AEROSPACE UV CURED Coatings; Yesterday, Today & Tomorrow

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Introduction

Over the past three decades suppliers to the AEROSPACE coatings industry, paint companies, the USAF, US Army, US Navy, US Coast Guard and civil aviation entities have, with limited success tried to implement the use of UV cure coatings. The benefits of the UV cure technology are well understood in that it will provide for the end user the following; 1) immediate dry to fly, 2) ultra-low VOCs / VHAPS, 3) one component and 4) technology that could potentially meet military specification MIL-PRF-85285D. From the early uses of UV-A cure stencils for Aerospace UV coatings the technology has evolved to the UV Cure Shark Skin coatings that have the promise of delivering drag reduction values in the range of 6-7%. Both the MicroTau Direct Contactless Microfabrication (DCM) technology and the Lufthansa Technik Airbus UV Cure Shark Skin coatings have the promise of accelerating these developments of Aerospace UV cure coatings acceptance in the marketplace. These UV cure technologies can be based on 100% oligomer as well as water based polyurethane dispersion technology. During this nearly three decades of development several hurdles have impeded UV Cure technology progress and use in the Aerospace market. This paper will report on these hurdles and potential solutions to further develop the UV Cure AEROSPACE coatings market.

[In this paper we will specifically look at intermediate and topcoats and not primers. Primers for both aluminum and composite aerospace materials are undergoing a dramatic change due to the need to reduce or eliminate chrome primers.]

1.) Changes in the Aerospace UV Cured markets

Over the last several years the aerospace coatings market has gone through an incredible number of changes in both polymer technologies and substrates. Today, the current number of 2K reactive primers and clear coats as well as base coats has increased pushing the limits of polymer chemistries. With the pressures to lower VOCs and VHAPS, solvent based systems have tried to evolve to water based chemistries. Substrates used by the OEM's have evolved from the traditional aluminum metals to composites.

2.) Introduction of UV curable Aerospace Coatings – The Past

a. ***UV-Curable Aerospace and Aircraft Coatings (SBIR/SERDP)***

A contract was awarded in 2005 - 2006 via Small Business Innovative Research (SBIR) and Strategic Environmental Research and Development (SERDP). During this testing protocol they found that trying to do the normal 3 mils WFT that they did not get proper cure. They found that if they did thinner layers that they were able to get the proper cure. These particular UV cure coatings were one component (1K) which is the traditional concept for a UV cure Aerospace coating. These researchers decided to go the dual cure route which uses the free radical cure produced by the UV light and then the so-called dark cure where the dual cure molecule has both acrylate functionality and polyisocyanate functionality. The so-called dark cure occurs through the moisture cure of the residual polyisocyanate on the molecule. These dual cure systems result in a 2K (two component) system with a limited pot life[1]. Test results via the MIL SPEC passed giving only concerns with percent elongation at 275 F. No artificial weather testing was performed [2].

b. ***UDRI testing in 2007 was funded on the concept of a UV cure black stencil***.

This black stencil was then carried forward to a C -130 unit to see if the system could meet the criteria needed to perform in the field. In 2008 a demonstration/evaluation was performed on a C-130 Hercules to evaluate its performance (Photo 1). Stencils were applied and cured via a 2,000 Watt H & S Auto Shot UV lamp[3]. (ref UDRI Report) An additional test area was applied on the wing flap directly in line with the jet engine blast. Since this C-130 was an operational aircraft it saw multiple missions around the globe and in specific austire, hot and dirty enviroments. After 600 flying hours and 14 months in theater the stencil coating performed quite well. The stencile displayed promising physical properties with room for improvement in the areas of flexibility and gloss. In the color change area the C-130 had Delta E values comparable to conventional 2K polyurethane fluoropolymers topcoats[3].

Photo 1 C-130 UV Cured Black Stencil Coating

c. ***Early requirements by the USAF to develop UV cure aerospace coatings 2009***

The USAF has worked hard to develop a UV cure system for DoD aircraft. In 2009 a report was published reviewing why the time and money was being spent on trying to develop a UV cure system for DoD aircraft. The specific requirement stemmed from the current USAF required 72 hour “dry to fly” time for the 2K polyurethane topcoat. Shown in Table 1 is references to the ability of the UV cure technology to dramatically drop the “dry to fly” time by cutting off nearly 89 to 100.5 hours of processing time to fully repaint an F-16.

Application	***Current Dry Time***	***Using UV Cure***	***Time Saved***
Primer	4 to 6 hours	30 minutes to 1 hour	3 to 5.5 hours
Topcoat	16 to 24 hours	30 minutes to 1 hour	15 to 23.5 hours
Stencils	72 hours	30 minutes to 1 hour	71 to 71.5 hours
		Potential time saved per Aircraft	***89 to 100.5 hours***

Table 1) Full Repaint Benefits (F-16)

Coating System	**Color**	**Color Match**	**Gloss Match**	**Wet Tape**	**Cross Hatch**	**Low Temp Flex**	**GE Impact**	**Pencil Hardness**	**Weathering (500 hours)**			
									Color Change	**Gloss Change**	**Post Test Low Temp Flexibility**	**Post Test GE Impact**
X	**Camo Gray 36173**	**P**	**P**	**P**	**P**	**P**	**F**	**HB**	**P**	**P**	**P**	**N/A**
Y	**Camo Gray 36173**	**P**	**P**	**P**	**P**	**P**	**F**	**HB**	**P**	**P**	**P**	**N/A**
A	**Camo Black 37038**	**F**	**F**	**P**	**P**	**P**	**F**	**F**	**P**	**N/A**	**P**	**N/A**

Coating System	Color	Color Match	Gloss Match	Wet Tape	Cross Hatch	Low Temp Flex	GE Impact	Pencil Hardness	Weathering (500 hours)			
									Color Change	Gloss Change	Post Test Low Temp Flexibility	Post Test GE Impact
B	Camo Black 37038	F	F	P	F	P	F	HB	P	N/A	P	N/A
C	Camo Black 37038	F	F	P	P	P	F	HB	P	N/A	P	N/A
D	Camo Black 37038	F	F	P	F	P	F	HB	F	N/A	P	N/A
E	Gloss White 17925	F	F	F	F	P	F	B	P	N/A	F	N/A
F	Gloss White 17925	F	F	P	F	P	F	HB	F	N/A	F	N/A
G	Camo Gay 36173	F	P	P	P	P	F	2B	P	F	P	N/A
H	Camo Gray 36173	F	P	P	P	P	F	< 6B	P	N/A	P	N/A

Table 2.) USAF/AFRL UV Cure Pigmented Top Coat Test Results (F=fail & P=pass)

Coating System	Color	Cleanability	Heat Resistance (1-hr 250°F)	Opacity	Lube Oil Resistance	Hydraulic Fluid Resistance (24-hr)	Jet Fuel Resistance (7-day)
X	Camo Gray 36173	F	P	P	P	P	P
Y	Camo Gray 36173	F	P	P	P	P	P
A	Camo Black 37038	Not Required	P	P	P	P	P
B	Camo Black 37038	Not Required	P	P	P	P	P
C	Camo Black 37038	Not Required	P	P	P	P	P
D	Camo Black 37038	Not Required	P	P	P	P	P
E	Gloss White 17925	P	P	P	F	P	P
F	Gloss White 17925	P	F	F	P	P	P
G	Camo Gray 36173	F	P	P	P	P	P
H	Camo Gray 36173	P	P	P	P	P	P

Table 3.) USAF/AFRL UV Cure Pigmented Top Coat Test Results (F=fail & P=pass)

The obvious benefit of the UV technology would be even more dramatic for the legacy transport aircraft (C-130, C-5 and C-17) since the surface area needing painting is much greater.

Under this program UV Cure Camo Black, Gloss White and Camo Gray were evaluated. As can be seen in Table 2. coating systems X and Y are 2K polyurethane coatings that are currently being used by DoD on military aircraft and in this test protocol were the controls. It is interesting to note that under this test protocol not even the 2K polyurethane Coating System X & Y passed the tough GE Impact test. Color match / Gloss match values were negative for the UV Systems and could be corrected with reformulating. A caveat would be in the Black systems since getting them to thoroughly cure requires pigmentation that the color eye has problems evaluating. UV Cure Coating Systems A, F and G results were closest to DoD aerospace requirements for their color.

Again, it is interesting that the Controls X & Y fail the Cleanability test and is probably the result of the low gloss requirements for these systems as can be seen in Table 3. Coating systems A, B, C, D and H results were closest to the DoD aerospace requirements[4].

In all of this original work very little is mentioned on the UV cure light sources that are being used to cure the UV curable systems [1].

Photo2.) UV Arc Lamp (electrode)

The first of these systems would be the traditional UV Arc lamp (electrode) which is a mature technology shown in Photo 2. The UV energy is developed by arc across the electrode that excites the mercury vapor to emit at a certain wavelength. The units are in wide use and have issues with UV bulb life.

However; researchers in the early development of UV Cure automotive refinish discovered that a full spectrum light source would have industrial hygiene (IH) issues when used in an open shop environment [4,5,6,7]. Working hand in hand with the UV light manufacturers, the researchers developed UV A light sources that were essentially UV Arc lamps that were doped with Gallium so that they would emit in the UV A region and not the UV B and C wave length regions.

Photo 3.) UV A only light source used by the Automotive Refinish industry (Photo provided by I-CAR)

Shown in Photo 3, these UV A lamps were much safer for open shop use then the full spectrum UV light sources. Of course, proper PPE (Personal Protective Equipment) needed to be followed according to regional safety standards.

Microwave electrodeless UV lamps were also considered but the cost and being a full spectrum light source had concerns on the IH issues for the open shop. These units are shown in Photo 4.

LED (Light Emitting Diodes) as can be seen in Photo 5 were also considered but at this point in time the energy density and costs were not possible for doing large aircraft. Cooling of the LEDs was another issue that was foreseen since on a larger scale the LEDs would need to be cooled to prevent them from becoming overheated and destroying themselves.

Photo 4.) UV Microwave (electrodeless) cure lamp

d. Early attempts to develop a UV-A Aerospace coatings- June 2010

Early work by AFRL (Air Force Research Lab) on the development of a UV cure coating was funded an (ESTCP) project.

This project looked at the ability of the UV cure systems to give performance in the following criteria: adhesion, flexibility, color/gloss match, color/gloss retention, fluid resistance and repairability. This Joint Test protocol can be seen in Table 4.

Evaluations were performed on 'commercial off-the-shelf' (COTS) coatings on a flat black and gloss white coating. The results for the flat black coating were: Adhesion equal to the performance of the controls, flexibility needing improvement, hardness in the desired range, fluid resistance passing MIL-PRF-85285 and weathering passed 3,000 hours for <1 delta E color change. The results of the gloss white system showed negative results in adhesion, flexibility and marginal on fluid resistance and weathering.[5]

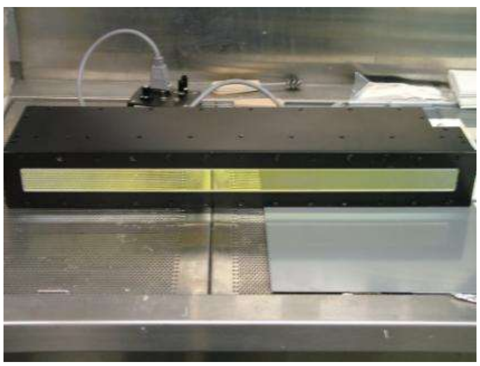

Photo 5.) UV cure LED unit that is water cooled

Appearance	
Color	ΔE of less than 1 from standard
Gloss	**At 60 : ≥90 for gloss; ≤5 for flat**
Adhesion	
Wet Tape	No peel away; target rating of 4A or 5A
Cross Hatch	No peel away; target rating of 4B or 5B
Flexibility	
Low Temperature	No cracking or adhesion loss over 1 inch bend (gloss and semi-gloss) or 2 inch bend (flat)
GE Impact	**Minimum of 40% elongation; no cracking, crazing, or loss of adhesion**
Resistance	
Pencil Hardness	2B or harder; initial hardness - data point for fluid resistance
Fluid Resistance	Softening no more than two (2) pencil hardness unit; no blistering or defects after exposure to lube oil, hydraulic fluid and JP-8 fuel
Resistance	
Accelerated Weathering (Color and Gloss)	**Color change (ΔE) of less than 1 after 500 hours; Min gloss of 90 for gloss; max five (5) for flat**
Heat Resistance	Color change (ΔE) of less than 1 after exposure to 250 5°F for 60 minutes
Humidity Resistance	No blistering, softening, loss of adhesion or defects
Cleanability	Cleaning Efficiency > 75%
Reparability	
Scuff sand /Wet Tape	No peel away; target rating of 4A or 5A
Scuff sand /Cross Hatch	No peel away; target rating of 4B or 5B
Stripability	
Chemical Strippers	Removal of the coating to the substrate
Dry Media (blasting)	Removal of the coating to the substrate
Laser Stripping	Removal of the coating to the substrate

Table 4.) Joint Test Protocol for MIL-PRF-85285 & Mil-PRF-32239

Eventually work was continued along this avenue and resulted in a US patent being issued that had an oligomer, monomer, PI , black pigmentation along with solvent resulting in a 85 degree gloss of less than 15.[7]

Since the testing of the high gloss white was a priority the approach up until now was based on oligomer, monomer, PI and solvent for adjusting spray viscosity. The new vendor suggested that a water-based UV cured polyurethane dispersion (UV-PUD) be evaluated to try and meet the MIL SPEC since it offered low intensity UV cure, flexible coating, high gloss and ultra-low volatile organic compounds (VOC) and hazardous air pollutants (HAPS).

Test	MIL -PRF 85285	UV PUD White Coating
GE Impact Test	> 60 %	60%
Dry / Wet Adhesion	> 4B / 4A	4B / 4A
Gloss	60 > 90	80
Initial Pencil Hardness	>2B	HB/F
Mobil Jet Oil	-2 pencils	-1
Hydraulic Fluid	-2 pencils	-1
JP-8 Jet Fuel	-2 pencils	-2
Humidity Resistance; 14 days	30 days	No blisters

Table 5.) Gloss white UV Cure Polyurethane Dispersion

The performance of the gloss white UV cure polyurethane dispersion met everything in the specification except for the 60-degree gloss level which needs to be at 90 or above. Unfortunately, the gloss value for this system came in at 80. Due to funding limitations this project was stopped. The idea that a water-based technology could come this close to the MIL-PRF 85285 specification shows great promise for the technology in the future.[9]

LED UV Cure Aerospace Topcoats 2011

As discussed previously UV LED light sources have also been evaluated for Aerospace primers and topcoats. An AFRL contract in 2010 – 2011 evaluated the performance of the UV A LED light source in combination with UV cure primers and topcoats. Five different UV cured primers were evaluated against a gray UV cured Topcoat. Four of the most promising stacks passed the fluid resistance, 1,000-hour salt spray, jet fuel, Skydrol and cryogenic bend tests. With the UV A LED light source footprint cure speed would be one square foot per minute. At this rate the UV A LED light source would take days to cure an entire C-17 aircraft. Other UV A light sources have been developed that have a much larger footprint but support for the UV A FL bulb technology has waned [10].

Commercial Aircraft Manufactures (CAM) Development of UV curable pigmented and clear coats for complex commercial artwork

In 2011 a commercial aircraft manufacturer (CAM) put together a team of individuals that included the following: two UV paint formulators, raw material suppliers and UV-Cure equipment suppliers. The purpose of the project was to develop UV cure clear and pigmented artwork for commercial aviation. An example of this artwork is shown in Photo 6.

Photo 6.) B 787 Art Work

Requirements by the CAM for this project were the following: reproduce the entire CAM approved color gamut, spray properties close to thermally curable paints, 'hang time' requirements, cure process requirements, overspray cure requirements, and engineering and appearance requirements. The project went with a UV A (see Photo 3) light source that would be used to scan over the aircraft body. The project lasted for 6 years and terminated in 2015[11].

e. Ultraviolet (UV)-Curable Coatings for Aerospace Applications (ESTCP) 2012

From the previous project USAF / AFRL funded a major project to see if UV Cure paint technology could meet the rigors of DoD aerospace specifications. This project was funded via ESTCP from Jul 2008 until Aug 2012.

Lab testing was done at a private laboratory without any oversight especially on the UV cure light source and application. In general, most samples were tested above the accepted wet film thickness which resulted in poor through cure. This poor through cure resulted in erroneous results. An example of this was the UV Gray 36173 and UV Black where after being subjected to 2000 hours of salt spray the UV coating was peeling of the panel at the scribe.

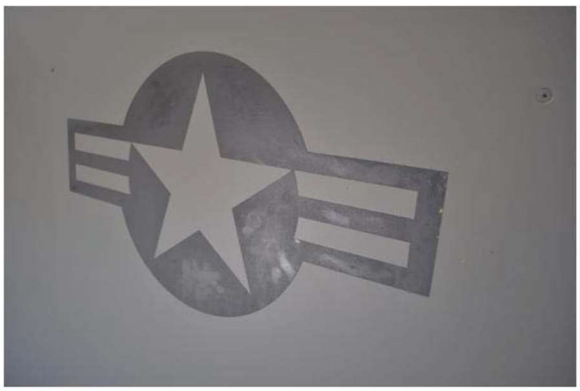

Photo 7.) UV Cure Black Stencil Stickiness

A demonstration/validation trip was made to Hill Air Force Base to evaluate the potential for these UV cure systems. Applications of both the UV cure gray and black systems were made with limited success. Again, problems were encountered with poor cure manifested by a surface that was sticky. This stickiness was attributed to lack of enough energy hitting the coating and overriding the oxygen inhibition that all UV cure systems are susceptible to. This problem with the Black Stencil can be seen in Photo 7. Unfortunately, the problem that occurred was that the power needed to run the UV lights was over 200 ft away and a large extension cord was used. It was calculated that this large extension cord reduced the energy output of the UV A lights by 20%. This reduction in energy is what caused the UV Black and Gray coatings to not fully cure. Since this was at the end of the funding for this project these obvious issues could not be resolved [12].

3.) Current products and innovation in the UV Cure aerospace market – The Present

Under the Air Force Research Laboratory's Engineered Surfaces, Materials and Coatings (ESMC) program a project was started in 2013. The program is targeting skin-friction drag which is reported to account for 50% of DoD legacy aircraft. The Ohio Aerospace Institute (OAI) is the prime contractor with Lockheed Martin as the main subcontractor.

A professor at Stevens Institute of Technology has reported that the largest legacy aircraft in DoD have the following fuel burn: Boeing C-17 461 million gallons in 2014, Lockheed Martin C-130 86 million gallons and the C-5 71 million gal.

The professor stated that the USAF wants passive technologies that would not change the structure or surface of the aircraft.

OAI conducted an online InnoCentive search to uncover technologies that might meet the criteria. Out of 95 submissions and through additional screening MicroTau Ltd. was awarded the contract (2016) and developed a Shark Skin (riblet) like structure that was manufactured from a UV curable aerospace paint.

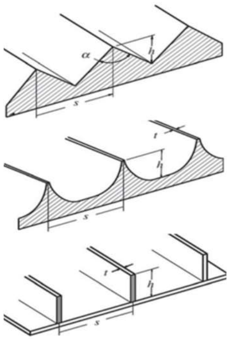

Figure 1.) Riblet shapes; sawtooth, scalloped, and blade

This UV cure coating technology has its roots in the automotive UV A cure technology. The twist is that utilizing photolithographic methods currently used in computer chip fabrication the MicroTau technique directly prints riblets onto the external surface of the aircraft. The uniqueness of the MicroTau technology is that is doesn't contact the wet UV paint and allows the formation of 3D geometries as shown in Figure 1 and Figure 2.

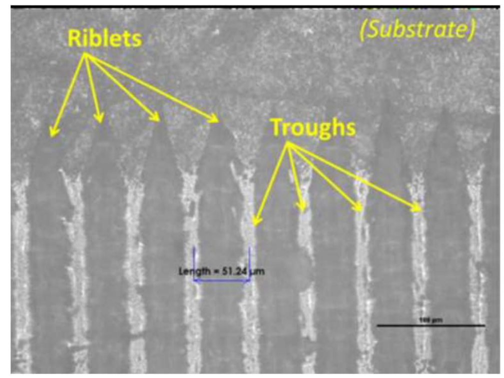

Figure 2.) Optical micrograph of the UV Cured riblets

This technology is the new hope in the development of a surface technology that might truly mimic the surface of a shark skin and allow for reduction of drag of legacy DoD aircraft. Results of wind tunnel testing have confirmed that the MicroTau UV Cure riblet coating gave 6% viscous drag reduction. It is calculated that just a 2% reduction in aviation fuel usage would reduce the annual CO2 emissions by 20 million tons annually[13].

This direct contactless microfabrication (DCM) technique results in a 3D printed profile that can be varied from the 'wing tip to the fuselage' to allow for the air flow performance to result in the lowest drag possible for legacy DoD aircraft at altitude [14, 15].

Others have tried to manufacture these riblets on the commercial aviation side with limited success. This commercial aviation technique for the manufacturing of riblet structures utilizes a UV cure aerospace paint that is applied to the aircraft surface. A silicon film mold that has the inverse of the riblet structure is then laid into the wet UV paint and a UV light then cures the riblet structures in place. This technology sounds impressive but has a major issue with trying to vary the shape and size of the riblets since the silicon film has a structure that can't be real time varied like the DCM techniques described above. [16]

4. Future outlook for the UV Cure aerospace coatings technology – The Future

With all of the resources that the US government has implemented over the last two decades for the development of a 1K UV Cure Aerospace coating the future definitely has a great foundation.

a. ***1K UV Curable non-isocyanate polyurethane aerospace coating*** - A recent SERDP (2018 to 2019) project was taken on looking at the development of a 1K UV Curable non-isocyanate polyurethane aerospace coating. This work resulted in coatings that had flexibility at -54 F, good chemical resistance of MEK double rubs > 90. These so-called UV-NIPU's also showed no significant change in appearance regarding aerospace fluids. These particular systems were all based on clear coats. When the best clear coats were selected and pigmented, they had problems with lubricating oil and aromatic fuel B. For some reason the researchers decided to build the dry film thickness (DFT) to 10 mils where most Aerospace coatings are applied at a 3 mil DFT. The clear coats were done in 5 DFT increments to reach 10 mils DFT. The pigmented systems were done in 1 mil DFT to reach the 10 mil DFT. The UV cure light source was a Fusion H-bulb which works good for clear coat applications but not for pigmented. The researchers used the right photoinitiator package for the pigmented system but needed to expose the system to a V-bulb (Gallium doped bulb to get the proper shift above the pigmentation absorbance) and immediately the H-bulb [17]. It would be great to retest these UV-NIPU systems with the proper UV light sources to see what significant improvements in the performance would occur. However; if future work is going to be attempted on the pigmented UV-NIPU systems it should be done with either the unit shown in Photo 3 above (UV-A electrode lamp) or the unit shown in Photo 5 above (UV A LED). The UV A and UV A LED-units at this point in time are more practical than the electrodeless UV light source for Aerospace coatings applications [18].

b. ***Developing superhydrophobic coatings that will keep the Shark Skin (riblets) clean*** - Another project that was funded by the Operational Energy Capability Improvement Fund (OECIF) from the office of the Assistant Secretary of Defense for Operational Energy Plans and Programs, ASD (OEPP) and the Air Force Research Lab (AFRL) in conjunction with Ohio Aerospace Institute. The projects focus was on developing superhydrophobic coatings that could be overlaid onto the UV cured Shark Skin (riblets) coatings to keep the riblets clean. If you can't keep the riblets clean they will lose their ability to reduce drag. The following is the process developed under this program: 1) clean the riblet surface with an atmospheric plasma pressure jet (APPJ), 2) one pass spray coating of a silane coupling agent, 3) apply the fluoroganosiloxane film with the APPJ using hexamethyldisiloxane (HMDSO) and hexafluropropylene oxide (HFPO). This technique results in a superhydrophobic surface that was subjected to weathering, dirt accumulation, impact, cleaning, solvents, jet fuel and abrasion resistance. The results showed that these coating held up very well to the durability testing. Open questions about these coating are: 1) what impact will adding a coating to the UV Cured riblet have on the performance for drag reduction since you have modified the surface of the riblet and 2) how long will these coatings maintain their superhydrophobic characteristics when subjected to the hysteresis of a military aircraft during a PDM cycle? [19]

Photo 8.). Application of a topcoat to an F-117A Nighthawk

c. ***UV Cure 2K Water based Chemical Agent Resistant Coating (CARC)*** -The Army Research Lab was awarded a patent that could potentially be used in Aerospace applications for the Chemical Agent Resistant Coating (CARC) as well as being Low Observable (LO). This technology has its roots in the development of 2K water bourne polyurethanes[20]. This technology also borrows from the UV A cure technology described in Photo 3 for UV A automotive refinish using the H & S Autoshot 1200 W light source. In addition; it uses UV curable polyurethane dispersion (UV PUD). What the technology teaches is that a polyol that has hydroxyl functionality is combined with a UV

PUD and then a water dispersible polyisocyanate is stirred in just prior to use. Included in the formulation are transparent (transparent to UV radiation) iron oxide pigments as well as pigments that result in low IR signature. Also important in the formulation as we described in Section 2 d. is a PI that operates in the 365 nm and above range so that the pigmentation does not affect through cure. One would have to wonder that such a unique coating system could not be utilized in stealth style aircraft as shown in Photo 8 [21].

5.) Conclusions

- One of the most important limiting factors for this UV Cure Aerospace paint technology is the design and size of the UV light for curing the paint on the aircraft.
- The future is bright for this technology especially when you see the incredible foundation that exists for the UV Cure aerospace coatings.
- The DCM 3D UV Cure printing technology has the potential to obtain a 2% reduction in aviation fuel usage and would reduce the annual CO_2 emissions by 20 million tons annually.
- Shown in the previous sections of this paper is the incredible amount of money that has been spent by the US Government/private industry in trying to develop UV cure coatings for Aerospace. The actual dollar amount is not specifically known but it has to be in the multi-millions of dollars.
- Recommend that RADTECH/AFRL host a joint summit to facilitate cross fertilization and demolition of silos that exist due to the types of government style contracts used in trying to develop UV Cure coatings for Aerospace.

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