Journal of Imaging Science and Technology® 50(4): 309–319, 2006.

A Survey of Environmental Conditions Relative to the Storage and Display of Photographs in Consumer Homes

Douglas Bugner, Joseph LaBarca, Jonathan Phillips and Thomas Kaltenbach
Research & Development, Eastman Kodak Company, Rochester, New York 14650
E-mail: douglas.bugner@kodak.com

Abstract. *The long term stability of photographic prints is known to be sensitive to a variety of factors. These factors include the chemical composition of the inks and media, as well as the ambient environmental conditions—light, heat, humidity, and air quality—under which the prints are stored and/or displayed. In order to correlate the results of accelerated testing in the laboratory with what actually happens to a photographic print under long term, real world conditions, it is necessary to better understand the typical ambient environmental conditions under which the prints are being displayed and/or stored. In phase I of this study, light levels, spectral energy distributions, temperatures, and humidities were monitored for 6–12 months in eight homes in each of four cities around the world (Rochester, Los Angeles, London, and Melbourne). For phase II, eight homes in each of four additional cities (São Paulo, Shanghai, Atlanta, and Tokyo) were monitored for 10–12 months. A key finding of these studies is that ambient home display conditions are dominated by relatively low intensity, indirect, window-filtered daylight. The long term temperature and humidity levels averaged close to the commonly cited conditions of 23 °C, 50% relative humidity, with the exception of Shanghai and São Paulo where somewhat higher levels were observed. These results are discussed in the context of designing and interpreting improved accelerated image stability test methods. © 2006 Society for Imaging Science and Technology.*
[DOI: 10.2352/J.ImagingSci.Technol.(2006)50:4(309)]

INTRODUCTION

The Importance of Image Stability

In the "portrait and social" end consumer environment, where the majority of photographic images are used and stored under either ambient illumination or dark storage conditions, it is extremely important to consider all of the environmental factors that can degrade an image in the design for print longevity. This includes the well-known effects of light and thermal fade on traditional silver halide photographs,[1] as well as the effects of image degradation caused by high humidity and atmospheric contaminants on newer technologies such as ink jet.[2–4] In general, images on display can encounter an extremely wide range of illumination conditions, including intensity and spectral quality. A room with a low level of illumination, such as a consumer's home or a museum, could be as low as tens of lux, with a predominantly low energy spectral distribution, while a commercial display at a product point of purchase could be thousands of lux with a higher energy spectral distribution. Likewise temperature, humidity, and air quality can also vary widely depending on the application environment.

Consequently, it is very important to have a better understanding of the environmental conditions in which the photographs will be displayed and stored. This is true from the perspectives of the end consumer, who simply wants to know how long the image will last, and the product designer, who needs to know how to correctly assess image quality and image stability trade-offs. The current ANSI/ISO standard provides the recommendation that predicting and reporting of image stability should be done in reference to conditions that are representative of those in which the image will be displayed or stored.[5] Given the recognition that newer imaging technologies are sensitive not only to light and thermal degradation mechanisms but also to ozone and humidity, it is critical to understand and quantify all of these variables so that accurate predictions of image stability can be made to either the consumer or the product designer.

The ANSI/ISO standard correctly points out that, regarding light levels, there is no single intensity that best represents all display conditions, and this can logically be extended to include temperature, humidity, and ozone levels. These real world parameters should be used to define the specific conditions for reporting image-stability performance. While the commercial market segment can have very extreme conditions, especially regarding light levels, images that are displayed and stored by consumers in the home tend to experience less extreme conditions. These applications include snapshots and formal portraits that are displayed in the home environment or stored in albums. An imaging material to be used in "portrait and social" home use applications is required to have print longevity performance that is reflective of the appropriate real world conditions in the end consumers' homes. The testing and reporting of that performance should be done in this context as well.

Prior Art on Image Stability Testing

As noted above, the two primary environmental factors that affect the stability of traditional silver halide images are light and temperature. Although light only affects prints that are on display, temperature affects prints under both dark storage and display conditions. In each case, the dominant response to these environmental factors is fading of the dyes that comprise the photographic image and/or staining of the white areas of the print or borders. The current ANSI/ISO

Received Aug. 24, 2005; accepted for publication Oct. 24, 2005.
1062-3701/2006/50(4)/309/11/$20.00.

standard for assessing the stability of traditional silver halide images describes methodologies for estimating the natural aging of photographic images with respect to either prolonged heat or light exposure.[5]

For heat induced fade/stain, the Arrhenius method is adapted.[6] This involves accelerating the rate of change at multiple temperatures above ambient; therefore, the Arrhenius equation can be used to estimate the rate of change over longer periods of time at ambient temperature. To accelerate light induced fade/stain, high intensity light exposures are recommended. Assuming the law of reciprocity holds,[7] one can calculate the amount of time it will take to reach the same amount of fade/stain under ambient lighting conditions. This will be discussed further below.

The explosion of digital images available from scanners, digital cameras, and the Internet has driven a commensurate demand for printing those images. Today, there are multiple technologies available for printing digital images on desktops in the home and/or office, including ink jet, thermal dye transfer, and electrophotography. There are concerns regarding image stability and physical durability, however, which have prevented the widespread application of these alternative technologies in the production of photographs intended for long term storage and/or display. Ink jet, especially, has been the subject of numerous studies for the effect of various environmental factors on long term display. Recent studies have also compared the stability of digital photographic prints, generated from various output technologies, with respect to light, heat, humidity, and ozone.[8,9]

Currently, there are no existing standards for testing the stability of digital photographic prints produced by these technologies. It is clear that, in addition to heat and light, environmental factors such as humidity and ozone have a significant effect on the long term stability of the various digital output technologies.[4] In parallel with the development of standardized methods for the accelerated testing of digital prints against factors such as light, heat, humidity, and ozone, it is important to better understand and quantify the environment in which these prints are being stored and/or displayed. In the context of the present study, the environment of the home consumer is of particular interest.

In the 1980s, Anderson and coworkers carried out the first attempts to characterize the home environment in the context of photographic storage and display.[10,11] In a year long field study conducted in 1981, Anderson and Larson concluded that the average indoor temperature and humidity for several homes in Rochester, New York, was approximately 21 °C and 50% relative humidity (RH).[10] This study also reported long term average light levels, measured both instrumentally and by a photographic print-keeping experiment. The instrumental readings, which covered 19 locations in a single home, including three locations in a sunroom, averaged 214 lux. The print-keeping experiment, in which the fade of an actual silver halide print displayed in the home was correlated with results obtained in a controlled light-fade chamber, indicated that the average light exposure experienced by the print in the home was approximately 99 lux.

In a follow-up study conducted in 1987, Anderson and Anderson found that light levels averaged between 100 and 200 lux over the course of a year.[11] The 1987 study also included the spectral distribution of the light energy, indicating a mix of both diffuse daylight and artificial light sources. Of particular note was the relatively low level of light in the ultraviolet (UV) region of the spectrum. This is important because the higher energy UV wavelengths tend to be more damaging to organic colorants.[12]

There is very little additional published data on long term home environmental trends in the context of the storage and display of photographs. Some studies have cited average environmental conditions for light levels, temperature, humidity, and ozone in the context of image stability testing, but the values mentioned are based largely on spot measurements and/or anectodotal information.[9] A recent study by HP scientists (Guo et al.) reports some temperature and humidity data for consumer's homes in North America and Singapore,[13] and Canon (Kojima et al.) has also recently published a similar study for temperature, humidity, and air pollutants for homes in Tokyo and Kanagawa, Japan.[14] The HP study, which did not provide a statistical summary, and which admittedly focused on homes in "hot and wet" locations, concluded that even in these worst case environments the temperature and humidity rarely exceeded 30 °C, 80% RH. The Canon study, which was limited to several homes and offices in Japan for approximately 1 year (2003), reported an overall average temperature and humidity of 23 °C, 51% RH. In addition, the Canon paper reported long term average indoor concentrations of ozone, nitrogen dioxide, and sulfur dioxide of 3, 19 and 1 ppb, respectively.

Clearly, there is a need for a more comprehensive assessment of the indoor environment in a broader cross section of homes around the world. To that end, in phase I, we monitored light levels, spectral energy distributions, temperatures, humidities, and ozone levels for 6–12 months in eight homes in each of four cities around the world: London, Rochester, Los Angeles, and Melbourne.[15] Based on the results of phase I, we decided to extend this study to an additional four cities, as will be described in further detail below.[16]

The primary objective of phase II was to expand upon the phase I data collection of ambient light levels (including the spectral energy distributions), temperatures, and humidities in typical consumers' homes around the world. In phase II, eight homes in each of four new locations were selected: Brazil (São Paulo), Japan (Tokyo), China (Shanghai), and the USA (Atlanta). Temperatures and humidities were monitored continuously in all 32 homes for 10–12 months. For reasons discussed below, light levels and spectral energy distributions were only collected in Shanghai and Atlanta, where measurements were taken every 30 min in each of the 16 homes over a period of 6–8 months. We had also intended to monitor long term ozone levels during phase II; however, equipment malfunctions prevented us from obtaining any meaningful long term data. Although

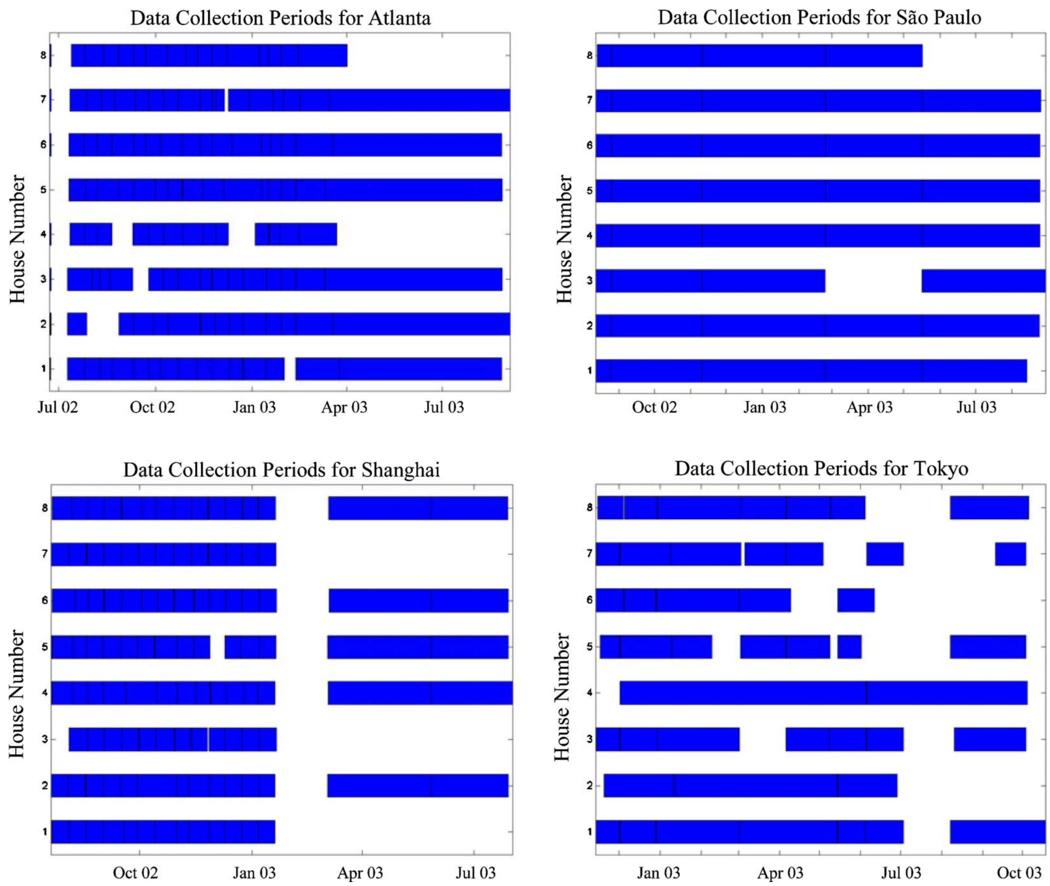

Figure 1. Plots of temperature and RH data collection periods, showing continuous trend in acquisition for phase II.

the primary focus of this paper is on phase II, we have included the phase I data in our overall statistical analysis and discussion.

METHODS

Choice of Cities

The following criteria were considered in the selection of cities for phase I and phase II:

- representative of relatively large populations of active photographic consumers;
- at least one city with known high concentrations of air pollution;
- at least one city with greater-than-average amounts of sunshine; and
- at least one city in the southern hemisphere to reflect opposite seasonality of the northern hemisphere.

In phase I, cities were in North America, Europe, and Australia. In order to expand the worldwide testing, phase II cities were selected in Asia (Tokyo, Japan and Shanghai, China), South America (São Paulo, Brazil), and North America (Atlanta, USA).

Choice of Participants

With the help of a cultural anthropologist and a statistician, participants were carefully selected to represent locations and compass orientations throughout the metropolitan region of each city. In addition, homes were chosen to represent the cross section of available housing options, including homes, condominiums, and apartments, as well as factors, such as socioeconomic status, and the types of heating, cooling, and ventilation (HVAC) system. Further details of the selection and documentation of participants' homes are described in the Proceedings of IS&T's 13th International Symposium on Photofinishing Technology, where the phase I study was first presented.[15] Additional information about the homes that were monitored for light, temperature, and humidity in Atlanta and Shanghai, including pictures of the interior and exterior of the homes, are provided in the supplemental materials.

Instrumentation and Data Analysis

The test equipment and data analysis have been previously documented in detail.[15,16] The temperature and humidity data logger and the spectroradiometer probe were positioned immediately adjacent to the photographic display, with the probe of the spectroradiometer oriented so the plane of the sensor was parallel to the plane of the photographs. Figure 1 shows the temperature and humidity collection periods for each of the homes included in this study. Each city had at least one home that participated only for a

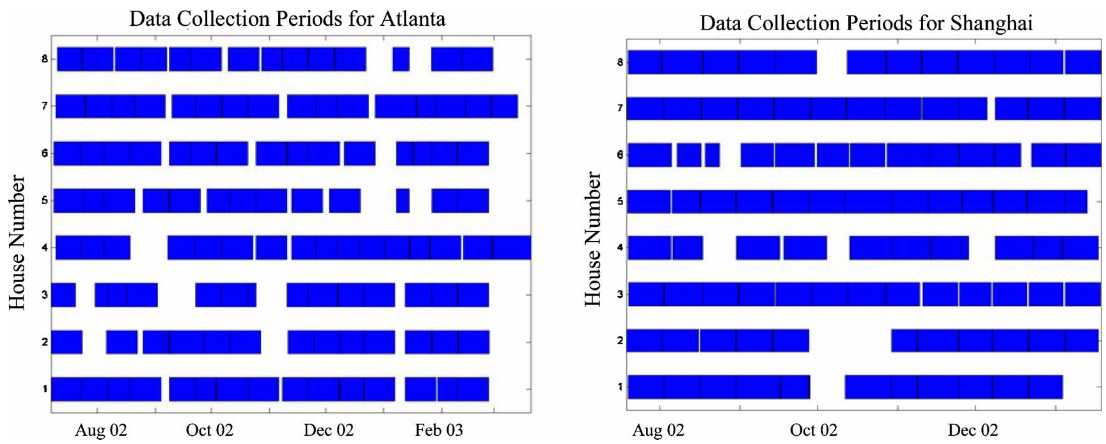

Figure 2. Plots of spectroradiometric data collection periods, showing continuous trend in acquisition for phase II.

portion of the long term duration of the study. Figure 2 shows the spectroradiometric collection periods for each of the homes included in this study. Gaps in data were due to instrumentation malfunction and/or known breaks in schedule.

One significant improvement over phase I was the technique used to establish the baseline in the spectral energy distributions. This resulted in a more accurate representation of the spectrum, especially in the near-UV (300–400 nm) region. The phase I spectra have been recalculated using this technique and updated results are included in this paper. Another improvement was that the spectroradiometers were left in place for the duration of the study. This was accomplished by restricting the placement of the 16 available spectroradiometers to the homes in Atlanta and Shanghai and is likely responsible for the improvement in the average standard error of phase II versus phase I. A third improvement relates to the statistical summary of the data. Previous results treated each city as a whole; however, this could result in a bias arising from differences in the number of observations within the individual homes, and might not have reflected the average home. Therefore, the statistical summary reported here is expressed in terms of the average consumer home within each city. Specifically, the statistical values (mean, standard deviation, percentiles, etc.) are evaluated for each home, and the average of the statistics for the eight homes is reported as the city value. This approach gives equal weighting to each home within a city. The total number of observations for all homes in a given city or phase is reported in Tables I and II as "Total *N*."

RESULTS AND DISCUSSION

Temperature and Humidity

The temperature and humidity data for the cities monitored in both phases I and II are summarized in Table I. Overall statistics are also included in Table I. As in the phase I report, two measures of humidity are reported: dew point and relative humidity. Histograms of temperature for each home in each of the four cities monitored in phase II are shown in Figs. 3–6. Figures 7–9 show the overall temperature, dew point, and relative humidity distributions for all eight cities included in phases I and II.

Atlanta and São Paulo exhibited lower temperature standard deviations compared to Shanghai and Tokyo. In the case of Atlanta, this appears to be the result of the presence of centralized heating and cooling in all homes. However, none of the homes in São Paulo had central HVAC systems. The reason for the low variability in temperature for São Paulo is most likely due to the temperate local climate and its proximity to the Atlantic Ocean. This is consistent with the observation that the standard deviation in dew point for São Paulo was also low. Shanghai exhibited a broad range of indoor temperatures (13.0–28.9 °C), including the warmest indoor temperature for all cities. All Shanghai homes had air conditioning, but usage was conservative. Shanghai and Tokyo exhibited a broad range of dew points throughout the year (2.8–22.2 and 3.1–19.4 °C, respectively). Both cities also had significant percentages of low indoor temperatures compared to Atlanta and São Paulo. Of the phase II cities, Tokyo had the lowest average temperature and dew point, but exhibited an intermediate average relative humidity (19.7, 10.5 °C, and 56.5% RH, respectively). The reasons for this will be discussed further below. These results are very similar to the previously mentioned Canon study.[14]

As observed for phase I, there is a general diurnal pattern for both temperature and relative humidity for a given home. This is driven primarily by the daily outdoor temperature cycle. As the outdoor temperatures drop at night, to some extent, so do the indoor temperatures. However, the dew point does not vary nearly as much. The net result is that, as indoor temperatures rise and fall during the course of 24 h period, the relative humidity tends to move in the opposite direction.

When the temperature and humidity distributions of the phase I and phase II cities are compared, Atlanta is most comparable to the phase I results. Shanghai and São Paolo, on the other hand, exhibit distributions that are centered at

Table I. Temperature, dew point, humidity summary for the average home in each city, and overall, for phases I and II.

	Mean temp (°C)	σ_{avg} (°C)	Mean DP (°C)	σ_{avg} (°C)	Mean RH (%)	σ_{avg}	*N* (avg home)	Total *N*
Rochester	20.2	2.9	7.1	5.2	43.9	10.9	12264	98110
Los Angeles	21.0	2.1	9.3	4.1	48.8	9.9	13226	105806
Melbourne	19.8	2.7	10.7	2.4	56.4	6.8	12622	100979
London	20.5	2.3	10.1	3.0	52.2	7.8	15100	120798
Phase I	20.4	2.5	9.3	3.7	50.3	8.8	13303	425693
Atlanta	21.8	2.7	10.8	5.3	51.2	12.1	17846	142765
Shanghai	22.4	5.9	13.8	6.9	59.5	11.8	12107	96852
São Paolo	23.3	3.2	15.7	3.3	63.4	9.9	16975	135798
Tokyo	19.7	4.4	10.5	5.4	56.5	10.2	12669	101350
Phase II	21.8	4.0	12.7	5.2	57.6	11.0	14899	476765
Phases I and II	21.1	3.3	11.0	4.4	54.0	9.9	14101	902458

Table II. Daytime light level statistical summary for the average home in each city and overall for phases I and II.

	Median (lux)	Mean (lux)	90th percentile (lux)	95th percentile (lux)	99th percentile (lux)	Average standard error (mean)	*N* (avg home)	Total *N*
Rochester	30.0	62.0	151	218	431	2.9	1213	9705
Los Angeles	54.1	71.5	140	177	312	2.0	2826	22611
Melbourne	46.8	93.7	211	343	617	3.6	2743	21940
London	33.9	76.1	151	208	964	4.4	2135	17080
Phase I	41.2	75.8	181	275	791	3.2	2229	71336
Atlanta	12.1	19.6	46.1	66.9	109	0.4	4644	37154
Shanghai	24.5	59.1	156	227	469	1.9	3661	29288
Phase II	18.3	39.4	101	147	289	1.1	4153	66442
Phases I and II	33.6	63.7	141	211	540	2.5	2870	137778

higher levels of temperature, dew point, and RH. This can be explained by the combination of more temperate climates, proximity to the oceans, and much lower utilization of centralized heating and cooling systems. The Tokyo data are somewhat skewed by unusually cool temperature readings in the 10–15 °C range for a couple of the homes. As noted above, lower overnight temperatures can lead to a greater frequency of high RH readings but not necessarily higher dew points. This is borne out in the Tokyo dew point histogram, which is, in fact, skewed to lower dew point temperatures, i.e., lower absolute humidities, compared to the other phase I and phase II cities.

Light Levels and Spectral Distributions

The combined phase I and phase II light level statistics and spectral distributions are summarized in Table II and Figs. 10–13. Table II and Fig. 10 show that the mean and median for the daytime light levels were well under 100 lux, with a 90th percentile in the range of 40–210 lux. It is important to note that >98% of the daytime measurements taken over the course of the phase I and phase II studies are below 500 lux, a light level often cited as representative of the average or typical home.[9,17,18] Another way to view the light level data is given in Fig. 11, which displays a histogram of the average daytime light levels for each of the 48 homes in-

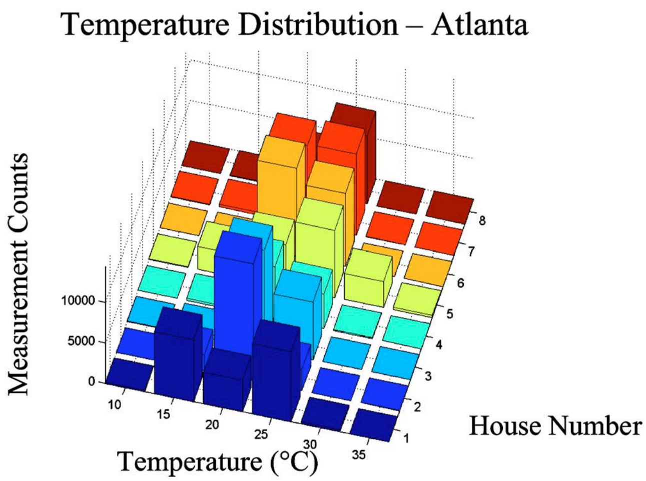

Figure 3. Temperature distributions for the eight homes monitored in Atlanta.

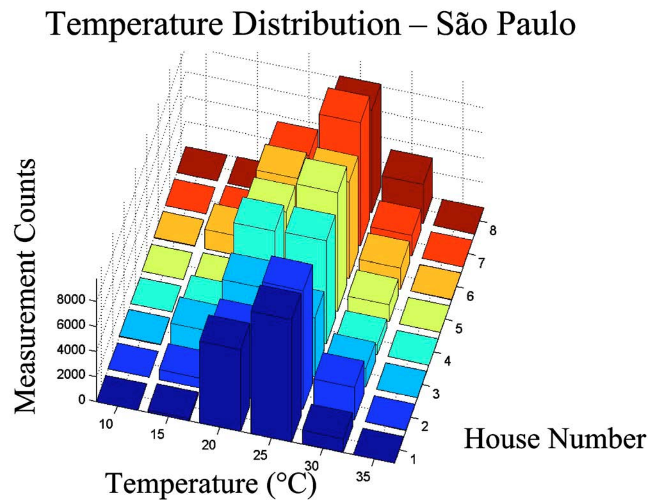

Figure 5. Temperature distributions for the eight homes monitored in São Paulo.

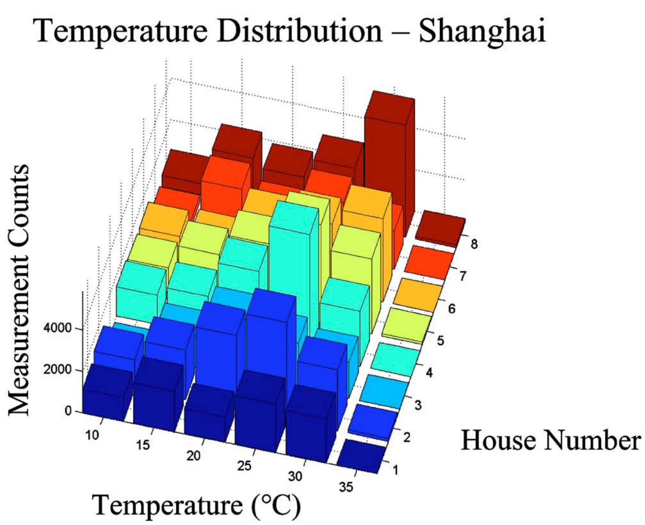

Figure 4. Temperature distributions for the eight homes monitored in Shanghai.

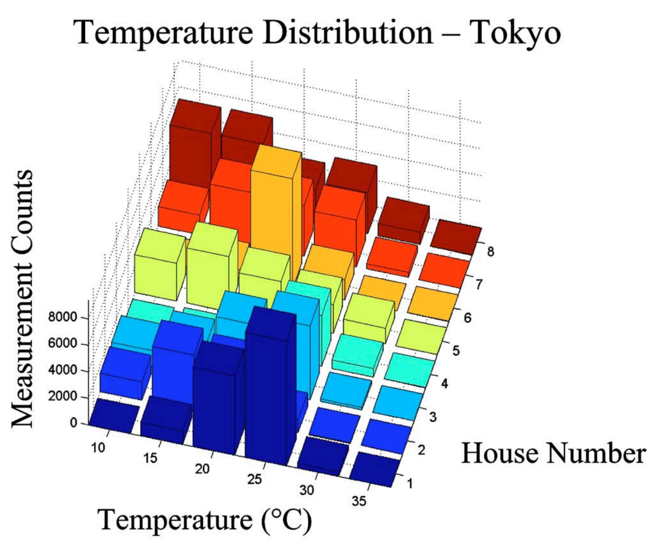

Figure 6. Temperature distributions for the eight homes monitored in Tokyo.

cluded in phases I and II. It can be seen that 47 of the 48 (98%) homes average less than 200 lux, and 41/48 (>85%) of the houses average less than 125 lux. None of the 48 homes averaged greater than 425 lux. If anything, these results indicate even lower average light levels than reported in the earlier Anderson studies, which were specific to just a couple of homes in Rochester, New York.

Somewhat surprising were the relatively low light levels found in Atlanta, given its location in the "sun belt." A review of the geographical and architectural characteristics of the homes in Atlanta found a preponderance of overhanging roof styles, wraparound porches, and shade trees, all of which are intentionally designed to limit the amount of interior exposure to direct sunlight (and also limit the generation of heat). Consistent with this finding is the observation that several Atlanta homes actually display inverse seasonality, i.e., the light levels are generally higher in the winter when the trees are bare of leaves, and the angle of the sun is low enough to dip below the overhanging roofline. Similar seasonality trends were noted in our phase I report.[15] Figure 12 illustrates the inverse seasonality trend for one such home in Atlanta. Additional information, including exterior views of the homes in Atlanta are provided in the supplemental materials. (*Available as supplemental material on the IS & T website at www.imaging.org.*)

In addition to providing a statistical analysis of long term light levels, another important objective of this study was to characterize the average spectral energy distributions of the lighting in consumers' homes. Figure 13 shows the spectral curves averaged from the ~66 000 individual daytime readings for Atlanta and Shanghai, along with the overall average curves for each phase, separately and combined. Although the overall magnitude of the irradiance varies for

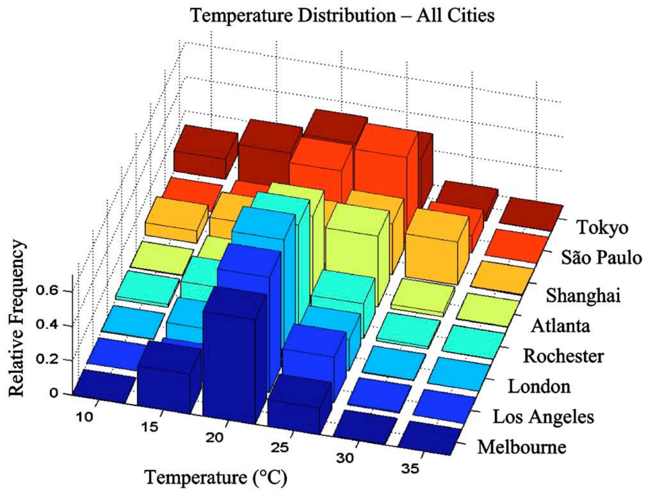

Figure 7. Overall temperature distributions for each city in phases I and II.

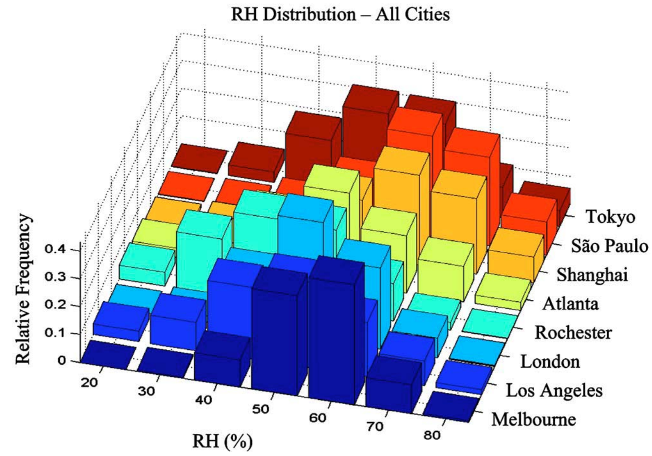

Figure 9. Overall relative humidity distributions for each city in phases I and II.

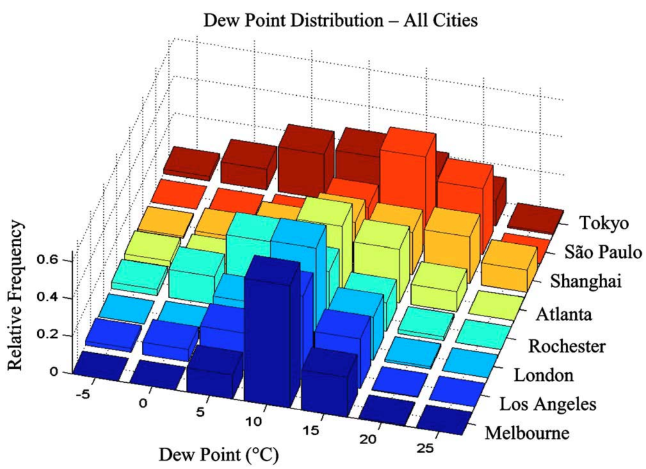

Figure 8. Overall dew point distributions for each city in phases I and II.

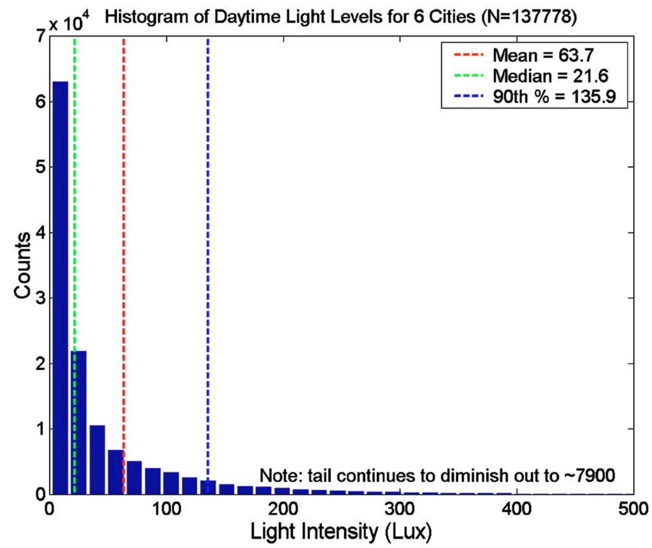

Figure 10. Histogram of daytime light levels for all homes, all cities, phases I and II.

each of the spectral distributions, which is consistent with the light level statistics given in Table II, the shapes of the curves are remarkably similar. These curve shapes are also consistent with those reported by Anderson and Anderson.[11] It is clear from the spectral distributions shown in Fig. 13 that the long term average indoor lighting conditions for the display of consumers' photographs are dominated by diffuse, window-filtered daylight. This long term average approximates the standard D45 spectrum as shown in Fig. 14.[19]

Impact on Accelerated Image Stability Test Methods

These results are being considered in the design of improved, accelerated image-stability test methods intended to simulate the home display environment. For example, it has been shown[16,20] that high intensity xenon arc illumination with appropriate daylight balancing filters provides a much better match to the average home spectrum shown in Fig. 13 than the high intensity fluorescent illumination currently being used by many labs. In order to isolate the effect of light on a photograph from the other environmental factors, light fade testing should be conducted under conditions of temperature, humidity, and pollutant levels that are known to be benign. Separate studies have shown that ink jet photographic materials (which are known to be sensitive to both humidity and ozone) that have been conditioned in a dark chamber kept at <35 °C, $<50\%$ RH, and <2 ppb ozone show essentially no change in density or appearance after many weeks of treatment.[21–23] To be consistent with other standards for photographic media, it is recommended that the temperature and humidity at the sample plane be kept at 23 °C and 50% RH. Ideally, the black panel temperature at the sample plane (the temperature of a D-max black patch) should also be kept at <25 °C. An essentially ozone-free environment can be achieved by using activated carbon filters in the air supply going to the lab or test chamber environment.

Likewise, for accelerated temperature (Arrhenius

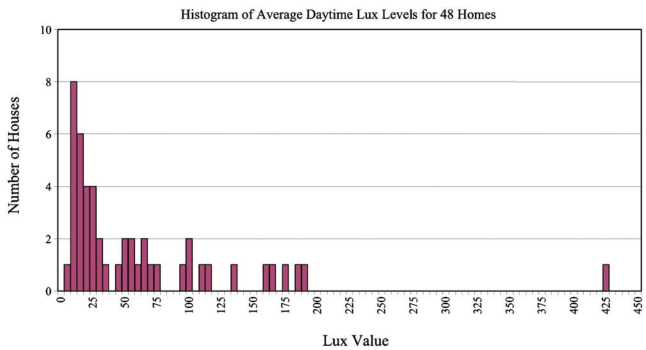

Figure 11. Histogram of average daytime light levels for each of the 48 homes in phases I and II.

method) or humidity testing, a dark, ozone-free environment should be maintained. In addition, for Arrhenius testing of humidity sensitive materials, the constant dew point approach has been shown to isolate the effect of moisture from any heat induced degradation.[22,23] For testing at high humidities, temperatures in the 20–25 °C range should be used to avoid confounding interactions with thermally induced changes.[23] Last, it follows that accelerated ozone testing should be conducted in a dark chamber maintained at 23 °C and 50% RH.[24]

In addition to the design of improved accelerated test methods, these studies can also be used to better translate the results of accelerated testing to predict the long term effects of ambient exposure to the various environmental factors found in the typical consumer environment. For light fade testing, assuming the law of reciprocity holds,[7] this can be done by simply dividing the cumulative exposure in lux-h required to reach a given level of image degradation, e.g., 0.30 density loss from a 1.0 initial density of a primary or neutral color patch, by the ambient light level [Eq. (1)]. This gives the predicted time in hours to reach the same level of density loss at the ambient home light level

$$\frac{\text{accelerated test light level (lux)} \times \text{test duration (h)}}{\text{ambient light level (lux)}} = \text{ambient prediction (h)}. \quad (1)$$

Defining an appropriate ambient light level for the home display environment to use in Eq. (1) is required. Previous studies[1,21] have used 120 lux as the representative light level for the typical home, based on the results reported by Anderson et al.[10,11] The results of the present study indicate that 120 lux appears to be a reasonably conservative estimate for the typical home light level because it falls close to the 90th percentile for the combined phase I and II statistics shown in Table II. Other studies have used light levels as high as 500 lux as the basis of their light fade predictions for the average home display condition.[9,17,18] This level corresponds to roughly the 99th percentile of the light levels measured in the present study, and thus, 500 lux of continuous long term exposure might be considered a worst case or extreme scenario. Ultimately, any future standard or specification for predicting the long term resistance to light fade of photographs on display must determine what the most relevant criterion is for defining an actual use light level. Words like "typical" and "average" imply statistical measures that most closely correspond to the median and the mean. For statistical distributions, such as shown in Figs. 10 and 11, the 90th percentile might be a more prudent criterion, given the wide variation in light levels observed among the 48 homes, especially if the light fade predictions are intended to be used for marketing purposes. One might even consider making predictions at two light levels with appropriate descriptors to better illustrate the influence of ambient light levels on long term image permanence in the home.

For Arrhenius testing, which is used to predict the long term effects of heat on image stability, 24 °C has been used as the ambient temperature to which the Arrhenius equation is extrapolated.[1,5,21] Others have used 25 °C.[9] In either case, this corresponds to roughly one standard deviation above the mean for the combined phase I and phase II results (Table I). Although the 90th percentile temperature is closer to 25.3 °C, an ambient assumption of either 24 or 25 °C is, again, reasonably conservative for the purpose of making long term predictions.

For accelerated humidity testing, there is no current standard methodology for correlating image degradation observed at high levels of humidity to a longer term exposure of a photograph to some lower ambient humidity level. One simplified approach is to assume the cumulative effects of intermittent exposure to high levels of humidity to be additive, and to make some assumptions as to what percentage of the time a photograph might be exposed to that high level of humidity.[13,21] This approach assumes that changes as a result of humidity only occur at the accelerated test condition, and that there is essentially no change at lower humidities. In fact, studies on ink jet prints have shown that the effect of humidity is, indeed, additive and that very little change is observed at relative humidities less than about 60% at 20–25 °C.[2,13,23] Given this set of assumptions, it may be possible to design an accelerated humidity keep test in which a sample is treated at 21 °C, 80% RH, and to use the data in Table I to make some assumption regarding the percentage of time that a home environment would experience that same level of humidity. Using the overall statistical summary given in Table I, 80% RH is approximately 2.6σ above the mean RH (54.0%). This corresponds to a probability of this condition occurring in the average home approximately 0.5% of the time. Using this line of reasoning, this treatment condition represents an acceleration factor of 200×. In other words, 6 months of treatment at 21 °C, 80% RH would simulate about 100 years of ambient humidity storage.

Although there is also no current standard practice for accelerated ozone testing, several labs have used methods analogous to that described above for accelerated light fade testing.[9,21] High concentrations of ozone are used to accelerate the image degradation, and a reciprocal relationship is assumed [Eq. (2)]

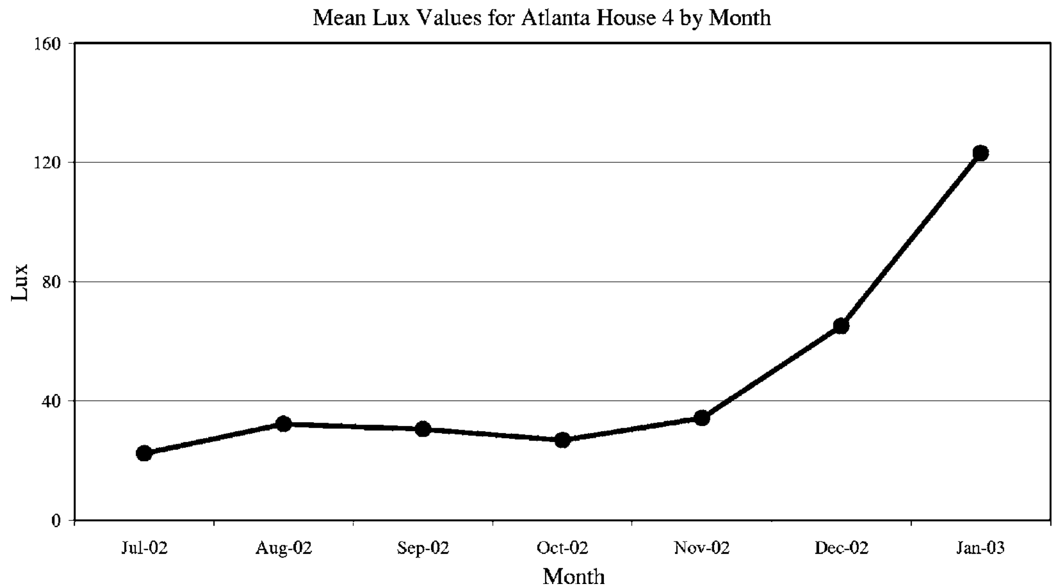

Figure 12. Mean monthly lux levels for house 4 in Atlanta.

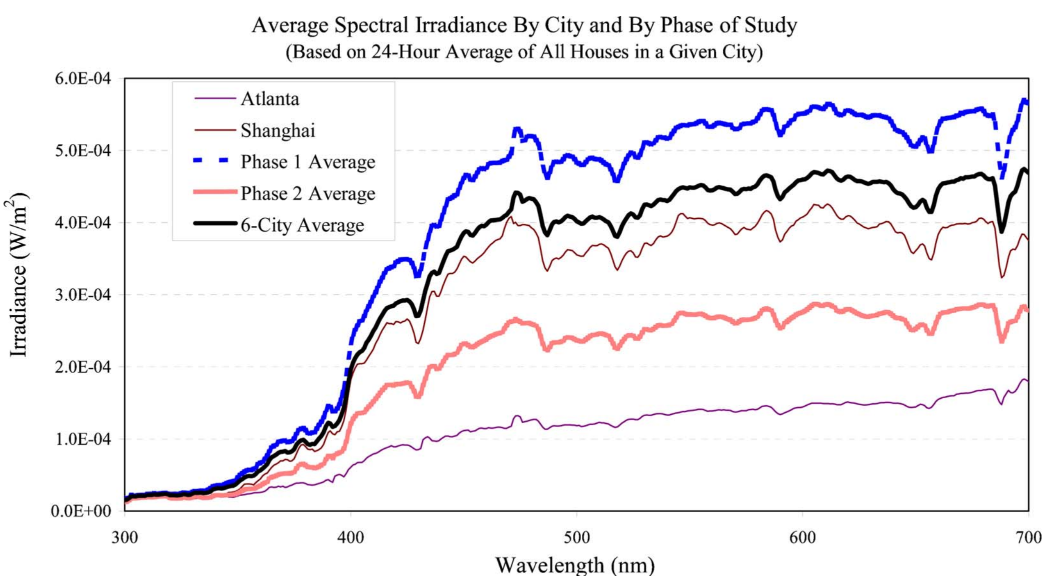

Figure 13. Average spectral energy distributions by phase II city, by phase, and overall.

$$\frac{\text{accelerated test } [O_3] \text{ (ppm)} \times \text{test duration (h)}}{\text{ambient } [O_3]\text{(ppm)}} = \text{ambient prediction (h)}. \quad (2)$$

Unfortunately, our home environmental study was unable to generate a statistically significant number of ozone readings because of equipment malfunctions. Therefore, we are unable to propose an ambient ozone concentration based on the same type of statistical analyses as provided above for light, temperature, and humidity. Other labs have reported limited long term ozone data that suggest ambient concentrations in the home in the range of 3–15 ppb (0.003–0.015 ppm).[14,25,26] Values of 5 and 10 ppb have been cited for the purpose of making ambient predictions of ozone fade based on accelerated test results.[9,21]

SUMMARY

In this study, we have extended our understanding of the typical home consumer environment for the storage and display of photographs to an additional 32 homes in four cities around the world: Atlanta, São Paulo, Shanghai, and Tokyo. Combined with our phase I study, we have now characterized the long term (6–10 months) indoor display environment in 64 homes in eight cities across five continents.

With respect to temperature and humidity, homes in São Paulo and Shanghai displayed somewhat higher readings than those for the phase I cities, while the Tokyo and Atlanta

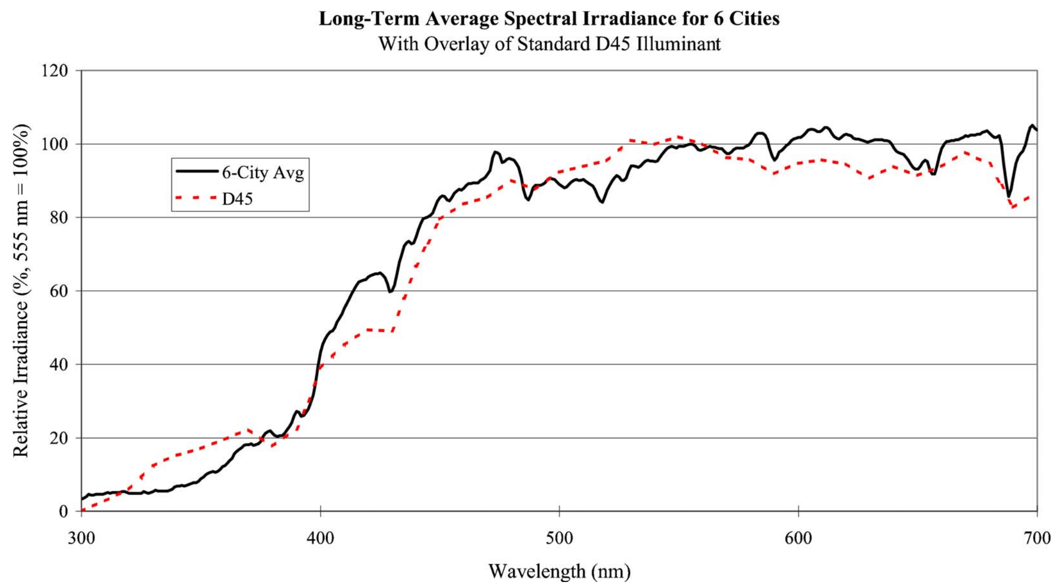

Figure 14. Standard D45 illumination spectrum.

were more in line with the phase I results. This can be largely explained by the lack, or conservative use, of air conditioning in Shanghai and São Paulo. Overall, the long term temperature and humidity statistics for all eight cities were found to average $21.1 \pm 3.3\ ^\circ\mathrm{C}\ (\pm 1\sigma)$ and $54 \pm 9.9\%$ RH $(\pm 1\sigma)$, with a dew point of $11.0 \pm 4.4\ ^\circ\mathrm{C}\ (\pm 1\sigma)$. The distributions of temperature and humidity were relatively normally distributed about the mean.

Light levels and spectral energy distributions, which were monitored only in Atlanta and Shanghai for phase II, were found to be somewhat lower than the levels observed for phase I, but the long term average spectral energy distributions were still dominated by diffuse, window-filtered daylight. The overall light level statistics for all six cities are best described by either an exponential or Weibull $(\beta = 1)$ distribution, with a median of 33.6 lux, a mean of 63.7 lux, and a 90th percentile of 141 lux.

The results of these studies have been used to recommend improved accelerated image stability test methods for the four primary environmental factors: light, heat, humidity, and ozone. It is now possible to conduct accelerated testing for each factor in isolation of the other three factors, allowing for a more precise understanding of the affects of each factor on the long term stability of photographs. The ultimate goal of this body of work is to assist in the generation of a family of new international standards that can be applied broadly across current digital photographic output technologies and that can be directly related to expectations and end-use environment of the typical home consumer.

ACKNOWLEDGMENT

The authors wish to thank the 32 participants who allowed their homes to be monitored for nearly 1 year for the phase II study. Special thanks are due to those who collected and organized the field data: Chris Houston and David Houston in Atlanta; Helio Piva and Patricia Belo in São Paulo; Christina Li and Judy Xu in Shanghai; and Masahiro Itoh and Yuri Yoshimura in Tokyo. Thanks are also due to Irene Baker, John Wysokowsi, Max Wu, and David Shen for providing instrumentation training to the field participants. Joyce L. Chan provided initial statistical analyses, and Gary Pino oversaw the transition of instrumentation from phase I to phase II. The authors also wish to acknowledge the assistance of David Kopperl, John Lynch, Mark Dawson, Joanna Smith, Jerome Flood, David Skye, Sheila Davis, Irene Baker, Caryn Cunningham, Erica DeIonno, Peter Freiburg, Paige Miller, Gary Pino, Jim Newmiller, Steve Bauer, Val Pilskins, Joseph Runde, Jack Chang, Steve Switalski, and Chuck Heckler in support of the phase I project.

REFERENCES

[1] J. LaBarca and S. F. O'Dell, *Proc. IS&T's 12th Int'l. Symp. on Photofinishing* (IS&T, Springfield, VA, 2002) pp. 38–47.
[2] P. Hill, K. Suitor, and P. Artz, *Proc. IS&T's NIP16* (IS&T, Springfield, VA, 2000) pp. 70–73.
[3] D. E. Bugner, R. Levesque, and R. Van Hanehem, *Proc. IS&T's NIP17* (IS&T, Springfield, VA, 2001) pp. 175–78.
[4] *A Consumer Guide to Traditional and Digital Print Stability* (Image Permanence Institute, Rochester Institute of Technology, Rochester, NY, 2003). A downloadable file (pdf format) of this document is available at http://imagepermanenceinstitute.org/sub-pages/consumerguide.pdf
[5] ANSI/NAPM IT-9.9 (1996) (soon to be ISO 18909).
[6] S. A. Arrhenius, Z. Phys. Chem. **4**, 226 (1889).
[7] T. H. James, *The Theory of the Photographic Process*, 4th Ed. (Macmillan, New York, 1977), pp. 133–134.
[8] D. E. Bugner and P. Artz, *Proc. IS&T's NIP18* (IS&T, Springfield, VA, 2002) pp. 306–309.
[9] Y. Shibahara, H. Ishizuka, N. Muro, Y. Kanazawa, and Y. Seoka, *Proc. IS&T's NIP18* (IS&T, Springfield, VA, 2002) pp. 330–333.
[10] S. Anderson and G. Larson, J. Imaging Technol. **13**, 49–54 (1987).
[11] S. Anderson and R. Anderson, J. Imaging Technol. **17**(3), 127–131 (1991).
[12] D. E. Bugner and C. Suminski, *Proc. IS&T's NIP16* (IS&T, Springfield, VA, 2000) pp. 90–94.
[13] S. Guo, N. Miller, and D. Weeks, *Proc. IS&T's NIP18* (IS&T, Springfield,

VA, 2002) pp. 319–325.

[14] Y. Kojima, H. Ogino, and T. Yamamoto, *Proc. IS&T's NIP20* (IS&T, Springfield, VA, 2004) pp. 724–728.

[15] D. E. Bugner, J. LaBarca, D. Kopperl, J. Phillips, D. Skye, I. Baker, C. Cunningham, P. Miller, and T. Kaltenbach, *Proc. IS&T's 13th Int'l. Symp. on Photofinishing* (IS&T, Springfield, VA, 2004) pp. 31–36.

[16] D. E. Bugner, J. LaBarca, J. Phillips, T. Kaltenbach, A. Bush, and J. Kapecki, *Proc. IS&T's Archiving Conf.* (IS&T, Springfield, VA, 2005) pp. 179–183.

[17] H. Wilhelm, *Proc. IS&T's NIP20* (IS&T, Springfield, VA, 2004) pp. 664–669.

[18] Y. Oki, K. Kitamura, T. Aoyama, and M. Hanmura, *Proc. IS&T's NIP20* (IS&T, Springfield, VA, 2004) pp. 710–713.

[19] CIE 15.2 (1986).

[20] J. Quill, G. Fedor, P. Brennan, and E. Everett, *Proc. IS&T's NIP20* (IS&T, Springfield, VA, 2004) pp. 689–698.

[21] D. E. Bugner, C. E. Romano, G. A. Campbell, M. M. Oakland, R. J. Kapusniak, L. L. Aquino, and K. E. Maskasky, *Proc. IS&T's 13th Int'l. Symp. on Photofinishing* (IS&T, Springfield, VA, 2004) pp. 38–43.

[22] D. E. Bugner, R. J. Kapusniak, M. Oakland, and L. L. Aquino, *Proc. IS&T's NIP20* (IS&T, Springfield, VA, 2004) pp. 716–719.

[23] D. E. Bugner and B. L. Lindstrom, *Proc. IS&T's NIP 21* (IS&T, Springfield, VA, 2005) pp. 348–352.

[24] D. E. Bugner, R. Van Hanehem, M. Oakland, P. Artz, D. Zaccour, and R. Levesque, J. Imaging Sci. Technol. **49**(3), 317–325 (2005).

[25] K. Kitamura, Y. Oki, H. Kanada, and H. Hayashi, *Proc. IS&T's NIP19* (IS&T, Springfield, VA, 2003) pp. 415–419.

[26] M. Thornberry and S. Looman, *Proc. IS&T's NIP19* (IS&T, Springfield, VA, 2003) pp. 426–430, and references cited therein.