DOI: 10.13009/EUCASS2023-449
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

Surfaces for space exploration

Malgorzata Holynska[1]†, Alice Suarez Kahan[1], Federica Arena[2], Mirko Prato[2], David Duday[3], Yann Chouard[4], Gernot Groemer[5], Sibylle Schmied[6], Adrian Tighe[1], Riccardo Rampini[1]*
[1] ESA/ESTEC
Keplerlaan 1, 2201AZ Noordwijk, The Netherlands, e-mail: malgorzata.holynska@esa.int
[2] Italian Institute of Technology
Via Morego, 30 16163 Genova, Italy, e-mail: mirko.prato@iit.it
[3] Luxembourg Institute of Science and Technology
5, Avenue des Hauts-Fourneaux, L-4362 Esch-Sur-Alzette, Luxembourg, e-mail: david.duday@list.lu
[4] COMEX SA
36, bd de l'Océan - CS 80143 - 13275 Marseille Cedex 9 – France, e-mail: y.chouard@comex.fr
[5] Austrian Space Forum,
Etrichgasse 18, 6020 Innsbruck, Austria, e-mail: gernot.groemer@oewf.org
[6] German Institute of Textile Research (DITF)
Körschtalstraße 26, 73770 Denkendorf, Germany, e-mail: sibylle.schmied@ditf.de

Malgorzata.holynska@esa.int
† Corresponding Author

Abstract

In order to successfully return to the Moon and establish a sustainable human presence, as well as pave the way for future Martian exploration, it is we must undertake new, targeted development efforts. With the successful launch of the Artemis I mission, flyby of the Moon and the safe return of the Crew Module, research laboratories are motivated to identify mission risks and to benefit from the significant progress in materials science which could be applied to these questions. This paper reviews challenges linked to different functional surfaces; those exposed to a harsh external environment and those making up the interior of space stations, illustrating them with selected ESA-funded projects.

The issue of biofilm formation in the confined environment of the ISS and in the interior of spacesuits will be amplified over longer time-periods by limited access to resources, decreased immune response of the crew and increased pathogenicity of mutating microbes. There are efforts towards achieving robust low-cytotoxicity surface treatments, especially for wet applications (e.g., water pipes), which do not contain heavy metals as it has been shown that these metals tend to leak into water condensate. The project presented here successfully produced efficient coatings based on natural antimicrobial agents and active nanoparticles. Moreover, in another project, photoactive surface treatments with titanium compounds also resulted in effective antimicrobial barriers with long-term stability, which could be additionally helpful in bioburden control.

The interaction with lunar dust, known for its abrasive nature and electrostatic charge, poses a significant challenge for surfaces directly exposed to the lunar environment, as observed during the Apollo missions. This is applicable to EVA suit external layers as well as thermal control surfaces, mechanisms and seals. Technology development efforts aiming at characterization of the impact of lunar dust on various materials, as well as mitigation strategies for the dust, will be summarized. In the framework of the PexTex (Planetary Exploration Textile) project a selection of state-of-the-art textiles for external surfaces of EVA suit for lunar exploration was undertaken [2]. An extensive series of material tests, including nuclear accelerator-based radiation tests, abrasion tests on a Double Head Abraser and in a tumbler chamber were performed using representative lunar regolith simulants. Moreover, the impact of

DOI: 10.13009/EUCASS2023-449

two lunar dust simulants on Optical Solar Reflector (OSR) surfaces' thermo-optical properties was studied to reveal distinct alpha/epsilon dependences.

1. Introduction

Space Agencies are now collaborating in efforts to bring humans back to the Moon and subsequently to Mars with the aim of establishing a long-term presence. The Gateway mission, part of the Artemis programme, will support missions to the Moon by providing a staging post with the crewed i-HAB module. The Artemis I uncrewed mission was launched by NASA's heavy-lift Moon rocket SLS on 16 November 2022 (Figure 1, 2) with the aim of preparing for a crewed mission [1].

Long-term lunar or Martian exploration mission success is intrinsically connected to the challenges faced by the materials used on said mission. For external surfaces exposed to the lunar environment, the challenging environmental factor is not only radiation, but also the lunar dust. In particular, lunar dust was an unexpectedly critical issue raised by the Apollo astronauts, and it is also present in cis-lunar space.
Lunar dust comprises a fraction of lunar surface material (regolith) with grain size smaller than 20 µm. It is strongly charged and adheres to exposed surfaces. The lack of weathering mechanisms such as the ones we have on Earth results in the persistence of sharp edges on the dust grains which are responsible for its abrasive effect, in some lunar regions combined with a significant chemical reactivity. The impact of lunar dust can affect thermal control surfaces, mechanisms, and external layers of EVA suits [2-3].
Inside a space station, material surfaces are exposed to diverse challenges, including, the presence of human inhabitants resulting in microbial burden and the formation of biofilms. This is well illustrated by the example of the International Space Station (ISS) which was inhabited for more than 20 years and resistant microbial strains developed therein. Therefore, efforts are being made to mitigate this by designing antimicrobial surfaces.

In this paper we highlight recent ESA-funded research developments in the area of surfaces for human spaceflight applications. These include the surfaces of EVA suits for lunar exploration, general study of the impact of lunar regolith on thermal control surfaces and antimicrobial surfaces for applications in confined space stations.

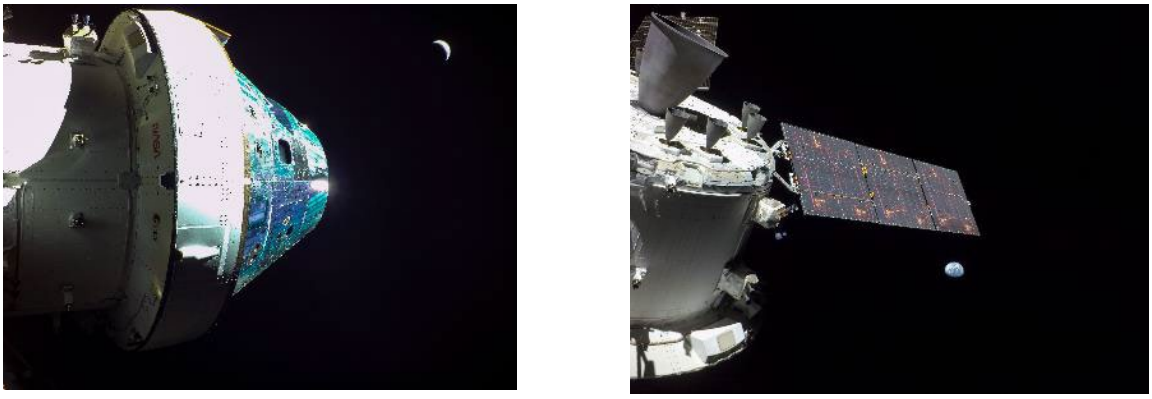

Figure 1: Images from Artemis I mission: (a) moment of preparation for the return flyby with Earth in background; (b) European Service Module-1 in flight (credit: NASA).

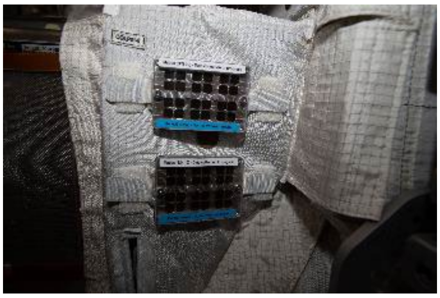

Figure 2: MATISS 2.5 experiment on the ISS (credit: ESA/NASA).

DOI: 10.13009/EUCASS2023-449

2. Biobased antimicrobial surfaces

The occurrence of infectious diseases inside inhabited crewed spacecrafts is considered a serious threat for the success of future space missions, more particularly since the recent discoveries of the first antibiotic-resistant pathogens in the ISS at the end of 2018. At the same time, the immune system of astronauts is altered, making the occurrence of infectious diseases easier [3]. To decrease the risk of infectious disease due to the formation of biofilms on indoor spacecraft surfaces and crew suits, the deposition of antimicrobial coatings combined with the surface cleaning with cleaning products is considered the most suitable approach. Several commercial antimicrobial coatings are accessible on the market for terrestrial applications and with a cytotoxicity level acceptable for commercial use. However, the future regulations on the use of chemicals (REACH - Registration, Evaluation, Authorisation and Restriction of Chemicals) and the confined conditions on inhabited spacecraft makes most of these solutions non-relevant for inhabited spacecrafts. A new generation of coatings, safer for the crews, needs to be developed. In the NbactSpace project, several alternative coatings were developed to replace the golden standard materials like silver, quarternary ammonium or TiO_2. The bio-based or biocompatible coatings were designed to be as safe and sustainable as possible (Figure 3). Efficient technologies based on plasma, atomic layer deposition or colloidal engineering were used to produce the coatings.

Figure 3: Goal of the NBacSpace project (credit: LIST).

The targeted applications for these coatings were water condensing surfaces used in heat exchangers (Figure 4) and any dry surfaces in the spacecraft. For water condensing surfaces that are prone to microbial contamination, antimicrobial coatings are needed because these surfaces are not accessible and difficult to replace. For the other "dry surfaces", even if they are more accessible, except some hidden parts, they are more critical because they are in direct contact with the crew. Some of these dry surfaces are more prone to microbial proliferation like toilet or kitchen parts as well as handrails. For these surfaces, a higher resistance to scratch is needed due to the contact with crew and their tools. Therefore, the durability of antimicrobial coating is a critical aspect particularly for metal-free coatings.

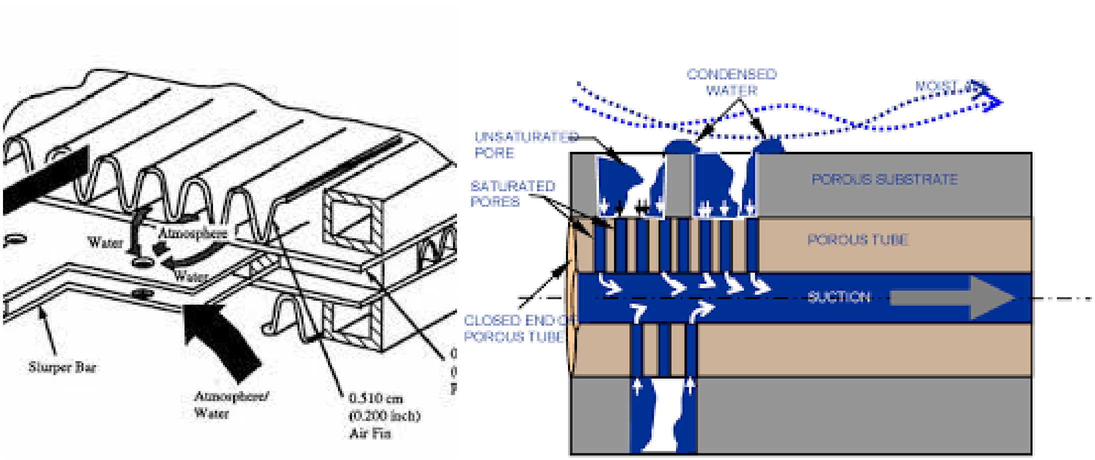

Figure 4: Water condensing surfaces in heat exchangers used in spacecrafts (credit: NASA).

For NbactSpace, we have selected alternatives to gold standard materials as antimicrobial agents: biosourced organic polymers like chitosan or lignin, biomolecules like antimicrobial peptides and a metal oxide treatment that is expected to be the most biocompatible metal oxide. For the matrix of the coatings which must provide adhesion, cohesion, durability and limited biocide release, 3 alternative materials were provided: a methacrylate-based material, which is

DOI: 10.13009/EUCASS2023-449

a synthetic organic approach whereby methacrylate can be combined with other monomer to generate functional polymer to later graft antimicrobial molecules; a siloxane based approach for the production of polydimethylsiloxane-like materials that combine the mechanical properties of polymers with the chemical stability of silica-based materials and a third approach that uses a biocompatible hydrogel cross-linked and functionalized to be water-resistant (Figure 5). To apply these materials on a surface, 3 different surface treatment approaches were used: atmospheric-pressure plasma that results in the decomposition and cross-linking of different organic or siloxane-based precursors; wet deposition of colloidal suspension to generate thin nanocomposite films (Figure 5) and nanopatterning to combine a topographical effect with chemical effects.

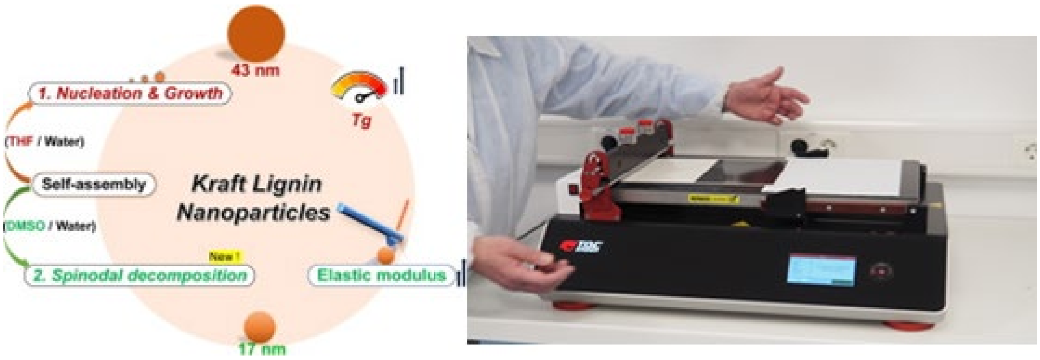

Figure 5: Fabrication of lignin nanoparticles and deposition of nanocomposite films in Luxembourg Institute of Science and Technology (credit: LIST).

A full analysis and test plan was designed and implemented to optimize and select the best antimicrobial surfaces on two different substrates (Figure 6). Physicochemical analyses to know the chemical composition, surface topography, microstructure, conductivity, and water contact angle were carried out. Then, biological tests including antibacterial and antifungal activity as well as cytotoxicity against skin cells were carried out with different model pathogens. The antibacterial tests were conducted after deposition and after ageing to validate the durability of the antibacterial effect. A third category investigated off-gassing, accelerated ageing, corrosion test, immersion test, adhesion/cohesion test and wipe's cleaning tests allowed to evaluate and validate the stability of the NBactSpace antimicrobial coatings.
The selected coatings had to demonstrate a significant antibacterial activity and no cytotoxicity combined with desirable mechanical, chemical and thermal stability with almost no molecule release.

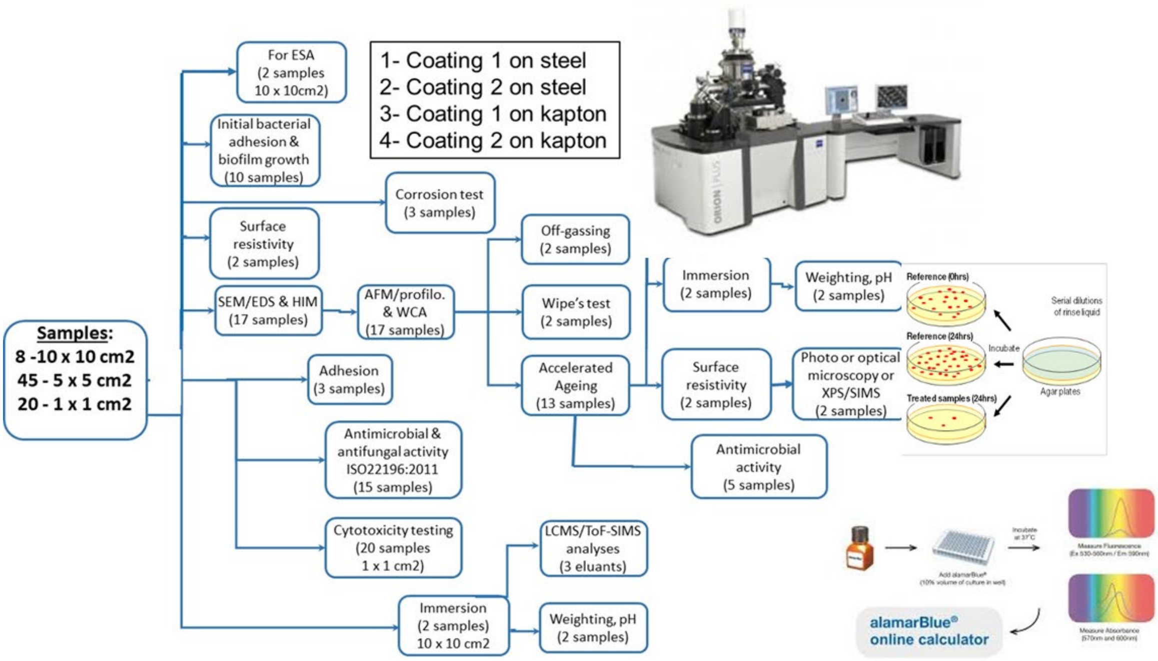

Figure 6: Test plan for the characterization and test of antimicrobial coatings in NbactSpace project (credit: LIST).

At the end of the project, only one type of coating passed all the functional and stability tests. This type of coating is based on a poly(vinyl alcohol) biocompatible matrix that is organically cross-linked to yield a higher stability in wet

DOI: 10.13009/EUCASS2023-449

environment and water. The antibacterial properties are generated by a combination of chitosan molecules and lignin nanoparticles engineered to reinforce the antibacterial properties. These coatings are deposited by a bar coating approach and then, thermally cured at mild temperature to remove water and improve the cross-linking (Figure 7). These coatings were shown to adhere even on mirror polished A4 size samples and resisted cleaning with the wet wipes used in the ISS. After accelerated ageing mimicking 3 years of use in space station environment, the coatings remain stable and antibacterial properties are still active (Figure 7). In conclusion, the NbactSpace final coating represents the best compromise between antibacterial activity, safety and stability, using only biocompatible and biodegradable materials and can be applied on and metallic or plastic flat surfaces.

Figure 7: Selected and upscaled antimicrobial coatings before and after accelerated ageing testing in NbactSpace project (credit: LIST).

3. Photoactive antimicrobial surfaces

Among the strategies available to limit the formation of biofilms and the proliferation of bacteria and fungi, the use of mechanically robust oxide films, endowed with photo-catalytic functions, represents a viable option that would allow to avoid the release of active compounds in the environment. In fact, while a broad range of antibacterial compounds has been developed for release-based coatings, as summarized by M. Cloutier et al. [4], their use in the confined space of a crewed spacecraft poses several potential issues related to the accumulation of the active agent in the environment (e.g., closed-loop life support systems) and in the astronauts' bodies [5]. Moreover, microorganisms continually exposed to sublethal concentrations of an antimicrobial agent have been shown to develop resistance to that specific compound [6].

On the other hand, materials that, under specific conditions, might induce the generation of reactive oxygen species (ROS), can display antimicrobial properties [7-8]. One common way to generate reactive oxygen species is by photoexcitation [9]. In semiconductors, ROS are generated by redox reactions of oxygen and water with photogenerated electrons (e^-) and holes (h^+) on the surface of the photocatalyst. The so-produced highly active radicals, such as superoxide anions ($O_2^{\bullet -}$), hydrogen peroxide molecules (H_2O_2), hydroxyl radicals ($HO\cdot$), and excited state singlet oxygen molecules ($^1O_2$) can oxidize and damage nearly all types of biomolecules (proteins, lipids, and nucleic acids) and kill cells [10].Importantly, ROS act on the microbes by oxidation, which does not depend on the type of microbe and will not cause medical resistance [11].

As a classical photocatalytic material, titania (TiO_2) has also been reported as a promising material for application in antimicrobial coatings. Some of the relevant publications [1] have been summarized in a recent review [5]. The main drawback of pure TiO_2 is that its activity is triggered only by UV light, while the spectrum of the lighting system on the International Space Station encompasses chiefly visible radiation [13]. This limit can be overcome, for instance, by adding dopants to TiO_2: it has been demonstrated, that dopants in the TiO_2 crystal structure can modify its bandgap and so that it is possible to activate the antimicrobial material under visible light [14].

In an ongoing collaboration between ESA and the Italian Institute of Technology (IIT), magnetron sputtering was employed to produce efficient antimicrobial TiO_2-based thin films (patent pending) with high mechanical strength and elevated antibacterial activity under visible light. The coatings were tested for their antibacterial properties against E. Coli and S. Aureus strains. After 24h of incubation, the biocidal tests demonstrated a good performance of coatings for the inactivation of both strains, with a remarkable antibacterial activity of about 100%. Moreover, the long-term antibacterial activity of the coatings was further tested after aging in a climatic chamber at a relative humidity of 90% and a temperature of 50°C, to simulate an accelerated aging within the internal ISS environment. The chemical, mechanical, and antibacterial properties of the aged coatings were analysed to evaluate their durability. After 192 hours of aging, the results showed only a mild decrease in the activity against the bacterial strains. These preliminary results further support the relevance of photoactive surfaces in the control of microbial proliferation. Further studies are ongoing to verify the nature of the photo-degradation products being dispersed into the cabin atmosphere once the bacteria are oxidised.

DOI: 10.13009/EUCASS2023-449

4. Surfaces of EVA suits

Apollo astronauts Pete Conrad and Alan Bean spent seven hours and 45 minutes performing EVAs on the surface of the Moon. Upon return to the lunar lander, their suits had nearly failed with lunar dust having eroded through several layers of Mylar. The longest EVA on the Moon was conducted during Apollo 17 (~ 43 h). In total, all Apollo Astronauts' EVAs amounted to approximately 150 hours [2].
Today, ESA and its international partners are considering a return to the Moon with the intention to establish a permanent presence on the surface. Although not all will be permanently crewed, some of the equipment will remain on the surface in preparation for subsequent missions).
Future EVAs on the lunar surface will require improved suit concepts compared to previous systems like the Apollo A7L Pressurized Suit Assembly or their Russian counterparts. Functionalities should include improved ergonomics and the use of smarter materials that are able to heal defects or monitor their integrity.
These novel functionalities might be addressed by recently developed materials, however these novel materials must be tested against the environment of space or planetary surfaces. It was the objective of PExTex (Textiles for Planetary Exploration) project to integrate these two aspects into one project and to deliver ESA an analysis of potential future EVA suit materials.

The specific goals of PExTex were:
1. to identify (novel) materials for future EVA space suit developments in Europe,
2. to propose and conduct a testing strategy to verify that such materials meet the conditions of future missions to the lunar surface,
3. propose avenues for further development.

The following basic requirements were considered:
- [RQ1] Demonstrated compatibility with the expected environmental conditions for 2500 hours with lunar temperature range (+120°C in sunlight, -170°C in darkness).
- [RQ2] Demonstrated compatibility for 2500 hours with lunar radiation environment (annual exposure to ca. 380 mSv at solar minimum and 110 mSv at solar maximum).
- [RQ3] Demonstrated compatibility for 2500 hours with lunar vacuum environment.
- [RQ4] The material shall sustain repeated pressure-vacuum cycling, considering a max. pressure up to 420 hPa over 312 pressurisation cycles.
- [RQ5] Demonstrated EMC and discharge protection during lunar EVA activity for at least 8 hours (from friction during movement of the suit and from the external environment).
- [RQ6] Demonstrated resistance to wear by abrasive regolith (considering lunar environment) for exposure of EVA suit over 2500 hours.
- [RQ7] Demonstrated bendability to 180° (for flexibility of astronaut movements, e. g. in knees and elbows).
- [RQ8] Demonstrated fatigue integrity over the expected suit life (120 cycles/hour, 2500 hours).
- [RQ9] The material shall ensure thermal insulation for EVA activities under external environment defined in [RQ1-RQ3]. and targeted max. temperature 25°C inside (with minimum at 17°C).
- [RQ10] The material shall not off-gas toxic substances as per [AD6].
- [RQ11] The material shall be non-flammable as per [AD7].
- [RQ12] Demonstrated dust mitigation strategy.
- [RQ13] Demonstrated compatibility (limited degradation) with long-term storage for 2 years at a space station / habitat. Folding of the suit shall be taken into account.
- [RQ14] Demonstrated impermeability to water and fluids.
-

The consortium along with ESA devised various methods for preselecting the candidate materials for the testing camping and as a result of those deliberations, the initial candidate materials were selected via "recommendation and comparative analysis".
As the first step of the selection process each consortium partner presented their preferred 3-5 materials for each functional layer from the textiles identified. Following the recommendation from each partner, an iterative process was conducted to advocate, compare and discuss the merits and demerits of each candidate textile to select the top 3-5 materials for each functional layer.
The top-ranking material from each functional layers were assigned as preferred PExTex candidate stack A, the second material from each functional layer as candidate stack B and so on. After which the materials were further iterated taking into account availability and regulatory considerations such as export regulations.

DOI: 10.13009/EUCASS2023-449

In addition to the comparative analysis, quantitative analysis for the recommended materials were performed as an outcome of the expert workshop held at Innsbruck, Austria. For the quantitative analysis, trade off analysis was performed for each material, (weightage for layer requirement parameters x merit for materials properties towards the parameter), assessing the material functions such as resistance against abrasion, temperature, UV and radiation degradation etc. for each layer.

Figure 8 shows the best-rated four choices of PExTex candidate material stack.

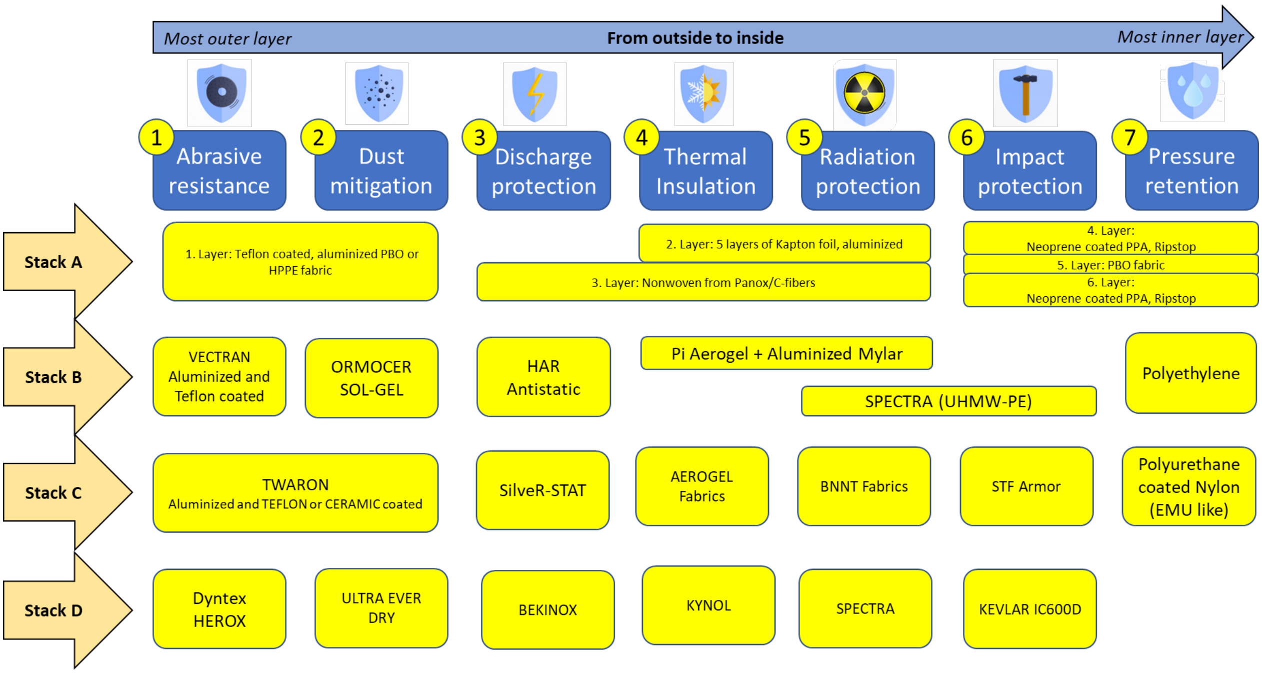

Figure 8: Materials selected in the framework of the PexTex project.

To test for abrasion resistance of the external layers against lunar regolith, textile industry-standard friction wheel test were conducted to investigate the abrasion response. The test was carried out using standardized friction wheels, allowing for a parametric analysis. The weight change was determined by the abrasion after the load (weight before/after), and visual inspection using optical microscopy was a complimentary technique used. These assessments were also be used as a pilot investigation for the tumbler test.

Figure 9: Experimental setup for (left) wheel abrasion test (modification with continuous regolith supply was used), (right) tumbler test.

The determination of the abrasion according to the Rotary Platform Double Head Abraser (Taber) serves to the rating of the abrasion resistance of the textile surface. The mass, which results from the sanding of the test specimen with friction wheels with different goodness under specific pressure serves as rate for the abrasion. The change of the color

DOI: 10.13009/EUCASS2023-449

corresponding to the grade of grey scale according to DIN EN ISO 105-A02 and the mass loss of the test specimens was also determined.
The authors would like to emphasize, that measuring the resistance to abrasion of textile and other materials is considerably complex: The resistance to abrasion is affected by multiple factors, such as the inherent mechanical properties of the fibers, the dimensions of the fibers, the structure of the yarns, the weaving patterns of the fabrics as well as the type, kind, and amount of finishing coatings and treatments added to the fibers, yarns, or fabric.
A Rotary Platform Double Head Abraser with Soil Simulant was also used for determining the abrasion properties, emulating the response of the materials when exposed to soil simulants. The weight change can be determined by the abrasion after the load (weight before/after), supplemented by optical microscopy observations to identify surface changes.
With the Tumbler Test the dust capacity can be determined after the stress (weight before/after), again with complementary optical microscopy after cleaning the treated samples. The samples are placed in a glass together with dust and tumbler. The glass is then inserted into the instrument and mobilized for 8hrs. The sample is then removed, carefully cleaned of dust and undergoes optical inspection for optical changes / destruction. Furthermore, the dust adhesion was assessed by comparing the textile sample weight before and after the test.
For the investigation of the wear and tear resistance of outer materials, EAC-1A lunar regolith simulant was selected. The fabric related results are summarized with respect to abrasion cycles and target information in Table 1.

Table 1: Results of visual inspection after application of friction wheels.

Fabric	Target Information	2,500 cycles	5,000 cycles
Alum. PBO/PTFE	RS penetration	Slight penetration	RS penetration, upper and bottom side
	Abrasion wear	PTFE slightly abraded	PTFE worn-out
Alum. Vectran/ PTFE	RS penetration	Slight penetration	RS penetration, upper and bottom side
	Abrasion wear	PTFE worn-out	PTFE worn-out and strongly damaged in some parts
Ceramic-coated Twaron	RS penetration	Very little RS adhere	Little RS adhere
	Abrasion wear	Almost no defects (1-2 defects per sample)	4-8 defects per sample Coating flaked in parts
Dyntex	RS penetration	RS penetration visible	RS penetration visible
	Abrasion wear	Slightly abraded	Complete worn through of textile, fabric destructed

Figures 10 and 11 show adhesion of regolith simulant for 2,500 cycles in abrasion wheel test and maximum tensile force for abrasion wheel test, respectively.

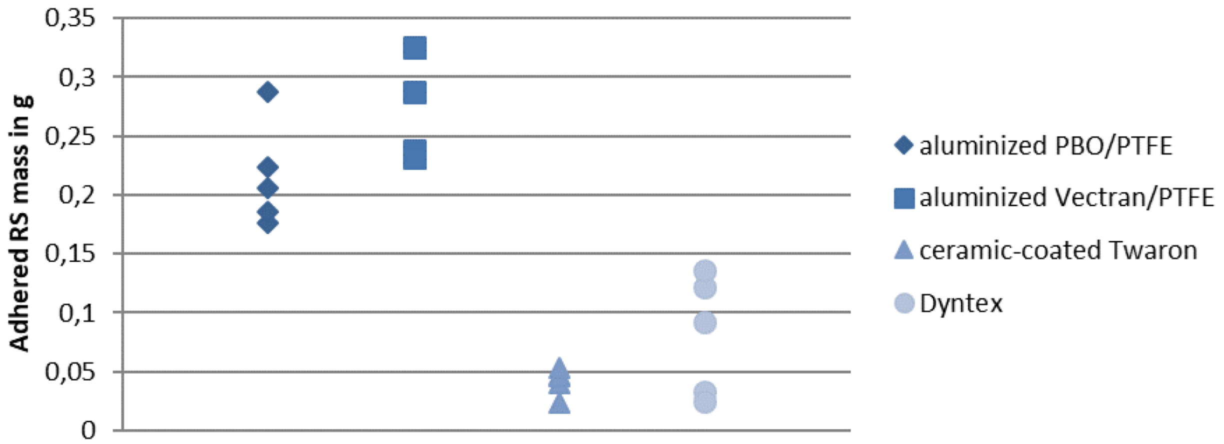

Figure 10: Results for adhesion of regolith simulant for 2,500 cycles in abrasion wheel test.

DOI: 10.13009/EUCASS2023-449

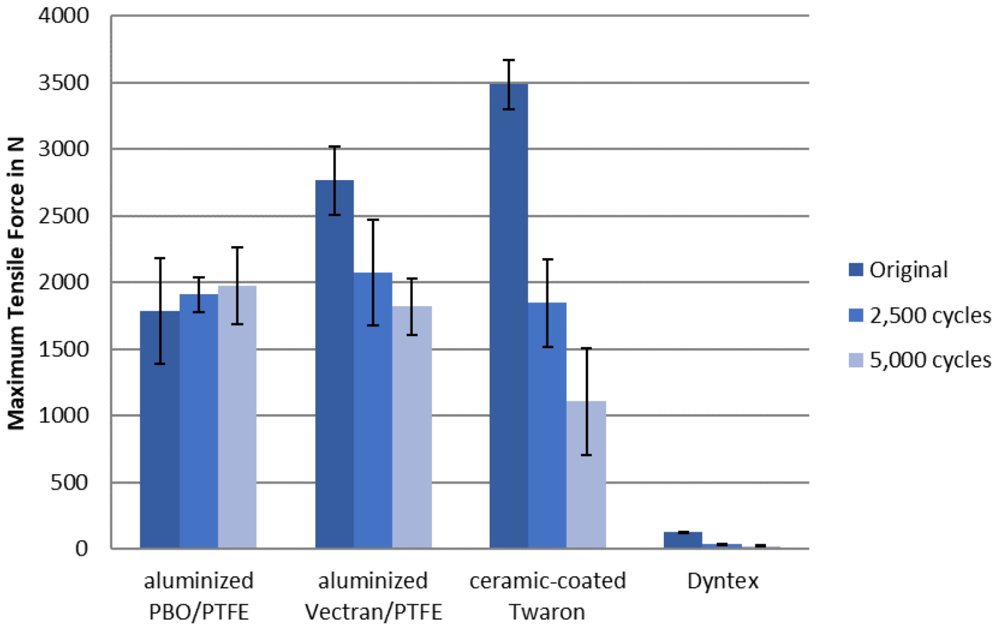

Figure 11: Maximum tensile force for abrasion wheel test.

Adhesion of regolith particles is a less important value (only 0,05g of adhered mass) for Twaron, but its tensile strength decreases significantly after multiple load cycles (3500N to more than 1000 after 5000 cycles). Conversely, aluminized PBO/PTFE and aluminized Vectran/PTFE which have the highest total particles adhesion, keep the highest tensile strength values after load cycling. The adhered regolith seems to create a critical layer which covers the material. However, it remains unclear whether all materials' properties would degrade under a regolith dust layer. In addition to the demonstration of Twarons' fatigue integrity, it is critical to note that its ceramic coating does not present a significant resistance to abrasion and fails under stress based on weak bonding between Twaron and a ceramic coating,so although each individual material of the compound fulfils the requirements and the combination is assumed suitable. It would be suggested that the bonding between these materials be improved.
We note that, within the framework of the PExTex project, the commercial-off-the-shelf textiles and material combinations properties investigated also depend on the manufacturing process, such as weaving, knitting and bonding.

Two approaches are considered for future tests:
- A stacked material needs to be manufactured into multiple, consistent stacked specimens. A stack is easier to test than an ergonomic demonstrator, which is larger. This is because the mechanical tests are small area tests although such tests are sufficient to measure mechanical or physical parameters of the stack. It is however unknown at this time as to scaling effects when increasing scale from coupons to ergonomic prototype of an EVA suit.

- Use of an ergonomic demonstrator, as we cannot estimate in where and which conditions within suit stack specimens will be exposed. On the other hand, integrated ergonomic test presents more information value and practical approach in relevant ergonomic scenarios such as human activity within lunar facility and/or analog mission.
Advanced test methods would require further input from the EVA expert community, including NASA and ESA astronauts and other end-users of such products, to enable credible test requirements and test parameters.

5. Interaction of lunar dust with spacecraft surfaces

Any surfaces exposed to the environment of other planetary surfaces will be exposed to the regolith present on the respective celestial body. Due to the extreme nature of the Moon, the lunar regolith differs significantly from that found on earth and presents new challenges for mission design. Apollo astronauts reportedly considered lunar dust to be the greatest challenge they experienced on the surface, and long-term missions for both equipment and humans necessitate this challenge to be properly addressed. Amongst other issues, dust can obscure surfaces, abrade coatings, change thermal behaviour, and deteriorate space mechanisms [15]. A direct example of dust obscuration impacting thermal control surfaces occurred during Apollo missions. A fine dust layer was deposited on the battery radiators for cooling on the lunar roving vehicle (LRV), which caused the batteries to overheat far beyond their projected operational maximum [16]. Testing must be carried out to predict the impact on specific missions with specific parameters for dust

DOI: 10.13009/EUCASS2023-449

contamination so that similar or worse situations do not arise. Some work has been done using calorimetry and simulant deposition to investigate these effects [17].

Several simulants are available for use to test contamination effects, with different intended purposes and varying levels of fidelity. For example, simulants are usually produced with the intention of replicating a specific geological area of the moon, highland or mare, and may aim to replicate the mineralogy of previous lunar missions. Some may be intended to emulate more complex components of the lunar regolith such as agglutinate contents, others more intended for lower-cost large-scale testing. We argue that the simulant most appropriate for a test may not be the most obvious choice based on intended simulation, due to a critical property for the test not being replicated well e.g., the best match for solar absorptance expected for a certain mare region might be a specific fraction of a highland simulant [18]. Previous work was done obtaining standardised data for various tests on several available lunar simulants, including solar absorptance values from reflectance spectra of 15 samples including both as-received simulants and separated simulant size fractions [19].

In order to understand the effect of lunar dust deposition on surfaces, several parameters must be known:

- Adhesion properties (for example the size distribution of the dust on the surface, the strength of the adhesion and resistance to removal, the coverage expected, thickness, roughness…).
- Thermo-optical properties of the dust (solar absorptance (α_S), thermal emittance (ε_{IR})) when in a deposition layer of that nature.

The complexity of lunar dust adhesion mechanisms [20] renders modelling this a non-trivial aspect of the problem, on which more research is needed. However, plots of thermo-optical changes in substrates of interest when exposed to varying levels of dust contamination can already be useful tools for preliminary analysis of the impacts on thermal control surfaces.

The thermo-optical impact of varying extents of EAC-1A lunar dust simulant (LDS) deposition on optical solar reflectors (OSRs) was previously investigated. α_S and ε_{IR} were measured for several levels of deposition quantified using optical microscopy for particle area coverage (PAC), and mass measurements for the mass concentration values for each deposition, presented in [19]. EAC-1A is the finest fraction of the EAC simulant produced by the European Astronaut Centre, developed by the European Space Agency [21].

Further testing was recently carried out using a different simulant on the same uncoated OSR substrate. LHS-1 was chosen as a representative highland simulant with a lower solar absorptivity value than the originally used EAC-1A, for comparison purposes. LHS-1 is a lunar highland simulant commercially available from by Exolith labs, produced from anorthite mined from the White Mountain anorthosite source in Greenland, and a glass-rich basalt [22]. The LHS-1 used in this study was obtained in 2021. Other than the simulant, parameters were kept the same, except for the addition of a witness sample used to characterize the surface roughness of the depositions. 8 data points were obtained for α_S (shown in Figure 12, left) and 7 for ε_{IR} (shown in Figure 12, right), in triplicate each time. (*See previous publication for detailed methods*).

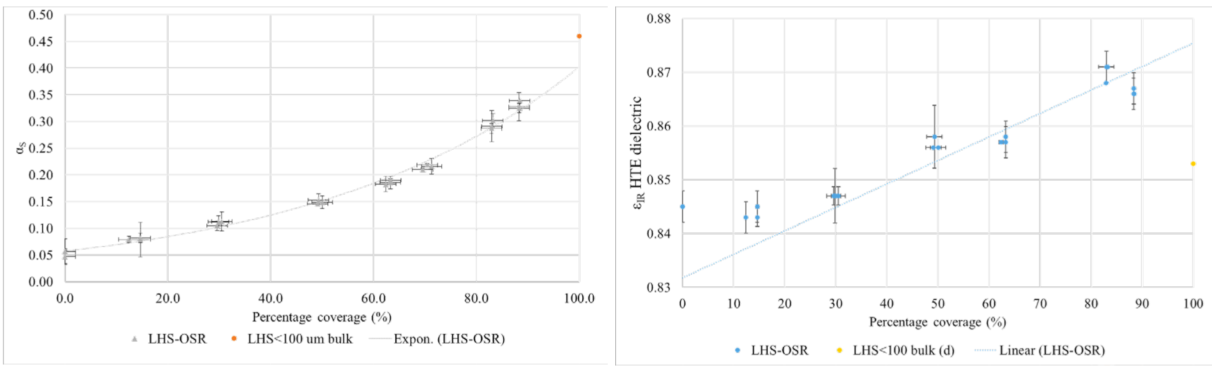

Figure 12: Thermo-optical property variation values with percentage area coverage for 3 areas of an OSR substrate with varying depositions of LHS-1 LDS, *left*: α_S, *right*: ε_{IR} hemispherical, as calculated for a dielectric surface.

The change in α_S with increasing PAC is best characterised as having an exponential behaviour. 100% coverage was not achieved with dust deposition on the OSR, as achieving that value would require very high masses to ensure saturation, requiring very thick stacks to be created on the surface. The point plotted at 100% is a separate measurement

DOI: 10.13009/EUCASS2023-449

of the value of the simulant (measured in a cell where a large volume was pressed to be fully opaque). The instrumental error is of ±0.03 for both emittance and absorptance. This is not plotted, what is shown in the error bars is the experimental error. Error values: as for each sample (each mask area), 3 measurements were taken, rotating the instrument each time so that if the beam is non-centred, different areas of area are sampled. Thermo-optical value error shown is using the experimental error and a 90% confidence interval. Percent coverage error bars are an estimation using ± the range in PAC obtained when sampling from the centre of the exposed area from the mask before and after thermo-optical measurements. 1.5% was used when the PM measurement was missing. The error bars for the bulk simulant as obtained from the standard deviation of the measurements are too small to see, the errors calculated including the instrumental error are ±0.04 for EAC-1A and ±0.06 for LHS-1 <100 µm fractions.

Figure 13 shows both sets of α_S data for the simulants (left), and then the same data divided by the α_S of the simulant (right) so that both data sets can be compared to the rule of mixtures more clearly. (Relative absorptance = $\alpha_{dusted\ surface}/\alpha_{LDS}$). The simple rule of mixtures assumes zero interaction between the particles on the surface, and models the change in thermo-optical properties as a linear combination of both components based on the area of each that is interacting with light. Figure 2 on the left shows that the values of α for LHS-OSR are lower than that obtained using EAC-1A simulant, which is due to the lower difference between the α of the substrate and that simulant. On the right each data point is normalised to the value of bulk α_S so that this difference is accounted for.

Values for α_S for the EAC-OSR system were above the line produced using the rule of mixtures, including the maximum value of α which was higher than the value for the bulk simulant (0.83 vs 0.72). This phenomenon was previously attributed to the non-monolayer deposition of LDS, whereby the light would pass through more LDS than accounted for by the PAC which measures only the particles present in the 2D plane. Conversely, for the LHS-OSR system, all values were below the theoretical line. This fits with existing literature observations [23] where authors have suggested that transparent particles would limit the applicability of the theory, due to the higher absorptivity of bulk LDS versus monolayer coverage (the LHS-1 fraction contained a higher percentage of transparent particles than EAC-1A). The other difference is that the shapes of the plots differ greatly, as EAC-OSR values can be fit well using a linear fit, whereas LHS-OSR values follow an exponential curve. An explanation for this is being investigated, but one hypothesis is that their difference in PSD below 100 µm and/or cohesion values might lead to a different relationship with mass for the increase in stack-formation for LHS-1 thus impacting the α values measured. Roughness indicator Sa (arithmetic mean height) was seen to increase linearly with PAC but might be a less steep increase for EAC-1A experiments (no data).

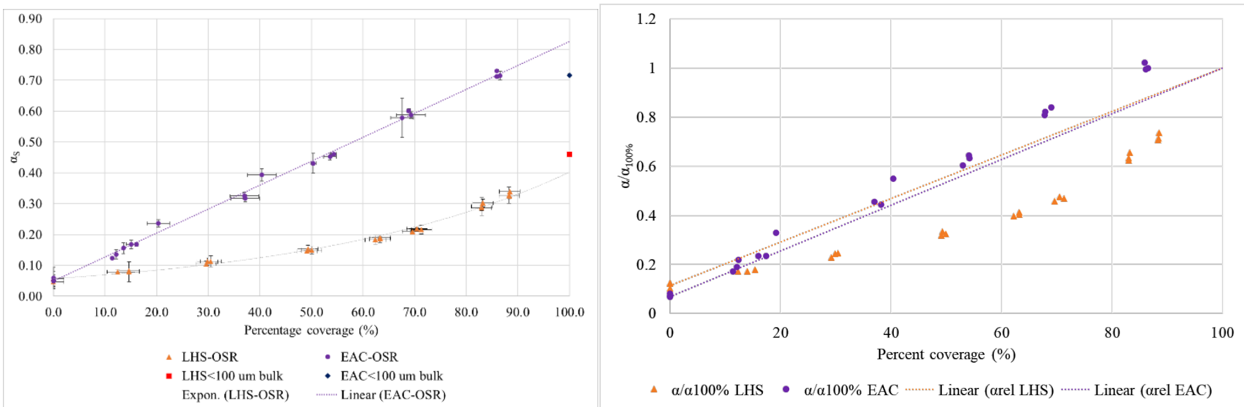

Figure 13: *Left:* α_S values with percentage area coverage for 3 areas of an OSR substrate with varying depositions of LHS-1 LDS (orange triangles) and EAC-1A LDS (purple points) with linear and exponential trendlines proposed, respectively. Values at 100% are the αS from measurements of the bulk dust, with EAC-1A in blue diamond and LHS-1 in red square. *Right*: relative α_S values of $\alpha_{dusted\ surface}/\alpha_{LDS}$ with percentage area coverage for 3 areas of an OSR substrate with varying depositions of LHS-1 LDS (orange triangles) and EAC-1A LDS (purple points). The lines in orange and purple show the ideal values of relative α_S for LHS-1 and EAC-1A tests respectively (the initial pristine OSR values differ slightly, or they would be identical). Error bars on left hand image are as described for previous figures.

DOI: 10.13009/EUCASS2023-449

4. Conclusion

We presented summaries of current ESA projects investigating surfaces relevant for the projected long-term lunar exploration, with a focus on antimicrobial surfaces for confined, pressurized space stations and on external surfaces in contact with lunar regolith.
Antimicrobial surfaces are sought that would be stable long-term under corrosive conditions and would not leak harmful substances like heavy metals into their environment.
On the lunar surface, abrasive and charged lunar dust particles interact with exposed materials leading to their erosion and change in thermooptical properties. A study was made on novel potential EVA suit textiles that could resist dust abrasion and other environmental influences, substantiated by means of such tests as abrasive header and tumbler tests. A more general study investigated contamination effects of OSR surfaces deliberately covered with controlled amounts of lunar dust simulants.

4. Acknowledgement

This research was in the framework of projects funded by the European Space Agency (ESA). The views expressed herein can in no way be taken to reflect the official opinion of the European Space Agency (ESA) and are not intended to endorse particular technologies, companies, or products.

References

[1] ESA website, Artemis I. ESA Orion ESM: The mission and Technical details, https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Orion/Artemis_I, accessed: March, 2023.
[2] Weiss, P., Mohamed, M. P., Gobert, T., Chouard, Y., Singh, N., Chalal, T., Schmied, S., Schweins, M., Stegmaier, T., Gresser, G. T., Groemer, G., Sejkora, N., Das, S., Rampini, R., Hołyńska, M., *Adv Mater Technol* 2020, 2000028.
[3] Liu, Y., Taylor, L. A. *Planet Space Sci* 2011, 59, 1769.
[4] Cloutier, M., D. Mantovani, F. Rosei. 2015. Antibacterial Coatings: Challenges, Perspectives, and Opportunities. *Trends Biotechnol.* 33:637-652
[5] Wang, M., D. Duday, E. Scolan, S. Perbal, M. Prato, C. Lasseur, M. Hołyńska. 2021. Antimicrobial Surfaces for Applications on Confined Inhabited Space Stations. *Adv. Mater. Interfaces* 8:2100118
[6] Levy, S.B. 1982. MICROBIAL RESISTANCE TO ANTIBIOTICS: An Evolving and Persistent Problem. *The Lancet* 320:83-88
[7] Lam, P.-L., R.S.-M. Wong, K.-H. Lam, L.-K. Hung, M.-M. Wong, L.-H. Yung, Y.-W. Ho, W.-Y. Wong, D.K.-P. Hau, R. Gambari, C.-H. Chui. 2020. The role of reactive oxygen species in the biological activity of antimicrobial agents: An updated mini review. *Chemico-Biological Interactions* 320: 109023
[8] Lizhen, Z., Z. Chengyuan, H. Rongtao, D. Yanwen, R. Changping, S. Xing-Can. 2021. Mechanisms of Reactive Oxygen Species Generated by Inorganic Nanomaterials for Cancer Therapeutics. *Frontiers in Chemistry* 9:630969
[9] Buchovec, I., A. Gricajeva, L. Kalėdienė, P. Vitta. 2020. Antimicrobial Photoinactivation Approach Based on Natural Agents for Control of Bacteria Biofilms in Spacecraft. *International Journal of Molecular Sciences* 21:6932
[10] Dwyer, D.J., M.A. Kohanski, J.J. Collins. 2009. Role of reactive oxygen species in antibiotic action and resistance. *Current Opinion in Microbiology* 12:482-489.
[11] Kumaravel, V., K.M. Nair, S. Mathew, J. Bartlett, J.E. Kennedy, H.G. Manning, B.J. Whelan, N.S. Leyland, S.C. Pillai. 2021. Antimicrobial TiO2 nanocomposite coatings for surfaces, dental and orthopaedic implants. *Chemical Engineering Journal* 416:129071
[12] (a) Bonetta, S., S. Bonetta, F. Motta, A. Strini, E. Carraro. 2013. Photocatalytic bacterial inactivation by TiO2-coated surfaces. *AMB Express* 3:59. (b) Gomes, A. I., J.C. Santos, V.J.P. Vilar, R.A.R. Boaventura. 2009. Inactivation of Bacteria E. coli and photodegradation of humic acids using natural sunlight. *Appl. Catal. B: Environmental* 88:283-291. (c) Nosrati, R., A. Olad, K. Nofouzi. 2015. A self-cleaning coating based on commercial grade polyacrylic latex modified by TiO2/Ag-exchanged-zeolite-A nanocomposite. *Appl. Surf. Sci.* 346:543-553
[13] Brainard, G.C., W. Coyle, M. Ayers, J. Kemp, B. Warfield, J. Maida, C. Bowen, C. Bernecker, S.W. Lockley, J.P. Hanifin. 2013. Solid-state lighting for the International Space Station: Tests of visual performance and melatonin regulation. *Acta Astronautica* 92:21-28.
[14] (a) Mathew, S., P. Ganguly, S. Rhatigan, V. Kumaravel, C. Byrne, S. J. Hinder, J. Bartlett, M. Nolan, S. C. Pillai. 2018. Cu-Doped TiO2: Visible Light Assisted Photocatalytic Antimicrobial Activity. *Appl. Sci.* 8:2067. (b) Leyland, N.S., J. Podporska-Carroll, J. Browne, S.J. Hinder, B. Quilty, S.C. Pillai. 2016. Highly Efficient F, Cu doped TiO2 anti-bacterial visible light active photocatalytic coatings to combat hospital-acquired infections. *Sci. Rep.* 6:24770. [15] Heiken,

DOI: 10.13009/EUCASS2023-449

G.H., Vaniman, D.T. and French, B.M., 1991. *Lunar Sourcebook, a user's guide to the Moon*.[16] Gaier, J.R., 2020. The impact of dust on lunar surface equipment during Apollo. *The Impact of Lunar Dust on Human Exploration*, *2141*, p.5002.
[17] Gaier, J. R., Siamidis, J. and Larkin, E.M., 2010. Effect of simulated lunar dust on the properties of thermal control surfaces. *Journal of Spacecraft and Rockets*, **47**(1), pp.147-152.
[18] Gaier, J.R., 2020. The impact of dust on lunar surface equipment during Apollo. *The Impact of Lunar Dust on Human Exploration*, *2141*, p.5002.
[19] Suarez Kahan, A., Delacourt, B., Dias N, Holynska, M., Tighe, A. Characterisation of lunar and Martian dust simulants and impacts on thermo-optical properties of space materials. In: 15th ISMSE Conference 2022.
[20] Walton, O. R. 2007, Adhesion of Lunar Dust NASA/CR-2007-214685.
[21] Engelschiøn, V. S., Eriksson, S.R., Cowley, A., Fateri, M., Meurisse, A., Kueppers, U. and Sperl, M., 2020. EAC-1A: A novel large-volume lunar regolith simulant. *Scientific reports*, **10**(1), pp.1-9.
[22] Exolith Lab. LHS-1 Lunar Highlands Simulant Fact Sheet. 2021 [cited 2023 Jan 27]. Available from: https://exolithsimulants.com/products/lhs-1-lunar-highlands-simulant
[23] Gaier, J., 2010, August. Effect of Simulant Type on the Absorptance and Emittance of Dusted Thermal Control Surfaces in a Simulated Lunar Environment. In *40th International Conference on Environmental Systems* (p. 6111).