Designing Lightfast Inks and Media for Multi-Dyeload Printers

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Abstract

Achieving industry-leading lightfastness in a multi-dyeload printer presents many challenges in addition to those present in 3 or 4 color writing systems. This report outlines some of the criteria and strategies used to develop a new multi-dyeload printer that delivers both office printing versatility and photo reproduction with breakthrough image quality and permanence benefits. A brief background discussion of a 6 ink writing system will be presented. Design rules concerning dye selection and media and ink formulation will be detailed. Some factors that impart light permanence challenges include color balance criteria, dye loading, writing system treatment during printing, media design, and ink-media interactions. The end result of this work is the development of the HP DeskJet 5550 printer, new HP #57 and HP #58 pens, and the new HP Premium Plus Photo Paper (replaced earlier product of the same name). This versatile printing system features photo reproduction with high gloss, excellent 6 ink photo image quality with ultra low granularity, 73 years predicted glass protected lightfade permanence, and 49 years unprotected lightfastness with low reciprocity factors.

Introduction

Advancements in digital capture methods, low cost color printing, and increased customer awareness have all played a part in the explosive growth of digital imaging. As digital cameras displace conventional analog cameras, there is an increasing need for digital photo reproduction to complement digital capture.[1] The major requirements for consumer digital photo reproduction are low cost, ease-of-use, image permanence, and image quality. Inkjet printing increasingly is the method of choice to achieve these attributes. In the past several years, inkjet printers have made tremendous strides in terms of price, image quality, and ease-of-use. However, matching the image quality and image permanence of traditional silver halide prints has forced tradeoffs between cost, image quality, photo gloss, printer flexibility, or the needs for special protection methods. The data in Figure 1 summarizes the reported lightfastness performance in traditional silver halide and inkjet prints as determined by a leading independent lab, Wilhelm Imaging Research, Inc.[2]

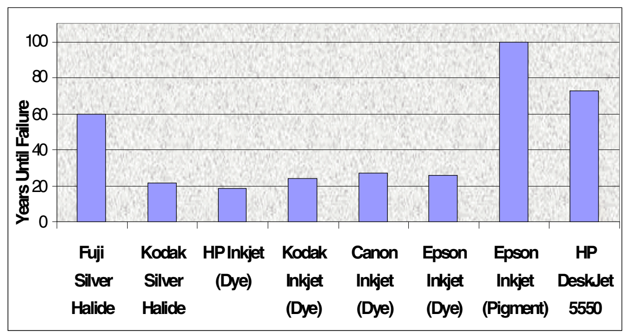


Figure 1. Predicted Lightfastness Stability for Several Photo Reproduction Systems as Reported in Reference 2 in Combination with the Results for the HP DeskJet 5550 as Tested by Wilhelm Imaging Research, Inc.

Through customer surveys done by Hewlett-Packard, it was determined that the customer demands for digital photo reproduction included the look and feel of traditional silver halide glossy photos, the fade resistance of silver halide photos, and the convenience, control, and low-cost of inkjet. In addition, this printing system would be especially useful if the at-home or small business text and color graphics needs could be satisfied in a single, versatile product. Up until now, such a system was not available. For example, Figure 2 below graphs the sheet gloss for the samples in Figure 1, showing the low gloss of some systems.

This report details the development of a new printing system, the Hewlett-Packard DeskJet 5550, that delivers all the versatility expected from a general use printer and, when coupled with the new HP Premium Plus Photo Paper and new HP #58 photo pen, delivers excellent image quality and high gloss for silver-halide quality photo reproduction. In addition, the light-fastness of this dye-based inkjet system is tested at 73 years glass protected exceeds all traditional consumer color silver halide products, as well as all dye based products that HP is aware of. This performance is achieved through careful optimization of the writing system, inks and media to deliver a truly optimized photo printing system.

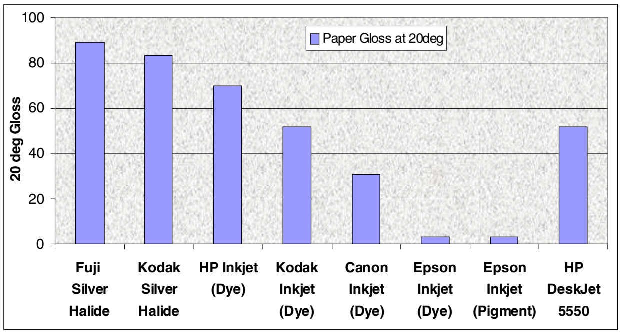


Figure 2. Sheet Gloss for the Photo Reproduction Systems in Figure 1 Showing Significantly Lower Gloss for Some Systems Relative to Silver Halide.

Design Criteria – Writing System

The design philosophy for the DeskJet 5550 was to develop a printer capable of printing both sharp, dark text and business graphics at high print speeds as well as stunning photos on a variety of substrates. A key element in this design was the swappable pen. The HP#57 cartridge is a dual use, high dye-load cyan, magenta, and yellow pen (CMY) and is standard in the printer. When the HP#56 high capacity black pen is installed (K^p), the printer is configured for $CMYK^p$ printing using the high dye load inks with a durable pigment black ink. With this pen configuration, the printer is tuned for printing high-speed text and vibrant business graphics on plain and photo papers.

For maximum flexibility, HP designed the DeskJet 5550 to also employ the HP#58 cartridge consisting of a light dye load cyan (c), light dye load magenta (m), and a dye based photo black (Kd). Swapping the #56 black pen (stored in supplied "garage") for the #58 photo pen results in a CMYcmKd print configuration. The printing software automatically detects the photo pen and adjusts itself for photo printing with maximum image quality. The light cyan and magenta are particularly useful for photo printing to deliver smooth color gradations at the lower tone scales such as found in skin tones, sky-blues, etc. The dye-based black mixes well with the dye-based color inks to provide smooth transitions to darker colors, as well as reducing ink usage by replacing composite black with true black in the high density, full area fills. Most multi-dye-load printers, including the DeskJet 5550, use a single yellow dye load because yellow has a low visual sensitivity and is naturally low in contrast, making a light dye load yellow ink unnecessary.

One challenge when designing the printing software for printers with low dye loads is the transition between the light dye-loads and the dark dye loads. The printer driver must balance the transition such that a density gradient of low to high optical density does not show an abrupt transition break (high dye loads used too early or too much can result in a sudden jump in optical density), and the total ink used must remain below a set limit such that ink flooding does not occur (high dye load used too late or too little can result in an excessive amount of ink in a darker area). Similarly, a composite black provides a smoother area fill in a low density area than a true black due to the lower density of the primary colors, and the composite black covers more white space at equal OD versus a true black. The proper balance of smooth transitions and appropriate ink usage was achieved through the extensive mixing of the light and dark dye loads at the upper end of the density range, as shown in the following graph. A similar strategy was used for composite black to true black transitions. Figure 3 gives a typical example of the partitioning that occurs between the light and dark dye-loads in a tone scale.

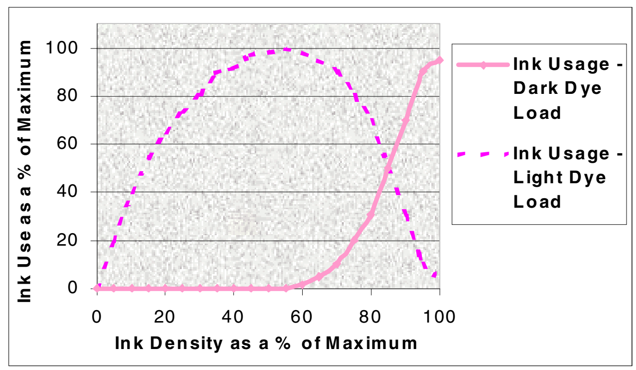


Figure 3. Partitioning of Usage Between Light and Dark Dye Loads in a Tone Scale Showing Extensive Ink Mixing at Higher Ink Densities

Design Criteria – Dyes

The constraints for image quality described above also have a large impact on the lightfastness performance. While the light dye-loads provide a large benefit for photo printing IQ, the light dye load inks are typically less light fade resistant than their high dye load counterparts.[3] This difference is particularly strong for the dyes that are prone to aggregation. In particular, phthalocyanines are known to undergo limited aggregation in solution, forming finite-size aggregates.[4] Figure 4 provides an example of spectroscopic evidence for aggregation of a phthalocyanine dye.

Accordingly, the aggregation state of the dye in the dark and light inks is expected to be different because of the shift in the equilibrium, both in the solution and on the media, with a corresponding impact on the lightfastness (see Figure 5). As a result, examining lightfastness at multiple starting optical densities is critical for multi dye-load printers.

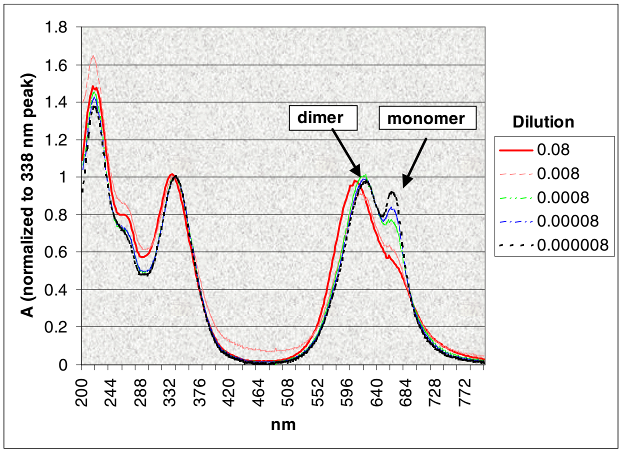


Figure 4. UV-Visible Absorption Spectra of a Phthalocyanine Dye in Solution as a Function of Dilution Showing Aggregation Absorbance at Higher Concentrations.

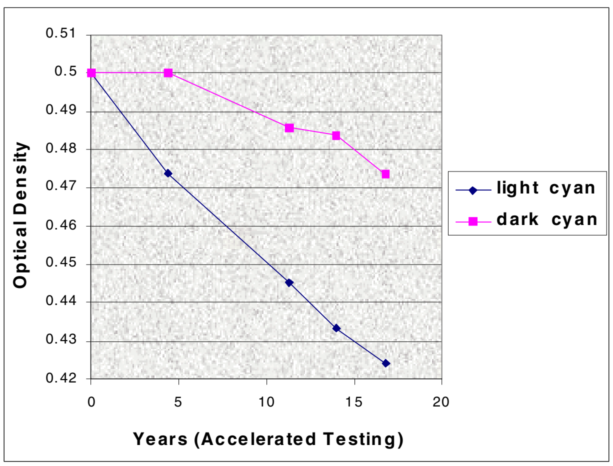


Figure 5. Light Induced Fade of Cyan at Two Different Dye Loadings Showing the Greater Accelerated Fade of the Light Cyan Ink Relative to the Dark Cyan Ink.

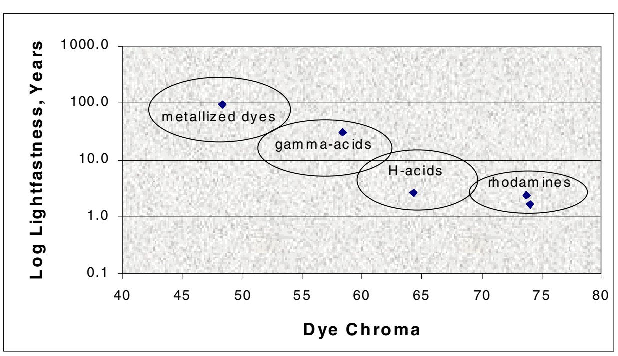


Figure 6. Lightfastness Versus Chroma for Representatives From Several Magenta Dye Classes Showing the General Trade-off Between the Chroma and Lightfade Resistance.

One strategy for increasing lightfastness in low-dye-load inks is to use dyes with somewhat lower chroma but superior light stability.[5] During the extensive testing and development phase of the DeskJet 5550 inkset it was generally observed that there is a tradeoff between lightfastness performance and chroma and/or hue angle. Figure 6 generalizes this trend for several magenta dye classes. However, for low-dye loads, the chroma of the dye is less constraining relative to the high dye load dyes because the low dye loads are used in the low-chroma portions of the print.

The challenge faced by the HP ink team was to improve lightfastness while at the same time decreasing the dye load but maintaining proper hue and chroma in order to improve image quality. This has traditionally been a problem, especially for magenta dyes. As a result, a patent-pending inkset was developed that met the needs for high-quality 6-ink printing as well as improved lightfastness.[6]

Another challenged faced by the HP ink team was developing a system that provided proper color balance between the light and dark dye loads during fade, as defined in the fade criteria adopted by HP.[7] Ideally, all dyes fade at the same rate in order to maintain color-balance throughout the life of the print. The color balance in this multiple configuration system is hinged upon the yellow dye, which, as mentioned earlier, is used throughout the tone scale in both printer configurations (CMYK^p and CMYcmK^d). In practice, designing 4 or 6 dyes with equal fade rates is nearly impossible. For example, as shown above, using the same dye in both the low and high dye-load inks would result in a greater lightfastness for the high dye load.

As a guideline for a strategy to select the best inks for lightfastness, it has been reported that lightfade generally shows an equal loss of density units across the tonal range.[8] The practical result of this effect is that at equal light exposures, lower density colors show a greater percentage loss of optical density and loss of detail relative to the higher density areas. To counterbalance this in the CMYcmK^d configuration optimized for photo printing, two strategies were employed. First, the low dye loads were designed to have the greatest fade resistance in order to minimize the larger percentage density loss inherent in the low density areas.[8] However, to maintain color balance in the low density areas (cmY), the yellow ink also had to be very fade resistant. On the other hand, the non-yellow high dye-loads had to be high in chroma for vibrant high-density colors. To maximize the performance of all of these design constraints, the second strategy employed was to bias the high dyeloads to be less lightfast than the yellow dye. This served to minimize density imbalance during fade between the high and low dye loads (mM and cC), minimize color imbalance between the high dye loads (CMYK^d) during fade, and to maximize gamut. This strategy maximizes color-balance in both 3 and 6 ink configurations while at the same time maintaining light-dark dye-load fade balance and high chroma.

This design approach was implemented and tested. Interestingly, during the design phase it was discovered that while the developmental DeskJet 5550 generally exhibited a larger percentage density loss in the lower density areas as expected in the CMYK[p] configuration, the CMYcmK[d] configuration exhibited a surprising uniform percentage density loss throughout the tone scale. Figure 7 illustrates these properties for magenta where the dye used in the low dye load ink exhibits greater lightfastness relative to the dye used in the high dye load ink.

In fact, the lightfastness of the high density portion of the tone scale was improved to a greater degree than what would be expected from an algebraic combination of lightfastness and percent usage of the low and high dye loads. It is speculated that some protective effect is occurring between the dyes used in the low and high dye load inks. Some evidence has been observed through dye blends at HP.[9]

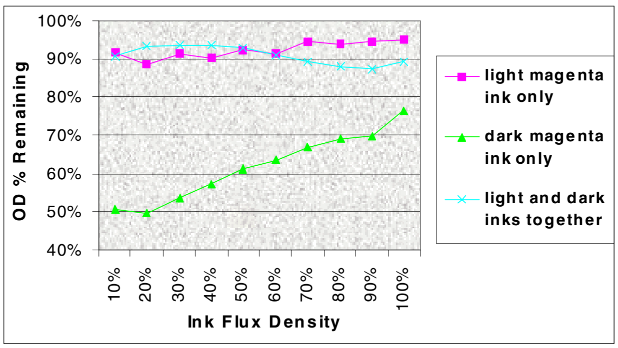


Figure 7. Light-Induced Fade of Magenta Ink as a Function of Ink Density for the Light and Dark Inks Printed Together (cf. Figure 2) and Separately. Note the Improvement in the Fade Performance of the High Density Areas of the Combined Ink Set.

Design Criteria - Media

The media design objectives for the photoprinting system were weighted more heavily towards the photo printing application because it is reasoned that photo media is more application-specific relative to the versatility objectives of the printer. As a result, meeting the consumer expectations for digital photo printing was high priority. Specifically, drytime, lightfastness and image quality were the major design criteria for the new HP Premium Plus Photo Paper that would enable the new HP DeskJet 5550 printing system to deliver its full value to the user.

The first design choice for the media was to specify the coating construction. Broadly, there are two types of coating technology, distinguished by their ink adsorption method; porous and swellable. Porous media absorb ink by capillary action into voids created between media pigment particles. This type of coating has the advantage of quick drying rates, but it is extremely susceptible to fading caused by airborne pollutants if it is not protected in some fashion (e.g. framing).[10] Swellable coatings absorb ink by a swelling of a polymer coating. This type of coating has the advantage of dye encapsulation that affords good fade properties, but care must be exercised during the drying process so that the print is not damaged or finger-printed.

The difference in fade resistance of the two types of coating can be illustrated though reciprocity factors.[11] Reciprocity occurs when the acceleration factor used in accelerated lightfade testing does not remain constant. Often this is seen when, at equivalent lux exposures, the fade measured at low light intensities is larger than that measured at high light intensities. While both swellable media and porous media can exhibit reciprocity behavior, HP and others have found that the reciprocity factor for porous media is generally much larger (see Figure 8, swellable reciprocity factors found to be generally in the range of 1-5 and constant with test time, porous reciprocity factors generally > 5).[11] This is attributed to an additive contribution of air fade to the light fade during the longer exposure times experienced during a lower lux lightfade test.

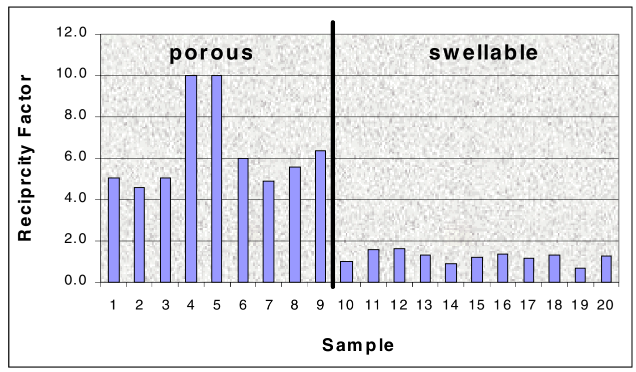


Figure 8. Reciprocity Factor Between 60klux and the Extrapolation from 4 Months of 1klux Lightfade Testing for a Selection of Porous and Swellable Coatings Showing the Greater Reciprocity Factor for Porous Coatings.

Since both porous and swellable media can deliver high gloss and excellent image quality, to showcase the photo permanence properties of the new DeskJet 5550 printing system, swellable coatings were an obvious choice.

The next stage in development was to design a system that maximized the major design criteria. It was known that gelatin polymers generally provided a dye environment that promoted good lightfastness. The problems with gelatin is that it is generally slow drying and tacky, and humidity changes can degrade IQ. The HP media development chemists had developed two new tri-functional polymers to address these issues, a patent pending drytime polymer and a patented IQ polymer. A designed experiment showed that incorporation of these polymers had different effects on the lightfade performance of magenta and yellow. Since yellow was the quickest to fade, an optimum was found whereby lightfade, IQ, and drytime performance was optimized. The next stage in the media development was to design a swellable media system that maximized the major design criteria. It was known through testing in HP labs as well as by others that gelatin polymers generally provide a dye environment that promotes good lightfastness.[12] The problems with gelatins are that they can be generally slow drying and tacky, and humidity changes can degrade the image quality. The HP media chemists developed two new tri-functional polymers to address these issues, a patent pending drytime polymer and a patented IQ boosting polymer. A designed experiment showed that incorporation of these polymers had different effects on the lightfade performance of magenta and yellow. As expected, decreasing the gelatin concentration decreased the light stability for the dyes, especially for magenta. But since yellow was the quickest to fade (due to the protecting effect on magenta shown in Figure 7) yellow became the design driver for the optimization strategy. The results of the study are shown in graphical form in Figure 9. In this experiment, sample 6 was found to have the optimum performance for IQ, drytime, and lightfastness, as well as other performance factors. Graphs and analyses similar to this were used to select the optimal component ratios in the new HP Premium Plus Photo Paper product.

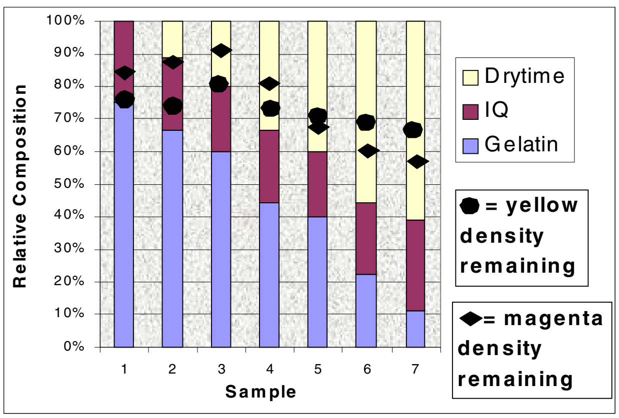
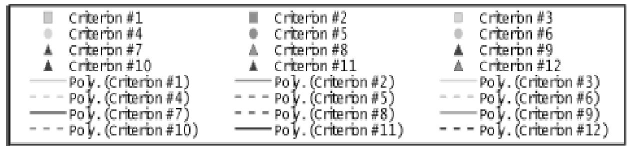


Figure 9. Results of Polymer Ratio Study Whereby Gamut, Drytime, and Gelatin Polymers were Optimized for Yellow Lightfade Performance, IQ, and Drytime.

Results and Conclusions

The DeskJet 5550 printing system was developed to meet the needs of the business printer and the digital photo printer in a single package. To accomplish this, writing system, inks, and media were developed and co-optimized to deliver outstanding IQ whether in CMYK[p] or CMYcmK[d] configuration. More specifically, a 6-ink photo printing system was developed with photo IQ and a predicted lightfastness of 49 years uncovered, 73 years glass protected. This lightfastness performance exceeds that of all traditional silver halide photo prints.[2] The failure mode in both cases was associated with yellow (pure color fade or color imbalance). This is in contrast to many systems where magenta is associated with the failure. The tested failure criteria and key is shown in Figure 9 and corresponds to the kinetic fade charts showing all failure criteria for glass protected and unprotected samples for the first failure criteria (0.6 OD for both conditions) as shown in Figures 10 and 11, respectively.



Criterion	Absolute Density Losses	Criterion	Color Imbalances
#1	Absolute loss of Red (cyan) Density in Neutral Patch	#7	Color Imbalance, R-G
#2	Absolute loss of Green (magenta) Density in Neutral Patch	#8	Color Imbalance, G-R
#3	Absolute loss of Blue (Yellow) Density in Neutral Patch	#9	Color Imbalance, R-B
#4	Blue (yellow) Density Loss, Pure Yellow Patch	#10	Color Imbalance, B-R
#5	Green (magenta) Density Loss, Pure Magenta Patch	#11	Color Imbalance, B-G
#6	Red (cyan) Density Loss, Pure Cyan Patch	#12	Color Imbalance, G-B

Figure 10. Failure Criteria and Criteria Key for Fade Plots in Figures 11 and 12.

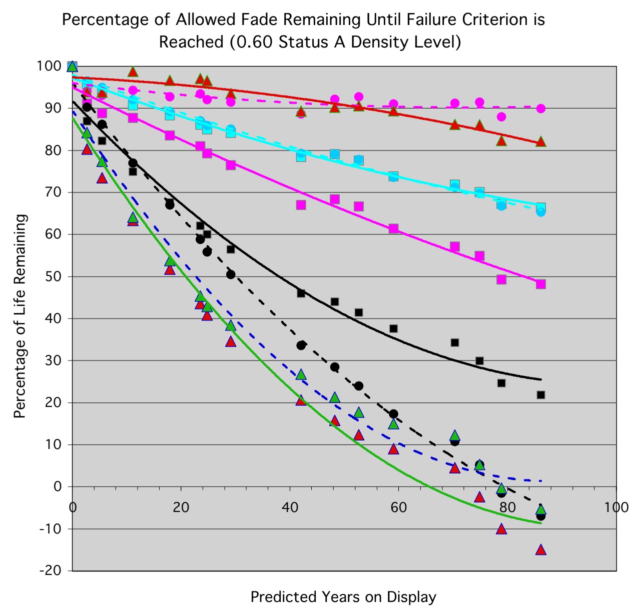


Figure 11. Results of Lightfade Testing for the Glass Protected Condition Performed by Wilhelm Imaging Research Using the HP DeskJet 5550, HP #57 and HP #58 pens, and the new HP Premium Plus Photo Paper Glossy, Showing the First Failure Mode with a Tested Lifetime at 73 years.

As mentioned earlier, a key final test for accelerated lightfastness test is the reciprocity test. In this test, the light exposure intensity is reduced to extrapolate to normal light intensities in order to better predict the accuracy of the accelerating assumptions. While this test is ongoing and after 1 year of equivalent exposure no reciprocity is detected, the full test will take several years due to the extreme lightfade resistance of the new HP system. Previous experience with this type of media that have been tested for longer times indicate that the reciprocity factors are similar to that for traditional silver halide (Figure 13),[13] indicating that the predictive capability of the test makes a good relative comparison to the previous generations of photo reproduction technology. And, as expected, the reciprocity factors for the new HP Premium Plus Photo Paper for unprotected fading are much lower relative to microporous media.

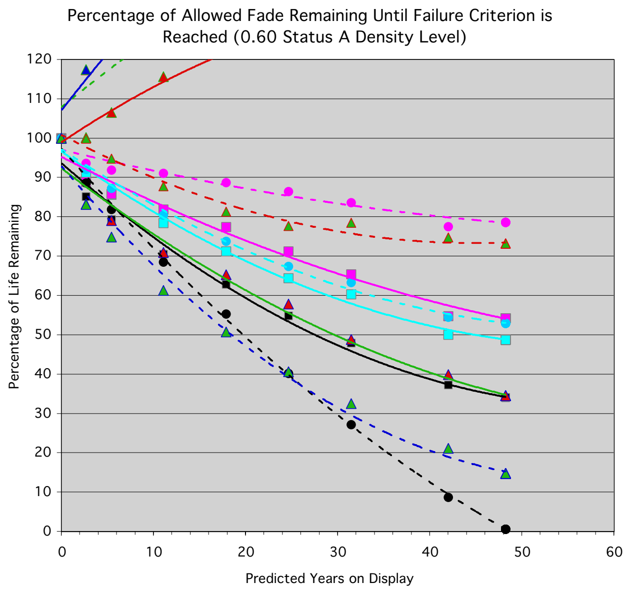


Figure 12. Results of Lightfade Testing for the Unprotected Condition Performed by Wilhelm Imaging Research Using the HP DeskJet 5550, HP #57 and HP #58 pens, and the new HP Premium Plus Photo Paper Glossy, Showing the First Failure Mode with a Tested Lifetime at 49 years.

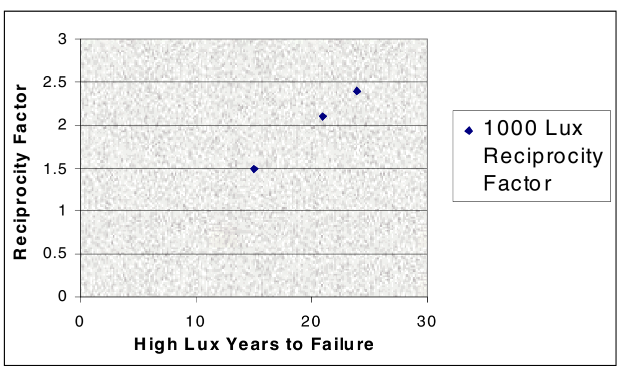


Figure 13. Reciprocity Factor for 1 klux Versus 35 klux Lightfade for a Similar Ink and Media Set to the HP #57 pen and the new HP Premium Plus Photo for Unprotected, Glass with 1" Gap, and Glass Protected Fading Conditions (in Order of Increasing Light Stability).

This lightfastness performance was achieved through selecting dyes and media that achieved superior fade resistance combined with selection criteria to account for fade balance in both color balance (CM, MY, and YC) and tonal scale balance (Mm and Cc). As a result, a superior digital reproduction solution that is also plain paper versatile is available for consumers migrating to digital capture and printing techniques.

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Biography

Eric Burch received his B.A. degree in Chemistry from Grinnell College in Grinnell, IA in 1989 and a Ph.D. in Chemistry from Northwestern University in Evanston, IL in 1994. His academic work focused primarily on photochemical mechanisms in single molecules and polymeric systems. Starting in 1994 he held a post-doctoral position at Oak Ridge National Laboratories working on new materials development and fabrication. Since 1995, he has worked at the Hewlett-Packard Company in San Diego, CA. He currently is a Senior Member of the Technical Staff working on system development of inkjet imaging technologies, focused primarily on media chemistry and printing system interactions.