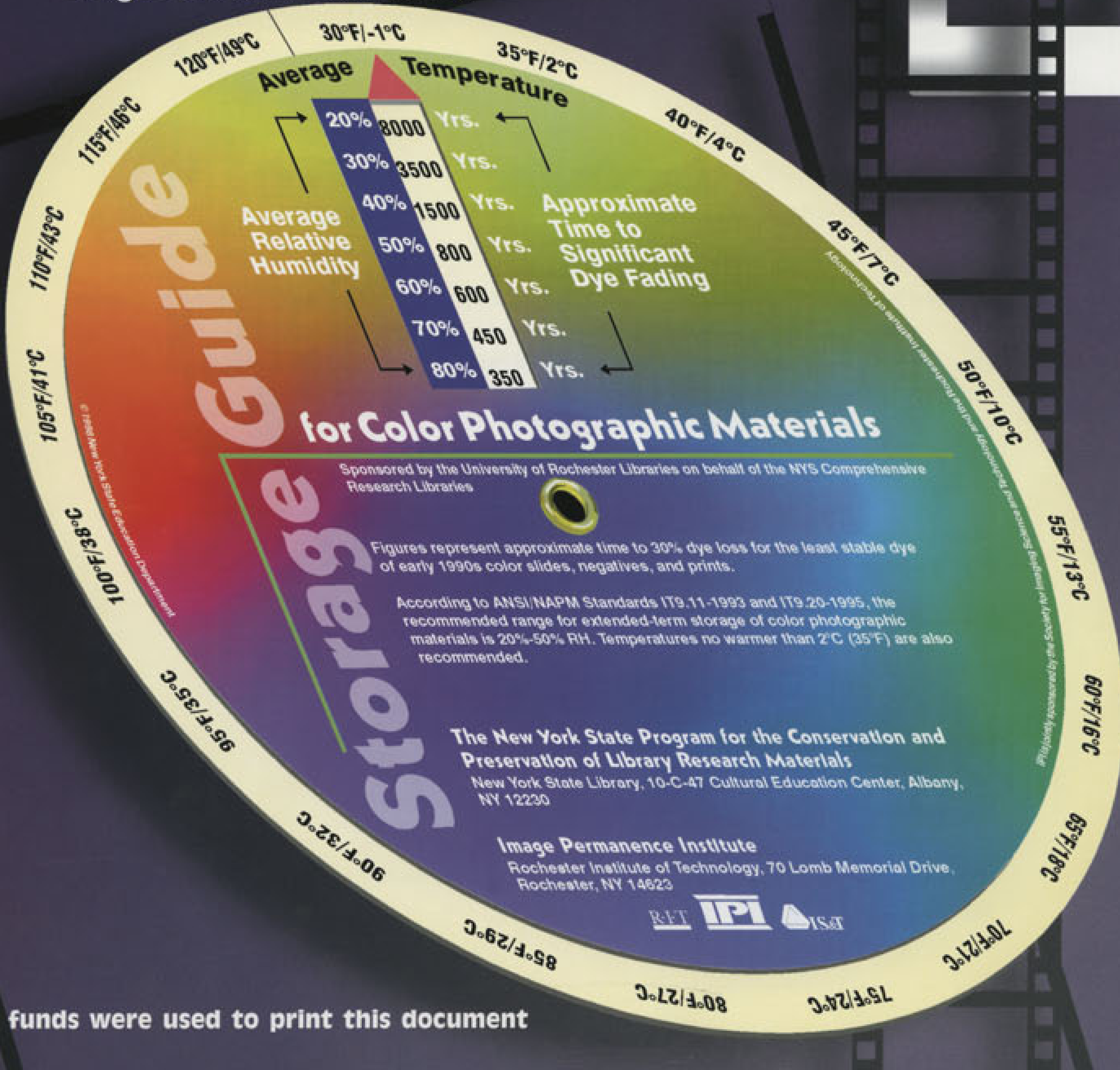
Storage Guide for Color Photographic Materials

James M. Reilly
Image Permanence Institute

Caring for color slides, prints, negatives, and movie films



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Figures represent approximate time to 30% dye loss for the least stable dye of early 1990s color slides, negatives, and prints.

According to ANSI/NAPM Standards IT9.11-1993 and IT9.20-1995, the recommended range for extended-term storage of color photographic materials is 20%-50% RH. Temperatures no warmer than 2°C (35°F) are also recommended.

The New York State Program for the Conservation and Preservation of Library Research Materials
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The Image Permanence Institute

Image Permanence Institute is an academic research laboratory located on the campus of the Rochester Institute of Technology in Rochester, New York. Since its founding in 1985, IPI's mission has been research for the advancement of the permanence and preservation of imaging media and information resources. IPI is cosponsored by RIT and by the Society for Imaging Science and Technology.

The scope of IPI's research covers the preservation of photographic materials, digital imaging issues, and issues related to the physical survival of information resource collections. IPI has been an innovator in the field of preservation practice; among the products and services developed by IPI are the Photographic Activity Test (a test for safe enclosures for photos), IPI SilverLock® (an image stability treatment for microfilm), and A-D Strips (a way to check acetate film for the form of deterioration known as "vinegar syndrome"). IPI is also well known for its accelerated-aging studies of photographic materials including acetate, nitrate, and polyester films, color dyes, and gelatin.

IPI serves the preservation community not only through its research but also as a ready source of technical information. IPI also provides technical and administrative support for the American National Standards Institute (ANSI) and the International Standards Organization (ISO) in the area of permanence and care of imaging media, including tape, optical disc, and photographic materials.

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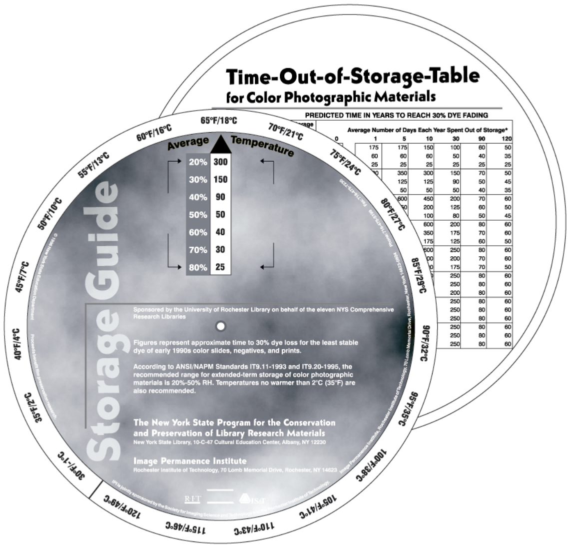
INTRODUCTION

It is a familiar fact that color photographs fade over time. In many cases this fading takes place very rapidly—in a few decades, or sometimes just a few years. Because color photography has been the dominant form of photography since the middle sixties, and because nearly all of the billions of photographs made annually are now made in color, it is important to understand how to store color photographs in order to obtain the desired service lifetime. Although it is unrealistic to expect that color photographs will survive for centuries when kept at ordinary room conditions, even the most fugitive color images can be preserved indefinitely by the use of appropriately cold and dry storage conditions. This publication explains why color images need special storage and suggests ways to make them last as long as possible.

Some of the hundreds of photographic color paper samples used in the University of Rochester/IPI research project on color image stability.

The information in this publication comes from accelerated-aging data obtained by the Image Permanence Institute in a project conducted and sponsored by the University of Rochester Libraries on behalf of the New York State Comprehensive Research Libraries as part of the New York State Program for the Conservation and Preservation of Library Research Materials. The project examined the image stability of four contemporary color photographic materials, each one a best-selling representative of its type. Included were a color negative film, a color slide film, a color print material, and a color motion picture release print film. The project was conducted from 1993 to 1996 and involved hundreds of individual samples of each product. A large number of samples was required because accelerated-aging tests were conducted at four different relative humidities and six different temperatures, with replicate samples at each condition to ensure statistical validity. This was one of the most extensive accelerated-aging projects ever done for the purpose of examining how storage conditions affect image fading.

The purpose of the accelerated testing was to obtain data for the construction of a generic overview of the stability of today's color photographic materials. Not all products on the market today have equal stability. It was hoped that



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The relationship between storage conditions and the life expectancy of contemporary color photos is given in the wheel accompanying this publication.

data from four widely used contemporary products could provide a reasonable estimate of the behavior of other contemporary materials, at least for purposes of planning and evaluating conditions for storage in the dark. While one can shield an image from light, there is no escaping the continual influence of heat and moisture on photographic color dyes. Spontaneous dye fading goes on 24 hours a day, 365 days a year. In this sense, behavior in the dark determines the maximum possible stability of a color photograph.

As it turned out, although the four products in the research study did not have identical stability, their behavior was similar enough that the creation of a single generic overview was possible. Organized in table or "wheel" format, the data collected during the project can be used to roughly estimate the life expectancy of contemporary color images under a variety of storage conditions. Alternatively, the wheel can tell what combinations of temperature and relative humidity (RH) will provide the desired life expectancy. One of the complicating factors in estimating the lifetime of color photographic materials is the fact that a given product's three component dyes—cyan, magenta, and yellow—may fade at different rates. In creating the wheel, the *limiting dye* of each product (the one that fades the fastest) was used. For all the products tested in this project the limiting dye was yellow.

STABILITY OF COLOR MATERIALS: SOME HISTORICAL BACKGROUND

Early Color Films and Papers

The first widely used color film based on the principles of modern photographic technology was Kodak Kodachrome Film™. Kodachrome was introduced in 1935 and substantially revised into something resembling its present form in 1938. Kodachrome (a film that produces color transparencies—i.e., color slides) was an anomaly among color photographic films for several reasons, one of which was its relatively good dark stability. When kept in the dark at room conditions, Kodachrome requires about 40 to 50 years for 30% yellow dye loss.

This level of permanence was a fairly good start for chromogenic color photography, but soon to come were much less stable color negative and print systems such as Kodacolor™, introduced by Kodak in 1942. Consumers, then as now, preferred to have prints rather than slides. Kodacolor had very poor dye stability under both light and dark conditions. With the early negative and print products of the Kodacolor family, 30% cyan dye loss could occur after only about five to seven years, with yellow dye loss close behind. Many late forties and early fifties color prints and negatives are now nearly monochromatic, having only magenta dye left (and even the magenta has faded to some extent).

Although Kodachrome film possessed good dark stability, its easier-to-process successors, such as Kodak Ektachrome™ (introduced in 1946), were marked by much poorer dye stability. Ektachrome's behavior was similar to that found in the early color negative and print materials. As the European photographic industry rebuilt itself after World War II, a number of new products were put on the market, but except for a few good performers their stability was as bad as, or worse than, comparable Kodak products.

Progress in Stability During the Fifties and Sixties

During the fifties, some stability improvements were made; a terrible yellow-orange staining that often discolored the white areas of color prints was greatly reduced. However, most products continued to have poor dark fading characteristics. This was true not only of different brands of films, but also of the different product types—slides, negatives, prints, and motion picture films. All of these product types made use of broadly similar dye sets, although the specific dye structures varied in small ways from product to product.

It is important to realize that photographic materials are constantly evolving; the manufacturers often change them without announcement. This is because small changes are continually made to correct problems in the products as they are noticed. This steady stream of small changes is occasionally punctuated by large alterations when major improvements occur. When this happens, the products sometimes are renamed and other times are not.

The explosion of the popularity of color photography that occurred in the sixties saw some additional gradual improvement in stability, but color prints still lost 30% of their cyan dye within ten to fifteen years. Museums consciously avoided purchasing works in color because they would not last. Still, Hollywood and the picture-taking public alike were thrilled with color and gave little thought to long-term storage of images. The great profits realized from the sale of color photographic materials helped to finance research on improvements in stability, and progress was made as fast as technology and other considerations (such as convenience in processing) would allow.

Test Methods to Predict the Life Expectancy of Color Materials

During the seventies, awareness of the impermanence of color photographs began to build. The evidence of fading color in older products was plain to see in many family albums and film vaults. Through the efforts of activists like Henry Wilhelm, film director Martin Scorsese, and others, the color fading issue was brought into prominence. Public discussion helped to make significant changes in the way the stability issue was approached by both the photographic industry and the archival community.

A densitometer was used to measure the fading behavior of color photographs in this research project.

One of the more important consequences of the higher profile of the stability issue during the seventies and eighties was greatly expanded stability testing, along with universal adoption of a new accelerated-aging technique called the Arrhenius method. The method was named for Svante Arrhenius, the nineteenth-century Swedish chemist who won the Nobel prize for his studies of physical chemistry. This way of doing accelerated aging made use of data from high-temperature tests and allowed for quantitative predictions of life expectancy. Typically in such tests, humidity was held constant, but five or more different temperatures between 50°C and 90°C (122°F and 194°F) were employed. If the data were well-behaved (i.e., met certain mathematical criteria), then extrapolations to temperatures lower than those actually used in the test were possible. Thus a prediction of the number of years required for 30% dye loss can be made for room conditions. (The 30% figure is chosen because it represents visually detectable density loss. Other amounts of fading could be used.) Kodak and others defined room conditions as 24°C (75°F) and 40% RH. This meant they conducted their accelerated aging at 40% RH, and all their predictions were based on storing photographs at a steady 40% RH condition.

Kodak, Fuji, Agfa, and other companies began to publish Arrhenius predictions of dye stability for their products in the late seventies. (Unfortunately, since most earlier products were not tested using this method, we have only estimates and not precise data on how stable they were.) Older test methods had used just one temperature and could be used only to compare one product against another. Even those relative comparisons often were in error. Single-temperature tests can be quite misleading; using several elevated temperatures gives a truer picture of fading behavior, because it shows precisely how the fading rate will be affected by variations in temperature. Such multi-temperature test data can be used to predict the fading rate at any temperature, for example at room conditions or in a freezer.

Because Arrhenius testing can be expensive, only limited research has been done on the RH dependence of dye fading. The data in the *Storage Guide for Color Photographic Materials* represents the most comprehensive study yet published on the effects of RH on the rate of color dye fading in photographs.

Activist and researcher Henry Wilhelm helped to bring the issue of color photograph instability to public prominence in the seventies and eighties. In 1993, he and coauthor Carol Brower published a comprehensive book that has become a standard reference on the subject of color image preservation. The book, *The Permanence and Care of Color Photographs: Traditional and Digital Color Prints, Color Negatives, Slides, and Motion Pictures*, was published by Preservation Publishing Company.

Early Eighties: The "Great Leap Forward" in Dye Stability

Increased concern over the instability of color images, plus the element of competition in a now-worldwide photographic industry, led to a significant improvement in dye stability during the late seventies and early eighties. More resources and new technology (for example, computer-aided design of dye molecules) were directed at the problem. All types of color film and prints improved greatly, to the point where many contemporary products can be expected to survive 30 to 50 years or more at room temperature without reaching 30% dye loss. This is about where color products stand in the nineties as well. Although today's films are much more stable than those of the fifties and sixties, the implications for preservation at this level of stability are sobering. Kept at room conditions, eighties color photographs will show serious losses about 20 years from now, seventies color about ten years from now.

Fortunately, the storage environment offers ways to greatly extend the useful life of color images. The objective of the research done for this project was to clarify the behavior of today's color photographs and to help collection managers decide on the environmental conditions necessary to meet their preservation goals.

Chromogenic Color Photography

Most of the color photographs in existence were made using the same chemical technology. They therefore behave similarly when it comes to fading. Just as most cars, regardless of age, have gasoline engines, the chemical technology of dye formation in most color photographs has been generally the same since the introduction of Kodachrome film in 1935. In other words, nearly all types of color photographs were formed from the same kinds of chemical reactions and thus have somewhat similar dye structures.*

Color photography includes images in both still and cinema formats and of various types: prints, color negatives, and transparencies such as 35mm color slides. All these different kinds of pictures share a common underlying structure and technique. They are all produced by a dye-forming process known as chromogenic development. The word *chromogenic* means *giving birth to color* and refers to the fact that the cyan, magenta, and yellow dyes in the final picture are formed during processing.

Chromogenic color photography is an extension of black-and-white photography. It was invented by Rudolph Fischer, a German chemist working just before the First World War. Fischer's brilliant insight was to select a developing chemical that would also act as a building block for cyan, magenta, and yellow dyes. To create a color image, the developer first must form a black-and-white image. This process chemically alters the developer, preparing it to act as one of the components of the dye structure. Dye couplers, the other necessary components for the dye structure, are available nearby to react with the altered developer molecules. Together, these components form a dye around the black-and-white silver image. The black-and-white image must then be removed by bleaches that attack only the silver, not the newly formed dyes. Normal fixing and washing follow. The result is a full-color photographic image consisting only of organic dyes.

While Fischer himself did not profit very much from his invention (there were a few more details to work out before chromogenic color became commercialized in the thirties), his idea that used-up developer reacts to form a color dye is still very much in use today. However, the number of black-and-white developing agents suitable for chromogenic dye formation is limited. Only a handful are in use, and one or two account for almost all the color processing done in the world. In practice, this limits the range of possible dye structures for chromogenic color photography. Even though important differences exist among dye couplers, there are only so many ways to put together a cyan dye molecule cre-

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* There are some exceptions, such as Polaroid images, which will be discussed separately.

ated by a given developing agent. The cyan, yellow, and magenta dyes used in color photography are not identical (each manufacturer uses different couplers) but chromogenic dyes are somewhat similar in chemical structure because they are all built up from the same few developing agents. Similarity in chemical structure, in turn, ends up dictating the practical limits of dye stability for many chromogenic dyes.

Thus we come to a key fact about chromogenic color photographs: their stability behavior is "programmed" into the dyes by the ways in which the dyes are formed. For dye molecules, structure is destiny. While some dyes have superb lightfastness and will last hundreds of years in dark storage at room temperature, such is not the case for most dyes used in color photography. They simply cannot be expected to last that long because the structure imposed on them from the beginning has inherent instabilities.

Products do differ, however. It is worth investigating the stability characteristics of a film or paper before using it. Nevertheless, the family resemblance among chromogenic products remains strong. From an archival perspective, the best way to guarantee long life for a color photograph is through storage, not through product selection.

For more information on the history of color photography, see:

Colour Photography: The First Hundred Years, 1840–1940 by Brian Coe (Ash & Grant Ltd., London, 1978)

History of Color Photography by Joseph S. Friedman (The American Photographic Publishing Company, Boston, 1947).

More about the technology of color photography is found in:

Imaging Processes and Materials: Neblette's Eighth Edition, edited by John M. Sturge, et. al (Van Nostrand Reinhold, New York, 1989)

Principles of Color Photography by Ralph M. Evans, et. al (John Wiley & Sons, Inc., New York, 1953)

The Reproduction of Colour in Photography, Printing & Television, Fourth Edition, by R. W. G. Hunt (Fountain Press, England, 1987).

Nonchromogenic Color Photography

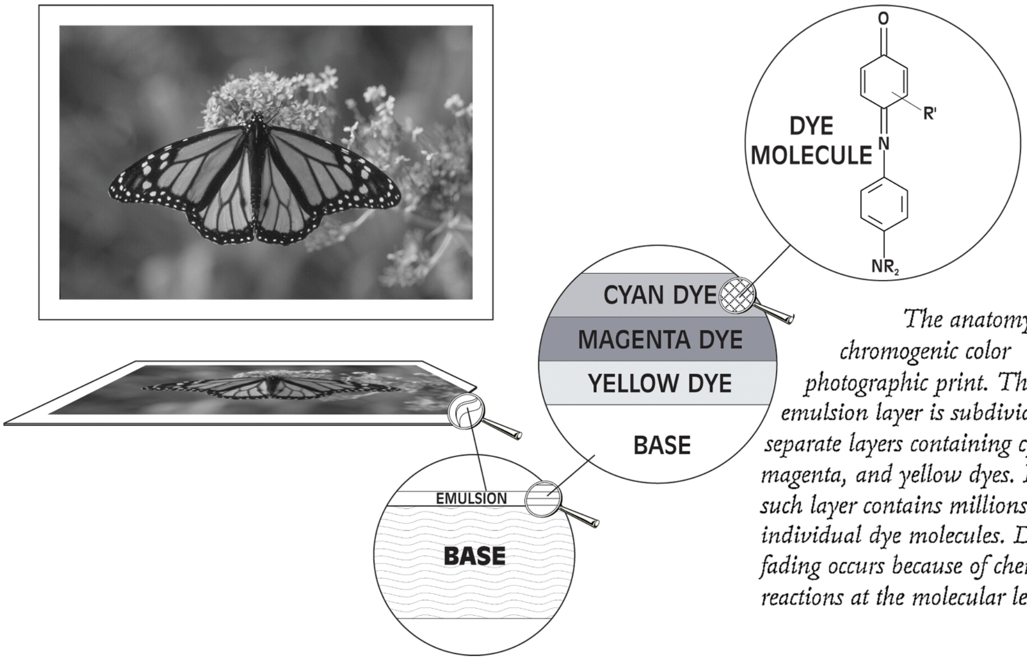
Not all color photographs were made with chromogenic dye-forming technology. Color photography existed before chromogenic technology, and a number of nonchromogenic approaches were and still are being used for special applications. Perhaps the largest category of nonchromogenic color images in archival collections is Polaroid™ instant photography. Polaroid images in color were introduced to the market in 1963 and have evolved through numerous changes in dyes and technical sophistication. The inherent dye stability of color Polaroid images was often superior to their chromogenic contemporaries, but this advantage is partially offset by some unique physical problems for some products. In general, the recommended care and storage of Polaroid images is similar to that of chromogenic color.

Images on Cibachrome™ (later renamed Ilfochrome™) comprise another significant group of nonchromogenic color photographs. Introduced in 1955, these prints and transparencies make use of an image-forming technology known as silver dye bleach, which yields images of outstanding dark stability. The dyes in Ilfochrome materials are of the chemical type called *azo dyes*. In the presence of heat and moisture, such dyes are inherently much more stable than chromogenic dyes. Their life expectancy cannot be predicted from accelerated-aging tests because, even at accelerated conditions, they do not fade enough for a prediction to be made. Their life expectancy in the dark at room conditions is probably in excess of several centuries. The lightfastness of Ilfochrome materials is better than that of chromogenic ones, but not on par with its own extraordinary dark stability. From the point of view of archival permanence, it is unfortunate that wider use was not made of silver dye bleach technology in color photography. Because chromogenic materials were more versatile and cheaper, silver dye bleach products are relatively rare in collections. Many examples can be found throughout the history of photography that demonstrate the fact that permanence has never been a strong factor in determining market success.

WHY DO DYES FADE?

Dyes used in color photography (or in any other application such as textiles or printing inks) are large, complex organic molecules composed of just a few elements. Typically, dyes consist only of carbon, hydrogen, oxygen, and nitrogen. The many millions of known dyes differ from each other mainly in the way the atoms of these few elements are arranged to form the structure of the dye molecule. Such seemingly minor details as whether a bond between atoms is a double bond (sharing two electron pairs) or only a single bond, or whether a molecule has two benzene rings (six carbon atoms arranged in a circle), can determine what color a dye is, or even if it is a dye at all. It may well be colorless—most complex organic molecules are (and happily so, or we might all be walking around with naturally green fingernails or fuchsia hair). When it comes to determining what color an organic molecule is, everything depends on the exact way in which the atoms are arranged.

If we start with a cyan dye, for example, all will be well as long as the original arrangement of atoms is intact. Should it be disturbed in some way, the likely result will be a loss in the ability of the dye molecule to interact with light. In other words, it will become a colorless structure, which is what "fading" actually means. The new arrangement of atoms that results from a realignment of the cyan dye structure (or else a split-



The anatomy of a chromogenic color photographic print. The gelatin emulsion layer is subdivided into separate layers containing cyan, magenta, and yellow dyes. Each such layer contains millions of individual dye molecules. Dye fading occurs because of chemical reactions at the molecular level.

ting of the large dye molecule into two smaller pieces) may produce a colorless new structure, or even a pale yellow dye. This transformation occurs one dye molecule at a time. Eventually, a large percentage of the many millions of molecules will be changed, at which point the fading becomes apparent to the eye.

When structural changes do occur in the dyes, the gelatin, or any of the other complex organic chemicals present in a processed color photograph, the most usual result is formation of a yellowish stain. In particular, the dye couplers (the components that react with the used-up developer to form the dye image) have a tendency to decompose into yellow or orange stains. This phenomenon, called *coupler staining*, is evident in the white borders of many older chromogenic color prints because the unreacted couplers are not removed during processing.

But back to *why* dyes fade. What causes structural rearrangements of dye molecules in the first place? The root causes are heat energy, moisture, and, to a lesser extent, air pollutants. These factors apply in *dark fading* which goes on in the dark and is governed by temperature and RH. If the photograph is displayed, then light energy must be added to the list of causes. *Light fading,* which occurs as a result of light exposure while on display, is a topic unto itself and can be a powerful and very rapid form of deterioration. These two kinds of fading are quite distinct, with differing chemical mechanisms and sometimes very different effects on the image. In dark fading, the cyan dye (of pre-eighties color photographs) typically fades fastest; in light fading, the magenta dye fades fastest. It is dark fading behavior that most affects the survival of a color photograph, and dark fading rates are of the most interest in the preservation context.

Fading Caused by Heat

Heat is a form of energy. What we call heat is really the energy of vibration and movement of individual atoms and molecules within the confines of their bonds to each other. The higher the temperature, the more rapid and energetic the movement. When we human beings are comfortable, we say we are neither hot nor cold (this occurs at "room temperature," about 72°F). But from the perspective of heat as movement on the atomic scale, room temperature is very warm indeed. Photographic color dyes are not very stable at room temperature.

To understand why, imagine a dye molecule as a tiny "chain gang" of individual atoms. As the temperature increases, the atomic "convicts" become more upset and agitated. They thrash about in all directions, occasionally colliding with each other. With molecules, as with people, the more energetic the movement, the more likely it is that someone will get hurt as a result of a collision. The chain-gang analogy is not really so far-fetched. It was one of the great insights of nineteenth-century science that the outward temperature of objects reflected an inner turmoil of movement and kinetic energy. This internal oscillation ceases altogether only at the coldest possible temperature, which is referred to as absolute zero (-459°F). At any temperature above absolute zero there is molecular movement and, with it, a consequent risk that vibration or collision will lead to the breaking of a chemical bond. As the temperature increases, the energy of atomic collisions increases, which in turn increases the probability that a bond may be stretched to the breaking point, resulting in a structural rearrangement.

Temperature is a continuum—there is no one "best" temperature for storing color photographs. Each degree of temperature increase speeds up the rate of dye fading; each degree of temperature decrease reduces the fading rate. The important point to understand is that at room temperature there is sufficient heat energy to cause the majority of chromogenic dye molecules in a color photograph to undergo rearrangement (i.e., to fade) in only a few decades. Some dyes may last for centuries at room temperature (their chemical structures are less easily disturbed), but they're not the ones we have to worry about in color photography.

If we find the rate of dye fading to be unacceptably fast at room temperature, then the only way to slow it down is to lower the storage temperature. This is why the conditions for extended-term storage of color photographs recommended by the American National Standards Institute (see below) call for near-freezing conditions. Only low temperatures such as these can slow the rate of spontaneous dye fading sufficiently to allow color images to be preserved indefinitely.

The Role of RH in Color Photograph Deterioration

Apart from temperature, the second most significant environmental factor in color dye fading is RH. It is important because it controls the amount of water that materials such as gelatin absorb from the atmosphere. When the RH is high, gelatin, paper, plastics, and other organic materials soak up water vapor. When the RH is low, the opposite happens; moisture contained in the materials is given out into the air and objects dry out. It is therefore the RH of the atmosphere that determines how much water will exist within objects in a storage area. It takes a while, but eventually all the water-absorbent objects in a room come to *equilibrium* with the RH of the surrounding air. For example, when a gelatin emulsion on a photograph is in equilibrium at 50% RH at room temperature, about 8% of the total weight of the emulsion is water. If the RH increases to 80%, then at equilibrium the gelatin will contain about 12% moisture by weight.

If we wish to regulate the amount of water contained by the photographs in storage, we can do so by adjusting the RH of the storage area. When the RH is changed, some time will be required for a new equilibrium to be established, but eventually the moisture content of the photographs will increase or decrease as necessary to come to equilibrium with the new RH condition. This is true regardless of temperature—almost. Even in a freezer, photographs slowly adjust their moisture content in accordance with the RH of the surrounding air. In a freezer, however, the actual moisture content (expressed as a percentage by weight) of a photograph in equilibrium with 50% RH is a little bit higher than it would be at room temperature.

Importance of RH Control in Color Preservation

The reason why RH is such an important environmental factor for storage of color photographs is that water plays a role in the chemical reactions that cause dye fading. In simple terms, dyes fade when they react with water in a process called *hydrolysis*. Keeping the water content of photographs low is the best way to minimize the fading caused by hydrolysis. The yellow dyes in modern color materials typically are the most humidity-sensitive (they fade faster in the presence of moisture than the other two dyes).

The recommended RH range for storage of color photographs is 20% to 50% RH. From the point of view of dye fading and hydrolysis, the lower the RH the better, but there are other reasons to avoid extreme dryness. Below 20% RH there is a risk of curl, brittleness, and other undesirable physical problems. At low RH, gelatin and other components of photographs contract and experience stresses that become increasingly powerful as RH falls below 20%. The result may be deformations in the size or flatness of the object, or even tears in the emulsion.

Above 50% RH the dangers of *dampness* become increasingly severe. *Excessive dampness is the most damaging condition of all for color photographs.* It causes increased dye fading, mold growth, and gelatin softening. As the RH increases from 50% to about 70% RH there is a profound change in the physical properties of gelatin. Increasing moisture makes the gelatin emulsion layer progressively softer and more swollen. The gelatin behaves less like a solid and more like a liquid. Given sufficient moisture, pressure, heat, and time, the gelatin layer of a photograph will gradually take the shape of any surface it is in contact with. Under damp conditions, gelatin may become stuck fast to whatever it is touching in a phenomenon called *ferrotyping*. Negatives and prints that experience ferrotyping may be ruined even if they do not stick permanently to another surface. Especially damaging to negatives is the deformation of the surface of the emulsion layer that occurs when a ferrotyped photo is separated from whatever it has been touching. Surface irregularities alter the effective density (lightness or darkness) of a negative in the affected areas. In extreme cases of ferrotyping, gelatin layers become stuck fast and cannot be separated at all. This is the most common reason why photography collections become ruined during fires or floods. Sudden wetting of photos in a flood is a catastrophe, but prolonged high RH can be just as dangerous because of gelatin softening.

Another danger of high RH is the risk of mold growth. Mold destroys gelatin by secreting enzymes that weaken and stain it. Sustained dampness is required for mold to grow, so RH control is an effective strategy for mold prevention. Mold growth and gelatin softening are particularly serious threats to color photographs because they can happen so quickly—within a few days or even hours under the right circumstances.

Air Pollution and Particulates

Temperature and RH are always present in storage environments and have a great deal of influence in determining the life span of color photographs. However, they are not the only environmental factors that need to be considered in planning a storage space. Air pollution and suspended particulates in the form of dust, mold spores, soot, and so on, can be significant factors in the storage of color photographs. Air quality is difficult to measure and can be difficult to control. What are the dangers to color images and how much attention should be paid to air quality issues? The subject of air quality can logically be divided into unwanted substances of a gaseous nature (air pollution) and contaminants in solid form (suspended particulates).

Gaseous Contaminants

Some insights into the relative significance of the gaseous contaminant issue in color photograph preservation come from observing the behavior of black-and-white films and prints. Color images are generally less sensitive than black-and-white silver images to atmospheric pollutants. Black-and-white images are affected by a wider variety of pollutant gases, and collections show abundant evidence of atmospheric attack. The fading of black-and-white images is typically from the edges in toward the center; local fading often appears where an image was partially exposed to the atmosphere. This localized fading behavior is almost unknown in color photographs, where fading is nearly always uniform across the entire image, and every image in a related group is usually faded to a similar degree. This reinforces the conclusion that inherent instability of the dyes, not atmospheric attack, is the cause of most of the fading. However, the effects of gaseous contaminants are still worthy of concern and protective action.

Photographic samples inside a simulated pollutant test chamber at the Image Permanence Institute.

Gaseous air contaminants can make their way into storage spaces for color photographs from a number of different sources. They can be part of the general air pollution affecting a whole city, or they can originate from a much closer source near or within the building or room; they may even originate from the enclosure that a color image is stored in.

There are three main types of gases that appear in storage areas: oxidants, acidic gases, and volatile organic compounds (VOCs).

Oxidants

Oxidizing air pollutants such as ozone and nitrogen dioxide are common in urban areas. The concentration of these pollutants rises and falls in a daily cycle because the sunlight and traffic that produce them also vary throughout the day. When the air in a city is polluted with oxidants, it is usually possible to obtain data on the concentration of these gases from government or municipal agencies. Sometimes only the peak concentrations are reported, other times detailed hour-by-hour readings are available. Because peak concentrations are buffered somewhat by enclosures or other storage circumstances, what matters is the seasonal or yearly average concentration.

Laboratory tests done at IPI indicate that ozone and nitrogen dioxide can indeed cause fading of chromogenic color dyes. This fading is dependent on temperature (higher temperatures mean faster fading in the presence of pollutants) and less dependent on RH. However, it appears that in most real-life circumstances, oxidizing air pollutants do not present a major threat to collections because of several mitigating factors.

First, the typical outdoor average concentrations, even in urban areas, range from 25 to 50 parts per billion (ppb), not high enough to cause major fading. Compared to some other kinds of dyes, the inherent sensitivity of chromogenic materials to oxidants is not particularly high, and the gelatin emulsion protects the dyes to some extent. Together, these facts mean that an unusually high concentration of oxidant (averaging 100 ppb or greater) would have to be present for a considerable period of time in order to cause serious dye fading.

Another mitigating factor is that indoor concentrations of oxidants are usually lower than the measured outdoor values. Indoor ozone concentrations can be as high as 70% of those outdoors. More typically, they are 40% to 50% of outdoor levels, depending on a number of factors, including interior surfaces, air exchange rates, and filtration. Indoor nitrogen dioxide levels track outdoor concentrations more closely than ozone levels do; they are often 80% to 90% of outdoor levels. IPI's research indicates that oxidizing air pollutants contribute only slightly to the observed fading of most chromogenic color images. Probably some fading is caused by air pollutants, but the rate of oxidant-induced fading is so much slower than the rate of heat- and moisture-induced fading that we never get to observe the effects of air pollution alone. The fading that we see in collections of older color images is due mostly to heat and moisture and not to oxidizing air pollutants.

Enclosures are still another mitigating factor. IPI research indicates that paper or cardboard enclosures are not effective in blocking out oxidizing gases, although they may react with pollutants to buffer or reduce levels. A plastic enclosure does provide protection by creating a physical barrier against pollutant attack, although pollutants can penetrate openings in it (the open end of a sleeve, for example). When photographs are in stacks or when film is in roll form, there is also some protection. Depending on how many layers of packaging exist between the atmosphere and the object, what those layers are composed of, and how the objects are arranged, there can be significant attenuation of pollutants. In most real-life storage circumstances, some attenuation of pollutant attack could be expected from the combined effects of typical sleeves, boxes, and cabinets.

Acidic Gases and VOCs

Apart from the oxidant gases nitrogen dioxide and ozone, the other types of gaseous pollutants—acidic gases, such as sulfur dioxide or hydrogen sulfide, and VOCs (volatile organic compounds), such as solvents—are not potent threats to the dyes in color photographs, although they can have ill effects in rare circumstances. It requires acidic gases in concentrations much higher than plausible in indoor storage to fade chromogenic dyes. (Concentrations as high as 5 ppm used in IPI research showed no fading.)

VOCs other than acetic acid are common in small concentrations in almost all buildings but are especially common in storage areas where photographic films are kept. Cellulose acetate film gives off a variety of VOCs as solvents evaporate from the film support. While immersion in some organic solvents will actually dissolve the dyes in chromogenic color photographs, the low concentrations of organic solvents in indoor air are not a threat.

One special case of practical significance concerning acid gases is the acetic acid given off by degrading cellulose acetate film base. Concentrations of acetic acid greater than 100 ppb are a concern because nondeteriorated acetate films may absorb acetic acid vapors and thereby degrade faster than they otherwise would. Color films on cellulose acetate support that are afflicted by advanced vinegar syndrome become very acidic and experience more rapid dye fading. For these reasons, it is important to control acetic acid vapors in storage vaults for color film.

Control Measures for Gaseous Air Pollutants

In practice, control of gaseous air pollutants for storage of color photographs is a matter of taking reasonable preventive measures against accidental high concentrations of dangerous gases. The first things to look for are localized sources of oxidants or VOCs, particularly acetic acid. A-D Strips, a simple and low-cost indicator of organic acid vapors produced by the Image Permanence Institute, may be used to detect the presence of acetic or other volatile organic acids in confined spaces such as cabinets or film cans. Consider the source of the air that enters the storage space. Does it contain fumes from auto exhaust, electrical machinery, copiers, laser printers, or paint? Also check available data on outdoor concentrations of ozone and nitrogen dioxide.

Although the threat of damage from gaseous pollutants is usually not severe in vaults or climate-controlled areas, the use of activated carbon filters to remove ozone, VOCs, and some acidic gases is prudent in many cases. The technology and application of gas-phase air filtration is a specialized field, and each case requires individual assessment by an expert. Low temperatures and other factors can affect the performance of such systems.

It is difficult and it can be expensive to monitor and control all forms of gaseous pollution to undetectably low levels. When a collection consists exclusively of chromogenic color photographs, it may be that reasonable control measures for gaseous air contaminants are enough and elaborate air purification systems are not necessary. This is particularly true when storage temperatures are low, as they definitely should be in any serious attempt to preserve chromogenic color images for long periods of time. The low temperatures will slow the rate of attack of any oxidizing pollutants, rendering them less of a threat. However, even in cold storage, activated carbon filters may still be useful. When sealed packaging is used to control moisture content, as it would be when conventional refrigerators or freezers are used for cold storage, air pollution control measures are not necessary, owing to the multilevel protection of low temperature and physical barriers to pollutant diffusion.

Particulates

Solids suspended in air are known as particulates. These include dust, soot, grit, mold spores, and other materials. Many sources of particulates exist—fresh concrete, old exposed or unsealed concrete, ceiling tiles, construction work, human beings and their clothes, carpets resuspending particulates in the air, industrial processes, and wind-borne sand and salt, to name but a few. It is obviously important to protect photographic materials, especially motion picture film and other small-format images, from all forms of dust and dirt. Here, the first level of defense is a photographic enclosure system. The second level of defense is air filtration, which protects not only the objects but their enclosures as well. Third, equipment and room finishes should be selected so as to avoid the generation or distribution of particulates. Fourth, the collection storage area should be cleaned and vacuumed before occupancy and at regular intervals.

Particulate filtration systems are common and cost much less than active air purification systems that are designed to remove gaseous contaminants. A reasonable recommendation for color photograph storage is that the filtration system be capable of removing 90% to 95% of the particulates having a size of one micron or larger, per the measuring technique specified in the ANSI/ASHRAE Standard 52.1-1992, *Gravimetric and Dust Spot Procedures for Testing Air-Cleaning Devices Used in General Ventilation for Removing Particulate Matter*.

ENCLOSURES FOR COLOR PHOTOGRAPHS

Collection managers cannot change the nature of photographic materials to make them fade and stain more slowly or be more physically robust. Nevertheless, among the things that collection managers *can* control are handling practices, environmental conditions, and the choice of storage enclosures.

Enclosures are a very important aspect of storing color photographs. Although temperature and RH are the primary factors in the survival of color images, enclosures and handling practices are next in importance. Whether for still photography or motion pictures, enclosures add to the useful life of collections by providing physical protection, by buffering rapid environmental changes, and by being inert, harmless containers during years of storage.

The Photographic Activity Test (PAT) is a method for determining which enclosures are chemically inert and will not fade or stain photos and film in archival storage. It is described by the American National Standards Institute (ANSI) as a "predictive test of interactions between storage enclosure and photographic image. It can also be used to evaluate possible photographic activity caused by components of enclosures such as adhesives, inks, paints, labels and tape."

The role that enclosures play in color photograph preservation depends on the kinds of objects involved, how they are used, what environmental conditions they are exposed to, and what the enclosures are made of. There is no single ideal enclosure design for a particular type of photograph; the handling patterns, storage environment, use environment, and economic circumstances of every collection are different. Enclosures typically are part of a multilevel system in which each object may have its own enclosure, which in turn may be enclosed in a box or folder, which is usually placed in a third level of storage consisting of shelving or cabinetry. Ease and safety in handling and the ability to integrate with the other storage levels should be designed into the overall system from the beginning. The subject of enclosures design is a large one; in this publication only the aspects of enclosures that pertain directly to use with color photographs will be discussed.

Color photographs are found in many different sizes and types—prints, negatives, transparencies, roll films, and sheet films—and all are physically delicate. Whatever style of design and construction is used, the most important thing is that the enclosure be able to physically perform the tasks desired of it. For example, motion picture film cans need to be strong enough to withstand the weight of other cans. Transparencies might need clear enclosures so that they can be examined without being directly handled. The enclosure system used with color photographs should protect them against continuous exposure to light, because light will fade the dyes. Proper archival storage of color photographs involves low temperatures. Transitions from one environmental condition to another are inevitable when photos are brought out of cold storage. In general, enclosures don't have much effect on warmup times, but they do have considerable influence on how fast objects come to equilibrium with a new RH condition. When selecting enclosures for use in cold storage, neither the functional design properties nor the moisture-buffering properties should be overlooked—both must be appropriate to the intended use.

One other aspect of enclosures is significant: their chemical inertness toward the photographs stored inside them. Enclosures should not emit harmful gases or leach out substances that would cause dye fading, staining of gelatin, or other problems. The glues, inks, labels, and coatings used in enclosure manufacture should all be inert and nonreactive with photographs. There are many examples in real-life collections of damage from inappropriate enclosures and adhesives. Most people are familiar with the stains and residues left by older cellophane tape, decomposing rubber bands, rusty paper clips, and the like.

The inertness of photographic storage enclosures can be evaluated by the Photographic Activity Test (PAT), an accelerated-aging procedure described in ANSI Standard IT 9.16-1993, *American National Standard for Imaging Media—Photographic Activity Test*. Passing the PAT is not a guarantee that a storage enclosure will be satisfactory in all aspects, merely that it will not cause staining or fading of photographs because of substances emitted by the enclosure.

On the whole, color photographs are somewhat less sensitive to contaminants originating from storage enclosures than are black-and-white silver images. Testing of enclosures with chromogenic images shows that few enclosures will cause dye fading, while many kinds of enclosures can fade silver images. This is supporting evidence for the conclusion that atmospheric contaminants are generally less of a threat to color images than to silver images. However, some enclosures can cause stains on both black-and-white and color photographs alike, so the inertness issue is still very important in choosing enclosures for color photograph storage.

General functional requirements for photographic storage enclosures and descriptions of appropriate materials (polyester, polypropylene, high alpha-cellulose papers, etc.) as well as inappropriate materials (PVC, chlorinated plastics, acid groundwood papers, etc.) can be found in ANSI Standard IT9.2-1991, *American National Standard for Imaging Media—Photographic Processed Films, Plates, and Papers—Filing Enclosures and Storage Containers*. Recent changes in this standard now permit paper and mat board enclosures for color photographs to contain alkaline buffering; previous versions of the standard permitted nonbuffered enclosures only.

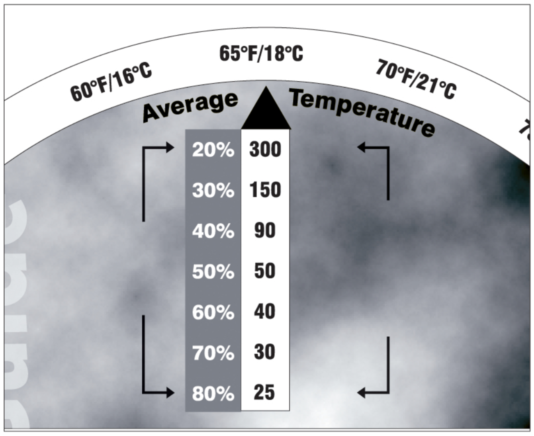
DETERMINING THE LIFE EXPECTANCY OF COLOR MATERIALS—THE WHEEL AND THE TIME-OUT-OF-STORAGE TABLE

Two archival management tools have been devised to present the accelerated-aging data on color materials in easy-to-use formats: the wheel and the time-out-of-storage table. These were based on the results of the research project sponsored by the University of Rochester and conducted at IPI on behalf of the New York State Program for the Conservation and Preservation of Library Research Materials. (The predictive data presented on the wheel is shown in tabular form on page 20.)

What the Data on the Wheel Represent

The wheel is a guide to the way in which storage conditions affect the rate of dye fading in color photographs. Its purpose is to determine the length of time that new color photographs would take to become noticeably faded. It applies to any type of color photographic image: slide, print, and negative, in any size or format, including cinema film. The data are applicable only to chromogenic color photographs, a category that includes most types of color photographs except Polaroid, Ilfochrome (formerly Cibachrome), Kodak Dye Transfer, and early color materials such as Dufaycolor and Lumiere Autochrome.

The wheel represents only the *dark* storage behavior of the materials. In other words, this is the degree of fading that could be expected of materials that are kept in the dark all the time and never displayed. In a sense, this is the *minimum* fading that will likely occur. Any display of the materials will only add to the loss of image density that occurs spontaneously in the dark. Light-induced fading is a separate topic that the wheel does not address.



The wheel relates storage conditions (temperature and RH) to the approximate life expectancy of contemporary color photographic images. Shown here are the values for 65°F (18°C).

The data on the wheel are the estimated number of years required at various storage conditions for color photographs to lose 30% of their image density.* This degree of fading is quite noticeable to the average person, but it doesn't mean there is no image left. The time estimates were obtained from a comprehensive accelerated-aging study on four best-selling types of contemporary photographic products.

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* Density is a measure of how light or dark the image is; when an image is losing density, it is fading.

Approximate Time in Years to Significant Dye Fading in Color Photographic Materials

Temperature	20% RH	30% RH	40% RH	50% RH	60% RH	70% RH	80% RH
30 F/-1 C	8000	3500	1500	800	600	450	350
35 F/2 C	4500	2000	1000	600	350	300	250
40 F/4 C	3000	1500	700	350	250	200	175
45 F/7 C	1750	900	450	250	175	125	100
50 F/10 C	1000	600	300	175	125	90	80
55 F/13 C	700	350	200	125	80	60	50
60 F/16 C	450	250	125	80	60	45	35
65 F/18 C	300	150	90	50	40	30	25
70 F/21 C	180	100	60	40	25	20	18
75 F/24 C	125	70	40	25	19	15	12
80 F/27 C	80	50	30	19	14	11	9
85 F/29 C	50	30	20	13	10	8	6
90 F/32 C	35	20	14	10	7	6	5
95 F/35 C	25	15	10	7	5	4	3
100 F/38 C	15	11	7	5	4	3	2
105 F/41 C	10	7	5	4	3	2	2
110 F/43 C	7	5	4	3	2	2	1
115 F/46 C	5	4	3	2	2	1	1
120 F/49 C	3	3	2	1	1	1	1

Data from the color storage guide wheel, shown in tabular form. Each value in the table represents the approximate time for 30% density loss if new contemporary color photos are kept in the dark at the specified conditions of temperature and RH.

How to Use the Wheel

The wheel can be used in two ways to evaluate storage environments for color photographs. One can work from *storage conditions* to obtain a life expectancy estimate, or one can work from *a life expectancy estimate* to obtain the various possible conditions that would produce the desired life expectancy.

In the first method, start with a specific temperature and RH combination and look up the life expectancy of color photographs that would be achieved at that condition. To begin, select a temperature. Temperature is the most significant environmental factor in determining the rate of dye fading. Each degree of temperature is more important than each percent RH in determining life expectancy. Storage temperatures in both Fahrenheit and Celsius are located on the outside edge of the wheel. Rotate the inner disc until the arrow points to the desired storage temperature. Next, look to the left of the window on the inner disc and select an RH value. In the window, aligned with that RH value, is the life expectancy estimate associated with that particular RH combined with the selected temperature. *Remember that the estimates of years to 30% dye fading assume that the conditions remain constant for the entire time.* (See pages 26–29 for a discussion of the impact of changing conditions on the expected life of color images.)

The second way to use the wheel is to choose a desired life expectancy and then locate the various combinations of temperature and RH that would produce it. There are many different sets of conditions that would result in any one particular life expectancy. This is because both temperature and RH contribute to the fading rate for color dyes. It is possible to "make up" for higher temperatures with a lower RH, and vice versa. There are practical limits on this equivalency, however. Conditions should not be made excessively dry to compensate for a higher-than-desired temperature, for example. The RH for storage of color photographs should be kept within the range of 20% to 50%. Still, the equivalency concept offers some useful flexibility in designing storage areas within this humidity range. Often it is difficult to control RH to the lower end of this range; by choosing an RH closer to 50% and lowering the temperature a few degrees, it is possible to design a storage area that operates efficiently and still delivers the desired life expectancy for the collections.

The Time-Out-of-Storage Table

Even if a special environment like a cold storage vault is provided for a collection of color photographic materials, objects do not always remain there. They may be brought out periodically for use, for vault maintenance, or for other reasons. The impact of the *combined effects* of a storage vault and a use (i.e., office or reading room) condition on the life expectancy of color photographs will of course depend on the temperature and RH of both areas. The time-out-of-storage table, shown here and also printed on the back of the wheel, contains the same data found on the front of the wheel with the added dimension of *time spent out of storage.**

The time-out-of-storage table makes use of an approach first suggested by Mark McCormick-Goodhart, a research scientist at the Smithsonian's Conservation Analytical Laboratory. It shows how the life expectancy of an object is affected when it is taken from a storage vault and used at room temperature for a period of time. The effects of leaving the storage environment and spending varying amounts of time at office conditions—75°F (24°C), 60% RH—can be profound. Life expectancy can be significantly diminished merely by removing an object from special storage and keeping it for an average of 30 days each year at office conditions.

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* The time-out-of-storage table is predicated on an office condition of 75°F (24°C), 60% RH. It is but one example of how time spent in a use environment modifies the life expectancy imparted to a color photograph by cold storage. Other use environments will impact life expectancy to a greater or lesser extent, depending on how different they are from the vault environment.

TIME-OUT-OF-STORAGE TABLE FOR COLOR PHOTOGRAPHS
Predicted Time in Years to Reach 30% Dye Fading

Primary Storage Conditions			Average Number of Days Each Year Spent Out of Storage at Use Conditions of 75 F (24 C), 60 % RH						
C	F	% RH	0	1	5	10	30	90	120
21	70	20	175	175	175	150	100	60	50
		40	60	60	60	60	50	40	35
		60	25	25	25	25	25	25	25
16	60	20	450	400	350	300	150	70	50
		40	125	125	125	125	90	50	45
		60	60	50	50	50	50	40	35
10	50	20	1000	1000	600	450	200	70	60
		40	300	300	250	200	125	60	50
		60	125	125	100	100	80	50	45
4	40	20	3000	2000	900	600	200	80	60
		40	700	600	450	350	175	70	60
		60	250	250	200	175	125	60	50
-1	30	20	>3500	3500	1250	600	250	80	60
		40	1500	1250	800	500	200	70	60
		60	600	500	400	300	175	70	50
-9	15	20	>>3500	>3500	1250	700	250	80	60
		40	>3500	3500	1250	600	250	80	60
		60	2000	1500	800	500	200	80	60
-18	0	20	>>3500	>3500	1500	700	250	80	60
		40	>>3500	>3500	1250	700	250	80	60
		60	>3500	3500	1250	600	250	80	60
-26	-15	20	>>3500	>3500	1500	700	250	80	60
		40	>>3500	>3500	1500	700	250	80	60
		60	>>3500	>3500	1250	700	250	80	60

>: greater than   >>: much greater than

The time-out-of-storage table is used to estimate the overall *life expectancy of contemporary color photographic images that spend part of the year in a storage vault and part of the year under different conditions in an office or reading room. See text for more information.*

Using the Table

The table is based on the assumption that objects in a collection reside most of the time in a primary storage area; this could be an ordinary room, a special vault, a refrigerator, or any other kind of physical storage arrangement. What matters is the temperature and RH of this primary storage area. The three columns at the left of the table are labeled "Primary Storage Conditions." The first two columns are temperature in Celsius and Fahrenheit; the third is RH.

To use the table, we must first locate the row that corresponds as closely as possible to the temperature and RH conditions in the primary storage area. We then look across the table at columns that refer to the average number of days each year an object spends *out* of the primary storage condition and in an office condition of 75°F (24°C), 60% RH. This is meant to reflect the reality that objects are often removed from storage for use, for exhibition, for curatorial research, because of equipment failure, for maintenance, or for other reasons. Thus the "120" (days out of storage) column means that the object spends four months each year in the use conditions and eight months in storage conditions. The numbers in the columns labeled "0" to "120" represent the approximate number of years it would take for new color photographs to lose 30% of their image density. The predictions show the combined effects of part-time vault conditions and part-time office conditions on color photos.

Consider the example of a new color photograph stored in a vault that is operating at 40°F (4°C), 40% RH. This is an excellent storage condition that should provide a very long life for color photographs. Referring to the front of the wheel, we can see that at these conditions it would take approximately 700 years for the color photograph to begin to display noticeable fading *if it never left the vault.* Now find the same conditions on the table under "Primary Storage Conditions." Looking down the column marked "0" under "Average Number of Days Each Year Spent Out of Cold Storage" (meaning that the object never leaves the vault), we again see the 700-year prediction. Looking across the row, the predicted number of years to significant dye fading drops sharply from 700 to 60 as the average number of days per year spent *out* of the vault increases.

At 30 days per year out of the vault, the photo's predicted life expectancy is only 175 years, just a quarter of its life expectancy if it never leaves the vault. It isn't difficult to imagine circumstances in which an object would average 30 days per year out of a cold storage vault, considering all of the possible reasons for intentional or unintentional removal or equipment shutdown. If the photo is out of storage for an average of 120 days per year, the predicted time is only 60 years, less than 10% of its life expectancy if it never leaves the vault.

What Happens to Objects Out of Storage?

The longer an object is out of cold storage, the more the warmer condition "takes over" in determining its overall life expectancy. Reading down the column marked "120", we can see that if a photo spends four months each year out of the vault there is little or no benefit from having the vault any colder than 50°F (10°C). The time spent in the use conditions determines the life expectancy of the object. *No matter how much colder than 50°F the vault may be, the four months per year at 75°F, 60% RH dictates that only about 60 years will pass before 30% dye loss occurs.*

ANSI AND ISO STANDARDS FOR COLOR PHOTOGRAPH STORAGE

The American National Standards Institute (ANSI) and the International Standards Organization (ISO) develop and publish standards that relate to the storage of color photographic materials. These documents are created by committees that represent the diverse points of view of manufacturers, consumers, and government agencies. In the United States, the designated organization that convenes standards committees on behalf of ANSI is the Photographic & Image Manufacturers Association (PIMA). Each of the ANSI/PIMA standards bears a designation that includes the letters "IT" (for imaging technology) and numbers to indicate the committee responsible for writing it and to uniquely identify the individual standard. The designation also includes the year of publication. Standards are living documents that undergo frequent revision. They must be either reaffirmed, revised, or withdrawn within five years of their publication in order to ensure that they are up to date. Standards bearing the "IT" prefix deal with many aspects of imaging besides storage and preservation, including manufacturing requirements, dimensions, processing, and test methods. The standards that relate to color photograph storage are part of a group that carries the designation "IT9" and includes documents covering physical properties, storage enclosures, storage conditions, and test methods for light stability and dark stability.

The ANSI and ISO standards concerning color photograph storage also include black-and-white photograph storage, but prints and film are covered in separate documents. The film storage documents apply to both negatives and transparencies. For prints, the current ANSI standard is ANSI IT9.20-1996, *American National Standard for Imaging Materials—Reflection Prints—Storage Practices*. The ISO standards also divide storage conditions into print and film categories; there is a very similar ISO standard with the designation ISO 6051, *Photography—Processed Reflection Prints—Storage Practices*. For film storage, the ANSI standard is IT9.11-1993, *American National Standard for Imaging Media—Processed Safety Photographic Film—Storage*. Its ISO counterpart is ISO 5466, *Photography—Storage of Photographic Film*.

The storage standards are not merely a table of recommended climate conditions. They include informative forewords and annexes that discuss the sources of the recommendations and the reasons why they are necessary. The standards present a great deal of useful information and are worthwhile reading for anyone who is serious about providing appropriate storage conditions for color photographs. ANSI and ISO standards attempt to be practical as well as to articulate a reasonable and rational approach to storage. In the case of color photographs, the ANSI and ISO storage standards define two categories of conditions: "Medium Term" and "Extended Term."

The medium-term conditions are designed for keeping objects for up to 10 years, and so are much warmer than extended-term conditions. ANSI and ISO currently define extended-term conditions as appropriate for keeping objects for an indefinitely long period of time. Formerly, extended-term conditions were called "archival keeping" conditions, but the term "archival" is ambiguous in meaning and is no longer used in standards documents.

The following table summarizes the recommendations for print and film storage per ANSI IT9.20-1996 and ANSI IT9.11-1993. The temperatures cited are *maximum* temperatures. Any temperature below those cited is also permissible (and in fact, is even better for color dye preservation). Note that several maximum temperatures are listed for extended-term conditions, each with its own RH range. All of these combinations of temperature and RH will meet the requirements of the standard. Because temperature and RH both influence dye fading, the warmest allowable temperatures have more stringent RH requirements. At colder temperatures, somewhat higher RH values are permissible. Color prints have a minimum RH of 30% in extended-term storage (as opposed to the 20% RH minimum for film) because prints are considered to be more vulnerable to physical damage due to brittleness at low RH.

ANSI/ISO RECOMMENDED CONDITIONS FOR COLOR PRINT AND FILM STORAGE

	Medium-Term Storage (Up to 10 Years)		**Extended-Term Storage (Indefinite Keeping)**	
	Maximum Temperature	RH Range	Maximum Temperature	RH Range
Color Prints (IT9.20-1996)	25 C	20%-50%	2 C -3 C	30%-40% 30%-50%
Color Film (IT9.11-1993)	25 C	20%-50%	2 C -3 C -10 C	20%-30% 20%-40% 20%-50%

THE IMPACT OF CHANGING CONDITIONS ON LIFE EXPECTANCY OF COLOR PHOTOGRAPHS

Measuring the Preservation Quality of Real-World Storage Conditions

The wheel is useful for planning new storage environments for color photographs and for estimating the preservation quality of existing ones. However, the estimates of life expectancy on the wheel assume that a photo spends its entire existence at the conditions specified. This isn't entirely realistic, even for a climate-controlled vault. Objects are brought from the vault for use, and equipment failures are inevitable. In fact, storage environments that change with the weather, the seasons, daily cycles, and HVAC system settings are the norm in real-life collections. Regardless of whether the storage conditions are static or dynamic, or whether prevailing conditions are good or bad, it is handy for collection managers to have an actual quantitative measurement of how the storage environment is affecting the decay rate of collections.

A numerical measure of the overall preservation quality of the storage environment is useful for management tasks such as monitoring equipment performance, justifying the need for improved climate conditions, or documenting the extra collection life that an investment in cool or cold storage has provided. In reality, two separate measures are needed: one for the conditions prevailing at the moment and one that is a cumulative, long-term average. To obtain an accurate picture of the cumulative behavior of a storage environment, temperature and RH readings must be taken for a long enough period of time to include seasonal or other cycles. In addition, the cumulative average must reflect the fact that deterioration proceeds faster at some conditions than others. How can this be done?

A starting point is the approach taken in the time-out-of-storage table. Here there is alternation between two storage conditions—a cold vault and an office—both of which are assumed to be unwavering in temperature and RH. As the table shows, the combined life expectancy is not just a simple average of the life expectancies associated with each individual condition. The warmer condition always has the greatest impact on overall life expectancy. The reason is simple: *dye fading may slow down in cold storage, but it never reverses itself.* Fading (and other forms of deterioration caused by spontaneous chemical reactions) is a journey down a one-way street. One month spent in warm temperatures takes a collection much farther down the road than many months in the cold. Cold temperatures slow the rate of dye fading, but warm temperatures accelerate it. To calculate a correct average for a dynamically changing environment, the warmer and damper periods of time must be given more weight than the colder and drier periods.

Calculations of this type were developed by the Image Permanence Institute and are an extension of the computational method used to create the time-out-of-storage table. If we know the life expectancies associated with all possible conditions (the wheel provides these), and we have a record of temperature and RH values taken at regular intervals over time (actual measurements in a storage space provide this), then we can calculate a running average of life expectancy. With the passage of each interval of time (typically one-half hour to four hours in length) the value is recalculated and continually updated. In practice, monitoring conditions for a year or so gives a fairly reliable estimate of the true overall preservation quality of a changing environment. The greatest variations are usually seasonal ones, followed by night/day cycles, weather events, regular environmental equipment cycles, and equipment setpoint changes or breakdowns. Analysis of such data shows clearly how the damage from warm and humid summers is not outweighed by the benefit of cool and dry winters. Differences in weather patterns from year to year also play a role. After two or three years of monitoring, however, the overall preservation quality of a storage environment can be quite closely characterized.

TWPI Concept Useful in Environmental Assessment

While the details of how to perform average life expectancy calculations are beyond the scope of this publication, they are discussed in *New Tools for Preservation* by James Reilly, Douglas Nishimura, and Edward Zinn. Because of the volume of calculations to be performed, a computer and a method for importing temperature and RH data into the computer are required.

The Image Permanence Institute has for some years been involved in the theory and practice of environmental assessment in preservation. IPI has suggested a common *generic* approach to evaluating storage environments for all types of organic materials (paper, plastics, adhesives, dyes, natural polymers, and so on.) IPI's generic approach, known as Time-Weighted Preservation Index (TWPI), is based on the observed similarity of deterioration behavior among organic materials. Published accelerated-aging data show that the relative impact of temperature and RH on deterioration rate is similar for many important kinds of materials—enough so that, for purposes of environmental assessment, one set of data can be used to interpret the effects of the storage environment on all types of organic materials.

The wheel in this publication cannot describe the exact behavior of every brand and type of color photograph; it is useful as a planning and evaluation tool because chromogenic color photographs are more alike than different in their response to the storage environment. Likewise, TWPI represents a generic overview—what scientists call a *model*—of the relationship between environment and deteriorative chemical change in all types of organic materials found in library, archives, and museum collections. *New Tools for Preservation* discusses this point in some depth and

COMPARISON OF FOUR MODELS OF CHEMICAL DECAY

	Life Expectancy Value, Years				
Model/Material	**70 F/21 C 80% RH**	**70 F/21 C 50% RH**	**70 F/21 C 20% RH**	**50 F/10 C 50% RH**	**30 F-1 C 50% RH**
IPI/Acetate Film[1]	17	38	87	158	731
Isoperm/Paper[2]	26	41	92	220	1540
NML/VHS Tape[3]	6	32	>64	>>64	>>64
NYS-IPI/Color Dyes[4]	18	38	182	169	843
Average	**17**	**37**	**106**	**182**	**1038**
TWPI	**17**	**38**	**87**	**158**	**731**

[1] James M. Reilly, *IPI Storage Guide for Acetate Film* (Rochester, NY: Image Permanence Institute, 1993).
[2] Donald K. Sebera, *Isoperms: An Environmental Management Tool* (Washington, D.C.: The Commission on Preservation and Access, June, 1994).
[3] J. W. C.Van Bogart, *Magnetic Tape Storage and Handling* (Washington, D.C.: The Commission on Preservation and Access, June, 1995).
[4] James M. Reilly, *Storage Guide for Color Photographic Materials* (Albany, NY:The New York State Program for the Conservation and Preservation of Library Research Materials, 1998).

is the source of the table above that compares four such models. The first model, from the *IPI Storage Guide for Acetate Film*, deals with decomposition of cellulose acetate film base. The second, from Donald Sebera's *Isoperms: an Environmental Management Tool* (see Annotated Bibliography, page 47) deals with paper deterioration. The third is from Van Bogart's *Magnetic Tape Storage and Handling* (see Annotated Bibliography, page 47) and is a model of environmental effects on the life expectancy of Hi Grade VHS tape. The fourth model is the one that was developed by IPI for the fading rate of dyes in contemporary color photographs (i.e., the color storage guide wheel).

The table shows the predicted life expectancy, in years, of the various materials at five different storage conditions. At the bottom of the table are the *average* predictions of the four models for each storage condition. The models are remarkably similar, especially at near-room temperature. At low RH and at extreme low temperature there are some larger differences, but at 50°F the models are quite close. At 30°F the largest difference is between about 800 years predicted life and about 1500 years predicted life—only a factor of two.

Differences among materials do exist; color dyes last relatively longer at low RH than other materials, for example. Materials still should be investigated and characterized individually so that their behavior can be better understood. But such differences are not enough to obviate the practical value of a generic "rule-of-thumb" overview of how environments affect deterioration rate. The generic TWPI model differs only slightly from the color photograph data or, for that matter, from the data for paper and VHS tape. Any one of the published data sets could be a universal model in the sense that environmental analysis and improvement plans based upon it would be generally sound and appropriate for all the other kinds of materials as well.* The principal difference between the color wheel data and the more generic TWPI model is that, at cold and dry conditions, color photographs, because their dyes are humidity-sensitive, will have a slightly longer life expectancy than the generic TWPI model suggests.

IPI created the TWPI concept in order to have one universal measurement for the effect of changing storage conditions on the preservation of collections. Most collections contain a variety of materials, and it would be confusing and impractical to do elaborate calculations for each one. A general model is valuable because it is broadly applicable and therefore is a worthwhile basis for the creation of instruments and analysis software. Like other scientific constructs (for example, the Richter scale for earthquakes), it has value as a shorthand method of assessment and communication. However, when a particular type of material (for example, color photographs) is the primary focus of a collection, specific information regarding that material should be consulted if possible. Any material type as numerous and important as color photographs certainly merits close investigation on its own.

There is a place in preservation management for both the generic overview and the specific investigation of individual materials. Many materials will not be researched as thoroughly as color photographs have been, but they are still important to collections. The generic approach of TWPI can also be very helpful in situations where collections are cared for by people who have not had advanced training in preservation and do not have access to specialized information about individual material types in their collections.

The Preservation Environment Monitor

IPI developed the data set and computational methods for TWPI and is committed to practical implementation of it through instrumentation, software, and services. With the help of a grant from the Division of Preservation and Access of the National Endowment for the Humanities, a federal agency, IPI has designed an instrument known as the Preservation Environment Monitor (PEM). This device incorporates the functions of hygrothermograph and datalogger. It measures, displays, and records temperature, RH, TWPI, and PI (PI stands for Preservation Index, a measure of the preservation quality of currently prevailing conditions). Through design of monitoring devices, software, and data-analysis services, IPI hopes to make practical tools for TWPI analysis more accessible to the archival community in the coming years.

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* In fact, IPI selected the data for cellulose acetate deterioration as the basis for the TWPI model simply because the acetate data was very well documented, was known to be reproducible, and fit the general theoretical requirements for a generic representation of decay rate.

WHAT ARE "REASONABLE AND RATIONAL" STORAGE CONDITIONS FOR COLOR PHOTOGRAPHS?

Reasonable and rational storage conditions for color photographs are those that will guarantee the survival of the images for as long as the owners or caretakers want them to last. The data in the wheel are an estimate of how long it would take for contemporary chromogenic color materials to lose 30% of the image density in the least stable dye. A quick perusal of the wheel will show that this can take as little as three years or as long as several millennia. It all depends on storage conditions.

Reasonable and rational RH conditions are dictated by the physical nature of photographs. Too dry and they are brittle; too damp and they get soft and sticky and become moldy. Mold is a catastrophe for photographic materials, because the mold microorganisms attack the gelatin, discoloring it, weakening it, or destroying it entirely. When the gelatin goes, the image goes with it. Obviously the best way to deal with mold is to prevent it from starting to grow in the first place. This can be done by ensuring that the photos are never stored in RH conditions above about 70% RH for more than a few hours at a time. This is another reason why a rational RH range for color photo storage is from 20% to 50% RH.

A reasonable and rational temperature is the one that delivers the lifetime that the owners desire. The wheel suggests that today's color materials will fade noticeably (lose 30% of their image density) in about 40 years if stored at room temperature and moderate RH. To keep modern photos from fading *at all*, temperatures much colder than room conditions are required. Some estimate of the relative fading behavior at different temperatures can be obtained from the wheel. For example, if new materials will lose 30% of their image density at room temperature, and it takes about ten times longer to lose that same density at 40°F, then, if they are stored at 40°F, probably they will lose only one tenth of 30%, about 3%, of their dye density in 40 years. Storing new photos at 40°F (4°C) is thus a reasonable guarantee that the images will fade very little over the next few decades. Still greater assurance of virtually no fading would be obtained if the photos were frozen. The colder the temperature, the longer the lifetime of the dyes.

Storage Conditions for Older Color Images

A practical question in the use of the wheel is how to judge the proper storage conditions for older color photographs—those early materials that fade even faster than contemporary images and especially those that already are significantly deteriorated from decades of storage at unfavorable conditions. What can be done about them? Clearly, the window of opportunity for preserving such images in good condition is closing, if not already long shut. To expect them to last as long as the data on the wheel suggests for new photographs is unrealistic. They are more unstable to begin with, and many of them are so deteriorated that further change would be unacceptable. *Older color images require significantly colder temperatures than contemporary ones for these reasons.* Institutions that take color preservation seriously and that have large groups of fifties and sixties color pictures often use below-freezing temperatures to arrest the progress of dye fading. An example is the John F. Kennedy Library, where a 0°F (-18°C) vault is used to keep chromogenic color prints, negatives, and motion picture film.

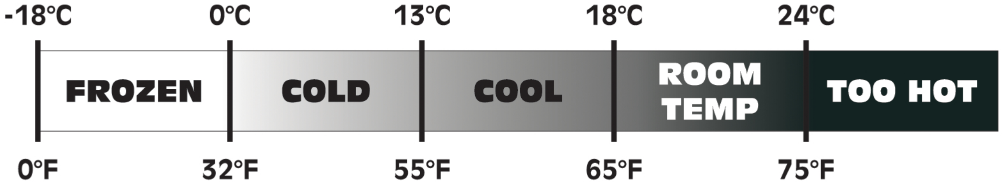
In general, the older the photograph and the closer it is to fading to a point of unacceptable dye loss, the more important it is to provide quite cold or even subfreezing storage temperatures. For many pre-eighties color materials, the dye that faded most rapidly in dark storage was the cyan dye. The limited amount of published data for late-sixties-era color films shows that cyan dye stability ranged from much less than half as stable as modern yellow dye stability (what the wheel is based on) to about two thirds as stable. Some products were worse than others. There is not enough published data to construct a wheel representing the general behavior of older films and prints. However, it is safe to assume two things: that the older materials started out with less dye stability than current products, and that they have already been kept in storage for several decades longer than current products. The combination of poor initial stability and poor storage conditions is especially harmful, and that is why so many color images have irretrievably faded to a pale shadow of their former selves within a very short time.

COOL AND COLD STORAGE IN PRACTICE

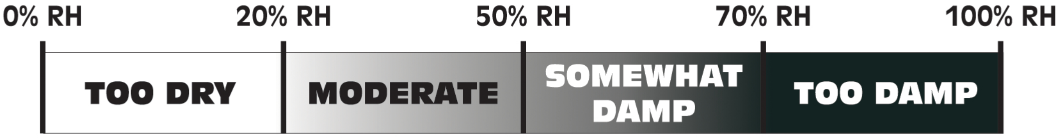
Many institutions recognize the necessity for cool or cold storage for color photographs but have questions about the cost and practicality of actually implementing such an approach. A key question is how much life expectancy does the collection need—and therefore how cold must the storage conditions be? This is not always easy to answer, because costs and impediments to access must be considered along with collection life span. "Cool" storage implies a temperature below normal room conditions but above 55°F (13°C). Cool conditions are relatively user-friendly and may provide more than sufficient life expectancy for recent color materials. However, when collection policy requires that almost no fading be allowed to occur from here on, then cold or freezer conditions are necessary. "Cold" storage is any temperature condition below 55°F (13°C). Freezer conditions (approximately 0°F or -18°C) provide an enormously long life expectancy for recent color images and almost guarantee no further change in already faded older color pictures. Whether or not cold storage or even freezer temperatures are necessary is a decision that should be based upon the age and condition of the collection, the length of time that the collection must be kept in good condition, and the curatorial importance attached to the issue of color dye fading.

Color photography is not the only type of material in archives that can benefit from cool or cold storage. Low-temperature storage is helpful in the preservation of films on cellulose acetate base (see the *IPI Storage Guide for Acetate Film)* as well as many other kinds of archived materials including nitrate film, paper, magnetic

Temperature Ranges for Color Photo Storage



Relative Humidity Ranges for Color Photo Storage

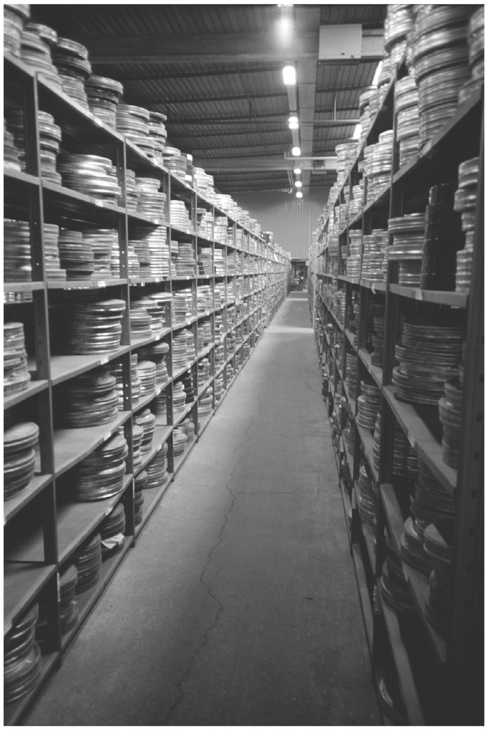


tape, etc. Therefore, in planning for storage of color photographs, also consider other kinds of materials in the collections that might need or benefit from cool or cold storage. A good example of the trend toward wider use of cold conditions is the recently constructed Norwegian National Library, where general stack storage for books and audiovisual materials is at a temperature of 46°F (8°C).

Planning for Cool or Cold Storage

One of the first practical issues to consider is the total size of the collection to go into cold storage. Large collections are probably best dealt with in specially constructed insulated rooms or prefabricated cold vaults. Such spaces involve considerable planning and expense but may be cheaper in the long run than maintaining a large number of individual refrigerators or freezers. On the other hand, smaller photograph collections often can be stored inside conventional refrigerators or freezers. This can be a functional and inexpensive alternative to special vaults.

The second issue to consider is access. Cold storage conditions almost always involve a delay for warmup when a photograph is to be used at room temperature. The delay is necessary to prevent possible water damage from condensation which would form on the photograph if it is too cold for the use condition. Cool conditions may not require any delay for warmup, depending on the temperature and RH of the use environment. The delay for warmup varies according to the use conditions and the mass of material handled at one time, but it is generally less than twelve hours and sometimes less than four hours.



For large collections, specially constructed cool or cold storage spaces are most efficient.

The issues involved in designing a cool or cold storage system can be quite complex. The advice of architects and engineers is essential for any type of vault construction and helpful even when conventional refrigerators or freezers will be used. But while engineering professionals can implement a plan, they cannot define its purposes. It is collection managers who should provide the rationale for the chosen temperature and RH conditions, determine how materials should be packaged during storage or warmup, and assess the overall impact of low temperature storage on institutional work flow. All of these related aspects must be reconciled before deciding upon a particular engineering approach.

Not all engineering professionals are familiar with the needs of cultural institutions, where a premium is placed on reliability and maintainability of equipment and where the consequences of a single failure can be catastrophic. The long-term ability of institutional personnel to understand and/or maintain the equipment used for cold storage also should be considered in the planning process. In large-scale projects, the best results are achieved when experienced and competent engineers design the project in the first place, when collection personnel understand the system (and are clear about what they want from it), and when the institution has an ongoing commitment to maintenance, together with competent vendors or in-house staff to perform it. Problems occur when any of these components of a project are missing. The most critical elements are the level of knowledge of the collection staff and the experience of the engineering professionals with creating special environments within cultural institutions.*

Monitoring for Equipment Failure

Although refrigeration technology is very reliable overall, failures are inevitable with both small and large equipment. Whether using conventional household equipment or large-scale vaults, any well-insulated space can hold heat as well as cold. When a failure in the refrigeration system occurs, even a small heat source inside the insulated area can make it quite warm. The heat from a few lights and fan motors can bring a cold vault to sauna temperatures within a short time. It would be very harmful for color photographs to be exposed to high heat or high humidity for more than a few hours. This is why it is extremely important to monitor all cold storage installations on a regular basis so that failures can be quickly detected. Large vaults usually have alarm systems to warn of equipment problems, but refrigerators and freezers may not. Cold storage in all forms requires constant attention to equipment and conditions in order to avoid undoing all the good that the system does when operating normally.

The Ins and Outs of Cold Storage—Part I: Condensation

When the storage environment for color photographs or other materials is kept at a different temperature and RH condition than that of the use environment, it is inevitable that objects will be required to make the transition between one condition and the other. In order to manage such a transition without causing harm to the objects, it is necessary to understand the potential dangers involved and the behavior of the objects with respect to moisture and temperature.

What are the dangers to color photographs and films? Most of the problems are related to moisture. Temperature change does not in itself

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* In building a cold vault, one approach is the selection of a specialized design-build vendor who can provide a turnkey (i.e., engineered, installed, and commissioned) solution. This approach can eliminate mistakes arising from insufficient experience with the needs of cold storage in cultural institutions or problems arising from a lack of coordination among various subcontractors involved in design and construction.

cause damage. Photographs can repeatedly endure freezing and thawing without any physical or chemical damage caused by temperature change alone. Archivists do not have to worry about "temperature shock." Another common fear is that photos may be harmed by the formation of ice crystals within the emulsion at freezing temperatures; research shows that this is *not* the case. Even soaking-wet color photographs can safely be frozen.

Avoiding Condensation

Too much moisture is very dangerous for photographs in cold storage. There can be several causes for excessive dampness or outright wetting in the practice of cold storage. These include sustained high RH in the cold space, melting ice, and condensation upon removal from storage.

The threat of condensation is always present when a cold object is brought into a warm space. To analyze and manage the condensation problem, several factors must be known:

- The kind of packaging around the objects when they are brought out into the use environment
- The temperature of the objects when in cold storage
- The temperature and RH of the use environment

Packaging

Packaging is important because condensation will pose no danger if the enclosure around the photographs is waterproof; whatever moisture condenses on the package during warmup will evaporate and likely do no harm. However, with no enclosures or in water-permeable sleeves and boxes, the photos may actually become wet, resulting in water spots or sticking problems.

In many collections employing cold storage, materials are routinely placed into polyethylene bags before they leave the cold conditions. Condensation still occurs, but it does no harm because it happens only on the outside of the plastic bags. The objects need only remain in the bags long enough to warm up to a temperature where condensation will no longer take place. They can then be safely removed and freely exposed to the use environment without danger of water damage from condensation.

Dew Point Temperature

Regardless of packaging, sooner or later during warmup objects will arrive at a temperature where condensation is no longer a risk. This is called the *dew point temperature*. Dew point temperature is an attribute of the use environment, not the cold storage environment. Condensation

DEW POINT TEMPERATURES FOR SOME COMMON USE ENVIRONMENTS

Temperature of Room	RH of Room	Dew Point Temperature
70 F (21 C)	50% RH	50 F (10 C)
70 F (21 C)	20% RH	28 F (-2 C)
70 F (21 C)	80% RH	64 F (18 C)
75 F (24 C)	50% RH	55 F (13 C)
75 F (24 C)	20% RH	31 F (-1 C)
75 F (24 C)	80% RH	68 F (20 C)

occurs in the use environment, and it is use environment conditions that must concern a collection manager. A dew point temperature exists for any space where the RH is less than 100%. Dew point represents the temperature at or below which condensation would take place. Condensation will occur as long as an object is at or below the dew point temperature for the room. Once an object has warmed to a temperature *above* the dew point, condensation is no longer a risk.

How is the dew point determined? Suppose that a photograph is brought from a freezer into a room that is 70°F (21°C), 50% RH. As long as the temperature and RH of the use environment are known, dew point temperature can be determined by using a computer program or referring to a *psychrometric chart* like that used by engineers to determine the moisture and temperature behavior of air. The table on page 35 shows dew point temperatures for some representative use environments. Using either of these methods, we would find that the dew point temperature for the 70°F (21°C), 50% RH conditions in our hypothetical room is 50°F (10°C). This means that if the temperature of the photo is 50°F or less, condensation will occur on it. If it has a temperature warmer than that, no condensation will occur. When the photograph first comes from the freezer, still at freezer temperature, it cools the air immediately surrounding it to almost the same temperature. This causes condensation to occur on the outside of the enclosure (or on the photograph itself if the room air can reach it). As the photograph warms, its temperature rises. Condensation continues until the air surrounding the photograph reaches the dew point temperature of 50°F (10°C). As the photograph warms further, eventually coming to equilibrium with the room temperature of 70°F (21°C), the condensate starts to evaporate.

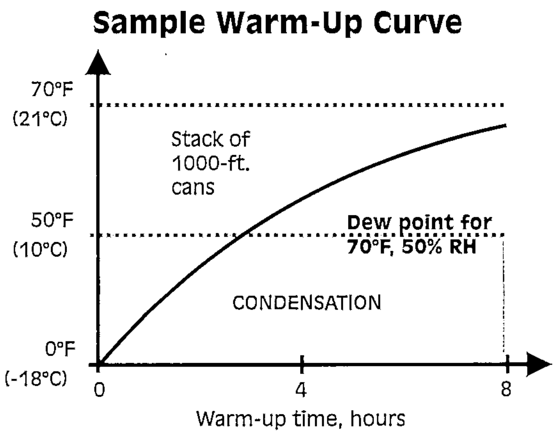


Illustration of how a stack of 1000-foot motion picture film cans behave when brought from a freezer into a room at 70°F (21°C), 50% RH. The curve shows the temperature of the film during warmup.

The whole temperature equilibration process (RH equilibration is something else entirely) usually takes less than twelve hours—sometimes much less, depending on the mass of the object. A stack of boxes of film takes longer to come to temperature equilibrium than does a single box. Also important is the amount of surface area exposed. In general, however, packaging materials provide little or no thermal insulation. Relatively small objects like a single 250-foot roll of 16mm film come to temperature equilibrium with their surroundings within four hours or so; a single sheet of 4 x 5 film requires less than one hour.

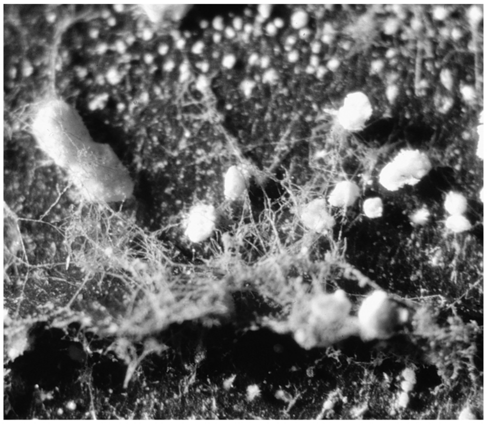
Determining Warmup Time

What is the minimum required warmup time for materials coming out of cold storage? The answer depends upon the length of time it takes for objects to warm up to dew point temperature. This in turn depends on the temperature and RH in the use condition. If conditions vary in the use environment, estimates for warmup time should be based on worst-case conditions. The worst case (longest required warmup time) will usually occur on a hot and humid summer day when the dew point temperature of the use environment is highest. The higher the dew point temperature, the longer it takes for a cold photograph to warm up to it.

If the need for access to a collection dictates absolute minimum warmup times, performing experiments to actually measure the temperature of typical objects is a good way to establish warmup procedures. However, care in measurement is required because objects warm up from the outside in. The center of a mass of material remains cool longer than the surface does.

Moisture Relationships in Cold Storage

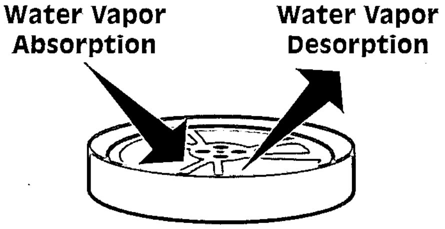
Color photographs always contain a certain amount of moisture. Even in very cold temperatures, they will absorb or desorb (give up) water according to the relative humidity of the surrounding atmosphere. Successful management of a cold storage operation requires a good understanding of the concepts of relative humidity, moisture equilibrium relationships, and the interactions between temperature and RH in a closed space. However, detailed discussion of these topics is beyond the scope of this publication; see the annotated bibliography for more information. This discussion will confine itself to some points of practical significance.



Close-up of mold growing on a photograph. Too high moisture content in color photos will lead to mold growth.

Moisture relationships are important because color photographs are vulnerable to damage from excessive dampness and from excessive dryness. Too much moisture content in a photograph can lead to mold growth, water spotting, sticking together, and deformation of the gelatin emulsion layer. Too much moisture also leads to faster rates of chemical forms of deterioration such as dye fading, acetate film base deterioration (a.k.a. the *vinegar syndrome*), and faster fading of black-and-white images. If conditions are too dry, and therefore there is too little moisture in the photograph, it may shrink, crack, and become too brittle to handle.

The secret to avoiding these problems is correct management of the moisture equilibrium relationships involved in the storage and use of color photographs. The goal is to maintain a moderate moisture content in the objects. One way to define this ideal of moderate moisture content is to express it in terms of the kind of environment that will produce the proper amount of moisture in the objects once moisture equilibrium has been established. At room temperature, an RH between 20% and 50% will result in a safe, moderate moisture content. At freezer temperatures, a surrounding atmosphere with an RH between 20% and 40% will have the same result. Moisture equilibration goes on inside freezers, but considerably more slowly than at room temperature. Low temperatures slow down the diffusion of moisture throughout the photograph. The rate of moisture equilibration is about ten times slower in a freezer than at room temperature.



Photographs absorb and desorb moisture from the surrounding air. An equilibrium is established when rates of absorption and desorption are equal. The amount of water in the object at equilibrium depends on the RH of the surrounding air.

RH Control in Cold Storage

Bearing in mind that the purpose of RH control in cold storage is to regulate the moisture content of the photographs, there are two basic options:

- Control the RH inside the cold storage area
- Precondition the photographs to a moderate moisture content and package them inside moisture- and vapor-proof enclosures.

Controlling the RH of the Atmosphere in Cold Storage

This option is used most often in specially constructed cold storage vaults. It relies on the fact that even at low temperature the moisture equilibration process still occurs, albeit more slowly. Regulating RH within a range of 20% to 40% inside a very cold space requires special dehumidification equipment operating cycles or defrost features that add to the cost of a cold storage installation.

An advantage of RH control in the cold space is that moisture-permeable enclosures such as document boxes, museum cases, filing cabinets, and the like can be used in storage with no additional enclosure required. (Of course, adequate precautions against condensation must be taken when the objects are removed for use.) There is a certain peace of mind associated with the controlled RH approach because all the objects will slowly equilibrate to a safe moisture content, regardless of how much water they contained when they were first put into storage. On the other hand, if all the photographs have been placed into packaging that is impermeable to water vapor, they will not equilibrate. It is this principle upon which the second option for controlling moisture relies.

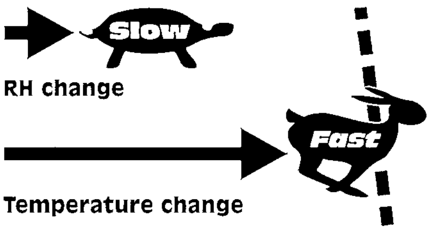
Moisture- and Vapor-Proof Enclosures in Cold Storage

The second option for controlling moisture content of color images in cold storage is moisture- and vapor-proof packaging. This ensures that no water or water vapor enters or leaves the objects inside the package making RH control in the cold space unnecessary. However, because the moisture content never changes, it is important to be sure the photographs have an appropriate moisture content *before* they are placed into cold storage. The sealed package option has the added advantage of protecting against accidental water damage from a sprinkler discharge or ice buildup in a freezer.

While the idea of tightly sealed packages is simple enough, in practice there are some complications. First of all, the packaging must be resealed each time an object is returned to cold storage. This can be both inconvenient and expensive if special heat-sealable materials are used for packaging. Large, frequently used collections are often better served by humidity-controlled storage, because moisture-proof packaging is very labor-intensive. Secondly, it is not as easy as it might seem to create truly vapor-proof packages. Many plastic materials that appear to be impermeable (for example, polyethylene freezer bags) actually have significant water vapor permeability. When a complete vapor seal is desired, special materials are required. Laminate films composed of layers of aluminum foil and polyethylene or polyester (for example, Marvelseal™ 360) are heat-sealable and vapor-proof. The aluminum layer delivers a high degree of vapor impermeability, and the plastic allows for heat-sealing. However, creating custom laminate film packages is both time-consuming and expensive, and there is no guarantee against imperfect seals.

Relative Equilibration Rates

How rapidly color photos adapt to environmental changes



One other aspect of the use of moisture- and vapor-proof packages concerns storage of acetate and nitrate films. Films on nitrate and acetate support are subject to chemical decomposition and may generate acidic gases. (This phenomenon is discussed at length in the *IPI Storage Guide for Acetate Film.*) Sealed packages prevent the escape of acid decomposition products, thereby accelerating the rate of base decomposition. For this reason, prolonged storage of acetate and nitrate films in sealed packages at room temperature should generally be avoided. On the other hand, sealed packages can be recommended for acetate film storage under cold conditions (less than 55°F/13°C). Low-temperature storage slows down the overall rate of decomposition to such a large extent that trapping of degradation products within the package becomes an insignificant factor. Thus, sealed packaging is appropriate for nitrate and acetate at cold storage conditions but not at room temperature.

Reusable Sealed Packages for Cold Storage

Given the difficulties associated with truly vapor-proof packages composed of heat-sealable laminates, an alternative approach is reusable packaging that is optimized for cold storage use (i.e., as sealed as is conveniently possible) and monitored with passive humidity indicators. This approach is an attempt to minimize vapor penetration but it ultimately relies on monitoring the RH inside the package and periodic renewal of the packaging as necessary. In this way, the objects can be protected against excessive moisture absorption during prolonged cold storage, but the expense and difficulty of one-use packaging can be avoided.

To design sealed but reusable packaging for use in cold storage, one must know something about the characteristics of various packaging materials and how much moisture is transported through them at low temperatures. Cardboard boxes present very little impediment to water vapor. Some plastics (polyester, for example) are almost impermeable. Others allow significant vapor transport. Metal cans for motion picture film storage may appear sealed but are not sufficiently vapor-tight for this purpose. It is difficult to estimate how long a particular combination of boxes, plastic layers, or other inclusions such as desiccants might last before allowing the moisture content of objects in cold storage to rise to unacceptable levels. This uncertainty, together with the possibility of an accidental imperfection in packaging, are the reasons for including passive RH indicators, usually in the form of a small card treated with cobalt salts that change color when the RH rises. A failed seal or improper package construction can be detected with such an inexpensive RH monitor, which should be checked every six months or so.

Both the Image Permanence Institute and the Conservation Analytical Laboratory at the Smithsonian Institution have researched the moisture relationships of packaging for cold storage of photographic materials. Mark McCormick-Goodhart of the Smithsonian has proposed a packaging system for slide or print storage that is a good example of the concepts behind the sealed-but-reusable approach. The photographs are placed inside a conventional archival cardboard box, then inside a reclosable polyethylene bag. On the outside end of the box, visible through the polyethylene, is a passive RH indicator card. Thus the RH inside the bag (a good indication of the moisture content of the box and its contents) can be seen without disassembling the package. Because even a relatively thick polyethylene bag is not vapor proof, a second reclosable bag is used. To extend the working life of the package system, a moisture-absorbent material such as desiccated archival mat board is placed within the outer bag. This absorbent material collects moisture and can be periodically renewed without disturbing the inner bag and its contents. McCormick-Goodhart estimates that if the package is undisturbed, more than 20 years in a freezer at high RH could pass before the moisture content of the inner bag

Conventional household freezers may be used for color photo storage, but moisture- and vapor-proof packaging is required.

would begin to rise. His design is commercially available in kit form, but it can easily be created from separately purchased components.

The Use of Conventional Refrigerators or Freezers for Cold Storage

For small collections or institutions, the most accessible forms of cold storage are conventional refrigerators or freezers. They have the advantages of ready availability and relatively low initial and operating costs. The normal temperature of household refrigerators is about 40°F (4°C), while household freezers typically maintain about 0°F (-18°C). The difficulties with the use of conventional refrigerators or freezers are controlling the moisture content of the objects stored inside and guarding against possible water damage due to melting ice or condensation. Although in some refrigerator/freezer models the RH inside the refrigerator compartment is maintained at moderate levels, in general it is better to rely on sealed packaging to control moisture content. Sealed packages also protect the photographs from water damage if there is a system failure or condensation problem.

In an upright or chest-type household freezer, a concern is the buildup of ice on surfaces and objects when warm room air enters the freezer. If no provision were made for dealing with this, then eventually a thick coating of ice would cover everything in the freezer, possibly damaging its cooling coils and causing a flood of water if the cooling system shut down for any reason. The more frequently a freezer is opened, the faster ice will build up. Ice should not be allowed to accumulate inside a freezer used for photograph storage.

Most freezers sold today are of the "frost-free" type. This usually means that they have a periodic warming cycle (approximately every 24 hours) in which the coils become warm for a few minutes, melting the ice on them and temporarily raising the temperature in the freezer to above freezing and briefly elevating the RH to 100%. The melted ice runs through a drain into a pan and later evaporates into the room air. Objects in the freezer during this brief cycle do not have time to warm up completely or to equilibrate to the fleeting high RH condition. However, although the defrost cycle of common freezer equipment is not usually a problem for photographs stored inside, it is still necessary to use sealed packaging, because the RH inside the freezer can become quite high for a variety of reasons, and because the risk of getting wet from melting ice is always present.

While conventional refrigerators and freezers can be very useful for small collections, if an institution finds itself purchasing a dozen or more units, then a purpose-built vault or cold room may be more economical and easier to maintain. Refrigerators and freezers add heat to the rooms they are in. Many together can produce significant amounts of heat that another air conditioning system must deal with.

The Ins and Outs of Cold Storage—Part II: Moisture Equilibrium Changes

We have dealt with condensation, warmup times, and packaging while in cold storage, but there is another important factor to consider when moving photographs from one environmental condition to another: changes in an object's moisture content. In an ideal world, the RH of every environment in which photographs were stored and used would be closely regulated so that the moisture content of the objects always remained at a moderate level—not too little, not too much. In this ideal situation, condensation would be the only issue to consider when photographs were moved in and out of cold storage. The moisture content of the photos would always be the same, wherever they went. There would be no question about whether photographs have had a chance to fully equilibrate to a different moisture content or whether they were experiencing extreme RH fluctuations.

In the real world, things are seldom so simple. Changes in moisture content as a result of equilibration to a new environment do happen. Collection managers have to know how to evaluate and manage such changes to prevent moisture-related damage. What are the dangers? As mentioned, too much moisture can lead to mold, gelatin softening, a faster rate of dye fading, and so on. Too little moisture can lead to mechanical damage from shrinking and cracking. To some degree, the extent and rate of change of moisture content can be factors in mechanical damage. Prolonged exposure to high RH conditions followed by a rapid drying out can be especially dangerous. Compared to some objects such as oil paintings on wooden panels, photographs are relatively robust in the face of RH extremes or RH cycling, but they are far from invulnerable.

The goal of managing moisture equilibrium changes in color photographs is to make sure they never have a chance to come to equilibrium with conditions that would make them too dry or too damp, or to experience too rapid a change of moisture content. This is done by knowing the environmental conditions they have been exposed to in the past, knowing what conditions they are going into, and by knowing how long it will take for a new equilibrium to be established. The enclosures and packaging surrounding photographs play a large role in determining how long it will take to reach moisture equilibrium in a new environment. Also important to know is the basic equilibration behavior of the object itself. Some objects are inherently slow to equilibrate. At room temperature, a roll of 35mm motion picture film freely exposed to the air takes about ten days to come to moisture equilibrium with a new RH condition.

Managing the Moisture Content of Color Photographs

The following table illustrates how enclosures and temperature can dramatically affect the rate of moisture equilibration of photographic materials. It gives the times required for a 100-foot roll of 35mm film to attain 90% of its final moisture equilibrium when coming from a 20% RH condition to a 50% RH condition. The data are from experiments performed at IPI by research scientist Jean-Louis Bigourdan.

Although the time required for film stored in metal cans or plastic boxes at freezer temperature to come to full moisture equilibrium was not determined in this experiment, it is logical to assume that several years would pass before equilibrium is reached in a freezer.

MOISTURE EQUILIBRATION TIMES FOR A 100-FOOT ROLL OF 35MM FILM IN VARIOUS ENCLOSURES AT ROOM TEMPERATURE AND FREEZER TEMPERATURE

Enclosure	Room Temperature 70 F (21 C)	Freezer Temperature 3 F (-16 C)
None	10 days	4 months
Cardboard box	10 days	4 months
Metal film can	3 to 4 months	
Plastic microfilm box	1 year	

In real-life moisture content management, the first thing to consider is where the objects have been in the past and whether or not they have had a chance to equilibrate while they were there. This determines their moisture content at the starting point of any transition to a new environment. The cold storage environment and the primary use environment (the reading room, the photo lab, the projection room, etc.) are the places where objects spend long periods of time, and where they likely have had a chance to fully equilibrate.

Using a Warmup Room

One of the most common questions about planning a cold storage facility is whether or not to provide a separate warmup space in which the RH and temperature are controlled at intermediate levels between the storage environment and the use environment. The idea is to avoid condensation and allow for slow and safe equilibration to a new RH condition. Condensation issues are straightforward enough with a warmup space. The dew point of the warmup room must be appropriate for the temperature of the cold storage space (see page 35). This is to make sure that condensation does not occur in the warmup room. For the warmup room to do its job of getting the objects ready to experience the use environment, its temperature must be at least equal to or higher than the dew point temperature of the final use environment, yet not so warm and humid as to cause condensation when objects are put there.

A warmup space eliminates the need to place objects into plastic bags to prevent condensation. However, what about moisture equilibration? How long, for example, would a cardboard box full of prints have to remain in the warmup space to equilibrate to the new RH, and what must the RH be to ensure a safe transition?

The time required for moisture equilibration of a stack of color prints in plastic sleeves inside a cardboard box is on the order of two weeks at room temperature. The configuration of the photos (rolls, stacks, tightly or loosely packed) plays a role, as does each layer of packaging. The two-week equilibration time for a box full of prints exemplifies a practical difficulty associated with humidity- and temperature-controlled warmup spaces: it often takes an inconveniently long time for moisture equilibration to occur. In most circumstances, a warmup room for RH equilibration would require weeks or even months to do its job, depending on how objects are packaged. Warmup rooms can sometimes be helpful, but their benefit in managing moisture equilibration has to be carefully evaluated. If user who must access a collection can't wait weeks for moisture equilibration to occur, then the primary benefit of a warmup space is condensation control, and condensation often can be managed in other ways, without the expense of an environmentally controlled intermediate space.

Because the packaging and arrangement of most photographic materials ensures a relatively slow moisture equilibrium rate, the danger from very abrupt RH changes is only moderate. The third remaining danger, that of coming to equilibrium with a too high or too low moisture content in the final use environment, has nothing to do with conditions in the warmup room. When the objects get to the use environment, the questions there are the same as always: what moisture content will the new RH condition ultimately produce in the objects, and will the objects have time to come to equilibrium before they are put back into storage or moved into some other circumstance?

Avoiding Physical Problems in Gelatin Emulsion Layers During Transitions In and Out of Storage

The most important thing to avoid during transitions in and out of storage and use areas is putting the photographs in a situation where the combined effects of heat, moisture content, and pressure lead to gelatin softening and consequent physical damage to the emulsion layer. It is not unusual for a photograph to experience temporary high temperatures during transportation in a truck or car. Keeping the moisture content at a moderate level helps to offset the effects of high temperature and pressure. A color photograph can tolerate higher temperatures and higher amounts of pressure from the weight of other photos on top of it if its moisture content is relatively low.

POSSIBILITIES FOR RESTORING FADED COLOR PHOTOGRAPHS

Chemical restoration treatments are not a possibility for faded chromogenic color photographs. The chemistry of the dyes is such that the fading reactions are not reversible. All that a trained conservator can do with a faded image is physically repair tears and then carefully paint in localized areas of loss. Overall fading cannot be successfully treated. Normally, faded color images are dealt with by corrective copying, either by conventional photographic means or by digitization. In the process of reproducing the image, loss of color balance and dye fading can be partially compensated for. However, the results are not guaranteed to be faithful to the original unfaded image, and very severe dye loss cannot be overcome.

In both the photographic copy method and the digital copy method, once a dye has faded away, nothing can be done to bring it back. Detail that is lost will remain lost. Of the two copy methods, digital reproduction is the most practical and successful. Correcting for dye fading in making a photographic copy is very labor-intensive and difficult. On the other hand, digital image processing is considerably less labor-intensive and can produce quite impressive reconstructions of faded color images when appropriate algorithms for compensating for dye loss are applied. However, the idea that digital imaging can seem to "unfade" color photographs should not be taken as an excuse for not providing proper storage for originals.

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