Impact of Light Bleaching on Dark Storage Test

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Abstract

Ongoing research of the dark storage test for print images has revealed several factors which influence the results. Although it has been known for many years that exposure to light can 'bleach' or whiten media that has yellowed with aging, it has not been studied extensively in the context of its impact on the dark storage test. Investigation into this phenomenon has found that simply exposing yellowed media test samples to office light for a few hours causes measurements to shift by 10%. This research studied how the type, intensity, and length of light exposure affected media at different stages of yellowing. One experimental observation is that some bleached media placed in the dark quickly begins to yellow again and in continued testing is indistinguishable from unbleached media. Moreover, the temporary whitening of media during measurements in the dark storage test is best avoided as it can have considerable repercussions on the data analysis.

Introduction

Research conducted during the past 5 years has identified several noise variables which affect the consistency of thermal (i.e. dark storage) test results with respect to media yellowing [1,2]. This paper will describe a series of experiments that focused on the impact of light on the dark storage test. Although samples are not exposed to light while in the test chamber at elevated temperature, they are likely to be exposed to light both prior to and after each test cycle.

All the data presented in this paper will be with respect to unprinted media samples and their behavior in the dark storage test. A figure of the test sample and its preparation is described in a prior paper [3].

Experimental Results and Discussion

As test samples are measured, they are exposed to light by the measurement device. Employing a method identical to one used in an earlier study of light sensitive inks [4], the measurement device was instructed to repeatedly measure the same location of a 'yellowed' thermal test sample. Although this is not typical practice for measuring these samples, the purpose was to understand the influence of the measurement device on the sample and as a means of evaluating the sample's response to a tightly controlled dosage of light. Results can be found in Figure 1. With each repeated measurement—occurring about every 3 seconds—the sample 'whitens' as revealed by decreasing Delta E measurements (i.e. it is changing back to its original color). The small increase in Delta E at measurement 50 corresponds to a delay between measurements of about 7 seconds as the measurement sensor rechecked the white calibration reference block away from the sample. This recovery of Delta E in the absence of light was observed in the earlier study on light sensitive inks and was verified through subsequent testing.

The two media shown in Figure 1 are representative of all media tested. Note that for the purpose of this study, the high initial delta E was achieved through prior exposure of test samples to ozone before placing in the thermal test [5].

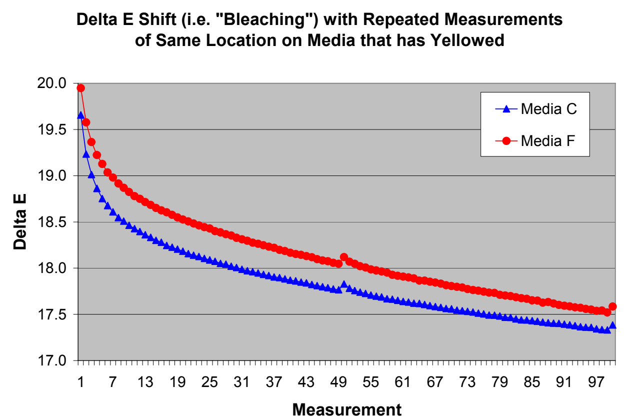

Figure 1. Repeatedly measuring same sample location results in bleaching the sample as it is exposed to high intensity flashes of halogen light for each measurement by the Gretag Spectrolino measurement instrument.

Thermal test samples may also receive incidental light from the ambient office conditions while being removed from the test chamber and in preparation for measurement. Test samples were prepared by running at different durations of time at elevated temperature to achieve initial yellowing levels targeting approximately 5, 10, 15, and 20 Delta E before being exposed to light. Table 1 shows measurements of media bleaching in an office environment at 500 lux with exposure times ranging from 1 hour to just over 1 week. In just 1 hour at 500 lux (0.5 klux-hours) the sample yellowing had decreased by about 6% Delta E. Exposure to office light for 1 week resulted in more than a 50% decrease in Delta E. However, when samples were placed back in the dark at ambient conditions of 23C/50% RH, the bleaching began to reverse; recovering more than 10% Delta E of yellowing that had been originally bleached out.

Table 1. Media samples of varying initial degrees of yellowing subsequently exposed to fluorescent office light at 500 lux.

Media	Initial Delta E	% Change in Delta E for Light Exposure (klux-hours)					1 Week in Dark
		0.5	2	4	24	96	
C	6.4	-3.3%	-6.5%	-10.4%	-33.2%	-58.0%	-40.4%
	10.5	-6.1%	-9.8%	-14.3%	-37.6%	-60.4%	-49.5%
	14.9	-5.8%	-10.3%	-15.0%	-38.4%	-60.8%	-52.5%
	19.3	-6.1%	-11.3%	-16.2%	-39.7%	-61.2%	-54.2%
F	5.1	-4.9%	-10.3%	-15.5%	-38.8%	-62.3%	-36.3%
	10.0	-6.1%	-11.8%	-16.8%	-38.6%	-59.1%	-46.5%
	14.6	-6.4%	-12.0%	-16.9%	-37.6%	-57.7%	-48.4%
	19.5	-7.5%	-12.8%	-17.5%	-37.4%	-57.0%	-49.9%

Table 2 shows another set of samples prepared in the same way but then exposed to high intensity CWF light. Measurements were taken at specific intervals to match the exposure dosage with ambient light. A dosage of light in ambient conditions that took 8 hours (4 klux-hours) only required 10 minutes in the high intensity light; however, both bleached samples showed close to a 15% reduction in Delta E. There were some signs of slight reciprocity failure for Media C as the light dosage increased, since at 96 klux-hours it had changed by 'only' 53% Delta E compared to 60% Delta E with office light exposure. After a week of exposure to high intensity CWF light (2880 klux-hours) the samples had nearly returned to their original condition prior to the thermal test. But once samples were placed back in the dark, the bleaching process began to reverse and yellowing returned at a much greater rate than if the samples had been left unbleached. However, this may have been a side effect of having pre-conditioned these samples with ozone.

Table 2. Media samples of varying initial degrees of yellowing subsequently exposed to high intensity CWF light at 24000 lux.

	Initial	% Change in Delta E for Light Exposure (klux-hours)					1 Week
Media	Delta E	4	24	96		2880	in Dark
C	6.8	-9.8%	-26.9%	-49.7%		-92.3%	-71.2%
	10.5	-12.0%	-30.1%	-53.3%		-93.7%	-80.0%
	14.7	-12.8%	-30.8%	-53.5%		-93.6%	-83.6%
	19.4	-13.2%	-31.5%	-53.1%		-92.8%	-84.6%
F	6.2	-15.7%	-37.4%	-60.3%		-97.6%	-66.1%
	10.0	-16.0%	-36.2%	-57.8%		-96.2%	-76.8%
	15.6	-15.7%	-35.3%	-56.4%		-95.0%	-82.1%
	20.1	-15.3%	-34.5%	-55.0%		-93.7%	-83.9%

The next experiment explored the impact of light bleaching of thermal test samples between each test cycle. One set of samples was always kept in the dark, having less than 10 lux ambient light exposure during transport and measurement (only being exposed to bright light briefly from the measurement instrument), another set was exposed to office light for 4 hours (2 klux-hours exposure), a third set was exposed to high intensity CWF light (85 klux-hours exposure), and the final set was exposed to high intensity Xenon light (also 85 klux-hours exposure). These last two sample sets were intended to gain knowledge about what effect long term office light exposure may have on both the thermal test and real life dark storage.

Each sample was initially measured in the dark (less than 10 lux), then placed in thermal test at 85C/50% RH for 160 hours, and then transported in the dark to another darkened room for measurement. After which the samples designated for light exposure were exposed to light, then all samples were measured again, including the "always dark" control before all were placed back in thermal test for another 160 hours.

Table 3 shows measurements from this test at 160, 320, and 640 hours (the 480 hour measurements were omitted for visual clarity). Paired with each thermal test cycle measurement is a measurement titled 'Repeat', which is the measurement taken after the designated light exposure for that sample. The "always dark" control samples have a slightly lower Delta E because of the small dose of light received a few hours earlier during its first measurement at the conclusion of each thermal test cycle.

The samples bleached with office light initially lost between 5-9% Delta E at the beginning of the test, but with each thermal test cycle and subsequent dose of light, the impact diminished to between 2-5% at the end of the test. The high intensity CWF and Xenon light resulted in much greater bleaching: 20-30% at the conclusion of the first 160 hour thermal test cycle and 10-20% at the conclusion of the final 160 hour cycle after 640 hours of cumulative thermal testing. And despite different spectral power distributions, both CWF and Xenon light had similar bleaching impact as determined by equivalent dosage in lux-hours.

The most fascinating observation from this experiment was that samples exposed to light would yellow more rapidly than the dark control during the next thermal test cycle, although usually not enough to completely reverse the impact of bleaching. However, some media bleached with Xenon light yellowed more in subsequent thermal testing. This is most apparent with Media X, a plain paper, which yellowed more than the dark control in the thermal test cycles, overcoming significant bleaching in the process.

Table 3. Media samples in thermal test with varying types of light exposure between each thermal test cycle.

		Delta E after Thermal Test Hours at 85C/50%RH						2 Weeks
Media	Condition	160	Repeat	320	Repeat	640	Repeat	in Dark
C	Dark	4.49	4.46	7.35	7.32	11.64	11.63	11.62
	Office	4.51	4.11	7.26	6.88	11.57	11.17	11.27
	CWF	4.43	3.10	6.92	5.11	10.60	8.33	8.65
	Xenon	4.58	3.08	7.08	4.95	10.77	8.20	8.52
D	Dark	5.85	5.82	9.98	9.96	18.39	18.38	18.31
	Office	5.88	5.60	9.98	9.68	18.18	17.80	17.83
	CWF	5.85	4.63	9.71	8.24	17.39	15.37	15.65
	Xenon	5.85	4.73	9.93	8.57	17.78	16.20	16.50
E	Dark	3.76	3.74	4.75	4.75	6.19	6.14	6.14
	Office	3.80	3.48	4.84	4.48	6.17	5.90	5.94
	CWF	3.85	3.09	4.79	3.99	5.86	5.09	5.19
	Xenon	3.84	3.20	4.93	4.20	6.32	5.63	5.64
F	Dark	4.19	4.17	6.70	6.69	11.24	11.18	11.18
	Office	4.11	3.85	6.49	6.23	10.88	10.40	10.50
	CWF	4.13	3.19	6.45	5.21	10.47	8.42	8.78
	Xenon	4.02	3.02	6.20	4.91	10.10	8.06	8.37
L	Dark	3.71	3.69	5.26	5.24	7.14	7.11	7.13
	Office	3.63	3.37	5.12	4.88	7.00	6.70	6.83
	CWF	3.68	2.81	5.18	4.22	6.71	5.79	5.96
	Xenon	3.69	2.72	5.10	4.04	6.53	5.53	5.65
U	Dark	3.57	3.55	5.04	4.98	7.00	6.95	7.00
	Office	3.54	3.24	4.90	4.64	6.77	6.44	6.56
	CWF	3.55	2.58	4.88	3.77	6.37	5.25	5.41
	Xenon	3.56	2.59	5.21	3.90	6.89	5.60	5.73
V	Dark	6.45	6.44	9.40	9.35	14.47	14.42	14.39
	Office	6.58	6.07	9.40	8.87	13.98	13.44	13.51
	CWF	6.56	4.72	9.02	6.83	13.44	10.72	11.09
	Xenon	6.51	4.66	9.11	6.79	13.38	10.63	10.99
W	Dark	11.09	11.06	16.00	15.97	26.81	26.76	26.72
	Office	11.18	10.53	15.86	15.23	26.75	25.86	26.00
	CWF	11.13	8.45	15.44	12.33	26.57	21.71	22.46
	Xenon	11.37	8.29	15.68	12.14	26.24	20.98	21.70
X	Dark	3.17	3.12	4.91	4.86	7.02	6.93	6.86
	Office	3.54	3.27	5.22	4.97	7.28	6.97	6.93
	CWF	3.49	2.63	5.09	4.08	6.83	5.81	5.77
	Xenon	3.48	2.65	5.59	4.39	7.76	6.61	6.53

The final light bleaching experiment further examined the diminishing impact of light bleaching with repeated light exposure. The test was designed to begin with completely yellowed samples. These samples would then be bleached with a consistent exposure of 100 klux-hours of CWF light. The bleached media samples would then be returned to a fully yellowed state to be bleached once again. To make this possible in a short period of time, the media samples were pre-conditioned with ozone. Doing so allowed the porous photo papers in the test to quickly reach Delta E values of 30-50. And before each exposure to light, the media samples were run in the thermal test for 160 hours at 85C/50% RH to ensure that they had once again reached maximum yellowing.

Figure 2 illustrates the cycling of this test with two media. Media C is a porous photo paper while Media D is a swellable photo paper and consequently unaffected by the ozone pre-exposure and thus did not yellow as much at the start of the test. Although the porous photo paper had already nearly reached maximum yellowing at the beginning of the test and the swellable photo paper was still attaining greater yellowing with each subsequent thermal test cycle, the impact of the light bleaching on the two was surprisingly similar. As seen in Table 4, Media C and D both experienced about a 31% decrease in Delta E with light bleaching after the first test cycle, and both experienced about a 16% decrease in Delta E after the fifth test cycle. Because the swellable photo paper was still yellowing throughout the test, the absolute magnitude of the bleaching Delta E was increasing even as the percentage of total Delta E was decreasing.

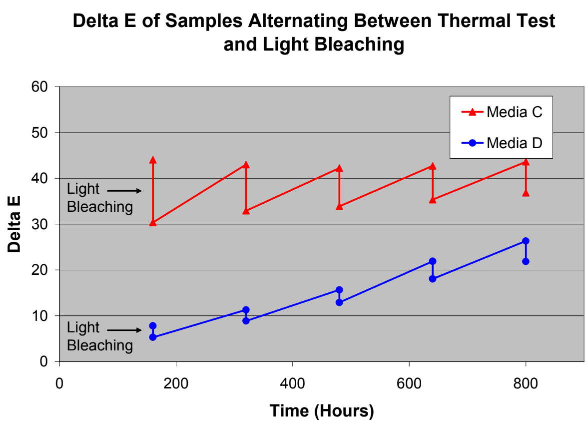

Figure 2. Impact of repeated light bleaching of media samples alternating with cycles of thermal testing.

It should be noted that not all porous photo papers were able to sustain their maximum Delta E throughout the test because the thermal test cycle was insufficient to be able to fully recover the yellowing of the bleached media sample.

Table 4. Impact of light bleaching on media samples in thermal test. Same light exposure (100 klux-hours) at conclusion of each thermal test cycle (160 hours per cycle).

	Impact of Light Bleaching (% change in Delta E) after Thermal Test Cycles at 85C/50%RH				
Media	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 4**	**Cycle 5**
A	-28%	-22%	-19%	-17%	-16%
B	-31%	-24%	-21%	-19%	-18%
C	-31%	-23%	-20%	-17%	-16%
D	-32%	-21%	-18%	-18%	-17%
E	-33%	-24%	-21%	-19%	-17%
F	-44%	-34%	-29%	-26%	-24%
G	-50%	-38%	-33%	-29%	-26%
H	-43%	-32%	-27%	-24%	-22%
I	-33%	-23%	-19%	-16%	-14%
J	-50%	-39%	-34%	-31%	-29%
K	-32%	-25%	-21%	-19%	-18%
L	-44%	-34%	-29%	-25%	-22%
M	-40%	-31%	-27%	-25%	-23%
N	-42%	-35%	-31%	-29%	-27%
O	-20%	-16%	-14%	-13%	-13%
P	-26%	-21%	-19%	-17%	-16%
Q	-29%	-22%	-20%	-17%	-17%
R	-39%	-30%	-26%	-23%	-21%
S	-41%	-31%	-27%	-24%	-22%
T	-36%	-26%	-21%	-18%	-16%
U	-39%	-29%	-25%	-22%	-20%
V	-41%	-32%	-28%	-25%	-23%
W	-41%	-31%	-27%	-24%	-22%

Conclusion

The purpose of these experiments was to further understand the impact of light bleaching of media samples in dark storage testing [6]. This is just one of many factors that have been identified which can influence the results and conclusions drawn from dark storage testing.

It was found that exposure to office light for a few hours can have a measurable impact on the recorded Delta E values of the media samples. Table 5 shows measurements of Media Y in a thermal test at 71C/50% RH. In the first row are the measurements of Delta E for the sample kept in the dark. The second and third rows illustrate the impact on the Delta E measurements if the Media Y sample was exposed to office light for 1 hour or 4 hours respectively. At a failure threshold of 10 Delta E, the time to failure for a sample kept in the dark is 574 hours. However, for samples exposed to light, the time to failure increased to 631 hours with 1 hour exposure to office light at each measurement interval and to 673 hours with a 4 hour exposure to office light.

Table 5. Impact of light bleaching on media in thermal test. Same light exposure (100 klux-hours) at conclusion of each thermal test cycle (160 hours per cycle).

	Delta E Measurements after Thermal Test Hours at 71C/50% RH					
Media Y	**160**	**320**	**480**	**640**	**800**	**Failure**
Dark	3.97	6.79	8.94	10.74	12.40	574
1 Hour	3.74	6.38	8.40	10.10	11.65	631
4 Hours	3.58	6.11	8.05	9.67	11.16	673

Therefore, while 1 hour of office light bleaches the sample by 6% Delta E, it lengthens the failure time by 10%. Likewise, the 10% drop in Delta E caused by bleaching the sample with 4 hours of office light results in a corresponding 18% increase in the length of time to failure.

However, the Arrhenius method requires testing at multiple temperatures and consequently the impact of light bleaching during each of those thermal tests can undergo many different permutations. Table 6 demonstrates several different scenarios when using the Arrhenius method to predict life estimates in years at 23C from thermal tests run at 71C, 78C, 85C, and 92C.

Table 6. Impact of light bleaching from office light on Arrhenius method evaluated at 71C, 78C, 85C, and 92C to estimate life in years at 23C.

Light Bleaching Impact on Arrhenius Method for Media Y					
Lighting Condition during Measurement				**Life Estimate**	**% Deviation**
71C	**78C**	**85C**	**92C**		
Off (Dark)	Off (Dark)	Off (Dark)	Off (Dark)	46.0	
1 Hour	1 Hour	1 Hour	1 Hour	50.6	10%
4 Hours	4 Hours	4 Hours	4 Hours	54.1	18%
Off (Dark)	Off (Dark)	Off (Dark)	1 Hour	35.5	-23%
Off (Dark)	Off (Dark)	Off (Dark)	4 Hours	29.7	-35%
1 Hour	Off (Dark)	Off (Dark)	Off (Dark)	62.9	37%
4 Hours	Off (Dark)	Off (Dark)	Off (Dark)	78.1	70%

If light bleaching is consistent with each sample measurement at all test temperatures, then the deviation in failure time observed at one temperature will propagate at the same magnitude to the life estimate calculated using the Arrhenius method. However, if light bleaching is inconsistent across the different temperatures the possible impact can range from a 23% decrease or 37% increase in life estimates with 1 hour exposure to typical office light, and can range from a 35% decrease to 70% increase in life estimates with a 4 hour exposure to office light. Because ambient light exposure can have such a large influence on thermal test results, it has been the authors' standard practice the past few years to transport and measure these samples at very low light levels [5].

In addition to increasing the difficulty in achieving consistent results between test laboratories conducting thermal testing, light bleaching is also of interest to conservators who are seeking to reverse the yellow stain of aging images [7, 8]. While this study focused on inkjet media, the data may be useful when combined with others' research into understanding the behavior of various media technologies to light bleaching and further discourage the use of light as a means of restoring yellow stained images.

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Author Biography

Matthew Comstock received his B.S and M.S. degrees from Purdue University in Mechanical Engineering specializing in heat transfer and thermodynamics. He joined Lexmark International, Inc. in 1999 as a development engineer for color laser products. Since 2005 he has been responsible for the Lexmark Image Permanence Lab in Lexington, KY. His work is primarily focused on image permanence test method development and image permanence testing.

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