Exploration Helmet Permanent Anti-Fog Study

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For the current Extravehicular Mobility Unit (EMU) spacesuit, an astronaut applies an anti-fog solution to the interior of the helmet bubble before each EVA. However, the anti-fog solution has been reported to cause eye discomfort during at least seven EMU EVAs when the anti-fog solution contacted the crew member's eyes. During STS-100, astronaut Chris Hadfield reported the eye irritation temporarily blinded him during his spacewalk. In addition, the wipe on anti-fog solution is a consumable that needs to be accounted for and a supply launched for missions. To solve this, NASA has tested different permanent anti-fog coatings. However, major issues have arisen with Human in the Loop (HITL) testing with the coatings. Cleaning and removing Valsalva devices which use pressure sensitive adhesives have been challenges to avoid damaging the permanent anti-fog coating. Due to these issues, further investigation is being completed evaluating two solvent based anti-fog solutions: Exxene's HCF-100 and FSI's Visgard 106-94. Each coating will be evaluated on polycarbonate samples for application consistency, steam cycles (mimicking breath cycles), cleaning durability, haze, and light transmission. This study will determine if either coating is a viable option to pursue as a permanent anti-fog for spacesuit helmet applications.

Nomenclature

CDG = Coatings Design Group
CSSS = Constellation Space Suit Systems
EMU = Extravehicular Mobility Unit
EVA = Extravehicular Activity
DI = Deionized
DVT = Design Verification and Test
GP = General Purpose
HITL = Human In The Loop
IPA = Isopropyl Alcohol
ISS = International Space Station
NASA = National Aeronautics and Space Administration
NBL = Neutral Buoyancy Lab
MPT = Manned Pressurized Time
UC = Ultraclear
WSTF = White Sands Test Facility
xEMU = Exploration Extravehicular Mobility Unit
xEVAs = Exploration Extravehicular Services

I. Introduction

PREVENTING fog on the helmet visor of a spacesuit is required to maintain a clear field of view and is crucial for executing a safe Extravehicular Activity (EVA) or spacewalk. First developed during Project Gemini, anti-fog

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treatments were a temporary wipe on surfactant film applied to the inner polycarbonate visor.[1] These worked by creating a hydrophilic film by minimizing the surface tension which resulted in a non-scattering film of water instead of single droplets.[1] The current Extravehicular Mobility Unit (EMU) spacesuit that is used on the International Space Station (ISS) still uses a similar temporary wipe on anti-fog to ensure a clear visor. However, this has two issues. First, this is a temporary treatment that requires re-application prior to each EVA. Second, it has been reported to cause eye discomfort for at least seven or more EVAs.[2]

NASA has been pursuing permanent anti-fog as a solution to replace the temporary treatment. Previously, coatings HTAF-308 and HTAF-601 have been pursued as options but failed during Human In The Loop (HITL) testing. Two new solvent based anti-fog solutions are now being evaluated: Exxene's HCF-100 and FSI's Visgard 106-94. This study will attempt to understand if either coating is a viable option to pursue as a permanent anti-fog for future spacesuit helmet applications as a replacement for the wipe-on anti-fog.

II. Background

To understand the history of the previous failed attempts at certifying other anti-fog coatings, a background is given for HTAF-308 and HTAF-601.

A. HTAF-308

The EMU program investigated a permanent anti-fog coating in early 2000 using HTAF-308 hard coat anti-fog made by Exxene corporation. According to Exxene's product data sheet, HTAF-308 is a water-based anti-fog coating made for long lasting resistance to fog and condensation.[3] The HTAF-308 coating was used on EMU helmets which were already in service with several hours of Manned Pressurized Time (MPT). This means the coating was not applied to pristine polycarbonate. The coating was also applied to helmets which were bonded into helmet rings.

The helmets went through a series of material property testing on flat coupons of polycarbonate and a White Sands Test Facility (WSTF) evaluation for toxicity testing. The coating initially passed this testing. The coating was then applied to helmets for Neutral Buoyancy Lab (NBL) testing and for manned use with the EMU in a thermal vacuum chamber run. During both the NBL testing and chamber testing, there was reports of delamination of the coating which flaked and peeled off. Figure 1 shows pictures of the delamination occurring in one of the NBL helmets used in HITL testing.[4] The discrepancy report from this incident stated the delamination was suspected to be caused by removal of the Valsalva device which is used for helping crew members clear their ears with the change of pressure and are held in place by a temporary pressure sensitive adhesive.

Figure 1: Delamination of the HTAF-308 coating after NBL testing.
Pictures from NBL DR WF433401 **[4]**

Due to the poor HITL test results, HTAF-308 was not incorporated into the EMU helmet design. There were a few contributing factors that were believed to have caused the delamination failure. First, the helmets coated were not new, pristine helmet assemblies. Ideally, the coating would be applied prior to the helmet ring being bonded to the polycarbonate. This would allow for the "seam line" to be covered by the helmet ring. Since the seam between the uncoated and coated polycarbonate was right at the subject's chin, it was more sensitive to losing adhesion and peeling due to physical abrasion of the subject's chin especially if they had facial hair. This is also where the Valsalva device is typically placed which was also blamed for the delamination in the case of the NBL helmets. The polycarbonate itself might have also had residual oils left from subject's face during HITL testing or the currently used wipe on anti-fog that was not sufficiently removed before the coating was applied. Finally, the HTAF-308 itself was no longer deemed a "permanent" coating by Exxene Corporation.

B. HTAF-601

During the Constellation Space Suit System (CSSS) development, permanent anti-fog coatings were also pursued. In the report by Ralph Toscano titled "Constellation Space Suit Program Preliminary Evaluation of Permanent Anti-Fog Coatings As Applied to Helmet Applications - TDS #1082", he details a market survey that was completed to down select and test coatings as viable candidates.[1] A primary and secondary or "back up" coating was to be identified. The following permanent anti-fog coatings were considered: Clear-It by InnoSense LLC, Vueguard 932 by Performance Coatings International, HTAF-601 by Exxene Corporation, and SciCron AF-100 by SciCron Technologies. SciCron was quickly dropped from consideration because it would not be available in time for the study.[1]

For this study, six coated, flat test coupons made from polycarbonate were prepared with the anti-fog coatings according to vendor's instructions.[1] Transmission, haze, adhesion and abrasion resistance, craze resistance, cold box, steam, and human breath response tests were tests completed. At the end of the tests, HTAF-601 and Clear-It were both recommended for further testing as the primary and secondary candidates.[1] After the report was finished, Clear-It was discontinued. Therefore, HTAF-601 moved forward as the primary candidate.

HTAF-601 was evaluated on two prototype spacesuit designs: PXS and Z-2.5. During Z-2.5 NBL testing, it performed well and was recommended to move forward to xEMU Design Verification Testing (DVT) evaluations.[5] However, towards the end of Z-2.5 testing in summer of 2020, the helmet did report to have some coating delamination occur. One area of delamination was due to the improper use of isopropyl alcohol (IPA) near the coating which stripped the section that it came in contact with while the helmet ring was being cleaned. The other area was suspected to have started delaminating after COVID protocols started to use Cleaner-C (50% ivory soap and 50% water) instead of distilled or deionized (DI) water only for cleaning the interior of the helmet bubble post-test. No debris or flaking was found, but the coating looked to have been rubbed away and was hazy in those areas.

Due to the history of mostly positive performance of the HTAF-601, xEMU chose to utilize it for its permanent anti-fog on the interior of the pressure bubble. All Design Verification Test (DVT) helmets were coated with the HTAF-601. Initially, a coated helmet was sent to White Sands Test Facility (WSTF) to confirm it would pass toxicity testing. The coating performed well and passed the tests which considered the internal xEMU suit volume. Overall, the permanent anti-fog did prevent fogging from occurring during HITL testing in the lab and NBL environments. However, the coating on the xEMU helmets did start to delaminate in a similar method as seen in Z-2.5 testing after greater than 40 hours of MPT. A couple examples of delamination can be found in Figure 2. The size and location of where the delamination occurred was not consistent across all helmets. It was consistent that delamination started to occur when the helmet had been used for greater than 40 hours of MPT during HITL tests.

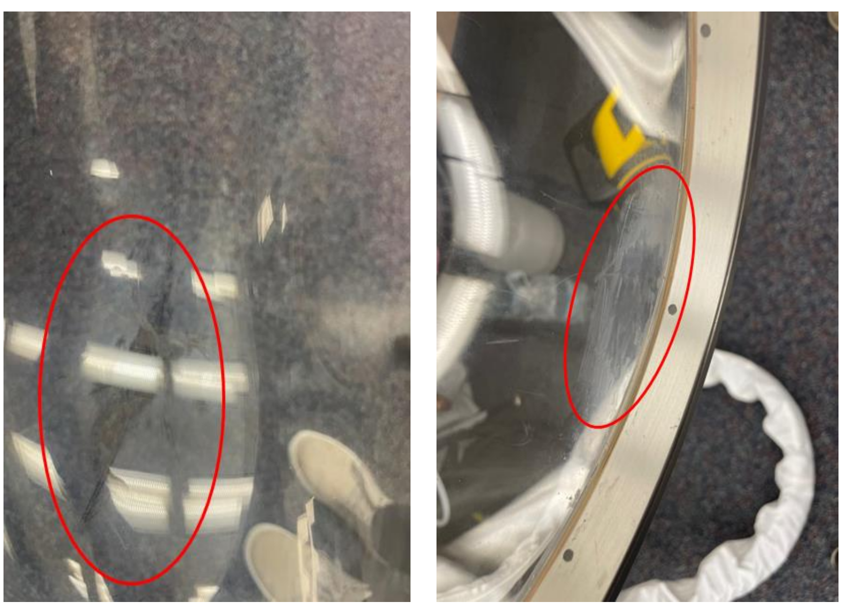

Figure 2: HTAF-601 Delamination on two xEMU helmets

There were a few contributing factors that were believed as potential causes for the delamination. First, the initial method of cleaning the helmets was using deionized (DI) water to dampen a clean, soft cloth and wiping the interior of the pressure bubble until cleaned. After seeing delamination, the team switched to using Kim-wipes for cleaning to ensure no chemical residue was left on the soft cloths previously used. Tests were done on helmet samples to see if distilled water would be better than DI water and if dabbing would be gentler than wiping. As seen in Figure 3, using distilled water while dabbing was determined to be the gentlest way to clean the coating. However, even with this improved cleaning method employed, the HTAF-601 continued to see delamination but it did seem to slow the progress and intensity. The second possible cause of the delamination could be the coating is applied too thin. The permanent anti-fog for most of the delivered DVT helmets is in the thickness range of two to four microns. Exxene considers the HTAF-601 to be a permanent coating, but then states the functionality of permanent anti-fog coatings benefits from the application of a thicker layer, in the range of six to twelve microns. However, the vendor's who coat the helmets with the HTAF-601 said that the required thickness is too thick to maintain helmet clarity and a smooth, consistent coating. The third potential cause could be the formulation of the coating itself. HTAF-601 is a water-based anti-fog coating. Potentially, breathe cycles from subjects during HITL testing could be breaking down the coating over time and making it more susceptible to damage. Switching to a solvent-based anti-fog coating could potentially mitigate this issue. The xEMU project started to investigate potential solutions such as adjusting cure times, adding a primer, or adding a crosslinking material for HTAF-601, but was informed Exxene was stopping production of this coating so efforts to optimize the HTAF-601 ceased.

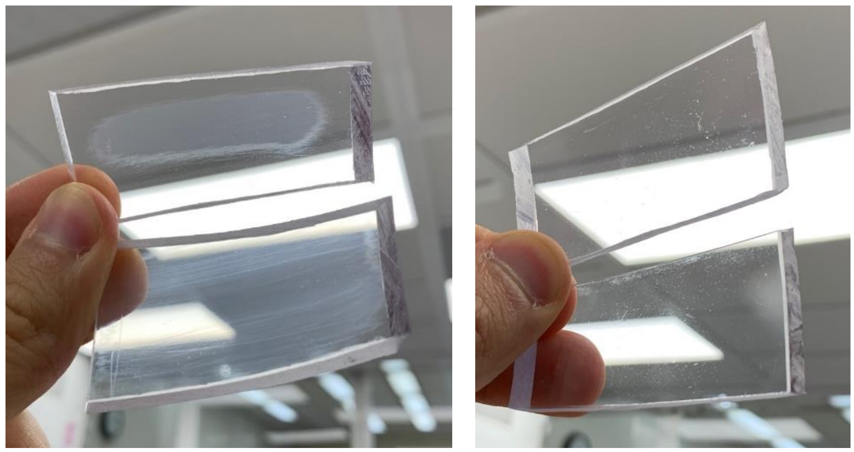

Figure 3: (Left) Samples wiped clean, Top: Distilled water, Bottom: DI water (Right) Sampled dabbed clean, Top: Distilled Water, Bottom DI Water

III. New Permanent Anti-Fog Coatings

Following lessons learned, NASA collaborated with Air-Lock Inc. to perform a market survey of permanent anti-fog coatings to investigate an alternative for HTAF-601. Solvent based coatings were especially interesting due to the delamination seen potentially coming from the water-based formulation of HTAF-601.

The team reached out to InnoSense due to the success of the Clear-It coating found during the CSSS market study. However, Clear-It manufacturing has been discontinued. Their alternate coating, FogGo is an anti-fog coating made from nanomaterials. It is reported to be very durable after days of cleaning and use.[6] Developed to meet the needs of the military, the coating is transparent and abrasion resistant.[6] However, FogGo is very expensive to procure and had very long lead times for delivery. Due to the cost and timeline required, it was not further considered with this study.

Exxene suggested HCF-100 Anti-Fog Coating as an alternative to HTAF-601. HCF-100 is a solvent based anti-fog coating that is formulated to provide permanent, non-fogging and anti-condensation surface on a variety of substrates.[7] It is reported to have chemical resistance against alcohols and typical household cleaners.[7] Due to this information, HCF-100 was chosen as a new candidate material for the new study.

Another permanent anti-fog very popular in the commercial market is Visgard 106-94. It is a two part polyurethane-based thermal cure coating.[8] The vendor reports it will provide excellent resistance to fogging, scratching, and chemical attack. It is intended for use on polycarbonate, acrylics, nylon, PVC, PETG, and certain other clear plastics without primers.[8] Visgard 106-94 was also chosen as a new candidate material for the study.

NASA's Materials and Processing team at JSC did review HCF-100 and Visgard 106-94 for open loop, breathing air applications for human in the loop testing. They did not have concerns with that application but did have concerns that the solvents used for both anti-fogs and the cure temperatures required could compromise the strength of the polycarbonate material of the helmet. With further studies, tensile testing of coated flat samples, burst testing of a coated helmet, and impact testing of a coated helmet should be considered to verify the anti-fog does not affect strength. In addition, toxicity testing should be performed under flight thermal vacuum conditions to verify there is no safety concern.

A. Testing

A process for how to manufacture, coat, and test the two coatings selected was developed in Table 1. The table is meant to represent the quantities and tests for one coating, and then would be repeated for the second coating. Samples of both General Purpose (GP) and Ultraclear (UC) polycarbonate material were used.

Table 1: Manufacturing and Test Process

Step	Task Description
1	Using extruded Tuffak GP material, Air-lock to produce: 1. 2 pcs of formed xEMU bubbles 2. 1 flat panel of Tuffak GP material, conditioned in Mineral Oil for 2hrs at 350F (panel is cut into coupons for testing purposes) 3. 1 flat panel of Tuffak UC material, conditioned in Silicone Oil for 2hrs at 350F (panel is cut into coupons for testing purposes)
2	Air-Lock to refine internal cleaning process for formed helmets / visors
3	Vendor to perform DOE so as to achieve optimal balance of coating thickness and visual performance.
4	Using Visgard 106-94 (or HCF-100) Anti-fog material, vendor will coat interior surface of 2 'test' bubbles, and one side of both flat panels from Step 1.
5	Vendor to perform coating thickness measurements on 2 test bubbles.
6	Vendor to cut flat panels into (10pcs) mineral and (10pcs) silicone 4" x 2" coupons
7	Vendor will perform adhesion testing, per ASTM 3359 on the following: - coupon from flat panel conditioned in mineral oil - coupon from flat panel conditioned in Silicone oil - Setup bubbles from step 1
8	Anti-fog Evaluation: - Vendor to cycle test and evaluate anti-fog at 122° F on test bubble #1 - Vendor to evaluate anti-fog after 24hr soak at 212° F on test bubble #2 - Evaluate for IPA resistance.
9	Vendor to perform "cleaning test" on flat coupons to determine durability of coating
10	Vendor to perform film thickness, haze, and light transmission measurements on coupons from step 9

The tests chosen were based from past experience from the CSSS market study and report combined with lessons learned from observed failures during xEMU DVT. For example, adhesion, haze, film thickness, and light transmission measurements are all standard tests previously completed. Steam cycle testing to represent breath cycles and cleaning tests with repetitive wiping of the coating were added for this series. The 24 hour soak at 212° F is a stress test of the anti-fog to see how well it performs in worst case conditions. Testing of these samples was used to gauge the anti-fog performance & adhesion when freshly applied to a bubble, and its subsequent 'durability'. This ‘durability’ assessment subjected the samples to a series of conditioning steps, then reassessed the coating’s performance.

B. Coating Thickness Results

The thickness of the coating will be governed by both the viscosity and percent of solids of the material and the geometry of the parts to which it is applied. These measurements show the coater’s ability to achieve the desired thickness, and the validity of the sample testing. As expected, the thickness varies in accordance with how these are processed. The bubbles are coated, then held at a slight angle, with the opening facing downward, to allow the material to flow off the part. This causes the regions at the center to be a bit thinner than the bottom 4 locations. As seen in Table 2 using Figure 4 for reference, all locations were within the recommended range.

Table 2: Coating Thickness Results

		Thickness (Microns)						
Sample #	**Material**	**Left**	**Right**	**Top**	**Bottom**	**Center**	**AVG**	**Manufacturer's Recommendation**
1	HCF-100	11.3	11.2	11.9	16.2	9.8	12.08	6.0 - 18.0 microns
2	HCF-100	12.3	10	12.3	14.7	10	11.86	6.0 - 18.0 microns
25	106-94	8.8	12	9.4	14.3	8.5	10.6	6.0 - 15.0 microns
26	106-94	10.6	11.4	10.6	14.7	9	11.26	6.0 - 15.0 microns

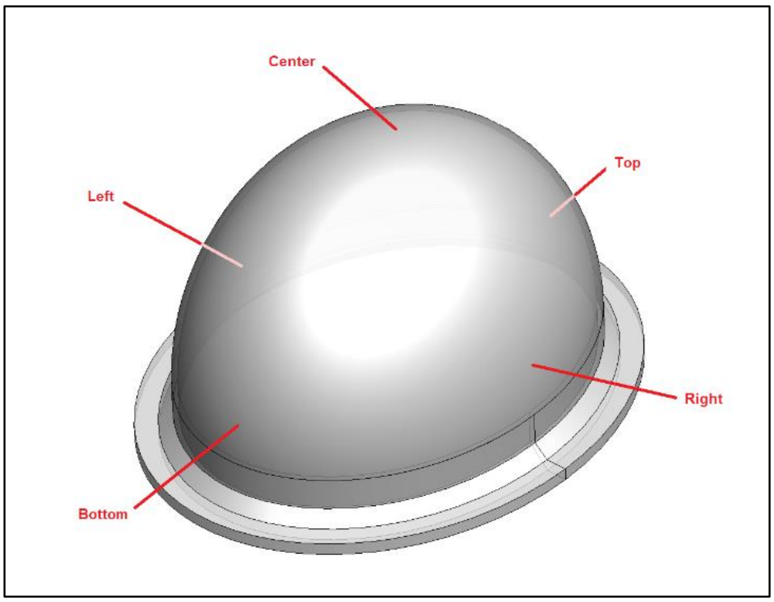

Figure 4: Thickness Measurements Locations on Bubble

C. Adhesion Test Results

For each material, adhesion was measured with one helmet, one mineral oil coupon, and one silicone oil coupon. Adhesion testing was conducted in accordance with ASTM 3359. This specification prescribes a test whereby a crosshatch grid is scored through the coating and into the plastic, a piece of mylar tape is adhered over the grid, pulled away at a 90° angle, then the results are graded according to a chart in the standard. For purposes of this investigation, anything less than a 5B (0% of area removed) result will be considered failing. As seen in Table 3, all samples passed the adhesion test.

Table 3: Adhesion Results

Sample #	Material	ASTM 3359 Adhesion Results
1	HCF-100 Helmet	5B
25	106-94 Helmet	5B
3	HCF-100 coupon - silicone oil	5B
27	106-94 coupon - silicone oil	5B
14	HCF-100 coupon - mineral oil	5B
18	106-94 coupon - mineral oil	5B

D. Resistance to Fogging Results (initial and repetitive use)

For this study, the ‘standard’ anti-fog test will be defined by placing the sample over a (partially) sealed, 500ml beaker of water at 122F, then visually observing the surface for three minutes. This same method is used for both bubbles and flat coupons. The first portion of this test involved the coated bubbles only. Each bubble was run through the standard anti-fog test, allowed to cool and dry, then repeated for a total of five cycles. No fogging was observed on either sample during this test as seen in Table 4.

Table 4: Initial Fogging Results

Sample ID #	Sample Description	Results				
		Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
2	HCF-100 coated xEMU Tuffak GP Bubble	remained clear	remained clear	remained clear	remained clear	remained clear
26	Visgard coated xEMU Tuffak GP Bubble	remained clear	remained clear	remained clear	remained clear	remained clear

The second portion of the test focused on the conditioned flat coupons as seen in Figure 5. For this, the same 'standard' test listed above was used, then repeated two hours later for a total of two cycles. At the completion of the second cycle, the ASTM 3359 Adhesion Test was performed, and as such pass/fail criteria for adhesion reported in Table 5 is defined in this standard. It should be noted that with the larger proportional volume of water in the coupon test, it results in a more abusive test than when run with the bubbles. Being a more extreme test than with the bubble, a difference between the two coatings can start to be seen.

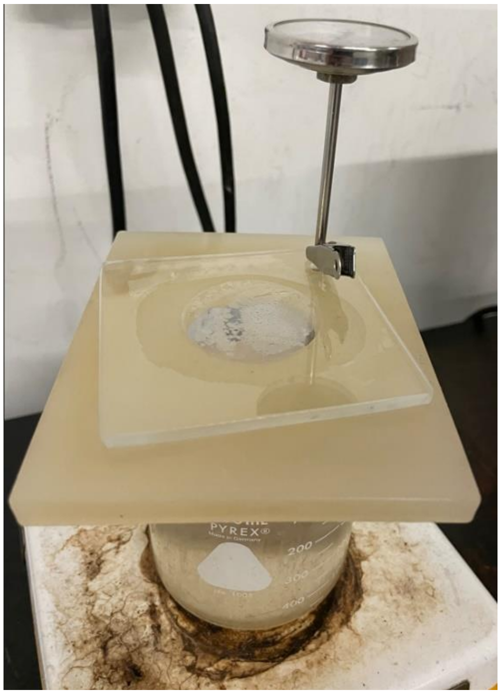

Figure 5: Flat coupon testing

The Exxene HCF-100 exhibited fogging around thirty seconds into the test. It cleared to some degree by the three minute mark but did not perform nearly as well as the Visgard 106-94 which showed no signs of fogging throughout the test. The mineral oil coupons showed no difference from the silicone oil coupons. All passed the follow-up adhesion testing as seen in Table 5.

Table 5: Condition Coupons Results

Sample ID #	Sample Description	Initial Fog Test	2hr Fog Retest	Adhesion (post test)
4	Exxene HCF-100 coated Tuffak UC panel silicone oil	- fog at 30sec - full fog at 1 min, then starts to clear and condense droplets	- fog at 30sec - full fog at 1 min - 2 min, then starts to clear and condense droplets	Pass
28	Visgard 106-94 coated Tuffak UC panel silicone oil	remained clear	remained clear	Pass

15	Exxene HCF-100 coated Tuffak GP panel mineral oil	- fog at 30sec - full fog at 1 min, then starts to clear and condense droplets	- fog at 30sec - full fog at 1 min - 2 min, then starts to clear and condense droplets	Pass
39	Visgard 106-94 coated Tuffak GP panel mineral oil	remained clear	remained clear	Pass

A human breathe fogging response was used as the ‘standard’ for this study because it is the common method of evaluation used by Coatings Design Group (CDG) and provides consistent test conditions. However, the Human Breathe Test has always been an informal method of evaluation used on anti-fog coatings. It is very basic and consists of exhaling onto the samples (at ambient conditions) from ~3”, then visually evaluating the results. None of the samples exhibited any fogging during this test.

Table 6: Human Breathe Response Fogging

Sample ID #	Sample Description	Results
49	Exxene HCF-100 coated Tuffak UC panel silicone oil	remained clear
50	Visgard 106-94 coated Tuffak UC panel silicone oil	remained clear
51	Exxene HCF-100 coated Tuffak GP panel mineral oil	remained clear
52	Visgard 106-94 coated Tuffak GP panel mineral oil	remained clear

E. Abrasion Testing Results

Abrasion testing was broken into two sections: taber abrasion and linear abrasion. Only flat coupons are used in this portion of the test. Taber Abrasion used panels were subjected to a taber abrasion tester with a CS10F wheel, loaded at 500g, and cycled 100 times. Measurements of Light Transmittance and Haze were taken prior to, and after the test as seen in Table 7 and pictures seen in Figure 6. Average thickness measurements were also recorded.

Table 7: Taber Abrasion Testing Results

Sample ID #	Sample Description	Results			
		Transmittance		Haze	
		0 cycles	100 cycles	0 cycles	100 cycles
10	Exxene HCF-100 coated - 10.6 µm Tuffak UC panel silicone oil	90.9	90.08	0.42	5.27

		Δ	0.82	Δ	-4.85
34	Visgard 106-94 coated - 11.8 µm Tuffak UC panel silicone oil	91.68	89.28	0.26	10.64
		Δ	2.4	Δ	-10.38
21	Exxene HCF-100 coated - 11.2 µm Tuffak GP panel mineral oil	86.1	85.65	0.82	4.21
		Δ	0.45	Δ	-3.39
45	Visgard 106-94 coated - 11.1 µm Tuffak GP panel mineral oil	86.95	85.3	0.74	8.82
		Δ	1.65	Δ	-8.08

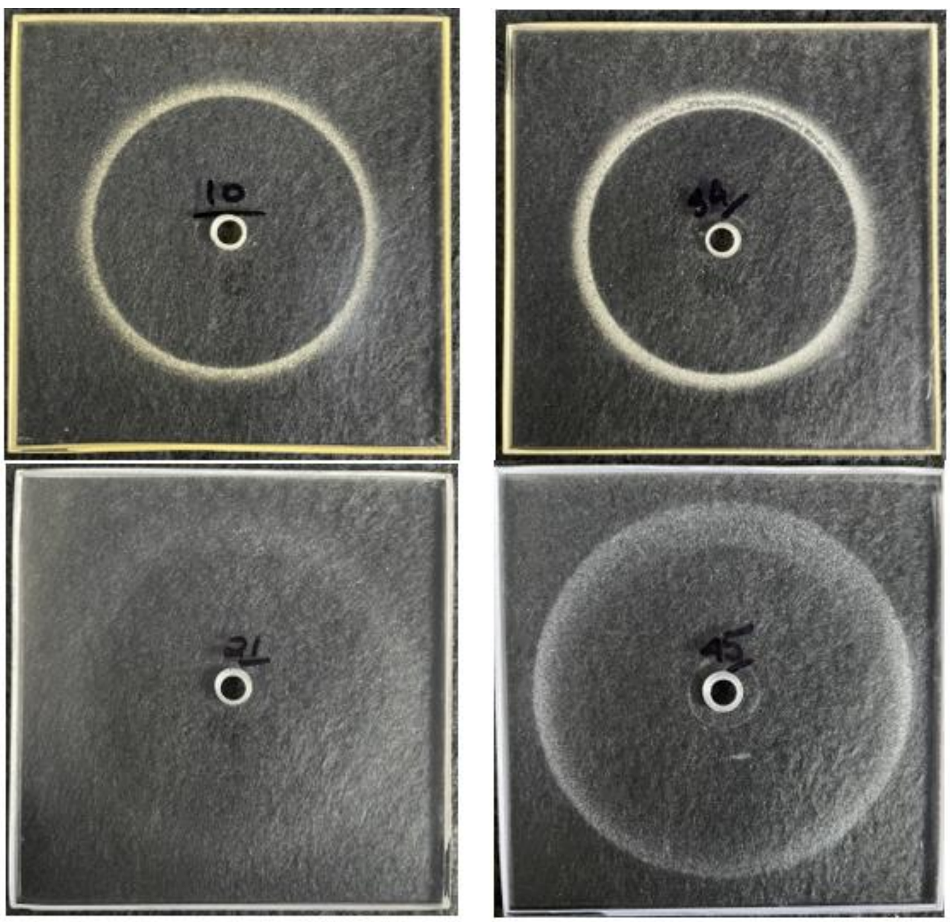

Figure 6: Taber Abrasion Test Results *Top left: Exxene HCF-100 coated Tuffak UC panel soaked in silicone oil, Bottom left: Exxene HCF-100 coated Tuffak GP panel soaked in mineral oil, Top right: Visgard 106-94 coated Tuffak UC panel soaked in silicone oil, Bottom right: Visgard 106-94 coated Tuffak GP soaked in mineral oil*

Linear abrasion used panels that were subjected to a linear abrader, using a scotch-bright pad at 3.5psi. Samples were cycled 200 times. Measurements of light transmittance and haze were taken prior to, and after the test. Average thickness measurements were also recorded as seen in Table 8 and pictures seen in Figure 7 and 8.

Table 8: Linear Abrasion Test Results

Sample ID #	**Sample Description**	**Results**			
		Transmittance		**Haze**	
		0 cycles	**100 cycles**	**0 cycles**	**100 cycles**
11	Exxene HCF-100 coated - 10.6 µm Tuffak UC panel silicone oil	91.5	91.4	0.53	0.73
		Δ	0.1	Δ	-0.2
35	Visgard 106-94 coated - 10.3 µm Tuffak UC panel silicone oil	92.1	91.7	0.33	4.62
		Δ	0.4	Δ	-4.29
22	Exxene HCF-100 coated - 10.9 µm Tuffak GP panel mineral oil	86.1	86	0.15	1.62
		Δ	0.1	Δ	-1.47
46	Visgard 106-94 coated - 12.6 µm Tuffak GP panel mineral oil	86.9	85.8	0.82	2.2
		Δ	1.1	Δ	-1.38

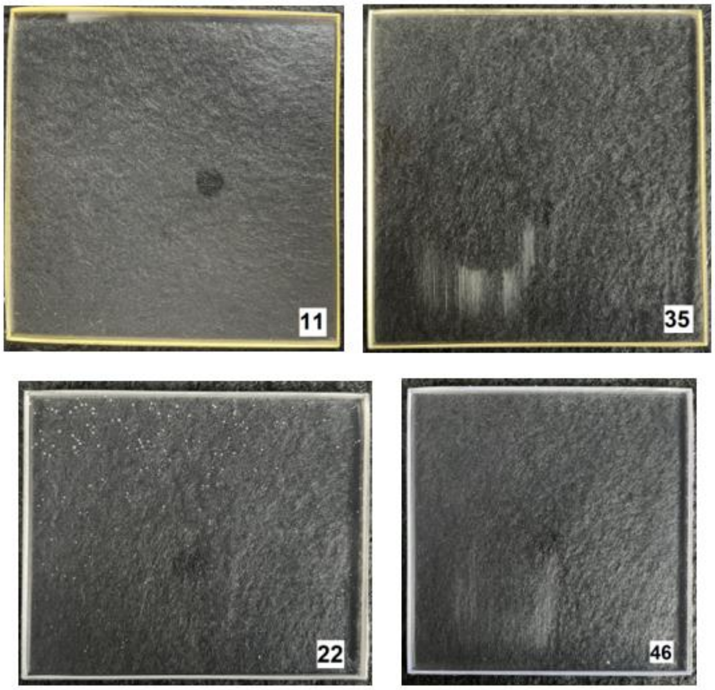

Figure 7: Linear Abrasion Test Results *Top left: Exxene HCF-100 coated Tuffak UC panel soaked in silicone oil, Bottom left: Exxene HCF-100 coated Tuffak GP panel soaked in mineral oil, Top right: Visgard 106-94 coated Tuffak UC panel soaked in silicone oil, Bottom right: Visgard 106-94 coated Tuffak GP soaked in mineral oil*

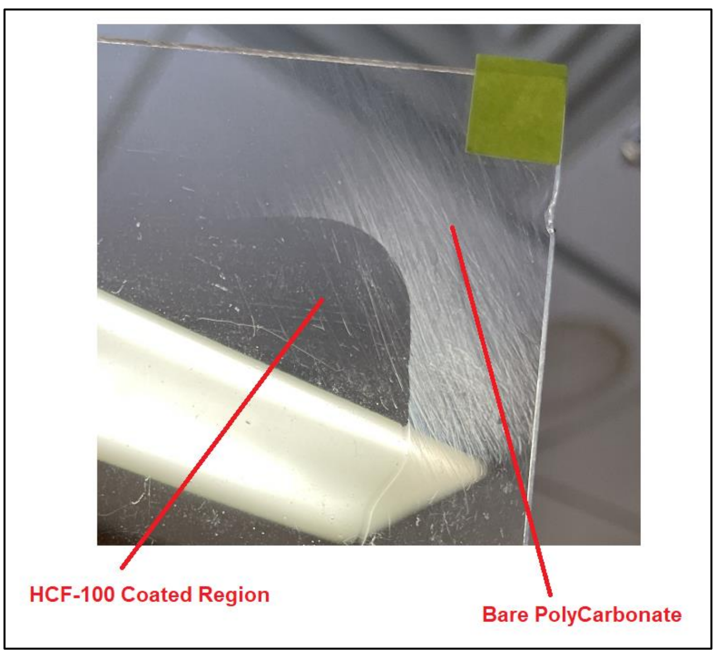

Figure 8: Representative Sample Highlighting the Abrasion Resistance of HCF-100

F. Cleaning Test Results

Three cleaning tests were completed with different solvents: Isopropyl Alcohol (IPA), Windex, and Orvus Paste. The first test considered the use IPA. This was chosen since it is a very common chemical used the spaceflight industry for cleaning. It has also historically been very detrimental to the HTAF-601 material. Coupons were wiped with an IPA soaked cloth, dried, then subjected to the standard anti-fog test. Results can be seen in Table 9. The HCF-100 performed very similar to the non-IPA wiped coupons, perhaps exhibiting fogging only a few seconds earlier. The 106-94 likewise did not see much impact from the IPA exposure. There was 'slight' fogging before the clear film developed, but nothing significant.

Table 9: IPA Test Results

Sample ID #	Sample Description	Results Standard anti-fog test	Adhesion (post test)
6	Exxene HCF-100 coated Tuffak UC panel silicone oil	- slight fog at 25sec - droplets condense by 2 minutes, remained that way till end.	Pass
30	Visgard 106-94 coated Tuffak UC panel silicone oil	- slight fog at 10sec - film formed at 20 seconds and remained that way till end	Pass
17	Exxene HCF-100 coated Tuffak GP panel mineral oil	- slight fog at 25sec - droplets condense by 2 minutes, remained that way till end.	Pass
41	Visgard 106-94 coated Tuffak GP panel mineral oil	- slight fog at 10sec - film formed at 20 seconds and remained that way till end	Pass

The second test used Windex as the cleaning agent. This is not a recommended cleaning method due to its constituent components incompatibility with the base polycarbonate material, but it was chosen by the coating vendor as their customers will frequently use it, hence it is a test they regularly conduct. For this test, each panel was saturated, wiped dry ten times, then subjected to the standard anti-fog test. Results can be seen in Table 10. The results of the Windex cleaning test were similar to the initial anti-fog results, with the Visgard outperforming the Exxene coatings. In a similar fashion to the IPA, the HCF-100 showed fogging slightly earlier. The Visgard developed a film but did not fog.

Table 10: Windex Results

Sample ID #	Sample Description	Results
8	Exxene HCF-100 coated Tuffak UC panel silicone oil	slight fog at 20sec, then condensation formed as it became saturated

32	Visgard 106-94 coated Tuffak UC panel silicone oil	remained clear, wetted out but no droplets
19	Exxene HCF-100 coated Tuffak GP panel mineral oil	slight fog at 20sec, then condensation formed as it became saturated
43	Visgard 106-94 coated Tuffak GP panel mineral oil	remained clear, wetted out but no droplets

The final test used an Orvus Paste solution. This is a mild detergent solution that Air-Lock routinely uses for cleaning of bare plastics throughout the fabrication process. For this test, each sample coupon was cleaned with the solution and a soft rag for approximately ten seconds, then rinsed and dried. The sample was then placed directly above a container of water at 170F and observed for fogging. The time it took for fog to appear was recorded and charted in Figure 9. As seen in previous tests, the Visgard initially exhibited better anti-fog properties. However, the repeated cleaning process has had a detrimental effect on the coating and its ability to resist fogging. The HCF on the other hand, remained fairly consistent throughout the cleaning.

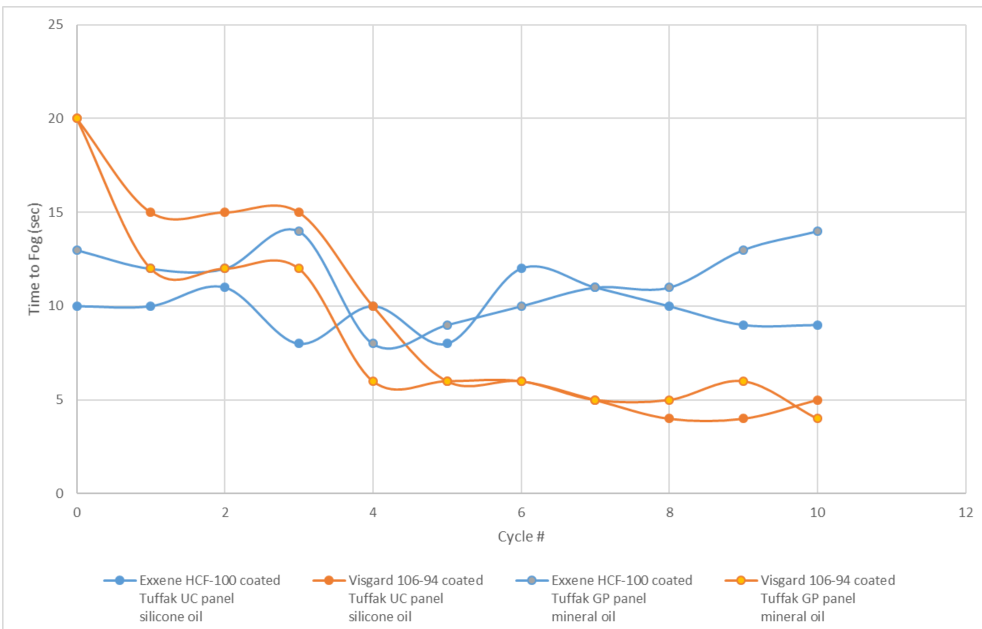

Figure 9: Anti-Fog Results for Time to Fog After Cleaning Cycles With Orvus Paste

G. Durability Testing

To determine the durability of the coatings, the panels were put through a number of conditioning steps meant to stress/degrade the coatings. The first two tests are commonly performed test that coating vendor performs, while the third test was meant to combine elements of the previous conditioning so as to find the limits of the materials.

The first durability test was to determine the coatings ability to withstand exposure to water (either from washing or condensation). Test samples were soaked for 24 hours in water at ambient temps, allowed to dry for 6 hours, then subjected to the standard anti-fog test. The results as seen in Table 11 of this test show no difference from the initial anti-fog testing of the bubbles.

Table 11: Durability Test 1

Sample ID #	Sample Description	Results	
		Anti-fog test	Adhesion before / after
1	HCF-100 coated xEMU Tuffak GP Bubble mineral oil	remained clear	pass / pass
25	Visgard coated xEMU Tuffak GP Bubble mineral oil	remained clear	pass / pass

As no change was observed after a long water soak at ambient temp, the second durability test was performed was to soak a set of coupons at 212F water for one hour, allowing to dry, then performing the standard anti-fog test. When compared to the initial anti-fog testing of the panels, there is some slight degradation as seen in Table 12. Both samples exhibited a period of fog formation before clearing for the remainder of the test. The results of the HCF-100 panels were comparable to the initial testing (fogging occurring slightly sooner this time). The results of the 106-94 were noticeably worse, as initial testing showed no fogging at all.

Table 12: Durability Test 2

Sample ID #	Sample Description	Results	
		Initial test	Adhesion (post test)
5	Exxene HCF-100 coated Tuffak UC panel silicone oil	- slight fog at 20sec - clear at 30sec, then droplets condense. Panel remains clear	Pass
29	Visgard 106-94 coated Tuffak UC panel silicone oil	- slight fog at 20sec - clear at 45sec, then droplets condense. Panel remains clear	Pass
16	Exxene HCF-100 coated Tuffak GP panel mineral oil	- slight fog at 20sec - clear at 30sec, then droplets condense. Panel remains clear	Pass
40	Visgard 106-94 coated Tuffak GP panel mineral oil	- slight fog at 20sec - clear at 45sec, then droplets condense. Panel remains clear	Pass

The last durability test combines many of the earlier conditions which were seen to have an effect on the coatings. Coupons were put through the Windex cleaning, placed in 212F water for one hour, then subjected to the anti-fog test. Adhesion testing was performed afterwards. This set of conditions had a dramatic effect on the coatings. As seen in Table 13, all samples showed significant fogging throughout the test. All of them passed adhesion testing.

Table 13: Durability Test 3

Sample ID #	Sample Description	Results	
		Anti-fog Test	Adhesion
9	Exxene HCF-100 coated Tuffak UC panel silicone oil	- starts to fog at 30 sec - turns to condensation at 90 sec thru to 3 min	Pass
33	Visgard 106-94 coated Tuffak UC panel silicone oil	- starts to fog at 30 sec - turns to condensation at 60 sec and flows out to a uniform film	Pass
20	Exxene HCF-100 coated Tuffak GP panel mineral oil	- starts to fog at 30 sec - turns to condensation at 90 sec thru to 3 min	Pass
44	Visgard 106-94 coated Tuffak GP panel mineral oil	- starts to fog at 30 sec - turns to condensation at 60 sec and flows out to a uniform film	Pass

H. Re-wetting assessment

While working with the coated samples, it was noticed that the materials, when wet from condensation or cleaning agents, seemed to have a different texture to them. The Visgard 106-94 was slippery and would be tacky for a short time after being wiped dry. By comparison, the Exxene HCF-100 presented no differently than a bare piece of polycarbonate plastic after wetting. As seen in Figure 10, the Visgard performs better to fogging than the HCF-100 when exposed to 170° F hot water. However, it starts to have an orange peel type texture. When left to dry, other differences appear. The Exxene HCF-100 will return to its pre-test state, with no visual evidence of any fogging or condensation remaining. For the Visgard 106-94, each of the droplets that ran down have dried and appear as a run (with thickness). This indicates some dissolution and re-deposition of the coating. This raises a significant concern the coating is rewetting and could potentially become droplets that could impact the crew member during a spacewalk.

Figure 10: Visgard (Left) versus HCF-100 (Right) when exposed to 170 deg F hot water *While the HCF-100 fogs more to the 170 deg F water, the Visgard develops an orange peel texture that starts to streak. This could be a concern for eye irritation.*

IV. Conclusion

Implementing a permanent anti-fog coating is a desired solution for future spacesuit helmets to prevent eye irritation during spacewalks and eliminate a consumable item. Historically, HTAF-308 and HTAF-601 coatings were implemented for consideration but ran into issues of pre-mature delamination from HITL testing and were discontinued by the manufacturer. Visgard 106-94 and HCF-100 were evaluated as potential candidates to be used for future testing. Though the Visgard 106-94 exhibited excellent anti-fog properties, and good overall performance, its issues with re-wetting would seem to disqualify it as a viable candidate. The HCF-100 performed well overall. Though it did exhibit less resistance to fogging, this was under lab conditions. Human testing may show its performance to be acceptable for use in suit applications. In particular, its performance on the cleaning tests are definitely encouraging. From this testing, the team would recommend doing further testing with the HCF-100.

The next steps would be to complete tensile tests with flat samples and burst, impact, off-gas and toxicity testing with the coating applied to a representative helmet bubble. If the coating passes with good results, it would be recommended for use during HITL testing to verify its performance. This coating could be used for vendors awarded by the Extravehicular Activity Services (xEVAS) or the EMU program.

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