Analysis of Plastic Degradation Due to Ionizing Radiation

April 24, 2020

by Hayden Cunningham

Advised by Dr. Gore

Dept. of Physics, Computer Science, and Engineering

Christopher Newport University

Approved:

1 Abstract

The purpose of this experiment was to observe, quantify, and compare the physical effects of radiation degradation on plastic samples using two different radiation-emitting sources. I compared the effects of radiation from a UV light source and six Radium-226 sources. After exposure, three tests were performed on the plastic samples: a bend test, a stress test, and an absorbance test. The force required to break or deform the plastic exposed to the Radium-226 sources for 24 hours was 22.025% less than the non-exposed samples. The force required to break or deform the plastic exposed to the ultraviolet light source for 24 hours was 16.86% less than the non-exposed samples. After 24 hours of exposure, the UV-exposed samples had an increase in absorbance of 114.33% compared to the unexposed samples and the Radium-exposed samples had an increase in absorbance of 144.10% compared to the unexposed samples. No visible stress patterns were observed as a result of any exposure type or length.

2 Introduction

Exposure to radiation can cause natural and synthetic polymers to degrade over time. Different types of radiation may have different effects on the constitution of plastics exposed to them. The purpose of this experiment was to compare the effects of ultraviolet and gamma radiation sources on samples of acrylic. Understanding how exposure to radioactivity effects the physical properties of plastic is valuable because plastic is used in nearly every industry in the modern world, from food service to spacecraft. Every day, plastics are exposed to radiation via sunlight, and understanding the effects of this radiation on the physical properties of plastics can help scientists better plan to improve the lifespan of these products.

Absorbed radiation can cause the bonds in a polymer to break, leading to degradation of the plastic. In this experiment, I observed and measured the effects of exposure to UV and gamma-emitting sources on plastic samples through three physical tests, measuring flexural strength, absorbance, and polarization stress patterns.

3 Theory

The three tests I performed were a bend test, an absorbance test, and a stress test. The bend test measured the flexural strength of the plastic samples before and after being exposed to the radioactive sources. Flexural strength is the amount of force an object can withstand without being permanently damaged or broken. In the bend test, I utilized a spring scale to pull directly upward on plastic samples clamped horizontally to the lab bench. Multiplying the mass indicated by the spring scale (in kilograms) by the acceleration of gravity ($9.81\frac{m}{s}$) yielded the force it took to break or permanently deform the plastic (Equation 1).

$$F = mg \tag{1}$$

Once the force required to bend or break each sample was recorded, they were plotted against the exposure time and compared to the control data to find the percent increase or decrease in the force the samples could withstand. This test was based on David W. Plester *et al.*'s findings that poly(Methylmethacrylate) had a significant decrease in tensile strength when subjected to prolonged exposure to a UV radiation-emitting source. (Plester, 1970)

The second test, the absorbance test, observed changes in the absorbance of the plastic samples as a result of the radiation degradation. Using a PASCO spectrometer with a fiber-optic cable, I measured and graphed the intensity vs. wavelength of a white light source viewed through the exposed plastic samples and compared it to the same light source viewed through unexposed samples. Using the Comparison Mode tool in the PASCO Spectrometer App, I compared the graphs to note differences due to the radiation degradation. The absorbance for each graph of intensity vs. wavelength will be calculated using the Beer-Lambert Law (Equation 2). At a given point on the graph, I designated I_0, an intensity on the un-exposed sample's line. At the same point on the exposed sample's line, I designated a point I, and calculated the Absorbance (A).

$$A = log_{10}\frac{I_0}{I} \tag{2}$$

The third test was a stress test. I placed exposed samples between two crossed polarizers to view stress patterns presented as a result of the radiation degradation. When clear plastics undergo physical stress, stress patterns become visible when the plastic is placed between crossed polarizers. This is because crossed polarizers are polarized such that no light can pass between them. If stress is induced in a material placed between them, it may bend the light passing between them and cause it to be presented in the form of stress patterns. These patterns can be seen as a discolored section when light passes through the sample under stress through crossed polarizers.

4 Methods

The experiment was carried out in the PCSE Research Lab in Luter Hall 342. Within the lab, the exposures were carried out in a wooden box to block alpha particles, beta particles, and UV rays from escaping, as well as to prevent outside light from interfering with the measurements taken. The interior of the box was painted matte black to avoid any interference from the box on the UV exposures. The spaces between the pieces of wood used were sealed with black caulking putty to ensure that no light will enter the box from the outside. Corner brackets and mounting brackets have been drilled into the sides of the box to reinforce its shape and ensure that the wooden panels stay in place, and two handles have been drilled into the sides to make moving the box easier. The box is only five-sided, as the top is open. For each exposure, the experiment was assembled on the floor of the lab and the box was placed top-down over it to block any outside light from entering or escaping and altering the experimental data. To avoid any risk of fire, a large PVC pipe was mounted to the top of the box, and a smaller PVC pipe was mounted to one side. Each pipe consisted of three 90-degree turns, and the inside of both pipes was painted matte black. To keep the system ventilated, a manually-controlled computer fan was placed at the opening of the large pipe, and oriented to suck air out of the top of the box. Small divots were drilled into the base of the box to allow the power cords for the UV and white light sources to pass under the box without allowing in additional light. A small hole the width of the Spectrometer's fiber-optic cable was drilled into the top of the box in order to collect data for the absorbance test. When the box was in use for exposures, the hole for the fiber-optic cable was covered. The wooden box is pictured in Figure 1.

Figure 1: Wooden Protective Box

The original plan for the experiments was to have nine samples for each exposure length, giving three samples per test. However, due to the sudden time restrictions, only six samples could be completed for each test.

The Ultraviolet exposures were carried out using an 18-inch Chauvet NV-F18 Ultraviolet light. During the exposures, the light was placed on the ground, and a metal rack made from a scarf hanger was placed flat on top of the light. The scarf hanger was chosen to use for the rack because it was comprised of 4"-diameter circles which could suspend the plastic above the light while making minimal contact with the samples. The light, rack, and plastic samples were then covered with the wooden box and left for the duration of the exposures.

The Radium-226 exposures were carried out by placing the plastic samples onto the floor, placing the Radium-226 sources directly onto them, and covering them with the wooden box to block any harmful radiation from escaping. The box was left covering the setup for the duration of the exposures. When the Radium-226 samples were not in use, they were kept in a secondary container within a metal cabinet in the PCSE Storage room on the third floor of Luter Hall. When the samples were in use, signs were posted on the door of Luter 342 and on the box itself explaining that there was minimal risk of being exposed to harmful radiation, but not to touch or move the box without first consulting myself or Dr. Gore. After handling the Radium-226 sources, I was sure to thoroughly wash my hands and not touch any food or drink.

The three tests were performed on 33 2” x 4” plastic samples provided by Christopher Newport University’s Plant Operations team. Six of the plastic samples were used as a control group to run the tests on in order to compare data from the exposed samples. This control group was exposed to neither the Radium-226 sources nor the Ultraviolet light source. For all three tests, six plastic samples were exposed at a time to each radiation source for three separate time intervals: 2 hours, 3 hours, and 24 hours.

4.1 The Bend Test

The Bend Test measured changes in the flexural strength of the plastic before and after exposures to the sources. The plastic samples were clamped to the lab bench using a C-clamp. The plastic samples were clamped below the lip of the bench, and a blue piece of plastic was clamped above the bench to use as a marker to bend the samples a standard distance. The distance between the two plastic pieces clamped to the lab bench was 2 cm. A small hole was drill pressed into the end of each sample and a spring scale was attached to the samples once they were clamped to the bench. A controlled bend was completed by slowly pulling the spring scale directly upward while closely watching the scale reading. Once the plastic was broken, reached the blue marker, or became permanently deformed, the mass measured at that point in kilograms was converted to Newtons. The Bend Test was performed one sample at a time while wearing protective goggles, as some samples broke and sent shards of sharp plastic flying. Multiple repetitions of each bend test were conducted in order to ensure consistency of data and to get an average value for the force required to bend or break the plastic.

Figure 2: Bend Test Configuration

4.2 The Absorbance Test

The Absorbance Test observed the effects of degradation by measuring the absorbance of the plastic before and after exposure to the radioactive sources. This test was originally intended to be performed in the wooden box, using a white light source, a PASCO Spectrometer with a fiber optic cable, and the PASCO Spectrometry App. However, due to complications with the Spectrometer, the test was performed on a table in my garage with the windows sealed, the door shut, and the lights off, leaving the only light source being the white light. The Spectrometry App was used to plot the Intensity vs. Wavelength of the light with the fiber optic cable held 2 centimeters from the light. The Intensity vs. Wavelength was plotted looking through an unexposed piece of control plastic. Then, the same configuration was repeated for a piece of exposed plastic. Using the "Show Comparison Mode" function in the Spectrometry app, the plots were presented together and could be compared within the app, measuring the Intensity and Wavelength at any selected point. In order to keep data consistent, all Intensities were measured at $\lambda = 270$ nanometers at the peak of the graph. From the Intensities presented, the Absorbances were calculated using the Beer-Lambert Law. The results were compared across exposure types and lengths, and between exposed and unexposed samples to observe changes in the observed Absorbance.

4.3 The Stress Test

The Stress Test gave a qualitative representation of the physical stress induced in the plastic samples by exposure to the radioactive sources. To perform the Stress Test, I held the plastic samples between two crossed polarizers and looked at a light source. If the radiation had induced any stress patterns in the plastic, they would have been easily visible as multicolored patterns on the face of the plastic. Photographs of the plastic were taken through the crossed polarizers using an Apple iPhone 11 Pro camera to record if any stress patterns were presented.

5 Data

5.1 Bend Test Data

Below are the data tables for the Bend Test organized by radiation source and exposure length. Table 1 is the table of data for the Bend Test.

Exposure Type	Trial Number	Mass (kg)	Force (N)	Bend/Break
Control	1	12.38	121.45	Break
Control	2	12.6	123.61	Bend
Control	3	11.36	111.44	Break
UV 2 Hour	1	11.01	108.01	Break
UV 2 Hour	2	10.90	106.93	Break
UV 3 Hour	1	10.68	104.77	Bend
UV 3 Hour	2	10.51	103.10	Break
UV 24 Hour	1	10.35	101.53	Bend
UV 24 Hour	2	10.11	99.18	Bend
Radium-226 2 Hour	1	10.81	106.05	Bend
Radium-226 2 Hour	2	10.64	104.38	Bend
Radium-226 3 Hour	1	10.50	103.01	Bend
Radium-226 3 Hour	2	10.20	100.06	Bend
Radium-226 24 Hour	1	9.84	96.53	Bend
Radium-226 24 Hour	2	9.58	93.98	Bend

Table 1: Table of Bend Test Data

Below are the graphs of average force required to permanently deform or break the plastic samples exposed to the Radium-222 sources and the UV source. (Figure 3)

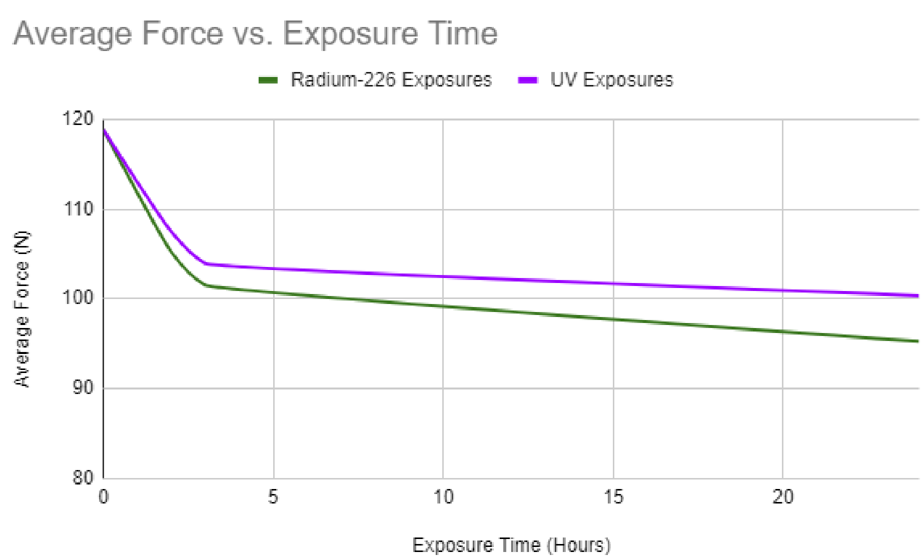

Figure 3: Bend Test Results

5.2 Absorbance Test Data

Using the Beer-Lambert Law to determine the Absorbance of the control group plastic, the following Absorbances were recorded for the UV and Radium-Exposed plastic.

Exposure Source	Intensity of Light	Observed Intensity	Control Absorbance
UV	21.897	19.300	0.054
Radium-226	17.827	19.235	0.053

Table 2: Control Group Absorbance

Below are the tables of the Intensities taken and Absorbances calculated for the plastic exposed to the UV and Radium-226 using the PASCO Spectrometer.

Exposure Length (Hours)	Control Intensity	Observed Intensity	Calculated Absorbance
2	21.897	19.300	0.055
3	21.897	19.235	0.056
24	21.897	13.862	0.199

Table 3: Table of Absorbance Test Data: UV Exposures

Exposure Length (Hours)	Control Intensity	Observed Intensity	Calculated Absorbance
2	17.127	13.643	0.099
3	17.127	12.218	0.147
24	17.127	8.107	0.325

Table 4: Table of Absorbance Test Data: Radium-222 Exposures

Below are the graphs of Intensity vs. Wavelength produced using the PASCO Spectrometer for both the UV-Exposed plastic and the Radium-Exposed Plastic

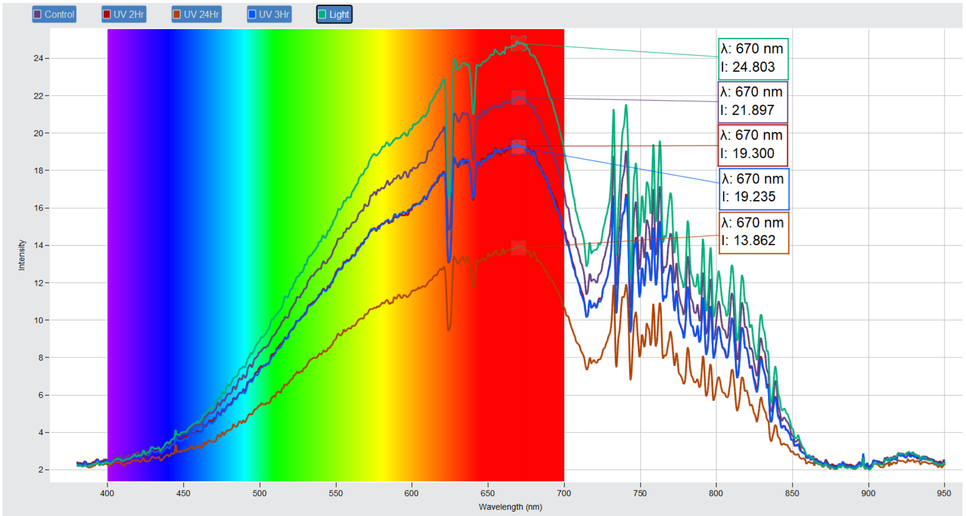

Figure 4: Intensity vs. Wavelength Graph - UV Source

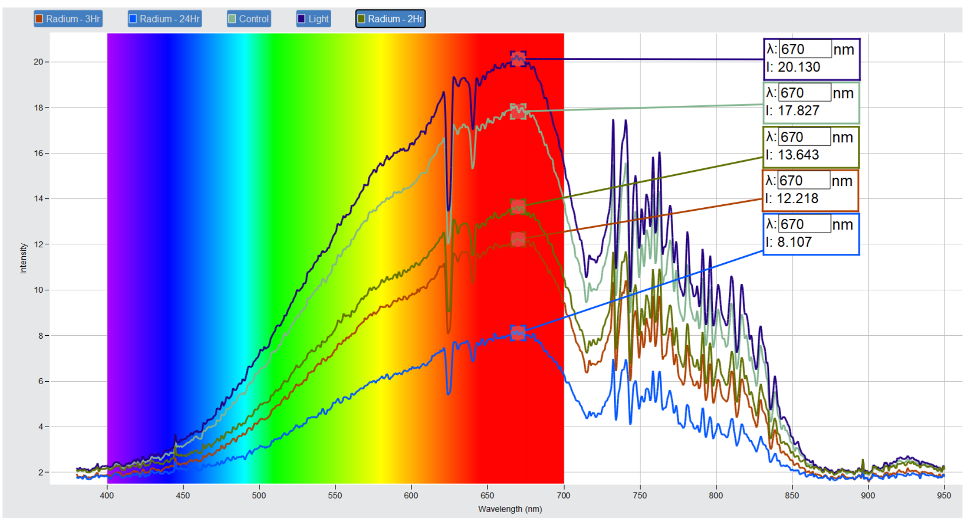

Figure 5: Intensity vs. Wavelength Graph - Radium-222 Sources

Figure 6 is the graph of the Absorbance measured with the PASCO Spectrometer for the Radium-222 Sources and UV Source for each exposure length.

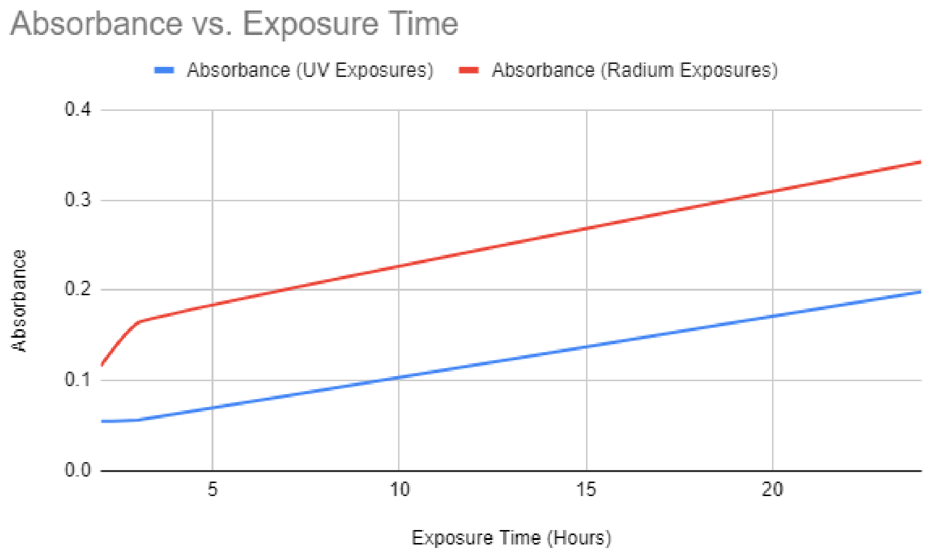

Figure 6: Absorbance Test Results

Table 5 is the table of the change induced in the plastic as a result of the Absorbance Test. The table includes the percent difference of the measured absorbance of the exposed plastic from the absorbance of the control plastic and the ratio of the observed intensity to the control intensity for each exposure type and length.

Exposure Type	% Difference from Control Absorb.	Observed/Control Intens.
UV 2 Hour	1.299	0.881
UV 3 Hour	3.936	0.878
UV 24 Hour	114.326	8.107
Radium-226 2 Hour	75.062	0.765
Radium-226 3 Hour	102.666	0.685
Radium-226 24 Hour	146.654	0.455

Table 5: Absorbance Test Comparisons

5.3 Stress Test Data

No stress patterns were visible for any exposure length or radiation source. Below is an image of a control sample viewed through the crossed polarizers (Figure 7). All pictures taken of the plastic samples post-exposure showed no visible stress patterns, regardless of radiation source or exposure length. Figure 8 is the photo of the 24-hour Radium-226-exposed plastic viewed through the crossed polarizers with no visible stress patterns.

Figure 7: Unexposed plastic viewed through crossed polarizers

Figure 8: 24 Hour Radium-exposed plastic viewed through crossed polarizers

In completing this project, there were sources of error which should be noted. Due to the sudden COVID-19 evacuation, I had to switch work environments from the lab in Luter Hall to my home garage. Switching from a lab environment to a home garage halfway through the completion of the experiment may have caused errors in the data, as I no longer had access to the lab equipment. For the Bend Test, most of the data collected for the Ultraviolet exposures were taken on a work bench in my garage, instead of the lab bench in Luter 342. This bench was significantly thicker than the lab bench, meaning that the plastic samples were bent further, resulting in some uncertainty in the samples which did not break. For the Stress Test and Absorbance Test, there is a higher possibility of interference in the observed results due to dust in the garage. I wiped down the plastic samples before each test, however doing so may have caused scratches to form on the face of the plastic, or not gotten enough of the dust off of the plastic to avoid interference. Future experimentation should be completed in a clean, dry lab environment.

6 Discussion and Conclusions

6.1 The Bend Test

There was a significant difference in the force required to permanently deform or break the plastic after exposure to the radiation sources. Both the UV and Radium-226-exposed samples saw an immediate drop in the force required to deform or break them which then became less dramatic over time. The Radium-226-exposed samples saw a greater change in the force, with the 24-hour exposed samples yielding an average force of 95.23 N, which was 23.03% lower than the average force from the control group (118.83 N). The UV-exposed samples saw a result of 100.36 N, 16.86% lower than the average force from the control group. A trend observed over both the UV and Radium exposures was that with increased exposure time, the plastic samples became more malleable than they were before. None of the samples exposed to the Radium sources for any length broke when the bend test was conducted. Only one of the samples exposed to the UV source for any time greater than two hours broke. Of the samples that did not break, the 24-hour exposed samples from both sources did not become visibly deformed, they immediately returned to their resting position after being bent, with no lasting effects from the bend.

6.2 The Absorbance Test

There was an increase in the absorbance of the plastic samples post-exposure for all exposure types and lengths. Compared to the control plastic, which had an average absorbance of 0.0535, the Radium-226 exposed plastic and the UV exposed plastic both experienced an increase in absorbance with increased exposure time. After 24-hour exposure, the Radium-226-exposed plastic had a 146.564% increase in absorbance, and the UV-exposed plastic had a 114.326% increase in absorbance. There was possible error in the data for the Absorbance Test, as I had to replace the Spectrometer's fiber optic cable after it stopped working. The replacement cable didn't arrive until two days before the final deadline for the project, so the data collection for this test was rushed, leaving little time for synthesis of the results.

6.3 The Stress Test

No stress patterns were presented in the plastic, regardless of exposure type or exposure length. I expected to see at least slight patterns emerge, as there were easily discerned differences in the pre and post-exposure data for the Bend Test and Absorbance Test. This means that no light passed through the polarizers, as there was no stress in the plastic to bend the light passing through. For future research, experimenters could make more clear results from this section by using a device to apply a standard amount of stress to the control group and exposed groups, and compare the differences in the stress patterns presented as a result of that additional stress. Doing so could indicate whether or not radiation degradation makes the plastic samples present more prominent stress patterns when placed under a constant amount of stress across all exposure types and exposure lengths.

It is worthwhile to note the specific output of each Radioactive source used in the experiment. While the output is not directly factored into any calculations in the experiment's results, it's important to know for future experimentation. Similar experiments can be performed with different radiation sources to compare results. The average output for the Radium-222 sources was 934.77 counts per second. Background radiation is typically anywhere from 12 to 16 counts per minute, or 0.2 to 0.27 counts per second. This means that the Radium-222 sources exposed the plastic to 4006.16 times higher levels of radiation than they would typically be exposed to from background radiation. A such, the plastic samples exposed to the Radium-226 were prematurely aged by a factor of 4006.16, meaning that the 24-hour exposure simulated the effects that 166.67 days of prolonged exposure to background radiation would have on the plastic samples. The wavelength of the UV light source was on the high end of the UV-A spectrum, measuring at approximately 400 nanometers. UV-A light makes up the majority of the sun's UV radiation reaching the Earth, so the UV exposures prematurely aged the plastic by simulating prolonged sunlight exposure.

7 References

1. Clark, J. "The Beer-Lambert Law," (2016). Retrieved from https://www.chemguide.co.uk/analysis/uvvisible/beerlambert.html

2. Gore, D. "The Physics of Radioactive Decay", (2011).

3. Krasnansky, V. J., et al. "Effect of Gamma Radiation on Chemical Structure of Plastics." Wiley Online Library, John Wiley Sons, Ltd, (2004) Retrieved from https://onlinelibrary.wiley.com/doi/abs/10.1002/pen.760010308.

4. Plester, D. W. "The Effects of Radiation Sterilization on Plastics", Retrieved from https://pdfs.semanticscholar.org/02c0/b193e9ffb262cb7c8ed66b7ad1d915ba5830.pdf

5. Redner, A. S., Hoffman, B. R. "Measuring Residual Stress In Transparent Plastics", (2017), Retrieved from https://www.mddionline.com/measuring-residual-stress-transparent-plastics

6. Yousif, E., Haddad, R. "Photodegradation and photostabilization of polymers, especially polystyrene: review", (2013) Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4320144/