Sealing technologies trade-off for a Phobos Sample Return Mission

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ABSTRACT

The Phobos Sample Return Mission (PhSR) is a phase of the Mars Robotic Exploration Preparation program, with the main objective to acquire and return 100 grams of Phobos soil (regolith) on Earth. First, a complete surface map with topographic and mineralogic information will be obtained by the spacecraft. After a successful sampling, an ERV containing the ERC with the regolith sample will head back to the Earth. Following touch-down, the ERC will be retrieved and opened in a dedicated environment. Given the importance and value of such return sample, it must be well protected between the moment when the ERC is closed on Phobos after the sampling operation until landing on Earth surface. Thus, a special containment system is necessary, capable of withstanding the harsh space environment and the mechanical stress occurred during the mission, while preserving the integrity of the regolith sample. Following previous sampling missions (Hayabusa, Stardust) and the problems raised by the contamination, one can say that the sealing system is probably the most important part of a sample containment system, as it shall protect the sample from Earth contaminants, but also to protect the Earth against possible micro-organisms or other hazardous substances found in space. This paper aims to analyse a variety of sealing technologies with importance in space applications like a sample return mission, measuring qualitatively and quantitatively the performance of a sealing

technology when it comes to fulfilling a series of requirements imposed by the sample return mission profile. Using these requirements and mission data as inputs, a trade-off analysis was made, to identify the most suitable sealing technology for a PhSR Mission. It was concluded that sealing technologies such as O-rings and Gaskets can be successfully used in these kind of missions, paying also attention to a proper design of the containment system.

KEYWORDS: *sealing system trade-off, sample return, exploration.*

NOMENCLATURE

COMOTI:	National Research and Development Institute for Gas Turbines
COSPAR:	Committee on Space Research
ERC:	Earth Re-entry Capsule
ERV:	Earth Return Vehicle
ESA:	European Space Agency
FEA:	Finite Element Analysis
MREP-2:	Mars Robotic Exploration and Preparation
MSR:	Mars Sample Return
PhSR:	Phobos Sample Return
S/C:	Spacecraft
SC:	Sample Container
TRL:	Technology Readiness Level

1 INTRODUCTION

Sample return missions represent one of the best opportunities to find more details (origin, composition, existence of micro-organisms, etc.) about the objects in our Solar System, details which cannot be determined at the landing site due to constraints like the available power, the mass of the equipment, the precision of the operations etc., attributed to the spacecraft. Also, as the technology progresses in time, the acquired samples can be restudied, making them a valuable scientific resource available for the future. [1]

Orbiting around Mars, Phobos is a low-gravity object, with great physical and scientific importance, as its origins are still a mystery. Along with its "brother", Deimos, Phobos' composition may provide information about objects from outer solar system, as well as information about the Martian surface material following impact ejecta. All this information can answer lots of questions concerning a future human exploration of the Mars system. [2]

In the frame of the Mars Robotic Exploration Preparation (MREP) program, ESA is considering a Mars Sample Return (MSR) mission as a long-term objective, progressing step-by-step towards this objective through short and medium-term MSR-related technology developments, which are validated during intermediate missions. In this sense, ESA is currently assessing a Phobos Sample Return mission (PhSR) as a phase of the MREP program. The goal of this mission is to collect and return Phobos surface material (regolith) in access of 100 g to Earth.

Concluding, a Phobos Sample Return mission is a great opportunity to answer the questions mentioned above: the Mars moons origins, the early geological history and composition of Mars, all these leading to the preparation of a future human exploration with European contribution to the Mars Sample Return. This opportunity also targets the validation of several critical technologies for the MSR, including sampling, sample transfer and sealing, Earth Return Capsule and Sample Receiving Facility.

2 SAMPLE RETURN MISSIONS – ADVANTAGES AND SPECIAL DIFFICULTIES

The analysis of the soil composition of other planets contributes to the understanding of our Solar System, a sample return mission bringing many advantages in this regard. One of them is the development of advanced state-of-the-art technologies which are used to analyse the extra-terrestrial samples, as the analysis requires precision, sensitivity, resolution and reliability. As the analyse technologies advance, the acquired samples can be re-examined to come up with new data about the sample's originating object. Furthermore, the laboratory analysis is not limited by the constraints imposed on the spacecraft by the mission profile in terms of electrical power, mass of the equipment to be carried in space, reliability and precision of the spacecraft systems and finally, the overall costs. Another advantage of studying these sample returns on Earth is that a wide international community can participate in the analysis and bring its contribution to solving the mysteries of our universe. [1]

Besides the mentioned advantages, the sample return missions come also with difficulties imposed by the profile of the mission. Usually, a space mission consists in arriving at the destination, doing some analysis with high-tech scientific instruments, feeding the data back to Earth and finally abandoning the spacecraft on the observed object's surface or in its orbit. In the case of a sample return mission, the spacecraft must travel to the targeted object, acquire a sample, secure it in a special containment system and then return it back to Earth. A mission profile like this brings lots of challenges when it comes to the spacecraft design and its systems, as all the operations must be successful in order to accomplish the goal of the mission. To resume the above idea, two of the key words for such a mission are reliability and redundancy of the spacecraft systems.
A special attention must be paid to the integrity of the acquired sample, as the contamination with substances of Earth origin is an important problem raised during the mission and it can make the difference between success and failure (or partial success). In addition, the need of returning the sample safely back to Earth and the planetary protection against possible micro-organisms or hazardous substances, makes the containment system a very important component of the spacecraft. In practice, it is not possible to obtain a perfectly contamination-free sample, but the contamination can be minimized a lot by ensuring a proper design of the containment system. The ability of the containment system to preserve as much as possible the purity of the sample is greatly influenced by the sealing system. The performance of the sealing system affects directly the acquired sample, but in return the sealing system itself can be affected. Thus, it is necessary to carry out a contamination assessment to remove the contamination that can be removed, but also to minimize the contamination that cannot be removed.

3 PHOBOS SAMPLE RETURN MISSION – GENERAL ARCHITECTURE

The Phobos Sample Return mission offers an excellent opportunity to acquire a new portion of essential information about the origin of other planets. Knowledge of this process is important for comprehending the formation mechanism of the Earth and its early history. [3] The launcher presumed for this mission is Proton or Ariane 6, the mission being design for two scenarios, a short mission of 2,7 years and a long mission of 4,8 years. A main advantage of the long mission scenario is to allow a much longer Deimos characterization phase. Prior to the sampling operation, the S/C will scan the Phobos' surface to retrieve a complete surface map with topographic and mineralogic data in order to decide the landing site. Once chosen the landing site, the S/C descends and lands to collect the sample using a robotic arm. After the success of the sample operation is confirmed, the Earth Return Vehicle (ERV) leaves Phobos to head back to Earth, where it delivers the ERC by direct atmospheric re-entry. More details are presented in the following paragraph.

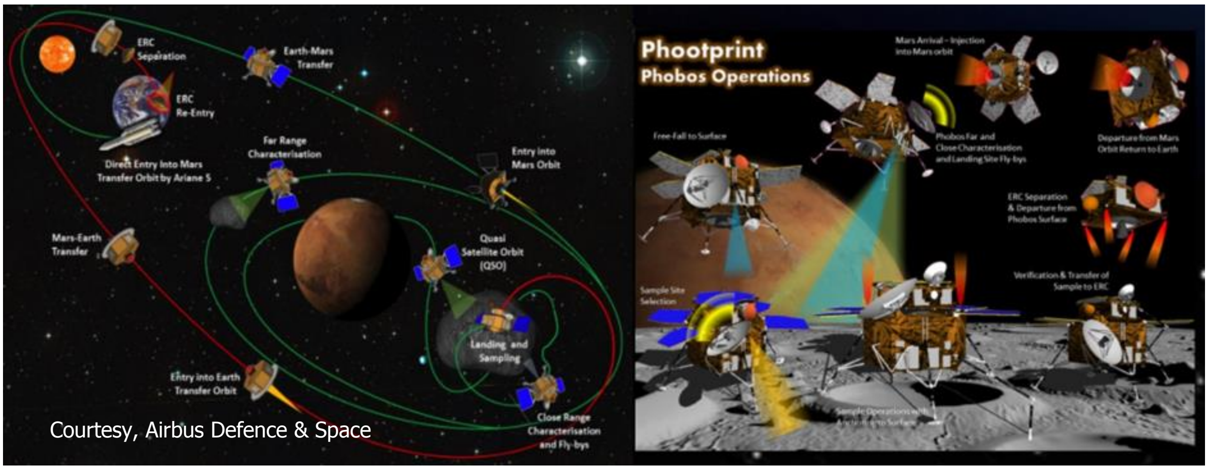
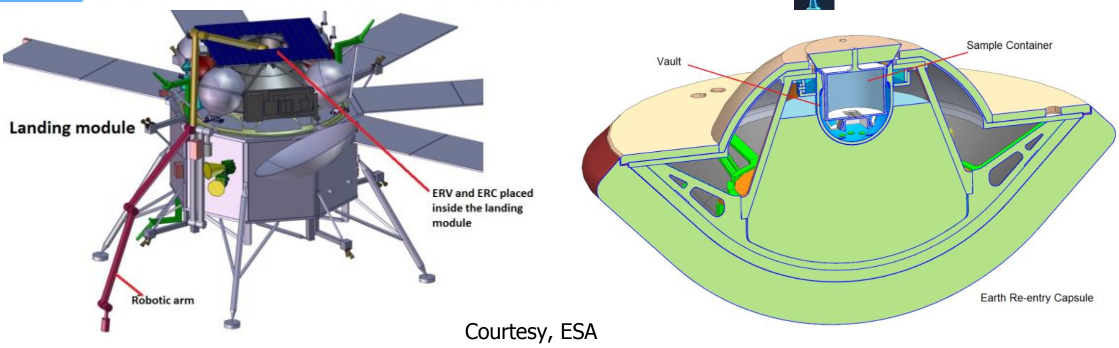


Figure 1: Mission Operation Concept [4]

The mission S/C consists of four elements: the Propulsion Module, the landing module, the Earth Return Vehicle and the Earth Re-entry Capsule. For the purpose of this paper, the elements of interest are the landing module and the earth re-entry capsule for which the main components are presented in Fig. 2.



Courtesy, ESA

Figure 2: Main components for the landing module and re-entry capsule [5]

The functional role of the components presented in the Fig. 2 are:

- The landing module containing the earth return vehicle, earth return capsule and robotic arm will land on Phobos;
- Earth Return Vehicle – the purpose of the ERV is to deliver Phobos samples (which are located in a vault inside the ERC) to Earth;
- Earth Return Capsule – contains the vault with the Sample Container and it will return the acquired sample to Earth with a passive landing without subjecting the sample to g-loads greater than 2000g. The ERC ensures mechanical and thermal protection for the Vault during the atmospheric re-entry.
- the robotic arm is responsible with maneuvering the sampling tool and the sample canister on Phobos, but also takes part in the closing operation of the Sample Container;
- The Sample Canister stores the sampled regolith collected by the sampling tool, while attached to the end of the robotic arm, and is then transferred and secured into the ERC;
- The sampling tool is used to collect the regolith and introduce it into the Sample Canister;
- The vault is fixed on the ERC internal structure, containing the sealing elements and it is a key component in avoiding the contamination of the sample.

For the "Breadboard of a sealing system for a Phobos Sample Return Mission", ESA imposed a series of requirements and bellow are presented the requirements which have direct implications over the sealing system and will be considered in trade-off. The trade-off analysis will help to determine the suitable sealing method for this project. Also, the general implication over the sealing system for each presented requirement was highlighted in the following table.

Table 1: System requirements implication over the sealing system

Req. No.	Requirement	Requirement general implication
Req - 1	No particle or droplet of a fluid > 1μm shall escape or ente sample canister	Implications over the sealing systems characteristics. Implications over how the sealing systems work.
Req – 2	The seal shall withstand a shock load of 2000g for 10 ms without failure	
Req – 3	The vault shall withstand the thermal environment encountered during the lifetime of the mission (operating temperatures -40^{0}C/+80^{0}C for vault and -60^{0}C/+60^{0}C for mechanical press and non-operating temperatures -100^{0}C/+90^{0}C for vault and -100^{0}C/+70^{0}C for mechanical press).	
Req – 4	The sample container vault shall be sealed using a maximum force of 40 N and a maximum torque of TBC Nm.	Implications over choosing the sealing system, the closing and tightness must be achieved using a force as small as possible.
Req – 5	The design of the vault shall be such as to minimize the control requirements on the robotic arm during insertion of the sample container into the vault.	
Req – 6	The vault shall be designed to be installed into the ERC	Implications over the sealing systems dimensions.
Req – 7	The sample container shall be cylindrical in shape	
Req – 8	The sample container design shall be taken from Airbus UK Phase A study.	

4 IDENTIFYING RELEVANT SEALING TECHNOLOGIES

In order to decide on a sealing method for PhSR, a trade-off workflow chart was followed to ensure that the trade-off is as comprehensive as possible and the obtained results are realistic, avoiding major risks for the next phases of the project. The trade-off workflow chart is divided in four main steps: **system requirements analysis** – from the imposed requirements (see Table 1), only those with implications over the sealing method were identified; **identification of the sealing methods** relevant to the project was made; along with the **identification of critical methods** that haven't reach yet the technological maturity for a space application and the impact over a sample return sealing system; and, finally, the **trade-off analysis**.

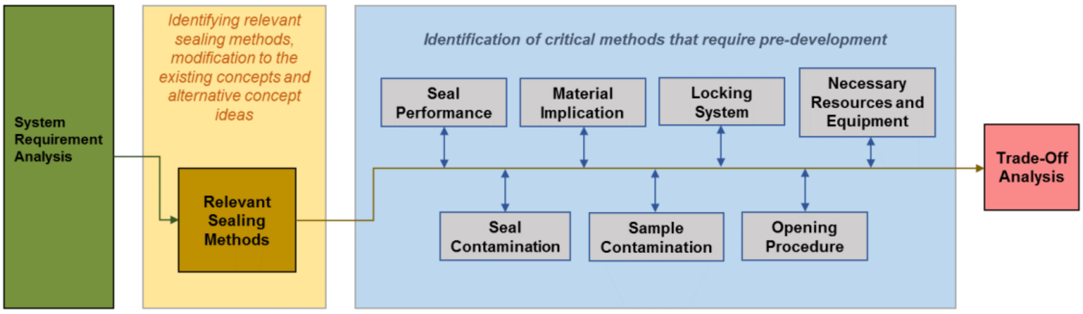


Figure 3: Workflow chart

Taking into account the nature of the mission and the working characteristics for the main sample and sealing system components, Vault and Sample Container, one thing can be concluded without performing a detailed trade-off analysis: a static sealing is going to be used because the two assemblies won't contain any moving parts. From definition, a static seal is the sealing between two surfaces that do not move relative to each other (except for small thermal expansion or separation by fluid pressure). [6]

Further, numerous static sealing methods were identified and then divided in two large categories: pre-loaded and fuse sealing methods.

For fuse sealing methods, the crimp, vibration, solder/weld and adhesive methods were considered and analysed.

For pre-loaded sealing methods, the O-ring, knife edge, gaskets and shape memory alloy methods were considered and analysed. These methods require an active force to be maintained during the return ~~duration~~ corresponding with the trip from Phobos to Earth surface.

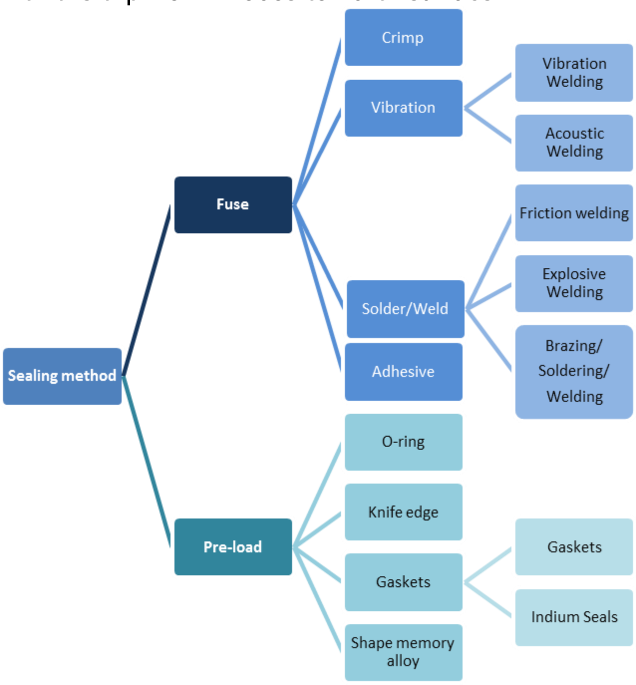


Figure 4: Sealing methods considered for the PhSR Mission

In order to have a unified approach, to define a suitable sealing method and after that to design and develop a sealing system concept, the analysis was conducted according to an imposed format and based on a series of criteria such as: advantages and disadvantages, relevant values, power, environment implications, dust tolerance, shock and vibration, risks etc.
Performing these analysis on each sealing method (see Fig. 4) it was concluded that some of the sealing methods need to be matured in order to reach a high TRL ready for implementation in a sealing system for a PhSR mission. In order to identify the critical technologies that need pre-development, a unitary approach was conducted, comprised of criteria such as sealing performance and contamination, sample contamination, material implication, necessary resources and equipment, locking and opening systems. The results of all these sealing method analyses served as inputs for the trade-off analysis presented in the following chapter.

5 SEALING METHODS TRADE OFF ANALYSIS

In order to conduct the trade-off analysis for the studied sealing methods, a number of factors/criteria have been defined. The factors/criteria which were used in the trade-off analysis resulted from the imposed system requirements, but also from COMOTI's experience regarding the development and production of components and products for the aerospace industry.
Criteria description is presented in Table 2.

Table 2: Criteria Description

No.	Criteria	Description
1	Constructive complexity	The followings points were taking into account: - the components of the sealing systems; - the additional components of the sealing systems (this components may remain on Phobos or may comeback on Earth); - opening procedures; - energy/forces consumptions; - other special requirements; Simple designs tend to have a lower chance of including an unforeseen failure mode and less failure modes in general (shall be take into account that if all systems components have high reliability or redundant systems the likelihood of proper functioning of the entire system can also increase);
2	Leak tightness	Prediction of the seal behaviour during the impact (2000g for 10ms); Prediction and assessment of the seal behaviour during the Phobos to Earth transfer;
3	Tolerance to particle contamination	The sealing system more favourable to be chosen for this application is dependent on the maximum debris which can be accommodated by the sealing surfaces and still assuring the requested seal at the imposed conditions (behaviour upon contamination with regolith). Also should be taking into account the additional mass and the increased number of robotic arm operations if a sealing cover is foreseen.
4	Feasibility	If the design is not possible or applicable to the mission, it will reflect that quality of the final solution. It should be analysed whether the studied sealing method has applicability in Phobos Sample Return Mission.
5	Sampled material contamination	Risks related to the impact over the quality of sampled material due to sealing phases; The sample can be affected by the different factors like: exposure to high temperatures and/or contact with other earth materials used in the sealing process. Also, should be taking into account the contamination of the sampled material during opening procedures (on laboratory).
6	Mass	Overall mass required for sealing (i.e. sealing mass plus additional mass needed to perform the sealing and locking system)
7	Power	Total power required to perform the sealing

8	Industry standard	Designs that are commonly used in industry (or variations of them) have a high appeal in current design because they are well verified and typically include large amounts of empirical data supporting their function.
9	Previous breadboard for space applications	Proven technology in other similar applications is a plus. If this concept has already been proven as a reliable system increases its value as potential solution to be adapted for a Phobos sample return mission
10	Testing especially related to leakage and to a shock of 2000g for 10ms	Evaluation of the difficulty and the resources necessary to realize realistic tests that could be compared with numerical simulations.
11	Numerical simulations especially related to 2000g	Credibility of FEA simulations taking into account the assumption that should be applied.
12	Complexity of locking systems	It should be evaluated the locking systems influence over the whole mission (risks, complexity). Particular sealing systems could not require any additional locking systems.
13	Reliability	The probability of the sealing system to perform its required functions under stated conditions for a specified period of time (shelf storage and mission)

After the criteria were defined, a criteria evaluation process has been undertaken by a team of experienced engineers from COMOTI. As it can be seen in Fig. 5 the various criteria were ranked and weighted to outline the most relevant aspects by attributing them the highest score impacts. Each team member gave each criterion a score between 1 and 10 depending on the perceived relevance of the criteria aspect. In order to have an equal weighting regarding the scores awarded by the six members of the team, the next algorithm has been used:

- for each member of the team a sum of the awarded notes for all the criteria has been calculated (this helps to identify the weighting factor of the notes awarded by each particular member);
- each note assigned by each member for a certain criterion has been divided to the value (sum of all member notes) obtained in the previous step, and after that, a sum of the obtained values has been made ('Total' column);
- the value obtained in the previous step was divided to six, which represents the number of members from the evaluation team, therefore obtaining the normalized score.

No	Trade off Criteria	Engineer 1	Engineer 2	Engineer 3	Engineer 4	Engineer 5	Engineer 6	Total	Normalized Weight
1	Constructive complexity	8	9	10	9	9	9	0.62	**0.10**
2	Leak tightness	10	8	1	9	10	9	0.46	0.08
3	Tolerance to particle contamination	10	7	2	9	8	10	0.46	0.08
4	Feasibility	10	10	1	8	9	7	0.44	0.07
5	Sampled material contamination	10	8	3	10	10	8	0.50	0.08
6	Mass	10	8	9	7	7	6	0.54	**0.09**
7	Power	10	8	9	7	9	6	0.56	**0.09**
8	Industry standard	5	8	3	6	7	5	0.36	0.06
9	Previous breadboard for space applications	8	5	4	8	7	9	0.44	0.07
10	Testing especially related to leakage and to a shock of 2000g for 10ms	8	7	1	7	6	8	0.37	0.06
11	Numerical simulations especially related to 2000g	9	6	2	8	8	2	0.35	0.06
12	Complexity of locking systems	9	6	3	9	5	7	0.40	0.07
13	Reliability	10	10	4	9	10	5	0.50	0.08
		117	**100**	**52**	**106**	**105**	**91**		

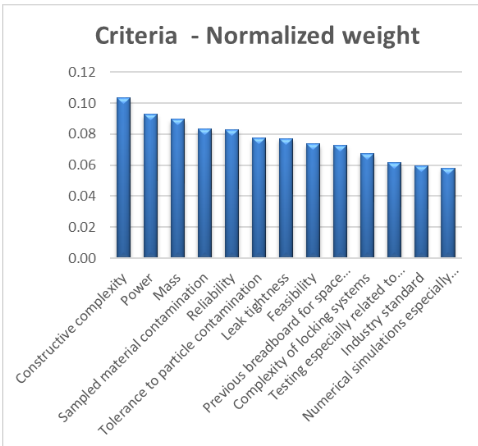


Figure 5: Weighting of the criteria. The team member normalized weights (left) and the relative magnitude of the criterions (right).

In Fig. 5 it can be seen that the three most important criteria are the Constructive complexity, Power and Mass. The criteria and the normalized weight was used in the following step of the trade-off analysis. In this step a mark between 1 and 10 was given for each analysed sealing method.
In order to have a more objective and global approach regarding the sealing methods ranking, a number of five engineers from COMOTI were involved in this process (other persons than the ones responsible with criteria weighting). The rank of each criterion was added and a total score for each sealing method was obtained (see Table 3). The obtained score was graphically represented in Fig. 6.

Table 3: Ranking the sealing methods

			Fuse sealing methods														Pre load sealing methods							
			Crimp		Vibration Welding		Acoustic Welding		Friction Welding		Explosive Welding		Brazing /Soldering		Adhesive		O-ring		Knife edge		Gaskets		Shape memory alloy	
No.	Criteria	Normalized weight	Score	Product	Score	Product	Score	Product	Score	Product	Score	Product	Score	Product	Score	Product	Score	Product	Score	Product	Score	Product	Score	Product
1	Constructive complexity	0.10	6.2	0.64	4.8	0.50	5.6	0.58	5.4	0.56	7.4	0.76	6.8	0.70	6.6	0.68	7.8	0.81	6.6	0.68	6.6	0.68	7.4	0.76
2	Leak tightness	0.08	5.4	0.42	8.8	0.68	8.8	0.68	9.6	0.74	9.6	0.74	9	0.70	7.2	0.56	8	0.62	7.2	0.56	7	0.54	6.6	0.51
3	Tolerance to particle contamination	0.08	4.2	0.33	5	0.39	5	0.39	6	0.46	6.6	0.51	5.6	0.43	3.8	0.29	5.6	0.43	5.2	0.40	6.2	0.48	4.6	0.36
4	Feasibility	0.07	5.4	0.40	3	0.22	2.4	0.18	3.8	0.28	5.4	0.40	6.4	0.47	5.6	0.41	8.8	0.65	8.2	0.61	7.2	0.53	5	0.37
5	Sampled material contamination	0.08	8.8	0.73	6.4	0.53	6.4	0.53	5.8	0.48	4.2	0.35	5.6	0.47	7.4	0.62	9	0.75	9	0.75	9.2	0.77	7.6	0.63
6	Mass	0.09	5.6	0.50	1.6	0.14	1.4	0.13	1.6	0.14	6	0.54	5.8	0.52	5.2	0.47	8.4	0.75	8.6	0.77	8.4	0.75	5.4	0.48
7	Power	0.09	4.8	0.44	1.8	0.17	1.6	0.15	2	0.19	8.6	0.80	6.2	0.57	5.6	0.52	9.2	0.85	8.2	0.76	8.4	0.78	5.6	0.52
8	Industry standard	0.06	7.8	0.47	5.8	0.35	5.2	0.31	6.6	0.39	5.4	0.32	7.4	0.44	6.8	0.41	9.6	0.57	8.6	0.51	9.4	0.56	5	0.30
9	Previous breadboard for space applications	0.07	3.8	0.28	2	0.15	1.8	0.13	2.2	0.16	3.6	0.26	6	0.44	3.2	0.23	9.2	0.67	7.6	0.55	7.4	0.54	5	0.36
10	Testing especially related to leakage and to a shock of 2000g for 10ms	0.06	6.6	0.41	7	0.43	7	0.43	7.6	0.47	7	0.43	7.8	0.48	7.2	0.44	7.6	0.47	7.2	0.44	7.6	0.47	6.6	0.41
11	Numerical simulations especially related to 2000g	0.06	5.8	0.34	7.8	0.45	7.4	0.43	8.2	0.48	8.4	0.49	8	0.47	6.2	0.36	5.8	0.34	6.2	0.36	7	0.41	7	0.41
12	Complexity of locking systems	0.07	9.2	0.62	10	0.67	10	0.67	10	0.67	10	0.67	10	0.67	8	0.54	7.2	0.48	5.8	0.39	5.6	0.38	7.8	0.53
13	Reliability	0.08	4.4	0.36	4.8	0.40	4.4	0.36	5.2	0.43	6.2	0.51	7.2	0.60	6.4	0.53	8	0.66	6.4	0.53	7.2	0.60	4.6	0.38
		1.00		5.93		5.08		4.97		5.46		6.79		6.96		6.06		8.06		7.32		7.48		6.02

Based on the scores presented above, the relative magnitude of the sealing methods rankings throughout the categories is presented in Fig. 6.

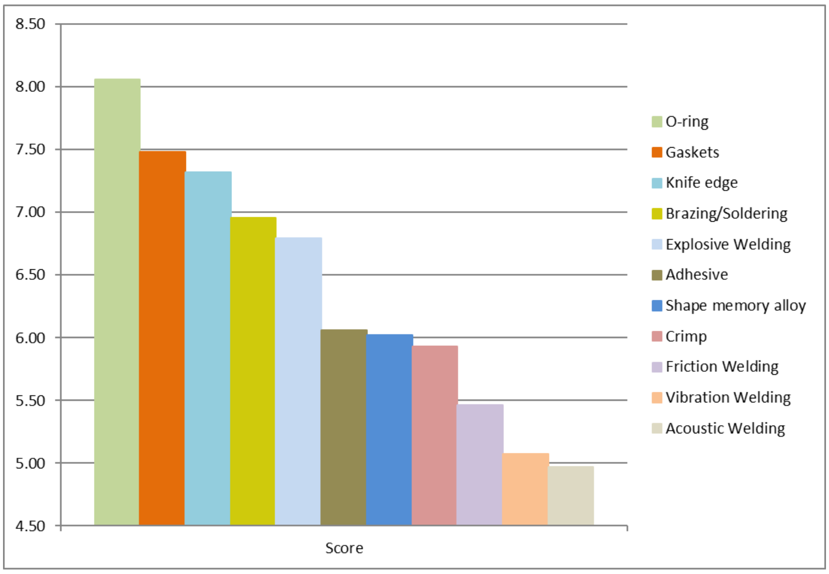


Figure 6: Results of the trade-off analysis

Considering the scores obtained from trade-off analysis, from highest rank to lowest rank the order of the sealing methods was: O-ring, gaskets, knife edge, brazing/soldering, explosive welding, adhesive, shape memory alloy, crimp, friction welding, vibration welding and acoustic welding.
The biggest gap between two adjacent technologies is registered between "Explosive welding" and "Adhesive" which splits the analysed methods in to separate groups. The first group involves sealing technologies that were considered more appropriate for this kind of mission, while in the second one technologies that require further pre-development are presented.
The second biggest gap is between the first two methods, "O-ring" and "Gaskets", showing the big amount of trust awarded to the "winner".
The gap between "Knife Edge" and "Brazing/Soldering" outlines the trust gained by the first three technologies taking into account that they were already proved to be reliable methods for sealing a sample return capsule.
Looking at "Friction Welding" and "Vibration Welding", it can be observed that despite the last three technologies are similar, the vibration and acoustic welding technologies are considered less appropriate than friction welding.

Moreover, we can see that the smallest gap is found to be between "Adhesive", "Shape memory alloy" and "Crimp" suggesting that they are similar from the trade-off point of view. Even though their score is rather low, this may lead to the selection of one of them to be considered in a more detailed analysis as a potential alternative solution.

6 REVIEWING THE SEALING TECHNOLOGIES

Based on the scores presented in Table 3 top five sealing methods was outlined taking into account the criteria used in the trade-off analysis.

No.	Criteria	Sealing methods				
1	Constructive complexity	O-ring	Explosive Welding	Shape memory alloy	Brazing/Soldering	Gaskets
2	Leak tightness	Friction Welding	Explosive Welding	Brazing/Soldering	Vibration Welding	Acoustic Welding
3	Tolerance to particle contamination	Explosive Welding	Gaskets	Friction Welding	Brazing/Soldering	O-ring
4	Feasibility	O-ring	Knife edge	Gaskets	Brazing/Soldering	Adhesive
5	Sampled material contamination	Gaskets	O-ring	Knife edge	Crimp	Shape memory alloy
6	Mass	Knife edge	O-ring	Gaskets	Explosive Welding	Brazing/Soldering
7	Power	O-ring	Explosive Welding	Gaskets	Knife edge	Brazing/Soldering
8	Industry standard	O-ring	Gaskets	Knife edge	Crimp	Brazing/Soldering
9	Previous breadboard for space applications	O-ring	Knife edge	Gaskets	Brazing/Soldering	Shape memory alloy
10	Testing especially related to leakage and to a shock of 2000g for 10ms	Brazing/Soldering	O-ring	Gaskets	Friction Welding	Adhesive
11	Numerical simulations especially related to 2000g	Explosive Welding	Friction Welding	Brazing/Soldering	Vibration Welding	Acoustic Welding
12	Complexity of locking systems	Brazing/Soldering	Explosive Welding	Vibration Welding	Acoustic Welding	Friction Welding
13	Reliability	O-ring	Gaskets	Brazing/Soldering	Adhesive	Knife edge

Figure 7: Top five sealing technologies for each criterion (ranking from left to right)

The graphical representation of the top five sealing technologies according to each used evaluation criteria (see Fig. 7) provides a more detailed image of trade-off results.
The **O-ring** (see Fig. 8) sealing method came first in the trade-off analysis because it was considered that a sealing system design based on O-ring does not raise any major constructive issues and the requirements imposed can be fulfilled. Also, the experience of COMOTI specialists regarding the static sealing systems had an impact over this. In Fig. 7 it can be noticed that this sealing method is the most feasible and reliable for a PhSR mission. Also, its adaptability to the robotic arm and the widespread use of this sealing type in the industry were considered as influential factors for the result of this analysis. It is considered that O-ring sealing methods involve low mass due to the fact that this method does not require additional devices or additional electrical and mechanical power.
It must be specified that the O-ring sealing method consists of sealing elements like elastomer, plastic, metal O-rings, C-rings, E-rings, altogether with spring energized O-rings.
The functioning principle for the sealing systems based on **gaskets** (see Fig. 8) is different, but very close to the one based on O-ring and this is the main reason why the two sealing methods are separated by a few points in the trade-off analysis conducted. The sealing systems based on gaskets have received a lower score regarding the constructive complexity because the way of attaching the gaskets is more difficult, having wider contact areas. From a sealing area contamination point of view, it was considered that the gaskets are more tolerant to a contamination with regolith dust. Like the sealing systems based on O-ring, it can be observed that this sealing method is harder to be simulated numerically. The necessary forces to ensure the sealing are high, usually tightening screws are necessary and this leads to the need of a complex locking system. All of these aspects made the method to obtain a low score in Mass and complexity of locking system.

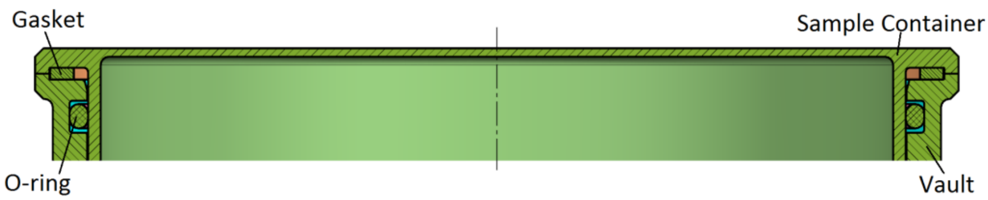


Figure 8: Conceptual layout of sealing elements like O-ring and Gasket for the Vault-Sample Container system

The **knife edge** sealing method is widespread in the industry; it has been used in other similar space missions and it's considered to be feasible and reliable for the a PhSR Mission. Like almost all studied sealing methods, the knife edge sealing method can be sensitive to regolith contamination and needs a closing and blocking system capable of assuring enough force in order to actuate this type of sealing (interpenetration of the metallic part provided with a gasket). Also, the method implies to maintain a predetermined strain so that the sealing is assured during the entire mission (ERC transfer from Phobos to Earth).

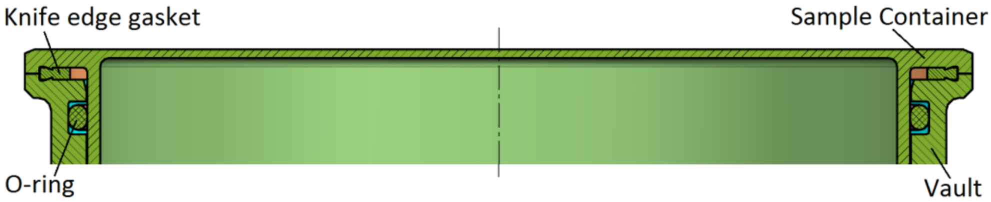


Figure 9: Conceptual layout of sealing elements like O-ring and Knife-edge for the Vault-Sample Container system

7 CONCLUSIONS

The trade-off analysis shows how COMOTI perceives the studied sealing methods which could be suitable for the PhSR Mission, taking also into account the experience of the engineers and researchers involved in this project. Following the trade-off analysis, a series of scores were obtained, emphasizing that the O-rings, gaskets, knife-edge and brazing could be reliable for the mission.
Based on several iterations conducted in the design phase and using the information obtained from the trade-off analysis, it was concluded that a sealing method based on spring energized type O-rings is the most suitable for a PhSR Mission. In Fig. 10 the layout of the sealing elements in the Vault-Sample Container system is graphically represented.

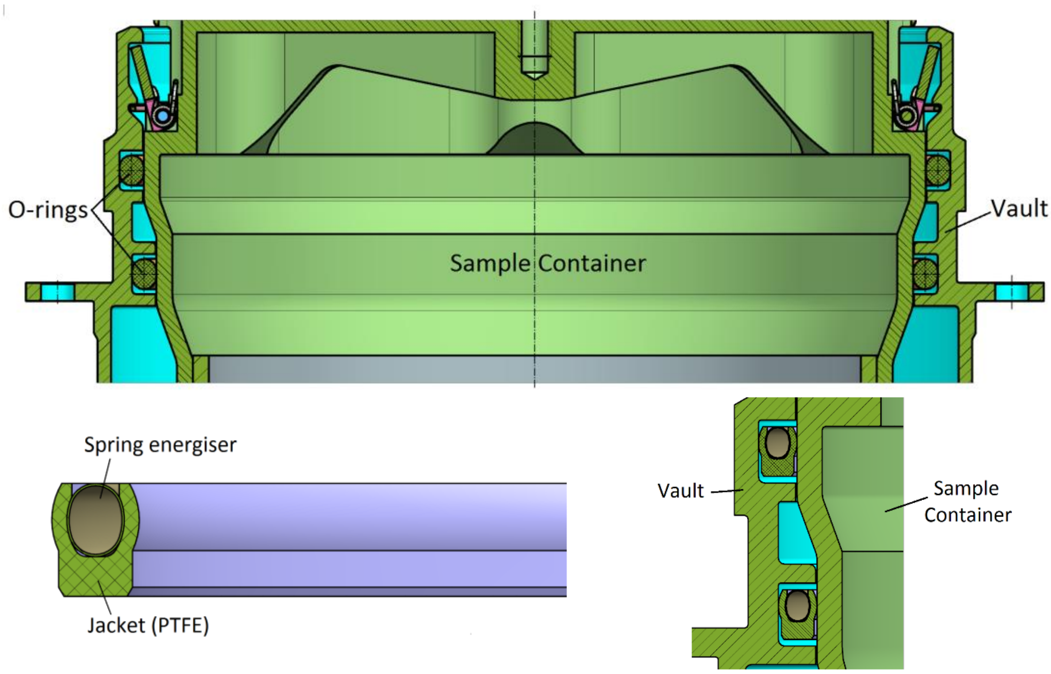


Figure 10: Actual concept regarding the sealing method proposed for PhSR

Considering the information regarding the sealing systems used in other space missions, it can be observed that many space agencies have chosen to use redundant sealing methods. In our case, the redundancy of the sealing system is ensured by placing spring-energized O-ring on two distinct diameters.
An aspect worth mentioning is the relatively low score, 8.06 out of a maximum 10 points. This means that even the best technology from this trade-off represents an implementation challenge. In the following phases of the project the results of the trade-off analysis must be validated in the frame of an extensive testing campaign.

REFERENCES

[1] – S. Sandford, 2011, "The Power of Sample Return Missions – Stardust and Hayabusa", *The Molecular Universe Proceedings IAU Symposium*, **No. 280**;
[2] – L. Murchie, D Britt, C. Pieters, 2014, "The value of Phobos Sample Return", *Planetary and Space Science*;
[3] – E.M. Galimov, Vernadsky, July 17, 2009, "Phobos Sample Return Mission: Scientific Substantiation", Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, ul. Kosygina 19, Moscow, 119991 Russia;
[4] – IPPW 11, S. Barraclough, A. Ratcliffe, R. Buchwald, H. Scheer, M. Chapuy, M. Garland, "Phootprint: A European Phobos Sample Return Mission", Airbus Defence and Space, D. Rebuffat, ESA ESTEC;
[5] – ESA, June 2014, "CDF Study Report", Phobos Sample Return, Phobos Moon of Mars Sample Return Mission;
[6] – 2016 "Parker O-ring handbook", www.parkerorings.com