Assessing Humid Permanence of Inkjet Photos

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Abstract

This paper is a systematic investigation of inkjet photo dark humid storage permanence. In the paper, we describe a humid fastness mechanism, investigate indoor environmental conditions, describe our test method, discuss a possible lifetime prediction method, and propose a preliminary criterion for humid color shift failure to enable a prediction example.

Introduction

As inkjet photo quality rivals silver halide (AgX) prints, image permanence is becoming one of the key selling points. In recent years, the light-fade stability of some inkjet prints has exceeded AgX.[1] Air fade has been identified as an issue related to porous/micro porous ink receiving coatings, and the air fade test plot, data reporting, and failure criteria are typically the same as those used by light-fastness test procedures.[2,3] In contrast, although humid permanence issues on inkjet prints has been identified for several years,[4-5] the industry still does not have a systematic and standard way to conduct the test.

An HP survey reveals that family photos are a most cherished possession. More than 70 percent of Americans cherish their family photos more than their personal writings, heirloom jewelry or diplomas and other awards of personal achievement. More than half of Americans keep their photos in a box or drawer. These photos would not likely experience light and air fade, but inevitably they would be exposed to humid conditions for at least a few days out of a year.

AgX prints do not suffer humid permanence issue. Dark stability of AgX photos is usually characterized by the Arrhenius test at 50% relative humidity (RH).[6] Conceivably, an elevated temperature (Arrhenius) experiment at high (>70% RH) humidity represent one method for predicting long-term humidfastness behavior, but in practice this approach is severely limited by non-linear effects (e.g. glass transitions) at higher temperatures.

In previous studies, Onishi, *et at.,* tested humidity fastness of inkjet prints at 40°C and 85% RH, and reported ΔE for 1.0 OD cyan, magenta, yellow, and black patches.[7]

Mark McCormick-Goodhart and Henry Wilhelm[8] tested inkjet prints at 24°C and 60 - 80% RH. Their test plot contained neutral and color patches of cyan, magenta, yellow, black, red, green, and blue that are printed with optical densities of 0.25, 0.5, 0.6, 0.7, 0.9, 1.0, 1.1, and maximum density. They used a failure criterion of maximum $\Delta E = 8$ for neutral patches.

This paper is a systematic investigation of inkjet photo dark humid storage permanence, including the humid fastness mechanism, environmental data, test method, lifetime prediction, and failure criteria.

Humid permanence is usually characterized by humid bleed (or line broadening) and humid color shift. For the latest inkjet systems, humid bleed is far less a problem than humid color shift. Therefore, this paper will focus on humid color shift.

Many of the inkjet media/prints reported in this paper were older generations. In addition, to obtain a wide distribution of humid permanence performance, we also used one brand medium with some other brand printer. Thus, the data reported in this paper are not indicative of current normal inkjet performance nor do they represent the performance of any one branded inkjet system.

Humid Fastness Mechanism

Humidity permanence includes humid color shift (HCS) and humid bleed (or line broadening). Figure 1 explains how HCS and humid bleed may happen. In humid environments, moisture is absorbed by the media. Accumulation of the liquid aquifer in the media will cause re-solubilization and diffusion of poorly mordanted dyes.

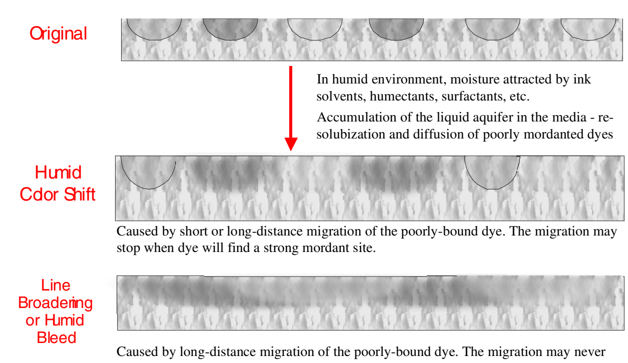

Figure 1.Expaination of how humid color shift and humid bleed happen.

HCS is caused by short or long-distance migration of the poorly mordanted dye. The migration may stop when the dye finds a strong mordant site. For primary colors, dye migration to white space causes a lightness decrease and chroma increase. For composite colors, depending on how much each dye migrates, the color could have lightness, chroma, and hue changes.

Humid bleed is caused by long-distance migration of the poorly-bound dye. The migration may never stop because of lack of strong mordant sites. Humid bleed makes prints look blurry and can induce colors to shift.

Environmental Data

In 1998-1999, HP conducted a potential climate exposure study for inkjet images at 42 homes in North America and Singapore. This study included office and home environments. This study found that:

- The office is usually a controlled environment while the indoor home has greater variation than office.
- Homes significantly moderate the outdoor environment.
- In an uncontrolled home environment, relative humidity tends to follow constant moisture curves, i.e., humidity tends to cycle up and down during the day and is strongly influenced by the season as well as the geographic location. Therefore, uncontrolled home RH is dynamic and cyclic in nature.
- Air conditioning usually decreases RH, and evaporative coolers increase RH with in a moderate range.

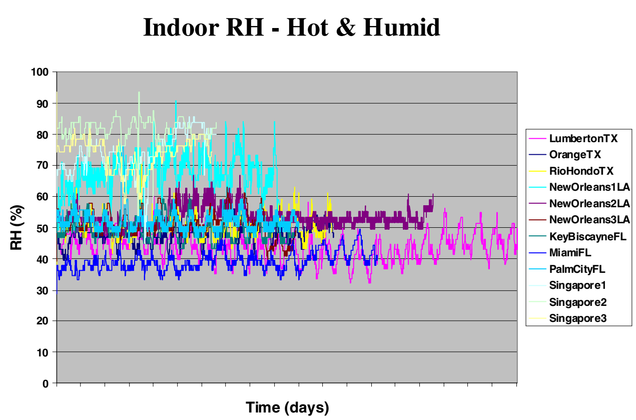

Figure 2.The indoor home RH at hot and wet geographic locations in a two-month period in summer. The Singapore people misunderstood the test instruction so that they purposely turned off the air conditioners throughout the test period.

Figure 2 shows the indoor home RH at hot and wet geographic locations in a two-month period in summer. These data show that even in humid climates, the indoor humidity in most homes does not exceed 80% RH, and in fact may only exceed 70% RH for certain times of the day. Note that the data are conservative because this study targeted extreme environmental locations.

Test Method

Test Plot

For humid permanence test, HP looked at humid color shift and humid bleed. Figure 3 shows the humid permanence test plot used by HP.

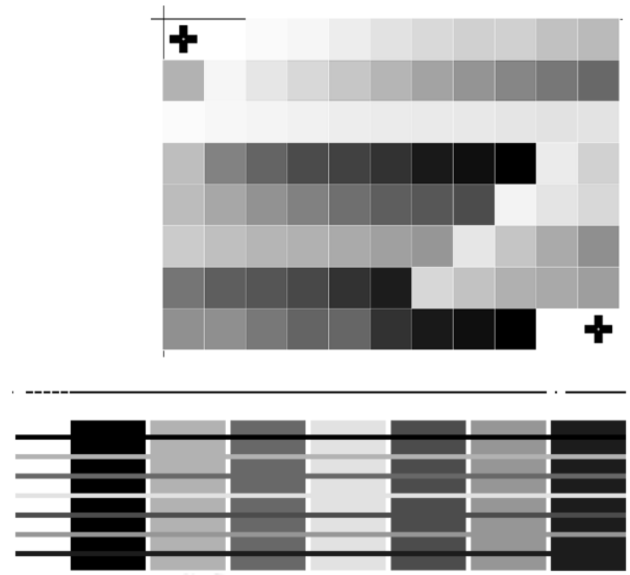

Figure 3. Humid permanence test plot. Top: humid color shift; bottom: humid bleed.

The bottom pattern is for the humid bleed test. It consists of black, cyan, magenta, yellow, red, green, and blue lines across white black, cyan, magenta, yellow, red, green color blocks.

The top color tiles are for the humid color shift test. It includes a white patch, 10 skin tones, and 10-step ramps of cyan, magenta, yellow, red, green, and blue.

Since it takes a long time to measure all the 85 colors tiles, an alternative test plot is the 10-step neutral ramp. The 10-step neutral ramp is not only quick to measure, but also emphasizes color balance in neutral patch, which is believed to be more objectionable than the color changes in high-chroma patches.[8]

If the neutral colors are composed of three primaries (cyan, magenta, and yellow), lightness, chroma, and hue shift of the neutrals will indicate the media/ink performance. For example, a lightness decrease indicates dye migration to white space or an increase in dot size. A lightness increase means dye loss or migration to the deeper layers of the inkjet receiving coatings. A chroma increase indicates unbalanced migration of the three dyes. The hue shift angle tells which dyes changed most.

In addition to the primary inks, some printer manufactures also blend pure black ink (dyes or pigments) in the neutral ramp. Depending on how much of the pure black is blended, the HCS of the 10 neutrals may not be proportional to that of all 85 colors. Figure 4 shows the color difference correlation between the average of 10 neutrals and the average of all 85 colors. These data were collected from 5 inkjet printers from 3 manufactures and 9 inkjet photo media. The data indicate that the 10-step neutral ramp is a good substitute for all 85 color patches.

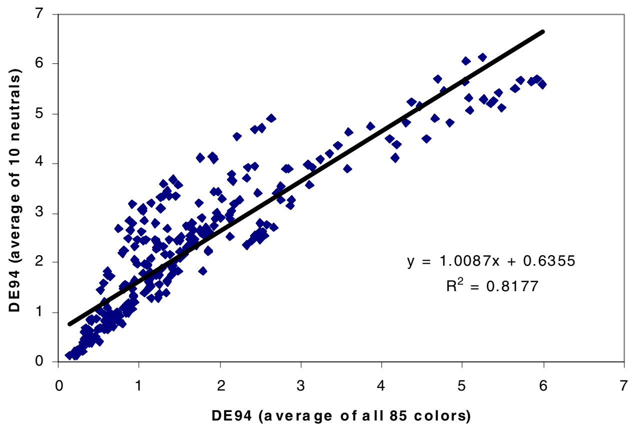

Figure 4. Color difference correlation between the average of 10 neutrals and the average of all 85 colors.

Test Conditions

For screening test, HP usually tests humid permanence at 30C/80%RH for 4 days. We also conduct the test at 25°C/60%RH, 25°C/70%RH, and 25°C/80%RH for longer times.

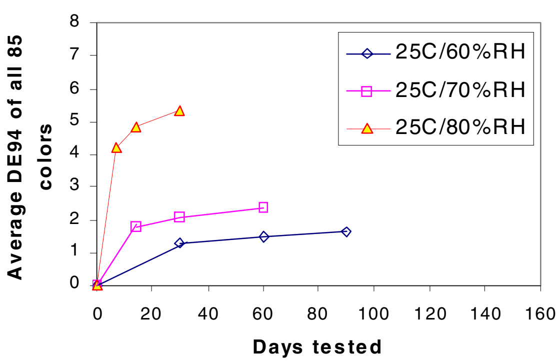

Figure 5. HCS of a typical inkjet print.

Figure 5 shows HCS performance for a typical inkjet print with one week dry down at <50% RH and office ambient temperature. Most inkjet prints had little or no HCS at or below 60% RH. HCS slightly increased at 70% RH, and significantly increased at 80% RH.

Test Locations

Humid permanence of inkjet photos varies with the storage locations. Figure 6 illustrates a few locations we tested. We put a 4-inch stack of inkjet photo paper in a shoebox. Samples at locations a and b simulate photos stored in a shoebox. The sample at location a is the top sheet in a shoebox, and the sample at location b is the middle sheet in a shoebox. Samples at location c simulate photos stored in a photo album. We found that inkjet prints in a photo sleeve and in a magnetic (adhesive) type of photo album have similar humid performance. Samples at location d simulate samples displayed in the open air, for example, on a refrigerator.

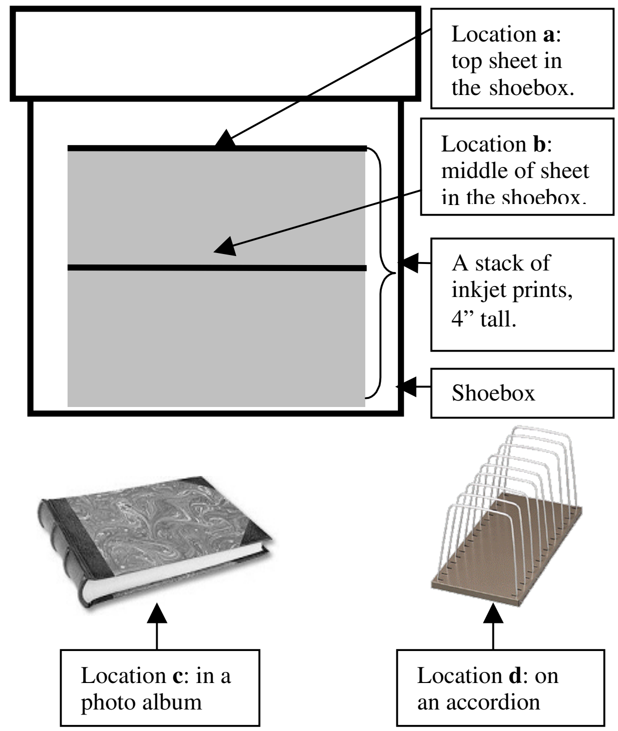

Figure 6. Humid permanence test locations.

Figure 7 is HCS (with one week dry down at <50% RH and office ambient temperature) at a constant high temperature/RH, at cycled environment, and at 4 test locations. This figure indicates that humid permanence would be significantly improved if inkjet photos were stacked (**b**) or protected by a photo album (**c**).

Metric

For humid bleed, the line width for each color-to-color combination was measured before and after the humid permanence test. Humid bleed is the difference in the line width. Depending on media/ink performance, we can report average/maximum bleed for all color combinations, the average/maximum bleed of selected color combinations, or just one color-to-color bleed.

For HCS, CIEL*a*b* for each color patch was measured before and after the humid permanence test and HCS is the color difference. We prefer to use ΔE_{1994} or later because they are more perceptually uniform than ΔE. We also prefer to use the average (instead of the maximum) color difference to characterize HCS because 1) the maximum color difference only tells one color's performance, and that color is different from one inkjet system to the other; 2) different colors have different acceptable color difference tolerance (see figure 12) that are not yet fully qualified.

Lifetime Prediction

Additive assumption

There is no clear accelerating method for humid permanence test. Applying Arrhenius test on inkjet photos has not been successful because many inkjet media coatings have abnormal chemical or physical changes at elevated temperature. In addition, humidity is not likely to be accelerated either since 80% RH is not uncommon in some geological region.

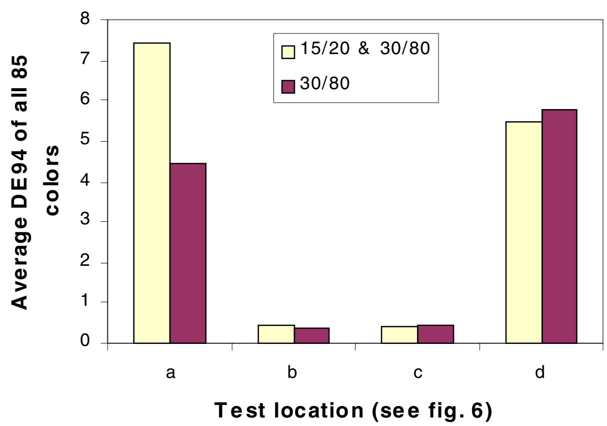

Figure 7. HCS at a constant high temperature/RH, at cycled environment, and at 4 test locations.

In the "Environmental Data" section, the investigation found that home-indoor environment is cyclic, i.e., it tends to be relatively hot and dry at daytime and relatively cool and wet at night. Therefore, the only possible acceleration we can do is to test inkjet photos at a constant high RH instead of cycled RH. For example, if a photo storage location has 4 hours a day at 80% RH or above and below 70% RH during the rest of the day, it will be up to 6 times accelerated if we test the photos 24 hours a day at 80% RH. In fact, this is what other researcher have done,[4,7,8] but did not refer to as an accelerated test.

An experiment has been conducted to confirm the above "additive assumption". One set of samples was stored at 30°C and 80% RH for 168 hour. Another set of the same samples were stored at 30°C and 80% RH for 16 hours and at 15°C and 20% RH for 8 hours in a day, until the total test time at 30°C and 80% RH reached 168 hours. All the samples had been dried for one week at <50% RH and office ambient temperature. The test result is shown in figure 7. For HCS at the four storage locations, samples at constant high RH and at cycled RH had similar performance if the cumulative time at the high RH is the same.

Extrapolation Validation

The above accelerated test method can only accelerate the test by a small factor. We still need to test some inkjet photos for months or years before we can see significant amount of change. Therefore, it is important to know the validity of potential extrapolations from available data.

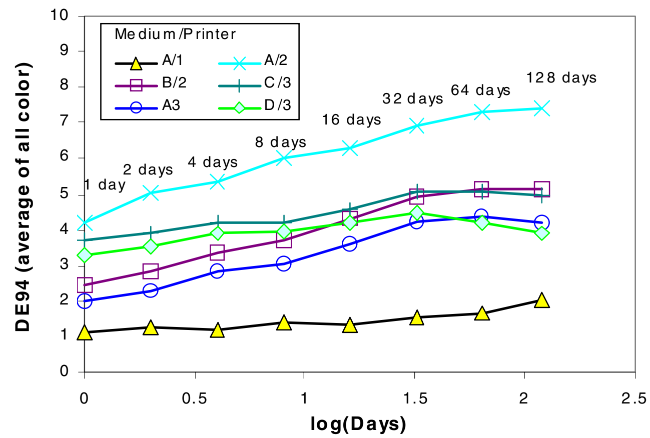

Figure 8. Non-porous media: HCS as a function of log(time) tested

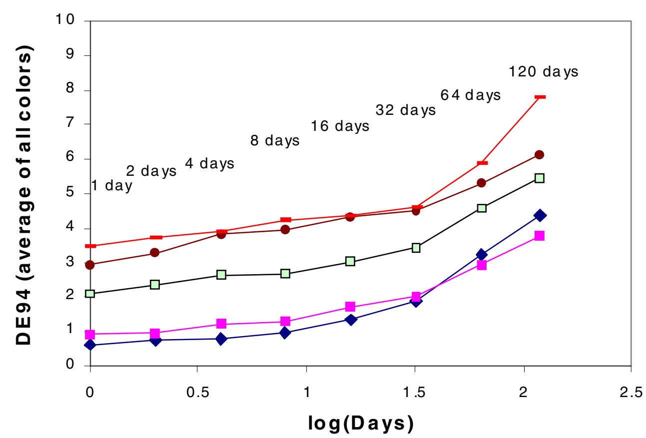

Figure 9. Micro-porous media: HCS as a function of log(time)

To confirm the validity of a logarithmic extrapolation, 11 inkjet prints were store at 30°C and 80% RH at location d (see figure 6). These samples were printed from 5 inkjet printers from 4 manufactures and 8 inkjet photo media. Humid HCS were measured at 0, 1, 2, 4, 8, 16, 32, 64, and 120 days. Note that, these samples were only dried for less than 10 minutes before the initial color measurement.

Figure 8 is HCS for non-porous media as a function of log(days) tested in 30°C and 80% RH. For non-porous media, the color changed quickly in the first few days, and slowed down at longer times. Approximately two thirds of the HCS happened in the first 4 days. The HCS and log(days) are roughly linearly related. Therefore, for non-porous inkjet media, HCS can be extrapolated and predicted from the first 4 days of data.

Figure 9 is HCS as a function of log(days) tested at 30°C and 80% RH for micro-porous media. For micro-porous media, HCS has two phases: a fast initial rate in the first few days followed by a slower rate after 10-20 days. HCS and log(days) are not linearly related. Therefore, a short duration test is not sufficient to predict long-term performance.

For micro-porous media, after 4 days at 30/80, L* decreased and chroma increased. This indicates that HCS in the first few days is caused by dye migration to white space. After 120 days at 30/80, L* increased and chroma decreased. This indicates that, for micro-porous media, long-term color change is probably dominated by air fade if the samples are exposed to open air, for example, location d in figure 6.

This experiment partially confirmed McCormick-Goodhart's conclusion that humidity fastness behavior was successfully modeled using a logarithmic fit of the data when samples were aged under tightly controlled and steady-state humidity levels.[4] The difference is that we observed an air fade issue when testing humidity fastness for micro-porous media.

Lifetime Prediction

In the previous sections, we have demonstrated the validity of the additive assumption and discussed when extrapolation is valid. The additive assumption means that inkjet prints at constant high RH and at cycled RH had similar humid permanence if the cumulated time at high RH is the same. A logarithmic extrapolation of test data is valid for non-porous media, but not for micro-porous media.

Based on the additive assumption, and data extrapolation, if we know how many hours a day the RH is greater than 80% at a particular geographic location and know the failure criteria, we should be able to predict a humid permanence lifetime for inkjet prints on non-porous media using a short test time. The following is an example.

Assumptions for the example: a) No HCS around or below 60% RH. b) A home has 50% of the time around 30°C and 80% RH, and 50% of the time around or below 60% RH. c) The failure criterion is AgX photo processing variation (see figure 10 and 11), which is an average ΔE94 < 6.63.

Table 1. Examples of predicted lifetime for the six non-porous media/printer in figure 8.

	Predicted Lifetime (example calculation)	
Medium/ Printer	**Extrapolation at 30°C/80% RH**	**50% of the time at 30°C/80% RH**
A/1	2.0×10^{12} years	4.0×10^{12} years
A/2	26 days	52 days
B/2	2.2 years	4.4 years
C/3	41 years	82 years
A/3	16 years	32 years
D/3	2.8×10^{5} years	5.6×10^{5} years

Table 1 shows the predicted lifetime for the six non-porous media/printer in figure 8. These data indicates that most of the inkjet medium/printers can survive a long time before they reach ½ of the AgX processing variation in color.

Some of the media/ink have HCS at lower RH than 80%. We have not tested the additive assumption and extrapolation validation at 70% and 60% RH yet.

Failure Criteria

Humid Bleed

Our psychophysics experiment showed that less than 2 mils of average color to color bleed or less than 8 mils maximum color to color bleed would not affect the perceived sharpness of a photographic print.

Humid Color Shift

Since AgX prints do not suffer humid color shift, characterizing humid color shift is relatively new to the photo industry. There are no standard test methods and failure criteria for reference, and failure criteria for humid color shift are challenging to define.

Unlike light-fade or air/gas-fade, optical density of inkjet prints increases in humid environments. Sometimes, humid color shift is beneficial because people prefer more vivid colors than the real world scene.

Another fact is that people can accept a large range of color appearance on AgX photo prints. For example, we took the same set of 4 digital photo files to 15 photo-processing labs, the lightness (see figure 11) and color balance (see figure 10) in the silver-halide print sets varied widely, yet all were good for sale for those labs. When we calculate the color difference among these photos, we eliminated two sets of outliers which were visually unacceptable to several observers. Figure 12 is a flowchart of how we calculated AgX processing variation.

The color difference for the sky blue shown in figures 10 and 11 is up to 22 ΔE units or 20 ΔE94 units. This fact might also explain why inkjet customers have been fairly satisfied with the humid fastness performance of previous generations of ink/media.

In addition, CIE color differences (ΔE, ΔE1994 or later) are measures of perceptual difference of colors rather than perceptual tolerance to changes in colors. For example, it is believed that color changes can be measurably significant yet still considered acceptable for sky blues. However, the same amount of color difference around a skin tone or a neutral color might not be acceptable.

Based on the assumption that the tolerance of color change is image-dependent, we would like to propose the following psychophysics experiment to study humid color shift failure criteria.

The test images should include faces, sky, grass, black and white photos, etc. These objects contain common memory colors so that the observers can judge their accuracy without a comparative reference.

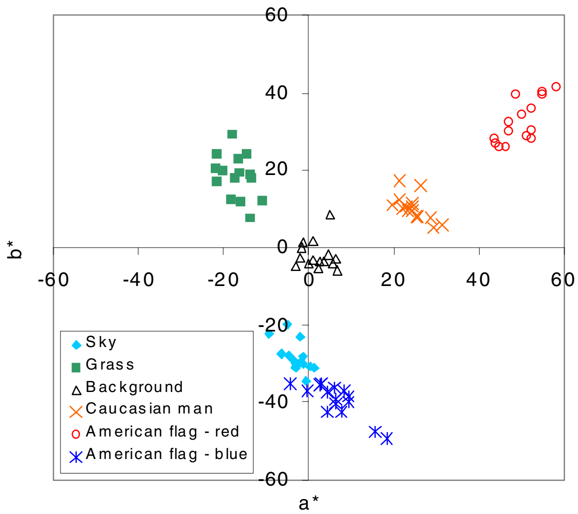

Figure 10. Color balance variation for digital AgX prints. These photographs were processed by 15 local and ".com" photo labs from the same set of digital files.

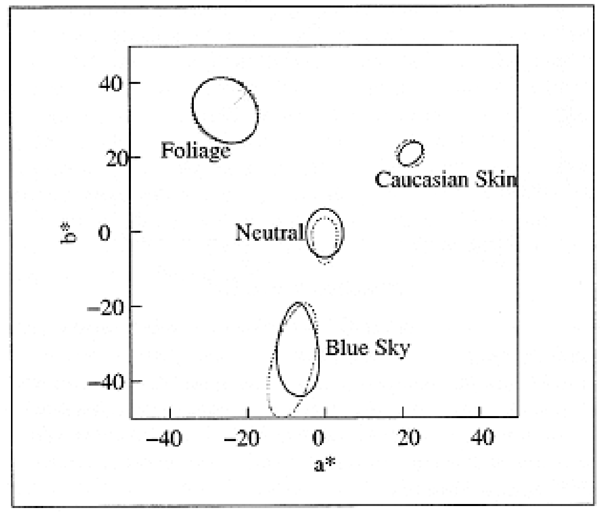

Figure 13. Memory color range illustration. Inside the circle is marginal acceptable, and outside the circle is marginal unacceptable. This graph was copied from Ref. 9.

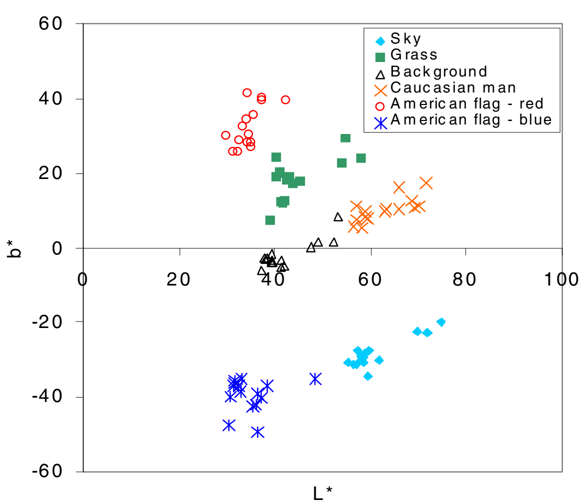

Figure 11. Lightness variation for digital AgX prints. These photographs were processed by 15 local and ".com" photo labs from the same set of digital files

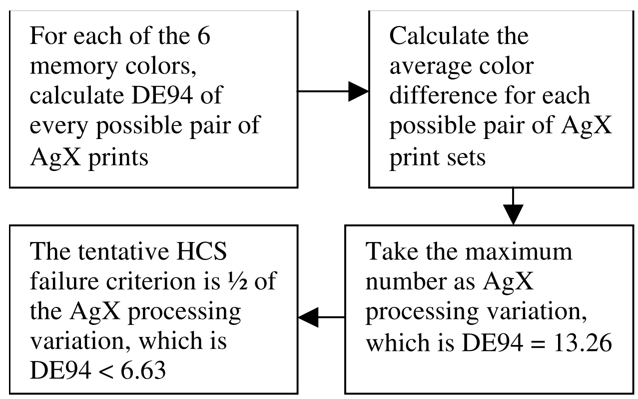

Figure 12. Flowchart of how we calculate AgX processing variation.

The selected images will be printed with various printers and inkjet media. The printed samples will be conditioned in humid conditions. Alternatively, we can adjust lightness and color balance of the digital file in AdobePhotoshop, and print the adjusted files with an inkjet printer.

The observers will look at the test print samples without comparing with the original image. He/she will be asked to give the sample an acceptability scale and why they scored the prints the way they did. The scale includes: completely acceptable, moderately acceptable, marginally acceptable, marginally unacceptable, moderately unacceptable, and completely unacceptable.

The resulting memory color acceptability would be plotted in the format like figure 13. These circles illustrate what the memory colors should be. Inside the circles are marginal acceptable memory colors, and outside the circles are marginal unacceptable memory colors. The circles are independent of the color appearance of the original images. For example, if a color shifted from one edge to the opposite edge, despite the large color shift, the final color is still acceptable as the memory color. If a color shifted from the center to the outside of the circle, although the color change is smaller, the final color is unacceptable as the memory color.

Nevertheless, to compare products, the color shift acceptability should depend on color difference, but not the precise position in a color space. Therefore, color shift acceptability should be functions of the size and shape of the memory color acceptability circle. We suggest the memory colors as a HCS test plot, and use each circles' average radius or diameter as HCS failure criteria.

Conclusions

To develop a standard humid permanence test procedure so that everybody can use to compare data, we need to define a nominal indoor condition (Temp/RH), a nominal storage location (shoebox, album, or exposed), and failure criteria.

The office is usually a controlled environment while the indoor home has greater variation than office. Homes significantly moderate the outdoor environment. In uncontrolled home environment, the relative humidity tends to cycle up and down during the day and is strongly influenced by the season as well as the geographic location. Therefore, uncontrolled home RH is dynamic and cyclic in nature.

The additive assumption means that inkjet prints at constant high RH and at cycled RH had similar humid permanence if the accumulated time at high RH is the same. In the "extrapolation validation" section, we found that data extrapolation is valid for non-porous media, but not for micro-porous media.

Based on additive assumption and data extrapolation validation, if we know how many hours the RH is above 80% at a particular geographic location and the failure criteria, we would able to predict humid permanence lifetime for inkjet prints on non-porous media using a reasonable test duration of several months.

Humid permanence is strongly dependent on storage location. Humid permanence will be significantly improved if inkjet photos were stacked or protected by a photo album.

Each memory color has an acceptability range. We suggest use memory colors as HCS test plot, and use the memory color acceptability ranges as HCS failure criteria.

References

1. Henry Wilhelm, How Long Will They Last? An Overview of the Light-fading Stability of Inkjet Prints and Traditional Color Photographys, *Proc. IS&T's 12th International Symposium on Photofinishing Technology*, pg. 32. (2002).
2. Shilin Guo and Nils Miller, Estimating Light-fastness of Inkjet Images: Accounting for Reciprocity Failure, *Proc. IS&T's NIP 17*, pg. 168. (2001).
3. Douglas E. Bugner, David Kopperl, and Peter Artz, Further Studies on the Apparent Reciprocity Failure Resulting for the Accelerated Fade of Inkjet Photographic Prints, *Proc. IS&T's 12th International Symposium on Photofinishing Technology*, pg. 54. (2002).
4. Mark McCormick-Goodhart and Henry Wilhelm, Humidity-Induced Color Changes and Ink Migration Effects in Inkjet Photographs in Real-World Environmental Conditions, *Proc. IS&T's NIP 16*, pg. 74. (2000).
5. P. Hill, K. Suitor, P. Artz, Measurement of Humidity Effects on the Dark Keeping Properties of Inkjet Photographic Prints, *Proc. IS&T's NIP 16*, pg. 70. (2000).
6. Svante August Arrhenius, *Zeitschrift fur physikalische Chemie*, Vol. **4**, pg. 226. (1889).
7. Hiroyuki Onishi, Masahiro Hidemasa, Hidemasa Kanada, and Teruaki Kaieda, Image Permanence of Inkjet Photographic Prints, *Proc. IS&T's NIP 17*, pg.192. (2001).
8. Mark McCormick-Goodhart and Henry Wilhelm, The Influence of Relative Humility on Short-Term Color Drift in Inkjet Prints, *Proc. IS&T's NIP 17*, pg. 179. (2001).
9. Karin Topfer, Brian Keelan, Scott O'Dell, and Robert Cookingham, Preference in Image Quality Modeling, *Proc. IS&T's PICS* 55, pg. 60. (2002).

Biography

Nils Miller, Ph.D., is the Ink/Media Technology Liaison and Senior Scientist in Hewlett-Packard's Inkjet R&D. His academic background is in Chemical Engineering and Physical Chemistry. He has been working in inkjet product and technology development for over 8 years, and in the past year has focussed on permanence-related issues.