Executive Summary Report

Feasibility Study on the development of Lunar Environment Simulator

ESA Contract No. 4000130476/20/NL/CRS

Name	Company / Responsibility	Signature	Date
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Introduction

Previous ESA Studies, such as the LUNA study "Artificial Analogue Concepts for Preparing Robotics and Human Exploration on the Moon" identified the gaps in European infrastructures to simulate surface operations with lunar soil (simulant) in vacuum: There exist several vacuum chambers or terrain models such as the coming EAC LUNA facility which can be used for equipment testing either in vacuum condition or on a simulated lunar terrain; but not both.

The here presented enhanced HYDROSPHERE Lunar Surface Simulator can be an additional asset in this orchestra of facilities: It offers the possibility to simulate lunar surface operations on a medium size scale (5m diameter) in vacuum conditions.

The proposed facility is an existing installation located in Southern France which is currently being enhanced. It served initially as diving simulator for COMEX and was also used for space projects in the past where it was listed as ESA Ground Based Facility.

Together with ESA's LUNA facility, and other testbeds in Europe, it can increase European capacity to develop and test various items for future lunar surface operations.

Figure 1: Hydrosphere Facility

The facility is composed of three hermetically closed chambers and one control center.

It was built to develop and test procedures for deep-sea diving. It was also used as a testing facility for mission simulations in hypobaric conditions such as mission towards the summit of Mount Everest at 8848m (approximately 0.3 bar) with a crew of eight subjects.

Objectives of the Contract

- An evaluation of the Hydrosphere GBF to create a lunar environment surface simulator with a DHVAC environment.
- A clear statement of working parameters of the enhanced Hydrosphere GBF, to be used by exploration stakeholders in assessing the future usage of the facility.
- A feasibility study and usage plan on how the facility can be practically used to support future European and ESA exploration activities.

Figure 2: The 5-meter diameter Hydrosphere pressure chamber that has been transformed to a vacuum chamber with lunar soil simulant.

HYDROSPHERE Facility Preparation

The main element of the facility is a 5m diameter sphere, which can be used as EVA or robotic testbed. Adjacent to the sphere is a second chamber, which can be used in the future as airlock to the EVA testbed and currently includes the hygiene facility. The third chamber is the habitat section that offers a space for a crew of maximum eight subjects. The habitat has a volume which is close to ISS' COLUMBUS laboratory.

The 5-meter diameter sphere can be serviced by a crane and allows to receive large elements of 1.8 m in diameter from the top (the hatch on the top can be opened).

The current enhancement project is to fill the sphere with a lunar terrain testbed and to perform vacuum tests with the whole system. While the here presented works concentrate on the test sphere, it should not be forgotten that the HYDROSPHERE offers the possibility to simulate in the future system simulations with a habitat simulator in the loop.

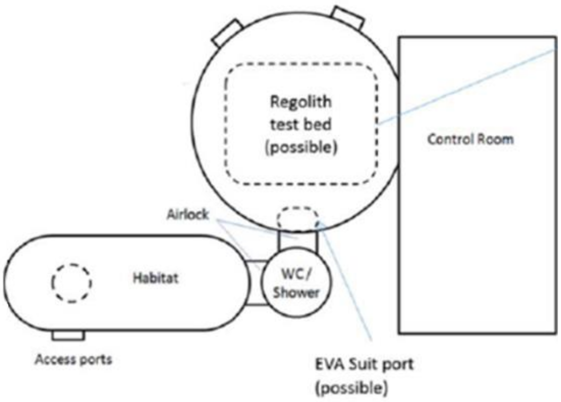

Figure 3: Hydrosphere Layout

As part of the feasibility studies first WP, COMEX performed enhancement work on the sphere chamber which includes the following tasks:

- Visual inspection of damaged seals and flanges.
- Refurbishing and/or replacement of seals.
- Design and procurement of replacement flange.
- Identify and removal of major outgassing infrastructure inside as well as unwanted electrical and mechanical connectors and pipes.
- Surface Treatment for the chamber walls, subfloor and floor areas using sand blasting method to support demonstration tests.
- Preliminary test using existing rotatory pump assembly.
- Leak test using bubble test method.

Figure 4: Damaged seals

Evaluation and removal of electrical and mechanical connectors

Hydrosphere used to house numerous numbers of mechanical and electrical connectors along with their control boxes inside the chamber.

Figure 5: Hydrosphere initial wirings.

Since the Hydrosphere was designed to work in high pressure situation most the cabling work was covered in rubber materials which are prone to outgas. COTS electrical flange can be used to replace all individual feedthrough points. Similarly hosing power and control box inside the chamber will only create added constraints for technical maintenance, removing them will also reduce the cost associated with the control boxes as replacement of vacuum rated component tend to be on the expensive side. Therefore, all old internal cables, cable tray, power system and other unwanted electrical system were removed from the chamber.

Figure 6: Inside the chamber after the removal of all electrical components

In addition to electrical connectors, Hydrosphere also had several water and fluid entry feedthrough points. Which were removed and closed permanently.

Figure 7: Left: Feedthrough connector. Right: Feedthrough entry points permanently closed

Removal and replacement of flange for Vacuum pump connection

One of the hydrosphere flanges was severely damaged, therefore the flange was removed. At the same time the turbo pump assembly required a larger suction point, therefore the replacement flange was custom designed to serve as the connection point for the turbo pump assembly to the hydrosphere.

Figure 8: Replacement Flange and the flexible connection pipe between hydrosphere and turbo pump

Internal surface treatment using sand blasting method

Hydrosphere walls, floor and subfloor were cleared of rust, loose paint and any residual outgassing element removed using sand blasting method.

Figure 9: Sand blasting process inside the hydrosphere (walls, floor, and subfloor)

Hydrosphere ready for vacuum performance tests

Figure 10: Hydrosphere chamber after sand blasting and removal of major outgassing elements

Test Campaigns

Preliminary test campaign

Following the completion of surface treatment and flange integration, preliminary leak test was carried out using series of existing rotary pump assembly. Three rotatory pumps were connected in series to the hydrosphere chamber.

Figure 11: Rotary pump series assembly used for preliminary test.

At first, a pressure leak of 1 liter per second was observed around the large side flange. To counter-act the leak, the flange connection points were covered by tight wrappers.

Finally, after 1 day test, the facility reached the pressure of **30x10^{-3} bar**.

Test campaign 1

After preliminary test and the installation of new flange to the side of the hydrosphere, dry screw pump assembly were procured and connected to the hydrosphere chamber to test the chamber ability to reach mid-vacuum levels and identify the associated leak area and rates.

Dry screw pump selected was Edwards 250/2600 with the maximum operation range of 1x10^{-5} bar. Dry screw pump was selected over the turbo pump mainly for budgetary reason, reduced lead time from local supplier and as well for the dry screw pump ability to perform better in dusty environment.

The selected dry screw pump has excellent powder dust handling capabilities, as they were developed to be used in material sintering industry. However dry vacuum pumps are not designed to continuously pump solid material (regolith simulant) thus adding an inlet filter would dramatically extend the pump services time.

To this extended a large polyester mesh filter with the capability to filter up to 99% of simulant of size 5µm is added on top of the dry screw pump inlet. However, from previously ESA funded PEXTEX study it was found that EAC simulant has an average grain size of 105 µm, but 9% below 4 µm in size, therefore the test was performed in stages to reduce the load on the pump as well as additional time were provided so the simulant dust can settle down in the closed chamber over a duration of a week.

Figure 12: Polyester filter selected for preventing micro simulants from entering the dry screw pump.

In addition to the filter, the pump assembly also included a liquid coolant chiller to keep the pump from overheating.

To test the filtration system 20kg mineral dust unused from the sand blasting were introduced into the chamber. The mineral dust has an average grain size of 100µm representing the regolith simulant grain size.

The facility reached the stagnation point at **2x10^{-3} bar** well below the pump's operational capacity. Major reason for the discrepancy was identified to be the improper welding of the new flange.

Test campaign 2

After rewelding the connector flange, the test was repeated with the same dry screw assembly. But instead on mineral sand a tray full of EAC-1 simulant was placed inside the chamber near the pump inlet area. The objective of these tests is to measure the degree of outgassing (of the simulant) and to extrapolate the possible maximum vacuum level reachable.

Figure 13: Dry screw pump + Filter + Chiller assembly

The trail run was carried out successful for 3 days and the facility reached the pressure of **3.4×10^{-4} bar**.

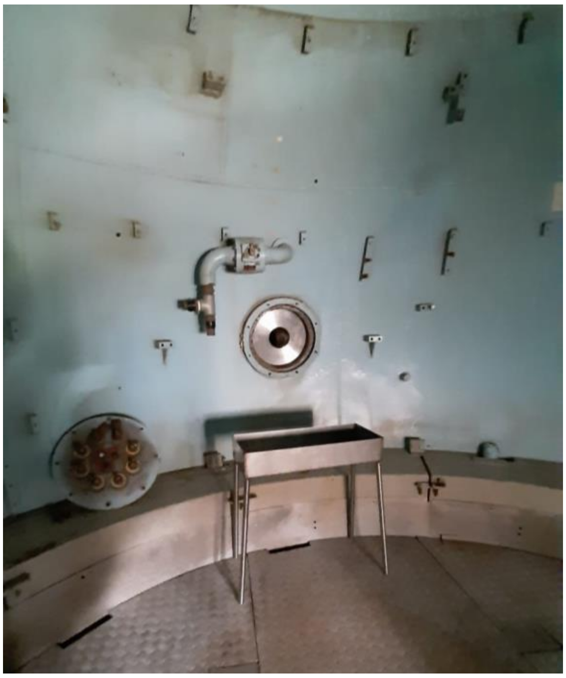

Figure 14: Tray containing EAC-1 simulant is placed near the inlet.

Final test campaign

After the second test trail run, a simple terrain modeling was modeled and it was estimated that it would require 3.5tonees of EAC-1 simulant will be required to simulate the traverse condition of lunar surface such as crater, ascending and descending elements of lunar surface.

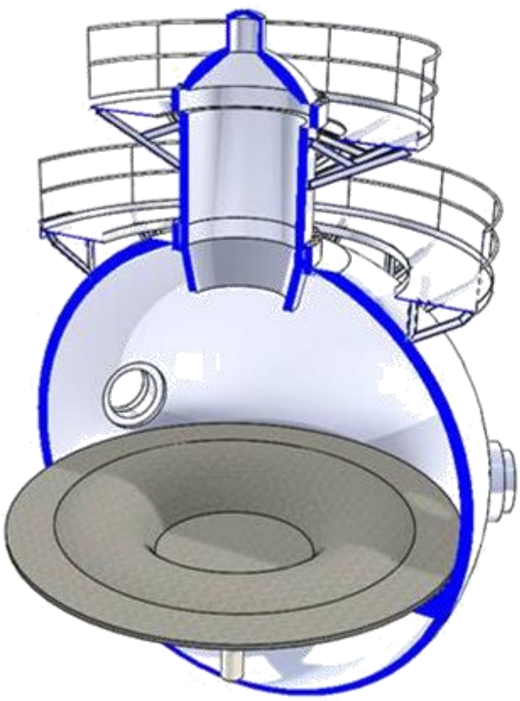

Figure 15: Hydrosphere Terrain Modelling concept

The EAC-1 simulant was received in large bags and were transferred into the hydrosphere with a simple pully and tube mechanism.

Figure 16: Simulant transfer into Hydrosphere

The hydrosphere reached 3.4×10^{-4} bar range in three days similar to the second test run.

The test duration was further extended to find the maximum possible limit, the facility reached approximately **4×10^{-5} bar** in 10days after which point the pressure range stagnated for the next four days hence the test was concluded after 14days.

Figure 17: EAC-1 Simulant terrain inside Hydrosphere

Current Capabilities

The below table presents the final operational parameter of the facility at the end of the test campaign.

Requirement	Current Range
Vacuum Level	4×10^{-5} bar
Temperature Range	No special means to regulate the temperature.
Terrain	3.5 tonnes EAC-1 simulant
Outgas measurement	None
Power Connection	None
Data Connection	None
Gravity Simulation	None

Future Roadmap

To convert the Hydrosphere facility into a lunar environment analogue simulator the follow upgrades are identified to be necessary:

Requirement	Target Range
Vacuum Level	> 1×10^{-12} bar
Temperature Range	+120°C to -180°C
Terrain	High Fidelity simulant
Outgas measurement	Gas analyzer
Power Connection	Flanges to support the connection
Data Connection	Flanges to support the connection
Gravity Simulation	Pogo system

Vacuum capabilities

In order to reach 1x10^{-12} bar:

- Onsite Machining of all flanges sealing areas to removes the cracks and scratches.
- Replacement of rubber sealing with metallic sealing.
- Dry screw vacuum pump backed by a booster pump along with two turbo molecular pumps (TMPs), and two cryogenic pumps (CPs) for high vacuum level.
- If mid-vacuum level is desired, then the pumping system then a combination of Venturi pump, a scroll pump, and a turbo pump can be utilized.

Cost estimation: 65 k€ to 135 k€

Thermal High capabilities

In order to reach 120°C, there are 2 solutions:

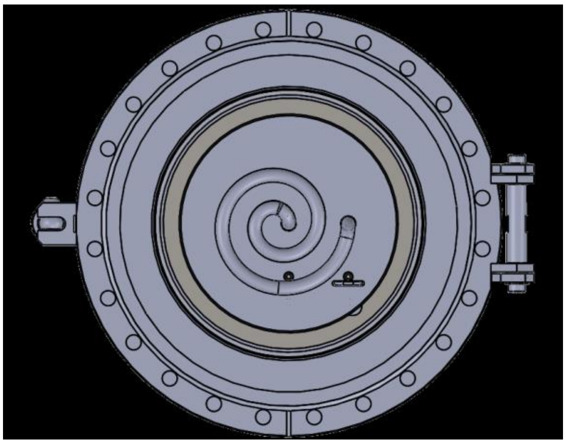

Figure 18: SOLUTION 1, Artificial sun assembly either inside or outside the chamber

Figure 19: SOLUTION 2, Vacuum rated IR heaters

Cost estimation: 45 k€

Thermal Low capabilities

In order to reach -180°C, a high-fidelity simulant pit of 2m in diameter will be placed in between the circulator loop to create the cold volatile zone.

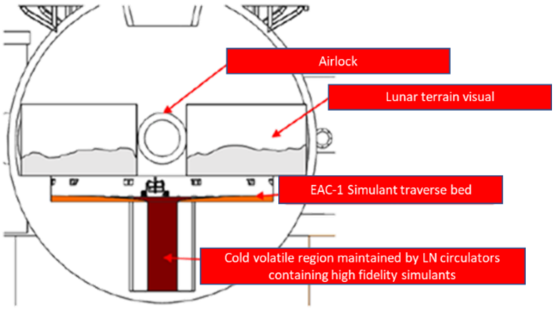

Figure 20: High Fidelity simulant pit

The proposed solution would be using a loop Liquid Nitrogen circulations system that can be either:

Closed loop:

- 200 k€ for 1000 W
- 350 k€ for 4000 W

Open loop:

- 30 k€ for Tank + Heat exchangers
- ~1-2k€ / Liquid nitrogen refill (approx. 1 refill/week, depending on the application)

Cost estimation: 50 k€ to 200 k€

Gas measurement capabilities

To measure outgasses and off-gasses molecules from the test subjects, COTS gas analyzer can be installed between the chamber and vacuum pumping system inlet. Added valve between the chamber and the pump needed.

Cost estimation: 7.5 k€ to 95 k€, depending on the list of gas to be measured and the precision levels to be measured

Gravity Simulation capabilities

To simulate lunar gravity (1/6 g), fixation points for the Pogo system installation are needed. Since test subject varies in size and shape from one another, it will be difficult to develop one size fit for all pogo system.

Therefore, we suggest providing only the basic fixation point and pulley system needed on to the chamber and the gimbal system shall be custom built based on each test subject requirement as part of the testing campaign scope of work.

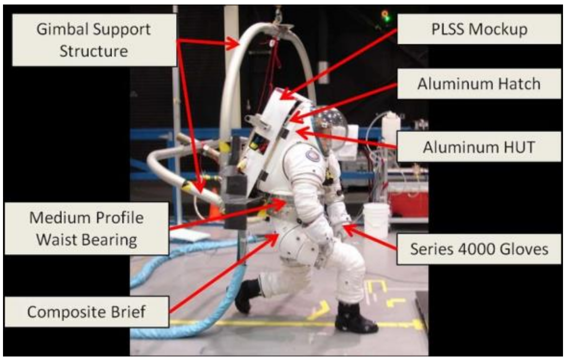

Figure 21: The Mark III advanced spacesuit technology demonstrator attached to the POGO gimbal

Cost estimation: 10 k€

Connectivity capabilities

To allow various power and data connectivity range between inside and outside the facility, more flanges must be added to the chamber.

Cost estimation: 0.5 to 1.5 k€ per flange

Other capabilities

For large test subjects, refurbishment of the overhead crane is needed to access the 1.8m diameter upper entry hatch.

Cost estimation: 50 k€

Use Cases

Robotic mission simulations – surface exploration

Concept of the Hydrosphere enhancements for future robot or EVA tests:

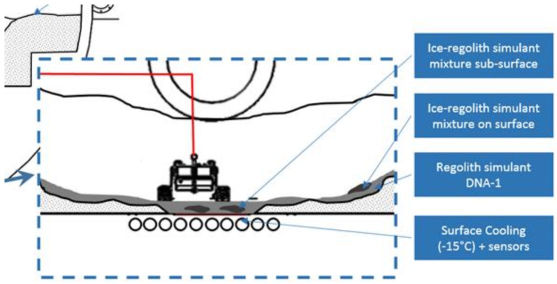

Figure 22: Rover control concept inside HYDROSPHERE

Human mission simulations – Habitats, Life-Support Systems

The Hydrosphere can serve to simulate future human missions on the lunar surface or towards planet Mars. Similar to experiments such as Mars500, human aspects of long-duration spaceflight or surface operations can be simulated inside the habitat.

The similarity of the volume of the Hydrosphere habitat to the internal volume of ISS' COLUMBUS was used in the ESA project BIOMODEXO (ESA contract 4000109832), where mathematical models of bio contamination were validated inside the habitat.

The internal ventilation of HYDROSPHERE is adapted to simulate the flow parameters of the ventilation system on ISS and future experiments will not only give a method to predict and detect the contamination by microbes but could also be used to develop methods against dust introduction (Moon) or planetary protection (Mars).

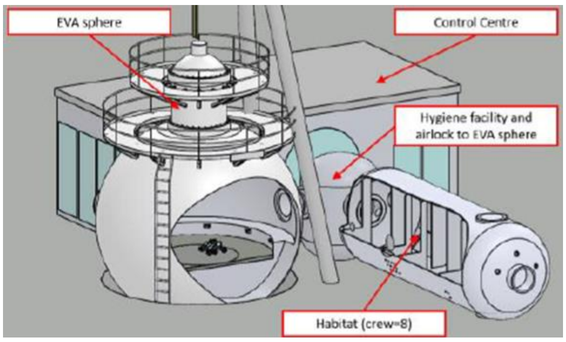

Figure 23: Future concept for Hydrosphere to simulate a lunar habitat, Airlock and EVA area

Human-robot interactions can be developed and evaluated from inside of the habitat (e.g. a crew member inside the habitation controlling a robot in the EVA sphere) or with direct interaction between a robot and an astronaut in the regolith testbed in the sphere.

The Hydrosphere development is based on knowledge gained from ESA projects and COMEX heritage will in return benefit ESA's planetary exploration roadmap and projects such as HERACLES.

Current ESA Lunar mission framework

In the frame of the HERACLES program HYDROSPHERE can serve to validate prototypes in lunar environment and to raise the TRL of several system components.

The below table lists the potential of HYDROSPHERE to serve as testbed of major items of HERACLES :

- Soil interaction with Lunar Ascent Element (LAE) and Lunar Descent Element (LDE).
- Assess mitigation techniques for removal of fine-grained dust from optical or mechanical components.
- Assess mechanisms and operation. The efficiency of sealings can be tested in a dusty- vacuum environment.
- Rover interaction with regolith simulant in lunar environment condition. Wheel soil interaction or sampling can be tested.
- Parts of the Robotic Landing Stack (RLS) can be tested inside the sphere.
- The control of surface elements from a crew in orbit at LOP-G can be tested through the control center in the habitat of HYDROSPHERE.
- Elements of the Ascender (ASC), such as airlocks, can be tested in the sphere.
- Elements of the Descender (DES), such as propulsion, can be tested in the sphere.
- Human Landing Stack (HLS) : Suitports and Spacesuit interaction with regolith.

In addition to Lunar environment, the simulator can also be used for other planetary applications such as for technology demonstration of Mars Sample fetch rover, Mars drones (flying systems in low density atmosphere) or other similar application identified under lunar exploration missions.

In general, any lunar and Mars exploration payload/ infrastructure that can be launched from Earth using the current and most future launch vehicles can be tested inside HYDROSPHERE, given that no single component is bigger than 1.8m in diameter to enter into the sphere hatch and with a height restriction of 5m.

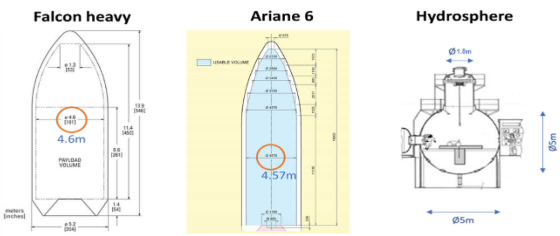

Figure 24: Faring comparison between Falcon heavy vs Ariane 6 vs Hydrosphere diameter. Credit: SpaceX, Ariane

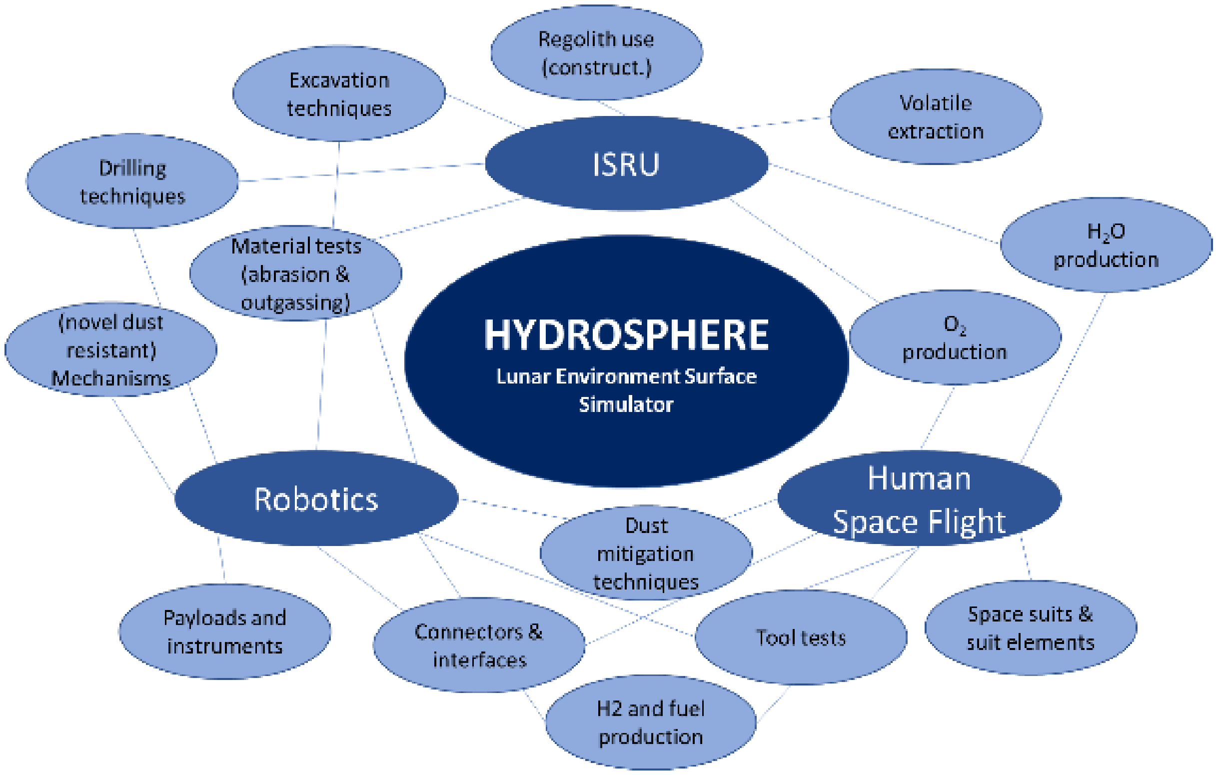

Figure 25: Hydrosphere use cases

HYDROSPHERE 'Cost to upgrade' Overview Table

The following table summarises the rough estimated costs to convert the Hydrosphere facility into a lunar environment analogue simulator:

Requirement	Target Range	Cost Estimation (detailed in §6.1 to §6.6)
Vacuum Level	> $1x10^{-12}$bar	65 kEUR to 135 kEUR
Temperature Range	+120°C to -180°C	+120°C : 45 kEUR -180°C : 50 kEUR to 200 kEUR
Outgas measurement	Gas analyzer	7,5 kEUR to 95 kEUR
Power Connection	Flanges to support the connection	0,5 to 1,5 kEUR per flange
Data Connection	Flanges to support the connection	0,5 to 1,5 kEUR per flange
Gravity Simulation	Fixation points for Pogo system	10 kEUR

Additional cost for sealing solution and surface treatment to be considered based on the targeted vacuum level.