European Innovation Council



JUMP INTO SPACE

Deliverable 2.1



Deliverable Title	Project Baseline
Work Package	2
Lead participant	UNITOV
Туре	Report
Dissemination Level	PU
Due Date	31 December 2024

Version	Date	Author	Partner	e-mail	Comments
1.0	11/12/24	P. Tockhorn, C. Becker	HZB		First draft
1.1	17/12/24	T. Nuns, S. Duzellier, D. Lévêque	ONERA	thierry.nuns@onera.fr	Part 3 + Annex I
1.2	18/12/24	K. Wojciechowski	SAULE		Up-scaling and minimodules
2.0	20/12/24	F. De Rossi	UNITOV	francesca.de.rossi@uniroma2.it	Editing, second draft
2.1	23/12/24	ALL	ALL		Proof-reading, comments, editing
3.0	27/12/24	F. Brunetti	UNITOV	francesca.brunetti@uniroma2.it	Final version and submission



JUMP INTO SPACE	Deliverable 2.1
Table of Contents	
List of Abbreviations	3
1. Deliverable abstract	4
2. Design of the Tandem Perovskite Solar Cells and Modules	4
2.1 State of the art	4
2.2 Substrates	7
 2.3 Materials for the Perovskite Solar Cells and Modules 2.3.1 Transparent Conductive Oxides (TCO) 2.3.2 Perovskite sub-cell configuration 2.3.3 Encapsulants 	7 7 7 9
2.4 Synthesis routes for new materials	9
2.5 Up-scaling 2.5.1 Minimodules	9 9
2.6 Conclusion	10
3. Operational Conditions	11
3.1 Test conditions to simulate operation in space3.1.2 State-of-the-art3.1.2 Test conditions for JUMP INTO SPACE	12 12 13
Annex I	13
 Space radiation: origin of charged particle radiation 1.1 Near Earth space environment 1.2 Interaction with the Earth magnetic field 1.3 Radiation belts 	14 14 14 15
2 Evaluation of the charged particle environment for LEO orbits	15
3 Electromagnetic radiation	17
4 Atomic Oxygen (AO)	18
5 Temperature	21
6 Vacuum and air-to-vacuum transitions	23
7 Summary of space environment parameters from the materials degradation standpoint	23



List of Abbreviations

PSC	perovskite solar cells
ALD	atomic layer deposition
AO	atomic oxygen
CTL	charge transport layer
CME	coronal magnetic ejection
ETL	electron transport layer
ESA	European Space Agency
GCR	galactic cosmic ray
HTL	hole transport layer
ITO	indium tin oxide
ISS	international space station
J _{sc}	short-circuit current density
LEO	low Earth orbit
NBG	narrow-bandgap
NiOx	nickel oxide
RJ	recombination junction
ICL	interconnecting layer
SAM	self-assembled monolayer
SEE	Single Event Effect
SPENVIS	space environment information service
SnO ₂	tin oxide
тсо	transparent conductive oxide
WBG	wide-bandgap
PET	Polyethylene terephthalate
PVDF	Polyvinylidene fluoride
PI	Polyimide
GlyCl	glycine chloride
EDAI2	ethylenediammonium diiodide



1. Deliverable abstract

This deliverable contains requirements, constraints and specifications for: designing materials, components, devices, synthesis routes, manufacturing processes; operation conditions (LEO environment).

2. Design of the Tandem Perovskite Solar Cells and Modules

The photovoltaic devices developed within this project are monolithic all-perovskite 2-terminal tandem solar cells and modules. A schematic of the device stack¹ is shown in Figure 1.



Figure 1. Schematic of a 2T-monolithic all-perovskite tandem solar cell.

2.1 State of the art

JUMP INTO SPACE project is dedicated to advancing the development of tandem PSC on flexible substrates, addressing a significant gap in the current state of the art: so far, PSC progress has predominantly been confined to rigid glass substrates, as shown in the Table below. This limitation restricts their application in emerging fields that demand lightweight, adaptable, and portable energy solutions, such as space technologies.

Table 1. Literature overview: main results reported in the last few years about tandem all-perovskite solar cells.

Date	PCE (%)	HSL WBG	ESL WBG	ESL Buffer WBG	RJ	HTL NBG	ETL NBG	ETL Buffer NBG	Substrate	Referen ce
09/20 24	27.17	Meo-2PACz	ВСР	SnO ₂	ITO	PEDOT:PSS	C ₆₀	ВСР	glass	[²]
02/20 24	24.5 (on 20.25 cm ²)	NiOx + VNPB + Me-4PACz	C ₆₀	SnO ₂	Au	PEDOT:PSS	C ₆₀	SnO₂	glass	[³]
02/20 24	22.2	NiOx + N719 dye	C ₆₀	SnO ₂	Au	PEDOT:PSS	C ₆₀	ВСР	PEN	[⁴]

⁴ Xie, Z. et al. (2024) Chemical Engineering Journal, 482, 148638. <u>https://doi.org/10.1016/j.cej.2024.148638</u>



¹ Yoon, G. W., et al. (2024). Advanced Energy Materials, 2400204. <u>https://doi.org/10.1002/aenm.202400204</u>

² Zeng, G., et al. (2024). Advanced Functional Materials, 2412458. <u>https://doi.org/10.1002/adfm.202412458</u>

³ Gao, H., et al. (2024). Science, 383(6685), 855-859. <u>https://doi.org/10.1126/science.adj6088</u>

11/20 23	27.5	2PACz	C ₆₀	SnO ₂	ITO	PEDOT:PSS	C ₆₀ or PEIE	SnO₂	glass	[⁵]
11/20 23	26.0	4PADCB	C ₆₀	SnO ₂	ITO/ Taurine	HTL-free	C ₆₀	ВСР	glass	[⁶]
11/20 23	27.8	2PACz	C ₆₀	SnO ₂	Au	PEDOT:PSS	C ₆₀	ВСР	glass	[⁷]
11/20 23	28.1	NiOx/ MeO- 2PACz	PDAI2/ 3MTPAI/ C₆₀	SnO ₂	ITO nanocrysta Is	HTL-free	C ₆₀	SnO ₂	glass	[⁸]
11/20 23	28.1	NiOx/2PACz	C ₆₀	SnO ₂	ITO nanocrysta Is	SAM	C ₆₀	SnO ₂	glass	[⁹]
10/20 23	28.1	NiOx/ Me- 4PACz	C ₆₀	SnO ₂	Au	PEDOT:PSS	C ₆₀	SnO ₂	glass	[¹⁰]
07/20 23	26.1	2PACz	C ₆₀	SnO ₂	Au	PEDOT:PSS/ PC	C ₆₀	ВСР	glass	[¹¹]
06/20 23	27.2	MPA2FPh-BT- BA	C ₆₀	SnO ₂	IZO	PEDOT:PSS/ 2F	C ₆₀	SnO ₂	glass	[¹²]
06/20 23	28.5	NiOx/ 2PACz, MeO-2PACz	C ₆₀	SnO₂	Au	PEDOT:PSS	C ₆₀	BCP or SnO ₂	glass	[¹³]
06/20 23	26.2	2PACz	C ₆₀	SnO ₂	ITO	PEDOT:PSS	C ₆₀	ВСР	glass	[¹⁴]
05/20 23	24.1	MeO-2PACz	EDAI/C ₆₀	SnO ₂	Au	PEDOT:PSS	C ₆₀	ВСР	glass	[¹⁵]
04/20 23	25.6	NiOx/SAM	C ₆₀	SnO ₂	Au	PEDOT	C ₆₀	ВСР	glass	[¹⁶]
03/20 23	25.3	NiOx/2PACZ, MeO-2PACz	C ₆₀	SnO ₂	ITO	PEDOT:PSS	C ₆₀	SnO ₂	glass	[¹⁷]

⁵ Yang, F., et al. (2024) Advanced Materials, 36(6), 2307743. <u>https://doi.org/10.1002/adma.202307743</u>

- ⁶ Ma, T., et al. Advanced Materials, 36(3), 2308240. <u>https://doi.org/10.1002/adma.202308240</u>
- ⁷ Zhou, S., et al. (2023) Nature, 624(7990), 69-73. <u>https://doi.org/10.1038/s41586-023-06707-z</u>
- ⁸ Wen, J., et al. (2023) Nature communications, 14(1), 7118. <u>https://doi.org/10.1038/s41467-023-43016-5</u>
- ⁹ Liu, C. et al. Angew. Chem. Int. Ed. e202313374 (2023) <u>http://doi.org/10.1002/anie.202313374</u>
- ¹⁰ Liu, C., et al., (2023) Science, 382(6672), 810-815. <u>https://doi.org/10.1126/science.adk1633</u>
- ¹¹ Chen, L., et al. (2023). Advanced Energy Materials, 13(32), 2301218. <u>https://doi.org/10.1002/aenm.202301218</u>
- ¹² Zhu, J., et al (2023) Nature Energy, 8(7), 714-724. <u>https://doi.org/10.1038/s41560-023-01274-z</u>
- ¹³ Lin, R., et al. (2023) Nature, 620(7976), 994-1000. <u>https://doi.org/10.1038/s41586-023-06278-z</u>
- ¹⁴ Luo, J., et al (2023) Advanced Materials, 35(22), 2300352. <u>https://doi.org/10.1002/adma.202300352</u>
- ¹⁵ Chiang, Y. H., et al. (2022). arXiv preprint <u>https://doi.org/10.48550/arXiv.2208.03556</u>
- ¹⁶ Li, T., et al (2023) Nature Energy, 8(6), 610-620. <u>https://doi.org/10.1038/s41560-023-01250-7</u>
- ¹⁷ Wang, Y., et al. (2023) Nature Communications, 14(1), 1819. <u>https://doi.org/10.1038/s41467-023-37492-y</u>



This project has received funding from the EIC under GA n. 101162377.

03/20 23	27.0	4PACz or 4PADCB	C ₆₀	SnO ₂	IZO	PEDOT:PSS	C ₆₀	SnO ₂	glass	[¹⁸]
03/20 23	26.7	PTAA/PFNBr	C ₆₀	SnO ₂	ITO	PEDOT:PSS	C ₆₀	ВСР	glass	[¹⁹]
12/20 22	27.2	Meo- 2PACZ/MeO- 4PACz	LiF/C ₆₀	SnO ₂	Au	PEDOT	C ₆₀	ВСР	glass	[²⁰]
12/20 22		NiOx/VNPB	C ₆₀	SnO ₂	ITO nanocrysta Is	HTL-free	C ₆₀	SnO ₂	glass	[²¹]
12/20 22	23.7	ΡΤΑΑ	РСВМ	SnO ₂	RJ-free	PEDOT:PSS	PCB M	ВСР	glass	[²²]
12/20 22		2PACz	TEACI/ PCBM	SnO ₂	ITO	PEDOT:PSS	C ₆₀	ВСР	PEN	[²³]
11/20 22	27.4	NiOx/ Me- 4PACz	C ₆₀	SnO ₂	Au	PEDOT	C ₆₀	SnO ₂		[²⁴]
08/20 22	23.1	ΡΤΑΑ	C ₆₀	SnO ₂	Au	PEDOT:PSS	PCB M	ВСР		[²⁵]
07/20 22	23.8	NiOX	РСВМ	SnO ₂	Au	PEDOT:PSS	PCB M	ВСР		[²⁶]
07/20 22	23.5	2PACz	LiF/C ₆₀	SnO ₂	ITO or Au	PEDOT:PSS	C ₆₀	ВСР		[27]
07/20 22	26.2	NiOx/VNPB	C ₆₀	SnO ₂	Au	PEDOT	C ₆₀	ВСР		[²⁸]
06/20 22	25.5	Meo-2PACz	LiF/C ₆₀	SnO ₂	Au	PEDOT:PSS	C ₆₀	ВСР		[²⁹]

¹⁸ He, R. et al. Nature 618, 80–86 (2023) <u>https://doi.org/10.1038/s41586-023-05992-v</u>

- ¹⁹ Zhao, Y. et al. Energy Environ. Sci. 16, 2080–2089 (2023) <u>https://doi.org/10.1039/D2EE04087E</u>
- ²⁰ Jiang, Q. et al. Science 378, 1295–1300 (2022). <u>https://doi.org/10.1126/science.adf0194</u>
- ²¹ Wu, P. et al. Adv. Energy Mater. 12, 2202948 (2022) <u>https://doi.org/10.1002/aenm.202202948</u>
- ²² Zhou, X. et al. ACS Energy Lett. 8, 502–512 (2023) https://doi.org/10.1021/acsenergylett.2c02156
- ²³ Lai, H. et al. Adv. Energy Mater. 12, 2202438 (2022). <u>https://doi.org/10.1002/aenm.202202438</u>
- ²⁴ Chen, H. et al. Nature 613, 676–681 (2023). <u>https://doi.org/10.1038/s41586-022-05541-z</u>
- ²⁵ Dai, X. et al. Nat. Energy 7, 923–931 (2022). <u>https://doi.org/10.1038/s41560-022-01102-w</u>

²⁹ Tong, J. et al. Nat. Energy 7, 642–651 (2022). <u>https://doi.org/10.1038/s41560-022-01046-1</u>



This project has received funding from the EIC under GA n. 101162377.

²⁶ Zhang, Z. et al. Nano-Micro Lett. 14, 165 (2022). <u>https://doi.org/10.1007/s40820-022-00918-1</u>

²⁷ Abdollahi Nejand, B. et al. Nat. Energy 7, 620–630 (2022). <u>https://doi.org/10.1038/s41560-022-01059-w</u>

²⁸ Wen, J. et al. Adv. Mater. 34, 2110356 (2022). <u>https://doi.org/10.1002/adma.202110356</u>

2.2 Substrates

By focusing on flexible substrates, JUMP INTO SPACE aims to unlock the full versatility of tandem PSC, paving the way for broader and more innovative uses of this cutting-edge PV technology.

Despite this, some initial optimization will be done on traditional ITO glass substrates. Then, the device stack will be transferred to standard ITO PET substrates, moving thus from rigid to flexible.

As soon as the research and development on the multi-purpose substrates delivers the first samples, films and devices will be prepared to test the compatibility between the innovative flexible substrates and the materials and deposition techniques.

Space relevant polymers, such as PVDF and PI, will be modified using ionizing radiations, creating nanochannels. Once validated, anisotropic distribution of metallic nanoparticles will be created through the obtained nano-channels, to further improve the UV cut-off and the visible range optical transmission.

Nanopatterned foils will be developed by texturing the foils by means of hot embossing. This approach is expected to kill several birds with one stone: 1) Reflection losses should be reduced in the full spectral regime usable for all-perovskite tandem solar cells, 2) wetting of the perovskite precursor solution and hence growth of the perovskite absorber layer(s) should be improved, 3) mechanical stress in the solar cell stack layers, particularly in the often brittle transparent electrodes, should be minimized. Depending on the used foil polymer materials the hot embossing processing conditions, such as pressure, temperature, cooling time, etc. must be adapted.

The final choice of the neat polymer foils to be used as substrates and to be modified to obtain JUMP INTO SPACE multi-purpose substrates will depend primarily on the maximum temperatures that they can withstand (120 °C for PET, 170 °C for PVDF, >300 °C for some type of PI) and whether they are compatible with the processing and operational temperatures, detailed in the following paragraphs.

These requirements should meet also the desired properties for the substrates as defined in the project's Objective 1 (KPI#1, KPI#2, KPI#3, KPI#4, KPI#5).

2.3 Materials for the Perovskite Solar Cells and Modules

2.3.1 Transparent Conductive Oxides (TCO)

TCO can be used at different sites in all-perovskite tandem solar cells. Typical TCO materials are fluorinedoped tine oxide (FTO), indium tin oxide (ITO) or aluminium-doped zinc oxide (AZO).

The most prominent application is as transparent front electrode. For this, the TCO layer must yield both high conductivity and transparency, which are typically competing material properties. Therefore, the material properties must be tuned for the best trade-off.

TCO layers may also be implemented in the recombination junction. In this application, sufficiently high charge carrier concentrations are required for the efficient recombination of charge carriers from the subcells. The lateral charge transport must not be as high as for the front electrode application and is ideally low to reduce shunting.

A third application of TCOs in all-perovskite tandem solar cells is as rear electrode, e.g. in bifacial applications or as protective layer to prevent metal migration from the rear electrode.

In addition to the material properties relevant during solar cell operation, other important factors are the deposition parameters and the use of scarce materials, e.g. indium. As for the deposition parameters, high deposition and/or post-annealing temperatures (>300°C) are favourable as these can significantly improve the charge transport properties. However, the underlying substrate may set boundaries to the temperatures applied, as already mentioned in the previous paragraph 2.2.

2.3.2 Perovskite sub-cell configuration

Both the narrow-bandgap (NBG) and wide-bandgap (WBG) sub-cells comprise of a heterojunction layer stack. For tandem applications, this stack is typically in p-i-n (so-called inverted) configuration, due to e.g.



low parasitic absorption losses. It means that the perovskite is deposited atop a p-type HTL and an n-type ETL is deposited onto the perovskite. This is the configuration adopted by JUMP INTO SPACE.

The p-i-n layer sequence limits the number of possible materials, e.g. due to deposition temperatures or used layer thicknesses.

2.3.2.1 Materials for the narrow-bandgap sub-cell

For the tuning of the NBG perovskite properties, typical action points are compositional and additive engineering. The A-site cation (Cs, MA, FA) stoichiometry must be carefully tuned for identification of an absorber with good stability and performance. At the B-site, a blend of Sn and Pb is used to reduce the bandgap to ca. 1.25 eV. This can be achieved with a ratio of ca. 50:50, which will be the starting point for JUMP INTO SPACE.

To reach lowest bandgaps, the X-site comprises of iodine. Specific to NBG perovskites is that many recipes use additives, such as elemental tin (Sn), tin fluoride (SnF₂), lead thiocyanate (Pb(SCN)₂), ammonium thiocyanate (NH₄SCN), glycine hydrochloride (GlyHCI) or rubidium iodide (RbI) to prevent oxidation of Sn, improve the crystallisation or the bulk quality. In this context, it must be noted that specific additives may interact with the underlying HTL layer and lead to undesired effects. Therefore, additives and HTL may be tuned together.

The dominant HTL in NBG sub-cells is water-based PEDOT:PSS. This material has some severe drawbacks such as parasitic absorption, acidity, the thermal load on the WBG sub-cell during annealing and the water-based dispersion. Interestingly, PEDOT:PSS is, despite the limitations on device performance, still the most widely used HTL in NBG perovskite solar cells, possibly due to the fact that recipes were specifically tuned for this HTL.

JUMP INTO SPACE will move to water-based PEDOT:PSS to some possible alternatives, such as solventbased PEDOT:PSS compositions, which eliminate some of the drawbacks, and SAMs. SAMs are a promising candidate as they feature i.e. low non-radiative recombination losses and negligible parasitic absorption. Yet, there are only few reports of SAMs in NBG perovskite solar cells.

As ETL for the NBG sub-cell, fullerenes such as C_{60} and PCBM are the dominant material in literature and JUMP INTO SPACE partners already use fullerenes (predominantly C_{60} and PCBM). A major challenge towards stability and efficiency is the improvement of the perovskite/ETL interface through interfacial layers or surface treatments. For the buffer layer between ETL and back electrode, typically BCP or ALD-SnO₂ are used, and this will be the starting point for JUMP INTO SPACE.

2.3.2.2 Materials for the wide-bandgap sub-cell

For the tuning of the WBG perovskite properties, typically the composition is tuned. The A-site cation (Cs, MA, FA) stoichiometry must be carefully tuned for identification of an absorber with good stability and performance. At the B-site, lead (Pb) is used. To reach highest bandgaps, the X-site comprises a blend of multiple halogens. Often, iodine (I) occupies the largest share (ca. 60%), while bromine (Br, ca. 40%) is used to widen the bandgap to ca. 1.8 eV. Chlorine may be added in low fractions (ca. 5-10%) to facilitate the crystallisation and further widen the bandgap. This will be the starting point for JUMP INTO SPACE.

A specific challenge for WBG perovskites is the halide segregation, which may occur under illumination and lead to I- and Br-phases. This effect compromises device performance through reduced V_{OC} and must therefore be prevented through careful tuning of the perovskite composition and the adjacent layers.

For the HTL, SAMs or bilayers of SAMs and NiOx are widely employed in literature. For upscaled allperovskite tandem solar cells, additional layers (e.g. NiOx) can be important for a better homogeneity with less pinholes leading to direct contact between perovskite and TCO. Moreover, fabrication with scalable deposition methods (e.g. slot-die coating) may require such additional layers to prevent poor wetting of the perovskite. Thus, JUMP INTO SPACE will start from a bilayer of SAM and NiOx.

Similarly to the NBG sub-cell, fullerenes such as C_{60} and PCBM are the dominant ETLs and the research focus is rather on the improvement for efficiency and stability of the perovskite/ETL interface through surface treatments. For the buffer layer between ETL and back electrode, typically ALD-SnO₂ are used. Thus, as for the NBG sub-cell, JUMP INTO SPACE will start from these materials.



2.3.3 Encapsulants

Initially, the standard encapsulation for space PV will be used: space grade cover glass with space qualified silicone. Then, the silicone will be replaced by thin oxide layers. To reach the final goal of removing the cover glass, different approaches will be explored: 1) the combination of flexible substrate/barrier layer with silicone or even COTS encapsulants with low-cost lamination process, adapted to perovskite temperature constraints; 2) particles of various sizes incorporated inside poly(dimethylsiloxane) (PDMS) resin matrixes; 3) use of more resistant polymers without any siloxane backbone.

Specific attention will be drawn on low outgassing encapsulants to ensure proper space compatibility, as well as low mass density layers.

2.4 Synthesis routes for new materials

The selection of organic-based charge transporting layers (CTLs) are preferred in this project over inorganic examples, due to the extra synthetic tuneability, that allows for a more flexible design towards enhanced stability against space-environmental degradation factors. Additionally, organic based molecules enable much milder deposition methods, e.g. low annealing temperatures, that are compatible with flexible substrates.

Currently, state-of-the-art organic CTLs, like MeO-2PacZ, and Spiro-OMeTAD are mostly synthesized using Pd-based cross-coupling reactions (e.g. Buchwald-Hartwig, Suzuki-Miyaura, Stille) that allow the formation of newly C-C bonds. More importantly, they enable the connection and construction of CTLs, comprising of different organic scaffolds that have certain desirable properties (e.g. stability towards particle irradiation, electron rich/poor). Additionally, these cross-coupling protocols are already massively used in industry (e.g. for production of Active Pharmaceutical Intermediates), as they are typically high yielding, relatively simple and safe procedures and inexpensive, thus envisaging an easy upscaling of the production, with beneficial returns on the cost of the tandem PSC modules.

Techniques to be used in JUMP INTO SPACE include flow reactors, a synthetic technique that enables the facile upscaling of materials via a continuous reaction flow, in which its parameters are thoroughly controllable. In fact, this is already applied for some CTLs, like PCBM. Finally, as PEDOT: PSS is a well-established material in the market, JUMP INTO SPACE can also exploit its well-known and relatively simple synthetic procedure (oxidative, chemical and electrochemical polymerisation) to manufacture structural analogues.

2.5 Up-scaling

Scaling up the fabrication of all-perovskite tandem solar cells to series-connected modules presents several challenges, particularly in ensuring uniformity and efficiency over large areas. One of the primary obstacles is achieving high-quality thin films of perovskite layers with consistent thickness and minimal defects, as any irregularities can significantly impact device performance and long-term stability. Additionally, managing the interface between sub-cells in a tandem configuration is critical to maintaining optimal charge carrier extraction and minimizing losses. Last but not least, series connection in modules requires precise laser patterning to electrically isolate and interconnect cells.

2.5.1 Minimodules

For the upscaling of JUMP INTO SPACE stack from lab-scale cells to 5×5 cm² mini-modules, a combination of solution-based printing techniques and vacuum-based deposition is required. In Figure 2, a schematic of a flexible all-perovskite tandem PV module from the current internal procedure by JUMP INTO SPACE partner SAULE is shown, with relative deposition methods in brackets. Commonly used in the PV industry, laser-based structuring sequence (i.e. P1-P2-P3 steps) is applied for establishing cell interconnections in the module. This is the starting point for all JUMP INTO SPACE activities on the 5×5 cm² mini-modules.







Figure 2. Schematic of the flexible all-perovskite tandem PV module, adopted by JUMP INTO SPACE as project baseline.

2.6 Conclusion

Table 2 summarizes the materials and deposition methods identified in this Deliverable as the project baseline.

	Lab-scale (single cell)	Scale-up (minimodule)		
Substrate	1. Commercial PET-ITO. 2. JUMP INTO SPACE multi-purpose substrate (<u>nano-patterning, hot</u> <u>embossing</u>)	1. Commercial PET-ITO. 2. JUMP INTO SPACE multi-purpose substrate (<u>nano-patterning, hot embossing</u>)		
HTL	Commercial NiO NPs dispersion (<u>spin-coating)</u>	Commercial NiO NPs dispersion (<u>blade-coating)</u>		
HTL modification	Commercial SAM (<u>spin-coating)</u>	Commercial SAM (<u>blade-coating)</u>		
WBG perovskite	Customized WBG precursor solution (<u>spin-coating)</u>	Customized WBG precursor solution (<u>blade-coating)</u>		
WBG perovskite passivation	Commercial salt (<u>spin-coating)</u>	Commercial salt (<u>blade-coating)</u>		
ETL	Commercial C ₆₀ (<u>thermal</u> evaporation)	Fullerene derivative (<u>blade-coating)</u>		
Buffer layer	Tin oxide SnOx (<u>atomic layer</u> <u>deposition)</u>	Tin oxide SnOx (spatial <u>atomic layer</u> <u>deposition)</u>		
Recombination layer	Au (thermal evaporation)	Au (<u>alternative scalable deposition</u> <u>needed</u>)		
HTL	Commercial polymer dispersion PEDOT:PSS (<u>spin-coating)</u>	Commercial polymer dispersion PEDOT:PSS (<u>blade-coating)</u>		
NBG perovskite	Customized NBG precursor solution (<u>spin-coating)</u>	Customized NBG precursor solution (<u>blade-coating)</u>		



This project has received funding from the EIC under GA n. 101162377.

NBG perovskite passivation	Commercial salt (<u>spin-coating)</u>	Commercial salt (<u>blade-coating)</u>
ETL	Commercial C ₆₀ (<u>thermal</u> <u>evaporation)</u>	Fullerene derivative (<u>blade-coating)</u>
Buffer layer	Tin oxide SnOx (<u>atomic layer</u> <u>deposition)</u>	Tin oxide SnOx (spatial <u>atomic layer</u> <u>deposition)</u>
Electrode	Ag (thermal evaporation)	Ag (<u>alternative scalable deposition</u> <u>needed</u>) or transparent conductive oxide ITO (<u>magnetron sputtering)</u>

3. Operational Conditions

The relative impact of any of the space environment effects on materials and devices depends on the type of mission to perform (e.g., communication, defence, Earth observation) and, more importantly, the orbit in which the spacecraft is placed. Figure 3 shows the variations in the space environment as a function of the orbit altitude.



Figure 3. Variation in the space environment and stressors with the orbit altitude.

Low Earth Orbit (LEO) extends up to 1,000 km. Medium Earth Orbit (MEO) is above 1,000 km and extends about 35,000 km. Geosynchronous orbit (GEO) begins at 35,786 km. Table 3 summarizes the main features of the space environment depending on the altitude, which can affect operation and stability and must be taken into account for the design and development of photovoltaics for space, in general, and for JUMP INTO SPACE devices, in particular.

Table 3. List of the main characteristics of the space environment depending on the altitude.

	LEO (Low Earth Orbit)	GEO (Geostationary Orbit)	Planetary mission and deep space
Altitude	200 to 1,000 km	>36,000 km	N/A
Temperature	-100 to 100°C 16 cycles/day	-150 to 120°C 1 cycle/day	Outer solar system: -180 to 260°C Inner solar system very hot
Pressure	10 ⁻⁴ to 10 ⁻⁹ mbar	10 ⁻⁹ to 10 ⁻¹⁰ mbar	Down to 10 ⁻¹⁴ mbar
Radiations	Hv [X-ray, (V)UV, Vis, IR]	Van Allen belts (partially), cosmic rays, sun activity	Cosmic rays, trapped planetary radiation



	Particles (98% e-, 2% p+, Van Allen belts)		
Impacts	Micrometeorites, debris	Micrometeorites, debris	Comets, asteroids
Atmosphere	Atomic oxygen	N/A	Planets (reactive gases)

JUMP INTO SPACE devices target LEO, i.e. orbits in the 100 to 1000 km altitude range, which includes Earth-observing satellites (EOS) and the special case of the International Space Station (ISS) at ~400 km.

The environment in LEO is fairly benign from the radiation standpoint, with a typical dose rate of ~0.1 krad/year. Most Polar Earth Orbits (PEO) are LEOs with high inclinations (>55°), but some PEOs may be more eccentric. The high inclination takes the orbit through the polar aurora regions, which can be rich in ion cosmic ray and solar flare particles. Higher radiation dose is accumulated during the passage through these regions; however, the transition time is typically small in comparison to a full orbit time. Thus, the dose rate is a few krad/year, similar to that in LEO. The major materials concern with LEO is UV and the presence of atomic oxygen (AO) inducing erosion of surface materials leading to degradation of mechanical and optical performance.

3.1 Test conditions to simulate operation in space

3.1.2 State-of-the-art

The testing of PSC under conditions resembling the space environment has garnered significant attention due to the unique properties of perovskite materials, including their high power-to-weight ratio and tunable bandgap, which make them particularly suitable for space missions.

To date, most studies have focused on evaluating the radiation tolerance of PSCs, via exposure to highenergy particles, mainly protons. Experiments conducted with particle accelerators to simulate this radiation have shown that perovskite materials are remarkably resilient, retaining a significant fraction of their efficiency even after substantial radiation doses. However, further research is required to understand the long-term impacts of cumulative radiation damage, particularly on module stability and encapsulation integrity.

Just few studies have investigated the effect of vacuum, UV, extreme temperatures. And only one study so far have reported on the combined effects of more than one stressor.

Table 4 shows an overview of test conditions and results of PSC relevant to JUMP INTO SPACE, i.e. tandem and/or PIN configuration, flexible substrates, alternative encapsulation strategies. This will be the starting point for defining the most appropriate testing conditions for materials and devices within this project.

Table 4. Literature overview of test conditions resembling the space	ce environment and results of PSC, relevant to JUMP INTO SPACE
--	--

PSC architecture	Test conditions	Energy / Pressure	Fluence / Exposure	Retained PCE	Ref.
PIN, Tandem: FACsDMAPbIBr(WBG)/ FACsPbSnI(NBG)	protons	68 MeV	10 ¹³ particles/cm ²	95%	Lang et al. 2021
PIN, flexible: MAPI	protons	100 keV	10 ¹⁰ - 10 ¹² particles/cm ²	90%	<u>Malinkiewicz et</u> al. 2020
PIN: FACsPb(IBrCl) ₃ + Al ₂ O ₃ encapsulated	protons	50-2500 keV	10 ¹² particles/cm ²	80%	<u>Durant et al.,</u> 2021



PIN & NIP: 3C-2H + 1 μm SiOx encapsulated	protons	50 keV	10 ¹³ - 10 ¹⁵ particles/cm ²	95% (100% encapsulated)	<u>Kirmani et al.</u> 2023
PIN: FACsPb(IBrCl)3 + 50 nm TiO ₂ /Al ₂ O ₃ encaps	protons	75 keV	10 ¹³ particles/cm ²	85%	<u>Afshari et al</u> <u>2023</u>
NIP, flexible: 3C-2H	neutrons	<800 MeV	10 ⁹ - 10 ¹⁰ particles/cm ²	85%	<u>De Rossi et al.,</u> <u>2021</u>
PIN: 3C-2H + 1 μm SiOx encapsulated	Oxygen + UV (lab UVO)	-	1800 s	80% encapsulated	<u>Kirmani et al.</u> <u>2023</u>
PIN: 3C-2H + 0.7 μm SiOx encapsulated	Oxygen (O2 plasma chamber)	-	2 h	40-43% (93% encapsulated)	<u>Seid et al. 2024</u>
PIN: 3C-2H, ITO or Au rear electrode + SiOx encapsulation	Vacuum + Temperature (dark)	10 ⁻² mbar	3600 h	~100% (ITO rear electrode + SiOx encapsulation	<u>VanSant et al</u> <u>2022</u>
PIN: 3C-2H	Vacuum + Temperature (MPPT @ AM0)	10 ⁻⁶ mbar	24 h	~100% (ITO rear electrode + SiOx encapsulation	<u>VanSant et al</u> 2022

3.1.2 Test conditions for JUMP INTO SPACE

The effects of the space environment on materials are complex and specific for each family of materials, as further detailed in the Annex below. The reproduction of the degradation mechanisms at ground shall be as representative as possible of the mission environment because of this specificity. The process is at first instance not critical, that is why generally test plans consider only 1 to 2 samples per type.

The definition of test parameters also strongly depends on the operational environment, i.e. LEO for JUMP INTO SPACE technology, but also on the features of samples (layer, substrate, stacking ...) in terms of nature and dimensions.

The objectives of the testing shall also be defined prior to designing the test plan: screening test plan is much simpler than "qualification" test campaign that requires a detailed test matrix with identification of measurement and characterization plan. The evaluation of end-of-life performance may require combined irradiation (electrons, protons and UV), simulation of the full mission dose and in situ measurements.

Thus, test campaigns and test plans will be defined in a later stage of this project, as soon as the preliminary selection of devices and structures to be tested will be performed.

Annex I

1 Space radiation: origin of charged particle radiation

1.1 Near Earth space environment

Most of information provided in the paragraph come from publications³⁰³¹ reported in the footnotes.

1.1.1 Galactic cosmic rays (GCR)

They are high-energy charged particles that originate outside of our solar system. Although their origin is not completely understood it is believed that supernova explosions are a significant source. They are composed mainly of hadrons.

All naturally occurring elements in the Periodic Table (up through uranium) are present in GCR, although there is a steep drop-off for atomic numbers higher than iron. Energies can be as high as 10¹¹ GeV, although the acceleration mechanisms to reach such high energies are not understood. Fluxes are generally a few cm⁻¹.s⁻¹, and vary with the solar cycle. Single Event Effects (SEE) are the main radiation effects in microelectronics and photonics. Their low fluxes make them not significant in the ionising dose or displacement damage effects on materials and electronics, compared to the solar source of charged particles.

1.1.2 Solar wind

The Sun is the source of a permanent emission of thermally excited coronal matter, the energy of which allows a release of solar gravity. This flow of particles is called the solar wind. It is a low-density plasma, made up of charged particles (notably electrons, ions and protons) and within which collisions are rare. Its properties (speed, density, temperature, etc.) vary depending on solar activity. The solar wind is made up of two main components. The first is a slow solar wind whose average speed measured at 1 au (astronomical unit – Sun-Earth distance) is approximately 400 km.s⁻¹. The slow solar wind comes from regions of the solar corona called helmet streamers (sometimes simply streamers). These are structures in the form of an elongated closed loop, connecting two regions of opposite polarity on the Sun. The second is a fast solar wind, whose speed measured at 1 au is typically of the order of 600–800 km.s⁻¹. The fast solar wind originates from coronal holes, which are regions of the solar corona of lower density and temperature, from which open field lines extend towards the interplanetary medium.

1.1.3 The eruptive activity of the Sun

In addition to the permanent emissions of solar wind, the Sun also exhibits turbulent activity accompanied by sudden and violent releases of energy in different forms. This activity, called eruptive, is in reality made up of different components more or less well correlated with each other. Solar flares result when the localized energy storage in the coronal magnetic field becomes too great and causes a burst of energy to be released. They tend to be electron rich, last for hours, and have an unusually high ³He content relative to ⁴He. A Coronal Mass Ejection (CME), on the other hand, is a large eruption of plasma (a gas of free ions and electrons) that drives a shockwave outward and accelerates particles. CMEs tend to be proton rich, last for days, and have a small ³He content relative to ⁴He.

1.2 Interaction with the Earth magnetic field

Solar wind and solar activity in a global point of view interact with the earth magnetic field in particular by distorting the geomagnetic field lines and injecting charged particles into the magnetospheric cavity. These particles will then see their movement directed by the Earth's magnetic field, which will contribute to the creation of currents inducing new components in the magnetospheric field. The magnetosphere is composed of several regions, characterized by the presence of plasmas with different properties. Figure 2 schematically represents these regions, seen in a longitudinal section. These regions can be roughly separated into two main categories: the outer magnetosphere and the inner magnetosphere. The first consists of regions of the magnetosphere for which the forcing of the solar wind makes the quasi-dipolar approximation of the geomagnetic field unsuitable, as opposed to the second.

 ³⁰ S. Bourdarie and M. Xapsos, "The Near-Earth Space Radiation Environment", IEEE trans. On Nuc. Sci, Vol. 55 n°4, pp. 1810-1832, 2008
 ³¹ G. Bernoux, "Apprentissage profond pour la prévision de l'activité géomagnétique ", PhD Thesis, 06 July 2022.





FIGURE 2 - SCHEMATIC REPRESENTATION OF THE EARTH'S MAGNETOSPHERE SHOWING ITS DIFFERENT REGIONS. CREDITS: ESA /C. T. RUSSEL

1.3 Radiation belts

They form a region of the inner magnetosphere. The intense magnetic field allows high-energy charged particles to be trapped in quasi-periodic motions, a direct consequence of Lorentz's law.

The belts are composed mainly of high to very high energy electrons and protons: 0,01 - 10 MeV for electrons and 0.01 - 1000 MeV for protons. Their overall extent is 1 - 10 TR (terrestrial radius) for electrons and 1 - 7 TR for protons. In practice, we usually observe two electron belts (1 - 2.5 TR and 2.5 - 10 TR) and a proton belt (partially overlapping with the inner electron belt). Figure 3 provides an artist's view of the electron belts.



FIGURE 3 - ILLUSTRATION OF THE EARTH'S ELECTRONIC RADIATION BELTS. CREDITS: NASA ILLUSTRATIONS, UNDER LICENSE CC BY-NC-ND 2.0

2 Evaluation of the charged particle environment for LEO orbits

Numeric tools allow the evaluation of the radiation constraint for space missions, for example SPENVIS³² and OMERE³³. These tools use some environment models. The typical ones are AE8 and AP8 (E and P for electrons and protons respectively) considered as standards for mission calculations. Extended models for a refined evaluation of the low energy electron fluxes are also available like the GREEN model³⁴.

Here are two examples of radiation environment for typical polar LEO orbits:

- International Space Station (ISS) with 400 km altitude and 51.6° inclination.
- Typical Earth observation polar orbit with 800 km altitude and 98° inclination.

³⁴ C. Inguimbert, P. Caron, Q.Gibaru, A. Sicard, N. Balcon, and R.Ecoffet, IEEE Tran. Nuc. Sci., Vol. 68. N°8, pp. 1754-1763, Aug. 2021.



³² SPENVIS. ESA's SPENVIS. [Online] 2024. <u>https://www.spenvis.oma.be/</u>

³³ OMERE. TRAD's OMERE. [Online] 2024. <u>http://www.trad.fr/spatial/logiciel-omere/</u>

The electrons and protons differential and integral fluxes are given in Figure 4 and Figure 5. It is then possible to evaluate the ionizing dose due to this environment behind a given thickness of shielding. The typical considered shielding material is aluminium. The corresponding dose profile is given in Figure 6. For these calculations, the worst case of AE8 and AP8 models for electrons and protons are considered.



FIGURE 4 – DIFFERENTIAL ELECTRONS AND PROTONS FLUXES EVALUATED FOR POLAR LEO ORBITS (98°).



FIGURE 5 – INTEGRAL ELECTRONS AND PROTONS FLUXES EVALUATED FOR POLAR LEO ORBITS (98°).





FIGURE 6 – DOSE PROFILE BEHIND ALUMINIUM SHIELDING FOR 1-YEAR POLAR LEO ORBITS (98°).

Charged particles (trapped electrons and protons, solar event protons - X-rays on the side facing sun- and solar wind) are at the origin of the ionizing dose profile absorbed by the materials. Surface materials, as solar panels, MLI and paints, are not shielded and therefore are subjected to a worst-case environment for a given mission with important dose surface (>> 10^9 rads). For orbits that cross trapped belts (GEO...), the absorbed dose profile exhibits a strong variation with depth as protons are stopped at the very surface (< 2 μ m).

In ionization process, an atom loses an electron and forms an ion (whatever the chemical link at play). At material level (organic), these excitation/ionization mechanisms will result in formation of free radicals or ions. These reactive intermediates can initiate chemical reactions which result in scission as well as in cross-linking reactions. The macroscopic effects are then linked to the accumulation with time of the ionizing dose (namely "cumulated effect") inducing surface and volume phenomena. The scission-to-cross linking ratio depends on temperature and flux (dose rate) leading in polymers to enhanced degradation or induced recovery. However, self-annealing of radicals is also promoted by increased temperature and the presence of oxygen. That is why test conditions such as irradiating at operational temperature, with limited dose rate (or annealing steps in the test sequence) and in situ measurement (under vacuum) are advised for investigation degradation of materials.

The same particles are also at the origin of displacement dose (non-ionizing) leading to creation of interstitials-vacancies, single or cluster of defects. The macroscopic effect of such phenomena mostly concerns inorganic materials and large fluence.

3 Electromagnetic radiation

The solar electromagnetic radiation spectra can be approximated by a black body curve with a characteristic temperature of 5762 K. The UV portion (wavelength, $\lambda < 400$ nm) of the electromagnetic spectrum is of particular importance in the determination of solar radiation effects on materials (Table 1). The integrated irradiance of the near UV electromagnetic radiation flux (180 nm < λ < 400nm) is approximately 118 W/m². In Figure 7 it is presented the sun electromagnetic spectra outside the atmosphere (at 1 AU = average Earth-Sun distance) and at sea level.





FIGURE 7 - SOLAR SPECTRAL IRRADIANCE CURVES (AM0 AND AM1).

bounds	^z dissociation (kJ/mol)
C-C	353
C-0	357
C-H	413
Si-O	460
Si-C	318

λ (nm)	200	250	300	400	500
z(kJ/mol)	600	480	400	300	240

UV is critical for surface materials facing the sun (AM0 solar spectrum, ASTM490) but also facing Earth due to the albedo effect (about 30 % AM0 in terms of received energy). The UV radiation spectrum comprises wavelengths of between 200 and 400 nm, which corresponds to energies of between 600 and 300 kJ/mol. These energies are in the same range as the bond energies of many organic compounds. Chemical reactions are induced when specific functional groups absorb the UV radiation. Free radicals liberated in the excitation/ionization process will trigger further reactions (bonds breaking and rearrangement: photolysis). Signs of photo-degradation include embrittlement (surface cracking), discoloration and loss of transparency.

4 Atomic Oxygen (AO)

Several forms (allotropes) of oxygen exist, while O_2 (molecular oxygen) being the most familiar since represents the breathable form on Earth. Ozone (O_3) and atomic oxygen (O_1 , single atom, abbreviated AO), both occur in the upper atmosphere and pose distinct reactive allotropes³⁵. At sea level, air is about 21% oxygen, 78% nitrogen, and 1% miscellaneous other gasses, such as argon. Under normal conditions, when an oxygen molecule splits apart for any reason, the atoms quickly reform into a new molecule. In the upper parts of the atmosphere, oxygen molecules are few and far between. The density of atmospheric species is varying as a function of altitude as depicted in Figure 8. AO is the main component of the residual atmosphere in LEO. AO has shown to cause severe damage to organic-based materials as well as polymers and metals. It is produced by the photo-dissociation of molecular oxygen (O2) in the upper atmosphere by solar radiation with wavelengths below 250 nm. Below altitudes of approximately 100 km, the AO has already reacted with the molecules of the upper atmosphere and therefore is barely present in the lower altitudes.

³⁵ Finckenor, M. e Dooling, D. "Multilayer Insulation Material Guidelines". Marshall Space Flight Center : Technical Report, National Aeronautics and Space Administration, NASA/TP-1999-209263, 1999.



TABLE 1 - DISSOCIATION ENERGY OF TYPICAL BOUNDS AND CORRESPONDING WAVELENGTH



FIGURE 8 - DENSITY OF ATMOSPHERIC SPECIES AS A FUNCTION OF ALTITUDE [DR7]

The AO number density strongly depends on the altitude and the solar activity (Figure 9). In order to provide the desired number densities, ESA's Space Environment Information System (SPENVIS) is utilized³⁶. Therein, four different reference atmosphere and ionosphere models are available to obtain the required AO number density:

- Mass-Spectrometer-Incoherent-Scatter (NRLMSISE-00),
- Marshall Engineering Thermosphere (MET-V 2.0),
- Drag Temperature Model (DTMB78) and
- International Reference Ionosphere (IRI2001).

At solar maximum the number density is greatest due to the expanded atmosphere. However, the AO number density varies for each atmosphere model and consequently determines the accuracy of the provided data. To provide a suitable model for the AO densities for LEO in consideration of the solar activity, the mean AO density values for low, moderate and high solar activity over a year using the NRLMSISE-00 atmospheric model can be approximated and plotted over the altitude (Figure 9).



FIGURE 9 – ATOMIC OXYGEN NUMBER DENSITY VERSUS ALTITUDE FOR SOLAR MINIMUM, NOMINAL (STANDARD ATMOSPHERE), AND SOLAR MAXIMUM CONDITIONS [DR7]

³⁶ G. Bernoux, "Apprentissage profond pour la prévision de l'activité géomagnétique ", PhD Thesis, 06 July 2022.



Considering the 11 years solar cycle, the mean AO fluence (number of AO atoms per unit of area) estimated per year is following the same temporal cycle as depicted in Figure 10 for a particular orbit. In this example, the fluence can be multiplied by a factor of 6 between the lowest and the highest level.



FIGURE 10 – ATOMIC OXYGEN FLUENCE PER YEAR DURING A SOLAR CYCLE, BASED ON THE MSIS-86 ATMOSPHERIC MODEL [DR7]

At LEO space vehicle are orbiting with velocities from 7.11 to 7.73 km s⁻¹. Thus, for satellite – AO collision interactions, the orbital velocity corresponds to an AO impact energy of ~ 5 eV^{37} . Degradation effects caused by AO are considered as one of the most serious threats to external surfaces of spacecraft and internal components. These effects are present at altitudes between 100 and 1000 km and can change optical, mechanical, electrical and chemical properties of surface materials.

AO interaction with organic materials results in severe degradation of surface through complex mechanisms of oxidation/desorption of oxidation products leading to modification of chemical composition of surface, loss of thermo-optical (TO) and mechanical performance. Synergy with other space environment component is also observed.

For instance, it was demonstrated for Kapton (any hydro carbonated polymers) that erosion is the result of formation of CO and CO2 volatile products (independent of temperature) following H abstraction (temperature dependent) whereas VUV intervenes in inducing chain scissions (promote desorption of oxidation products).

Degradation effects caused by AO are considered as one of the most serious hazards to spacecraft materials present at altitudes between 200 and 700 km. Table 2 gives an estimation of the potential erosion of a space wild-used polyimide material (Kapton H) during a one-year travel at a circular polar orbit for different LEO altitudes. This estimation is realized with the SPENVIS tool and the NOAA Space Weather prediction during the July-2025 to June-2026 period (supposed to be a high solar flux period). As previously mentioned, if the AO erosion is very harsh at the ISS altitude (~400 km), it becomes negligible for altitudes above 700 km. There is no more AO effect from 800 km altitude. Below 400 km altitude, the AO erosion is very high for polymer materials and some synergies exist with other species – like N_2^{38} – more present at such very low altitudes (see Figure 8).

³⁸ Yokota K. et al., "Effect of simultaneous N2 collisions on atomic oxygen-induced polyimide erosion in sub-low Earth orbit: comparison of laboratory and SLATS data". CEAS Space Journal (2021) 13:389–397.



³⁷ Bank, Bruce A., et al. "Atomic oxygen effects on spacecraft materials". NASA/TM - 2003-212484. 2003.

Altitude (km)	Density (cm ³)	Flux (/cm².s)	Fluence (at/cm²)	Eroded thickness (µm)
300	4.7 10 ⁸	3.6 10 ¹⁴	1.1 10 ²²	341.2
400	8.9 10 ⁷	6.8 10 ¹³	2.2 10 ²¹	64.8
600	4.3 10 ⁶	3.3 10 ¹²	1.0 10 ²⁰	3.1
800	2.6 10 ⁵	2.0 10 ¹¹	6.2 10 ¹⁸	0.2

TABLE 2 – AVERAGE AO DENSITY AND FLUX, FRONT FLUENCE PER YEAR AND ASSOCIATED EROSION THICKNESSOF A KAPTON H POLYIMIDE FOR THREE DIFFERENT LEO ALTITUDES (CIRCULAR POLAR ORBIT) AND HIGH SOLARFLUX (BASED ON SPENVIS TOOL AND NOAA SPACE WEATHER PREDICTION FOR JULY-2025 TO JUNE-2026
PERIOD)

Moreover, the LEO environment includes other components as ions and VUV that acts in synergy with AO for degrading materials³⁹. The following table (Table 3) shows the 300 km environment actual composition. Temperature is also an important parameter as discussed in the next part.

Species	Density (cm ³)	Flux (#/cm².s)	Energy (eV)
0	5 10 ⁸	4 10 ¹⁴	5.3
N2	1.5 10 ⁸	1.2 10 ¹⁴	9
O ₂	1.2 10 ⁷	10 ¹³	10.6
O*	10 ⁵	8 10 ¹⁰	5.3
O ₂ +	10 ⁴	8 10 ⁹	10.6
UV (175-190 nm)	3 10 ⁻³ mW/m ²		

TABLE 3 - 300 KM SPACE ENVIRONMENT

5 Temperature

Sun, as well as earth, is the important heat source to warm an object in space. The overall temperature an object experiences in space depends mainly on the object dynamics (rolling, spinning), material properties (α solar absorptivity between 250 and 2500 nm, ϵ InfraRed emissivity between 3 and 20 µm) and object mass and energy exchange structures. Because the temperature of an object is a time evolving process through heat transfer processes, the object motion or the solar irradiation of specific areas dictates variable temperature levels within the object. In space, an absent atmosphere prevents thermal changes through convection; instead, the heat transfer process is carried through conduction and radiation. An object gathers energy mainly from two radiation sources: earth and sun, or through heat conduction from adjoining elements. An object facing the Sun will absorb incident solar energy until it reaches a balance point with the emitted IR energy. Should the object reach a thermal level above the surrounding environment, the object will start

³⁹ Tagawa M. et al., "Synergistic Study on Atomic Oxygen-Induced Erosion of Polyethylene with Vacuum Ultraviolet". JOURNAL OF SPACECRAFT AND ROCKETS, Vol. 41, No. 3, June 2004.



acting as a thermal emitter, dissipating thermal radiation into space until the absorption/emission balance is redressed (Figure 11).



FIGURE 11 - HEAT STREAMS OF AN OUTER-SURFACE OBJECT.

The accurate calculation of an object temperature in space is a complex process, requiring calculation through attitude matrices. For the energy dissipated into space and the three-dimensional calculation of the thermal conduction, one must use the Stefan-Boltzmann's law and the Fourier's law of heat conduction respectively. However, an accurate temperature calculation of objects in space is outside the scope of this project.

Under normal circumstances, metals can reach up to 260 degrees Celsius when continuously orbiting the Sun. In a 90 min orbit, an artificial satellite may experience a temperature variation between 120 degrees Celsius and -180 degrees Celsius, i.e. a swing of 300 degree Celsius between the exposed and non-exposed orbital points. To reduce object material temperature, the selection of materials and protective coatings or blankets is critical. These measures narrow the temperature band a spacecraft experiences to a 120 degrees Celsius and -129 degrees Celsius interval. A careful selection of materials with a low α and lower ε yields favourable α/ε ratios. However, this ratio can be further improved through special coatings. The application of transparent Teflon with high ε to metallic surfaces can further reduce the object temperature, replacing the relatively low metal ε with a high ε Teflon. As result, a metal structure can reach a steady state temperature of -23 degrees Celsius when facing constant Sun.

Elevated temperature accelerates most of the degradation processes that occur in polymers (See 3.9.2, greater mobility of chains) such as ageing, oxidation (in presence of oxygen), chemical attack and mechanical stress induced by thermal cycling (TC, creep and fatigue).

Temperature is therefore a major parameter in the process of materials degradation when acting in synergy with other components of space environment, especially radiation, but also may promote recovery phenomena (annealing of color centers in inorganics).

For organic materials, degradation increases with temperature due to the greater chain mobility (higher scission/x-linking ratio)⁴⁰. In inorganic materials, temperature governs annealing of colored centers as observed in optics⁴¹.

At low temperature, synergy with space radiation is not straightforward and depends on materials type^{42,43}: degradation mechanisms are "frozen" in materials sensitive at room temperature while no significant change is observed in more resistant materials (epoxy, polyimide), silicones are more sensitive at low temperatures.

For missions with strong temperature constraints (range and cycling), it was shown that the representative simulation of the mission profile was required to expect a reliable estimate materials degradation and prediction of End-of-Life performances⁴⁴.

⁴⁴ "Space Radiation Effects of simulated venus-mercury fly-by on solar absorptance and transmittance properties of solar cells, coverglasses and adhesives", L.B. Fogdall et al, AIAA-71-452.



⁴⁰ "Space environment effects on polymeric materials", R.L. Kiefer et al., Nasa technical report NAG-1-678.

⁴¹ "Effect of radiation on glasses in borosilicate and boron-lead-silicate systems", V. I. Pavlenko, Glass and Ceramics, Vol. 59, Nos. 1 – 2, 200.

⁴² "Behaviour of Organic Materials in Radiation Environment", Marc Tavlet and Sorin Ilie, IEEE, 2000.

⁴³ "Results of radiation at cryogenic temperature on some selected organic materials for the LHC", H. Schönbacher et al, CERN 96-05, July 1996.

Moreover, at macroscopic level, temperature cycling (alone or in synergy with space radiation) induces mechanical stress that can result in enhanced overall degradation or at stress location^{45,46}. As already mentioned, temperature is also at play in the AO degradation via the kinetics of desorption volatile products and at promoting VUV/dose degradation of polymers (mobility of chains).

6 Vacuum and air-to-vacuum transitions

One of the most distinguishable environmental conditions that the astronauts must endure in space is the virtual absence of atmosphere. The atmosphere as we know maintains a relative constant concentration of nitrogen (70 %) and oxygen (21 %), among others gaseous elements. At sea level, the atmosphere pressure is around 760 torr (1013 mbar) but with increasing altitude, the atmospheric pressure drops. At 5 km height, the pressure drops to 50 % the value measured at sea level and about 50 km altitude, the pressure loss amounts to 99.9 %.

The presence of oxygen during irradiation induces oxidation reactions and the formation of free radicals in the material. This mechanism impacts on the scission/cross-linking rate at play. Several orders of magnitude for the degradation level can be observed between radiation response in air (worst case) and under vacuum. Annealing mechanisms are also observed with oxygen during vacuum-to-air transitions with kinetics varying from minutes to hours^{47, 48}. Ground testing of surface materials requires vacuum conditions (< 10⁻⁷ mbar) for particles exposures (surface dose implies beams of low energy particles, contamination control and representativeness of degradation mechanisms).

7 Summary of space environment parameters from the materials degradation standpoint

Depending on the environment and the family of materials of concern, here are the main degradation mechanisms that can be observed:

- Temperature: mechanical stress due to thermal cycling (TC), higher scission/ x-linking ratio or colour centres bleaching at temperature > RT.
- UV (mostly polymers): bonds breaking and rearrangement (photolysis), excitation and ionization.
- Charged particles: ionization (bonds breaking, radicals and colour centres depending on materials type), displacement damage (radiolysis), physical sputtering (solar wind), blistering (metals only, and for large fluence).
- AO (polymers, metals, thin coatings): oxidation leading to erosion of surface materials.

With operational conditions combining these constraints, synergy will lead to enhanced degradation and potential generation of debris.

⁴⁸ "Space environment effects on polymeric materials", R.L. Kiefer et al., Nasa technical report NAG-1-678.



⁴⁵ "Telescope Solar Arrays Surface and Bulk Degradation of Teflon® FEP Retrieved from the Hubble Space", M. Moser et al., High Performance Polymers 2008; 20; 429.

⁴⁶ "Degradation of Teflon FEP Following Charged Particle Radiation and Rapid Thermal Cycling", Townsend J. et al., 20th Space Simulation Conference: 201-209 (NASA/CR- 1998-208598-Preprint).

⁴⁷ "Eight years GEO ground testing of thermal control coatings", J. Marco, S. Remaury, C. Tonon. ISMSE conference 2009

Solar <u>flare</u>	MeV-GeV	Non <u>ionising</u> Damage	Photonics	JAT M
Radiation belts	MeV	Ionizing Ageing	Materials	
Plasma (hot -> ionosphérique)	keV-MeV	Surface- <u>bulk</u> charging, sputtering	Dielectric, insulators, surface (propu)	
Atomic oxygen (residual atm.)	eV	Oxydation, (chemical) erosion	Polymers	10. M
Electromagnetic radiation (sun)	200-400 nm (<10eV)	Ageing, temperature effect	Surface materials, Coatings, optics	
Space debris	Hypervelocity impacts	Surface pits, holes	Surface mat. & Sub-systems	
Vacuum	(10 ⁻⁴) 10 ⁻⁹ – 10 ⁻¹⁴ mbar	Outgassing (contamination)	Surface materials, optics	
Temperature	Top & cycling	Mechanical stress	Materials	

