Estimating Light-fastness of Inkjet Images: Accounting for Reciprocity Failure

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Abstract

Among the key assumptions of the accelerated method for predicting light-fastness is that the rate of fade at high illumination intensities is equal to the rate of fade at the lower illumination intensities present in more real-world conditions. If these two fade rates are dramatically different then a reciprocity failure exists for that image that can lead to misleading light-fastness predictions. According to H. Wilhelm ('The Permanence and Care of Color Photographs, pg.67), "…[M]ost color materials exhibit at least some 'reciprocity failure' in light fading or light-induced stain formation in high-intensity, short-term tests." Thus, high-confidence light-fastness predictions for all color images should check for reciprocity failure.

In this paper the authors describe a practical test method for accounting for possible reciprocity failures in Inkjet imaged prints. The media with swellable ink receiving layer (similar to first generation Inkjet photo media) are seen to have little or no reciprocity failure with the ink sets tested thus far. However, the media with micro-porous ink receiving layer tested have all shown significant reciprocity failures (by a factor of the order of 100) that would lead to greatly exaggerated light-fastness predictions if left uncompensated for.

A simple method for identifying whether air exposure contributes to the apparent light fade is also presented. Based on this method it is concluded that air exposure significantly contributes to the apparent light fading of the micro-porous media when samples are not protected from air contact.

Introduction

Among the key assumptions of the accelerated method for predicting light-fastness is that the rate of fade at high illumination intensities is equal to the rate of fade at the lower illumination intensities present in more real-world conditions. If these two fade rates are dramatically different then a reciprocity failure exists for that image that can lead to misleading light-fastness predictions. The causes of reciprocity failure could be light, temperature, and components carried by air (water vapor, oxygen, and so-called contaminants such as ozone or oxides of nitrogen and sulfur), here referred to as 'air fade' or 'gas fade'.

The most frequently used light-fastness procedure by digital imaging industries is a highly accelerated test using high intensity lamps (30 – 70 klux) and test images directly protected (from air) by glass covers. The two common assumptions--often made, but rarely verified--are that a) the high intensity lux-hr data templates linearly with low-intensity data, and b) this assumption 'a' is valid regardless of whether samples are glass-protected or unprotected. Labs uncomfortable with assumption 'b' sometimes assume instead that customers will only display samples that are protected (by glass, etc.) from contact with air; this assumption is contradicted by market research conducted by Hewlett-Packard and the market experiences of other inkjet companies.

Therefore, this paper is proposing a new light-fastness procedure that explicitly checks for reciprocity failure by including a highly accelerated light-fastness test and a test under low light intensity for a longer duration.

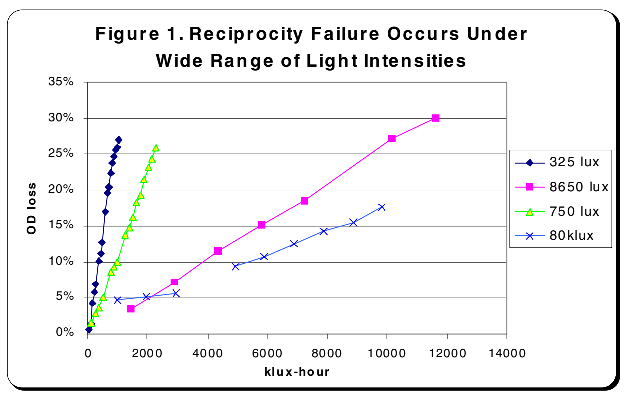

Figure 1. Reciprocity failure occurs under wide range of light intensities. 'Reciprocity Failure' refers to the unequal slopes of these 4 lines.

This author's previous study (see figure 1) shows no minimum light intensity below which there is no reciprocity failure. However, 1000 lux seems like a reasonable low light intensity since it is realistic and it is still 4–5 times accelerated when keeping lights on 24 hours a day (compared to 450 lux and 12 hours a day). In addition, preliminary data to date (Figure 1) indicate a relatively low reciprocity failure at 1000 lux (relative to real indoor light intensity). This report recommends how long we should test at 1000 lux, how to estimate light-fastness, and how to calculate reciprocity factors.

Experiment

The experimental design included two variables, lamination and light intensity. Comparing samples with and without laminate tells us how sensitive the samples are to gas fading. Comparing samples at low and high intensities tells us the light intensity effect on fading. This author believes that laminate is convenient and it is the same or better than a glass cover for gas fading protection. However, a glass cover mimics photo frame and therefore is closer to the end users experience. A well-sealed glass cover is recommended for future fade resistance test.

The following are the experimental details:

1. Highly Accelerated Fade Resistance Test.

Laminated and non-laminated samples were tested in HPUV fadeometer. HPUV fadeometer uses un-filtered cool white fluorescent light with intensity about 70 klux. Temperature was about 40°C and relative humidity was about 10 - 15%. High velocity airflow occurs over the samples in the fadeometer. Optical density loss from an initial 0.5 OD target was measured at 4927 klux-hours (2.5 years, assuming office light is 450 lux and 12 hours a day) and 9855 klux-hours (5 years, assuming office light is 450 lux and 12 hours a day).

1. Low Intensity Fade Resistance Test

Laminated and non-laminated samples were put in a light box for 4 months (1.1 years, assuming office light is 450 lux and 12 hours a day). The light box has cool white fluorescent light with 750 lux intensity. Temperature was 23°C and relative humidity was about 50%. OD loss from an initial 0.5 OD target was measured every month.

2. Measurement Error

Two X-rite spectra colorimeters are used to read color OD. The measurement standard deviation is 0.005 OD.

3. Sample Drying

All samples were prepared by using commercially available inkjet printers and the recommended branded media. Samples were dried for at least 24 hours before lamination, and the samples were only laminated on the image side. Previous drying experiments indicated that volatiles in ink evaporate from inkjet prints within 30 minutes after printing.

Results

1. Coated Paper with Dyes

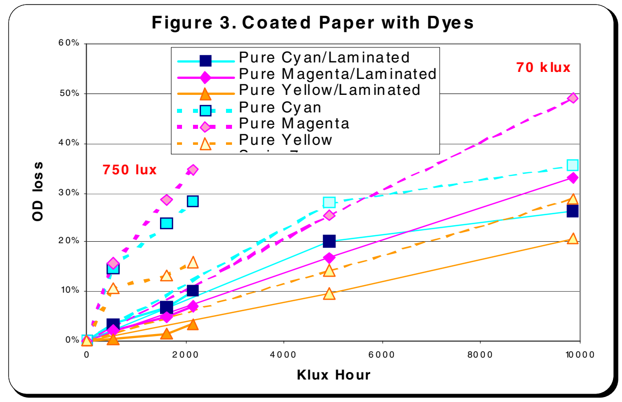

Figure 3. Coated paper with dyes

In this paper, coated paper refers to media having special coatings on the surface of plain paper to keep colorant from sinking to the paper fibers. These coatings are usually porous. Coated paper includes Epson Matte Paper-Heavy Weight, HP Professional Brochure and Flyer Paper (Two-sided Matte Finish), and so forth.

Figure 3 shows the test results of one representative coated paper printed with dyes. This graph plots OD% loss as a function of exposure. The slope of a curve indicates fade rate. At both high and low light intensities, laminated samples have better apparent light-fastness than non-laminated ones. The graph also shows that non-laminated samples have reciprocity failure but the laminated ones appear to have no reciprocity failure. Consequently, for this particular coated paper tested, gas fading is the major contributor to reciprocity failure.

2. Porous-Coating Inkjet Photo Paper With Dyes

Porous coatings contain small, inorganic particles such as alumina that create voids in the coating. The voids between the particles work as pores to absorb the ink. Air migrates through the coating, exposing layers of ink to contaminants in the air. Porous-coating inkjet photo paper include such paper as Epson photo paper, Epson premium photo paper, Canon photo paper, Canon Photo Paper Pro, Kodak picture paper (soft gloss), HP Professional Brochure and Flyer Paper (Two-sided Gloss), and so forth. Figure 4 shows the test results of one representative porous photo paper.

At both high and low light intensities, laminated samples have better fade-resistance than non-laminated ones. Unlike the coated paper tested, both laminated and non-laminated porous-coating media appear to have reciprocity failure, although the latter is much larger. Consequently, for this particular porous-coating medium, reciprocity failure is caused by not only gas fading but also some other unknown factors.

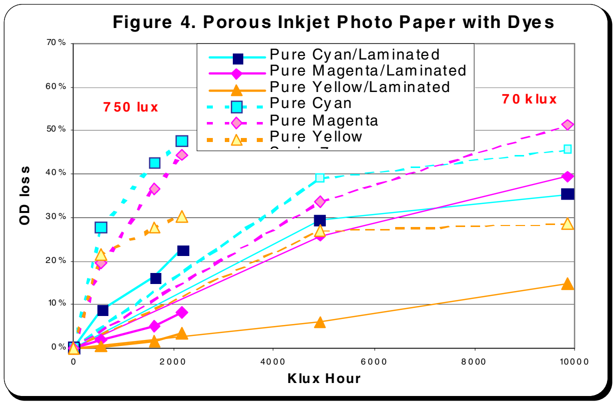

Figure 4. Porous inkjet paper with dyes

3. Non-Porous Coating Inkjet Photo Paper With Dyes

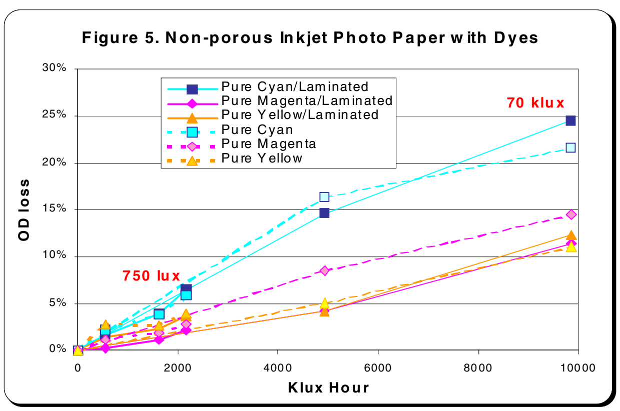

Figure 5. Non-porous inkjet photo paper with dyes

Non-porous coatings contain organic polymers. The coating swells to absorb the ink so only a thin layer of ink is exposed to air and direct light. Non-porous-coating inkjet photo media include such paper as HP Premium Plus Photo Paper, HP Colorfast Photo Paper, Kodak Premium Picture Paper (high gloss), and so forth. Figure 5 shows the test results of one representative non-porous-coating medium.

Unlike coated paper and porous photo paper, for non-porous media, low intensity curves appear to have similar slope as the high intensity ones, which indicates no or little reciprocity failure. There are small differences between laminated and non-laminated samples. However, if we take all three colors into consideration, it is difficult to determine which test result is better.

4. Porous Inkjet Photo Paper With Pigment Inks

Few desktop printers on the market use pigment inks. Figure 6 shows the test result of a representative porous-coating medium with pigment inks. Similar to porous-coating media with dyes, the porous-coating medium with pigments is vulnerable to gas fading and has large reciprocity failure. This test result disproves a general assumption that pigments are not subject to reciprocity failure or gas fade, and always outperform dyes.

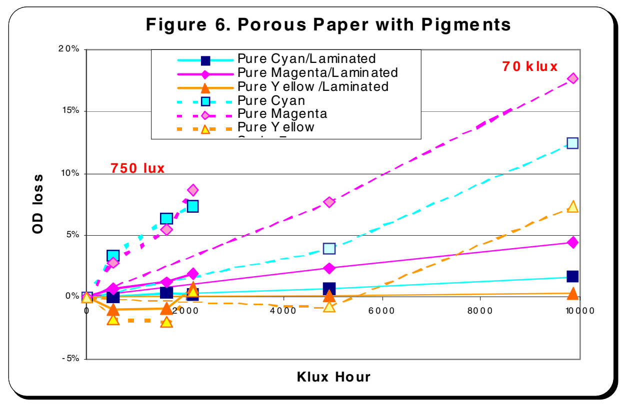

Figure 6. Porous inkjet photo paper with pigments

Test Duration

1. Highly Accelerated Test

For highly accelerated light-fastness test, most media/ink combinations could reach at least one end point in a few weeks. Therefore, under high light intensities, it is reasonable and desirable to test until failure.

2. Low Intensity Test

If a medium is very lightfast and does not have reciprocity failure, it will take years or tens of years to test this medium *to failure* at 1000 lux. Fortunately, however, results in this report show that it is possible to adequately check the reciprocity assumption with 1 to 4 months of 1,000 lux fade data.

In this experiment, samples were tested for four months at 750 lux. For coated paper and porous-coating media, one can clearly see the slope differences between high and low light intensities, and between covered and uncovered samples. However, the non-porous-coating media tested has good fade resistance and does not demonstrate reciprocity failure. Consequently, it is unnecessary to test for longer times because the slopes of high and low intensity already curves match very well.

In summary, current inkjet technologies clearly divide special inkjet media into three types: Coated paper, porous/micro-porous-coating photo paper, and non-porous photo paper. Porous paper and coated paper appear vulnerable to gas fading and therefore tend to have large reciprocity failure. Non-porous coatings appear much more robust to gas fading and thus tend to have no or little reciprocity failure. A four-month test at 1000 lux is long enough to distinguish these inkjet coatings and give more meaningful fade resistance data.

Repeatability Among Test Labs

This experiment was conducted at San Diego, California. The exact pollutants and the concentrations at the test areas are unknown. Depending on air quality, the data may not be repeatable if the same test is conducted at other locations.

30 out of 50 media/inks the Authors tested demonstrate significant reciprocity failure. Appendix A (available upon request) is a list of these media. Light-fastness test labs are encouraged to test at least two of the media listed in Appendix A to ascertain indirectly the air quality in their labs, and to always include the two media as controls in all future testing.

If a given test lab does *not* see significant reciprocity failure with these control media, they should consider all their unprotected (i.e. no glass, no laminate) light fade data to be not useful for meaningful predictions, and thus should only make predictions for glass-protected samples and should clearly label these predictions as "glass-protected light-fastness," for example. The labs (like HP San Diego or Corvallis) that *do* see significant apparent reciprocity failure with the controls can have greater confidence around making predictions for both gas-protected and unprotected Light-fastness based on this proposed 2x2 method. All labs should additionally test samples with a controlled gas fade test as soon as one is defined.

Fade Resistance Estimation and Reciprocity Failure Factor Calculation

Fade resistance data processing involves data plotting, curve fitting, reciprocity factor calculation, end points estimation, and fade resistance estimation.

1. Data plotting

Data should be plotted in the format of %OD remaining versus lux-hour.

2. Curve Fitting

Light-fastness estimation and reciprocity failure factor calculation require a proper curve fitting to either interpolate or extrapolate to failure point. To minimize potential bias when curve fitting, a good test standard should specify the exact curve fit technique. This author found an exponential curve ($y = b*m^x$, where, y = %OD remaining, x = lux-hour, m and b are the parameters determined by curve fitting) most referable because it is a monotonic curve and enables simple fade resistance calculation using a common tool such as Excel. Figure 7 is an example of exponential curve fitting.

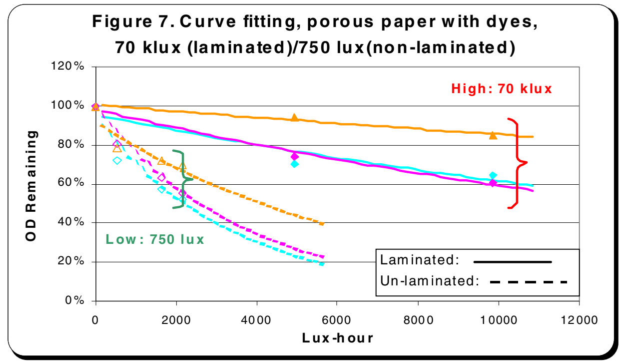

Figure 7. Curve fitting for the porous photo paper with dyes tested in this experiment. Data collected from 70 klux laminated and 750 lux non-laminated samples.

3. Apparent Light-Fastness Estimation

The failure end-points are estimated by either interpolation or extrapolation of the fitted curves to the failure criteria. The end points should be reported in lux-hour or estimated years.

Apparent light-fastness estimation should be based on the end points under both high and low intensities. Note that calculated apparent light-fastness does not require the calculation of the reciprocity failure factors described in step 4. Figure 12 plots the estimated time to reach the first end point under both high and low light intensities for four media types. The calculated overall reciprocity failure factor is also shown. To simplify the data processing, only the analysis of the pure primary colors and/or the primary colors in the neutral is necessary. Color balance calculation is not recommended for this test. The authors find that the following rules are very useful during data processing:

- Data obtained by interpolation are considered to have high confidence accuracy.
- Data obtained by less than two times extrapolation are considered to have medium confidence accuracy.
- Data obtained by more than two times extrapolation are considered to have low confidence accuracy.
- If the estimated end points have high or medium confidence accuracy, then the overall fade resistance is the first end point at both high and low intensity.
- If the estimated light-fastness data in step A have low confidence accuracy, then the overall light-fastness should be given in a range bracketed by the first end point at high intensity and the first end point at low intensity. In this case, testing at low intensity for longer time is preferred, since that would increase the confidence level.

4. Reciprocity Failure Factor Calculation

A. Overall Reciprocity Failure Factor

The overall reciprocity failure factor is calculated by the first end point at high intensity light divided by the first end point at low intensity light.

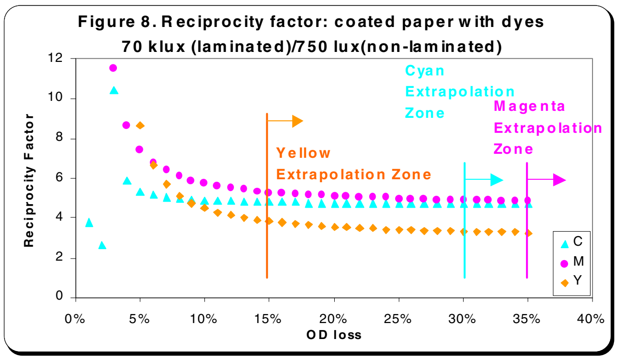

Figure 8. Reciprocity failure factor vs. OD loss: coated paper with dyes at 70 klux (laminated)/750 lux (non-laminated)

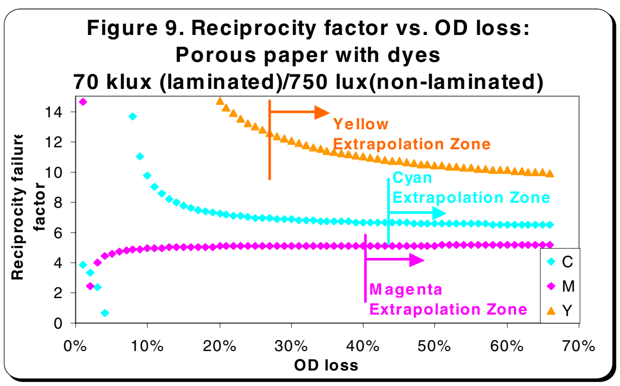

Figure 9. Reciprocity failure factor vs OD loss: porous paper with dyes at 70 klux (laminated)/750 lux (non-laminated)

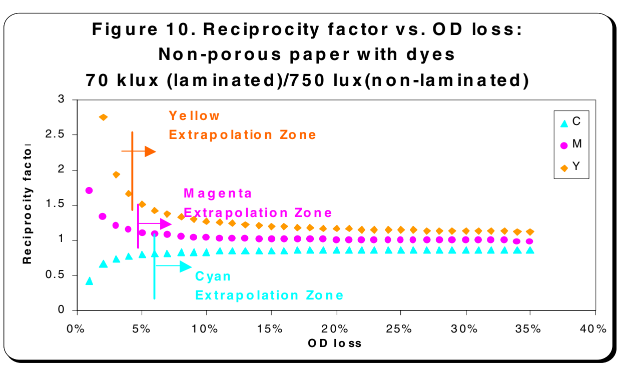

Figure 10. Reciprocity failure factor vs. OD loss: non-porous paper with dyes at 70 klux (laminated)/750 lux (non-laminated)

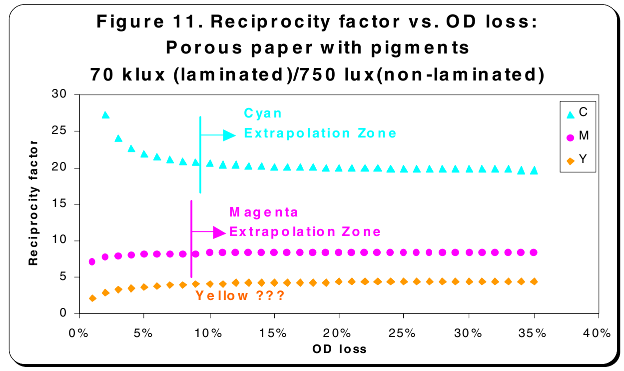

Figure 11. Reciprocity failure factor vs. OD loss: porous paper with pigments at 70 klux (laminated)/750 lux (non-laminated)

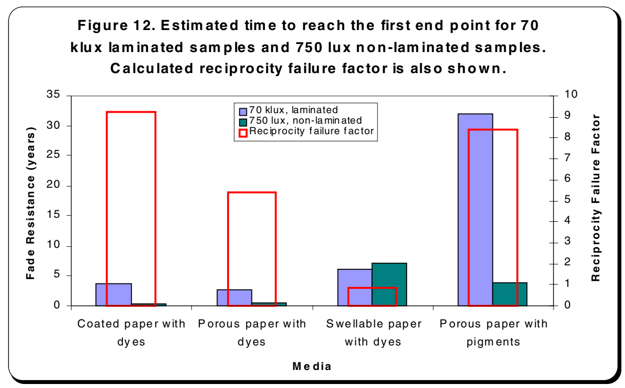

Figure 12. Estimated times to reach the first end point for 70 klux laminated samples and 750 lux non-laminated samples. Calculated reciprocity failure factor is also shown.

B. Reciprocity Failure Factor For Each Color

This author has tried several methods to calculate reciprocity failure factor and found that it is the best to plot the ratio of exposures (lux-hour) at high and low intensities as a function of %OD loss, and take the plateau value of the ratio as the reciprocity failure factor. Figures 8 through 11 are reciprocity factor plots for the four media/ink reported in this paper. Many other media/ink combinations have been tested, and all curves level off at a certain %OD level.

This method can be expressed by simple math described below.

- Exponential curve: **y = b*m^x**
  - y: %OD remaining
  - x: lux-hour
  - b, m: curve fitting parameters
- At an equal %OD remaining: $\mathbf{b_1 * m_1 \hat{} x_1 = b_2 * m_2 \hat{} x_2}$
- Since both x_1 and x_2 start from 0 lux-hour and 100%OD remaining, $b_1 = b_2 =$ 100%OD remaining.

Hence, reciprocity failure factor:

$$x_1/x_2 = \{log(b_2) - log(b_1)\}/\{ x_2*log(m_1) \} + log(m_2)/log(m_1) = log(m_2)/log(m_1)$$

- However, the curve fitting tool does not force the fitted curve to pass through the initial point. Thus, b_1 and b_2 might be slightly different.
  If $b_1 \neq b_2$,
  - the shape of the reciprocity failure factor curve as a function of %OD remaining is the inverse of x_2.
  - when $\mathbf{x_2 >> \{log(b_2) - log(b_1)\}}$, $x_1/x_2 \approx$ $\mathbf{log(m_2)/log(m_1)}$ = constant
- Therefore,

Reciprocity Failure Factor for Each Color
F = log{m(low intensity)}/log{m(high intensity)}

This author is aware of the fact that extrapolated data could have big error bars. To reduce the noise level, multiple samples and/or multiple measurements should be taken.

Conclusions

1. Coated paper and porous inkjet photo paper (with dyes or pigments) appear vulnerable to gas fading and therefore tend to have large reciprocity failure.
2. Non-porous inkjet media appears much more robust to gas fading so that it tend to have little or no reciprocity failure.
3. Light-fastness should be estimated at both high and low intensities.
4. A combination of the highly accelerated test and the four-month test at 1000 lux with and without surface protection (glass cover or laminate) is adequate to derive meaningful reciprocity failure estimation.
5. For the media that have good fade resistance and significant reciprocity failure, it may require more than 4 months at 1000 lux to derive apparent light-fastness estimation with high confidence.

Appendix A. A list of media/ink tested by the authors (available upon request).

Appendix B. A comparison between 1000 lux fade and accelerated air fade.

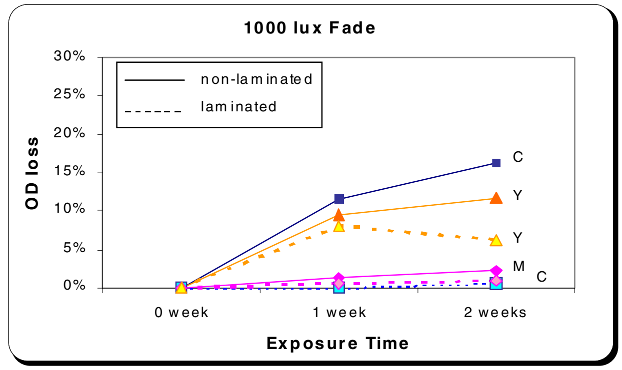

Figure 13. A commercially available media/ink (laminated and non-laminated) was tested at 1000 lux cool white fluorescent light. It was approximately 30°C and 45% humidity. There was no accelerated air flew.

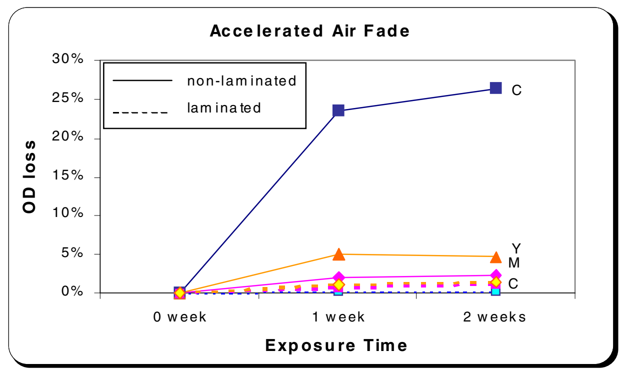

Figure 14. The same (as in Figure 13) commercially available media/ink (laminated and non-laminated) was tested at 0-50 lux light (the mixture of day light and fluorescent light). It was approximately 23°C and 50% humidity, and the air flew was accelerated by a fun.

Biography

Shilin Guo holds a bachelor degree in chemistry and a master degree in Imaging Science. She is an inkjet media development and test engineer at Hewlett Packard Company.