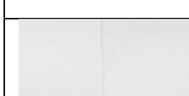
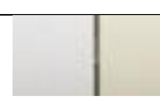
Compatibility of Aircraft Interior Surfaces with 222 nm Far-UV Light Exposure

John Harris Ph.D., Stephanie Metting, Ankita Sharma, and Angela Elting

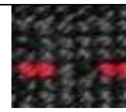
Executive Summary

To ensure safe air travel, there is a strong interest in using 222 nm Far-UV light to disinfect aircraft interior surfaces. However, the impact of 222 nm Far-UV light exposure on the mechanical properties of aircraft interior materials, as well as their color and appearance, has not been previously evaluated. This is because airplane interior materials are not normally exposed to wavelengths of light that are shorter than 280 nm. To understand the impact of 222 nm Far-UV light exposure, we evaluated a comprehensive set of materials used for aircraft interior parts. Specifically, this study included material samples for parts in the galley, passenger cabin, lavatories, and crew rest. These samples were extensively exposed to 222 nm Far-UV light to simulate and evaluate the impact of an in-service, UV disinfection program over the lifecycle of an aircraft. The evaluation found mostly superficial effects on the materials after exposure, affecting only their color and appearance. Even severely discolored material samples maintained desired mechanical properties and met key specification requirements such as tensile strength, elastic modulus, breaking strength, and flammability.

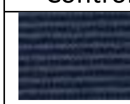
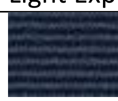
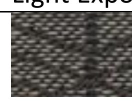
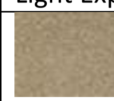
- Following exposure to 222 nm Far-UV, interior coatings did not exhibit any significant yellowing (see guide below).
- Thermoplastic materials exhibited a varied response, ranging from insignificant to severe yellowing.
    - Color changes appeared more pronounced for thermoplastic materials that were white or off-white, compared to darker colors.
    - Polyvinyl fluoride (PVF), polypropylene, and nylon exhibited the best photo-stability

Color Guide	Insignificant Yellowing	Slight Yellowing	Moderate Yellowing	Severe Yellowing
	 Control Test	 Control Test	 Control Test	 Control Test

- Carpet materials extensively exposed to 222 nm Far-UV light were almost indistinguishable from control samples.

Control	222 nm UV Light Exposed	Control	222 nm UV Light Exposed
			

- Fabric samples for drapery and seat covers exhibited insignificant to slight color changes after 222 nm Far-UV light exposure. There was no impact on the breaking strength properties of exposed fabric materials.

Control	222 nm UV Light Exposed	Control	222 nm UV Light Exposed	Control	222 nm UV Light Exposed
					

- No adverse impact on mechanical properties, such as tensile strength and modulus, were observed with thermoplastics materials.
- No adverse impact on flammability properties were observed when tested in accordance with the Federal Aviation Administration (FAA) 60 second, vertical Bunsen burner test.

Introduction

The travel restrictions imposed by the COVID-19 pandemic, as well as a sharp reduction in traveler demand, have significantly impacted the aviation industry. To help restore passenger confidence in commercial air travel, the industry is looking to rapidly implement disinfection methods that are effective in killing SARS-CoV-2 virus and other pathogens. This includes the use of ultraviolet (UV) light between 200 nm and 280 nm to disinfect aircraft interior surfaces.

What Does Disinfection Mean?

The U.S. Centers for Disease Control and Prevention (CDC) defines the difference between cleaning and disinfection as the following:[1]

Cleaning

Cleaning removes visible soil (e.g., organic and inorganic material) from objects and surfaces. It is normally accomplished manually, using wipes, or mechanically, using water with detergents or enzymatic products. Cleaning does not necessarily kill pathogens but removes them. Removing pathogens lowers the total number of pathogens, thereby reducing the risk of spreading infection.

Disinfection

Disinfection eliminates many or all pathogens. Disinfection does not necessarily clean dirty surfaces or remove pathogens but instead kills pathogens. When a surface is disinfected after cleaning, the risk of spreading infection can be further reduced.

Why is UV Light a Concern?

Multiple studies have characterized the properties of UV stability for some widely used thermoplastic materials. These general studies describe instances of fading, discoloration, deterioration, and material embrittlement for some thermoplastic materials after exposure to UV light.[2] The evidence of poor visual and mechanical performance for thermoplastic materials exposed to UV light raises concerns for aircraft interiors, which extensively use thermoplastic type materials and have stringent flammability, mechanical, and visual requirements. To adequately understand the impact of long-term UV light exposure, Boeing evaluated specific aircraft interior materials for their visual appearance and other critical mechanical properties after repeated exposures to 222 nm Far-UV light.

Boeing Material Compatibility Study

To evaluate the impact of exposure to 222 nm Far-UV light on aircraft interior materials, Boeing selected materials from the main cabin, galley, lavatory, and crew rest. The materials included carpets, drapery, leather and wool fabric, floor mats, thermoplastics, coatings, and seals. Samples of these materials were exposed to 222 nm Far-UV light to simulate the dosing that might be received during an in-service, interior surface, UV disinfection program. Following a period of exposure that simulated the lifecycle of the aircraft, the performance of these materials was tested by various Boeing labs. The evaluation included mechanical and flammability property tests as well as the characterization of the material's visual appearance.

How were the materials exposed to 222 nm Far-UV light?

The material samples were exposed to 222 nm Far-UV light under controlled conditions inside a hood. This study used a Krypton Chloride (KrCl) excimer lamp as a UV light source, with a low pass filter that blocked longer wavelengths of light and allowed a narrow, intense band of UV light with a maximum emission at 222 nm (Figure 1). For the sample exposures, multiple KrCl lamps were mounted on aluminum frames, with sample platforms above and below the lamp, to double the exposure capacity of each lamp assembly as shown in Figure 2.

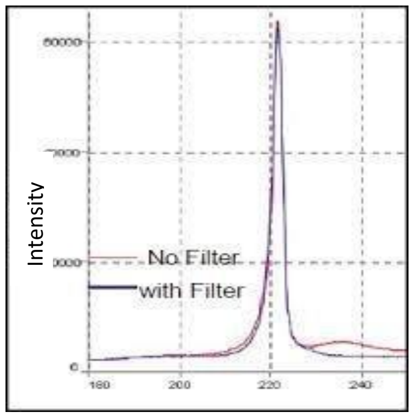


Figure 1: Plot of Low-pass Filtered Emission of KrCl Lamp

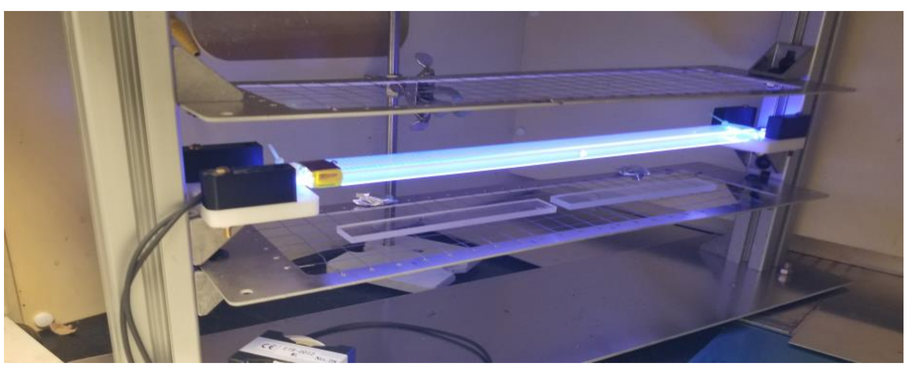


Figure 2: Photo of KrCl Far-UV Lamp Assembly from Boeing Compatibility Study (Photo: Boeing)

How did the study simulate in-service UV disinfection dosing for the aircraft lifecycle?

In order to simulate the 222 nm Far-UV light exposure expected during a typical disinfection process, it is necessary to quantify the intensity of the 222 nm Far-UV lamp as well as define the conditions of a typical in-service disinfection process.

Lamp Intensity

Light is a form of radiant energy measured in units of joules (J) or millijoules (mJ). When a lamp is on, it emits light continuously and the intensity of the light is recorded in watts (W) or milliwatts (mW). Lamp intensity, also known as "irradiance", is related to radiant energy by the following relationship:

$$\text{Lamp intensity} = 1\ \text{mW/cm}^2 = 1\ \text{mJ/sec} \bullet \text{cm}^2.$$

If, for example, a lamp with an irradiance of 1 mW/cm^2 is used to expose a 1 cm^2 sample to its light for 10 seconds, then the sample received a total exposure of 10 mJ/cm^2. For this study, a 'dose' of light was defined using this relationship. The lamp intensity can also be thought of as the number of photons hitting within a square centimeter every second with units of mW/cm^2. Therefore, as the irradiance is increased, the number of photons hitting within the same area is also increased.

Lamp Power Supply

The intensity of light emitted from the KrCl lamp is dependent on the power being supplied to the lamp. In general, light intensity can be increased by providing more power to the lamp. In the Boeing compatibility study, the lamp power supply was fixed. All lamp assemblies consisted of a 300 watt power supply dedicated to a single KrCl lamp.

Inverse Square Law of Light

Another way to increase the amount of light hitting the samples is to reduce the distance between the light source and the surface of the sample. When the distance between the light and the sample is doubled, the relative intensity (irradiance) at the sample surface is reduced by a factor of four. This relationship is known as the inverse square law of light.[3] Consequently, moving the sample closer to the lamp will afford an increase in the irradiance received by the sample. In the Boeing study, the distance between the KrCl lamp and the samples was fixed at two inches.

Fixing the lamp-sample distance and the lamp power supply simplified the calculations needed to simulate long term exposure to 222 nm UV light. The lamp intensity could be recorded using a commercially available power meter to ensure that it remained constant throughout the study.

Assumptions Defining a Typical Disinfection Process:

In order to be able to simulate in-service disinfection using 222 nm UV light, it was necessary to apply basic assumptions defining this process throughout the aircraft lifetime. The dosage of light required to kill the SARS-CoV-2 virus was based on results from a recent study[4] suggesting a single dose of radiant energy of 3 mJ/cm^2. This lethal dosage of light is also referred as "lethal fluence." A conservative estimate of daily, in-service disinfection activities was assumed to be four daily doses. Therefore, assuming four daily doses at 3 mJ/cm^2 , the total daily dose of radiant energy would be 12 mJ/cm^2. The aircraft is also assumed to be in-service for 360 days each year.

An example is provided in Figure 3 of the calculations used to estimate the exposure time for a 10 year in-service period (simulated).

- 1.0 mW = 1.0 mJ/s (in this example each second of irradiance provides 1 mJ/cm^2 energy)
- UV exposure time to achieve lethal fluence = (3 mJ)/(1 mJ/s) = 3 seconds
- Exposure time per day = (3 s/cycle) x (4 cycles/day) = 12 sec/day = **(12 mJ/cm^2)**
- Exposure time in 10 years (3600 days) = (12 s/day) x (3600 days) = 43,200 sec
- (43,200 sec)(1mJ/sec • cm^2) = 43,200 mJ/cm^2 cumulative radiant energy from lamp
- 10 year cumulative radiant energy exposure = 43,200 mJ/cm^2
- (43,200 s)(1 min/60 s)(1 hour/60 min) = 12 hours 222 nm lamp exposure*.

*This is the 'in-lab' exposure time needed to simulate 10 years of in-service UV disinfection dosing

Figure 4. Example of cumulative exposure calculation

How was the Boeing Material Compatibility Study Conducted?

The Boeing study to understand the compatibility of various aircraft interior materials with 222 nm Far-UV light exposure followed the assumptions described above. The comprehensive set of passenger cabin, lavatory, galley, and crew rest materials was exposed to 222 nm Far-UV light for a time representative of 25 years of in-service, UV disinfection dosing. Over that span of time, a total of 36,000 doses of UV disinfection might be carried out. This requires a minimum target for total energy exposure of 108,000 mJ/cm^2 for the samples in the study. Actual exposure times were calculated to achieve this level of exposure and varied based on the measured irradiance of each lamp. Throughout the test, the irradiance of each lamp was periodically characterized using a power meter to ensure the stability of lamp intensity output. No significant fluctuations in lamp intensity were detected that would impact total exposure times.

Boeing Material Compatibility Study Results

Upon completion of exposure to 222 nm Far-UV light, the material samples were evaluated for color shift and mechanical performance, including tensile strength, elastic modulus, breaking strength, and flammability. As described in the executive summary, the performance test results showed:

- Color changes varied by material.
    - Thermoplastic samples showed color changes ranging from insignificant to severe yellowing.
    - Most fabrics exhibited relatively small color changes, even after extensive exposure.
- Interior coatings exhibited good to excellent photo-stability.
- No adverse impact on the mechanical properties of thermoplastic and textile materials.
- No adverse impact on the flammability properties when evaluated in accordance with the FAA 60 second, vertical Bunsen burner test.

A summary of the performance test results is provided in the Executive Summary. In addition, the results for all test materials have also been tabulated and are located in Appendix A.

Recommendations

The addition of UV photo-stability to the set of property requirements for aircraft interior materials presents an opportunity to material scientists and designers to find new design solutions. If the UV disinfection of aircraft interiors is going to be part of a 'new normal' process with airlines, then the following recommendations might be considered:

- Since white or near-white colored thermoplastics exhibited the greatest degree of color change, using thermoplastic materials with darker pigmentation would help to slow the rate of yellowing and reduce the overall color change.
- Consideration should be given to those thermoplastic materials with superior photo-stability properties for interior applications, such as polyamide (nylon), polyvinyl fluoride, and polypropylene.

- Future designs should avoid installing materials with different photo-stability properties next to each other, as the differences in the rates of color change will be noticeable over time.
- Polyurethane coating materials exhibited excellent photo-stability in this study and could be used to coat some thermoplastics that are susceptible to color change as a short term solution.
- Establish OEM-industry partnerships to find long-term solutions, such as the development of new resin systems with improved photo-stability properties.

Appendix A: Summary of Material Performance – Post Exposure to 222 nm UV Light

Material Description	Representative Item(s)	Application	Color Impact	Remarks
Carpets	100% Wool (multicolor, dark) & 100% Nylon (multicolor, dark)	Floor Coverings	Slight Change	The degree of color shift is expected to be different for distinct colors of materials.
Polycarbonate (PC), Opaque Colors	Lexan ML4539 (White)	Armrest	Moderate Yellowing	Noticeable color shifts may occur by 6 months.
Woven Drapery Fabrics	Lantal 100% Wool (Pattern gray) & Lantal 100% Fire-Retardant (FR) Polyester (Solid blue)	Curtains	Insignificant Change to Slight Change	The degree of color shift is expected to be different for distinct colors of materials.
Polyurethane Paint, Semi-Gloss, Flat, and Non-Reflective	Sherwin Williams Polane L or Jet Flex H99 Series (Semi-gloss white); Mankiewicz 346-57 (Flat gray); Mankiewicz ALEXIT Suede-Coating (Flat brown)	Decorative Coatings	Insignificant Change	Evaluated semi-gloss white, flat gray and flat brown colors.
Decorative Laminates	Boeing products (BAC5596 Types IVA/VIA and XXI, White and Textured)	Decorative Surfaces	Moderate Yellowing	Noticeable color shifts may occur by 24 months.
Polycarbonate (PC) with Polysiloxane Hard Coat	Lexan MRAC (Transparent)	Window Dust Covers	No Change	
Thermoplastic Polyurethane (TPU)	ABCO 2449-CF (White, Beige, Blue, Navy) and ABCO 2449 HT (White)	Rub and kick strips, trim, seat track covers	Severe Yellowing	Noticeable color shifts may occur by 12 months. The degree of color shift has been demonstrated to be different for distinct colors of materials (white is worst).
Polyamide (PA12 Nylon)	Vestamid x7167 (White)	Rub and kick strips, trim, end caps, various other plastic parts	Slight Yellowing	Noticeable color shift not expected before 5 years.

Material Description	Representative Item(s)	Application	Color Impact	Remarks
Vinyl Floor Mats	Air flex GP AB2 (1 pattern) and Gerflor AVM 282 G (2 patterns)	Floor Coverings	Insignificant Change	Materials may become glossier, slightly darker, and show a very slight tackiness increase after significant exposure.
Silicone Rubber and Foam	SE5569U with TS-50 (Boeing BMS1-72, Off White) and BF-1005A (Boeing BMS1-68, Off White)	Gaskets, interior seals and gap fillers	Slight to Moderate Yellowing	Noticeable color shifts may occur by 24 months.
Polycarbonate (PC) Copolymer	Lexan FST-9705 (White and Gray)	PSU, Gaspers, reading lights	Moderate Yellowing	Noticeable color shifts may occur by 8 months. Color shift was more rapid in the white material than in the gray material.
Acrylonitrile Butadiene-Styrene/Polyvinyl Chloride (ABS/PVC)	Boltaron 6800 (White)	Lavatory Flush Button	Severe Yellowing	Noticeable color shifts may occur by 6 months.
Polypropylene (PP)	RTP 199 X 151857 A S-204468 (White)	Lavatory Assist Handle, Toilet Seat and Lid	Insignificant Change	
Leathers, Genuine and Artificial	Douglass Interiors Indigo Leather; Tapis Baltic Ultra leather (Blue); Tapis Beige Ultrasuede	Seat Upholstery	Slight Yellowing or Fading	The degree of color shift is color dependent for different materials.
Woven Seat Fabrics	Lantal 100% Wool (dark blue, ribbed); Lantal 92% Wool/8% Nylon blend (multicolor pattern); Lantal Fire-Retardant Polyester (Gray pattern)	Seat Upholstery	Insignificant color change, Fading	The degree of color shift is color dependent for different materials. Small increase (<5%) in fabric fraying over time.

Material Description	Representative Item(s)	Application	Color Impact	Remarks
Polyvinyl Chloride (PVC) Blend	Kydex 6565 (Off-White and Gray)	Possible Uses in Seat Assemblies: Back, Shoulder Area, Tray Tables	Severe Yellowing	Noticeable color shifts may occur by 2 months.
Polyvinyl Chloride/Polycarbonate (PVC/PC) Blend	Kydex FST (Gray)	Possible Uses in Seat Assemblies: Back, Shoulder Area, Tray Tables	Moderate Yellowing	Boeing tested a medium gray material in the absence of white material. Color shifts are anticipated to be more significant for white or lighter-color materials.
Polyphenylsulphone (PPSU)	Radel R-7159 (White)	Stowbin edge trim	Severe Yellowing	Noticeable color shifts may occur by 3 month.
Polyetherimide (PEI) Copolymer	Ultem 9085 (White)	Window Reveal, Outer and Inner	Moderate Yellowing	Noticeable color shifts may occur by 24 months.
Polyether-ketoneketone/ Polyvinyl Fluoride (PEKK/PVF)	ESP 41-141153 (White)	Window Shade and Handle	Insignificant Change	
Unsaturated Polyester Resin	Granicoat (speckled gray, speckled black)	Lavatory Countertop	Insignificant Change	

References

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