Title:	**GRAphene Executive Summary**		
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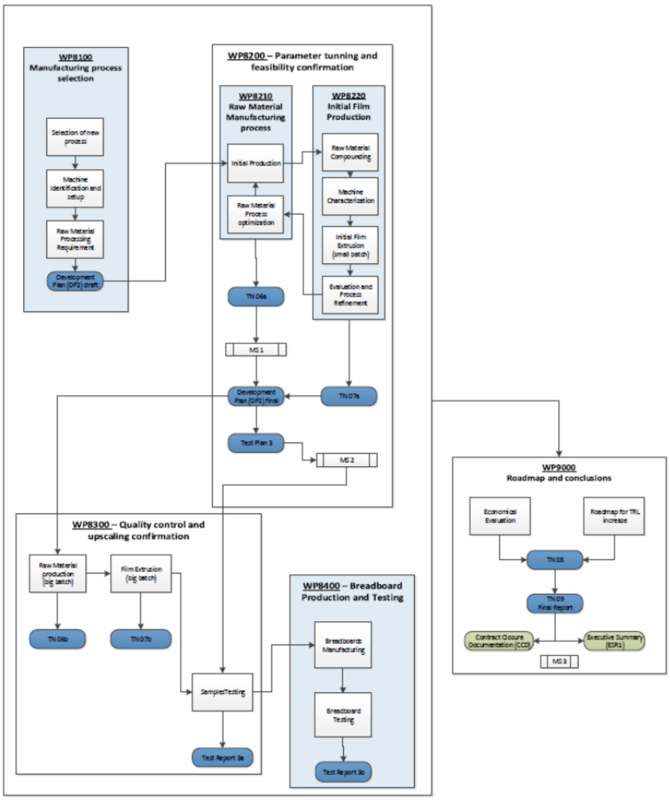
Due to its well-established unique properties Graphene and its derivate have demonstrated to be a material of choice for many applications. The incorporation of Graphene into polymeric matrices has showed potential to improve material properties like strength, modulus, thermal stability and also gas permeability.

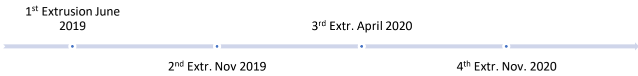
The aim of the activity, developed by Omnidea-RTG in conjunction with ESA, Pleione SA and Fraunhofer IVV, was to produce a thin film polymer-based product enhanced with Graphene nanoparticles to decrease He gas permeability while maintaining thermal bonding properties and without major penalties in UV resistance, for use in high-altitude inflatable structures. The proposed technological application is the usage of this thin film as envelope inner layer for high altitude airborne platforms which, from a lower altitude (vs. a LEO satellite) can perform Earth Observation or, alternatively, satellite data correction/validation.

The original ESA activity (contract 4000115792) focused on achieving a good baseline, in terms of Graphene per weight solution to create the TPU-GRA material, while this continuation activity focused on process control, industrialization potential demo and economical merits analysis.



Following task 8100 to confirm the feasibility of the production of the graphene thin film using the new industrial machine (and respective results summarized in the previous version of this document (i.e. [RD 4]), WP 8300 was destined to present the developments in material production and extrusion achieved for the "large batch" of produced TPU-GRA which was afterwards tested in WP8400 as summarized in [RD 3].

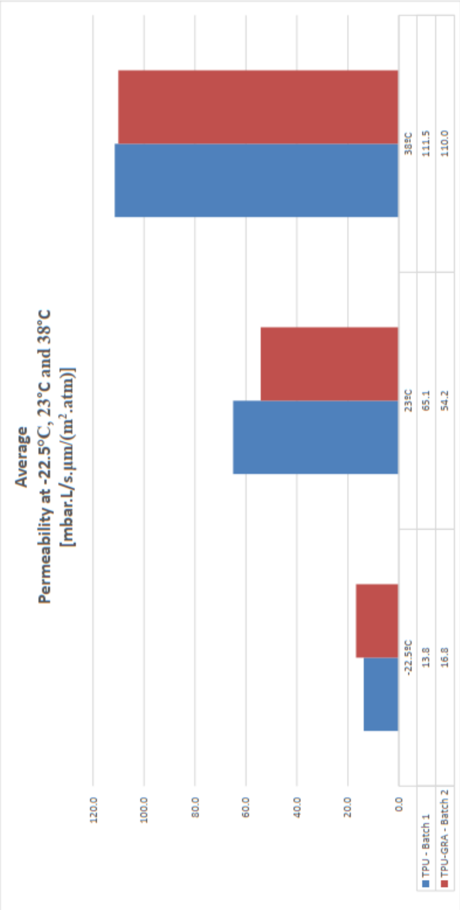
In reality task 8100 was finished by the 2nd extrusion attempt, having been calibrated but not achieved in the first extrusion attempt. Conclusion of WP8200 was more complicated since the extrusion attempt aimed at confirming parameter stabilization (extrusion attempt #3) was not successful in obtaining a good extrusion material, even if it was successful at confirming leakage properties thus, the decision had to be taken to extract the samples and breadboard material from extrusion batch #2. WP 8200 was then finalized by Nov. 2020 when the 4th extrusion successfully confirmed the extrusion #2, from Nov. 2019; thus, in all, 4 extrusion iterations were needed to finalize WP 8200, more than the originally 2 envisaged.



Success in obtaining the target thickness (100um) as well as a uniform thickness distribution across the width of the extruded film also proved challenging. This caused performance issues during manufacturing and testing, as it negatively influenced the TPU-GRA permeability.

The sheets of Graphene enhanced material (TPU-GRA) provided by Fraunhofer-IVV had low defects and good homogeneity and consistency of the base material dispersion but big differences in thickness. The TPU-GRA material of this activity achieved very good mechanical properties and kept the good "elastic" TPU properties with an average reduction in the tensile strength of only 30% with a slightly higher elongation at break.

The permeability of the polymeric samples is better at lower temperatures, with both the TPU and the TPU-GRA samples confirming this trend. The Graphene enhanced samples presented better permeability than the TPU baseline for ambient temperature and just ever so slightly at elevated temperatures; nonetheless they have a worse performance at low temperatures. In the end the activity was able to produce to produce TPU-GRA material endowed with lower permeability than the comparable TPU material, with improvements of up to 17% at ambient temperature. With the progress during the activity, it was possible to finally achieve pressurizable breadboards which could even be burst tested.



For envisaged future developments a setup based on high shear dispersion with Industrial type evaporators is the envisaged option to again increased production capability one order of magnitude, using of a conveyor belt furnace/dryer and condensation system for safe/economical solvent collection/evaporation. This method is easy to combine with a pilot line (to directly extrude the thin film from the produced pellets) or to keep extruding in an external.

The economical evaluation described the production method used in the original activity, followed by the production method used in the current activity and finished by explaining the production method envisaged for a potential follow-on step; in doing so, the roadmap became an active part of the economical evaluation. This is because the critical assumption for the economical evaluation is that it would be unfair to compare the production costs of TPU-GRA with those of "base TPU" since the latter is produced in thousands of tons per year. From there, a case was created where production of up to 20 tons per year could be envisaged without breaking critical model assumptions. Afterwards the return on investment is measured from the difference between the extra TPU-GRA envelope cost (as TPU-GRA will always be more expensive than TPU) vs. the savings made on Helium costs, due to the lower monthly diffusion of TPU-GRA.

These calculations are presented bundled with a sensitivity analysis where one can see the impact of changing critical assumptions such as TPU-GRA production rate, Helium average monthly leakage rate, envelope size and Helium price. The conclusion is that, assuming the TPU-GRA delivers a 20% reduction in monthly average losses, for any annual production rate between 20 and 100 tons and current Helium prices, TPU-GRA have a positive net present value and a return on investment within a maximum of 2 years, as long as the envelope has an internal volume bigger than 600m3. As the current trend in HAPS envelopes is to go beyond this the economical evaluation shows that the original interest in developing TPU-GRA as a future alternative to "simple TPU" was justified.

Comparison as TPU-GRA Annual Production scales up and cost scales down
(@ constant Envelope volume, Helium prices and Helium envelope losses)

Annual Production	600	5280	**21120**	84480	168960	kg
Length	32.00	32.00	32.00	32.00	32.00	m
Radius	4.00	4.00	4.00	4.00	4.00	m
L/D ratio	4.0	4.0	4.0	4.0	4.0	m
Area of envelope	603	603	603	603	603	m2
Envelope volume	1877	1877	1877	1877	1877	m3
TPU-GRA - Price per m2	11.2	4.5	3.5	2.5	1.7	€/m2
TPU-GRA - Inner Envelope cost	6,755 €	2,710 €	2,085 €	1,520 €	1,022 €	
TPU - Price per m2	1.7	1.7	1.7	1.7	1.7	€/m2
TPU - Inner Envelope cost	1,013 €	1,013 €	1,013 €	1,013 €	1,013 €	
Price difference (TPU-GRA VS TPU)	**5,741 €**	**1,697 €**	**1,072 €**	**507 €**	**8 €**	
Helium prices	50 €	50 €	50 €	50 €	50 €	
Helium density STD	0.176	0.176	0.176	0.176	0.176	kg/m3
Overpressure	10%	10%	10%	10%	10%	
Helium contained in inner envelope	363	363	363	363	363	kg
Helium envelope losses per month - TPU-GRA	3.2%	3.2%	3.2%	3.2%	3.2%	
Helium envelope losses per month - TPU	4.0%	4.0%	4.0%	4.0%	4.0%	
Savings per month	2.9	2.9	2.9	2.9	2.9	kg
Savings per year	34.9	34.9	34.9	34.9	34.9	kg
Savings value per year	**1,744 €**	**1,744 €**	**1,744 €**	**1,744 €**	**1,744 €**	
Comparison (Material Cost Vs Helium Loss gains)	-3,997 €	47 €	672 €	1,237 €	1,735 €	

Comparison as Envelope volume scales up
(@ constant Annual Production, Helium prices and Helium envelope losses)

Annual Production	21120	21120	21120	21120	21120	kg
Length	8.00	12.00	16.00	24.00	32.00	m
Radius	1.00	1.50	2.00	3.00	4.00	m
L/D ratio	4.0	4.0	4.0	4.0	4.0	m
Area of envelope	38	85	151	339	603	m2
Envelope volume	29	99	235	792	**1877**	m3
TPU-GRA - Price per m2	3.5	3.5	3.5	3.5	3.5	€/m2
TPU-GRA - Inner Envelope cost	130 €	293 €	521 €	1,173 €	2,085 €	
TPU - Price per m2	1.7	1.7	1.7	1.7	1.7	€/m2
TPU - Inner Envelope cost	63 €	142 €	253 €	570 €	1,013 €	
Price difference (TPU-GRA VS TPU)	**67 €**	**151 €**	**268 €**	**603 €**	**1,072 €**	
Helium prices	50 €	50 €	50 €	50 €	50 €	kg
Helium density STD	0.176	0.176	0.176	0.176	0.176	kg/m3
Overpressure	10%	10%	10%	10%	10%	
Helium contained in inner envelope	6	19	45	153	363	kg
Helium envelope losses per month - TPU-GRA	3.2%	3.2%	3.2%	3.2%	3.2%	%
Helium envelope losses per month - TPU	4.0%	4.0%	4.0%	4.0%	4.0%	%
Savings per month	0.0	0.2	0.4	1.2	2.9	kg
Savings per year	0.5	1.8	4.4	14.7	34.9	kg
Savings value per year	**27 €**	**92 €**	**218 €**	**736 €**	**1,744 €**	
Comparison (Material Cost Vs Helium Loss gains	-40 €	-59 €	-50 €	133 €	672 €	

Comparison as Helium price changes
(@ constant Annual Production, Envelope volume and Helium envelope losses)

Annual Production	21120	21120	21120	21120	21120	kg
Length	32.00	32.00	32.00	32.00	32.00	m
Radius	4.00	4.00	4.00	4.00	4.00	m
L/D ratio	4.0	4.0	4.0	4.0	4.0	m
Area of envelope	603	603	603	603	603	m2
Envelope volume	1877	1877	1877	1877	1877	m3
TPU-GRA - Price per m2	3.5	3.5	3.5	3.5	3.5	€/m2
TPU-GRA - Inner Envelope cost	2,085 €	2,085 €	2,085 €	2,085 €	2,085 €	
TPU - Price per m2	1.7	1.7	1.7	1.7	1.7	€/m2
TPU - Inner Envelope cost	1,013 €	1,013 €	1,013 €	1,013 €	1,013 €	
Price difference (TPU-GRA VS TPU)	**1,072 €**	**1,072 €**	**1,072 €**	**1,072 €**	**1,072 €**	
Helium prices	30 €	40 €	**50 €**	60 €	70 €	kg
Helium density STD	0.176	0.176	0.176	0.176	0.176	kg/m3
Overpressure	10%	10%	10%	10%	10%	
Helium contained in inner envelope	363	363	363	363	363	kg
Helium envelope losses per month - TPU-GRA	3.2%	3.2%	3.2%	3.2%	3.2%	%
Helium envelope losses per month - TPU	4.0%	4.0%	4.0%	4.0%	4.0%	%
Savings per month	2.9	2.9	2.9	2.9	2.9	kg
Savings per year	34.9	34.9	34.9	34.9	34.9	kg
Savings value per year	**1,046 €**	**1,395 €**	**1,744 €**	**2,093 €**	**2,441 €**	
Comparison (Material Cost Vs Helium Loss gains)	-26 €	323 €	672 €	1,020 €	1,369 €	

Comparison as monthly Helium envelope losses vary
(@ constant Annual Production, Envelope volume and Helium prices)

Annual Production	21120	21120	21120	21120	21120	kg
Length	32.00	32.00	32.00	32.00	32.00	m
Radius	4.00	4.00	4.00	4.00	4.00	m
L/D ratio	4.0	4.0	4.0	4.0	4.0	m
Area of envelope	603	603	603	603	603	m2
Envelope volume	1877	1877	1877	1877	1877	m3
TPU-GRA - Price per m2	3.5	3.5	3.5	3.5	3.5	€/m2
TPU-GRA - Inner Envelope cost	2,085 €	2,085 €	2,085 €	2,085 €	2,085 €	
TPU - Price per m2	1.7	1.7	1.7	1.7	1.7	€/m2
TPU - Inner Envelope cost	1,013 €	1,013 €	1,013 €	1,013 €	1,013 €	
Price difference (TPU-GRA VS TPU)	**1,072 €**	**1,072 €**	**1,072 €**	**1,072 €**	**1,072 €**	
Helium prices	50 €	50 €	50 €	50 €	50 €	kg
Helium density STD	0.176	0.176	0.176	0.176	0.176	kg/m3
Overpressure	10%	10%	10%	10%	10%	
Helium contained in inner envelope	363	363	363	363	363	kg
Helium envelope losses per month - TPU-GRA	2.0%	2.6%	**3.2%**	3.8%	4.4%	%
Helium envelope losses per month - TPU	2.5%	3.3%	**4.0%**	4.8%	5.5%	%
Savings per month	1.8	2.4	2.9	3.5	4.0	kg
Savings per year	21.8	28.3	34.9	41.4	48.0	kg
Savings value per year	**1,090 €**	**1,417 €**	**1,744 €**	**2,071 €**	**2,398 €**	
Comparison (Material Cost Vs Helium Loss gains	18 €	345 €	672 €	999 €	1,326 €	

The following could be a summary of achievements accomplished during the current De-risk phase of the project:

- Confirm the best GRAphene formulation once the new film manufacturing process is stable, to guarantee the quality improvement. ⇒ accomplished √
- Improve the production of the raw material, from in-situ processing to pellets-type production, providing repeatability and transition to industry standard machines. ⇒ accomplished √
- Improve the manufacturing scalability by changing the process from Doctor Blade into a process closer to those used in the plastic film industry. ⇒ only partially accomplished
- Confirm economic viability of the proposed technology and provide roadmap towards future developments. ⇒ accomplished by analysis √