A technical solution for windows in mass-screened Lunar habitats

AC-24-A1.2.3

A TECHNICAL SOLUTION FOR OPTICAL VIRTUAL WINDOWS IN MASS-SCREENED LUNAR HABITATS

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Abstract. In recent years, a renewed interest in lunar exploration has arisen once again. A review of the research on exploration of the Moon shows that there are significant challenges related to establishing a base for humans in the harsh lunar environment. If the Earth's surface is protected by its magnetosphere and its atmosphere against cosmic radiation, solar flares, and micrometeorite impacts, the lunar surface, instead, has no magnetic field that deflects charged particles and no radiation-absorbing and micrometeorite-consuming atmosphere at all. The possibility of protecting human beings from radiation and micrometeorites by exploiting passive shielding techniques, using the locally available regolith to build a thick massive envelope, is effective, but it has an intrinsic drawback: the buildings must have small viewports, or even no viewports at all. Numerous studies conducted since the 1950s in harsh terrestrial environments such as deserts, undersea habitats, and Antarctica have shown that Habitability and Human Factors (H&HF) in Isolated and Confined Environments (ICEs), like lunar habitats, are critical for the well-being of crew members. Among these factors, the capability to have an external view is essential. In lunar habitats the integration of passive radiation shielding with viewports or vision systems can enhance psychological well-being, reduce stress, improve spatial awareness and facilitate the monitoring of external activities. However, the technical solutions developed so far, such as small observation posts with protective shutters or digital virtual screens, do not allow for or limit direct and continuous external view. The paper proposes an optical virtual window based on image reflection that is compatible with a massive structure, allowing direct observation while protecting against radiation exposure and impacts of micrometeorites. This technological system enables the direct view of the external environment, mitigating psychological effects derived from long stays in ICEs, enhancing operational task control, with positive effects on the safety of the crew.

Keywords: Habitability and Human Factors (H&HF), Isolated and Confined Environments (ICE), Cosmic Radiation Protection, Micrometeorite Impact Protection, Mass-screened Lunar Habitat, Optical Virtual Window.

ACRONYMS

AR	Augmented Reality
ARS	Acute Radiation Syndrome
ESA	European Space Agency
GCR	Galactic Cosmic Radiation
HF	Human Factors
H&HF	Habitability and Human Factors
HZE	High-Z high-Energy
HOEs	Holographic Optical Elements
ISS	International Space Station
ICME	Interplanetary Coronal Mass Ejections
ICE	Isolated and Confined Environment
NASA	National Aeronautics and Space Adm.
SPE	Solar Particle Event

1. INTRODUCTION

The last crewed mission to the Moon, in 1972, marked the end of the Apollo space program. At the time, the ratio of information gathered to the huge investment required seemed not to justify further missions, and for decades it was decided to suspend sending astronauts to the Earth's satellite [1].

However, the situation has deeply changed. Nowadays, the renewed interest in lunar exploration is driven by the potential for scientific discoveries, the search for resources such as Helium-3, Uranium and Titanium and even platinum group metals, the development of new technologies, and the strategic importance of establishing a human presence on the

Moon, even as launch platform to more distant destinations [2].

Furthermore, we are now aware of the potential to utilize on-site resources, such as ice where available, or regolith, to produce water [3]. This is crucial for the survival of crew members and valuable for extracting hydrogen and oxygen, which can be used for various purposes, including life-support systems, energy production, and the production of rocket propellants [4].

Despite the change in objectives, and technological means compared to the first lunar missions, the environmental challenges that await future lunar missions remain unchanged.

While the Earth's surface is protected by its magnetosphere and its atmosphere against cosmic radiation, solar flares, and micrometeorites, the lunar surface, instead, has no magnetic field and no radiation-absorbing and micrometeorite-consuming atmosphere at all.

Therefore, unlike orbital habitats like the International Space Station (ISS), which benefits some protection from radiation thanks to the Earth's magnetosphere, a habitat on the Moon needs barriers against intense cosmic radiation.

Exposure to radiation can cause both short-term damage, similar to that caused by solar events, and long-term damage, such as the development of malignant cancer [5, 6, 7]. Although the short-term effects, such as Acute Radiation Syndrome (ARS), may immediately compromise the accomplishment of tasks and hence the success of space missions, actually it is long-term effects that currently represent one of the greatest barriers to human lunar exploration.

Despite these challenges, there is scope for engineering to partially mitigate radiation exposure. The protection of astronauts remains a top priority, requiring the design of habitats equipped with protection against micrometeorites and cosmic radiation, minimizing exposure to potentially lethal threats.

Up till now, the constructive solutions for lunar habitats have been consisted in preassembled metallic modules, preassembled inflatable modules, in-situ additive-manufactured habitats, lava tubes, while the protection against radiation has been demanded mostly to passive systems such as thick water-filled cavities or massive shielding by lunar regolith [8, 9, 10, 11].

Though, protecting human beings from radiation and micrometeorites through massive envelopes, while effective, has an intrinsic drawback: the limitation of observation of the external environment due to the need to maintain the continuity of the protective system.

The capability to observe the external environment is a crucial factor for crew members' well-being, as it has been demonstrated by numerous studies on Habitability and Human Factors (H&HF) in Isolated and Confined Environments (ICEs) carried out since the 1950s in extreme environments similar to lunar habitats like deserts, underwater and Antarctic facilities [12].

Thus, providing or enhancing the capability of external observation in lunar habitats can boost psychological health, reduce stress, enhance spatial awareness and aid in monitoring external activities.

However, the technical solutions developed so far, such as small observation posts with protective shutters or virtual screens, do not allow for or limit direct and continuous external view and are characterized by a high degree of technological complexity (movable components or digital devices) that does not favor resilience in a harsh environment.

The need to establish systems that safely allow the described activities drives research towards developing less complex and more reliable technological solutions.

2. RADIATION EXPOSURE ON THE MOON

Unlike the terrestrial environment, the lunar one is dominated by the solar wind that pervades the entire solar system and the Galactic Cosmic Radiation (GCR).

The former is mainly made of hydrogen ions (protons) flowing at high speed out of the Sun's corona. This radiation emission from the Sun – usually referred to as *space weather* – is quite variable in time.

The latter is a ionizing radiation that includes protons and High-Z high-Energy ions (HZE ions). GCR interacts with atomic electrons and nuclei of lunar soil, structures, and equipment, generating secondary recoil particles spectra that pose challenges to shielding methods [13].

Figure 1 shows a summary of the results of the measurements performed by the AMS-02 experiment onboard the ISS on various species of cosmic-ray nuclei from 2011 to 2017, from protons to oxygen nuclei [14, 15, 16, 17, 18].

As shown, protons are the most abundant component of cosmic rays, while the flux of helium nuclei is about 10% of the proton flux, and the fluxes of heavier nuclei are even lower.

From time to time, large quantities of charged particles, mostly protons, are emitted by the Sun in a Solar Particle Event (SPE), also known as solar flare. Associated with solar flares are the slower, but usually larger, bursts of plasma known as Interplanetary Coronal Mass Ejections (ICME). They may disrupt the standard pattern of the solar wind, launching in the surrounding space electromagnetic waves and fast particles (mostly protons and electrons) to form showers of ionizing radiation.

Solar flares, intense but relatively brief phenomena, constitute a danger to spacecraft and extraplanetary habitats. Most of the activity is over in about 4-6 hours, but the flow can continue for some more hours. Since they are unpredictable, interplanetary spacecraft and extraplanetary settlements must carry a radiation shelter in which the crew will hide during dangerous solar events.

Solar activity varies cyclically in time with a period of about 11 years: when it is at its minimum, GCR increases and at the opposite it decreases when the former is at its maximum: the level of GCR can be 2–3 times higher at solar minimum than at solar maximum [19].

The influence of solar activity on the cosmic-ray fluxes is the well-known solar modulation effect [20, 21, 17].

Hard spectrum SPEs pose a major radiation hazard to crews beyond Low Earth Orbit (LEO). They potentially occur at any point in the cycle and cannot presently be predicted [22], but the danger posed by SPEs are lower at solar minimum and increases with the increase of solar activity.

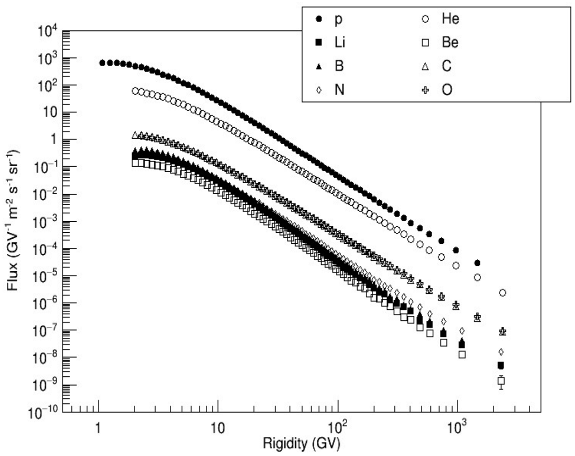

Fig. 1. Fluxes of different species of cosmic-ray nuclei as functions of magnetic rigidity measured by the AMS-02 experiment in the years from 2011 to 2017.

The average radiation dose to which a human is exposed on Earth depends on the local radiation background but is of the order of 3.6 millisievert per year (mSv/y). People employed in some industrial activities, involving exposure to radiation, may be exposed to a maximum of 50 mSv/y. The radiation dose acceptable for astronauts depends on their gender and age; values generally accepted for their whole carrier are those reported in Table 1. These values are expected to cause no more than a 3% increased risk of developing cancer, which NASA and the astronaut corps consider tolerable [23].

On the Moon, the annual dose equivalent due to cosmic rays at times of solar minimum is about 300 mSv/y (30 rem/y). Also, the lunar surface is not protected from solar flare particles; at energies above 30 MeV, the dose equivalent over the 11-year solar cycle is about 10 Sv (1000 rem).

Most of those particles arrive in one or two gigantic flares, each lasting about two days. These doses greatly exceed the permissible annual dose for the human body: 5 mSv/y (0.5 rem/y) for the general public and 50 mSv/y (5 rem/y) for radiation workers [24]

For lunar settlers the acceptable limit would depend on how long they stay in the base but an indicative value would be about 740 mSv/y (for middle aged males, less for women, in particular if young).

Studies of NASA have shown that because crewmembers are exposed to radiation from the space environment, there is a possibility for increased cancer morbidity or mortality [25].

Tab. 1. Career limits for astronauts in LEO (expressed in Sv) based on [23].

Age	[yrs]	25	35	45	55
Male	[Sv]	0.7	1.0	1.5	2.9
Female	[Sv]	0.4	0.6	0.9	1.6

Much of our current knowledge about long-term effects of radiation exposure comes from studies of populations exposed to atomic radiation at Hiroshima and Nagasaki, but many fundamental questions, such as the specific mechanisms of biological response to radiation in space, could only be addressed through experiments conducted in extraterrestrial environments [26].

Thus far, five main approaches to mitigate the risk of radiation exposure have been identified: operational reduction of exposure (limiting the time of exposure), protective shielding (conceiving a building envelopes that can screen incident radiation), screening for genetic predispositions of crewmembers, prevention through pharmaceuticals used as radioprotectants and biomolecular intervention after radiation exposure, which may be possible in the future [7].

3. RISK OF MICROMETEORITE IMPACT ON THE MOON

The risk of micrometeorite impact on the Moon is one of the major safety concerns for future human and robotic missions. In fact, devoid of a significant atmosphere, the Moon is constantly bombarded by micrometeorites, which are small fragments of rock and metal from space. These impacts can cause significant damage to structures and equipment on the lunar surface.

The mass of meteoroids falling on the lunar surface can vary from a minimum of a few tens of grams up to about 10 - 20 kg, while the fall speeds on the Moon are between 20 and 72 km/sec depending on the orbits of the objects with respect to the Earth-Moon system [27].

These meteoroids can originate from cometary showers that periodically cross the Earth-Moon system several times a year, or from asteroidal bodies and are therefore sporadic, and it is in this second case that the mass of meteoroids can take on more important values.

The impacts of micrometeorites on the lunar soil are so intense that they heat the point of impact to temperatures ranging from 2,000 °C to 6,000 °C.

The energy produced by a micrometeorite impact on the Moon depends on the mass and velocity of the micrometeorite. For example, a 1-gram micrometeorite hitting the Moon at a speed of 20 km/s releases an energy of about 200,000 joules (J), equivalent to the kinetic energy of a 1-ton car traveling at 20 m/s (about 72 km/h) [28].

At such speed, a micrometeorite of 5 kg can excavate a crater over 9 meters across, hurling 75 metric tons of lunar soil and rock on ballistic trajectories above the lunar surface and vaporizing some of the lunar soil into the exosphere [29].

Larger impacts, such as those caused by meteoroids weighting several hundred kilograms, can release much greater energies, creating significant craters and generating seismic waves detectable by lunar seismographs.

The frequency of micrometeorite impacts varies depending on the location on the Moon and the time of year. For example, during meteor showers, such as the Leonids, the Moon can be subject to a significant increase in the number of impacts [27].

The lunar impact rate is very uncertain and more observations are needed to establish the rate of large meteoroids impacting the Moon. Due to the relevance of such issue, NASA research program 'Lunar Impact Monitoring Program' [30] aims to determine the frequencies and sizes of large meteoroids (over 500 grams) that strike the lunar surface through Earth-based observations in preparation for the potential establishment of permanent lunar bases.

In fact, these impacts can not only produce effects on the lunar surface, but can also compromise the integrity of human-built structures, such as habitats.

Moreover, one of the most significant effects of micrometeorite impacts is the production of lunar dust. This extremely fine and abrasive dust can infiltrate equipment and life support systems, causing malfunctions and reducing operational efficiency.

To mitigate the risks associated with micrometeorite impact, several protection solutions are being developed. These include the use of impact-resistant materials, as well as the implementation of detection and early warning systems to identify and react to impending impacts [27].

4. OUTDOOR VISION IN LUNAR HABITATS

Due to its characteristics, a lunar habitat can be defined as an Isolated and Confined Environment (ICE). ICEs are environments, in which physical parameters deviate seriously from accustomed milieu due to physical remoteness and a circumscribed spatial range [31].

The term *habitability* describes the suitability and value of a built habitat for its inhabitants in a specific environment [32], while Human Factors (HF) mainly refer to interactions between humans and other elements of a system [33].

Habitability and Human Factors (H&HF) are important factors in the design of any inhabited building type but in the case of ICEs, like habitats on the lunar surface, H&HF become a critical issue, because due to the environmental and constructive restraints, habitable volume is limited [34].

Research on living and working conditions in ICEs began in the 1950s [12] in relation to some military and industrial activities. Naval submariners, oil company workers, polar station researchers are exposed to such remote and hostile environments that confine and isolate them from civilization.

Lunar habitats have strong similarities with polar and underwater ones, where because of specific spatial characteristics, several physical and social factors can cause stress in the inhabitants [32].

In particular, studies on H&HF in ICEs, have found some critical sources of stress (i.e. stressors), such as isolation, limitation of the environmental awareness, volume limitation and continuous artificial lighting, which can adversely affect the crew [35, 36, 37, 32].

In response, habitability design has been envisioned as a viable contributor to both active and passive countermeasures for certain stressors. Particularly for long, remote mission scenarios, stress can be reduced through appropriate indoor architecture and auxiliary systems [38, 39].

This approach, was initially applied by one of the first space architects, Galina Andreevna Balashova, in designing interior spaces, furniture and control panels of the Soyuz spacecraft and of the Salyut and Mir space stations, also taking inspiration from the *modulor* concept elaborated by the architect Le Corbusier [40].

In general, areas where appropriate design has already been employed as a stress countermeasure in ICEs include:

- enhancing performance;
- enhancing psychological functioning;
- enhancing social cohesion.

Furthermore, stressors deriving from habitability constraints can affect crew safety and goals accomplishment. In particular, Cohen elaborated an 'Interaction Model' between Human Factors and crew safety (Fig. 2) in which he identified some critical habitability factors to be compensated [41].

In Cohen's model, among the most effective countermeasures the outdoor vision plays a critical role, as it can mitigate some stressors that can lead to performance degradation and potential safety hazards.

Current data collected with respect to visibility consists primarily of post-mission crew debriefs [42].

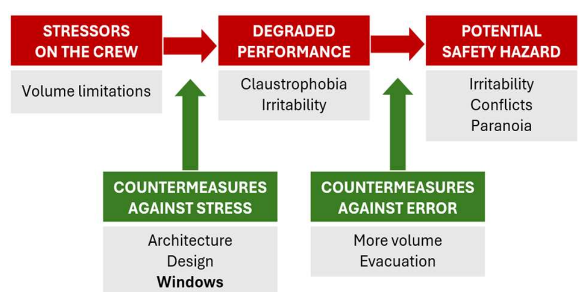

Fig. 2. Safety-Human Factors Interaction Model. Critical habitability factors; adapted from the original [41].

Vision restriction in the habitats and in workspace may be caused by inadequate lighting systems, poor viewport access ergonomics or by other causes and can be a factor affecting normal duties.

Moreover, limitation of visibility is a likely contributory cause for error, injury, or poor task performance.

Restrictions on the use of existing onboard viewports is a stressor that can create some frustration among crewmembers.

Some studies indicate that should be at least one viewport for each eight crewmembers and each viewport should accommodate at least two crewmembers to avoid psychological disturbances [43, 44, 45].

A further crucial aspect of the endowment of viewports is the environmental awareness as visual perception is the primary method that allows crewmembers to obtain information about their physical environment.

Viewports allow crew's observation capability of the Earth, scientific observation, measurements capability and rest, relaxation and improve crew's morale in long-duration missions.

It must also be considered that the ability to look through a viewport provides means for the eye to focus to the apparent optical infinity and, thereby, stimulate the neurophysiological accommodative mechanism, contrasting the loss of the perception of depth.

Summing up, although many researches and missions' reports, since the Sixties, confirmed the vital importance of viewports in Isolated and Confined Environments (ICEs) in relation to the issues above mentioned [46], generally, in the great majority of projects of space habitats, there is little endowment of viewports and in any case those viewports allow a limited view of the external environment [42].

For instance, LEO habitats, such as the International Space Station (ISS), have generally small-dimension viewports or portholes [47, 48].

This approach to design, pursued in order to reduce the risk of exposure to cosmic radiation and micrometeorite impact, usually exploits ablative components, shutters or external shields as those installed in the ISS Cupola Module.

On the other hand, an alternative approach may consist in the development of 3-D screens, especially exploiting light, thin films. However, this approach implies to carry out an assessment on both the capability of managing the complexity of such systems, and their technological resilience, which are aspects that become crucial in relation to the issues related to the operational phase of a lunar mission.

In any case, the need for accessible and safe external vision solicitates to develop of reliable and manageable alternative technological systems.

5. AN OPTICAL VIRTUAL WINDOW FOR MASS-SCREENED LUNAR HABITATS

The quest of technologies for visioning which meet the requirements of safeguard against environmental threats, accessibility and psychological reassurance in ICEs, addresses research towards simple, accessible, reliable, resilient and safe solutions, which are not excessively complex and do not require laborious maintenance in the harsh lunar environment.

Among the solutions which can be adopted, optical systems as periscopes and hyposcopes offer a starting point for the development of visioning systems for habitats in extraterrestrial environments.

In the terrestrial context, those devices allow the observation of external spaces without direct exposure, or the observation of objects or scenes that cannot be observed directly due to obstacles or unfavorable environmental conditions.

For instance, in the military field, they are used in tanks and submarines, as they allow to observe the surrounding environment without exposing to enemy fire and detection.

They can also be adapted for the observation of atmospheric phenomena, objects recognition or navigation, even by the integration of electronic systems or augmented reality [49]. Likewise, in nuclear power plants they are used to inspect areas at high risk of radiation [50].

Essentially, operating principle of such systems is based on the reflection of light through a series of mirrors (or prisms) arranged in such a way as to reflect an image. Nevertheless, their design and characteristics can vary greatly depending on the specific needs and environmental conditions in which they must operate.

Some models are equipped with advanced lenses and optical imaging systems to improve image quality, while others may include digital technologies for greater accuracy and functionality.

The wide range of their applications demonstrates how periscopes and hyposcopes can be conveniently adapted to a safe and protected vision in lunar environment, due to the fact that allow external observation minimizing the exposure to harmful agents, such as radiation, impacts of micrometeorites and extreme temperatures.

Thus, exploiting optical systems it is possible to bring the image of the external landscape directly inside, without filters or electronic systems, reducing the complexity of technology and enhancing its reliability and resilience.

In the case of a mass-screened lunar habitat without viewports, a system of optical chimneys could be integrated in the building envelope and installed according to preset angles (Fig. 3), so as to capture the widest angle of vision possible, even of 360°, and create a very large virtual windows (Fig. 4).

Each optical chimney has an eyelid that protrudes from the external surface of the envelope of the habitat.

The eyelid has a double function: it protects the optical chimney against both cosmic radiation and micrometeorite impact.

The optical chimney develops from the eyelid and it consists of different functional and technological components (Fig. 5).

The ending part of the chimney is provided with a horizontal optical tube (a), with a multi-layered windowpane (b), made of different glazed components. Proceeding from the outside to the inside the functional layers are arranged in a such way: ablative layer for mechanical protection against micrometeorites, light modulating layer, image-adjusting lens, pressure pane and radioprotective/pressure pane. The function of this windowpane is to capture and adjust the image and ensure both radioprotection and preserve indoor atmosphere.

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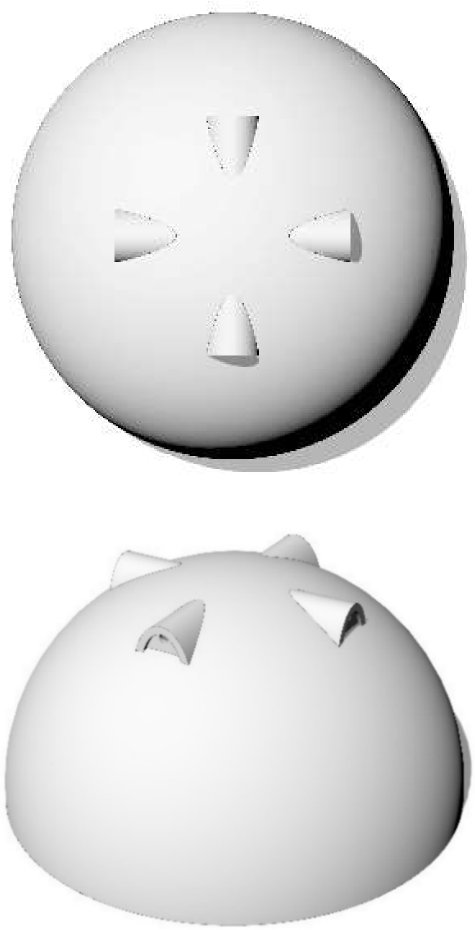

Fig. 3. Optical chimneys are integrated in the envelope of the habitat and installed according preset angles.

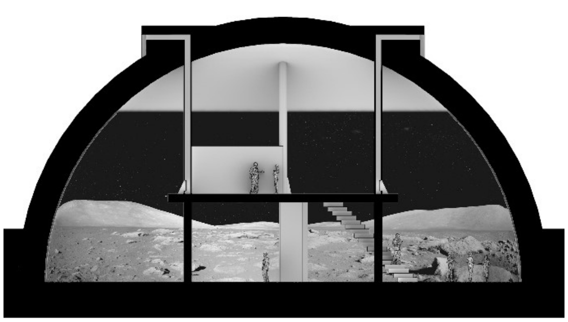

Fig. 4. Indoor virtual window of 360° view.

The ending part of the chimney is provided with a horizontal optical tube (a), with a multi-layered windowpane (b), made of different glazed components. Proceeding from the outside to the inside the functional layers are arranged in a such way: ablative layer for mechanical protection against micrometeorites, light modulating layer, image-adjusting lens, pressure pane and radioprotective/pressure pane. The function of this windowpane is to capture and adjust the image and ensure both radioprotection and preserve indoor atmosphere.

The eyelid also contains a directional spotlight (c) to light the external surroundings for operational tasks and, especially, during the long lunar night that can last up to 14 days.

Beyond the windowpane, a system of prisms and mirrors develops (d). It reflects the image along its optical path.

Indoor, the optical chimney is composed of a vertical optical tube, internally painted black (e). It extends along the optical height up to the observer's eye and contains a lens system for image focusing.

At the coupling of the tube with the intrados of the massive envelope, a multi-layered glass is installed that acts as a redundant diaphragm for pressure sealing (f). Its predisposition allows to maintain or replace the indoor section of the optical chimney.

Finally, at the end of the optical path, a prism reflects the image onto the internal wall of the habitat, which has been treated with a reflective chrome-based coating (g).

This treatment is essential for achieving a high-fidelity reproduction of the projected image. In fact, the chrome-based coating provides a smooth, highly reflective surface that enhances the brightness and the contrast of the projected image, making it as realistic and detailed as possible.

The radioprotective capability of the system is due to the fact that ionizing radiation always encounters a massive, dense and compact obstacle along its path, thanks to the geometry of the chimney.

Otherwise, the light is reflected by a series of prisms and mirrors along the optical path, to its final destination, the inner surface of the envelope, where the image is rendered, creating an extended and immersive virtual window.

Differently from digital virtual windows, which usually need ancillary stereoscopic devices, this system can easily reproduce the perception of depth, stimulating neurophysiological accommodative mechanism of eyes.

The whole system can be implemented by the overlap with Augmented Reality (AR), in order to associate data to physical environment, allowing astronauts to experience a more accessible interaction with it and getting additional information related to mission tasks. For this purpose, electro-optic systems as Holographic Optical Elements (HOEs) can be used to enrich projected images [51].

Briefly, one of the most relevant aspect of this system is its capability to provide a dynamic and authentic view of the outside, which improves the situational awareness of the crew, acting on H&HF with positive effects.

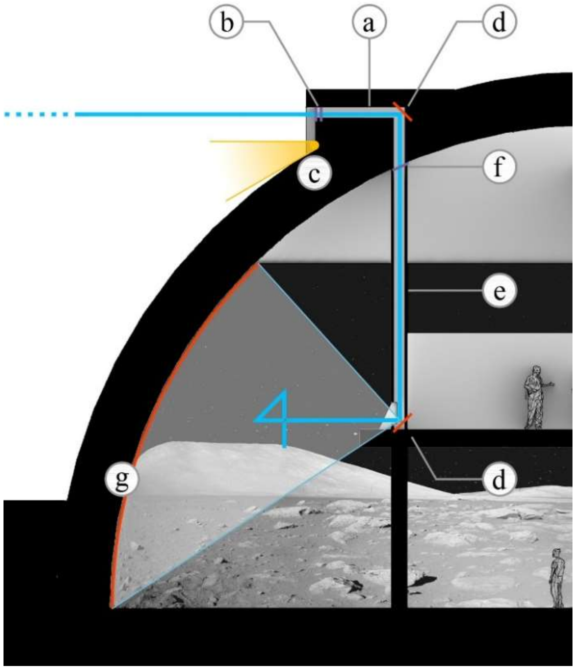

Fig. 5. Functioning scheme and components of the system.

6. CONCLUSIONS

Among the major concerns in space habitats there are the threats of radiation exposure and micrometeorite impact, as well as psychological problems that arise during long stays in ICEs.

In order to face to those concerns, many solutions have been investigated so far, which have mainly delegated to the envelope the function of protection from harmful environmental agents.

Massive envelopes represent the solution that arouses greater interest as their construction technique is affordable because it typically exploits local resources such as regolith.

This technique is effective, however it has an intrinsic drawback: the buildings must have small viewports, or even no viewports at all, in order to distribute the mass seamlessly and achieve uniform protection.

Although since the 1950s many researches on H&HF in ICEs have demonstrated that the capability of external vision is a critical factor for crew's psycho-physical well-being, visioning systems for mass-screened space habitats so far conceived have consisted in dimensionally-limited or just digital devices.

Such solutions, as small observation posts with protective shutters or virtual screens, limit or even do not allow for direct vision of the external environment. The system illustrated in this article, on the other hand, allows continuous and wide observation of the surrounding environment in complete safety.

Furthermore, it must be taken into account that high degree of technological complexity of digital devices as virtual screens produces fragility, that requires an evaluation of degree of reliability, resilience and maintainability in the scenario of a lunar mission.

Conversely, the system illustrated is essentially based on optics and static components, thus it is characterized by a low complexity that increases the degree of reliability and simplifies maintainability in the harsh lunar environment. In addition, the system is able to operate even in the absence of an energy source.

The system is designed to capture images from different viewpoints, thus creating an immersive 360-degree visual experience, which accurately reproduces the surrounding lunar panorama (Fig. 6).

The capability of viewing the external environment and the way it takes place, generate beneficial effects on psycho-physical well-being and affect positively on the performance of mission tasks.

The positive impact can also be strengthened by overlapping ancillary technologies such as HOE or AR to the solution conceived.

However, the system, due to its own technological articulation, functioning and environmental parameters, has specific field and limits of application: the vision but not the transmission of natural light.

These limits solicitate to implement the technology, as in terrestrial conditions, the external vision usually enables natural lighting, as well.

As, in the terrestrial day/night cycle, natural lighting is characterized by a variation over the time of the light spectrum that influences the circadian rhythm, triggering a physiological response, this aspect must be taken into account, especially in relation to the misalignment of the lunar day/night cycle with respect to the terrestrial one.

In fact, in ICEs, and therefore in space missions, circadian rhythm de-synchronization can result in adverse physiological and cognitive effects, such as headaches, insomnia and difficulty in concentrating.

Circadian rhythm de-synchronization can be overcome through the implementation of the system by its integration with devices for a programmable artificial lighting at night.

This approach is corroborated by the results of researches such as "Circadian Light", carried out by ESA in collaboration with the Danish Ministry of Higher Education and Science and the architecture studio SAGA Space Architects, whose aim is to reproduce in space missions natural lighting variations of the terrestrial environment for crew's circadian synchronization through the use of artificial sources [52].

The lines of development that have been illustrated demonstrate how the proposed solution can be further implemented in order to offer the possibility of tailoring the experience and enhance habitability according to the requirements of the crew, based on environmental conditions, mission tasks or individual preferences.

These technologies will make it possible to create human-centered living environments for long-term lunar missions that offer protection against the major threats for crewmembers' safety and health in the harsh lunar environment.

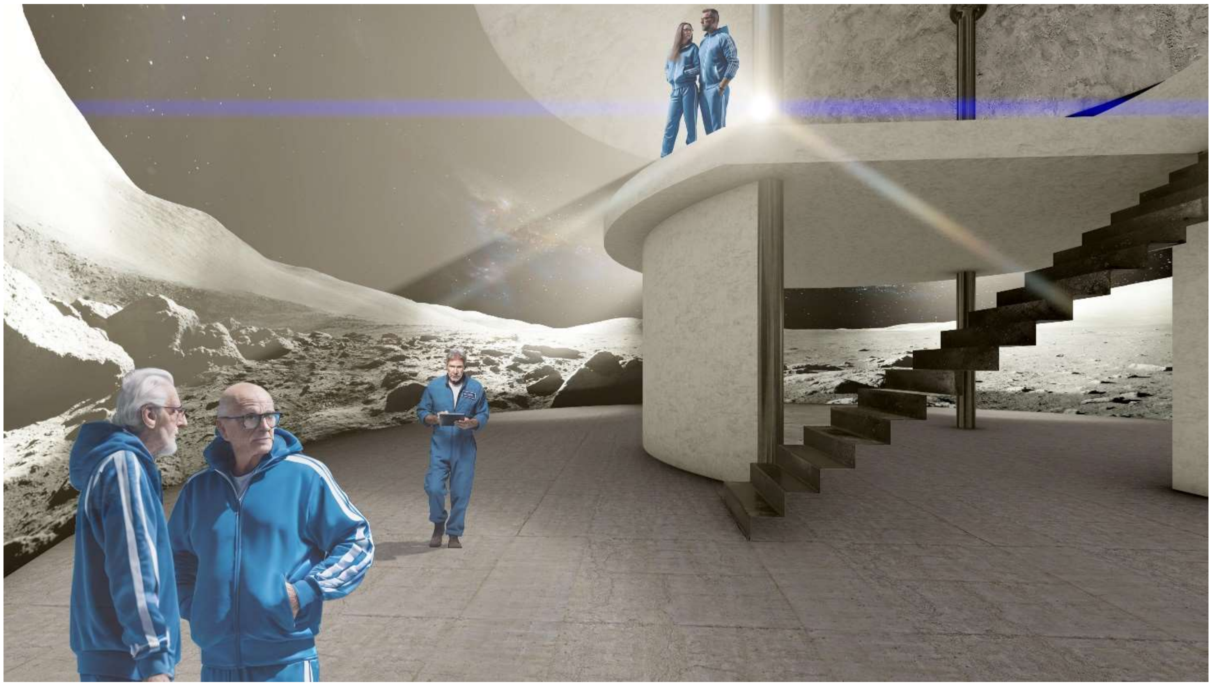

Fig. 6. Interior of the habitat. Here, the captured images are projected onto the walls. The optical virtual window creates an immersive experience that gives the illusion of being in the external environment.

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