EXECUTIVE SUMMARY REPORT

Name	Company / Responsibility	Signature	Date
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1. Introduction

Moonwalkers Pete Conrad and Alan Bean had spent seven hours and 45 minutes performing EVA on the surface of the Moon. Upon return to the lunar lander, their suits had nearly failed with lunar dust having nibbled through several layers of Mylar. The longest EVA on the Moon has been conducted during Apollo 17 (~ 43 h). In total, all Apollo Astronauts' EVAs amounted to approximately 150 hours.

Today, ESA and its international partners are considering a return to the Moon with the intention to establish permanent infrastructures on the surface (not permanently crewed; but some of the materials will remain on the surface waiting for subsequent missions).

Figure 1 - ©NASA

The PExTex project was performed in view of this future activity: The objective of the project was to identify suit materials that can withstand lunar environment conditions over longer periods of time and to propose a test plan to the Agency to verify these materials or material combinations. Ideally not only "classical" space suit materials were identified in the frame of this project, but also smart materials or intelligent textiles that could lead to a future, European space suit design, or a contribution of European technologies as bricks of a novel lunar space suit.

Objectives of the PExTex Project

Future EVAs on the lunar surface will require improved suit concepts compared to previous systems such as the Apollo A7L Pressurized Suit Assembly or their Russian counterparts. Functionalities should include improved flexibility and the use of smarter materials that are able to heal defects or monitor their integrity.

These novel functionalities might be addressed by new materials developed recently which on the other hand have to be tested versus the harsh environment of space or planetary surfaces. It was the objective of PExTex to integrate these two aspects into one project and to deliver ESA an analysis of potential future EVA suit materials.

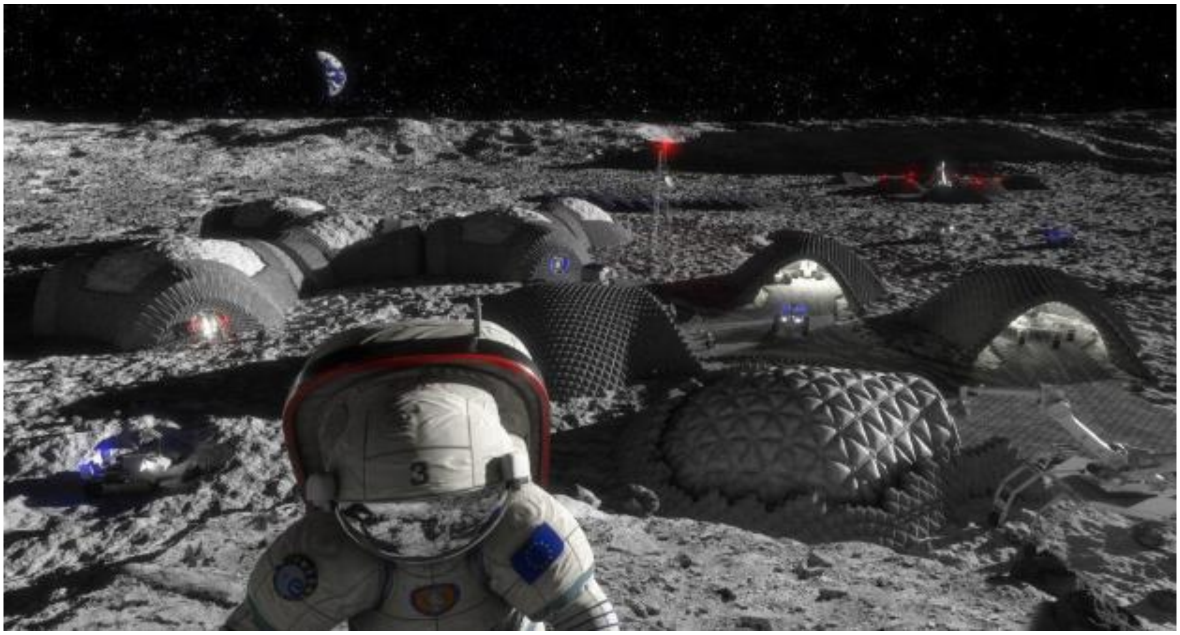


Figure 2: A MOONBASE concept by REGOLIGHT consortium (© LIQUIFER Systems Group)

The Objectives of PExTex were:

- to identify (novel) materials for future EVA space suit developments in Europe,
- to propose and conduct a testing strategy to verify that such materials meet the conditions of future missions to the lunar surface.
- propose avenues for further development

The work in PExTex was separated in the following four tasks:

Task 1. Requirements review and candidate materials selection
Task 2. Development of a testing plan including new testing platforms
Task 3. Manufacture and testing of samples
Task 4. Final recommendations

2. Requirements review

The purpose of this first part was:

- to provide a comprehensive literature survey on advanced materials, an electronic database that provides detailed information concerning candidate material requirements, their objective and added advantage of using smart and advanced materials for building a future EVA spacesuit.

- to identify candidate materials for the coming phase of tests to be performed in the frame of the project.

This part was structured in the following sections:

Section 1: Gives a Literature Review on space suit materials of previous generation space suits.

Section 2: Lists the requirements that potential candidate materials need to fulfill (or withstand) in order to be applicable to lunar surface operations. These requirements are based on environmental conditions (e.g. lunar vacuum and temperatures) and operational constraints (e.g. movement constraints). This chapter will also propose a potential way to cluster materials for the future study and the layering of those systems; their architectures.

Section 3: Targets novel space suit materials. The objective of this study is not to "rebuilt" past or existing suit systems but to submit novel solutions for future missions.

Section 4: Proposes candidate materials for the second phase of the study; the tests of the materials.

Figure 3 - ©NASA

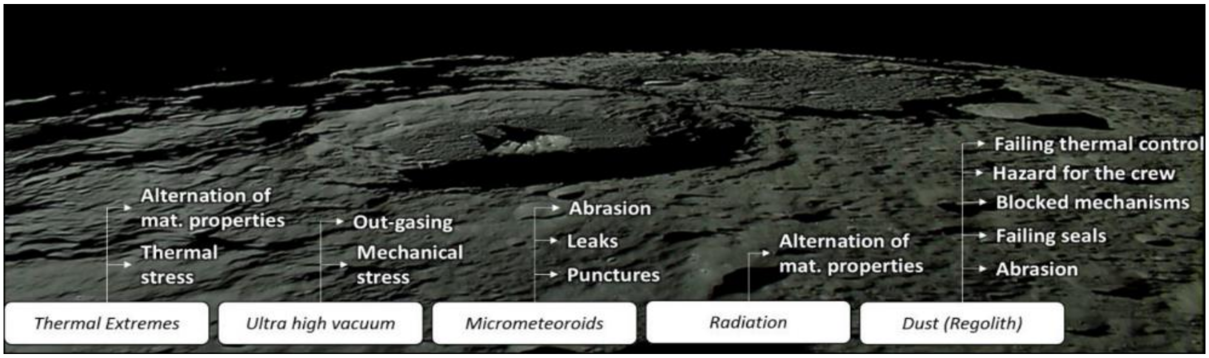
2.1. Updated requirements for future space suit materials

PExTex is targeting to consider the lessons learned from the past APOLLO missions while taking into account the expected EVA suit performance for future lunar missions.

The space suits of APOLLO were not designed to last over longer periods of time (some improvements were done in the update of the A7L to A7LB, but more related to operational requirements). Coming missions will go beyond the "plant a flag" and short duration sample activity.

According to the current strategy discussed by the agencies, as a first step, after an initial landing currently planned by NASA, the "Gateway", a space station in lunar orbit, shall provide access to lunar surface. In the far future, a sustainable human presence on the surface of the Moon (the Moon Village) could be aimed at. For neither approach a constant exchange of suits will not be efficient. Therefore, new suits must last over longer periods of time. Such mission requirements need to be taken into account in this project. Other related aspects are maintenance and repair, but also mobility and potential changed concepts for ingress and egress. The work within PExTex therefore started with an update of the requirements that were defined in the SoW and the proposal.

The red line within through-out those requirements are the environmental conditions that such suits will have to withstand over longer periods of time. The graphic below (from the proposal) states some of them which were reflected in the list of the Statement of Work. Others are related to operational constraints (e.g. such as bending capability, cleaning capability). The following chapter lists the requirements of importance for PExTex.



2.1.1. Requirements list

[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 requirements of the SoW were completed by Additional Requirements proposed by the consortium:

[A-RQ1] Demonstrated reparability over the expected service lifetime.

[A-RQ2] Demonstrated possibility to monitor the material integrity status (level of damage or remaining functionality) during the use of the EVA suit. (Finally not performed, due to low TRL level of materials)

[A-RQ3] High velocity impact tests (MMOD). The requirement is mentioned in the SoW. It is proposed a 7km/s impact with projectiles of 0.5 to 1.5mm (0° and 45° angles). This requirement can be combined with A-RQ2 (monitoring). (Finally not performed, due to cost over project budget)

[A-RQ4] Punctuation risk evaluation (against rocks, tools)

[A-RQ5] Capability to clean the material from (lunar) dust (Finally not performed, due to low TRL level of materials)

[A-RQ6] Test of the biological growth potential (for inner layers)

3. Candidate materials selection

This part was structured in the following sections:

Section 1: Introduces the methodology used by the consortium for selecting the candidate materials for the PExTex testing campaign and provides the reasoning behind the recommended material from the consortium partners.

Section 2: Discuss the rationale behind the selected pre-candidate materials for each of the functional layer going forward to the testing campaign.

Section 3: Presents different smart materials and their functionality identified so far by the consortium for a future spacesuit.

3.1. Method selection

The consortium along with ESA discussed on various methods in preselecting the candidate materials for the testing camping and as a result of the discussion, it was agreed the material will selected via "recommendation and comparative analysis" method.

As first step of the selection process each consortium partner presented their top 3-5 materials for each functional layer from the materials identified. Following the recommendation from each partner, a telecon was organized to present, compare and discuss the merit and demerits of each recommended materials from the partner in order to select the top 3-5 materials for each functional layer.

The top-ranking material from each functional layers were assigned as top 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 depending on their availability.

In addition to the comparative analysis, quantity 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 (weightage for layer requirement parameters x merit for materials properties towards the parameter) was performed for each analyzed material, assessing the materials functions such as resistance against abrasion, temperature, UV and radiation degradation etc. for each layer.

The below figure shows the top four choice PExTex candidate material stack.

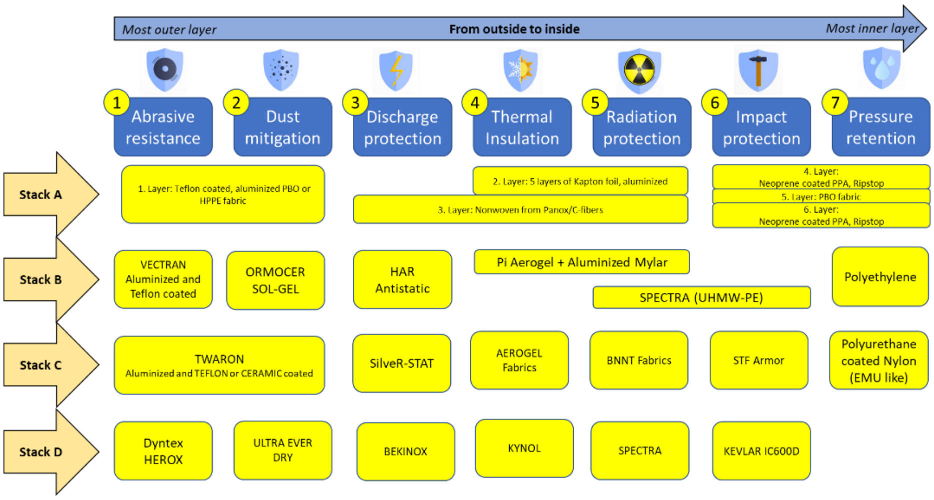


Figure 4 - PExTex precandidate materials

4. Materials characterization and test plan

This part was intended to present the tests platforms to be employed to analyze the criteria specified in the requirements list. A major fraction of the tests to be conducted using facilities hosted by the consortium. The remaining tests were either performed at external facilities, managed by third parties or in custom-built setups to bridge the gap between existing and required test capabilities. Those were delivered to ESA for any future tests. The test platforms are selected/ designed to meet requirements (RQ1 to RQ14) and additional requirements (A-RQ1 to A-RQ6) which established from first part.

Out of the 14 requirements, 9 requirements (RQ5 to 9 and RQ 11 to 14), are done using a different combination of 16 in-house DITF facilities.

RQ2 will be performed in two stages by OeWF: 1) First by GEANT4 simulation and 1) Second using Particle Accelerator at MedAustron

In order to fulfill the remaining requirements (RQ 1, 3, 4 & 10) a dedicated test platform will be designed and built by COMEX.

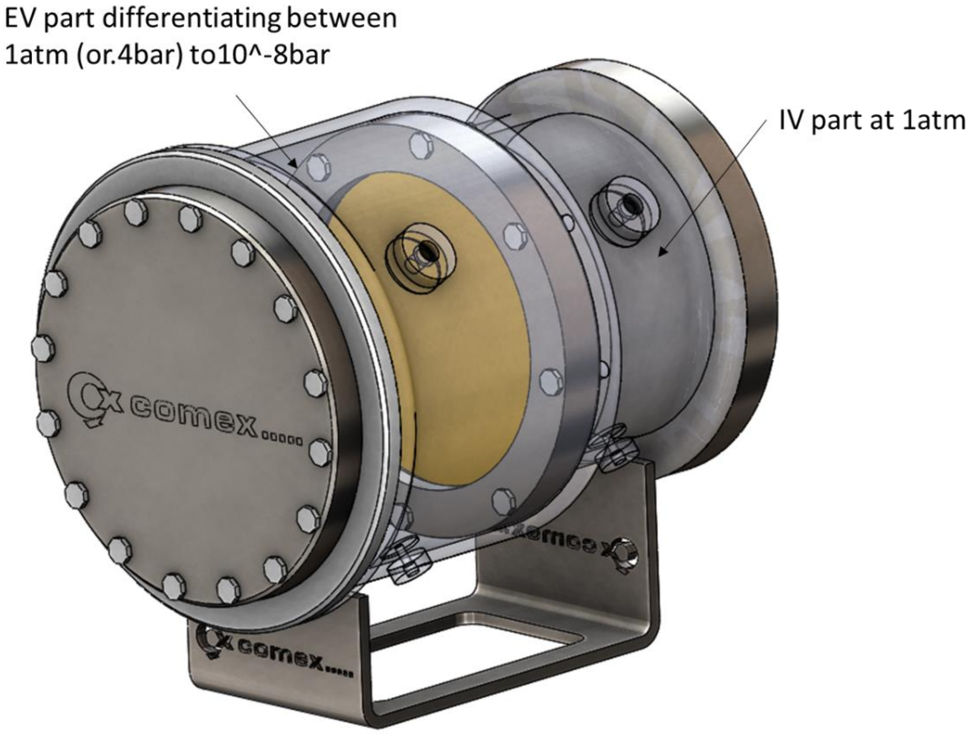


Figure 5 - Pressure Vacuum cycling schematics. ©COMEX SAS

The order and schedule of all tests to be conducted, is specified in the Test Plan. This plan aims at starting the campaign with basic tests, for a screening of all materials and the potential for early elimination of unsuitable candidates. More complex tests are foreseen for later stages of the project, possibly only to be performed on a reduced set of textiles, which excelled in the first tests. In preparation for particle accelerator tests evaluating RQ2 (compatibility with the lunar ionizing radiation environment), numerical simulations are performed using the software GATE. These simulations and their results are described in here as well.

This part covers the work contained in Work Package 2 (see **Erreur ! Source du renvoi introuvable.**). The objective of WP2 is the development of a test plan and the design of test platforms, filling the gaps in existing testing facilities. Also included in that work package is the simulation of the textiles' response to the lunar radiation environment using GATE/GEANT4.

This part is structured in the following sections:

Section 1: Gives an overview of the workflow for the test plan development and features the resulting plan itself.

Section 2: Regolith Simulant trade-off" This chapter presents the trade-off concerning the choice of lunar regolith simulants to be used for testing.

Section 3: Describes the tests to be conducted and the test platforms used.

Section 4: identifies the test strategy and test platforms identified to fulfill additional requirements.

Section 5: The interaction of the fabrics with the lunar ionizing radiation environment is simulated using the software GATE (based on GEANT4). This chapter specifies the setup used for the simulation and gives the obtained results.

Section 6: Test sample materials: Provides the final list of materials that will be tested during the PExTex test campaign.

4.1. Test Sample Materials

Not all sample materials can be procured by the consortium members within the project scope (mostly budget wise) for the required sample size needed to perform all the above-mentioned tests.

ORMOCER SOL-GEL – restricted by company IP rights. Consortium did not manage to obtain samples under NDA.

HAR Antistatic, Pi-Aerogel and Aerogel fabrics: Are discontinued for test campaign, as they cost around 60k euro per sq.m.

BNNT fabric: High cost as the product is still at R&D phase requiring considerable amount of manhour to produce a sample product.

STF Armor: Discontinued from further investigation as it requires export regulation from US Army.

After filtering the sample materials for test campaign, they consortium ended up with two stacks for all layer material with a possibility to form third stack and four material option for the first layer.

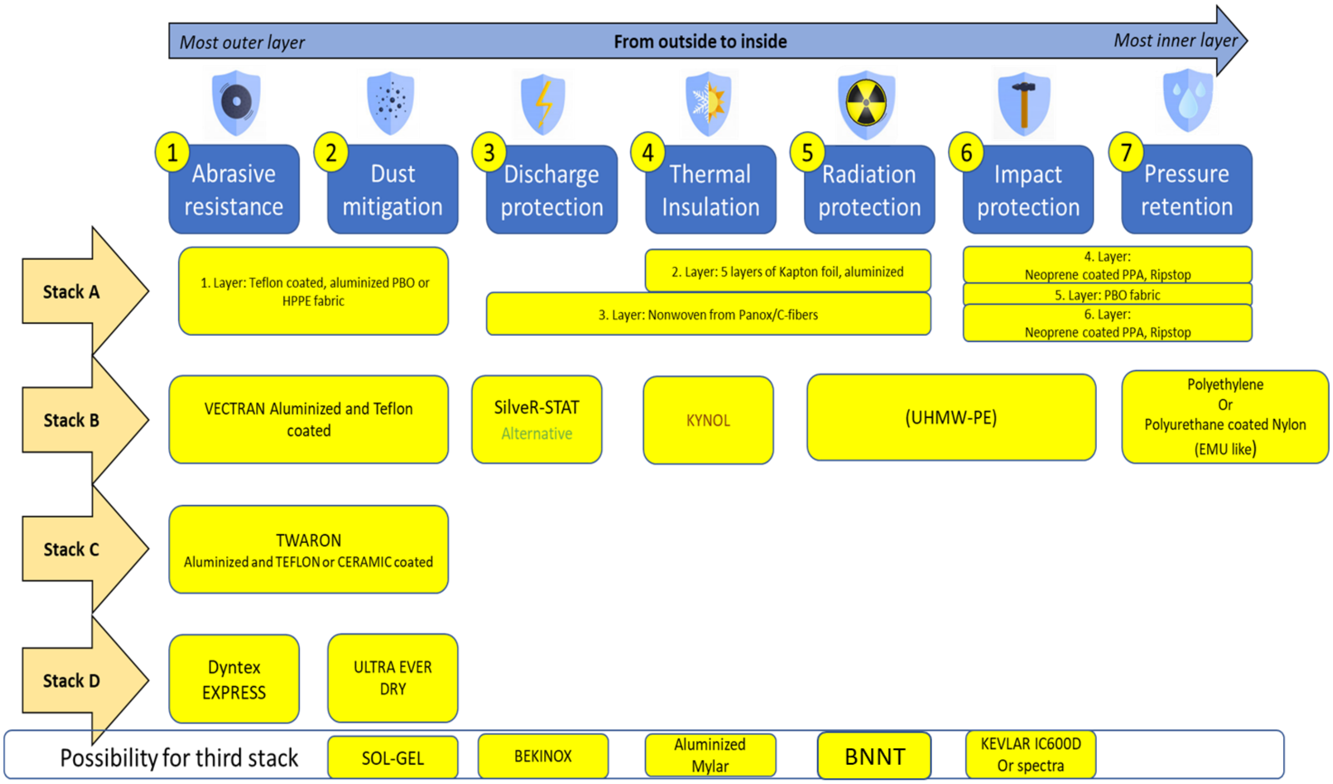


Figure 6 – Test campaign final sample materials table

5. Test results

The purpose of this part was to present the results of all the tests carried out in accordance with the protocol and the test facilities described in previous part.

The test results presented in this part aimed to establish a solid database to identify two of the most promising materials (and eliminate those that would be unsuitable) against the criteria specified at the beginning.

This part described the measurements performed with the adequate instruments as proposed in the previous part and a comparison of the results to reference data from literature or from reference samples testing, but also a comparison between the tested materials.

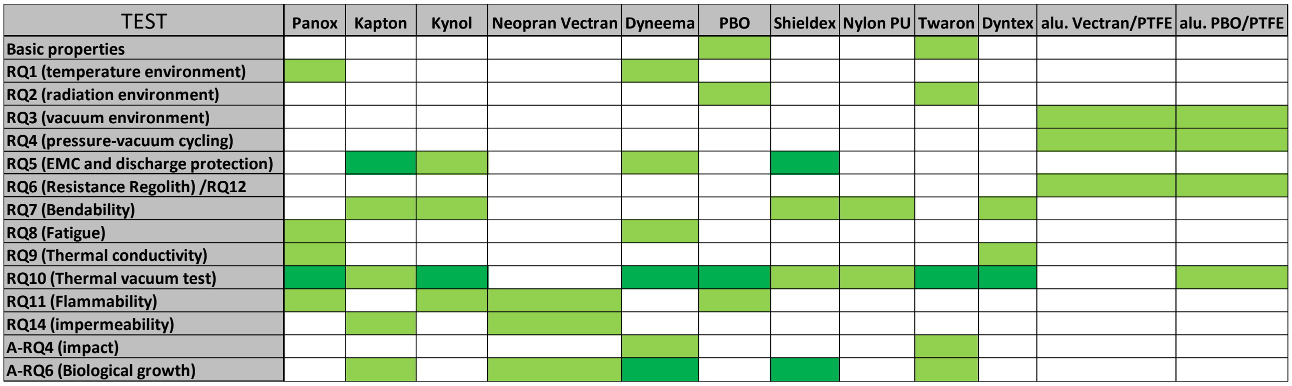
The objective was to obtain sufficient data to identify in the next part the two highest performing candidate materials

This part was structured in the following sections:

- Section 1: Gives an overview of the reference samples basic properties and of the sample's preparation.
- Section 2: Presentation of test results on samples, organized by requirement.

6. Tests Conclusions

6.1. Selected Materials by the consortium for a future spacesuit



TEST	Panox	Kapton	Kynol	Neopran Vectran	Dyneema	PBO	Shieldex	Nylon PU	Twaron	Dyntex	alu. Vectran/PTFE	alu. PBO/PTFE
Basic properties						🟩			🟩			
RQ1 (temperature environment)	🟩				🟩							
RQ2 (radiation environment)						🟩			🟩			
RQ3 (vacuum environment)											🟩	🟩
RQ4 (pressure-vacuum cycling)											🟩	🟩
RQ5 (EMC and discharge protection)		■	🟩		🟩		■					
RQ6 (Resistance Regolith) /RQ12											🟩	🟩
RQ7 (Bendability)		🟩	🟩				🟩	🟩		🟩		
RQ8 (Fatigue)	🟩				🟩							
RQ9 (Thermal conductivity)	🟩									🟩		
RQ10 (Thermal vacuum test)	■	🟩	■		■	■	🟩	🟩	■	■		🟩
RQ11 (Flammability)	🟩		🟩	🟩		🟩						
RQ14 (impermeability)		🟩		🟩								
A-RQ4 (impact)					🟩				🟩			
A-RQ6 (Biological growth)		🟩		🟩	■		■		🟩			

Figure 7 - Material selection

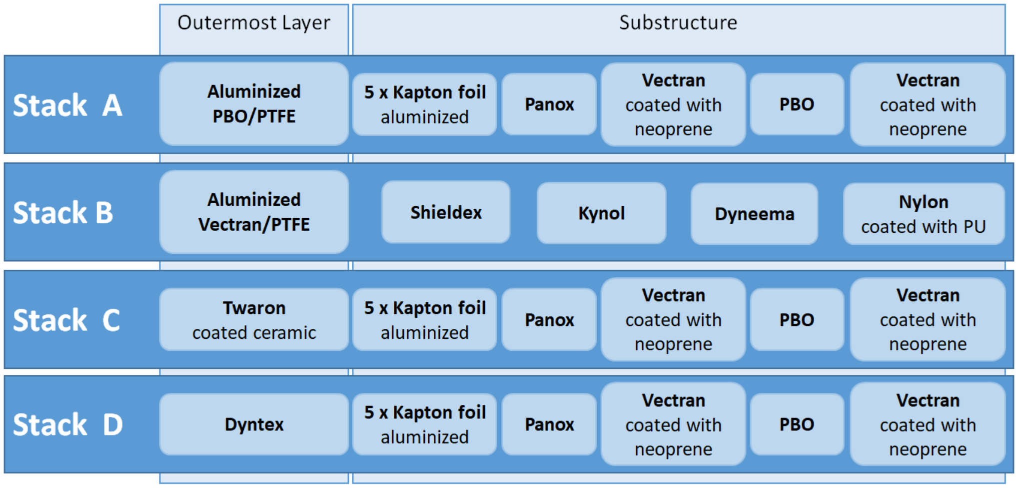
Depending on the properties targeted, we can select the best materials in consequences to create a stack. Note: Dark green is used when the material is not the best for the requirement but has an interesting property.

Panox, Kapton, Dyneema and Twaron fit with the most requirements.

6.2. The consortium analysis-recommendations

From previous figure, it is clear that no combination of any two materials can meet all the requirements. Hence stacking more materials together is expected to provide a more comprehensive coverage over all the requirements.

Several stacks are proposed based on the results of individual material test performance and expected compatibility between materials. This part aim to select the best stack to fit with requirements.



	Outermost Layer	Substructure				
Stack A	**Aluminized PBO/PTFE**	**5 x Kapton foil** aluminized	**Panox**	**Vectran** coated with neoprene	**PBO**	**Vectran** coated with neoprene
Stack B	**Aluminized Vectran/PTFE**	**Shieldex**	**Kynol**	**Dyneema**	**Nylon** coated with PU	
Stack C	**Twaron** coated ceramic	**5 x Kapton foil** aluminized	**Panox**	**Vectran** coated with neoprene	**PBO**	**Vectran** coated with neoprene
Stack D	**Dyntex**	**5 x Kapton foil** aluminized	**Panox**	**Vectran** coated with neoprene	**PBO**	**Vectran** coated with neoprene

Figure 8 - Stacks composition

6.3. Stack conclusion

We analyzed the results of tests performed on the different stacks. However, it should be noted that it was not possible to perform each test on all the stacks.

TEST	Stack A	Stack B	Stack C	Stack D
Basic properties (thickness)		🟩		▨
RQ2 (radiation environment)	🟩		▨	
RQ6 (Resistance Regolith)		🟩	🟩	
RQ9 (Thermal conductivity)	🟩			▨
RQ11 (Flammability)	🟩		🟩	
RQ13 (storage)			🟩	
RQ14 (impermeability)	🟩	Not tested	🟩	🟩
A-RQ4 (impact)		🟩	Not tested	Not tested

Figure 9 - Stack selection

Stack C composed by Twaron, Kapton, Panox, Neopren Vectran and PBO seems to be the most promising stack. Stack A (Aluminized PBO/PTFE, Kapton, Panox, Neopren Vectran and PBO) is also a promising candidate which is not surprising since the only difference between the two stacks is the outermost layer (Aluminized PBO/PTFE for stack A and Twaron for the C).

In stack C, we find Panox, Kapton and Twaron which are among the best materials studied individually, which could mean that the properties of each material do not necessarily deteriorate with stacking.

7. Proposed avenues for further development

7.1. Materials modifications

We have seen that some materials fit well with some requirements but not all. Maybe fabricants can improve some properties of these materials to fit with more requirements. To do so, space industry should for example take contact with industrials to explain their needs and ideas to their materials.
An update of the state of the art on the materials that are made today could be envisaged.

7.2. Criteria modifications

It would be interesting to define the different criteria of acceptation characteristics per characteristics. Indeed, there are not target values to validate a sample about each requirement. For example, to consider a sample as good performer in terms of max tensile strength, the comparison between selected materials is the focus. We additionally recommend determining a target value to reach. It is important to know if better materials are needed or if these materials are sufficient.

7.3. Tests recommendations

For some of the tests performed, we proposed improvement or correction solutions, on the test bench, or on the material conception itself. The needed further tests for another project could be remake or make differently in order to have additional interesting information.

7.4. Material joining method

There are various joining techniques such as welding, gluing and sewing. But which technique can be used depends on the one hand on the material and certainly also on the later application. An important note on the later joining technique: convex and concave surfaces such as sleeves can only be sewn. Gluing or welding is not possible here. Conclusion: We can only try to treat the future stacks with suitable joining techniques. Afterwards, the result of the joining must be evaluated by suitable tests and it may be that different joining techniques are used for specific use of material stacks for specific areas on a potential suit level application. The DITF can support here, depending on the requirements, with trials and tests. Details would have to be clarified in a potential follow-on activity.

7.5. Advanced test methods for long term technology maturation

Two approaches are possible for future tests and each one has advantages and disadvantages:

- A stacked material needs to be manufactured into multiple, consistent stacked specimens. A stack is certainly always easier to test than an ergonomic demonstrator, which is certainly much larger. This is because the mechanical tests are small area tests although such tests are only 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. The DITF can support here, depending on the requirements, with trials and tests for different stacking based test methods.
- 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. The OeWF can support here, depending on the requirements, with trials and tests. Use of an ergonomic prototype does not demonstrate the functionality of the EVA suit prototype in relevant space environments. Such a prototype would require a much higher level of manufacturing maturity of the stacked material options, which is likely many years in the future from today.

Further development of test methods would require input from EVA expert community, including NASA and ESA astronauts and other end-users of such products, to enable credible test requirements and test parameters.