Influence of UVC LED disinfection on polycarbonate materials

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Abstract

The invention of LEDs that generate germicidal deep-ultraviolet (UVC) light has driven advances in surface disinfection. This study explored how UVC disinfection influences polycarbonate-based plastics, commonly used to make medical equipment, car interiors, and consumer electronics, by exposing them to light from UVC LEDs equivalent to thousands of disinfection cycles. Our test results showed that physical properties like strength and heat resistance were fully retained after UVC exposure. White-colored materials turned yellow, black-colored materials showed essentially no color shift, and in all cases the surface finish was preserved. The color shift was essentially the same whether the samples were irradiated at high or low intensity, or in a continuous or intermittent fashion. UVC-induced color changes appeared to penetrate no more than several micrometers below the part surface. While they may change color, polycarbonates seem well-suited to applications where they will be repeatedly disinfected by UVC light.

Introduction

With the growing effort to fight transmission of infectious diseases, there's great interest in finding more effective and convenient ways to disinfect surfaces. Deep-ultraviolet (UVC) light is one alternative to chemical disinfection. UVC is an established technique for disinfecting drinking water and purifying air that is now finding increased use in sanitizing surfaces for products like medical equipment, car interiors, and consumer electronics.

While UVC-emitting fluorescent bulbs have been available for decades, recent advances in semiconductor technology have driven the development of high-performance LEDs built to deliver UVC light at precisely the wavelengths with the most potent germicidal effect: 260-270 nm. UVC bulbs continue to be popular for purification equipment, but the small size, versatility, and energy efficiency of UVC LEDs gives designers exceptional freedom to design innovative new disinfection systems.

Because surface disinfection using UVC is new, relatively little is known about the effect of UVC light on materials. Plastics used in hospital equipment, car interiors, and personal handheld devices may benefit from periodic disinfection. Among the most common materials used for these types of equipment are polycarbonates, which are premier engineering thermoplastics with a unique combination of strength, impact resistance, heat resistance, and versatility and consistency in manufacturing, combined with a moderate price. The purpose of this study was to better understand how polycarbonate materials behave after exposure to UVC doses used for disinfection.

The UVA and UVB radiation from sunlight cause polycarbonates to yellow and degrade over months and years of outdoor exposure, as is the case with many plastics. UVC radiation is fully absorbed by Earth's atmosphere, so its effect on polycarbonate properties is not well understood. Because polycarbonate absorbs very strongly at UVC wavelengths, UVC light is not expected to penetrate nearly as deeply into surfaces as UVA and UVB light do. The shallow penetration depth of UVC could have a protective effect on polycarbonate parts.

Two studies using very high doses of UVC light showed good long-term property retention in a polycarbonate[1] and a PC/ABS blend[2], demonstrating the suitability of polycarbonate-based materials even in applications where they reside very close to UVC lamps.

Experimental

We chose a total fluence (dose) of 120 J/cm^2 to approximate a lifetime of UVC disinfection cycles for a plastic equipment housing. The appropriate fluence depends on how often a part is disinfected, its service life, and the UVC exposure of each disinfection cycle. The dose of UVC required to kill microorganisms with a given effectiveness has been compiled for a wide range of species.[3] A fluence of 120 J/cm^2 represents 6,000 cycles at a typical disinfection dose of 20 mJ/cm^2, or 4,000 cycles at a more thorough 30 mJ/cm^2 dose, applicable to parts that are disinfected several times per day over the course of several years.

The materials chosen for this study are listed in Table 1. Various polycarbonate grades and polycarbonate blends in applications ranging from electrical equipment, medical devices and automotive interiors were studied. Further product information is available at www.solutions.covestro.com. Test specimens were injected molded per datasheet recommendations and physical properties were measured using ISO standard test methods. Color of rectangular plaques was assessed using a HunterLab UltraScan PRO diffuse sphere spectrophotometer using the CIELAB color space per ASTM E313 with D65 illumination and 10° observer, with additional kinetic measurements assessed using a PCE Instruments PCE-CSM 2 handheld specular 45°/0° color meter.

Materials were exposed to radiation from Klaran® LE Series UVC LED light engines, manufactured by Crystal IS. The peak emission is near 265 nm and the full width at half maximum is about 12 nm. UVC 9-LED light engines were assembled into vented light boxes and the intensity was measured by a

TABLE 1 – Materials used in this study.

Application Area	Product Name	Color
Electrical and Electronic Equipment	Bayblend® FR3010 012622	White
	Makroblend® EL700 012772	White
	Makrolon® RW2407 010226	White
Medical Devices and Equipment	Bayblend® M301 FR 013771	White
	Bayblend® M850 XF 013771	White
	Makrolon® Rx1805 013771	White
	Makrolon® 2458 013184	White
	Makrolon® 2458 550115	Clear
	Makrolon® 2458 704363	Gray
	Makrolon® 2458 901528	Black
Automotive Interiors	Bayblend® T85 HD 901510	Black
	Bayblend® T85 XF 901510	Black

Gigahertz Optik X1-1 optometer. Test specimens were placed within a defined area where the illumination was demonstrated to be near-uniform. Intensity was tuned by adjusting the distance from the LEDs to the test specimens, in the range of 0.10 to 0.35 W/cm^2 (1 to 3.5 W/m^2). At 0.10 mW/cm^2, a fluence of 120 J/cm^2 was achieved after 13.9 days of continuous exposure or 27.8 days of intermittent exposure with 30-minute on/off cycle times.

Results and Discussion

The 120 J/cm^2 simulated lifetime dose of UVC radiation induced a surface yellowing of the polycarbonate-based materials. The effect was pronounced in white-colored materials, with a Delta E (ΔE*, color shift) of around 12 units. The color shift was significantly less in a medium-gray colored polycarbonate, a Delta E of 7. In black colors, the Delta E was less than 1, which is considered not perceptible. Sample chips are pictured in Figure 1 and the full results are in Table 2.

The different white materials contained different amounts of white pigment, but the pigment loading appeared to have little influence on the amount of color shift seen. The color shift was also similar for different material types: polycarbonate (Makrolon®), general-purpose PC/ABS (Bayblend® T), and flame-retardant PC/ABS (Bayblend® FR).

Interestingly, the clear transparent material Makrolon® 2458 550115 showed a Delta E of only 3 in transmission, significantly less than the opaque white samples. The moderate color shift likely results from the very shallow penetration depth of UVC radiation into the polycarbonate surface (illustrated in Figure 4). Considering how efficiently polycarbonate absorbs UVC radiation, the extent of surface damage in all samples is likely very similar despite the different Delta E values. White pigment may simply show the yellowing, while black pigment hides it. Notably, the surface finish of all samples was unchanged after UVC exposure, with full retention of surface gloss per ASTM D523.

FIGURE 1 – Appearance of materials before and after of UVC exposure, for four different colors of the same polycarbonate product, Makrolon® 2458.

We found the magnitude of the color shift was essentially independent of how the UVC radiation was applied: continuously at 0.10 mW/cm^2, intermittent on/off at 0.10 mW/cm^2, or at a higher intensity of 0.35 mW/cm^2. The comparison of these dosage modes on polycarbonate of different colors is illustrated in Figure 2. The results suggest that the observed color shift mainly depends on the total dose (fluence) of UVC radiation the parts see. This may facilitate comparisons between UVC exposure experiments done at different irradiances.

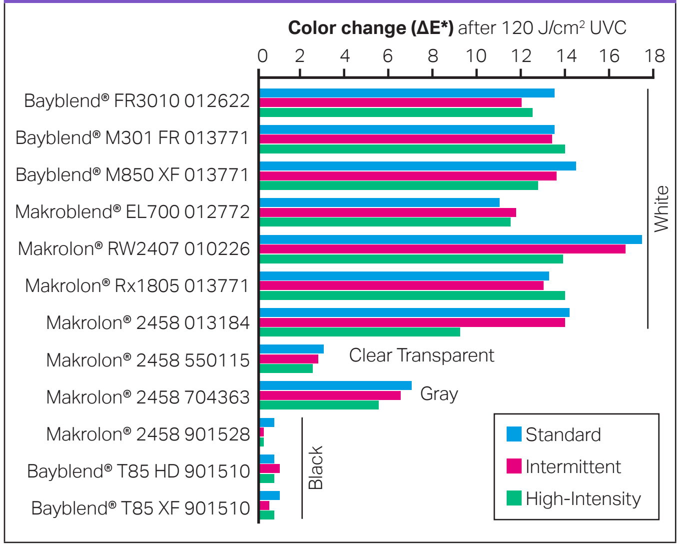
Kinetics of the color shift versus UVC exposure were measured using a handheld color meter; see Figure 3. A saturation response was seen for all samples: yellowing was much more rapid at first, with roughly half of the eventual color shift seen at 120 J/cm^2 coming within the first 30 J/cm^2 of exposure. There was no significant difference in yellowing whether the samples were irradiated continuously or intermittently. The rapid saturation behavior was also seen for polycarbonate elsewhere[1]; it implies that additional UVC radiation beyond 120 J/cm^2 may result in only slightly more yellowing.

Aesthetics are important for many products that are repeatedly disinfected, but often a more pertinent question is whether a material's physical properties are retained after disinfection.

TABLE 2 – Color shift data for different polycarbonate and PC blends after 120 J/cm^2 exposure (0.10 W/m^2 continuous).

Polymer Type	Product Name	Color	ΔL* (lightness)	Δa* (redness)	Δb* (yellowness)	ΔE* (color diff.)
PC+ABS	Bayblend® FR3010 012622	White	-1.4	-3.4	13.1	**13.6**
PC+ABS	Bayblend® M301 FR 013771	White	-1.5	-3.4	13.2	**13.7**
PC+ABS	Bayblend® M850 XF 013771	White	-1.5	-3.8	14.0	**14.6**
PC+PET	Makroblend® EL700 012772	White	-1.6	-1.6	10.8	**11.1**
PC	Makrolon® RW2407 010226	White	-1.8	-4.3	16.8	**17.4**
PC	Makrolon® Rx1805 013771	White	-1.2	-3.7	12.8	**13.4**
PC	Makrolon® 2458 013184	White	-1.3	-3.9	13.8	**14.4**
PC	Makrolon® 2458 550115	Clear	-0.1	-1.1	2.8	**3.0**
PC	Makrolon® 2458 704363	Gray	-0.5	-2.3	6.4	**6.8**
PC	Makrolon® 2458 901528	Black	0.6	0.0	0.0	**0.6**
PC+ABS	Bayblend® T85 HD 901510	Black	0.6	-0.2	0.1	**0.7**
PC+ABS	Bayblend® T85 XF 901510	Black	1.0	-0.2	-0.1	**1.0**

FIGURE 2 – Post-UVC color shift after 120 J/cm²



We chose one polycarbonate and one PC/ABS blend and compared their tensile properties, impact resistance, and heat resistance before and after UVC exposure. All properties were fully retained within experimental error for all three exposure modes: continuous, intermittent, and high intensity, as shown in Table 3.

It's interesting to note that no property changes were detected despite the distinctive yellowing seen in the white samples. While these were bulk properties measurements, tensile properties and impact properties can be sensitive to surface damage, since a damaged surface can induce a brittle failure mode[4]. Also, the Vicat softening temperature measurement uses a small needle to probe the material, so it can be sensitive to surface degradation as well. The fact that these properties were retained is an encouraging indication that polycarbonates are mechanically suitable for repeat UVC disinfection.

The lack of physical properties or surface change after UVC exposure contrasts the experience of outdoor weathering of polycarbonates. UVA and UVB are known to result in surface degradation and reduced bulk properties given sufficient exposure. A likely contributing factor is the shallow penetration depth of UVC, which results from the very high absorption of polycarbonate in the UVC wavelength range[5]. A cross-sectional light microscopy image of a microtomed UVC-exposed sample showed visible yellowing only near the sample surface, depicted in Figure 4. The rapidly yellowing surface layer may act as a protective barrier shielding the bulk material underneath from UVC exposure.

Conclusions

Polycarbonates and PC blends appear to be well suited to applications in which they are repeatedly disinfected by UVC. Although lighter colors yellow when exposed to a simulated lifetime dose of UVC radiation, transparent and darker colors show a milder color shift, and black colors show no perceptible change. The high absorption of UVC radiation by polycarbonate appears to result in a shallow penetration depth, with the outer surface of the plastic part protecting the bulk from damage. While the cumulative dose of 120 J/cm² studied here approximates thousands of disinfection cycles, even higher doses may be of interest for applications in which polycarbonates are used in the housings of UVC lamps or for equipment which is kept very close to UVC sources. The rapid saturation kinetics of yellowing implies that even much higher doses may result in only slightly more yellowing.

FIGURE 3 – Color shift vs. fluence (or dosage) for white, gray, and black colors of Makrolon® 2458

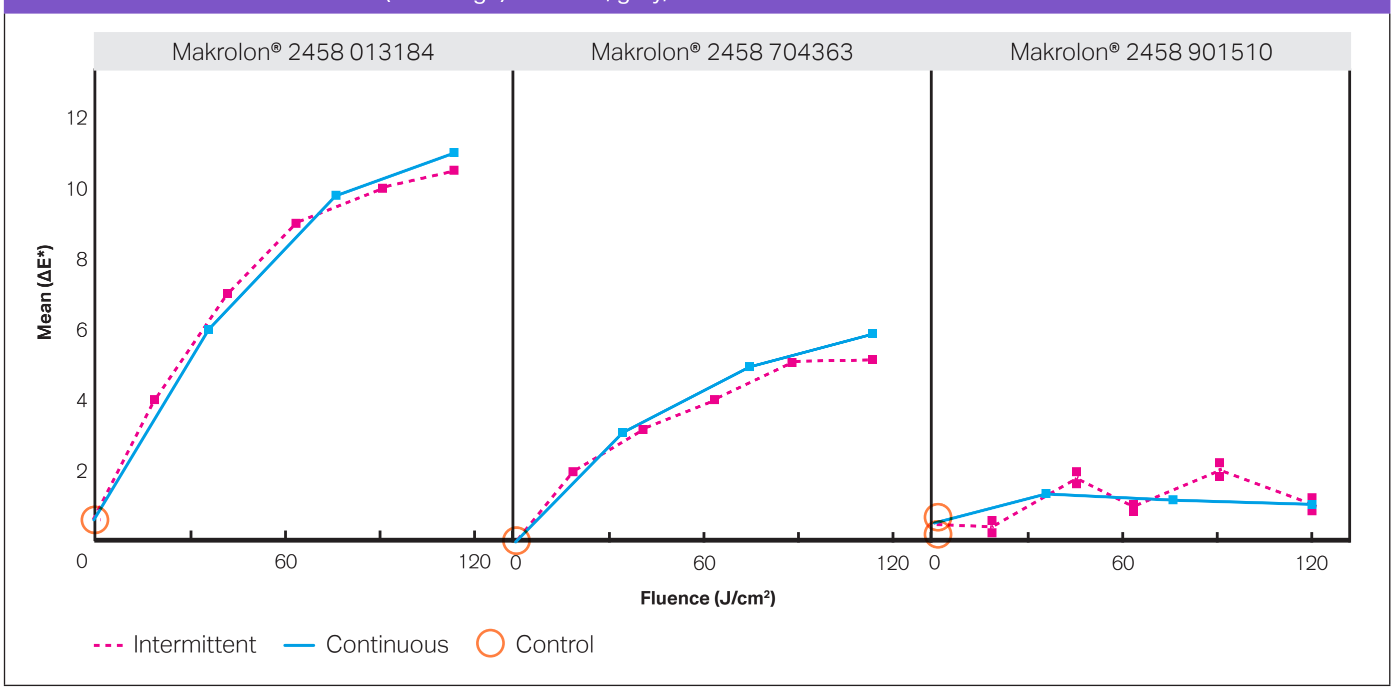


TABLE 3 – Physical properties retention after 120 J/cm² UVC exposure via three different exposure modes.

Bayblend® T85 XF 901510 (black PC/ABS)			**No UVC** Control	Post-UVC Continuous	Post-UVC Intermittent	Post-UVC High-Intensity
Izod notched impact strength, 23°C (4mm)	ISO 180/A	kJ/m²	45	45	47	46
Tensile modulus	ISO 527-1, -2	MPa	2390	2390	2400	2370
Tensile yield stress	ISO 527-1, -2	MPa	53.7	53.6	53.7	53.6
Vicat softening temp. (50 N, 120°C/h)	ISO 306	°C	127	127	127	127

Makrolon® 2458 550115 (clear PC)			**No UVC** Control	Post-UVC Continuous	Post-UVC Intermittent	Post-UVC High-Intensity
Izod notched impact strength, 23°C (3mm)	ISO 7391 / ISO 180/A	kJ/m²	56	60	62	56
Tensile modulus	ISO 527-1, -2	MPa	2460	2460	2440	2460
Tensile yield stress	ISO 527-1, -2	MPa	62.8	62.9	62.9	62.9
Vicat softening temp. (50 N, 120°C/h)	ISO 306	°C	144	144	144	144

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FIGURE 4 – Cross-sectional light microscopy (160×) view of the surface of a white part; the sample is at the bottom and the background appears black. The yellowing is seen to penetrate only a small distance from the surface, with most of the color shift appearing within 15 microns of the surface, and nearly all of it within 50 microns. Additionally, the surface is smooth and unperturbed by UVC exposure.

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