Durable Antifog Coatings for Spacesuit Helmets

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Maintaining a high level of visibility through the helmet of NASA Extravehicular Mobility Unit (EMU) is very difficult under inclement operational conditions. The interior of the helmet bubble will fog up in a high humidity / cold environment with high work rate breathing for extravehicular activity (EVA) that can last up to 8 hours. Currently used wipe on antifog solutions have problems with i) durability, requiring reapplication for every EVA, ii) can potentially get in the astronaut's eye, impairing their vision, and iii) bottles of solution are a consumable that need to be continuously restocked. Luna Labs has developed a durable, transparent coating that is projected to maintain optical and antifogging properties for the lifetime of the equipment. Luna Labs has leveraged our established Gentoo™ sol-gel coating platform to create a robust, transparent, long-lasting, and antifogging coating. Additionally, the proposed sol-gel coating is thin (2-8 µm), low cost (cents/ft^2), and easy to apply while providing excellent abrasion durability and antifogging properties. Luna Labs has produced a coating formulation to possess antifogging properties so that moist air will wet out, forming a microscopically thin sheet of water that does not scatter light. A custom superhydrophilic additive which crosslinks into the durable coating matrix provides superb antifogging properties. This non-scratch transparent coating that will provide continuous antifogging efficacy for >8 hours and environmental durability to last the lifetime of coated component. This technology is relevant to NASA spacesuit applications, as well as for automobiles, aircraft, eyewear, SCUBA masks or any other applications that require transparent antifogging properties.

Nomenclature

EMU	=	extravehicular mobility unit
EVA	=	extravehicular activity
IPA	=	isopropyl alcohol
DI	=	deionized
UC	=	ultra clear
NASA	=	National Aeronautics and Space Administration
RT	=	room temperature

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I. Introduction

ENSURING visibility for astronaut EMU helmet visors is vital for operational success and safety during EVA or space walks. Helmet fogging is the most significant limiting factor for astronaut visibility and is currently minimized by the use of disposable antifogging wipes. Disposable wipes are problematic due to their potential to chemical irritation to the end-user astronaut's eyes, and their requirement to be re-applied prior to every EVA or spacewalk (1). The ideal solution would be a durable antifog coating that would survive the service life of the equipment, but no coatings are commercially available.

Luna Labs has developed a permanent sol-gel coating that mitigates fogging activity while retaining optical clarity of the underlying substrate. The coating is designed as an inexpensive, easy-to apply antifogging solution that is scalable to apply to curved surfaces. The coating chemistry is inherently non-toxic and non-hazardous associated with a water/alcohol based chemistry that results in a highly cross-linked inorganic/polymer hybrid film with excellent impact resistance, flexibility, and toughness. The sol-gel system utilizes a series of hydrolysis-condensation reactions to result in a dense three-dimensional network. An overview of the cured network is shown in Figure 1.

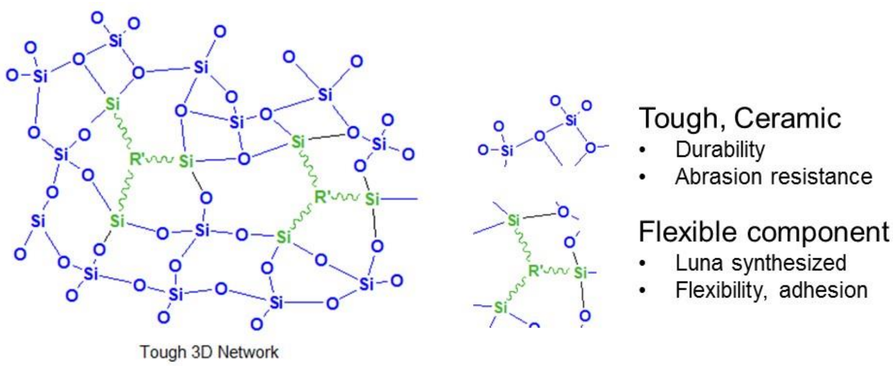


Figure 1. Basis for the sol-gel performance: Combination of a hard ceramic component with flexible linkers produce high toughness for abrasion resistance and durability.

Luna Labs has developed a superhydrophilic version of this sol-gel coating system that provides strong antifogging behavior and longevity. These coatings have excellent durability due to use of unique hard inorganic nanoparticles for abrasion resistance within a tough elastomeric hybrid for flexibility and adhesion to polymeric substrates. The coating is uniform and thin (3-6 microns) compared to traditional protective polymeric coatings. Representative photos of polycarbonate coated with Luna Labs' antifog solution are shown in Figure 2.

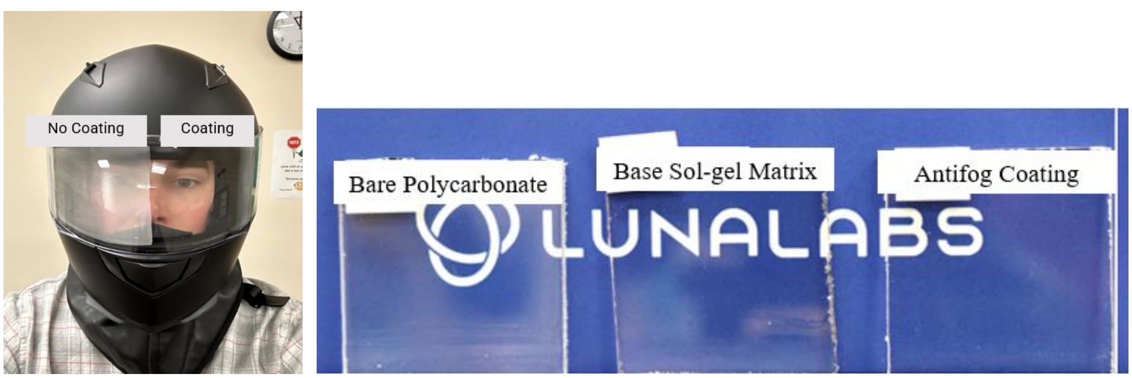


Figure 2. Representative pictures of Luna Labs' antifog coating: half of a motorcycle helmet visor (left) and on a cut polycarbonate substrate compared to bare polycarbonate and the base sol-gel matrix.

II. Evaluation of Antifog Coating Properties

A variety of performance evaluation methods were investigated during the work including simulated breathing fog response efficacy testing, coating adhesion to polycarbonate, Taber abrasion, resistance to cleaning with common solvents, and resistance to common solvents. The sol-gel coating was applied via flow-coating over bare, UC impact resistant polycarbonate and glass. An overview of coating evaluation test methods is provided in Table 1.

Table 1. Antifog Sample Test Procedures.

Test	Method	Target
Antifog Efficacy	Expose coating surface to 122°F water vapor and evaluate fog presence.	Remain optically clear (no fogging) after 3 minutes exposure
Coating Thickness	Measure coating thickness on multiple coating locations	3 – 6 microns average across coating surface
Adhesion	ASTM 3359	5B (0% coating removal)
Abrasion Resistance	ASTM D1003, D4060	100 Taber abrasion cycles using CS-10F abrasion wheels and 500g weight; $\Delta T <5\%$, $\Delta H <2\text{-}3\%$
Resistance to Cleaning	ICES Antifog Cleaning Test	Test antifog efficacy and adhesion after wiping coatings 20 times with: - Water - Isopropanol
Solvent Resistance	Luna Labs developed	Test antifog efficacy and adhesion after 24 hour soak in: - Water - IPA

A. Antifog Efficacy

Luna Labs' antifog coating was tested for antifogging efficacy following a 'standard' lab-scale antifogging[2] test procedure, defined by placing a sample over a partially covered beaker of water heated to 122°F, then visually observing the presence of fog for 3 minutes (2). The antifog efficacy test setup is shown in Figure 3. Samples were exposed to hot water vapor by placing the sample coupons over a partially sealed, 500 ml beaker of water set to 122°F, then visually observing the surface for three minutes. An example image of the 'standard' lab-scale antifog test is shown in Figure 3. Each formulation was tested for five cycles. Time to fog (the amount of time it takes samples to fog after the coupon has been placed over the beaker), and time to de-fog (the amount of time it takes samples to de-fog after removing from the beaker) were reported. If samples did not fog, results state 'remained clear'. Resistance to fogging results are provided in Table 2.

The coatings were subjected to a second antifogging efficacy test in order to determine whether the coating can maintain antifogging and optically clear for the duration of an 8-hour EVA or spacewalk. Luna Labs found that the coating maintains antifogging efficacy under constant exposure to hot steam (122°F) for at least 8 hours, shown in Table 3.

Table 2. Antifog efficacy results.

Sample ID	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
Luna Labs' Antifog Coating	Remained clear	Remained clear	Remained clear	Remained clear	Remained clear
Bare Polycarbonate	Fogged immediately	Fogged immediately	Fogged immediately	Fogged immediately	Fogged immediately

Table 3. Extended duration antifog efficacy results.

Sample ID	8-hour cycle
Luna Labs' Antifog Coating	Remained clear
Bare Polycarbonate	Fogged immediately

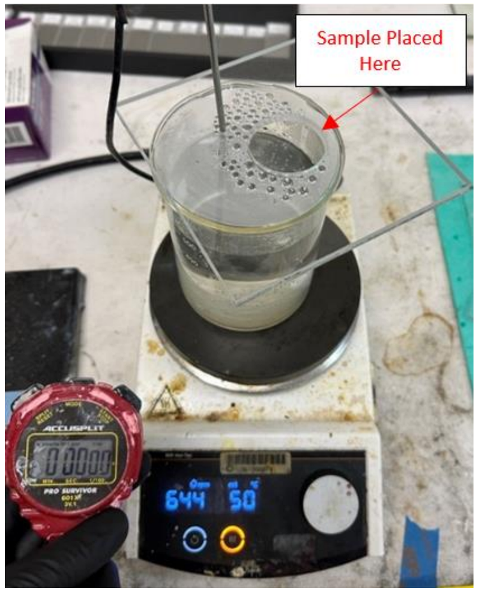


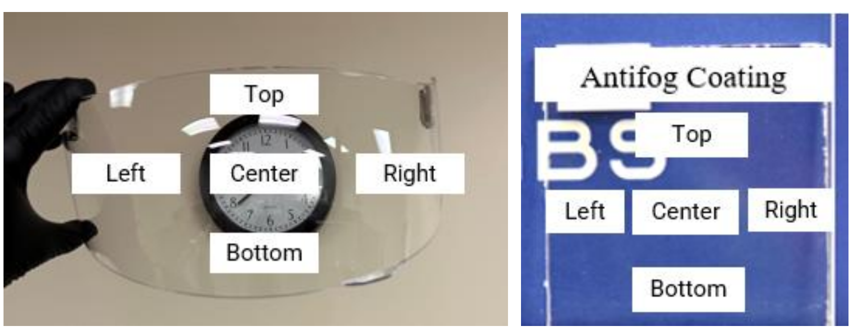
Figure 3. Lab-scale antifog efficacy testing setup.

B. Coating Thickness

Thickness data was taken on flat and curved coupons using a Filmetrics Thin Film Analyzer.[3] The target thickness for samples is 3-6 microns with a low deviation between measurement locations. The curved surface coupon chosen was a polycarbonate motorcycle helmet visor, and the flat coupon was a 4"x4" square cut polycarbonate substrate. Results are shown in Table 4.

Table 4. Coating thickness results.

	Thickness (microns)				
Sample ID	Top	Left	Center	Right	Bottom
Luna Labs' Antifog Coating on a flat surface	3.4	3.6	3.7	3.7	4.6
Luna Labs' Antifog Coating on a curved surface	3.2	4.1	3.6	3.9	4.5



[3] www.filmetrics.com

Figure 4. Thickness Measurement Locations on curved (left) and flat (right) substrates.

C. Coating Adhesion Results

Adhesion testing was performed in accordance with ASTM 3359 crosshatch adhesion test. Samples were tested on all antifogging coupons, before and immediately after the coupons were subjected to five cycles of fogging resistance testing. Coupons which showed no delamination (perfect 5B result) were classified as passing. Samples which showed any delamination (>0%) were classified as failing. Adhesion testing results are shown in Table 5.

Table 5. Crosshatch adhesion results.

Sample	Pre-Fogging Resistance Test	Post-Fogging Resistance Test
Luna Labs AF-1	5B	5B
Base Matrix	5B	5B

D. Optical Clarity and Abrasion Results

Optical measurements were taken using a BYK Haze-Gard Plus in accordance with ASTM D1003, before and after subjecting samples to Taber abrasion. Taber abrasion was performed using a Taber 5135 Abraser. Coupons were subjected to 100 cycles of Taber abrasion using CS-10F abrasion wheels and 500g weights. Results show initial optical properties and change in optical properties post-abrasion. Results are shown in Table 6 and Table 7.

The base matrix provides excellent abrasion resistance and resilient optical properties. This coating system is highly resistant to abrasion and remains optically clear up to 1000 Taber abrasion cycles using the same test conditions, shown in Figure 5. The addition of the hydrophilic additive, zwitterion silane, results in slight surface roughness which negatively effects abrasion results.

Table 6. Antifog efficacy testing results.

Sample ID	Transmittance (%)	Haze (%)	Clarity (%)
Luna Labs' Antifog Coating	90.4	1.42	99.1
Bare Polycarbonate (Control)	90.3	0.45	99.8
Base Sol-Gel Matrix	90.2	0.66	99.6

Table 7. Change in optical properties post-100 cycles of Taber abrasion.

Sample ID	ΔT (%)	ΔH (%)
Luna Labs AF-1	1.3	10.68
Sol-Gel Base Matrix	0.1	0.18
Bare Polycarbonate (Control)	0.1	16.15

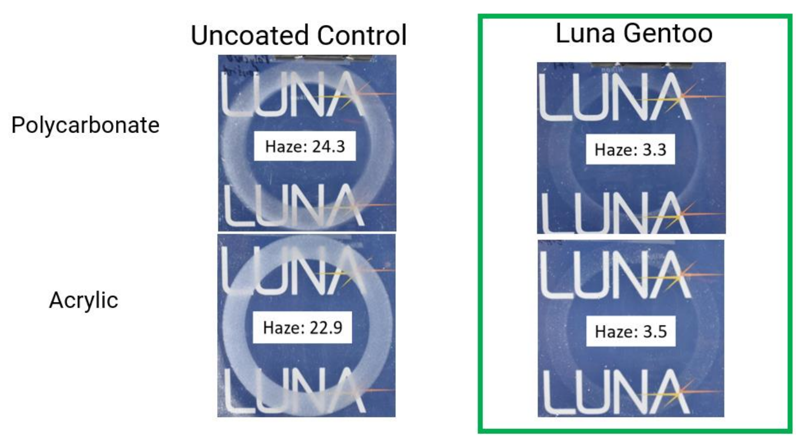


Figure 5. Taber abrasion results comparison of uncoated polycarbonate and acrylic substrates vs. Gentoo™ after 1000 Taber abrasion cycles.

E. Chemical Resistance Results

Chemical resistance testing was performed by submerging antifog samples in DI water and reagent grade isopropyl alcohol (IPA) for 24 hours, then tested for adhesion and antifogging efficacy immediately following removal from the solvent. Samples were wiped clean using a lent-free cloth prior to testing. Chemical resistance adhesion and antifogging testing results are shown in Table 8 and Table 9.

Table 8. Fogging resistance and adhesion results after soaking samples in DI water for 24 hours.

Sample ID	Standard anti-fog test	Adhesion
Luna Labs AF-7	- Fogging at 7 sec - Film formed at 90 seconds then remained clear	5B
Sol-gel base matrix	Fogged immediately	5B

Table 9. Fogging resistance and adhesion results after soaking samples in IPA water for 24 hours.

Sample ID	Standard anti-fog test	Adhesion (post-test)
Luna Labs AF-1	Remained Clear	5B
Sol-gel base matrix	Fogged immediately	5B

III. Acknowledgements

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IV. Conclusion

Luna Labs' protective sol-gel coating has been shown to be effective at maintaining the optical clarity of polycarbonate substrates when exposed to hot steam or fog. The results of excellent antifogging performance and abrasion resistance demonstrate that the coatings are relevant to improve visibility of transparent substrates including polycarbonate and glass. For these reasons, the polymer/inorganic hybrid coating technology described herein represents a significant advance in the optical antifogging market.

References

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