Materials Research Proceedings 69 (2026) 1272-1277 https://doi.org/10.21741/9781644904251-220

Flexible Poly(Vinyl Alcohol) Gels for Radiation Shielding in Next-Generation Spacesuits

Lucia LAMBERTINI[1,a], Maria Gabriella SANTONICOLA[2,b] and Susanna LAURENZI[1,c*]

[1]Department of Astronautical Electrical and Energy Engineering, Sapienza University of Rome, Via Salaria 851-881, 00138 Rome, Italy

[2]Department of Chemical Engineering Materials Environment, Sapienza University of Rome, Via del Castro Laurenziano 7, 00161 Rome, Italy

[a]lucia.lambertini@uniroma1.it, [b]mariagabriella.santonicola@uniroma1.it, [c]susanna.laurenzi@uniroma1.it

Keywords: Spacesuit Radiation Shielding, Poly(Vinyl Alcohol) Gels, Shielding Materials

Abstract. Protecting astronauts from radiation during space missions is a critical challenge. In the current context, where space agencies are working to establish permanent bases on the lunar surface, radiation shielding becomes an even more crucial issue. Indeed, as missions venture farther from Earth, crews lose the natural shielding provided by the Earth's magnetic field and atmosphere, resulting in high exposure to ionizing radiation**.** This study explores the integration of poly(vinyl alcohol) (PVA) gels as flexible intermediate layers in lunar spacesuits to enhance radiation shielding on lunar surface. Experimental tests demonstrated that PVA gels possess similar density and thermal conductivity to nylon but greater flexibility, denoted by their high strain at failure during tensile tests. Numerical simulations highlights that the gels' inclusion in spacesuits highly reduces total effective doses equivalent due to Solar Particle Events.

Introduction

Spacesuits have been designed primarily to ensure protection against extreme temperatures, micrometeoroids, and orbital debris [1, 2]. They consist of multiple specialized layers, each engineered for a specific function. The outermost layer, made of orthofabric composites, acts as a shield against micrometeoroids and space debris. Beneath this layer, an insulation system composed of aluminized mylar and dacron fabric provides thermal regulation. Finally, the innermost layers consist of the Pressure Bladder Garment (PBG), made of urethane-coated nylon, and the Liquid Cooling and Ventilation Garment (LCVG), made of nylon with embedded water tubes, designed to maintain a stable internal temperature.

Currently, polymer-based materials have been selected as promising solutions between innovative shielding techniques, due to their lightweight and excellent mechanical, thermal, and electrical properties. Their shielding performance has been further improved by incorporating specific fillers, including boron nitride, polyurethane, graphene, and carbon nanotubes [3 - 8]. However, their inherent rigidity and limited flexibility make them unsuitable for wearable systems such as spacesuits employed during Extravehicular Activities (EVAs). This limitation can be addressed by integrating ductile, hydrogen-rich, and flexible materials with high radiation stopping power directly into the suit's structure. As demonstrated by the PErsonalized Robotics as SErvice Oriented applications (PERSEO) project, hydrogen-rich materials, such as liquid water, are particularly effective in attenuating Galactic Cosmic Radiation (GCR) and Solar Particle Events (SPEs) [9]. However, the use of liquids in microgravity environments determines significant challenges, including increased system volume and complex fluid management. To overcome

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 license. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under license by Materials Research Forum LLC.

Materials Research Proceedings 69 (2026) 1272-1277 https://doi.org/10.21741/9781644904251-220

these constraints, gels have been proposed as innovative solution to enhance radiation protection inside spacesuits for missions beyond LEO [10].

This study examines the feasibility of enhancing radiation shielding for next-generation spacesuits during EVAs on the Moon without compromising their ergonomics by proposing the integration of poly(vinyl alcohol) (PVA) gels as an intermediate layer between the PBG and the LCVG of the spacesuit. Experimental tests were conducted to compare the physical properties of PVA-based gels with those of nylon, which is the primary material used in both the PBG and LCVG systems. The results show comparable density and thermal conductivity between the two materials. Moreover, the gels demonstrated higher flexibility, as evidenced by their local strain under tensile stress. Numerical simulations using the On-Line Tool for the Assessment of Radiation in Space (OLTARIS) confirmed the shielding potential of the gels. Indeed, integrating gel layers within the spacesuit resulted in reductions in both total effective dose equivalent and average organ dose equivalent.

Fabrication of PVA/BA gels

The following materials were purchased from Sigma Aldrich and used as received: PVA (Mw = 30,000 Da, ρ = 1.3 g/cm³, product no. 8438680100), BA (product no. B0394), and ethanol (ρ = 0.790 g/cm³ at 20 °C, product no. 02860-1L). Ultrapure water (resistivity 18.2 MΩ·cm) was produced using a Direct-Q3 UV purification system (Millipore, Molsheim, France).

PVA/BA gels were prepared via chemical crosslinking following a previously reported protocol [10]. Briefly, a 30 wt% aqueous PVA solution was prepared by magnetic stirring at 80 °C for 1 h. Separately, a 10 wt/vol% BA stock solution was prepared in ethanol under identical conditions. Crosslinking was initiated by adding the BA solution to the PVA solution to achieve a final BA concentration of 4 wt/vol%. The resulting mixture was poured into glass molds and conditioned in a climate chamber at 30 °C and 50% relative humidity for 72 h.

Comparison of Nylon and gel properties

The experimental results shown in Table 1 suggests that the PVA/BA gels possess a density (1.25 g/cm³) and thermal conductivity (0.27 W/m·K) comparable to those of Nylon 6 used in aerospace applications. However, the gels exhibit higher ductility compared to 9–25% for nylon, failing at about 65 % strain during tensile tests. Although the Young's modulus (12.75 MPa) is much lower than that of nylon, the gels demonstrate excellent flexibility due to their high water content (≈ 55 %), which also suggests potential benefits for radiation attenuation.

Table1: Comparison of physical and mechanical properties of PVA/BA gels and nylon.

Samples	PVA/BA gels	Nylon	Ref.
Density [g/cm³]	1.25*	1.14	[11]
Thermal conductivity [W/(mK)]	0.27*	0.10 ÷ 0.30	[12]
Strain at maximum elongation [%]	64.71*	9 ÷ 25	[13]
Young modulus [MPa]	12.75 ± 0.86	2450 ÷ 3100	[13]

* Standard deviation < 0.01.

Numerical simulations

Radiation exposure during lunar extravehicular activities (EVAs) was analyzed using NASA's OLTARIS platform [3], which employs the deterministic HZETRN transport code to solve one- or three-dimensional Boltzmann equations. Two primary lunar radiation environments were considered: Galactic Cosmic Radiation (GCR), including both free-space and albedo-reflected

Materials Research Proceedings 69 (2026) 1272-1277 https://doi.org/10.21741/9781644904251-220

components, and Solar Particle Events (SPEs), in which the external environment is negligible. For this study, GCRs were modeled during solar minimum, corresponding to maximum ionization, using a solar modulation parameter of 475 MV and the Badhwar–O'Neill (BON) 2020 model. SPEs were represented using the Tylka Bands Fitting for the October 1989 event. Material cross-sections were calculated with OLTARIS based on the chemical compositions and densities reported in Table 2.

Table 2: Input data used for defining materials on the OLTARIS tool.

Materials	Density [g/cm^3]	Elemental mass percentages []
Aluminized Mylar	1.40	0.624 C, 0.042 H, 0.332 O, 0.002 Al
Dacron	1.38	0.625 C, 0.042 H, 0.333 O
Neoprene coated Nylon	1.05	0.589 C, 0.077 H, 0.205 Cl, 0.060 N, 0.069 O
Nylon	1.14	0.637 C, 0.098 H, 0.124 H, 0.141 O
Orthofabric	1.80	0.470 C, 0.021 H, 0.380 F, 0.058 N, 0.071 O
Polycarbonate	1.20	0.706 C, 0.059 H, 0.235 O
S-glass composite	1.29	0.478 C, 0.046 H, 0.304 O, 0.022 N, 0.150 Si
Urethane coated Nylon	1.13	0.523 C, 0.077 H, 0.246 O, 0.154 N
PVA/BA gel	1.25	0.2147 C, 0.0999 H, 0.0018 ^{10}B, 0.0073 ^{11}B, 0.6763 O

Geometrical model

Simulations investigated the potential integration of gels within spacesuit structures modeled using NASA's Z2 CAD design [14] to assess possible enhancements in radiation protection during extravehicular activities (EVAs). The spacesuit model was oriented normal to the lunar surface and coupled with the MAX and FAX phantoms to assess human exposure. A MATLAB-based ray-tracing algorithm generated 512 rays from a central target and divided the CAD geometry into five anatomical regions aligned with the phantoms. For each region, material composition and thickness followed the Z2 configuration, with optional PVA/BA gel layers (0.5 – 3 cm) added between nylon and urethane-coated nylon. The resulting material profiles were compiled into an XML file compatible with OLTARIS for radiation transport simulations.

Results and discussion

Fig. 1 illustrates simulations in which a PVA/BA gel layer of varying thickness (0 – 3 cm) was incorporated into conventional spacesuit configurations. Under GCR conditions (Fig. 1a), initial Total Effective Dose Equivalents (TEDEs) were nearly identical for both sexes (288.1 mSv for the male and 286.1 mSv for the female phantom). At a 3 cm gel thickness, TEDEs decreased to approximately 260 mSv, corresponding to modest reductions of 9.7 % and 9.5 %, respectively. This limited improvement underscores the weak shielding capability of gels against highly penetrating GCR particles. In contrast, the SPE scenario (Fig. 1b) demonstrates a pronounced shielding effect. Without gel, TEDEs reach hazardous levels of 1313 mSv (male) and 1211 mSv (female). Introducing a 1 cm gel layer reduces these values by nearly 50 % (49.6 % and 47.1 %), while a 3 cm layer achieves dose reductions exceeding 60 % in both phantoms. The narrowing difference between male and female exposures with increasing gel thickness further indicates that effective shielding minimizes sex-based dose disparities. Overall, these results confirm that PVA/BA gels offer limited protection against GCR but are highly effective in mitigating SPE radiation, providing substantial reductions in TEDEs.

Materials Research Proceedings 69 (2026) 1272-1277 https://doi.org/10.21741/9781644904251-220

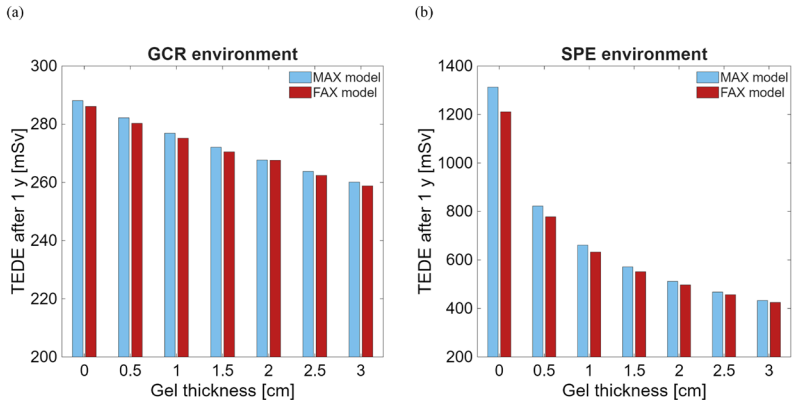


Fig.1: Total Effective Doses Equivalent (TEDEs) after 1 y for MAX (male) and FAX (female) models as a function of gel layer thickness (0 – 3 cm) under (a) Galactic Cosmic radiation (GCR) and (b) Solar Particle Event (SPE) environments.

Fig. 2 and 3 illustrate a comparative analysis of the average organ doses equivalent in male and female phantoms during a 1-year mission. Under GCR conditions (Fig. 2), the skin receives the highest doses (~ 500 mSv in FAX and ~ 450 mSv in MAX), followed by the lens and salivary glands. Increasing the protective gel layer thickness yields only minor reductions, highlighting the limited effectiveness against GCR particles. In contrast, during SPE (Fig. 3), the high skin doses (> 10^5 mSv) decrease sharply with increasing gel thickness, confirming the attenuation capability of gels against solar protons.

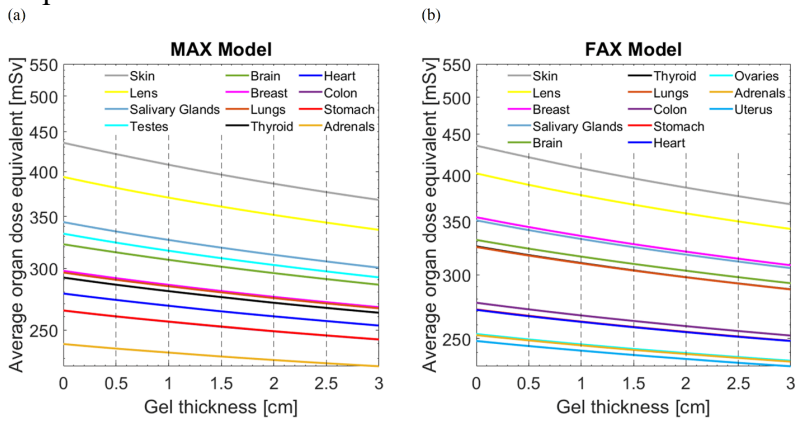


Fig. 2: Average organ dose equivalent as a function of gel thickness integrated into the spacesuit under Galactic Cosmic Radiation (GCR) exposure, for MAX (a) and FAX (b) phantoms.

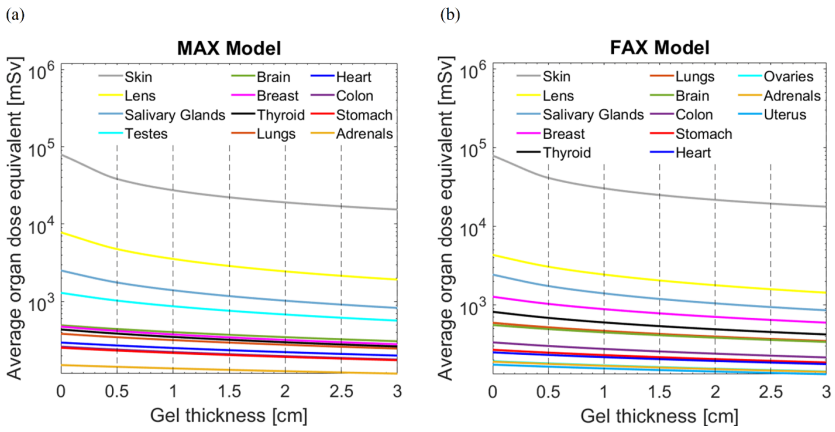


Fig. 3: Average organ dose equivalent as a function of gel thickness integrated into the spacesuit under Solar Particle Events (SPE) exposure, for MAX (a) and FAX (b) phantoms.

Conclusions

This study demonstrates that PVA/BA gels are promising materials for improving personal radiation protection in astronaut spacesuits. Experimental characterization showed that the gels have physical properties comparable to nylon, including similar density and thermal conductivity, but with much higher flexibility (Young's modulus = 12.75 MPa; strain ≈ 65 %). Numerical simulations using OLTARIS tool confirmed the gels' radiation-shielding potential when positioned between the PBG and LCVG. A 1 cm gel layer was identified as the optimal configuration, balancing protection and added mass (~ 21 %). Under GCR exposure, dose reductions were modest (≈ 4 %), while under SPE conditions, reductions reached nearly 50 % for both male and female phantoms.

Acknowledgements

This study was carried out within the Space It Up project funded by the Italian Space Agency, ASI, and the Ministry of University and Research, MUR, under contract n. 2024-5-E.0 - CUP n. I53D24000060005.

References

[1] C. Paige, D. Newman, S. J. H. Lombardo, An Integrated Innovative 3D Radiation Protection Fabric for Advanced Spacesuits and Systems, 2020 IEEE Aerospace Conference, Big Sky, MT, USA, Pages 1-11, IEEE, 2020. https://doi.org/10.1109/AERO47225.2020.9172794

[2] J. M. Waller, K. Rojdev, K. Shariff, D. A. Litteken, R. A. Hagen, A. J. Ross, Simulated Galactic Cosmic Ray and Solar Particle Event Radiation Effects on Inflatable Habitat, Composite Habitat, Space Suit and Space Hatch Cover Materials, 2020.

[3] E. Toto, L. Lambertini, S. Laurenzi, M. G. Santonicola, Recent Advances and Challenges in Polymer-Based Materials for Space Radiation Shielding, Polymers, Vol. 16, 382, 2024. https://doi.org/10.3390/polym16030382

[4] W. Zhang, Y. Feng, J. T. Althakafy, Y. Liu, H. M. Abo-Dief, M. Huang, L. Zhou, F. Su, C. Liu, C. Shen, Ultrahigh molecular weight polyethylene fiber/boron nitride composites with high neutron shielding efficiency and mechanical performance, Advanced Composites and Hybrid Materials, Vol. 5, Pages 2012-2020, 2022. https://doi.org/10.1007/s42114-022-00539-7

[5] F. Zaccardi, E. Toto, S. Rastogi, V. La Saponara, M. G. Santonicola, S. Laurenzi, Impact of proton irradiation on medium density polyethylene/carbon nanocomposites for space shielding applications, Nanomaterials, Vol. 13, Article 1288, 2023. https://doi.org/10.3390/nano13071288

[6] Y. Shang, G. Yang, F. Su, Y. Feng, Y. Ji, D. Liu, R. Yin, C. Liu, C. Shen, Multilayer polyethylene/hexagonal boron nitride composites showing high neutron shielding efficiency and thermal conductivity, Composites Communications, Vol. 19, Pages 147-153, 2020. https://doi.org/10.1016/j.coco.2020.03.007

[7] P. R. De Oliveira, A. K. Sukumaran, L. Benedetti, D. John, K. Stephens, S.-H. Chu, C. Park, A. Agarwal, Novel polyimide-hexagonal boron nitride nanocomposites for synergistic improvement in tribological and radiation shielding properties, Tribology International, Vol. 189, Article 108936, 2023. https://doi.org/10.1016/j.triboint.2023.108936

[8] V. Pavlenko, N. Cherkashina, R. Yastrebinsky, Synthesis and radiation shielding properties of polyimide/Bi_2O_3 composites, Heliyon, Vol. 5, Article e02890, 2019. https://doi.org/10.1016/j.heliyon.2019.e01703

[9] G. Baiocco, M. Giraudo, L. Bocchini, S. Barbieri, I. Locantore, E. Brussolo, D. Giacosa, L. Meucci, S. Steffenino, A. Ballario, The PERSEO Experience: A Water-Filled Garment Prototype for Personal Radiation Protection of Astronauts Successfully Tested on Board the International Space Station, Aerotecnica Missili & Spazio, Vol. 99, Pages 111-114, 2020. https://doi.org/10.1007/s42496-020-00048-0

[10] L. Lambertini, G. Coccarelli, E. Toto, M. G. Santonicola, S. Laurenzi, Poly(vinyl alcohol) gels cross-linked by boric acid for radiation protection of astronauts, Acta Astronautica, Vol. 221, Pages 142-154, 2024. https://doi.org/10.1016/j.actaastro.2024.05.020

[11] H. Mahfuz, V. Rangari, M. Hasan, S. Jeelani, W. Wright, S. Deteresa, Enhancement of strength and stiffness of Nylon 6 filaments through carbon nanotubes reinforcement, Appl. Phys. Lett. 88 (2006) 083119-083119. https://doi.org/10.1063/1.2179132

[12] D. Murphy, B. Tucker, D. Sykes, Advanced Liquid Cooling and Ventilation Garment Using Thermally Conductive Tubing, in: 49th International Conference on Environmental Systems, 2019.

[13] DuPont Performance Polymers, DuPont™ Zytel® 101L BKB080 Nylon Resin: Technical Data Sheet, E.I. du Pont de Nemours and Company, Wilmington, Delaware, USA, 2015. https://www.dupont.com/products-and-services/plastics-polymers-resins/thermoplastics.html.

[14] Information on https://nasa3d.arc.nasa.gov/detail/nmss-z2.