2. Accelerated Tests for Measuring Light Fading, Dark Fading, and Yellowish Stain Formation in Color Prints and Films

> Prints made on paper currently available will fade, and badly, over a relatively few years. *Not so with color prints made on Konica SR Paper.* The rich color and details in these pictures will show virtually no signs of fading in 100 years. Our advanced emulsion technology enhances dye stability. In fact, accelerated aging tests show that dye images will retain more than 70% of their original density for 100 years or longer under normal album storage conditions.[1]
>
> Konica Corporation advertisement
> in *Professional Photographer,*
> October 1984

The introduction of Konica Color PC Paper Type SR in April 1984 was a landmark in the history of color photography for a number of reasons. Konica Type SR paper, which Konica also calls "Century Print Paper" and "Long Life 100 Paper," was the first of a new generation of color negative papers to have a long-lasting cyan dye (cyan dyes with poor dark fading stability were the weak link in Kodak Ektacolor papers and all of the other chromogenic papers on the market at the time). In addition, the new Konica paper and a companion stabilizer used without a final water wash made possible the now-ubiquitous "washless" minilab, which can be easily installed in any location because no water supply or waste-water drain is required. (Surprisingly, Type SR prints processed with the Konica "washless" stabilizer are even more stable than the same prints given the previously mandatory wash in running water.)

In another important first for the photography industry, Konica's advertisements and technical literature for the new paper included data from predictive accelerated dark fading tests and touted the paper's superior image stability as its principal advantage over color papers made by Kodak, Fuji, Agfa, and 3M. With the introduction of Type SR paper and "washless" processing, Konica focused attention on the permanence issue in a way that had not been done before, and forced the entire photographic industry to accept image stability as a legitimate component of overall product quality.

Recommendations

See Chapter 1 for a comprehensive list of the longest-lasting color films and print materials, based on overall light fading, dark fading, and dark staining performance.

Accelerated light fading and dark fading tests played an essential role in the research and development effort that led to Konica Type SR paper, the outstanding Fujicolor SFA3 color negative papers introduced in 1992, and all other color papers and films on the market today. Konica relied heavily on accelerated image stability tests in its research on "washless" stabilizers for prints and films. How such tests are performed is the subject of this chapter.

Color Image Fading and Staining

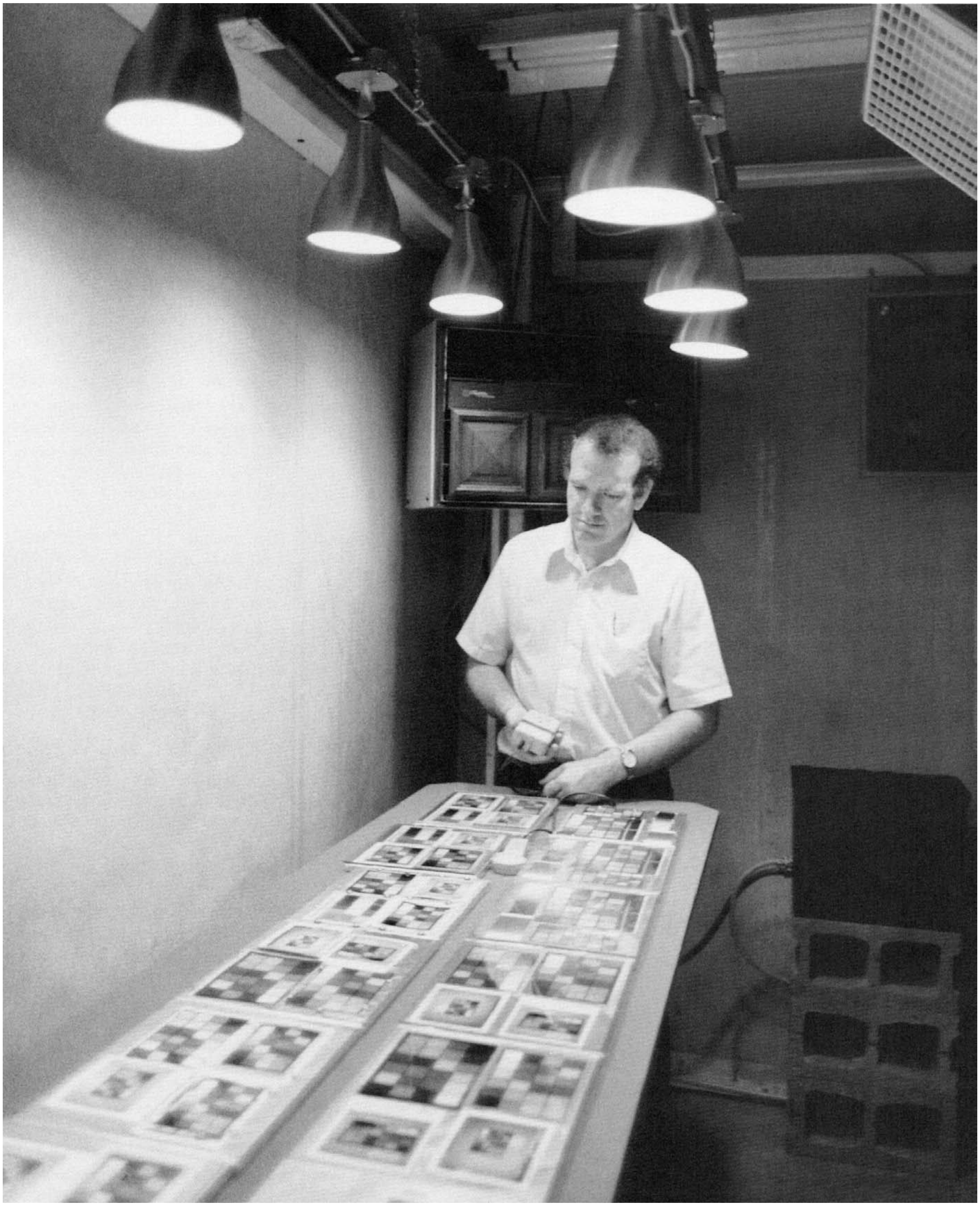
The deterioration over time of color photographic images is characterized by overall loss of dye density; shifts in color balance caused by unequal fading of the cyan, magenta, and yellow dyes that make up the image (in any given color material, the three dyes virtually never fade at the same rate); changes in contrast; loss of detail; and overall staining (almost always yellowish in color).

In addition, color photographs may crack, delaminate, be attacked by fungi and other microorganisms, or suffer from scratches, abrasions, fingerprints, and other physical deterioration. Cracking of RC paper generally is initiated by exposure to light on display and occurs most commonly when an RC print is physically stressed by fluctuating relative humidity. Light-induced cracking frequently is found in RC prints from the late 1960's and the 1970's. Especially in mounted prints, RC paper cracking can be caused by widely fluctuating relative humidity alone (even when the prints are stored in the dark).

Color image deterioration, which stems from the *inherent* instability of the organic dyes (and unreacted dye-forming couplers) employed in most color photographs, can be separated into seven principal categories:

1. **Light fading caused by exposure to light and ultraviolet radiation during display or projection.** Absorption of visible light and UV radiation by the image dye molecules causes them to break down into colorless compounds and/or stain products (usually yellowish). Although it may be possible to chemically restore the silver image in a faded black-and-white photograph, there is no known way to chemically restore the dye image of a color photograph once it has deteriorated.

   The rate of light fading is specific to each type of color print or color film and is a function of the intensity of the illumination and the duration of exposure. With most modern color print materials, the wavelength distribution of the illumination is not nearly as important as the intensity of the illumination. With some materials, high ambient relative humidities can increase the rate of light fading. Light fading is not something that suddenly happens to a print; it is a gradual process that



Carol Brower – August 1983

Accelerated light fading tests provide data for predicting the image life of color print materials displayed under a variety of conditions in homes, offices, and public buildings. Henry Wilhelm is shown here checking the illumination level in a low-level, long-term, 1.35 klux (125 fc) incandescent tungsten test that simulates display conditions in museums and archives. Conducted in a special temperature- and humidity-controlled room in the Preservation Publishing Company research facility, the tests employ forced-air cooling to maintain 75°F (24°C) and 60% RH at the sample plane. These tests, which are believed to constitute the first long-term investigation into the effects of low-level tungsten illumination on color photographs, were started in 1982 and had been in progress for more than 10 years at the time this book went to press in 1992.

begins the moment a print is exposed to light on display. Short of total darkness, there is no minimum light level below which light fading does not occur.

The light fading stability of current materials varies over a wide range, with some materials being *far* more stable than others. For any given product, the cyan, magenta, and yellow image-forming dyes each have different fading characteristics, and this results in progressive changes in color balance as fading proceeds over time.

Most current color print materials, including *all* current color negative papers made by Fuji, Kodak, Konica, and Agfa, have a UV-absorbing emulsion overcoat and, largely for this reason, UV radiation is not a major factor in the fading of these prints when displayed under normal indoor conditions. Instead, it is visible light that is the principal cause of image deterioration. Some products, however, including Kodak Ektatherm thermal dye transfer color print paper used with Kodak's XL 7700-series digital printers, do not have a UV-absorbing overcoat and fade much more rapidly when significant UV radiation is present.

2. **Light-induced yellowish stain formation.** In most kinds of color prints and transparencies, dye fading is accompanied by formation of low-level yellowish stain, which is most readily apparent in the highlight areas of the image. For most current products, light-induced staining is a relatively minor problem compared with the fading of the cyan, magenta, and yellow image dyes themselves.

3. **Dye fading that occurs in dark storage.** Dark fading stability also is specific to each type of color film and print material; some products are much more stable than others. The cyan, magenta, and yellow dyes in a given material usually have significantly different rates of dark fading and, as fading progresses over time, this results in an ever-increasing change in color balance. For a given material, the rate of dark fading is a function of temperature and, usually to a lesser extent, relative humidity. (Unlike the case with black-and-white materials, pollution is generally not a major factor in color film and print fading.) Dark fading is a slow but inexorable process that begins the moment a color film or print material emerges from the processor.

   Dark fading and light fading are entirely separate phenomena. In Kodak Ektacolor paper, for example, magenta is the most stable of the three image dyes in dark storage, but it is generally the *least* stable when exposed to light. Dark fading proceeds in combination with light fading when prints are displayed.

4. **Dark-storage yellowish stain formation.** With Ektacolor paper and most other modern chromogenic print materials, yellowish stain that forms over time during dark storage is likely to be a more serious problem than is the fading of image dyes in the dark. Progress is being made, however, and current Fuji color papers, including Fujicolor Paper Super FA Type 3, Fujicolor Professional Paper SFA3 Type C and Type P, and Fujichrome Paper Type 35, employ recently developed low-stain magenta couplers that have sharply reduced the rate of yellowish stain formation in dark storage for these products. Konica Color QA Paper Type A5, introduced on a limited scale in Japan in 1990, also employs a new type of low-stain magenta coupler.

   Some non-chromogenic materials that employ preformed image dyes, including Ilford Ilfochrome (called Ilford Cibachrome, 1963–91), Kodak Dye Transfer, and Fuji Dyecolor, are, for most practical purposes, permanent in the dark and exhibit no significant fading or staining even after prolonged storage under adverse conditions. Although almost all types of color photographs suffer from light fading, it is generally true that only chromogenic materials are subject to inadequate dye stability and excessive yellowish stain formation in dark storage.

   When color prints made on *current* materials are displayed under typical conditions in a home or office, light is almost always the most significant factor in the fading and staining that occur over time, with dark fading and staining making a much smaller contribution to overall image deterioration.

5. **Choice of processing method.** Whether a material is processed in the "washless" mode with a stabilizer as the final bath, or is processed with a water wash, can make a significant difference in the rate of yellowish stain formation in dark storage and also, usually to a lesser extent, in the rate of dye fading. To give one example, Konica Color Paper Type SR has a much lower rate of stain formation along with somewhat better dark storage dye stability when processed in the "washless" mode with EP-2 chemicals and Konica Super Stabilizer (most minilabs now employ "washless" processing) than it does when the same paper is processed with EP-2 chemicals and a water wash (a water wash is standard practice in commercial labs and in large-scale photofinishing labs).

   Both types of processing are considered "normal," and both are common throughout the world. But because the differences in the rates of stain formation are so great with Konica Type SR paper, separate stability data must be reported for each type of processing. Increased rates of fading may also result from the use of "non-standard" processing chemicals (e.g., the substitution of color developing agent CD-4 for the recommended CD-3 in the KIS Ultra-X-Press minilab color print process to shorten processing time of Ektacolor paper greatly reduces the paper's light fading and dark fading stability).

6. **Processing shortcomings.** Regardless of the processing method selected, decreased dye stability and/or higher stain levels may be expected with improperly replenished or contaminated processing chemicals, omission of the recommended stabilizer bath from the C-41 and E-6 processes, inadequate washing, etc. Such processing faults can adversely affect image stability — sometimes catastrophically — when materials are kept in the dark and/or are exposed to light.

7. **Image fading, staining, and physical deterioration caused or exacerbated by postprocessing treatments.** Light fading stability and/or dark storage stability may be adversely affected by application of print lacquers (see Chapter 4), retouching colors, print "texturizing" treatments, high-pressure canvas mounting, and other postprocessing treatments. In most cases, the stability of a color print is at its best if no postprocessing treatments are applied.

The Need for Accelerated Tests

In most applications (projected color slides and photographs displayed outdoors in direct sunlight are notable exceptions), modern color materials fade and stain too slowly to evaluate their stability characteristics within a reasonable time under the non-accelerated conditions of normal display and storage. With most current materials, many years or decades of "natural aging" would be required before meaningful data could be obtained, and by that time the information would be of little value to most people.

Photographers, photofinishers, color labs, and other consumers need to know the stability characteristics of a color material *before* they buy it in order to select the most stable material available that otherwise meets their needs. Indeed, the primary concern of most photographers is the film or paper they are using at the moment or are contemplating using in the near future. Nothing can be done to improve the inherent stability characteristics of color photographs already taken (although knowledge about the stability characteristics of older materials is valuable in attempting to provide proper storage conditions).

As a fundamental part of research and development, manufacturers of color materials have a constant need to evaluate quickly the stability of new dyes and emulsion additives that may be included in future film and print materials. Any change or improvement in processing procedures must be evaluated in terms of its effect on image stability before being introduced into the marketplace.

In the years before 1980, Kodak and the other manufacturers of color materials generally conducted image stability tests only for internal product development and were careful to keep the information secret from the public. More recently, stability-related claims have become commonplace in advertising new products and in technical literature (especially for color papers). Obviously, if such claims are to be made, reliable stability data must already be in hand before new products are introduced.

Types of Accelerated Stability Tests

Various accelerated tests have been devised that attempt to simulate in only weeks or months the fading and staining that will occur during many years of normal display and storage. High-intensity light fading tests expose a print to light that is many times brighter than normal indoor illumination levels, and high-temperature dark fading tests, usually with controlled relative humidity, speed up the fading and staining that would gradually take place during many years of storage in the dark at normal temperatures.

Current accelerated fading tests treat light fading and dark fading separately. Although data from both types of tests can be correlated to try to predict their combined effects during very long-term display under low-level lighting conditions, such correlation can be difficult. This was especially true with older chromogenic materials, such as Ektacolor 74 RC paper (1977–85), that had relatively poor dark fading stability. With these products, dark fading could make a significant contribution to the total fading occurring in displayed prints.

With current print materials that have better dark fading stability, most of the fading that takes place during long-term display will be caused by light, thereby simplifying stability predictions. With Ilford Ilfochrome (called Ilford Cibachrome, 1963–91), Kodak Dye Transfer, and Fuji Dyecolor, all of which have preformed dyes that are exceedingly stable in dark storage, essentially all the image deterioration observed during long-term display can be attributed to the effects of light.

UltraStable Permanent Color prints and Polaroid Permanent-Color prints, both of which employ extremely stable color pigments in place of the organic dyes found in other color materials, are a special case. The pigment images are so stable that in a practical sense they do not fade or stain during prolonged display or when kept in the dark. The white polyester base of UltraStable and Polaroid Permanent-Color prints is also extremely long-lasting. Thus, the stability of the gelatin carrying the pigments — rather than the pigments themselves — will probably determine the eventual life of these prints. With such extraordinarily stable color photographs, even highly accelerated light fading tests must continue for many years before meaningful image-life predictions can be obtained.

Comparative Tests and Predictive Tests

Accelerated light fading and dark fading tests fall into two broad categories:

Comparative tests compare the stability of one product with another under accelerated conditions but do not attempt to indicate how long it will take (e.g., in years) for a certain degree of fading or staining to occur during display or dark storage under normal conditions.

Predictive tests attempt to predict the number of months or years of display or dark storage under normal conditions (or other specified temperatures and relative humidities) that a product will last before a specified amount of fading or staining occurs. The predictions obtained from such tests can of course also be used to compare one product with another.

Because of reciprocity failures in high-intensity accelerated light fading tests, and because the temperature dependence of the fading may vary with different dyes, predictive tests may not be reliable when based on a single accelerated test condition. For this reason, predictive tests necessarily are more complex than comparative tests, and if predictive tests are to have validity, predictions made with representative products must be verified with data obtained under normal display and storage conditions. To accumulate such "natural aging" data, however, generally takes many years.


November 1985

American National Standards Institute Subcommittee IT9-3 worked for nearly 12 years to complete **ANSI IT9.9-1990, American National Standard for Imaging Media – Stability of Color Photographic Images – Methods for Measuring.** The subcommittee is shown here meeting in Grinnell, Iowa, in November 1985 in a room provided by Grinnell College.

American National Standards Institute (ANSI) 1969 Standard for Color Stability Tests

The first ANSI standard for color stability test methods, *ANSI PH1.42-1969, American National Standard Method for Comparing the Color Stabilities of Photographs,*[2] was published in 1969. It was based on work done at Kodak during the 1950's and 1960's and described a single-temperature comparative dark fading test and several comparative light fading tests for color film and print materials.

ANSI PH1.42-1969 never achieved wide application and during the 1980's it was more or less abandoned by Kodak, other manufacturers, independent labs, and this author, all of whom developed improved image stability tests to meet their own requirements. Over time the methods of reporting data also evolved along different lines at each of the manufacturers and the few independent labs conducting stability tests, with the result that it has often been difficult if not impossible to compare data from one manufacturer or independent lab with another.

The New ANSI IT9.9-1990 Color Stability Accelerated Test Methods Standard

In 1991, *ANSI PH1.42-1969* was replaced by *ANSI IT9.9-1990, American National Standard for Imaging Media – Stability of Color Photographic Images – Methods for Measuring.*[3] This new Standard, which received final approval by ANSI in 1990, specifies a predictive Arrhenius test for dark storage stability and five comparative tests for light fading stability.

For the predictive dark storage test, the new Standard specifies a complex, multi-temperature, controlled-humidity Arrhenius test that provides a much more complete assessment of dark storage changes and can yield a prediction, in years, of how long it will take for a specified density loss, color balance shift, or stain level to occur at any selected temperature, including, of course, "normal room temperature." As with the single-temperature tests in *ANSI PH1.42-1969*, data from Arrhenius tests can be used to rank the stability of various products.

Neither the old nor the new Standard specifies limits of acceptability for dye fading, color balance shift, or stain formation. Although the new Standard makes use of a set of limits (called "image-life end points" in the Standard) for illustrative purposes, the values given are *not* part of the Standard, and this is clearly stated in the document. Determining a set of limits for a particular application (e.g., professional portrait and wedding photography, amateur snapshot photography, fine art photography in museum collections, or commercial display in stores, airports, and other public areas) is left entirely to the user.

For several reasons, this is not a very satisfactory situation. With no agreement as to how much fading, color balance change, and staining can be tolerated in common applications, different people using the Standard likely will come up with highly divergent image-life predictions for a particular product stored or displayed in exactly the same

December 1978

Subcommittee IT9-3 has gathered every 6 months since the first meeting, which took place at the National Geographic Society in Washington, D.C. in December 1978. With the new IT9.9-1990 Standard approved by ANSI, the group continues to meet to work on the next revision of the Standard. Shown here is Howell Hammond of Eastman Kodak, the first chairperson of the subcommittee, leading a meeting at the National Geographic Society. Meeting at various locations in the U.S. and Canada, the group has often had opportunities to visit museum and archive collections.

way. This will make it difficult to compare product stability data from different testing labs, and could result in confusion for everyone.

Furthermore, because of marketing considerations, manufacturers will tend to select liberal limits for their published image-life predictions to make it appear that their products have a very long display and storage life. For competitive reasons, a manufacturer of a color paper that develops high levels of yellowish stain over time, for example, likely will select a much higher limit for d-min stain than will a manufacturer with a more stable product that does not have a serious staining problem.

Despite the lack of specific fading and staining limits, the Standard *does* specify a common format for reporting data and requires that the values chosen by the user for all fading, color balance change, and staining limits be listed. This is a significant advance and should result in a great deal more image stability data being disclosed for color films and papers than has been the case.

The new Standard is the result of almost 12 years of work by a task group with the following members:

Peter Z. Adelstein – Image Permanence Institute
John H. Auer – Agfa Corporation
Charleton C. Bard – Eastman Kodak Company
Ronald Cieciuch – Polaroid Corporation
Milton Ford – National Geographic Society
Remon Hagen – Ilford AG [Switzerland]
Howell Hammond (Chairperson) – Eastman Kodak Company
Klaus B. Hendriks – National Archives of Canada
Donald R. Hotchkiss – 3M Company
Thomas J. Huttemann – Eastman Kodak Company
Martin Idelson – Polaroid Corporation
Haruhiko Iwano – Fuji Photo Film Co., Ltd. [Japan]
Junichi Kohno – Konica Corporation [Japan]
David F. Kopperl – Eastman Kodak Company
Peter Krause – Ilford Photo Corporation
Shinichi Nakamura – Konica Corporation [Japan]
Eugene Ostroff – Smithsonian Institution
A. Tulsi Ram – Eastman Kodak Company
James M. Reilly – Image Permanence Institute
Rudolf Tromnau – Agfa-Gevaert AG [Germany]
James H. Trott – National Geographic Society
Henry G. Wilhelm (Secretary) – Preservation Publishing Company
Richard Youso – National Archives and Records Administration

With Howell Hammond of Eastman Kodak serving as chairperson, the first meeting of the task group took place at the National Geographic Society in Washington, D.C. in December 1978, and the group has met twice a year ever since. This author joined the task group at its inception in 1978 and has served as its secretary since 1985.

The final draft of the new Standard was approved by the

ANSI Board of Standards Review in August 1990, and the Standard was published in November 1991.

Even after completion and publication of *IT9.9-1990,* the ANSI task group (now called ANSI Subcommittee IT9-3) continues to meet every 6 months and is working on the next revision of the Standard. Some of the original subcommittee members have since retired or have been transferred by their employers to other responsibilities; at the time this book went to press in late 1992, ANSI Subcommittee IT9-3 consisted of the following individuals:

Peter Z. Adelstein – Image Permanence Institute
Donald R. Allred – Iris Graphics, Inc. (Scitex Corp.)
John H. Auer – Agfa Corporation
Thomas Craig – National Geographic Society
Ronald Cieciuch – Polaroid Corporation
Edgar Draber – Agfa-Gevaert AG [Germany]
Walter Fontani – 3M Company
David J. Giacherio – Eastman Kodak Company
Remon Hagen – Ilford AG [Switzerland]
Klaus B. Hendriks – National Archives of Canada
Haruhiko Iwano – Fuji Photo Film Co., Ltd. [Japan]
Junichi Kohno – Konica Corporation [Japan]
Masato Koike – Dai Nippon Printing Co., Ltd. [Japan]
David F. Kopperl – Eastman Kodak Company
Peter Krause – Ilford Photo Corporation
Robert E. McComb – Library of Congress
Mark McCormick-Goodhart – Smithsonian Institution
Mark Ormsby – National Archives and Records Administration
Eugene Ostroff – Smithsonian Institution
Steven Puglia – National Archives and Records Administration
A. Tulsi Ram – Eastman Kodak Company
James M. Reilly – Image Permanence Institute
Charles H. Schallhorn (Chairperson) – Eastman Kodak Company
Idalee Tierney – Eastman Kodak Company
Sarah Wagner – National Archives and Records Administration
James H. Wallace, Jr. – Smithsonian Institution
Henry G. Wilhelm (Secretary) – Preservation Publishing Company

With members from the U.S., Japan, Germany, Canada, and Switzerland, this was the first ANSI photographic task group to have a truly international representation.

In 1993 the new ANSI Standard will, with some modification, be issued as an ISO International Standard (published by the International Organization for Standardization, a worldwide federation of national standards institutes headquartered in Geneva, Switzerland).

Accelerated Light Fading Tests

By using light levels that are much more intense than those encountered in normal display conditions, accelerated light fading tests attempt to simulate in a short time the effects of light on prints during long-term display. For example, for a given amount of fading, a print displayed in normal indoor lighting conditions should last 20 times longer than a print subjected to an accelerated test under a light level 20 times more intense. In other words, according to the "reciprocity law" on which accelerated light fading tests are based, the total amount of radiant energy (intensity x time) to which a print is exposed should determine the amount of fading. This concept is similar to doubling a camera shutter speed (from $\frac{1}{250}$ to $\frac{1}{500}$ second, for example) and opening up the lens aperture one *f*-stop (from *f* 8 to *f* 5.6): the exposure of the film is the same.

Comparative accelerated light fading tests have been used extensively by Fuji, Kodak, Konica, Agfa, and Polaroid, and five such tests are described in *ANSI IT9.9-1990.*

Reciprocity Failures in Light Fading and Light-Induced Stain Formation

Since the mid-1970's, one of this author's principal interests has been the relationship of fading and light-induced stain formation in high-intensity accelerated tests with the fading and staining that occurs in color prints exposed to much lower light intensities for correspondingly longer periods of time — that is, the validity of the light-fading reciprocity law.[4] An understanding of the relationship between high- and low-intensity fading and staining behavior is crucial if the data obtained in high-intensity tests are to be relevant for predicting the fading and staining rates of prints on long-term display in homes, offices, and museums.

This author's investigations have shown that most color materials exhibit at least some "reciprocity failure" in light fading or light-induced stain formation in high-intensity, short-term tests. That is, a color print or transparency material may fade or stain a different amount when exposed to high-intensity illumination for a short period than it does when exposed to lower-intensity illumination for a longer period — even though the total lux-hour light exposure (intensity x time) and the temperature and relative humidity are the same in both cases. Color slides also are subject to reciprocity failures in accelerated projection tests. As discussed in Chapter 6, intermittent projection can produce much more fading than continuous projection for the same total illumination time. The duration of each projection and the interval between projections are important variables; some color slide films exhibit much larger reciprocity failures than others.

ANSI IT9.9-1990 specifies a predictive Arrhenius test for dark storage stability, discussed later, but offers only single-intensity comparative tests for light fading stability. Because of the uncertainties posed by reciprocity failures in high-intensity, short-term tests, the Standard does not permit extrapolation of accelerated test data for making "years of display" predictions under normal home or office display conditions.

Predictive "years of display" estimates of light fading stability have in the past been published only infrequently, although Fuji has been publishing "years of display" estimates for Fujichrome Type 34 and Type 35 reversal papers since 1987 and, more recently, for Fujicolor Super FA papers.[5] These predictions are based on single-intensity accelerated tests. In 1988, Ilford[6] and, to a much more limited extent, Kodak[7] also started publishing single-intensity light fading data in the form of predictive "years of display" estimates.

Carol Brower – August 1983

The low-level, long-term, 1.35 klux fluorescent illumination test facility at Preservation Publishing Company. Tests here began in 1977 and had continued for more than 15 years at the time this book went to press in 1992. Data from these tests are compared with data from short-term, high-intensity fluorescent tests to investigate light fading and light-induced staining reciprocity failures in color print materials. Identical samples of each print material are exposed to bare-bulb illumination uncovered, covered with glass sheets, and covered with Plexiglas UF-3, a sharp-cutting UV filter. Maintained at 75°F (24°C) and 60% RH, and with the same illumination intensity as is used in the 1.35 klux tungsten test, the samples allow a direct comparison to be made between the long-term effects on color prints of the two types of illumination.

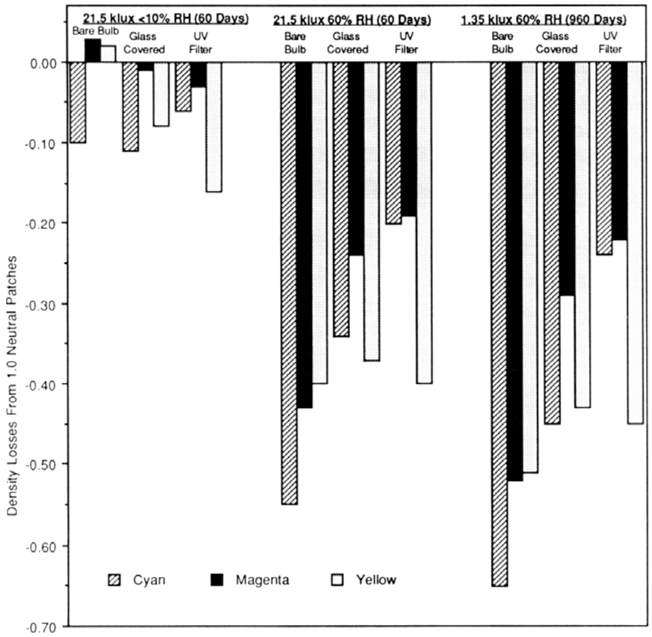


Figure 2.1 Humidity effects, spectral dependence, and reciprocity failures in the fading of Polacolor ER instant color prints. The prints received the same total klux-hour light exposure under the three test conditions. When the moisture content of the prints was very low because of heating by the nearby fluorescent lamps in the high-intensity 21.5 klux test, the fading was markedly reduced compared with the 21.5 klux temperature- and humidity-controlled test where the relative humidity at the sample plane was maintained at 60%. In low-intensity 1.35 klux tests, the fading of all three dyes increased somewhat further because of reciprocity failures.

This book marks the first comprehensive effort — even if not always conclusive — to treat accelerated light fading data in a predictive manner when dealing with color print and color slide materials. That such image-life predictions could even be attempted was made possible by the availability of a sizable amount of data from long-term, low-intensity 1.35 klux tests that could be compared with high-intensity 21.5 klux data for representative products.

Early Evidence of Reciprocity Failures in Accelerated Tests with Color Prints

In 1976–77, when this author's initial light fading tests on prints were in progress, several apparent discrepancies were noted between outdoor tests in direct sunlight and much lower intensity indoor tests with fluorescent lamps. These early tests were conducted on Kodak Ektacolor 37 RC, Polaroid Polacolor 2, Kodak Instant Print Film PR-10 and Polaroid SX-70 prints. The Polacolor 2 prints appeared to be relatively more stable than Ektacolor 37 RC prints in direct sunlight tests than they were when framed and hung on this author's office wall (the Polacolor 2 prints were overmatted and, when the overmat was lifted, visual evidence of image fading was apparent much sooner than with the Ektacolor prints).

Since the most obvious differences between these two test conditions were spectral energy distribution and light intensity, the influence of both of these variables was investigated. In the initial phase of the work, a densitometer was not available and this author was forced to rely on visual analysis by comparing faded prints with identical unfaded prints.

After the discovery that placing a sheet of ordinary glass over an Ektacolor 37 RC print exposed to sunlight or (more significantly) fluorescent light substantially improved the print's cyan dye stability, the work was expanded to include print samples covered with both glass and Plexiglas UF-3 ultraviolet-absorbing acrylic sheet. At that time, this author did not have temperature- and humidity-controlled high-intensity test equipment; consequently, the crucial importance of moisture in the light fading of Polacolor 2 was not fully appreciated (emulsion moisture content proved to be relatively unimportant with Ektacolor and most other chromogenic papers insofar as light fading is concerned). Much of what this author initially attributed to "light fading reciprocity failure" was in fact caused by the low moisture content of the Polacolor 2 prints that resulted from heating by the intense infrared and visible light of direct, outdoor sunlight.

Nonetheless, these early findings, even if misleading, did prompt this author to begin a systematic investigation of the separate roles of light intensity, wavelength distribution, time, emulsion moisture content, and sample temperature. The results of these investigations for one print material, Polacolor ER, are shown in **Figure 2.1** (Polacolor ER is an updated, lower-contrast version of Polacolor 2 and gives somewhat improved color and tone-scale reproduction. With respect to **Figure 2.1**, the older Polacolor 2 product has generally similar light fading behavior).

Comparisons of light fading data from a variety of color print materials covered with glass and Plexiglas UF-3 ultraviolet-absorbing acrylic sheet clearly showed that with Ektacolor and most other types of color print materials displayed in normal indoor conditions, visible light was a much more important factor in light fading than was UV radiation, contrary to what had been suggested in some of the literature.

Reciprocity Failures in Accelerated Light Fading Tests Can Lead to Faulty Assessments of Image Stability

This author's research indicates that with nearly every type of color print, high-intensity light fading tests (e.g., at 21.5 klux) can be expected to produce *less* overall fading, and *less* yellowish stain, than the equivalent light exposure spread out over the months and years of normal display (**Table 2.1**). And because each of the cyan, magenta, and yellow image dyes in a given type of print has a specific response to high-intensity light, not only is the overall amount of fading usually greater in long-term display, but the relative amount of fading of each dye is also unequal; with most color papers, this results in a different degree of image color balance change (**Figures 2.2 and 2.3**). In extreme cases, even the direction of color balance change can be altered.

Some types of prints exhibit much greater "reciprocity failure" — differences in fading and staining in tests with

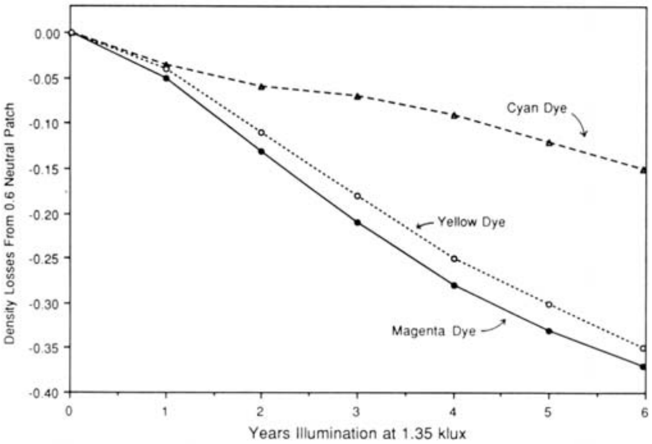


Figure 2.2 Light fading of Kodak Ektacolor Plus Paper over a 6-year period in a 1.35 klux fluorescent test (print covered with glass). In this moderately accelerated test, the yellow dye faded much more rapidly than it did in a high-intensity 21.5 klux test with the same total light exposure, resulting in a different and visually more severe color balance shift toward cyan (also see **Figure 2.3**).

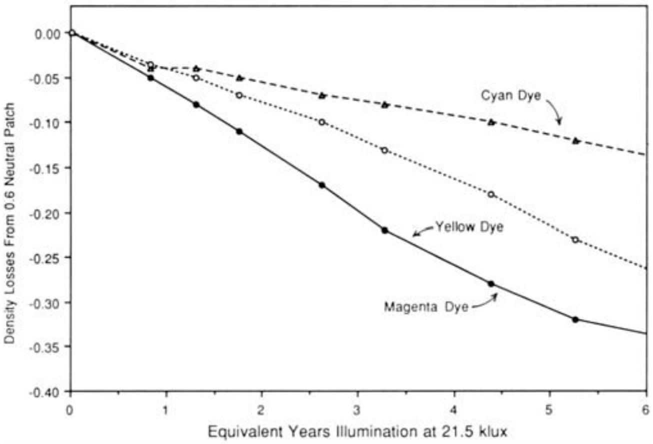


Figure 2.3 Light fading of Kodak Ektacolor Plus Paper in a high-intensity 21.5 klux test. Although the test time was much shorter, the total klux-hour light exposure was the same as in adjacent **Figure 2.2**. The yellow dye suffered a significant reciprocity failure in the 21.5 klux test, producing a markedly different color balance change than in the long-term 1.35 klux test.

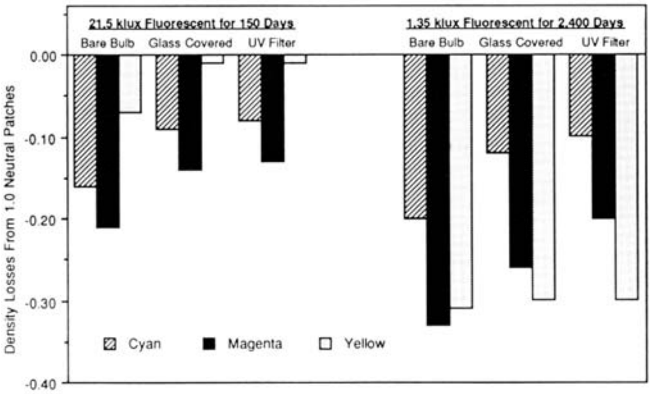


Figure 2.4 Ilford Cibachrome (Ilfochrome) prints exhibit large reciprocity failures in light fading; the effect is most pronounced with the yellow dye, which faded far more in the long-term, low-level 1.35 klux test than it did in a much shorter high-intensity 21.5 klux test. The Cibachrome cyan dye was greatly affected by the strong 313 nm UV emission of the fluorescent lamps while the fading of the yellow dye showed little spectral dependence in the 1.35 klux test.

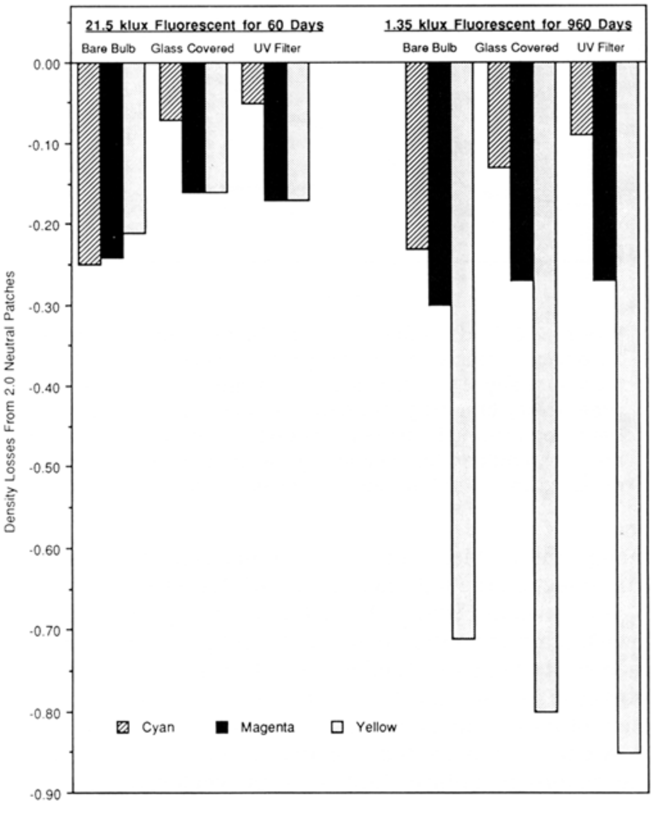


Figure 2.5 Some chromogenic papers have large reciprocity failures. The yellow dye in Agfacolor Type 589 paper (1981–83) faded far more in long-term, low-level 1.35 klux tests than it did in high-intensity 21.5 klux tests. Interestingly, the print shielded from UV radiation with a Plexiglas UF-3 filter exhibited more yellow dye fading than the print exposed to bare-bulb illumination.

high-intensity light — than others. Ilford Ilfochrome (Cibachrome) prints fade significantly faster when exposed to the same amount of light in long-term, low-intensity tests than in shorter, high-intensity tests. The Ilfochrome yellow dye in particular exhibits markedly different behavior in the two test conditions, with far greater fading taking place in the long-term, low-intensity test (**Figure 2.4**).

Although there are exceptions (e.g., the now-obsolete Agfacolor Type 589 color paper, as shown in **Figure 2.5**), the cyan, magenta, and yellow dyes in chromogenic prints such as Ektacolor, Fujicolor, Konica Color, and Agfacolor typically exhibit much less of a reciprocity failure, and Kodak Dye Transfer prints show this effect hardly at all (al-

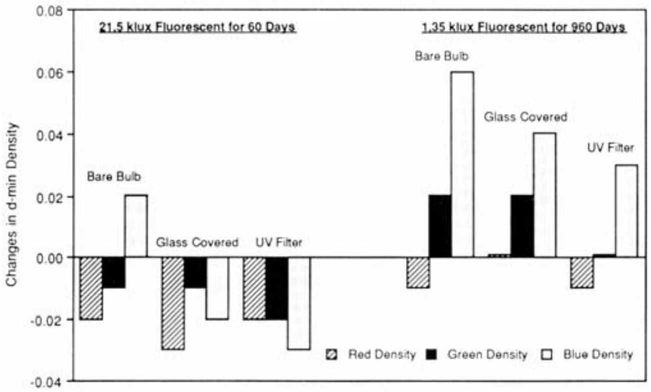


Figure 2.6 The yellowish stain level of Kodak Ektacolor 74 RC paper (initial type, 1977–82) was significantly higher in the 1.35 klux test, although with this product, as well as with most other color negative papers, the magenta dye fading that occurred during the test was visually much more objectionable than the yellowish stain.

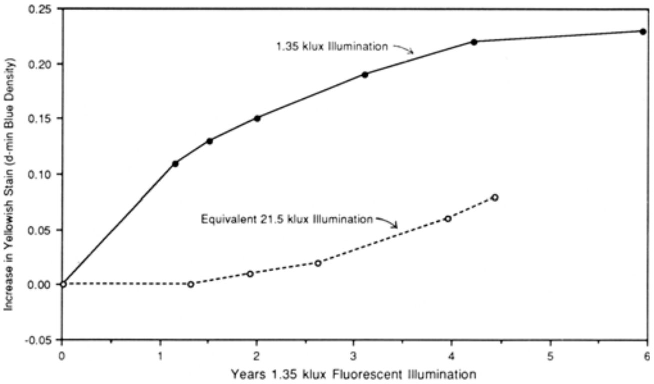


Figure 2.7 In every chromogenic paper studied by this author, higher levels of d-min yellowish stain occurred in 1.35 klux illumination than in short-term 21.5 klux illumination (with the same total light exposure in both cases). As shown in this graph, Agfacolor Type 7i paper (1984–85) suffered a dramatic increase in yellowish stain level in the low-level test.

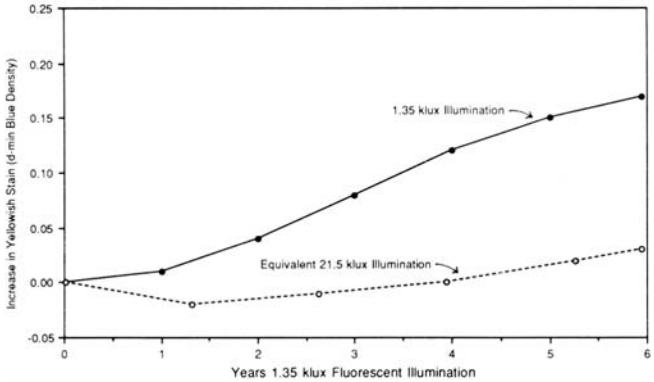


Figure 2.8 Kodak Ektacolor Plus Paper (1984—) suffered a significant yellowish stain reciprocity failure in this author's high-intensity 21.5 klux test. To a greater or lesser degree, every chromogenic paper studied exhibited similar behavior, leading to the conclusion that high-intensity tests are meaningless for evaluating the tendency for a color paper to form light-induced yellowish stain.

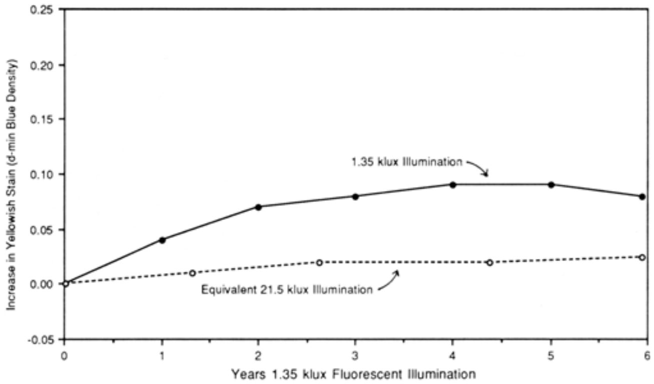


Figure 2.9 Although Konica Color Paper Type SR (1984—) exhibited significant yellowish stain formation reciprocity failure, the magnitude of the failure was less than that of any other color negative papers tested. These samples were given normal EP-2 processing with a water wash.

though the ambient relative humidity can have a significant effect on the light fading rate of Dye Transfer prints).

As shown in **Figures 2.6, 2.7,** and **2.8**, light-induced yellowish stain formation can also be subject to pronounced reciprocity failures. Konica Color Paper Type SR is noteworthy in its low staining reciprocity failure compared with most other chromogenic papers (**Figure 2.9**).

A generally accepted explanation for at least some of the reciprocity failures that occur in accelerated light fading of color prints is that atmospheric oxygen is involved in the dye fading mechanisms, and during high-intensity light fading, oxygen may be depleted, to a greater or lesser extent, at the sites of the image dye molecules, resulting in a slowing of photochemical reactions. Oxygen availability may be further hindered by low humidity, which sharply reduces the permeability of gelatin to atmospheric oxygen. The dependence of the light fading of chromogenic yellow and magenta dyes on oxygen availability was suggested by Robert Tuite of Eastman Kodak in 1979[8] and was further investigated by Yoshio Seoka *et al.*[9] and Toshiaki Aono *et al.* of Fuji in 1982.[10]

The slow diffusion of deterioration by-products *out* of the gelatin emulsion may also be a factor in light fading and light-induced staining reciprocity failures.

As there is a need to know — at least in an approximate way — the stability characteristics of color materials in order to select the most stable product otherwise suitable for the intended application, the use of short-term accelerated light fading tests is unavoidable. As long as the potential shortcomings of the tests are known and the behavior of different types of materials in long-term tests with low-level illumination is understood, high-intensity tests can provide a great deal of information. The tests also offer guidance concerning permissible display times, the possible benefit to be gained by UV filters, and the potential influence of relative humidity on light fading stability.

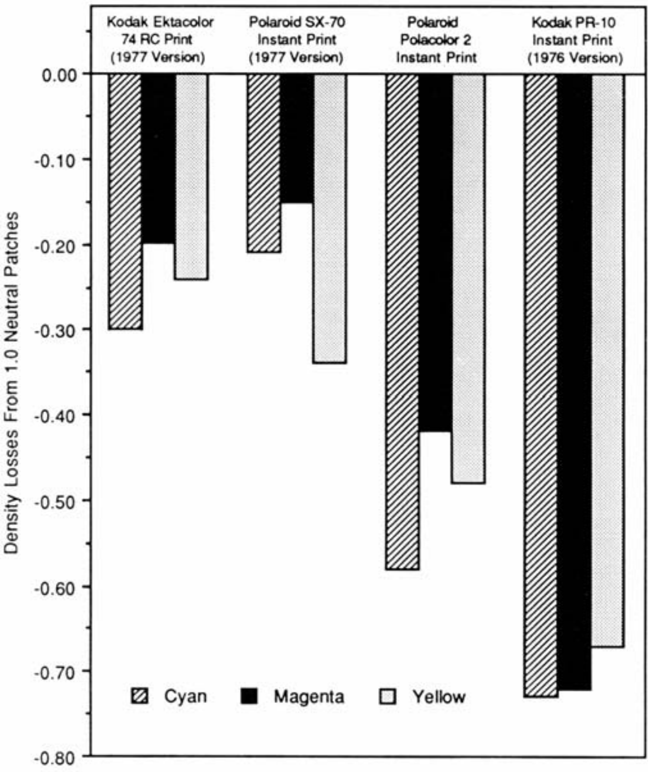


Figure 2.10 The fading that occurred in four types of color prints after 8 years of display in this author's kitchen (prints exposed to indirect daylight and bare-bulb fluorescent illumination) was similar to that which occurred in 1.35 klux tests.

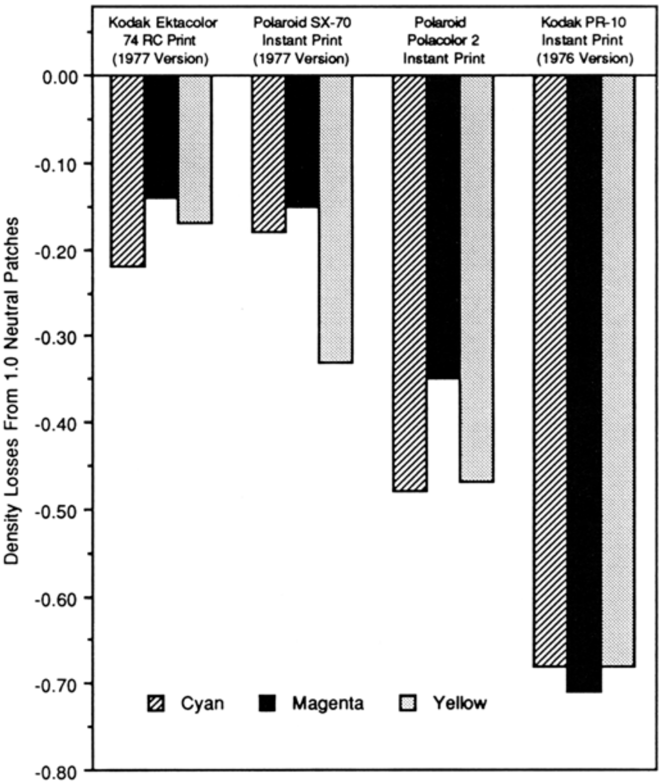


Figure 2.11 After 8 years of display in a bedroom (indirect daylight and low-level tungsten illumination) in this author's home, the four types of color prints showed a fading pattern similar to that which occurred in the kitchen.

Correlation of Accelerated Test Results with Fading and Staining That Occur in Normal, Long-Term Display Conditions

It is critically important for persons involved in image stability testing to periodically study the fading and staining behavior of both framed and unframed prints in long-term display under normal conditions (**Figures 2.10**, **2.11**, and **2.12**) and to attempt to relate this information with results from accelerated fading tests. If fading and/or staining patterns (e.g., the direction and degree of color balance change, level of stain formation, etc.) are significantly different, the accelerated test procedures must be called into question and efforts must be made to improve the tests.

For those working in the image stability field, accelerated tests can take on a life of their own, and a conscious effort is required to keep informed about what is actually happening to color photographs in storage and on display in homes, offices, and institutions around the world.

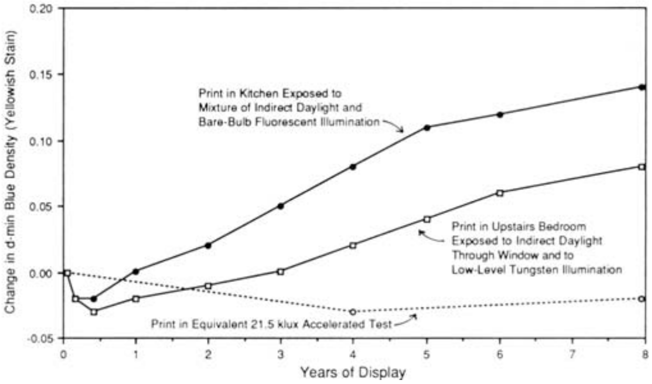


Figure 2.12 During 8 years of home display, Ektacolor 74 RC prints (initial type, 1977–82) exhibited significantly greater d-min yellowish stain levels than they did in equivalent 21.5 klux tests. The higher stain level in the print displayed in the kitchen can probably be attributed to two factors: exposure to airborne contamination from food cooking on the kitchen stove and the bare-bulb fluorescent illumination in the room.

RC Base-Associated Image Fading and Yellowish Staining

This author's investigations indicate that in addition to fading caused by the effects of light on the image dyes themselves, displayed color prints made on RC (polyethylene-resin-coated) papers may suffer from direct or indirect chemical attack of the image dyes, the results of which can render them more susceptible to light fading and/or cause greatly increased rates of dark fading and staining. Research on this phenomenon is continuing, but the evidence obtained to date suggests that this degradation of dye stability and the increased rates of yellowish stain for-

(continued on page 75)

Table 2.1 Reciprocity Failures in Accelerated Light Fading and Light-Induced Staining of Color Prints

Accelerated light fading tests at 21.5 klux (2,000 fc) and 1.35 klux (125 fc) with prints given the same total light exposure (intensity x time) in both conditions. Glass-filtered Cool White fluorescent illumination at 75˚F (24˚C) and 60% RH. Initial densities of 1.0 with full d-min corrected densitometry.

Test duration of up to 8 years (2,920 days)

Light Fading Reciprocity Failure Factor (RF Factor) is a numerical representation of the difference in fading rate between 21.5 klux high-intensity and 1.35 klux low-intensity test conditions; the RF Factor is computed by dividing the density loss at 1.35 klux by the density loss at 21.5 klux. An RF Factor of 1.0 indicates that the particular dye suffered no measurable reciprocity failure; that is, the dye faded the same amount in both the high-intensity and low-intensity test conditions.

Illumination at 21.5 klux is 16 times more intense than at 1.35 klux. To equalize the amount of light to which the prints were exposed in both conditions, test times at 1.35 klux were 16 times longer than for the 21.5 klux test. The densitometric data given here were fully corrected for any minimum-density increases (stain) that occurred in the course of these tests.

Extrapolations made from high-intensity test data to predict print fading and staining rates at the low illumination levels found in normal indoor display conditions will probably be reasonably accurate for print materials that have low RF Factors (e.g., 1.5 or lower for the image dye that is the least stable in the 21.5 klux tests). Color print materials with RF Factors greater than approximately 1.5 likely will have a significantly shorter useful life when displayed for long periods under normal indoor illumination conditions than is predicted by short-term, high-intensity accelerated light fading tests.

Boldface Type indicates products that were being marketed in the U.S. and/or other countries when this book went to press in 1992; the other products listed had either been discontinued or replaced with newer materials.

Chromogenic Prints:	21.5 klux (2,000 fc) Density Losses	1.35 klux (125 fc) Density Losses	Reciprocity Failure Factor (RF Factor)
Konica Color PC Paper Type SR **Konica Color PC Paper Professional Type EX** (EP-2 process with water wash)	90-Day Test	1,440-Day Test	RF Factor
Cyan Loss from 1.0 Neutral:	–0.09	–0.13	1.4
Magenta Loss from 1.0 Neutral:	–0.23	–0.23	1.0
Yellow Loss from 1.0 Neutral:	–0.11	–0.19	1.7
Cyan Loss from Cyan Patch:	–0.12	–0.21	1.8
Magenta Loss from Magenta Patch:	–0.38	–0.40	1.1
Yellow Loss from Yellow Patch:	–0.15	–0.22	1.5
Minimum-Density Yellowish Stain:	+0.03	+0.09	[Stain: +0.06]
Konica Color PC Paper Type SR **Konica Color PC Paper Professional Type EX** (processed with Konica Super Stabilizer in a "washless" Konica minilab)	90-Day Test	1,440-Day Test	RF Factor
Cyan Loss from 1.0 Neutral:	–0.10	–0.16	1.6
Magenta Loss from 1.0 Neutral:	–0.19	–0.22	1.2
Yellow Loss from 1.0 Neutral:	–0.11	–0.23	2.1
Cyan Loss from Cyan Patch:	–0.14	–0.25	1.8
Magenta Loss from Magenta Patch:	–0.38	–0.40	1.1
Yellow Loss from Yellow Patch:	–0.17	–0.37	2.2
Minimum-Density Yellowish Stain:	+0.00	+0.04	[Stain: +0.04]

Chromogenic Prints:	21.5 klux (2,000 fc) Density Losses	1.35 klux (125 fc) Density Losses	Reciprocity Failure Factor (RF Factor)
Ektacolor Plus Paper **Ektacolor Professional Paper** (EP-2 process with water wash)	90-Day Test	1,440-Day Test	RF Factor
Cyan Loss from 1.0 Neutral:	–0.08	–0.12	1.5
Magenta Loss from 1.0 Neutral:	–0.23	–0.31	1.4
Yellow Loss from 1.0 Neutral:	–0.14	–0.33	2.4
Cyan Loss from Cyan Patch:	–0.11	–0.18	1.6
Magenta Loss from Magenta Patch:	–0.42	–0.51	1.2
Yellow Loss from Yellow Patch:	–0.24	–0.55	2.3
Minimum-Density Yellowish Stain:	+0.00	+0.11	[Stain: +0.11]
Ektacolor 74 RC Paper Type 2524 Ektacolor 78 Paper (EP-2 process with water wash)	90-Day Test	1,440-Day Test	RF Factor
Cyan Loss from 1.0 Neutral:	–0.09	–0.20	2.2
Magenta Loss from 1.0 Neutral:	–0.27	–0.35	1.3
Yellow Loss from 1.0 Neutral:	–0.16	–0.31	1.9
Cyan Loss from Cyan Patch:	–0.12	–0.35	2.9
Magenta Loss from Magenta Patch:	–0.48	–0.59	1.2
Yellow Loss from Yellow Patch:	–0.27	–0.54	2.0
Minimum-Density Yellowish Stain:	+0.00	+0.07	[Stain: +0.07]

Chromogenic Prints:	21.5 klux (2,000 fc) Density Losses	1.35 klux (125 fc) Density Losses	Reciprocity Failure Factor (RF Factor)
Ektacolor 37 RC Paper Type 2261 (EP-2 process with EP-3 Stabilizer)	90-Day Test	1,440-Day Test	**RF Factor**
Cyan Loss from 1.0 Neutral:	–0.12	–0.20	1.7
Magenta Loss from 1.0 Neutral:	–0.24	–0.35	1.5
Yellow Loss from 1.0 Neutral:	–0.22	–0.45	2.1
Cyan Loss from Cyan Patch:	–0.14	–0.30	2.1
Magenta Loss from Magenta Patch:	–0.41	–0.56	1.4
Yellow Loss from Yellow Patch:	–0.37	–0.80	2.2
Minimum-Density Yellowish Stain:	+0.01	+0.10	[Stain: +0.09]
Kodak Ektachrome 2203 Paper	90-Day Test	1,440-Day Test	**RF Factor**
Cyan Loss from 1.0 Neutral:	–0.14	–0.32	2.3
Magenta Loss from 1.0 Neutral:	–0.23	–0.37	1.6
Yellow Loss from 1.0 Neutral:	–0.21	–0.37	1.8
Cyan Loss from Cyan Patch:	–0.16	–0.40	2.5
Magenta Loss from Magenta Patch:	–0.49	–0.75	1.5
Yellow Loss from Yellow Patch:	–0.44	–0.81	1.8
Minimum-Density Yellowish Stain:	+0.03	+0.15	[Stain: +0.12]
Fujicolor Paper Type 8901 (EP-2 process with water wash)	90-Day Test	1,440-Day Test	**RF Factor**
Cyan Loss from 1.0 Neutral:	–0.10	–0.16	1.6
Magenta Loss from 1.0 Neutral:	–0.21	–0.26	1.2
Yellow Loss from 1.0 Neutral:	–0.13	–0.30	2.3
Cyan Loss from Cyan Patch:	–0.16	–0.25	1.6
Magenta Loss from Magenta Patch:	–0.43	–0.50	1.2
Yellow Loss from Yellow Patch:	–0.23	–0.54	2.4
Minimum-Density Yellowish Stain:	+0.03	+0.09	[Stain: +0.06]
Fujicolor Paper Type 8901 (EP-2 process with EP-3 Stabilizer)	90-Day Test	1,440-Day Test	**RF Factor**
Cyan Loss from 1.0 Neutral:	–0.09	–0.17	1.9
Magenta Loss from 1.0 Neutral:	–0.20	–0.36	1.8
Yellow Loss from 1.0 Neutral:	–0.16	–0.73	4.6
Cyan Loss from Cyan Patch:	–0.13	–0.24	1.9
Magenta Loss from Magenta Patch:	–0.40	–0.57	1.4
Yellow Loss from Yellow Patch:	–0.28	–1.07	3.8
Minimum-Density Yellowish Stain:	+0.02	+0.14	[Stain: +0.12]
Agfacolor PE Paper Type 7i	90-Day Test	1,440-Day Test	**RF Factor**
Cyan Loss from 1.0 Neutral:	–0.10	–0.22	2.2
Magenta Loss from 1.0 Neutral:	–0.33	–0.46	1.4
Yellow Loss from 1.0 Neutral:	–0.22	–0.43	2.0
Cyan Loss from Cyan Patch:	–0.11	–0.30	2.7
Magenta Loss from Magenta Patch:	–0.60	–0.70	1.2
Yellow Loss from Yellow Patch:	–0.26	–0.57	2.2
Minimum-Density Yellowish Stain:	+0.06	+0.23	[Stain: +0.17]
Agfacolor PE Paper Type 589	60-Day Test	960-Day Test	**RF Factor**
Cyan Loss from 1.0 Neutral:	–0.07	–0.17	2.4
Magenta Loss from 1.0 Neutral:	–0.23	–0.48	2.1
Yellow Loss from 1.0 Neutral:	–0.21	–0.57	2.7
Cyan Loss from Cyan Patch:	–0.10	–0.17	1.7
Magenta Loss from Magenta Patch:	–0.62	–0.72	1.2
Yellow Loss from Yellow Patch:	–0.30	–0.72	2.4
Minimum-Density Yellowish Stain:	NA	NA	—
3M High Speed Color Paper Type 19	60-Day Test	960-Day Test	**RF Factor**
Cyan Loss from 1.0 Neutral:	–0.10	–0.19	1.9
Magenta Loss from 1.0 Neutral:	–0.16	–0.37	2.3
Yellow Loss from 1.0 Neutral:	–0.12	–0.45	3.8
Cyan Loss from Cyan Patch:	–0.12	–0.22	1.8
Magenta Loss from Magenta Patch:	–0.30	–0.74	2.5
Yellow Loss from Yellow Patch:	–0.21	–1.14	5.4
Minimum-Density Yellowish Stain:	NA	NA	—

Silver Dye-Bleach and Dye-Imbibition Prints:

Ilford Ilfochrome Classic Prints (called Cibachrome II Prints, 1980–91) (P-3 process – glossy polyester base)	**183-Day Test**	**2,920-Day Test**	**RF Factor**
Cyan Loss from 1.0 Neutral:	**–0.11**	**–0.16**	**1.5**
Magenta Loss from 1.0 Neutral:	**–0.19**	**–0.32**	**1.7**
Yellow Loss from 1.0 Neutral:	**–0.04**	**–0.32**	**8.0**
Cyan Loss from Cyan Patch:	**–0.14**	**–0.19**	**1.4**
Magenta Loss from Magenta Patch:	**–0.32**	**–0.54**	**1.7**
Yellow Loss from Yellow Patch:	**–0.20**	**–0.72**	**3.6**
Minimum-Density Yellowish Stain:	**+0.00**	**+0.00**	**[Stain: +0.00]**
Kodak Dye Transfer Prints (“standard” Kodak Film and Paper Dyes)	**90-Day Test**	**1,440-Day Test**	**RF Factor**
Cyan Loss from 1.0 Neutral:	**–0.09**	**–0.13**	**1.4**
Magenta Loss from 1.0 Neutral:	**–0.06**	**–0.07**	**1.2**
Yellow Loss from 1.0 Neutral:	**–0.18**	**–0.19**	**1.1**
Cyan Loss from Cyan Patch:	**–0.16**	**–0.23**	**1.4**
Magenta Loss from Magenta Patch:	**–0.10**	**–0.10**	**1.0**
Yellow Loss from Yellow Patch:	**–0.27**	**–0.40**	**1.5**
Minimum-Density Yellowish Stain:	**–0.04**	**–0.02**	**[Stain: +0.00]**
Fuji Dyecolor Prints (dye transfer type)	**90-Day Test**	**1,440-Day Test**	**RF Factor**
Cyan Loss from 1.0 Neutral:	**–0.06**	**–0.13**	**2.2**
Magenta Loss from 1.0 Neutral:	**–0.06**	**–0.09**	**1.5**
Yellow Loss from 1.0 Neutral:	**–0.26**	**–0.30**	**1.2**
Cyan Loss from Cyan Patch:	**–0.10**	**–0.19**	**1.9**
Magenta Loss from Magenta Patch:	**–0.13**	**–0.13**	**1.0**
Yellow Loss from Yellow Patch:	**–0.81**	**–0.85**	**1.1**
Minimum-Density Yellowish Stain:	**–0.00**	**–0.00**	**[Stain: +0.00]**

(continued)

Dye Diffusion-Transfer Prints:	**21.5 klux (2,000 fc) Density Losses**	**1.35 klux (125 fc) Density Losses**	**Reciprocity Failure Factor (RF Factor)**
Polaroid Polacolor ER Prints (Types 59; 559; 669; and 809)	**60-Day Test**	**960-Day Test**	**RF Factor**
Cyan Loss from 1.0 Neutral:	**–0.34**	**–0.45**	**1.3**
Magenta Loss from 1.0 Neutral:	**–0.24**	**–0.29**	**1.2**
Yellow Loss from 1.0 Neutral:	**–0.37**	**–0.43**	**1.2**
Cyan Loss from Cyan Patch:	**–0.43**	**–0.60**	**1.4**
Magenta Loss from Magenta Patch:	**–0.38**	**–0.39**	**1.0**
Yellow Loss from Yellow Patch:	**–0.40**	**–0.42**	**1.1**
Minimum-Density Yellowish Stain:	**–0.07**	**–0.05**	**[Stain: +0.00]**
Polaroid 600 Plus Prints **Polaroid Type 990 Prints** **Polaroid Autofilm Type 330 Prints** Polaroid Spectra Prints Polaroid Image Prints (Spectra in Europe)	**60-Day Test**	**960-Day Test**	**RF Factor**
Cyan Loss from 1.0 Neutral:	**–0.25**	**–0.25**	**1.0**
Magenta Loss from 1.0 Neutral:	**–0.24**	**–0.25**	**1.0**
Yellow Loss from 1.0 Neutral:	**–0.26**	**–0.32**	**1.2**
Cyan Loss from Cyan Patch:	**–0.38**	**–0.39**	**1.0**
Magenta Loss from Magenta Patch:	**–0.50**	**–0.49**	**1.0**
Yellow Loss from Yellow Patch:	**–0.26**	**–0.30**	**1.2**
Minimum-Density Yellowish Stain:	**–0.13**	**–0.13**	**[Stain: +0.00]**
Polaroid Autofilm Type 339 Prints **Polaroid High Speed Type 779 Prints** Polaroid 600 High Speed Prints	**60-Day Test**	**960-Day Test**	**RF Factor**
Cyan Loss from 1.0 Neutral:	**–0.25**	**–0.29**	**1.2**
Magenta Loss from 1.0 Neutral:	**–0.14**	**–0.19**	**1.4**
Yellow Loss from 1.0 Neutral:	**–0.27**	**–0.34**	**1.3**
Cyan Loss from Cyan Patch:	**–0.33**	**–0.40**	**1.2**
Magenta Loss from Magenta Patch:	**–0.23**	**–0.24**	**1.0**
Yellow Loss from Yellow Patch:	**–0.34**	**–0.45**	**1.3**
Minimum-Density Yellowish Stain:	**–0.02**	**–0.01**	**[Stain: +0.00]**
Kodak Ektaflex Prints (1981–1988)	60-Day Test	960-Day Test	**RF Factor**
Cyan Loss from 1.0 Neutral:	–0.20	–0.18	0.9
Magenta Loss from 1.0 Neutral:	–0.27	–0.37	1.4
Yellow Loss from 1.0 Neutral:	–0.16	–0.21	1.3
Cyan Loss from Cyan Patch:	–0.22	–0.19	0.9
Magenta Loss from Magenta Patch:	–0.25	–0.33	1.3
Yellow Loss from Yellow Patch:	–0.17	–0.18	1.1
Minimum-Density Yellowish Stain:	–0.00	–0.00	[Stain: +0.00]

mation are probably caused by oxidants or other degradation products generated, after long-term exposure to light and UV radiation, by the titanium dioxide-pigmented polyethylene layer coated between the emulsion and paper core of RC prints. (As discussed in Chapter 17, a similar mechanism involving light and titanium dioxide-pigmented polyethylene may be responsible for the light-induced silver image discoloration that has occurred in many black-and-white RC prints.)

Because this type of light-induced "dark fading" and light-induced "dark staining" has to date been observed *only* in color prints made on RC papers, it is tentatively called "RC base-associated fading and staining." It is characterized by relatively large density losses in both high-density and low-density areas of the image. The density loss as a function of original density more closely resembles the approximately equal percentage losses throughout the density range characteristic of dark fading than it does the usual type of light fading in which visual changes are concentrated in lower-density portions of the scale. As shown in **Figures 2.13** and **2.14**, Ektacolor 74 RC prints made in 1978 and tested by this author showed drastic changes when kept in the dark for 10 years after being subjected to accelerated light fading tests. Identical prints that had not been exposed to light exhibited comparatively little fading and staining during this period of storage in the dark.

RC base-associated fading and staining are usually not apparent in short-term, high-intensity accelerated light fading tests. However, in long-term display under more moderate lighting conditions — particularly when prints are framed under glass or plastic sheets that restrict the exchange of air next to the emulsion surface — this kind of deterioration can substantially shorten the life of a print. This author believes that RC base-associated fading was a major factor in the rapid and severe fading observed in many displayed Kodak Ektacolor 20 RC, 47 RC, 30 RC, 37 RC, and 74 RC prints made between 1968 and 1977.

Examples of apparent RC base-associated fading and staining observed by this author showed quite different effects among the various RC color papers manufactured since 1969, and even the same brand and type of paper may exhibit different kinds of fading effects depending on the year it was made (**Table 2.2**). Use of Kodak Ektaprint 3 Stabilizer (and apparently some other low-pH stabilizers) instead of a final water wash can increase the tendency for prints to exhibit RC base-associated fading. To date this author has observed apparent RC base-associated fading effects in chromogenic color papers made by Kodak, Agfa, Fuji, and 3M.

It is possible that long-term exposure of the RC color prints to light results in a further lowering of the emulsion pH, which in turn could increase the rate of "dark fading," especially of the pH-sensitive yellow dyes used in most chromogenic color papers.

Lending support to the notion that the RC base itself is the principal cause of RC base-associated fading is a comparison of the long-term light fading behavior of Konica Color Paper Type SR, coated on an RC base, and Konica Color Paper Type SR (SG), which is coated on a solid polyester base. After 8 years of exposure to low-level, glass-filtered 1.35 klux fluorescent illumination, the yellow dye in the RC-base print had faded significantly more than was the case with the yellow dye in the polyester-base print (**Figure 2.15**). This gave the RC-base print a decidedly bluish appearance, which was especially noticeable in high-density areas of the image. The emulsions of both Konica products are identical, and they received identical EP-2 processing with "washless" Konica Super Stabilizer. The prints were covered with glass for the duration of the tests. In short-term, high-intensity 21.5 klux glass-filtered fluorescent tests, no difference whatever was observed in the fading behavior of the two types of Konica prints.

In a further example, as shown in **Figure 2.16**, serious yellow staining occurred in Ilford Cibachrome II RC prints during the course of several years of dark storage after an accelerated light fading test, but not in Cibachrome II polyester-base prints under identical conditions.

In terms of accelerated light fading tests, RC base-associated fading and staining is a very troubling phenomenon. It injects potentially large uncertainties into predictions of color print life based on short-term accelerated tests.

"Framing Effects" in Light Fading with Prints Framed under Glass or Plastic Sheets

Studies with a variety of chromogenic color negative papers have shown that framing or enclosing these prints with glass or plastic sheets can have a significant effect on fading and stain formation when certain of these materials are displayed for long periods under typical indoor illumination levels. This phenomenon is probably related to the light-induced RC base-associated fading and staining discussed above.

The manner of processing (e.g., a water wash, use of a low-pH stabilizer, etc.) may have a pronounced influence on the rate of dye fading of these framed and displayed

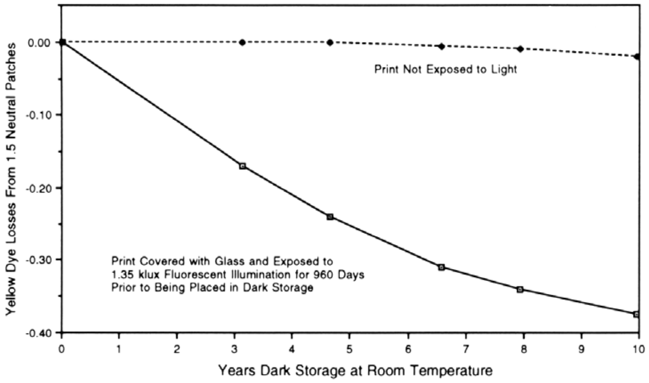


Figure 2.13 Light-induced "dark fading" of Ektacolor 74 RC paper (initial type: 1977–82), processed with Kodak EP-3 chemicals including EP-3 Stabilizer, a low-pH "stabilizer" which is used as a final rinse prior to drying. After exposure to light for 960 days, the print was placed in the dark. Dramatic fading of the yellow dye occurred during the next 10 years in the dark and was still continuing in 1992. An identical print that was never exposed to light suffered negligible yellow dye fading during 10 years of storage in the same environment (75°F and 60% RH).

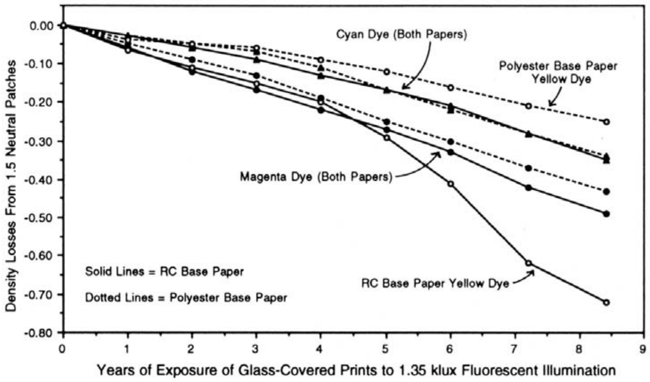


Figure 2.15 In a comparison of the long-term light fading behavior of Konica Type SR paper on RC base and polyester base, the yellow dye in the RC-base print faded significantly more than did the yellow dye in the polyester-base print. The RC base itself is believed to be the principal cause of the increased rate of dye fading observed in this example. The prints had received identical EP-2 processing with Konica "washless" stabilizer. The prints were covered with glass during the 8½ years of exposure to low-level 1.35 klux fluorescent illumination.

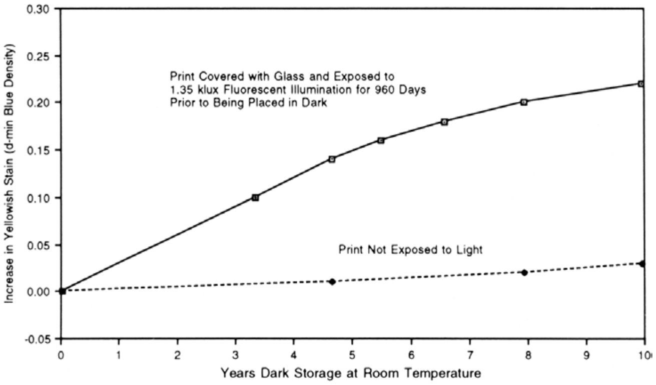


Figure 2.14 Light-induced "dark staining" of Ektacolor 74 RC Paper (initial type: 1977–82). Yellowish staining occurred at a much more rapid rate after a print was exposed to light for 960 days and then placed in the dark than it did in an identical print that was never exposed to light. Both prints were stored in the same environment.

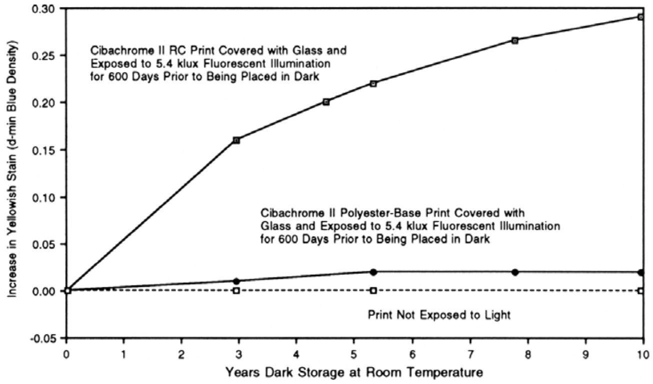


Figure 2.16 Ilford Cibachrome II RC paper suffered a large increase in yellowish stain during dark storage after a period of light exposure. Only negligible staining occurred with the glossy, polyester-base version of Ilford Cibachrome II (Ilford Cibachrome was renamed Ilford Ilfochrome in 1991).

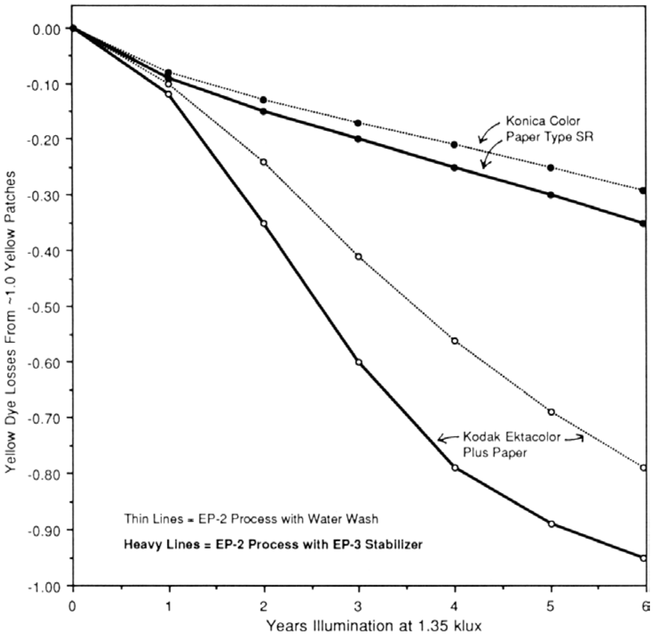


Figure 2.17 Use of Kodak Ektaprint 3 Stabilizer (a low-pH stabilizer) has a deleterious effect on the light fading stability of the yellow dye in Kodak Ektacolor Plus and Ektacolor Professional papers. Konica Color Paper Type SR was much less affected by EP-3 Stabilizer. This effect is subject to significant reciprocity failures and did not occur in this author's high-intensity 21.5 klux test.

print materials (**Figure 2.17**). Most commonly the "framing effect" in chromogenic prints is manifested by an increase in yellow dye fading in particular and, unlike what is generally observed with light fading, is most noticeable in high- and maximum-density areas of a color image. The disproportionate loss of yellow dye eventually causes the image to suffer a pronounced blue shift in color balance. An example of the "framing effect" with Fujicolor Paper Type 8901 (processed with EP-3 Stabilizer) is shown in **Figure 2.18**. To a greater or lesser degree, Ektacolor and most other chromogenic papers are also affected in this manner.

The framing effect has been observed in prints framed directly against glass and in prints that are separated from the framing glass by a cardboard overmat. In a 3-year test conducted by this author with prints in a 1.35 klux fluorescent test, the fading rates of a number of color negative papers were compared when: **a)** prints were resting on an aluminum-foil-covered board and covered with a glass sheet but not sealed with tape along the edges; **b)** placed between a glass sheet and a piece of 4-ply, 100% cotton-fiber mat board and sealed along the edges with tape; and **c)** placed between two sheets of glass and sealed along the edges with tape. For the papers tested, the fading rates for all conditions were quite similar.

Experience has shown that the framing effect generally is subject to large reciprocity failures in high-intensity light stability tests; therefore, long-term tests with illumination intensities of 1.0 klux or lower should be employed to meaningfully evaluate this phenomenon. Although the framing effect has been studied principally in chromogenic prints, other types of materials possibly are affected similarly.

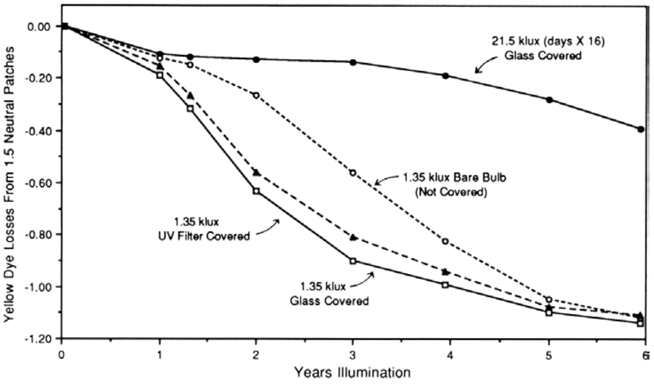


Figure 2.18 The "framing effect" (also called the "enclosure effect") in a chromogenic paper. The yellow dye in Fujicolor Type 8901 paper (1984–86), processed with Kodak Ektaprint EP-3 chemicals which include a low-pH stabilizer as the final rinse, faded more rapidly when covered with a glass or plastic sheet than it did when the print was not covered and was freely exposed to circulating air. This framing effect is subject to large reciprocity failures and generally does not occur in short-term, high-intensity tests.

A test frame devised by this author that can be used to evaluate the framing effect in color papers is described in *ANSI IT9.9-1990* in Annex D, pages 26–27 (the Standard uses the term "enclosure effects" to describe what this author calls the "framing effect").

Percentage Dye Density Losses in Light Fading as a Function of Original Density

An important difference between dark fading and light fading is that dark fading usually involves an approximately equal *percentage* loss of density throughout the density range of the print (**Table 2.3**). That is, if a dark, high-density area of a print loses 30% of its density, a low-density highlight area of the print will usually lose about the same percentage of density. This means that while the contrast of the dye image becomes lower — and the image becomes lighter overall — both shadow and highlight detail are retained in approximately equal percentages as dark fading progresses.

With light fading, the situation is very different, and with many kinds of prints it can be characterized by more or less equal loss in *density units* throughout the density range (**Table 2.4**). Because highlight areas of a print have a low dye density to begin with, relatively little exposure to light on display can significantly reduce apparent detail in these low-density areas of the image.

For example, in a typical wedding photograph, the detailed areas of a white wedding dress typically have a density of about 0.20 to 0.35, of which about 0.10 can be attributed to the RC paper base itself. This means that the white cloth of the wedding dress is depicted by a dye density of only 0.10 to 0.25, and it takes relatively little exposure to light on display to cause this small amount of image dye to fade completely. The result is still a photograph of a white dress, but the sense of richness, detail, texture, and weave in the cloth is gone, while higher-density portions of the image remain relatively unchanged. These density-loss characteristics of light fading and dark fading are also described in Annex A of *ANSI IT9.9-1990*.

Most chromogenic print materials, both color negative papers and reversal papers for printing transparencies, have light fading patterns similar to that of Kodak Ektacolor 74 RC. Ilford Ilfochrome prints (called Cibachrome prints, 1963–1991) also follow this general behavior in light fading, although in accelerated tests, the rate of yellow dye fading increases after prolonged exposure to light, causing the relative percentage losses of dye to shift over time. In early stages of the tests, the yellow dye is more stable than either cyan or magenta, but after extended exposure the yellow becomes the least stable of the three.

Some other types of prints, notably dye diffusion-transfer prints such as Kodak Ektaflex (1981–88) and Polaroid Polacolor ER, have light fading characteristics as a function of image density that more closely resemble the kind of uniform percentage losses associated with dark fading. Particularly when light fading reaches an advanced stage, this results in washed-out shadows and gives these prints a very different — and usually inferior — appearance from prints made on Ektacolor and similar papers that have faded the same amount in middle-density areas.

The Importance of Starting Density in Light Fading Tests

Study of many faded color prints of pictorial scenes indicates that the density range of about 0.45 to 0.6 generally shows the most noticeable fading after exposure to moderate amounts of light. For this reason, this author has employed a starting density of 0.6 (approximately 0.5 above d-min with current color negative papers) for

Table 2.2 Light Fading Patterns of 1,384 Kodak Ektacolor RC Portraits

Iowa high school class composites made with individual prints; Ektacolor RC paper processed between 1970 and 1974. Prints examined in January 1980.

			Number of Faded Prints and Direction of Changes in Color Balance		
School Name	Class Year	RC Cracks	Cyan	Yellow	Magenta
Adel Community High School	1971	yes	78	–	–
Central Decatur Community School	1971	–	70	–	–
Maxwell Community School	1971	yes	27	–	–
North Polk	1971	–	51	–	–
Waukee Community School	1971	yes	46	–	–
Woodward Granger Community High	1971	–	47	–	–
Adel Community High School	1972	–	–	63	14
Central Decatur Community School	1972	yes	–	75	6
Clark Community School	1972	yes	–	55	30
New Monroe	1972	–	–	48	6
Madrid Community High School	1972	yes	–	38	4
Southwest Warren Community School	1972	yes	–	41	6
Van Meter Community School	1972	yes	–	19	4
Waukee Community School	1972	yes	30	–	–
Central Decatur Community School	1973	–	–	–	65
Dallas Community School	1973	–	1	–	26
Deerfield Community School	1973	–	–	–	46
Madrid Community High School	1973	–	–	–	61
North Polk	1973	–	–	–	49
Southwest Warren Community School	1973	–	–	–	60
Van Meter Community School	1973	–	–	–	32
Waukee Community School	1973	–	–	–	24
Woodward Granger Community High	1973	–	–	–	51
Central Dallas Community School	1974	–	–	–	25
Deerfield Community School	1974	–	–	–	37
Maxwell Community School	1974	–	–	–	29
Stuart-Menlo Community School	1974	–	–	–	63
Waukee Community School	1974	–	–	2	57
	Totals:	–	350	339	695

Note: RC cracking was common on prints processed through 1972 (types which faded toward cyan or yellow); however, it can be assumed that prints processed during years after 1972 (generally types which faded in the magenta direction) would also develop RC cracks at some point in the future if placed on permanent display.

In general, the prints were actually processed late in the calendar year preceding the "Class Year." For example, prints listed under the 1972 Class Year were for the most part processed in late 1971. Some, however, were taken and processed later, and this probably accounts for the mixed fading pattern observed in many of the 1972 Class Year composites.

Table 2.3 Percentage Losses of Cyan Dye in Kodak Ektacolor 78 and 74 RC Papers Resulting from Dark Fading

90 days in the dark at 144°F (62°C) and 45% RH (Data from neutral patches)

Starting Density above d-min	Density Loss at End of Test	Percent Density Loss
0.20	– 0.11	– 45%
0.30	– 0.14	– 47%
0.40	– 0.19	– 48%
0.50	– 0.24	– 48%
0.60	– 0.28	– 47%
1.00	– 0.46	– 46%
1.50	– 0.72	– 48%

Table 2.4 Percentage Losses of Magenta Dye in Kodak Ektacolor Plus and Professional Papers Resulting from Light Fading

60 days under 21.5 klux (2,000 fc) illumination (Data from neutral patches)

Starting Density above d-min	Density Loss at End of Test	Percent Density Loss
0.20	– 0.13	– 65%
0.30	– 0.14	– 47%
0.40	– 0.15	– 38%
0.50	– 0.15	– 30%
0.60	– 0.15	– 25%
1.00	– 0.15	– 15%
1.50	– 0.14	– 9%

determining the image life of displayed prints for "Home and Commercial" applications, and a starting density of 0.45 for "Museum and Archive" applications.

The *ANSI IT9.9-1990* Standard specifies that a density of 1.0 above d-min be used for both light fading and dark fading tests; this value was selected for reasons of industry tradition, convenience (using the same value for both light fading and dark fading tests), and simplicity (for reflection prints, a simple ½ d-min correction is adequate at a density of 1.0).

This author strongly believes, however, that because of the disproportionate loss of density in low-density areas of color prints and slides that have been subjected to light fading, a starting density of 0.6 (0.5 above d-min) gives a much better correlation with the visual assessment of light fading in portraits, wedding photographs, and most other types of pictorial scenes. For a given set of fading and color-balance change criteria, using 0.6 for light fading also correlates better with the visual assessments of image degradation in dark-faded prints that have changed to approximately the same degree, as determined from a starting density of 1.0. (The previous *ANSI PH1.42-1969* Standard specified that *two* densities, 1.0 and 0.5, be used with color prints and color slides.)

If a starting density of 1.0 is used for both light fading and dark fading, and the same set of change limits is used for both, the result is likely to be an unrealistically optimistic assessment of the light fading stability of a color print material. To give an example, if one were to select a 30% dye loss limit from a starting density of 1.0 (which Konica and some others have adopted for published dark fading predictions) and apply this "acceptability limit" to light-faded prints, there would be severe fading and loss of detail in low-density portions of the color images. Portraits and wedding photographs that have light-faded to this degree would be unacceptable to most people.

Particularly in dark fading, where density losses are often accompanied by significant levels of yellowish stain, the starting density that is chosen can have a major influence on the assessment of color balance changes. An example of this for a color negative paper is shown in **Figure 2.19**.

Light Fading of Neutral Gray Areas versus Pure Cyan, Magenta, and Yellow Areas

Another characteristic of light fading with most papers is that parts of an image containing relatively pure cyan, magenta, or yellow colors fade more rapidly than the colors do when they are combined in a gray scale. In fact, with some print materials, a pure color patch can fade two or three times more rapidly than when the other two colors are present in equal amounts to form a neutral gray; the increased fading rates of pure magenta image areas in Ektacolor and similar chromogenic papers are often striking (**Figure 2.20**). In these papers, the magenta dye layer is below the cyan dye, which apparently absorbs a considerable amount of the wavelengths that contribute to magenta fading. The presence of the yellow dye layer below the magenta layer also offers some protection to the magenta dye because the yellow absorbs some wavelengths that would otherwise be reflected back from the base and cause magenta fading.

Prints that have a more or less homogeneous mixture of the three dyes in a single layer, such as the dye-diffusion-transfer processes like Polacolor ER and the now-obsolete Kodak Ektaflex print materials, and Kodak Dye Transfer prints, generally exhibit this effect less than materials such as Ektacolor and Ilfochrome, which have the image dyes isolated in distinct layers.

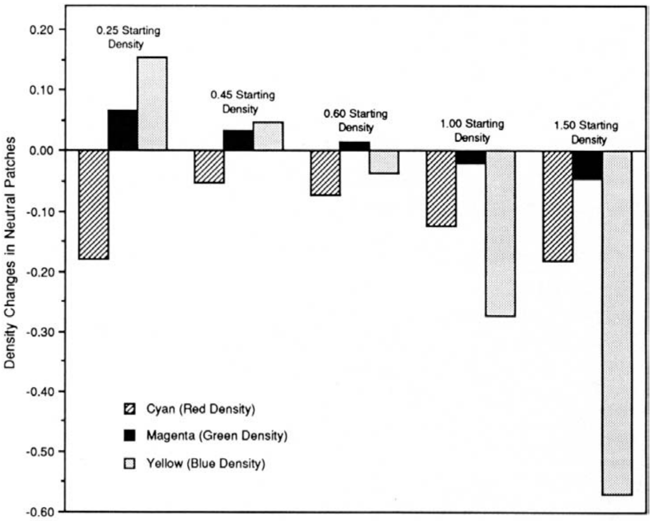


Figure 2.19 As shown here in Agfacolor Type 8 Paper (AP95 washless process), yellowish stain that occurs in dark storage can have a pronounced effect on perceived color balance. The degree and direction of color balance change generally vary as a function of density.

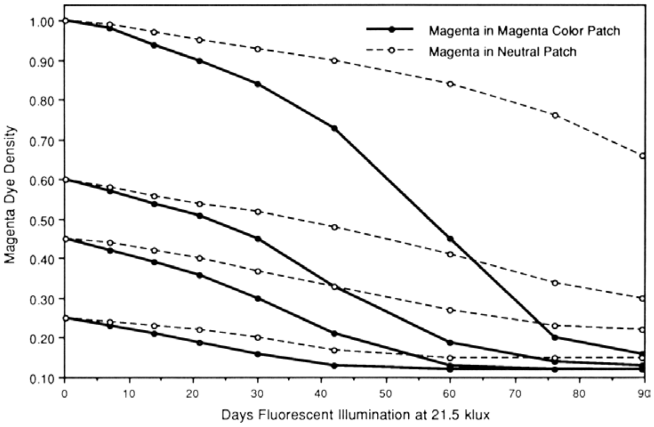


Figure 2.20 In light fading, with most color papers, pure cyan, magenta, and yellow dye patches fade much more rapidly than when all three dyes are present in approximately equal amounts in a neutral patch. The effect was especially pronounced with the magenta dye in the now-obsolete 3M High Speed Color Paper shown here. In dark fading, most products exhibit little if any difference in the rates of fading of pure colors and colors in neutral patches.

Light Fading of Skin Colors

It is apparent that the mostly magenta and yellow dye mixture reproducing the light and dark colors of human skin behaves differently than gray patches or separate cyan, magenta, and yellow colors in response to light. Comparisons of the light fading stability of light and dark skin colors in both EP-2 and RA-4 compatible color negative papers are given in Chapter 3. Because of the importance of skin-tone reproduction in portraits, this author plans to further study the visual responses to fading and staining of representative flesh-tone colors with the aim of devising a set of criteria limits specifically for these colors.

Types of Accelerated Light Fading Tests

A good light fading test simulates actual conditions of display as closely as possible. The temperature and relative humidity conditions and the wavelength distribution of the light source should all match the display condition one would like to simulate. Ideally, the *intensity* of the test illumination should also be the same as the actual display condition, and the alternate light/dark (day/night) periods encountered in most display situations should be duplicated. However, the stability of most current color materials requires test periods of many years before useful fading and staining limits are reached, and for this practical reason, accelerated tests must be employed to study light fading stability.

The three principal light sources for illuminating photographs are fluorescent light, indirect daylight through window glass, and incandescent tungsten light. Each of these light sources has a distinctly different spectral distribution and ultraviolet content, and because of this, each type of illumination has a different fading and staining effect on each dye of each of the many different color print materials. In addition, extremely intense tungsten halogen illumination is used in slide projectors (projector-caused fading of color slides is discussed in Chapter 6), and some photographs are subjected to extremely intense, direct outdoor sunlight.

ANSI IT9.9-1990 specifies illumination sources, wavelength distribution, and intensity for all five of these illumination conditions:

> These tests are intended to simulate common use conditions. Selection of the appropriate test should be based on the conditions of intended use. In most homes, for example, indirect daylight through window glass is the principal illumination causing displayed photographs to fade. (The low-intensity illumination provided by incandescent tungsten lamps in homes usually contributes very little to the deterioration of color photographs. Fluorescent lamps, however, which generally provide more intense illumination than tungsten lamps, are increasingly found in homes. When fluorescent lamps are present, they may make a significant contribution to the fading of displayed prints.) In offices and public buildings, fluorescent lamps are usually the primary source of illumination. Photography exhibits in galleries, museums, and archives are most often illuminated with standard incandescent tungsten lamps or quartz-halogen tungsten lamps. Exposure to direct sunlight is the principal cause of fading in color print materials used outdoors (e.g., billboards, outdoor displays, and identification badges).

This high-intensity 21.5 klux (2,000 fc) fluorescent test allows rapid evaluation of new color papers as soon as they become available. Shown here with the lamp fixtures raised so that the print samples can be seen, the test set-up employs high-velocity forced-air cooling to maintain 75°F (24°C) and 60% RH at the sample plane. Uncovered (bare-bulb), glass-covered, and Plexiglas UF-3 covered print samples, which are mounted on aluminum foil-covered boards, are moved forward every 24 hours to a new location under the lamps so that all samples receive equal illumination during the course of the test. This equipment was designed and constructed by this author in 1983.

Accelerated Fluorescent Tests

This author uses two types of accelerated fluorescent light fading tests. One is a short-term, high-intensity test with an illumination intensity at the sample plane of 21.5 klux (2,000 fc). The other is a long-term, low-intensity test with an illumination intensity at the sample plane of 1.35 klux (125 fc). Standard single-phosphor Cool White fluorescent lamps are employed; because of their low cost and high energy-efficiency, Cool White lamps are by far the most common type of fluorescent lamp worldwide.

In both tests, the sample-plane temperature is 75°F (24°C) and the relative humidity 60%. The tests are conducted in temperature- and humidity-controlled rooms. Because of the heating effect of the fluorescent lamps in the high-intensity 21.5 klux test (the lamps are only about 2 inches from the sample plane), high-velocity forced-air cooling is required to maintain the proper temperature and relative humidity in the samples.

To determine the sensitivity of materials to UV radiation, identical samples are exposed to: a) direct, bare-bulb illumination; b) glass-filtered illumination with standard window glass covering the sample; c) UV-filtered illumination with Rohm and Haas Plexiglas UF-3, a sharp-cutting UV filter. Bare-bulb fluorescent illumination exposes prints to the ultraviolet 313 nanometer mercury vapor line emission of the fluorescent lamps; this can greatly increase the fading rate of one or more dyes in Kodak Ektatherm prints (and most other electronic "hardcopy" print materials), Kodak Dye Transfer prints, Polacolor 2 and Polacolor ER prints, and other materials manufactured without a UV-absorbing emulsion overcoat. Ordinary window or framing glass effectively absorbs this harmful wavelength. Plexiglas UF-3 absorbs essentially all ultraviolet radiation; virtually all of the fading that occurs with this filter in place can be attributed to the effects of visible light.

The high-intensity 21.5 klux test is a short-term test which with most products runs about 4 months; the test provides data very quickly and allows evaluation of new color papers shortly after samples become available. This test was extensively used for the color paper image-life predictions and product comparisons in Chapter 3.

The long-term, low-intensity 1.35 klux fluorescent test has 1⁄16 the illumination intensity of the 21.5 klux fluorescent test, and test periods run between 5 and 10 years for most products. Unlike the high-intensity 21.5 klux test, the 1.35 klux test gives a good measure of the level of yellowish stain that might occur during normal, long-term display. By comparing 1.35 klux data with data from the 21.5 klux test, an indication of a product's tendency toward reciprocity failures in light fading can be obtained. Data from the long-term 1.35 klux test were absolutely critical for this author to be able to give "years of display" predictions for current products with reasonable confidence.

The 1.35 klux test produces a reasonably good simulation of the fading and staining that can be expected in long-term display under normal home and office conditions; this would be this author's primary light fading test were it not for the 3- or 4-year test periods most current color papers require to reach this author's fading limits. By the end of 3 years, some products are no longer even on the market!

An illumination intensity of 6.0 klux is specified for the accelerated fluorescent test in the *ANSI IT9.9-1990* Standard. This intensity is a good compromise between short-term, high-intensity tests that yield data quickly and long-term, low-intensity tests that better simulate normal display conditions. With current color papers, this author's fading limits should be reached in 6 months to a year with the ANSI 6.0 klux test.

Tungsten Illumination Tests

This author's long-term 1.35 klux incandescent tungsten test is intended to simulate display conditions commonly found in museums and archives. Although 1.35 klux is about four times more intense than the 300 lux illumination level recommended by this author for display of color photographs in museums (see Chapter 17), data from the 1.35 klux accelerated test allow reasonably accurate image-life predictions to be made for color prints displayed under museum conditions.

The tungsten test has shown that extra UV protection (e.g., a Plexiglas UF-3 filter) is of little or no value when prints are displayed under tungsten illumination. Tungsten illumination has an undeservedly good reputation as being safe for color prints. In fact, in this author's tests, some materials — including Cibachrome (Ilfochrome), the now-discontinued Agfachrome-Speed material (**Figure 2.21**), and Kodak Instant Print Film PR10 — faded more rapidly under 1.35 klux tungsten illumination than they did under 1.35 klux fluorescent illumination.

With all three of the materials mentioned above, the cyan dye suffered significantly greater fading under tungsten illumination than under fluorescent, and this can probably be explained by the fact that the peak absorption of cyan dyes is in the red portion of the spectrum and, at any given lux intensity, tungsten illumination has much greater energy in the red wavelengths than does fluorescent illumination. (To match the sensitivity of the human visual system, a luxmeter has its peak sensitivity in the green portion of the spectrum and does not fully take into account the differences in red or blue energy in different types of illumination.) Because red wavelengths have such low photochemical activity, this author was surprised that these wavelengths had such a pronounced effect on the fading rates of the cyan dyes in the three materials.

One of the difficulties in accelerated light fading tests with incandescent tungsten lamps is that the high infrared (IR) output of the lamps makes it difficult to maintain this author's standard 75°F (24°C) and 60% RH conditions at the sample plane. Because of this problem, this author has not even attempted to run an incandescent tungsten test at 21.5 klux. *ANSI IT9.9-1990* specifies an intensity of 3.0 klux for its incandescent tungsten test.

Indoor Daylight Tests

This author's indoor daylight test is run under illumination from a large, north-facing glass window. The illumination intensity is about 0.78 klux averaged over a 24-hour period; the accumulated light exposure is measured with a Minolta integrating lux-hour meter. Duplicate print samples are tested under window glass and Plexiglas UF-3 filters. The tests typically run for a period of several years. When close to a window, north daylight has relatively high UV and blue light components, so this is a good test to show what protection is afforded by a UV filter. Farther from a window, indoor daylight illumination usually has a much lower UV content because of absorption by wall, floor, and ceiling surfaces.

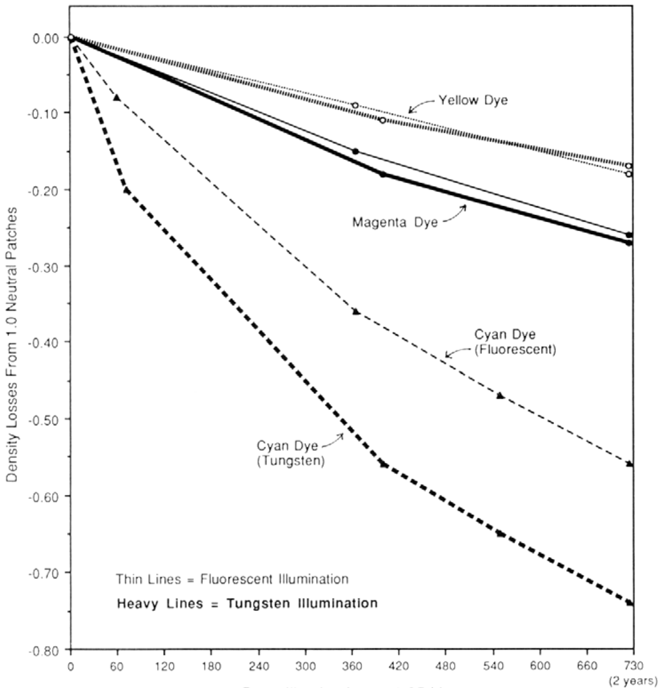


Figure 2.21 In the now-obsolete Agfachrome-Speed print material (1983–85), the rate of cyan dye fading is significantly greater under glass-filtered tungsten illumination than under glass-filtered Cool White fluorescent illumination of the same klux intensity. For the cyan dye in Agfachrome-Speed, the same relationship also held true for samples exposed to bare-bulb illumination and for samples covered with a Plexiglas UF-3 ultraviolet filter.

Carol Brower – August 1983

Averaged over a 24-hour period, 12 months a year, the intensity in this north-daylight test is approximately 0.78 klux. This test is useful primarily to determine what improvement, if any, is afforded by framing prints with UV-absorbing filter material. This test was started in 1983. As with this author's other light fading tests, this test is maintained at 75°F (24°C) and 60% RH. In the center of the sample area is the sensor of a Minolta integrating lux-hour meter which is in place year-round to measure the accumulated light received by the samples.

ANSI IT9.9-1990 specifies an intensity of 6.0 klux for the indoor daylight test. To obtain better repeatability than is possible with a test using actual daylight, the Standard specifies a filtered xenon arc illumination source that is a reasonable simulation of north daylight; the required wavelength distribution is given in the Standard.

Outdoor Sunlight Tests

This author has not routinely conducted light fading tests in direct, outdoor sunlight. However, a 100-klux simulated outdoor sunlight test with a xenon arc illumination source is provided in *ANSI IT9.9-1990.*

"Standard" Display Conditions for Predictive Tests

Based on measurements of illumination intensity in a wide variety of display situations (**Table 2.5**), this author selected 450 lux (42 fc) for 12 hours per day as the standard home and office display condition on which to base the "years of display" image-life predictions for color papers given in Chapter 3. For incandescent tungsten illumination in museums and archives, 300 lux (28 fc) for 12 hours per day was selected. In display situations where the daily klux-hour light exposure is either greater or less than these "standard" illumination conditions, it is a simple matter to recalculate the image-life predictions so that they correlate with actual display conditions.

Table 2.5 Survey of Lighting Conditions in Display Areas (1977–1988)

Summary of Table 17.1 in Chapter 17

Location	Illumination Intensity Median Level	Illumination Intensity Average Level
A. Museums and Archives	215 lux (20 fc)	1,057 lux (98 fc)
B. Commercial Galleries	430 lux (40 fc)	549 lux (51 fc)
C. Public Buildings (e.g., offices, libraries, hospitals, and airports)	1,325 lux (123 fc)	3,686 lux (342 fc)
D. Homes	635 lux (59 fc)	3,213 lux (299 fc)
A, **B**, **C**, and **D** grouped together:	375 lux (35 fc)	1,808 lux (168 fc)

Much More Research on Accelerated Light Fading Procedures Is Required

When employing accelerated light fading data to make predictions of print life under typical long-term display conditions, errors introduced by reciprocity failures, RC base-associated fading, and other factors are, in most cases, probably significantly greater than the possible errors in the accelerated test procedures described here. It is obvious that a much better understanding of the actual behavior of photographs during long-term display at low light levels is needed if accelerated light fading tests are to have greater predictive value. For example, the long-term effects on low-intensity light fading of relative humidity, temperature, framing under glass, and coating prints with lacquers all need to be investigated with each of the many different color print materials.

Test Methods to Determine Dark Fading and Staining Characteristics of Color Materials

This author's tests of color print and color film dark storage stability, reported in **Tables 5.5a** through **5.9** in Chapter 5, were performed according to the general outline described in *ANSI PH1.42-1969, American National Standard Method for Comparing the Color Stabilities of Photographs.* Although replaced by *ANSI IT9.9-1990* in 1991, this was the applicable Standard when these tests were conducted.

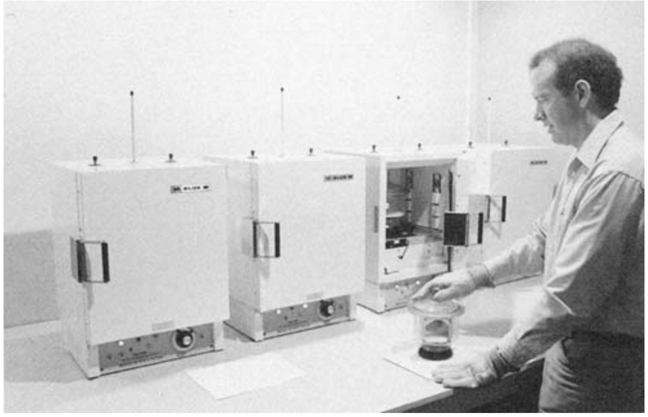
For the basic accelerated dark fading test, *ANSI PH1.42-1969* specified a temperature of 140°F (60°C) and 70% RH. According to the Standard, "This condition is used to simulate results which occur with long-term storage." The Standard also specified a test at 100°F (37.8°C) and 90% RH to simulate tropical storage conditions.

Experimental work by this author in the late 1970's suggested that the 70% RH level at 140°F was too severe. With Kodachrome film and Cibachrome prints, the test produced unaccountably rapid dye fading and exudation of sticky substances (probably coupler solvents) on the emulsion surfaces of incorporated-coupler films and prints. In the case of Polaroid SX-70 prints, the test conditions led to severe reddish-yellow stain formation. These kinds of image deterioration were of a nature that this author had never observed in photographs in actual, long-term storage under less severe conditions (even in the tropics, where relative humidities frequently are higher than 70%). For this reason, this author adopted a more moderate level of 45% RH and a temperature of 144°F (62°C). These test conditions were employed for the data reported in Chapter 5; they were also used for the comparisons of dark storage stability of color films and color print materials published by Bob Schwalberg, this author, and Carol Brower in the June 1990 issue of *Popular Photography* magazine.[11]

At the outset of these investigations in 1977, this author set the test ovens at 140°F (60°C) as specified by *ANSI PH1.42-1969.* With the aid of more precise temperature measurements at the sample desiccator locations in the ovens, it was later determined that the actual temperature was 144°F (62°C), so it was decided to continue using this temperature to make all test data comparable.

The relative humidity was maintained by placing test samples in sealed glass desiccator jars containing a saturated sodium dichromate solution in a compartment at the bottom. The saturated sodium dichromate solution (containing an excess of sodium dichromate so that some of the salt remained undissolved) maintained the air inside the desiccators at a relative humidity of 45% at a temperature of 144°F (62°C).[12]

With representative products, tests were also conducted at 75% RH using a saturated sodium chloride solution in the desiccators. Although this author has little confidence in the 75% RH data in terms of what might be expected to happen under real-world storage conditions, several conclusions were reached: in dark storage, high humidities cause some dyes to fade much faster, but other dyes are


Carol Brower – August 1983

This author's single-temperature dark fading tests are performed in precisely controlled ovens with a temperature of 144°F (62°C). Desiccator jars with a saturated sodium dichromate solution in the bottom maintain a relative humidity of 45%. These tests were started in 1983, and Cibachrome (Ilfochrome) prints, Dye Transfer prints, and a few other materials with exceptional dark fading stability have remained in the ovens since that date. This author plans to acquire new humidity-controlled ovens for Arrhenius testing in 1993.

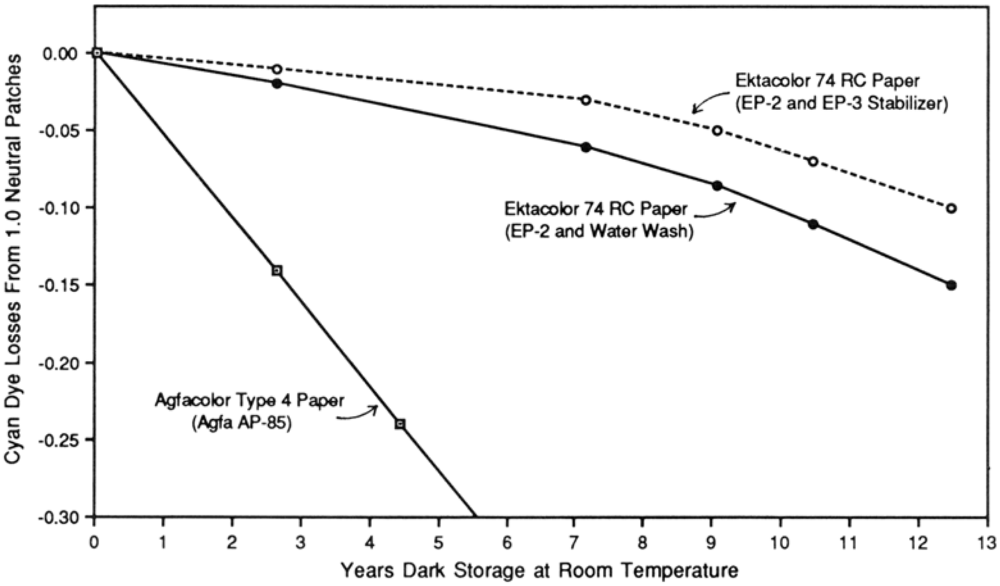


Figure 2.22 Data from room-temperature dark storage of Ektacolor 74 RC paper (initial type, 1977–82) and Agfacolor Type 4 paper (1974–82). The storage temperature was 75°F (24°C) and the relative humidity 60%. As can be seen, the dark storage stability of the cyan dyes in these papers is poor, with Agfacolor Type 4 paper suffering catastrophic fading in only a few years. The accumulation of natural aging data is an essential part in any long-term testing program. Comparisons between natural aging data and accelerated test data are the only way that predictions based on accelerated tests can be verified.

little affected, and high humidities sharply increase yellowish stain formation in incorporated-coupler chromogenic materials such as Kodak Ektacolor paper and Ektachrome film. Ilford has reported that high-humidity tests (above 60% RH) conducted at high temperatures may cause physical deaggregation (resulting in a loss of optical density) in the azo dyes in Ilfochrome (Cibachrome).[13] Similar dye deaggregation is not believed to occur at normal storage temperatures, and for this reason, accelerated dark fading tests at high humidities will produce misleading results with Ilfochrome.

In some cases, a material is so unstable (or enough time is available) that non-accelerated, real-time tests at normal room temperature are possible within a reasonable length of time (**Figure 2.22**). The now-discontinued Agfacolor Type 4 paper is an example; when stored in the dark in this author's office at 75°F (24°C), sample prints suffered a 20% cyan dye loss in 1,175 days (3.2 years). In an accelerated test at 144°F (62°C), a 20% cyan density loss occurred in 9 days. From this, one could draw the cautious conclusion that this author's accelerated test increased the rate of fading about 130 times. The number of years required for a 10% cyan dye loss to occur in Kodak Ektacolor 74 RC prints kept in the dark at 75°F (24°C) showed a similar relationship with data from this author's accelerated tests reported in Chapter 5.

This means, for example, that Kodak Ektacolor Plus paper, which reached a 20% cyan dye loss after 230 days at 144°F (62°C) and 45% RH in this author's test, would be expected to last approximately 80 years at 75°F (24°C) and 45% RH before the same degree of fading occurred. This is in good agreement with Kodak's Arrhenius prediction of 76 years for the paper. (Kodak's published data for Ektacolor Plus show that the yellow dye is slightly less stable than the cyan dye; that this author's tests showed cyan to be the least stable can probably be attributed to an older method of d-min correction that was used by Kodak.) Comparison of this author's data for a number of other Kodak film and print materials with Kodak's Arrhenius data for these products yielded a generally similar relationship.

The single-temperature tests in *ANSI 1.42-1969* were intended for comparing products in terms of their dye stability and their tendency to form yellowish stain during dark storage; these tests could also help evaluate different modes of processing (such as the effects of a washless stabilizer on color print stability), or the effects of post-processing treatments such as print lacquers. Although these single-temperature tests indicated, in a general way, how one product compared with another in terms of overall dye stability, they were not able to predict how many years under a specified storage condition (e.g., at normal room temperature) a product would last before losing a given amount of dye density. Single-temperature tests also do not provide a good assessment of changes in color balance (caused by the image dyes fading at different rates), nor does the indicated rate of yellowish stain formation necessarily relate to the rate of dye fading that would occur at room temperature.

The Arrhenius Test: A Predictive, Accelerated Dark Fading and Dark Staining Test Method

The dark fading test specified in the *ANSI IT9.9-1990* Standard is a *predictive* test based on the now well-known Arrhenius equation formulated in the late 1800's by Swedish physicist and chemist Svante August Arrhenius (1859–1927) to describe the relationship between temperature and the rate of simple chemical reactions.[14] Arrhenius received a Nobel prize in chemistry in 1903 for his electrolytic dissociation theory; he was the author of works on biological chemistry, electrochemistry, physical chemistry, and astronomy.

The Arrhenius equation was applied in the 1950's by Fred H. Steiger[15] of the Rohm and Haas Company in Philadelphia, Pennsylvania and others in accelerated aging studies of fabric dyes, anti-static treatments, curing rates of plastics, the deterioration of rubber, and the life of polyester-glass laminates.[16,17]

Steiger described the Arrhenius equation as follows:

> Arrhenius expressed the effect of temperature on the rate of reaction by the expression
>
> $$\frac{d\ \ln k}{dT} = \frac{E}{RT^2} \qquad (1)$$
>
> where k is the rate constant of the reaction, R is the universal gas constant, T is the absolute temperature and E is an equation constant. If E is assumed to be independent of temperature, the above expression may be integrated to
>
> $$\ln\ K = -\frac{E}{RT} + I \qquad (2)$$
>
> where I is an integration constant.
>
> The constant E represents the heat of activation or the energy required to convert unreactive molecules to “active” ones. This quantity may be determined by plotting ln K against l/T since equation 2 shows the slope of such a plot to be –E/R. The integrated form of the Arrhenius equation is used most frequently to calculate the heat of activation of a reaction.
>
> The phenomenon of aging, which we attribute to inanimate items, may be treated as a single chemical or physical reaction or a series of reactions of that item with itself or its environment. Since the rate of most of these reactions is dependent on temperature, it is possible to use the Arrhenius equation to solve problems involving the aging of materials.

The Arrhenius equation was first applied to the study of the dark fading of color photographic materials by George W. Larson and his co-workers at Eastman Kodak in the 1960’s. The first publication of image stability data based on an Arrhenius test was by Peter Z. Adelstein, C. Loren Graham, and Lloyd E. West of Eastman Kodak in an article entitled “Preservation of Motion-Picture Color Films Having Permanent Value,” in the November 1970 issue of the *Journal of the SMPTE.*[18] Tucked away in the article was a small graph showing predicted times for a 10% density loss of the least stable dye (cyan) of samples of an unidentified Kodak motion picture color negative and motion picture print film stored at a wide range of temperatures.

Although it went almost unnoticed at the time, this small graph represented a major breakthrough in the evaluation and preservation of color materials. The data represented in the graph provided the rationale for the construction of low-temperature, humidity-controlled storage facilities for the long-term preservation of color films and prints at museums such as the John F. Kennedy Library, the Art Institute of Chicago, the Peabody Museum at Harvard University, and at NASA in Houston, Texas (see Chapter 20).

In 1980 Charleton Bard, George Larson, Howell Hammond, and Clarence Packard of Eastman Kodak published an article describing the application of the Arrhenius test at Kodak in detail,[19] and this article provided the basis for the Arrhenius dark storage test that appears in the *ANSI IT9.9-1990* Standard. **Figure 2.23** illustrates how Arrhenius test data are graphically plotted by Kodak to yield dark storage predictions in terms of “years of storage” at a specific temperature (for actual products, Kodak generally has published only the upper of the two graphs).

Svante Arrhenius (1859–1927), the Swedish physicist and chemist whose study of the influence of temperature on the rate of chemical reactions provided the theoretical foundation for the predictive, accelerated dark aging test that now bears his name. In 1903 Arrhenius was awarded a Nobel prize for his work in chemistry. (Photograph courtesy of the Swedish Information Service)

Reproduced in **Figure 2.24** is the original dark storage stability graph published by Konica in April 1984 for Konica Color Paper Type SR paper. The graph was based on Arrhenius test data, and this was the first time that such data for a color product had been included in nontechnical advertising and promotional publications.

In Arrhenius tests, the rate of stain formation and the fading characteristics (dependence of fading on temperature) of each dye are determined separately, and this allows prediction of color-balance changes as well as meaningful evaluation of stain growth and how stain will affect color balance. To date, however, none of the manufacturers have reported data on color-balance changes as influenced by stain formation. And, with the exception of Fuji for its low-stain Fujicolor Super FA and SFA3 color negative papers (**Figure 2.25**) and Fujichrome Type 34 and Type 35 color reversal papers, none of the manufacturers have disclosed data on yellowish stain formation for their respective products during dark storage.

Since the publication of Arrhenius test data for Konica Type SR paper in 1984, other manufacturers, notably Fuji and Agfa, have also published Arrhenius data for their color

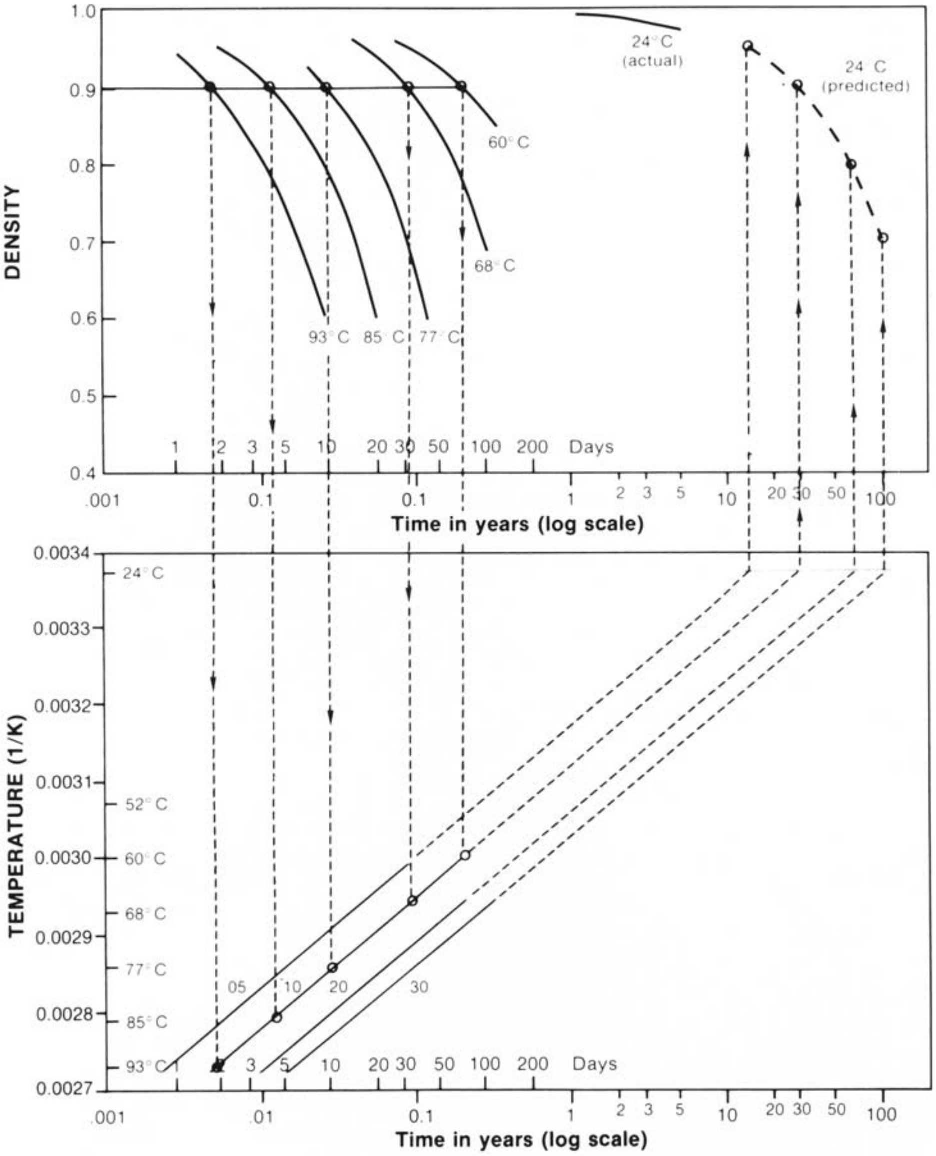


Figure 2.23 An Arrhenius plot generated by Eastman Kodak using data obtained in five accelerated dark fading tests, each employing a different temperature but the same relative humidity. This illustrative plot is based on yellow dye fading data from a Kodak product. Similar Arrhenius plots can also be produced for cyan and magenta dye fading, and for d-min stain growth. Data for yellow dye fading (reproduced in the upper left) serve as the starting point for this illustration of the method of projecting high-temperature keeping data to predict long-term keeping at lower temperatures. The first step in making the prediction is to replot the original data from the upper left on a new plot with the reciprocal of the absolute temperature on the vertical scale (solid lines at lower left). The downward arrows show how one density level is replotted (0.90 density retained corresponds to 0.10 dye loss) to record the data points that determine the straight line representing constant dye density loss. The same method is used to establish the other straight lines representing 0.05, 0.20, and 0.30 density loss. Extending the straight-line plots (dashed lines) to the 24°C (75°F) line gives an estimate of the time that it would take at 24°C (75°F) to reach the corresponding density level (dye loss). The predicted dark keeping can also be shown on the density-time plot (upper right) to correlate with actual keeping data. (From: **Dye Stability of Kodak and Eastman Motion Picture Film**, Kodak Publication DS-100, May 29, 1981. Reproduced with permission of Eastman Kodak Company.)

print papers. Kodak published detailed Arrhenius data for most of its color films, color papers, and color motion picture films in the early 1980's, but more recently the company has returned to a policy of non-disclosure regarding the stability of most of its products.

Although Arrhenius tests show that the dependence of fading on temperature differs to some degree with different dyes in different products, it is nonetheless possible to average data from a wide range of products and come up with a general relationship between temperature and rate of fading. Kodak has published a number of such generalized estimates and they have been plotted in **Figure 20.1** (page 696) in Chapter 20. Such plots allow determination of an approximate "fading rate factor" for any storage temperature of interest. This in turn allows storage-life estimates to be made for a particular product kept in cold storage if a room-temperature estimate (75°F [24°C]) for the product is available. This is how the image-life predictions for Kodak products stored at various temperatures given in Chapters 9, 19, and 20 were derived.

Running Arrhenius tests is complex and requires four or more precision, humidity-controlled ovens; the high cost of the equipment has kept the tests from being performed except by the major photographic manufacturers. Independent laboratories are beginning to acquire the necessary equipment and expertise to run the tests, however, and in 1986, B. Lavedrine, C. Trannois, and F. Flieder at the Centre de Recherches sur la Conservation des Documents Graphiques in Paris published results from Arrhenius tests on Kodak, Fuji, and Agfa-Gevaert negative and reversal motion picture films.[20]

More recently, the Image Permanence Institute at the Rochester Institute of Technology began conducting Arrhenius tests with color materials on a consulting basis and for grant-funded research projects. (It is against the policy of IPI to routinely publish stability comparisons of color products. Like RIT itself, IPI has received substantial funding from Eastman Kodak, and this has imposed certain re-

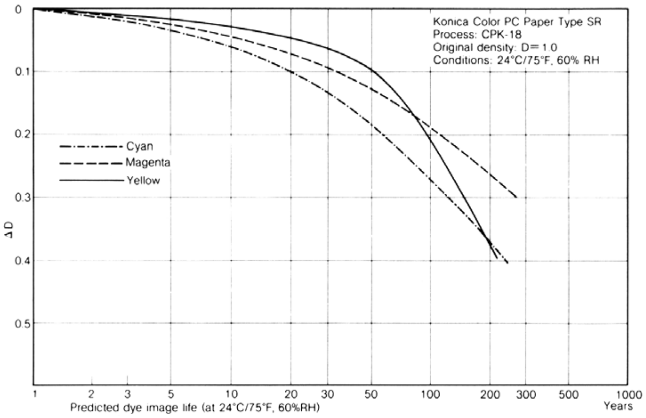


Figure 2.24 Reproduced here is the original dark storage dye-stability graph for Konica Color Paper Type SR published by Konica in April 1984. Based on data obtained in Arrhenius tests, this graph marked the first time that such stability data were included in consumer-oriented advertising. Using a 30% dye loss criterion, Konica was able to claim that Type SR prints would last more than 100 years in album storage under normal conditions. (From: **Konica Technical Data Sheet – Konica Color PC Paper Type SR**, Konica Pub. No. TDSK-213E, April 1984. Reproduced with permission of Konica Corporation.)

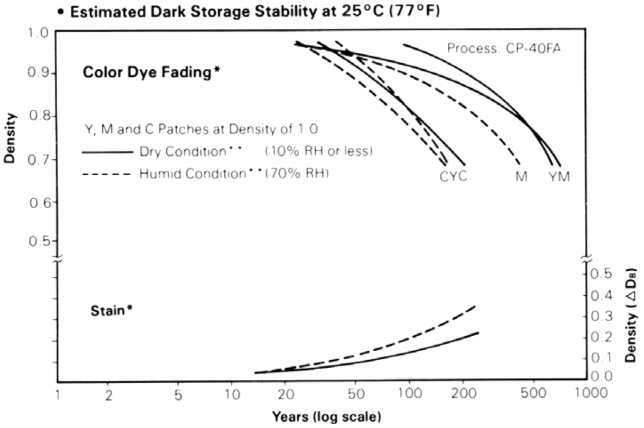


Figure 2.25 Arrhenius tests can be used to predict dye fading and yellowish stain formation in terms of "years of storage" at specified temperature and humidity conditions. Predictive data for yellowish stain formation were first published by Fuji in 1987 for Fujichrome Paper Type 34; in 1988 similar data were published for Fujicolor Paper Super FA and Fujicolor Color Professional Paper Super FA. Stain data were also published for Fujicolor Paper Super FA Type 3 (shown here), introduced in 1992. (From: **Fuji Film Data Sheet – "Fujicolor Paper Super FA Type 3**," Fuji Ref. No. AF3–723E, January 1992. Reproduced with permission of Fuji Photo Film Co., Ltd.)

strictions on IPI in terms of what the institute can do and what it will publish.)

This author hopes to acquire the necessary equipment for Arrhenius testing in 1993.

Precision and Accuracy of Arrhenius Tests

The general validity of Arrhenius test procedures has been confirmed by comparisons that have been made between Arrhenius predictions and the fading and staining that actually occurred with a variety of color films and papers stored under normal room-temperature conditions for many years by Kodak and the other major manufacturers. Kodak in particular has accumulated extensive natural aging data on the company's color films and papers. Kodak's Long Range Testing Program monitors densitometry changes over time in samples of hundreds of products stored at 75°F (24°C) and 40% RH, and at 79°F (26°C) and 60% RH. In addition, freezer samples for checking densitometer calibration and for visual reference are preserved at –10°F (–23°C).[21]

This author has a more modest long-range monitoring program for samples of color prints and films stored in the dark at normal room temperatures. These tests were started in 1978 and already have yielded much useful data on color print dye fading and d-min yellowish stain formation; dark fading curves for Agfacolor Type 4 and Ektacolor 74 RC color papers are presented in **Figure 2.22**. The tests have also provided rough "years of storage" correlations with this author's single-temperature accelerated test data included in Chapter 5. Densitometer check samples of selected materials are preserved under refrigeration.

Many potential variables can be encountered when running an Arrhenius test; for accurate and repeatable results, every aspect of the test procedure must be controlled precisely. In a 1986 presentation on application of the Arrhenius procedure for testing color papers,[22] Charleton C. Bard of Kodak said:

> The sources of variability are many; some of the principal ones being paper manufacture, process, sensitometry, densitometry, incubation conditions, data processing, and the actual number of data points used to prepare the Arrhenius plot. [It is best] to repeat, independently, the test procedure many times (e.g., more than 10 times). Unfortunately, for the very stable papers currently available, this procedure takes a lot of time. Thus, it is quite probable that while this long test procedure is under way, the product being tested is no longer for sale.

Based on the experience of the Image Stability Technical Center at Kodak, Bard offered some estimates of the precision and accuracy of Arrhenius predictions for color prints:

> For a dye that has a predicted time of up to 30 years to lose 10% of its density when stored in the dark at the specified conditions (such as 24°C/40% RH), the predicted time (30 years) is probably reliable to no more than ± 6 years (± 20%).
>
> For a dye that has a predicted time of about 100 years to lose a specified amount of density,

Precision temperature- and humidity-controlled ovens are used for incubating film and print samples in Arrhenius tests. Because products must be tested for long periods at a minimum of four different temperatures (typically 55°, 65°, 75°, and 85°C), and perhaps two or more relative humidity levels, a large number of ovens may be required. Suitable ovens cost between $3,000 and $10,000 each. Shown here are the test ovens at the Image Permanence Institute at the Rochester Institute of Technology in Rochester, New York. James Reilly, director of IPI, is checking samples of Ilford Cibachrome (Ilfochrome) micrographic film and other color microfilms undergoing Arrhenius testing.

May 22, 1991

the true value of the time could be as low as 50 years and as high as 200 years.

Therefore, for a very stable paper, >50 years for a 10% dye loss, the best statement that usually can be made is that for album keeping, the print will remain acceptable for more than a century (at 24°C, 40–60% RH). Of course, to be absolutely certain of the validity of this statement, we will have to wait for more than a century.

Increased Fading Rates With Color Motion Picture Films Stored in Standard Film Cans

All of the dark storage dye stability data given in this book were based on Arrhenius tests conducted with free-hanging film samples exposed to circulating air. Research disclosed by A. Tulsi Ram et al. of Eastman Kodak in late 1992 showed that storing films in sealed or semi-sealed containers (e.g., vapor-proof bags and standard taped or untaped metal and plastic motion picture film cans) could substantially increase the rates of dye fading and film base deterioration.[23] Therefore, the estimates given in this book for color motion picture films probably *considerably* overstate the actual stabilities of the films when they are stored in standard film cans under the listed temperature and humidity conditions. For further discussion of this topic, refer to Chapter 9.

Relative Humidity Levels for Accelerated Dark Storage Tests

What is the best relative humidity for conducting dark storage tests? Ideally, accelerated tests should be run at the same humidity level in which photographs are stored and displayed; this varies considerably depending on geographic location and season of the year. New Orleans, Louisiana, situated on the coast of the Gulf of Mexico, is much more humid than Phoenix, Arizona, located in the desert in the southwestern United States. No comprehensive study has been published about worldwide, population-based, *indoor* relative humidity, but what information is available strongly suggests that the worldwide average is above 60%, since the majority of the world's population lives in tropical or subtropical areas.

A 1981 Kodak study of the environmental conditions in two "typical" homes in Rochester, New York found that the indoor relative humidity ranged from 31% to 74%, with the year-round average of the two homes being 54%.[24] Because Rochester is a northern city with a long winter (indoor relative humidities are generally low during cold months), the average relative humidity would be expected to be higher in much of the country.

The *ANSI IT9.9-1990* Standard "recommends" a relative humidity of 50% for the Arrhenius tests, although the user of the Standard may select a different humidity level if the expected storage condition is higher (or lower) than 50% RH:

> Because the effects of humidity on image stability can differ markedly from one product to another, it is useful to evaluate its effect. This is done by means of a series of temperature tests carried out at different relative humidities. If the relative humidity during storage is expected to be significantly lower than 50% RH, such as in an arid climate, or significantly higher, as in a tropical climate, the relative humidity selected for the test should correspond to the climate. However, at relative humidities above 60%, especially at the high temperatures employed in accelerated tests, misleading results may be obtained because of difficulties in maintaining constant moisture levels and because of abrupt changes in the physi-

> cal properties of some components of photographic image layers, such as gelatin. Furthermore, the combination of high temperature and high relative humidity may cause changes that are not typical of a photograph's behavior under normal storage conditions.

This author believes that 60% is probably the single most representative relative humidity for stability tests, and this level — or two levels: 60% and 40% — will probably be adopted by this author for future work (60% RH has been used satisfactorily for many years in this author's accelerated light fading tests — see Chapter 3). Konica has used 60% RH for most of its published Arrhenius data (**Figure 2.26** shows the influence of relative humidity on the dye fading of Konica Type EX and Type SR papers). Fuji has run Arrhenius tests at <10% RH and at 70% RH, and Arrhenius predictions for Fuji products stored at both of these humidity levels are given in **Table 5.12** in Chapter 5 (these two humidity levels apparently were chosen based on *ANSI PH1.42-1969*).

Most data published by Kodak are based on 40% RH tests, although Kodak also routinely runs tests at 60% RH.[25] Reporting data for two relative humidities is helpful because this gives a clear indication of the humidity-dependence of fading and staining for a material. The dark fading rates of some dyes are greatly increased by high-humidity storage, while other dyes are little affected. It is to Kodak's advantage to use 40% instead of 60% RH for its published predictions of product life because with some products (e.g., color negatives with yellow dyes that are highly humidity-sensitive) the fading rate will *double* when the humidity is increased from 40% to 60%.

At What Point Are the Fading and Staining of a Color Print "Objectionable"?

Light-caused fading and staining of a color print on display are slow but steady processes that start immediately when the print is hung on a wall or placed in a frame on a desk. The rate and nature of image deterioration are functions of the inherent stability of the print material; the intensity, duration, and spectral distribution of the light used to illuminate the print; whether or not the print is framed; and the ambient temperature and humidity.

What constitutes objectionable fading and/or staining of a print is a highly subjective matter, and individuals may have sharply different opinions as to what is acceptable and what is not. And it is not simply a matter of how much of the cyan, magenta, and yellow image dyes has been lost: some pictorial scenes show fading and staining much more readily than others. Pictures with large areas of near-neutral low- and medium-density areas show fading effects much more than high-contrast scenes consisting mostly of saturated colors and large, dark areas. People are more sensitive to changes in the color rendition of flesh tones, blue skies, concrete roads and sidewalks, fried chicken, green grass, and other colors with which they are familiar — the so-called "memory colors" — than they are to the colors in abstract scenes and pictures of things like painted houses and cars, which could plausibly be any of a variety of colors.

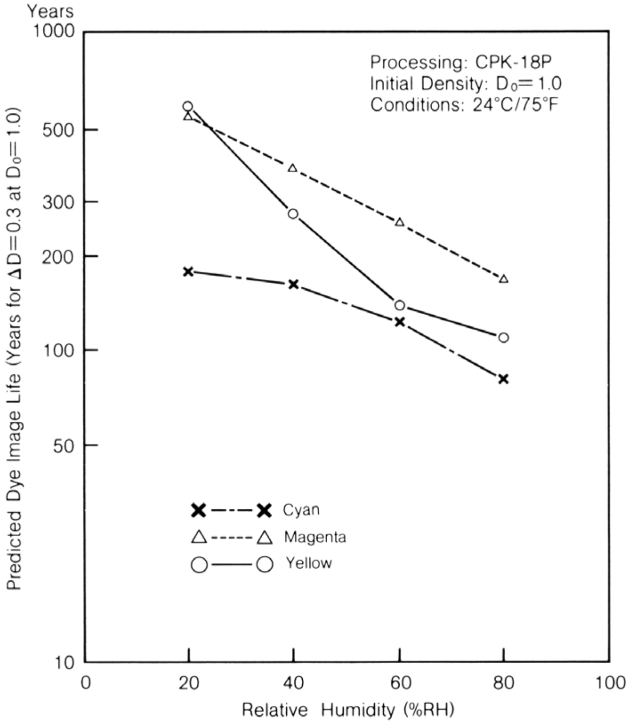


Figure 2.26 In high-humidity conditions, color photographs generally fade faster and form higher levels of yellowish stain than they do when stored under more moderate conditions. Shown here are Arrhenius predictions for 20%, 40%, 60%, and 80% RH for Konica Color PC Paper Professional Type EX (Type EX has the same stability characteristics as Konica Color PC Paper Type SR). Most of the dye stability data published by Konica to date have been for 60% RH, but it is likely that Konica and the other major manufacturers will in the future adopt 50% RH for published data because this is the value recommended by **ANSI IT9.9–1990**. (From: **Konica Technical Data Sheet – Konica Color PC Paper Professional Type EX**, Konica Pub. No. TDSK–231E, February 1987.)

With most color materials, light fading is characterized by a disproportionate amount of dye fading in the lower density portions of the image. This results in a loss of highlight detail while the darker parts of the image may appear to be unchanged. In the case of a white wedding dress, the sense of texture and weave in the cloth is usually conveyed by a very low-density image (typically about 0.20 to 0.35) and can be totally lost after only a relatively short period of display. With a photograph of this type, it is difficult to know if the print *ever* had significant highlight detail — that is, was it once a good print which is now somewhat faded, or was it just a poor photograph to begin with?

Perceptions of fading can be closely intertwined with the image quality of a print when new. Obviously, if a print is made with an overly green color balance, it will be difficult to tell if it shifts a bit further toward green as a result of magenta dye loss during light fading because the image quality of the print is objectionable whether or not it has faded.

Serious photographers usually want the very best visual print quality they can get. For photographers who make their own prints, it can be quite instructive to study color balance and density differences between the final print made from a particular negative and the closest rejected trial print. Although the types of changes that occur when a color print fades — especially the losses of highlight detail caused by light fading — are visually more complex than simple color balance and density variations, print comparisons of this type will furnish a good indication of the kinds and magnitudes of print quality deviations the photographer considers unacceptable.

For photographers selling quality work, there are many reasons why similar image-quality standards for evaluating new prints should also be used to determine when a print has faded an "objectionable" amount. This is not to say that a print no longer has any value and should be disposed of when fading has progressed beyond this point, or that the customer is even consciously aware of the fact that the print has faded. But it does mean that the photographer considers the print to have changed beyond a point where he or she would want to sell it if it were new. The print has lost the richness and clarity that the photographer worked so hard to obtain, and while the customer may not be able to define what if anything is wrong with the image, the perception will grow that there is nothing really special about the quality of the image. At this point, if an unfaded comparison print is available, the average person will immediately see the difference — and will have a strong preference for the unfaded print.

Eventually, the fading will reach a point where the customer is consciously aware of the fact that "something is wrong" with the print and — if the customer considers the image important — may even take it back to the photographer to ask for a replacement. Examination of faded prints returned to a number of portrait studios clearly indicates that most people do not return prints until they have become severely faded and discolored; however, it is likely that the relatively small number of faded prints that actually get returned represent only the tip of the iceberg of conscious or subconscious customer dissatisfaction. As long as a person in a portrait can still be recognized, the picture will probably continue to have some value to a loved one even if it is seriously faded and discolored.

Kodak and other manufacturers have often tried to justify the inadequate stability of their products by claiming that the average person will tolerate a significant amount of fading and still consider a print to be acceptable — as long as an unfaded print is not available for side-by-side comparison.[26]

While this may be true, it avoids the central issues of image quality and suggests that people should be content with mediocre photographs. For the serious photographer, it is not a question of what deficiencies in color prints people will tolerate but how to deliver a product that will convey a lasting feeling of exquisite tone and color reproduction.

For a museum collection, *any* clearly visible deterioration should be considered objectionable if it can be seen when a print in perfect condition is compared side by side with the print that has been displayed. The intent here is to preserve the color photograph in an essentially unchanged state so that the viewer can have the experience of looking at exactly the same image the artist originally created.

The feelings of luminosity, clarity, and color intensity — which in many scenes can exist right along with very subtle tonal gradations and color variations — of a carefully printed Ektacolor print can be considerably diminished by even a small amount of fading and overall yellow staining.

Image-Life Limits for Fading and Staining of Color Prints

After examining a large number of prints made on a variety of color print materials and which had faded as a result of exposure to light on normal long-term display, and prints which had faded under controlled conditions during accelerated light fading tests, this author developed two sets of criteria with limits for losses of density, changes in color balance, and stain formation. The initial work on these two sets of image-life criteria was done in 1978.[27]

In formulating these sets of image-life criteria, this author devoted considerable study to a group of six photographs printed from medium-format Kodak color negatives on Kodak Ektacolor 74 RC Paper — consisting of individual and family portraits and two representative wedding photographs — which had been incrementally faded using accelerated light fading and dark fading procedures. These prints were typical of high-quality portrait and wedding photographs made by professional photographers in the U.S. One of these negatives was subsequently selected to make carefully matched prints on nearly every chromogenic color negative print paper available in the U.S. since 1980 — including color negative print papers manufactured by Kodak, Fuji, Konica, Agfa, Mitsubishi, and 3M.

One set of image fading and staining limits, which is intended for general use, allows a fairly large degree of fading and color balance change to occur before the limits are reached. The other set of criteria specifies much smaller density losses and deviations in color balance and is intended for critical museum and archive applications.

These sets of criteria limits are weighted in an attempt to account for the differing human visual sensitivities to losses of cyan dye (red density), magenta dye (green density), and yellow dye (blue density). With most pictorial scenes, fading of the magenta dye is more obvious than the same degree of fading of the cyan dye. People are much more tolerant of the fading of yellow dye than they are of losses of cyan and magenta; likewise, a much greater degree of yellow stain can be accepted than would be the case if the stain were of another color. Yellow contributes very little to the perception of image detail, contrast, or the sense of light and dark; however, the amount of yellow dye present has a significant effect on the hue and "warmth" of a photograph and is a critical component of skin-tone reproduction.

Unequal losses of cyan, magenta, or yellow dyes that result in changes in color balance are much more noticeable than density losses when all three dyes have faded approximately the same amount. For this reason, both of these sets of image-life criteria limits (end points) allow greater overall dye fading than density loss imbalances among the three dyes.

General Home and Commercial Use

For general home and commercial applications, color prints will be considered to have faded and/or stained an objectionable amount when the *first* limit (end point) has been reached in any of the following image-life criteria, as determined from changes measured in gray-scale densities of 0.6 and 1.0, and in d-min (white) patches:

Absolute dye density loss (stain-corrected):

Loss of cyan dye (red density)	25%
Loss of magenta dye (green density)	20%
Loss of yellow dye (blue density)	35%

Color imbalance (not stain-corrected):

Color imbalance between cyan dye (red density) and [minus] magenta dye (green density)	12%
Color imbalance between magenta dye (green density) and [minus] cyan dye (red density)	15%
Color imbalance between cyan dye (red density) and [plus or minus] yellow dye (blue density)	18%
Color imbalance between magenta dye (green density) and [plus or minus] yellow dye (blue density)	18%

Change limits in minimum-density areas (clear whites), expressed in density units:

Change [increase] in red or green density	0.06
Change [increase] in blue density	0.15
Color imbalance between red and green densities	0.05
Color imbalance between red and blue densities	0.10
Color imbalance between green and blue densities	0.10

Critical Museum and Archive Use

For museum and archive applications (and also for important commercial and documentary photographs, where color and tone reproduction are critical), color prints will be considered to have faded and/or stained an objectionable amount when the *first* limit (end point) has been reached in any of the following image-life criteria, as determined from changes measured in gray-scale densities of 0.45 and 1.0, and in d-min (white) patches:

Absolute dye density loss (stain-corrected):

Loss of cyan dye (red density)	9%
Loss of magenta dye (green density)	9%
Loss of yellow dye (blue density)	13%

Color imbalance (not stain-corrected):

Color imbalance between cyan dye (red density) and magenta dye (green density)	7%
Color imbalance between cyan dye (red density) and yellow dye (blue density)	11%
Color imbalance between magenta dye (green density) and yellow dye (blue density)	11%

Change in minimum-density areas (clear whites), expressed in density units:

Change [increase] in red or green density	0.04
Change [increase] in blue density	0.08
Color imbalance between red and green densities	0.03
Color imbalance between red and blue densities	0.04
Color imbalance between green and blue densities	0.04

Because 0.45 was chosen as the principal measurement point in the "Museum and Archive" criteria set, the difference between the "Museum and Archive" and "Home and Commercial" sets of criteria is greater than might be supposed for chromogenic print materials such as Kodak Ektacolor paper. For these products, the lower the initial density is, the sooner a given percentage of dye loss is reached in light fading (unlike dark fading, where the percentage loss tends to be equal throughout the density scale). With light fading of dye-diffusion transfer materials such as Polaroid Polacolor ER, this may not be true, and, quite to the surprise of this author, some of these prints reached a density loss criteria limit at an initial density of 0.6 or 1.0 sooner than they did at 0.45.

For museum and archive collections, this author believes that the suggested criteria limits should be considered the maximum amount of image change that can be tolerated; with many kinds of pictorial content, differences will be clearly visible when an identical — but unfaded — print is compared with a print that has been displayed long enough to reach one of the suggested "Museum and Archive" criteria limits. Museum curators may want to adopt a more restrictive set of criteria for their collections.

The ANSI Test Methods Standard Does Not Specify Limits for Fading and Staining

The new *ANSI IT9.9-1990* Standard includes a set of image-life criteria (called "color photograph image-life parameters") that do not specify change limits (called "end points" in the Standard). According to the Standard:

> The image-life parameters listed are the critical characteristics that have practical significance for the visual degradation of color images; however, the numerical end points given here [in the Standard] are only illustrative. The

> subcommittee that produced this standard was not able to specify broadly applicable "acceptable" end points because the amount of image change that can be tolerated is subjective, and will vary with the product type and specific consumer or institutional requirements. Each user of this standard shall select end points for the listed parameters which, in that user's judgment, are appropriate for the specific product and intended application. Selected end points may be different for light and dark stability tests.

The set of criteria in *ANSI IT9.9-1990* also does not make provision for selecting *different* limits for cyan, magenta, and yellow dye losses, or for *different* limits for different directions of color balance change. In the future, ANSI may adopt a set of specifications for what constitutes "acceptable" fading and staining for color print and film materials.

At the time this book went to press in 1992, no one yet had published Arrhenius predictions based on the set of image-life parameters specified in *ANSI IT9.9-1990.* Since 1984, Konica has used a simple "30% loss of the least stable image dye" limit on which to base its claim of a 100-year dark storage life for Konica Color Paper Type SR (also called "Century Print Paper" and "Long Life 100 Paper" in Konica's promotional literature for the paper). This is a fairly large loss in dye density and results in a significant color shift toward magenta. Especially with Type SR paper processed with a normal water wash, the dye loss is accompanied by a high level of yellowish stain. One could speculate that Konica's principal motivation in selecting the large, 30% density loss figure was so that the claim of a 100-year print life could be made.

Eastman Kodak's Guidelines for Color Image Fading

In a March 1991 Eastman Kodak publication entitled *Evaluating Image Stability of Kodak Color Photographic Products,*[28] the company issued the following dye-loss guidelines (from a 1.0 neutral patch) for prints, transparencies, and other color materials that are directly viewed (these guidelines do not apply to color negative materials):

- **0.10 Dye Loss** (remaining density 0.90)
  A 10% dye loss is only observable in a critical side-by-side comparison with an unfaded sample of the same image.
- **0.20 Dye Loss** (remaining density 0.80)
  A 20% dye loss is observable in a critical evaluation of the image by itself by someone familiar with the original quality of the image.
- **0.30 Dye Loss** (remaining density 0.70)
  A 30% dye loss is sufficient that most observers are aware that the image has faded and has less quality. However, since this is a very subjective evaluation, losses beyond 30% may continue to be acceptable depending on the intended use of the photographic material or the nature of the image.

Kodak went on to say: "These are only general guidelines, and assume some neutral and some non-neutral fading. Neutral fading (equal fading of different colors) is far less evident than non-neutral fading (unequal fading of colors). The most extreme case is where fading of one dye in the material is significantly different from the fading of the other two dyes."

Following Konica's lead, Kodak has in a few instances also based claims of a 100-year+ life for Ektacolor paper stored in the dark on a 30% loss of the least stable image dye.

ANSI Abolishes the Term "Archival," Replacing It with "LE Ratings" for B&W Films

In 1990, ANSI Committee IT9, which has jurisdiction over ANSI standards pertaining to physical properties and permanence of photographic materials and other imaging media, voted to abolish the long-standing "archival" designation in ANSI standards for black-and-white films and in standards concerned with storage conditions for photographic materials.

For films, ANSI replaced the "archival" designation with Life Expectancy ratings (LE ratings), which are given as "years of useful life" under specified processing and storage conditions. Definitions for these new terms are included in *ANSI IT9.1-1991, American National Standard for Imaging Media (Film) – Silver-Gelatin Type – Specifications for Stability*[29] (the wording given here is tentative and may be somewhat altered in the published version of the Standard):

> **Archival Medium.** A recording material that can be expected to retain information forever so that it can be retrieved without significant loss when properly stored. However, there is no such material and it is not a term to be used in American National Standard material or system specifications.
>
> **Life Expectancy (LE).** The length of time that information is predicted to be retrievable in a system under extended-term storage conditions. (Note: The term "Life Expectancy" is a definition. However, the actual useful life of film is very dependent upon the existing storage conditions [see *IT9.11*].)
>
> **LE Designation.** A rating for the "life expectancy" of recording materials and associated retrieval systems. The number following the LE symbol is a prediction of the minimum life expectancy in years for which information can be retrieved without significant loss when stored under extended term storage conditions, e.g., LE–100 indicates that information can be retrieved after at least 100 years storage.
>
> **Extended-Term Storage Conditions.** Storage conditions suitable for the preservation of recorded information having permanent value.
>
> **Medium-Term Storage Conditions.** Storage conditions suitable for the preservation of recorded information for a minimum of ten years.

In *ANSI IT9.1-1991,* the maximum LE rating for black-and-white films with a cellulose ester (e.g., cellulose triacetate) base is set at 100 years when the film is kept under Extended-Term storage conditions, and the maximum LE rating for polyester-base films is 500 years.

If ANSI subcommittee IT9-3, the group responsible for the *ANSI IT9.9* color stability test methods Standard, is able to come to agreement on what constitutes "acceptable" levels of fading and staining for color prints and films, and can also define a set of standard storage and display conditions, the concept of LE ratings could be expanded to include color materials.

Densitometric Correction for Minimum-Density Yellowish Stain

In this author's tests, most types of prints developed some yellow stain density as a consequence of exposure to light, but in almost no case was a minimum-density (stain) criterion the first limit to be reached. In accelerated dark fading tests, the minimum-density change limits were often reached very quickly, but Ilford Cibachrome (Ilfochrome), Kodak Dye Transfer, and Fuji Dyecolor prints developed little if any stain density during these light fading tests.

For determining absolute density loss of the cyan, magenta, and yellow dyes, this author has "d-min corrected" (also called "stain-corrected") all densitometric data prior to analysis. That is, increases in red, green, or blue density measured at d-min have been *subtracted* from the all densities above d-min. If stain density were not subtracted, it would, to the degree that stain has occurred, mask the dye fading that has actually taken place. For example, a yellowish d-min stain causing a blue density increase of 0.08 could make a medium-density yellow dye appear not to have faded at all when in fact it lost 0.08.

While it is true that the human eye does not "subtract" stain density in this way (a person looking at a print sees the visual combination of the image dye and stain), it is essential that stain be subtracted for meaningful analysis of density loss. Otherwise, it would be of *benefit* for a print to develop stain density because this would lessen measured dye fading. In this author's sets of image-life fading limits, losses of absolute density can be thought of as "information" losses, measured as losses of image detail and contrast.

The concept of stain-correcting (d-min correcting) data makes the assumption that stain measured at d-min occurs to the same degree throughout the density range of the print. Unfortunately, this assumption is not always justified; some types of photographs (e.g., Polacolor 2 prints) generate more stain in high-density areas than at d-min.

Stain in chromogenic prints is caused mostly by "printout" of unused magenta coupler, and logic would dictate that in high-density portions of an image, most of the magenta coupler has been converted to image dye and therefore less stain should be present. However, with a conventional densitometer, stain density cannot be distinguished from dye density, except by inference from changes observed at d-min, and for this reason we have no recourse except to base corrections on d-min measurements.

It is obvious that even with its shortcomings, d-min corrections made in this manner are better than simply not stain-correcting density data at all. One certainly does not want to reward a print material for stain! It is believed that most of the product-fading information published by Kodak and the other major manufacturers has been derived from d-min corrected data (Kodak has not generally published stain characteristics for prints and films stored in the dark).

Determining color imbalances is another matter, however, and based on study of many moderately faded (and stained) pictorial prints, it is apparent that much better visual correlation is obtained when densitometric data are *not* d-min corrected. Shifts in color balance toward yellow, for example, are accentuated by yellow stain, and this is visually most apparent in low-density portions of the image. At the critical densities between about 0.35 and 0.60, stain is frequently a major determinant of perceived color shift (shown previously in **Figure 2.19**).

In the tests conducted by this author to help formulate the criteria sets described here, changes in pure cyan, magenta, and yellow patches were also measured and analyzed, although fading limits for these separate colors were not included in either the "Museum and Archive" or "Home and Commercial" criteria limits. When these colors also exist in a print in equal amounts to form a neutral gray, the pure colors often fade much faster than they do in a neutral gray area. The significance of this is very scene-dependent and can be difficult to interpret; for example, a "blue" sky on a print typically consists mostly of cyan dye, much of which can be lost and still leave a blue sky, even if it is a lighter shade of blue.

The particular relationship of pure-color versus gray-scale fading also differs with each type of print material, and this author feels that a great deal more study is required if meaningful limits are to be assigned. In general, the analysis of gray-scale fading appears to be the best single indicator of the overall light fading performance of a material.

How much and what kind of image fading and staining are objectionable, and defining the "useful" life of a displayed color print, are topics that are certain to be discussed and argued about for years to come. Although much effort has gone into determining the two sets of criteria limits given here, they are obviously not the last word on the subject. Statistical studies need to be done to better evaluate the responses to faded images by people of different backgrounds and cultures. Variation of tolerance to yellowish print stain among individuals in different parts of the world is a highly interesting aspect of this subject and certainly merits further investigation.

This author expects that these criteria will be modified in the future as more experience is gained with faded prints made on the broad range of color products now on the market; it is also possible that separate sets of criteria should be devised for dark-faded prints and transparencies because this type of deterioration has some significant visual differences from fading and staining caused by light fading.

The selection of a particular percentage of density loss, beyond which fading will be considered objectionable, will always be somewhat arbitrary. Given the variety of pictorial scenes, the different fading characteristics of the many types of print materials in use, and the variations in indi-

John Wolf – July 1980

Henry Wilhelm taking density readings from print samples that have been undergoing accelerated light fading tests. Since this work began in 1977, this author has made more than one million individual densitometer readings. At first, as was the case when this photograph was taken in 1980, the data were manually transcribed into notebooks. Since 1983, however, the data have been downloaded electronically from Macbeth and X-Rite densitometers to a Hewlett-Packard HP-125 computer for recording, d-min correction, and analysis according to the sets of image-life criteria described in this chapter. To facilitate this work, a number of computer programs were written for this author by June Clearman, a mathematician and programmer.

vidual responses to faded photographs, it would be difficult to say that a minimum-density color imbalance of 0.06 between yellow and magenta is acceptable while a 0.08 color imbalance is not. Yet, in some cases, that small 0.02 variation in acceptability can result in a large difference in the stability ranking of a product.

In spite of these limitations, the two sets of image-life criteria given here can be quite helpful in comparing the image stability of one product with another, and in making predictions of how long a particular type of print can be displayed before objectionable fading occurs. The criteria correlate reasonably well with visual perceptions of faded color images, and this author believes they represent a significant improvement over past methods of evaluating the fading and staining of color photographs.

Densitometers for Measuring Fading and Staining

Photographic densitometers are electronic instruments that measure the optical density of photographic materials. Transmission densitometers are used with transparent films, and prints are measured with reflection densitometers. The instruments have long been employed in the photographic industry for research and development work, process control, and other purposes.

Color densitometers have separate filters, or “channels,” that measure the densities of the cyan, magenta, and yellow dyes that form the images in most color materials. In what is sometimes confusing to those not familiar with color densitometry and the subtractive system of color image formation, the cyan dye is measured with a red filter (because cyan dye absorbs light primarily in the red portion of the spectrum) and changes in cyan dye density are often referred to as “red density” changes. The same holds true for magenta dye density changes (“green density” changes), and yellow dye density changes (“blue density” changes).

During the course of this work, which had its beginnings in 1976, this author has used ESECO, Macbeth, and X-Rite densitometers. More than one million individual density readings have been made by this author during this 16-year period. Especially in research conducted over long periods of time, a number of potential problems with densitometers may arise.

To maintain accuracy of the system, especially when densitometer filters are replaced (or, a much more critical matter, when the entire instrument is replaced with a new model), it is *essential* that representative color print and film samples be preserved in a freezer at 0°F (–18°C) or colder. These “freezer check” samples can be withdrawn from cold storage from time to time to verify instrument calibration. Any deviations from the original readings made with these samples can be used to make numerical corrections to current readings. This subject is discussed in greater detail in Chapter 7, and is also discussed in *ANSI IT9.9-1990.*

Computer Acquisition and Processing of Densitometer Data

When this author acquired his first densitometer and began doing systematic research on color stability in 1977, each reading had to be transcribed by hand into notebooks. This not only was tedious and time-consuming but also required constant double-checking to keep transcription errors to a minimum. (If a mistake is made and a number is incorrectly entered into a notebook, it is usually difficult to detect, and if it happens to be detected, it is usually impossible to precisely correct after the fact.)

During the course of a test, densitometer readings from each individual sample may be taken ten or more times.

Bob Schwalberg – October 1989

This author, his son David Wilhelm, and Carol Brower discussing some of the test data accumulated over the years. Data files are stored on computer disks, and hardcopy printouts (shown here in ring binders) are generated by computer after each sample has been read with a densitometer.

With each sample, which consists of a photograph of a Macbeth ColorChecker color test chart, four readings (through the red, green, blue, and visual densitometer filters) are made from 11 of the patches in the ColorChecker image. Included among the patches that are measured are a 6-step gray scale; cyan, magenta, and yellow patches; and light and dark skin tone patches. In addition, a reading is made from a separate clear d-min (white) patch. This comes to a total of at least 480 individual densitometer readings per sample. To improve the reliability of the whole testing procedure, a minimum of three replicate samples are run for each product under each test condition. Over the years this has involved thousands of samples and well over one million individual density readings.

After the data are recorded, there remains the task of determining at exactly what point the limit for each of the previously described fading and staining criteria has been reached. Because the test samples do not have precise 1.0 or 0.6 (or 0.45 for "museum and archive" applications) neutral density patches from which to report changes in red, green, and blue densities, it is necessary to mathematically interpolate the desired densities from adjacent patches that are both higher and lower in density than the target densities. Additionally, the density loss criteria require that data be corrected for yellowish or other stain that develops in d-min areas over the course of a test.

With an ever-increasing number of product samples being added to this author's testing program, the amount of work involved soon became so overwhelming that it could not continue without computerizing the entire data acquisition, d-min correction, and criteria analysis process.

Over a period of several years, beginning in 1983, June Clearman, a mathematician and computer programmer who at the time worked at the Robert N. Noyce Computer Center at nearby Grinnell College, wrote a series of programs to run on this author's Hewlett-Packard HP-125 computer to handle all of the necessary data recording and analysis tasks (see **Appendix 2.1** on page 99 for a description of some of the mathematical procedures employed in these programs). Both the Macbeth TR-924 and X-Rite 310 densitometers used by this author were hardwired directly to the HP-125 computer using interface routines written by Clearman, and this eliminated the need for manual transcription of data into notebooks.

Special programs were written to enter into the computer the densitometer data that had been transcribed in notebooks during the previous 6 years. Keyboarding and verifying the accumulated notebook data were a major undertaking, but this transcription permitted d-min corrections, density scale interpolations, and criteria analysis to be done by computer with the data from the older products and proved to be a very valuable addition to this author's product-stability database.

Today, these data files are stored on about 200 floppy disks. To avoid data loss in the event of fire or tornado (most of the town of Grinnell was destroyed by a tornado in 1882, and a tornado hit the edge of town in 1978), a complete backup set of data disks is kept in a safe deposit box in a Grinnell bank. In addition, hardcopy printouts in binders are kept for all of the data. In the future, the whole system will be transferred to Apple Macintosh computers and additional programs will be written for Arrhenius testing and other data-handling and analysis needs.

Processing of Test Samples

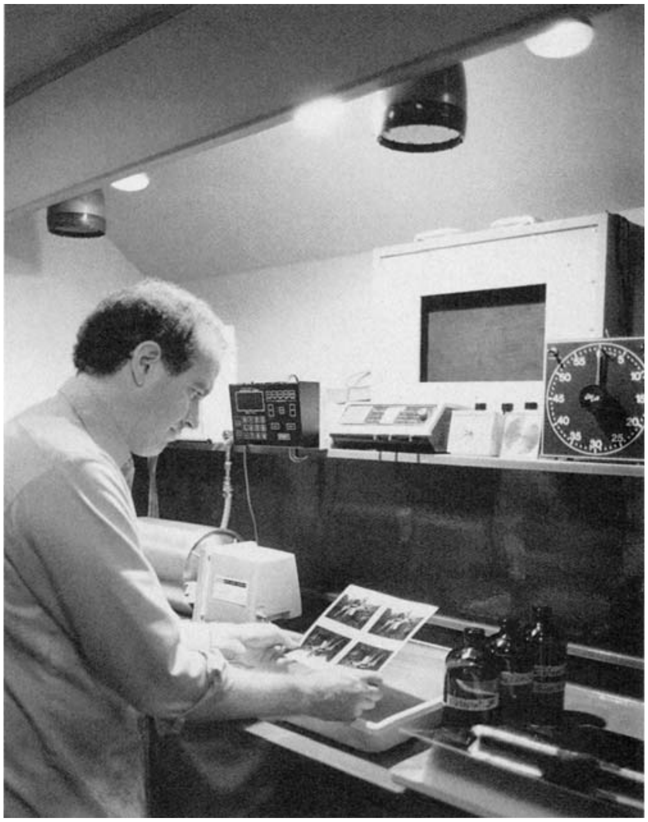
When Kodak, Fuji, and other manufacturers test color films and papers, their samples have received optimal processing and thorough washing under carefully controlled laboratory conditions. This is done both to show the products to their best advantage and to be sure that tests will be repeatable over time (that is, to eliminate processing variations as a consideration).

In the real world of replenished processing lines, hurried lab schedules, and efforts to keep chemical and water costs to a minimum, conditions frequently are not so well controlled, and image stability can suffer. In some cases, processing shortcomings such as chemical exhaustion, excessive carryover of processing solutions from one tank to the next, inadequate water flow in wash tanks, or omission of a stabilizer bath have resulted in drastic reduction in image stability.

In recent years, a number of companies have entered the photographic processing chemicals market, generally supplying chemicals at lower cost than do Kodak, Fuji, and the other major manufacturers. What effects that processing chemicals from these outside suppliers might have on long-term image stability is not known. Some companies, in an effort to shorten processing time or reduce the number of processing steps, have substituted color developing agents, eliminated stabilizer baths, and taken other shortcuts that could adversely affect image stability. For predictable results, it is recommended that only chemicals from the major materials manufacturers (i.e., Kodak, Fuji, Agfa, and Konica) be used for processing test samples. Processing recommendations, replenishment rates, wash flow, and temperature specifications should be followed to the letter.

Most labs try to retain tight control on color developer activity — that is, to reduce any process deviation resulting in image-quality losses that can be visually assessed immediately after processing. But other processing problems, such as too-diluted (or omitted) C-41 or E-6 stabilizer baths, excess bleach/fix carryover, or inadequate washing, may not manifest themselves until years later.

In an attempt to represent the real world of good-quality, replenished-line processing, all C-41 color negative films, E-6 transparency films, and Kodachrome films in this author's testing program were processed by the Kodalux Processing Services of Qualex, Inc. Eastman Kodak owns almost half of Qualex (the former Kodak Processing Laboratories are now part of Qualex), and Kodak chemicals are used exclusively. Because of Kodak's close involvement with Qualex, it was assumed that the labs pay close attention to proper chemical replenishment and washing, and the consistency of stability data obtained from the same type of film processed at different times by Kodalux suggests that this is, at least for the most part, true.


Carol Brower – September 1983

Carefully processed print samples for testing are produced in the Preservation Publishing Company darkroom. Most of the prints have been processed with a Kodak Rapid Color Processor (Model 11) equipped with a precision, electronically controlled temperature regulator. Processing chemicals are freshly mixed, used only once, and then discarded. Prints are thoroughly washed, both front and back.

In order to obtain closely matched pictorial prints for reproduction in this book, for use in articles, and for corresponding Macbeth ColorChecker[30] test samples for densitometry, EP-2 and R-3 compatible papers were processed by this author with Kodak chemicals in a Kodak Rapid Color Processor (Model 11) which has been fitted with a precise electronic temperature regulator. Each test print was made with fresh chemicals (Kodak Ektaprint EP-2 Stop Bath was used between the developer and bleach/fix), and the prints were carefully washed.

Processed Cibachrome samples were furnished by Ilford in Switzerland, and additional samples were processed by this author. Kodak Dye Transfer prints were made in several different New York City labs. Fuji Dyecolor prints were made by Fuji in Japan. UltraStable Permanent Color prints and Polaroid Permanent-Color prints were supplied by Charles Berger, the inventor of both processes.

Konica, Fuji, and Agfa RA-4 compatible paper samples were processed by their respective manufacturers from test negatives furnished by this author; in most cases, print samples processed with a water wash and with a washless stabilizer in a minilab were made available. Kodak declined to furnish processed samples of its Ektacolor RA-4 papers to this author, so these prints were obtained from several different one-hour labs using Kodak minilabs and Kodak RA-4 chemicals. In addition, sample prints made on Ektacolor Supra, Ektacolor Portra, and Ektacolor Portra II papers were obtained from several top-quality professional labs in 1991 and 1992.

Exactly what constitutes “typical” or “normal” processing cannot be specified at this time. Also unknown is how the stability of each of the vast number of different film and print materials on the market is affected by different types of processing chemicals and by process deviations — some products are obviously more sensitive to improper processing than are others. Yellowish stain formation during dark storage appears to be particularly affected by processing and washing conditions; a sobering study on this topic was presented in 1986 by Ubbo T. Wernicke of Agfa-Gevaert entitled “Impact of Modern High-Speed and Washless Processing on the Dye Stability of Different Colour Papers.”[31]

This author has accumulated a large store of unprocessed color paper, transparency films, and color negative films in refrigerated storage so that, if necessary, additional work can be done in the future with materials that are no longer being manufactured.

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(Chapter 2 – Appendix 2.1 on following pages)

Appendix 2.1 – Methods of Computer Analysis of Densitometer Data

By June Clearman
Programmer/Analyst

The programming of the automatic transfer of densitometer readings to a computer for storage on magnetic disks, the calculation of the various curves, and the application of image-life criteria required several assumptions and simplifications. The reading of a new sample with a stepwise visual scale (either a gray scale and/or a step wedge of cyan, magenta, yellow, or other selected colors) could yield values that were not necessarily the same as the readings for any other new sample, or even the same as another copy of a particular sample. Although these steps were roughly arranged in an exponential (or logarithmic) progression, so that there was a temptation to fit a smoothed exponential curve to the data, there was really no logical reason to do so. The reason for wanting to fit a curve at all rather than to deal only with the discrete points of the readings was for the purpose of comparison among samples. One could make immediate comparisons by following, on different samples, what happens from an initial density reading of, for instance, 0.6 at specific intervals of elapsed time. In our judgment, the densitometer, with proper checking, could be trusted, within its range, for greater accuracy than the process producing the samples, or the assumption of a logarithmic progression. Therefore, any method for assuming values between the actual steps on the scale would have to be an interpolation between actual data points rather than a smoothed curve-fit method. That decision led to the next decision, which was the choice of an interpolation technique.

Interpolation Methods

The simplest way to interpolate between two points is by joining them with a straight line. That method appears to involve no assumptions about the data beyond the initial assumption that the known points are accurate. However, if one were to join the end points only of a set of points, or the endpoints and the midpoint, such lines would probably miss all the intervening points somewhat, and we would realize that straight-line interpolation indeed is making an assumption about the shape of a curve within any interval. Furthermore, any straight-line joining of data points on a graph shows abrupt changes of direction from point to point, so that each recorded point represents a discontinuity in the curve. Even just intuitively, we wish to reject such discontinuities. One feels that a proper joining of half the recorded points should yield a curve not substantially different from one using all the points or from one using twice the number of recorded points (if we only had them). Probably the best, and simplest, method of accomplishing a smooth joining of readings taken at nonregular intervals is a method called "spline fitting," which will be explained below.

Our initial readings of a sample have the actual recorded data from our stepwise visual scale, to which we have arbitrarily assigned integer values corresponding to the order of the steps. That is, a value of 1 has been assigned to the step value of the least dense patch of the graduated visual scale, 0 to a clear minimum-density patch if such exists, and so forth. Using these values as the independent variable, and interpolating between the readings associated with these points, we then can say that a particular value of densitometer reading would exist at a particular non-integer value of the independent variable, if we can simply accept the reality of such a step as 1.55 or 2.68 (i.e., a step placed somewhere on a graduated scale between any two known steps). Then if, for instance, we find one of our desired initial densities yielding a step value of 2.68, on a second, or any subsequent, reading we may ask, given the density values at step 2 and step 3, what would the density at step 2.68 be, had we such a step. We are essentially reversing the process we used for the first reading. Instead of looking for the step value that corresponds to a particular density, we are now looking for what density value we should have been able to read had we arranged physically to have such a step value. This reversal of the interpolation process must, of course, use the same basic procedure as the initial interpolation, except that here, instead of trying to find the particular value on the step scale that represents a desired density value, we are looking for the density value that would be yielded by that particular step value. This reversal of procedure makes for a degree of simplification.

On the original reading, besides solving for the values needed to do the interpolation, we needed a search procedure on the interpolation curve to find, within a programmed degree of accuracy, the particular density values we had decided would be useful for comparisons. We have adopted a binary search technique, which simply means that starting with a known interval, we examine the midpoint and, from it, determine which half interval contains the desired value. A recursion of this method, given a continuous monotonic curve, quickly yields an interval sufficiently small for any desired degree of accuracy.

Determining Failure Points for Image-Life Parameters

Application of the various image-life criteria to the successive sets of readings presents yet another situation where the spline-fit technique seemed to be a relatively simple and sensible way to arrive at a value of elapsed time that we knew must occur between any two actual sets of readings. Theoretically, the actual shape of the curves of density against time should be derivable from the chemistry involved. Practically, however, this is much too complex, encompassing as it does the chemistry of the particular photographic material and the chemistry of any subsequent image-deterioration effects — effects of the support material, staining, light sources, temperature, relative humidity, and so forth. So here again we must settle for an assumption that the actual density readings are the most accurate thing we have and that any attempt to connect the curves should be relatively smooth and continuous, but not a curve fit that departs from the actual data on some least squares or other error-tolerance scheme unless there are a sufficiently large number of readings to clearly define the curve shape.

Any such scheme implies the choice of a curve form, preferably one derived from the actual physics or chemistry of the phenomena under examination. This might be a polynomial expression, or exponential, or one or another transcendental expression. The choice of any one of them would require justification in terms of the physical and chemical processes involved. Therefore, we attempted to use spline fitting here also. However, in many cases where the density change was very small over relatively long time periods, or where the curve changed direction very quickly over short periods, we felt that a straight line might be as essentially correct an interpolation as any other method.

The problem of numerical accuracy, for instance, where a density change of only 0.02, for example, occurs over a period as long as perhaps 185 days is such that one can say very little about the exact spot where the change was 0.01. The computer was therefore programmed to yield both spline-fit and straight-line values. (Straight-line values were used for determining the criteria failure points reported in this book; spline-fit and other methods of curve smoothing as applied to irregular fading curves are a subject of continuing study.) It should be noted that, regardless of whether the criteria were applied to a single curve or were imbalance criteria involving the ratios between two curves, the fit and search routine was applied to the curves themselves, and not the ratios.

The Spline-Fit Curve Smoothing Method

This interpolation method was named after a handy drafting device. Consisting of a flexible lead core encased in rubber, a spline can be bent to meet many points and produce a graph with a continuous slope and curvature.

What we do is solve for any point within any pair of adjacent points by using a third-degree polynomial, unique to each interval, that is determined in such a way that it passes through the end points of the interval and matches up each such interval, with the polynomials for the intervals on each side, maintaining continuous first and second derivatives through the endpoints. This means that the slope at any interval endpoint (p_k, y_k) is the same whether we compute it from the left using the interval $[p_{k-1}, p_k]$ or from the right using the interval $[p_k, p_{k+1}]$. These conditions would uniquely determine every polynomial for all intervals, except that at the first and last points we have nothing to match. This means that we are missing two conditions to complete our interpolation process. One solution is to require that the second derivative at each end point be a linear extrapolation of the second derivative at the neighboring points (i.e., the third derivatives are constant for p_1 and p_2 and for p_{n-1} and p_n, i.e., $y'''_1 = y'''_2$ and $y'''_{n-1} = y'''_n$). Other endpoint methods could be used to determine the two missing conditions for a complete system of **n** equations in **n** unknowns.