, some critical open points were solved, such as the possibility to use a metal seal. This change will be fully implemented and validated in the next phase of the development (see next section). Some parts will be modified and the design updated in order to to change the position of the seals and redefine the details of the seats (the new baseline foresees two radial polymeric seals and one metal seal axially compressed).

The closure device will also be adapted in line with the design changes of containers and lids and with the level of force required to close the containers properly, with all the seals.

6. ABOUT THE FUTURE

Now that the original Bio-Container System concept has been validated and consolidated through a significant experimental test campaign performed at breadboard level, the next step is the development and test of a more complete and representative Engineering Model of the system. This phase is under discussion with ESA at the moment.

The next phase will start with the implementation of the design modifications reported as outcomes of the current phase. Moreover, the need for an update of the design would in any case be necessary since the input requirement in terms of diameter of the Orbiting Sample has changed: the OS increased from a sphere 260mm in diameter to a sphere 280mm in diameter. Since the dimensions of the two containers are driven by the diameter of the Orbiting Sample (OS), also a scaling of the whole system must be taken into account in the next phase.

Apart from the needed design updates, the focus of the next phase will be on impact tests in order to verify the bio-container performances against the re-entry shock. Indeed, from a mechanical point of view the containers have to withstand to the re-entry loads without compromising the containment function. This is a very challenging input requirement that the next phase is meant to verify by test, as well as by analyses.
Full scale Engineering Models of the complete Bio-Container System will be tested against impact under different conditions (i.e. different soils, impact angle, etc.).

Moreover, an extensive environmental test campaign is foreseen on the integrated Engineering Model in order to take into account all the mission phases from launch from Earth to re-entry into the Earth’s atmosphere and impact at landing.

It is foreseen to perform these activities in the next two years, at the end of which, if the tests consolidate and verify the design, the Bio-Container System can be brought to a level of a Qualification Model.