MOISTURE AND TEMPERATURE EQUILIBRATION: BEHAVIOR AND PRACTICAL SIGNIFICANCE IN PHOTOGRAPHIC FILM PRESERVATION

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1.INTRODUCTION

The importance of climate conditions in the preservation of hygroscopic materials is well recognized. For a large variety of museum objects and archival records, heat and humidity are the primary factors that govern the occurrence and rate of biological decay, chemical instability and mechanical damage. With these risk categories identified, the management of temperature and humidity has been approached in terms of (1) low and high limits, (2) average levels and (3) magnitude of fluctuation. This strategy has been periodically re-examined, and recommendations made for various preservation situations and degrees of risk [1, 2, 3, 4, 5, 6].

Recent advances in preservation science have led to additional studies on climate control. The physical response of various organic materials to fluctuations in temperature and RH and the buffering role of microclimates in various real-life situations has received increasing attention [8, 9, 10, 11, 12, 13, 14, 15]. These investigations underline the importance of the dynamic interaction between climate and object—that is, between the macroenvironment and microenvironment. This is a time-dependent relationship that is determined both by the nature of the object and by the moisture-buffering capacity of the enclosure used. The enclosure is more than physical protection. By containing the object and the space surrounding the object, it creates a microenvironment that may differ in important ways from the macroenvironment. Enclosures may thus be a major factor in overall climate management.

The main thrust of this paper is to further explore the thermal and moisture equilibration rates of photographic film and to discuss some of the issues encountered in motion-picture and sheet-film storage, those rates help determine the impact of climate changes on the physical and chemical stability of archival objects. This tutorial study provides additional information on climate fluctuation, the impact of seasonal drift, and the growing attention being given to cold storage. This paper is intended to serve as a source of basic information in this field as well as a review of some of the important variables.

Background

The development of the cinematographic film industry prompted a number of early papers focusing on the relationship between climate conditions and the physical properties of film.

a. Moisture equilibrium curve

Photographic film has a multiple-layer structure (image layer, support, and additional coating) and combines different materials such as gelatin binder and plastic support. Those components are hygroscopic; they contain moisture and exchange water vapor with the surrounding air as a result of humidity changes. In other words, when placed in a new environment, the material will tend toward a state of equilibrium by losing moisture if the air is dryer, or absorbing moisture under higher humidity. This behavior is usually illustrated by the *moisture equilibrium curve* (an isotherm curve), which expresses the moisture content as a function of RH conditions at a constant temperature.

This type of representation is pertinent because the moisture content of organic materials is primarily determined by the relative humidity of the air [16,17]. In addition, the structural components of an object may each have different equilibrium curves. Specifically, the various layers of photographic materials contain different quantities of moisture under identical climate conditions and respond differently to humidity changes (see Figure 1).

The importance of humidity conditions on the physical behavior of photographic film was discussed in the early literature [16,17,18,19]. When moisture content increases, the component layers expand and the gelatin binder becomes more susceptible to physical transformations (e.g., softening, tackiness, ferrotyping). When moisture content decreases, materials may become brittle, physical stresses between the various layers occur, adhesion weakness may appear, and dimensional changes of the different structural components may result in physical distortion.

Recently, the impact of temperature on the moisture equilibrium curve of photographic materials has been re-examined because of greater interest in cold storage for film preservation and in high temperature incubation to predict life expectancy. The moisture content of photographic film is not completely independent of temperature but holds more moisture at low temperature at the same relative humidity. This behavior exists in various organic materials (e.g., grain, dry milk, cotton, paper) and was recently investigated in gelatin [20, 21] and film [22]. It is a significant factor in cold storage practices and will be further discussed in this paper.

b. Equilibration rates

Thermal and moisture equilibration rates have been major concerns for specific products such as aerial film and motion-picture film [16, 18, 23, 24, 25] for which dimensional stability is of great importance. In these investigations, the impact of packaging and film configuration, format, and mass were discussed in practical terms. The slower moisture equilibration rate at lower temperatures was pointed out, and the respective rates of moisture absorption compared to desorption was investigated. The slower moisture desorption rate was attributed to the drying of the outer emulsion layer [18]. Most of these studies were completed over 25 years ago and they have been revisited in this paper for current materials.

Because of the hygroscopic character of most components of museum objects and modern information storage media, institutions have attempted to minimize temperature and relative humidity fluctuations, mainly to avoid mechanical damage. Fluctuating conditions also may be relevant to their chemical stability. The effect of relative humidity fluctuations on paper stability, and its practical significance has been discussed [10, 11]. Although much emphasis has been put on the tight control of the macroenvironment, periodic climate changes (daily or seasonal) are part of collection reality. To date, a limited number of microenvironment studies have focused on the buffering capacity of enclosures. They involve various types of materials (e.g., museum cases [9, 12], tape cassettes [15], wood boxes [13], packaging [14]) and provide information on the impact of the microclimate on collection life.

This paper reports information on a broader range of storage situations primarily relevant to film but including a few insights on photographic prints and books. Results on both thermal and moisture equilibration rates are reported and discussed in terms of their practical significance. In addition, the impact of periodic macroclimate changes has been empirically evaluated.

Most uses of photographic film (viewing, projection, duplication) require the disruption of the storage climate conditions. Through displacement, transport, and direct access, archival records may experience either small or drastic climate changes (e.g., back and forth between cold storage and the user's room). In this context, the understanding and judicious use of the microenvironment are essential.

2. EXPERIMENTAL AND RESULTS

2.1 MOISTURE EQUILIBRATION AT ROOM TEMPERATURE

Since film may be exposed to humidity changes during storage or use, conditioning rate is a basic consideration in film preservation. Because of their moisture-buffering capacity, different types of enclosures may minimize humidity changes. Therefore the moisture-conditioning rate for both roll and sheet film was determined when stored in various enclosures.

Experimental and analysis

The conditioning process was monitored either gravimetrically or by inserting a temperature/humidity sensor inside the mass of film. Because the conditioning rate is somewhat independent of the relative humidity range, it is conveniently expressed as the percentage equilibration over time. Data are plotted so that 0% equilibration represents the initial RH and 100% represents the final RH.

The independence of equilibration rate from RH range was verified empirically by monitoring the moisture equilibration of two separate roll films in moisture permeable cardboard boxes. One was preconditioned to 21°C,20% RH and the other to 21°C, 50% RH for a sufficient time so that complete equilibration was achieved. After preconditioning, both rolls were exposed to 21°C, 70% RH inside a climate-controlled chamber. The weight-change curves reflect the two RH differentials used in the experiment (see Figure 2) but the resulting percent equilibration curves are quite similar (see Figure 3). Figure 3 makes it possible to extend the validity of the results obtained from a given RH differential to other humidity ranges. Another common way to compare the effectiveness of various enclosures is based on equilibration time to reach a given percent equilibration. This is a valid indicator of the moisture-buffering capacity of various enclosures and configurations.

Effect of enclosures

A series of motion-picture roll films was first preconditioned to 21°C, 20% RH, then enclosed in various containers and exposed to 21°C, 50% RH. The moisture exchange was monitored by the weight change over time. Since the moisture diffusion takes place primarily through the film width, the results for 100-ft. rolls are also valid for longer rolls. The conditioning rates are illustrated in Figure 4 for a cardboard box, a metal can, and a plastic box. The film enclosed in the cardboard box takes 15 days to reach 90% equilibration, but the roll enclosed in the untaped metal requires several months. The roll of film in the plastic box takes even longer (i.e., over one year).

It is noteworthy that no significant difference in moisture equilibration time is observed between a roll with no enclosure and a roll enclosed in a cardboard box. This indicates that the conditioning process is governed by the rate of moisture diffusion into the film roll and is not altered by the characteristics of the cardboard enclosure (i.e., gaps, permeability to water vapor, moisture absorption and desorption rate of the cardboard). (A similar situation was shown in a comparison of magnetic tape in a cassette with a bare tape pack [15].) In other words, the cardboard box does not provide efficient buffering against humidity changes.

The situation is different for film enclosed in a metal can or a plastic box, where the limiting factor is determined by the container, based on the nonpermeable material for the metal can or tightness of the seal for both these closed containers.

The same general behavior was observed for resin-coated prints stored in cardboard or metal boxes. To put the results plotted in Figure 5 in perspective, the 90% moisture equilibration time is approximately one hour for a single sheet and one month for 150 sheet stack in a metal box. These differences demonstrate the importance of enclosures in buffering outside humidity changes.

Absorption versus desorption rates

Another factor relates to the moisture equilibration rate when film is exposed to either higher or lower humidity conditions. The absorption and desorption of moisture was explored between 21°C, 20% and 21°C, 50% RH. The equilibration half-times were obtained for 100-ft. film rolls enclosed in a metal can and in a plastic microfilm box (see Figure 6). Because of the importance of the seal tightness, the same containers were used for both the absorption and desorption study. Moisture desorption is slower than moisture absorption and this had been attributed to a case hardening of the gelatin during desorption [18]. This is consistent with studies dealing with materials other than photographic film [9, 12]. In some situations, depending upon the conditioning times, the average moisture content of photographic film in a fluctuating humidity environment may be higher than the average of the two extreme conditions.

2.2. HUMIDITY CYCLING

It has been established that the magnitude of RH cycling may be critical for the physical stability of multiple-layer artifacts, and allowable RH fluctuation has been addressed for different materials [3, 4, 6, 7]. However, there is a limited amount of data with which to quantify the damping effect of enclosures upon humidity cycling. Consequently, a series of RH cycling experiments were undertaken focusing on film containers, museum cases, and books. The various enclosure configurations were placed in a programmable climate-controlled chamber at a temperature of 21°C and exposed to daily RH changes of either 50%±10%RH or 60%±20%RH. Each RH level was maintained for 12 consecutive hours. The changes were monitored by several temperature/humidity data-loggers[1] placed both outside and inside the containers.

Film containers

In Figures 7 and 8 several microfilm containers, either empty or containing a 100-ft. roll of film, were tested. The daily RH magnitude (the difference between the highest and lowest RH levels) in the microenvironment is plotted for each enclosure. A single vertical line represents the RH cycling magnitude in the macroenvironment (i.e., 20% and 40% RH respectively). The moisture buffering effect of the various enclosures is measured against these two references.

The following conclusions can be drawn:

[1] Four different measurement devices were used during this study depending on the physical dimensions that were required: Vaisala HMP 130Y Series Humidity and Temperature Transmitter, Spectrum Temperature

(1) A proportional relationship exists between the fluctuations of the inner microenvironment and outer macroenvironment. This is consistent with all empty containers.
(2) The cardboard box has very little moisture-buffering capacity as opposed to the untaped metal can and the plastic box. The RH fluctuation inside the cardboard box, whether empty or with roll film, is of the same order of magnitude as the outside humidity fluctuation. This observation is consistent with the moisture equilibration study described previously.
(3) The enclosed hygroscopic material (roll film) effectively buffers the RH fluctuation. A macroclimate RH fluctuation of 40% RH was translated into a mere 1% microclimate RH variation when a 100-ft. roll of film was enclosed inside either a metal can or a plastic box. (This 1% variation was introduced by the measurement device). This demonstrates that within a reasonably tight enclosure the organic material governs the inner RH by exchanging moisture with the microenvironment. Because the moisture changes are rather small compared to the total moisture content of the film, the latter can be dominant in controlling the microenvironment.

A study of the behavior of 1000-ft. roll films in metal, nonvented and vented plastic cans has provided additional data attesting to the buffering effect of photographic film. Film in a vented plastic can displayed a fluctuation smaller than 5% RH when exposed to daily ±20% RH cycling from a starting RH of 60%.

In summary, these observations demonstrate that the buffering of humidity changes depends on enclosure characteristics as well as on the moisture capacity of the enclosed material itself. In practical terms, the tighter the seal of the enclosure, the

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and RH logger 2000 (Veriteq Instruments), SR-002 Temperature and RH logger (ACR Systems inc.) and LTH-8K Datalogger (Kiwi Instruments).

greater the impact of the film in minimizing the microenvironment RH changes. With the exception of roll film stored in cardboard boxes, the moisture exchange as a result of daily RH cycling is generally insignificant compared to the total water content of the film itself.

Archival Boxes

A similar study was applied to two typical museum boxes. However, the emphasis was on the RH gradient existing between the microenvironment and the core of the protected material. A stack (28x35.5x4.5 cm) of twelve mat-board mounts was enclosed in a drop-front cardboard document box and a Solander museum case. One data-logger was inserted within the stack of mounts, a second was placed in the space surrounding the stack and a third monitored the outside conditions. Figures 9 and 10 illustrate the RH records when a daily RH cycling (50%±10%RH) was applied at 21°C.

The direct comparison between figures 9 and 10 shows the greater moisture-buffering effectiveness of the Solander museum case compared to the cardboard document box. Although full moisture equilibration of the mat boards was not achieved within any 12-hour period, the microenvironment inside the cardboard document box tended to mimic the RH cycling that occurred outside the box. In the Solander museum case, the 20% RH macroenvironment fluctuation was translated into less than 5% in the microenvironment.

In both cases, however, the RH measured within the stack of mat boards was represented by a flat RH line. This is explained by a significant RH gradient through the mass of material due to the slow rate of moisture diffusion from the outside of the stack to the core. An RH difference exists not only between the surrounding space and the core of the mat-board stack, but also between the core and the edges of the stack. A hygroscopic object is not a homogenous entity regarding moisture conditioning rate; the perimeter equilibrates more rapidly to humidity changes.

Seasonal humidity drift

The previous discussion dealt with daily or short-term humidity fluctuations. However, under practical storage conditions long-term seasonal humidity drifts can be very important. In fact, roll films in containers and books on shelves do accommodate to seasonal humidity changes. This was studied by placing a humidity sensor inside a book for a period of three months. Even if the core of a book does not experience humidity cycling during a short period of time (see Figure 11), it is still affected by seasonal changes (see Figure 12). The core of the book is protected from the short-term RH changes by the paper mass, but a gradual change in core RH over time is observable.

The slow moisture diffusion rate causes conditions at the core of the book to lag behind the conditions outside the book, but eventually equilibrium is reached. This situation parallels real-life storage areas characterized by yearly alternation of dry and humid conditions. Because these seasonal drifts take place over several months, moisture equilibration might be partly or fully achieved depending upon the enclosure used. The effect of humidity changes on the microenvironment inside enclosures is mostly dependent upon the humidity profile over time and on the types of enclosures.

2.3. MICROENVIRONMENT RH VERSUS TEMPERATURE CYCLING

Relative humidity represents the moisture content of the air expressed as a percentage of the maximum amount it can hold at a given temperature. This maximum increases as temperature increases. Consequently, for a given absolute humidity in a closed system, the relative humidity varies with temperature, decreasing at higher temperatures and increasing at lower temperatures. Accordingly, temperature cycling should be reflected in relative humidity changes. However, as indicated by the following experiment, this is not necessarily always the situation inside archival enclosures.

In this investigation, a drop-front cardboard box containing a stack of cardboard mat boards was preconditioned to room conditions and then exposed to daily temperature cycling (±5°C from 20°C starting point) while the RH was maintained at approximately 50% RH. As before, three temperature/humidity dataloggers were used. One was inserted in the middle of the stack, the second was placed inside the box, and the third monitored the outer environment.

Thermal equilibration was rapidly achieved for both locations inside the box. However, temperature cycling caused unexpected RH changes both inside the box and in the middle of the enclosed material itself. In this particular storage situation, the temperature increase caused an increase in RH, rather than the reverse.

This behavior, at first glance contradictory, can be explained by the fact that the cardboard enclosure and mat-board mounts are themselves very hygroscopic. Cardboard absorbs moisture when the temperature drops and desorbs moisture when the temperature rises. In other words, the cardboard by exchanging moisture in response to temperature changes, alters the microenvironment RH. This change in the microenvironment is reflected in a small but still measurable effect within the stack of mat-board mounts. The quantity of water vapor involved in such changes is rather small compared to the total moisture content of the material.

Nevertheless, the impact of temperature cycling on the percent moisture content of hygroscopic materials deserves further careful study. In addition, a closer examination of Figure 13 shows that an equilibration process followed the first rapid change leading to a new RH equilibrium for the twelve subsequent hours. Although the difference is rather small (less than 5% RH for a 10°C temperature difference), it shows that the moisture equilibration curve is affected by temperature.

2.4. MOISTURE EQUILIBRATION AT LOW TEMPERATURE

Effect of temperature

The increasing use of subzero storage temperatures prompted an investigation of the rate of moisture equilibration at such conditions. Only limited data had been reported in this area [24].

Figure 14 shows the general effect of temperature on the moisture-conditioning rate of roll film. Two 100-ft. roll films were first preconditioned to 21°C, 20% RH and then enclosed in untaped metal cans. One roll was exposed to 21°C, 50% RH, and one was stored inside a frost-free freezer set at approximately -16°C, 50% RH. The rate of conditioning was determined gravimetrically. After three months at 21°C, 90% moisture equilibration was obtained, while at -16°C the film had reached only 20% equilibration after one year. This verifies earlier work that moisture conditioning occurs much more slowly at lower temperatures.

Moisture equilibration of 4”x5” sheet film was also investigated at subzero temperature. Two stacks of 150 sheets were preconditioned to 21°C, 20% RH and 21°C, 50% RH. Both sets, each enclosed in a cardboard box, were then stored inside the -16°C, 50% RH frost-free freezer. The equilibration rate was monitored using a temperature/RH sensor which was inserted within the film stack. The two moisture conditioning curves are illustrated in Figure 15. For the sheet films initially conditioned to 21°C, 20% RH an equilibrium was achieved after six months at -16°C (Figure 15), while only two weeks were required at 21°C (Figure 5). This represents a ten-fold difference in moisture-conditioning rate between room temperature and freezer conditions.

Effect of enclosures

The moisture conditioning rate at low temperatures is also very dependent upon the type of enclosure and these findings were reported in another paper [22]. In summary, similar equilibration times were obtained when roll films were stored inside a frost-free freezer either without an enclosure, or enclosed in a permeable container such as a cardboard box. Other open systems tested behaved similarly. However, the effect of enclosures is significant when tighter containers such as metal cans or plastic boxes are used. None of the typical enclosures used in real-life storage situation (e.g., cardboard boxes, metal cans, plastic boxes) prevented the moisture content of the film from increasing during storage inside the freezer.

Effect of temperature on moisture equilibrium curve

An interesting observation in Figure 15 is the very rapid initial drop in equilibrium relative humidity when the temperature is decreased from 21°C to -16°C. This can be understood by consideration of the change in the moisture equilibrium curve with temperature.

Although the impact of temperature on the moisture equilibrium curve was described in early papers, it received less attention than did the impact of RH changes [16, 24, 26]. Recently, the increasing use of cold storage has led to a re-evaluation of the relationship between temperature and moisture content. Data have been produced regarding the behavior of gelatin [20, 21] within a wide temperature range (i.e., from -20°C to 80°C). The moisture equilibrium curve of contemporary motion-picture film on cellulose triacetate base has been further investigated over a wider temperature range [22]. The data from this publication are reproduced in Figure 16.

It can be seen that at constant RH, the moisture content of the film is greater at lower temperatures. In other words, film in equilibrium at 50% RH contains a significantly higher weight of water when kept at -16°C (3.6%) than it does at room temperature (2.9%).

The transfer of sheet films from room conditions into cold storage can be followed in Figure 16. The initial conditions 20°C, 50% RH are represented by point A and the film was rapidly cooled to point B. This corresponds to a 10% drop in RH and explains the plot in Figure 15. Subsequent moisture equilibration moves the film from point B to point C, but this process may take several months.

2.5. THERMAL EQUILIBRATION

In a changing environment, temperature equilibration rates as well as moisture rates must be considered. This section deals with the former. Thermal equilibration has been approached empirically in order to cover a wide variety of film storage situations. One goal is to provide practical guidelines for cold storage practices.

Experimental

Thermal equilibration was investigated on photographic film (motion-picture film and sheet film) enclosed in various storage containers. The various configurations were stored at subzero temperature and brought to room conditions. The warm-up process was documented by using a series of thermocouples (type T) connected to a datalogger system.

Analysis

In earliers studies [25], the rate of temperature change was expressed as percentage of equilibrium [25]. Such a percentage rate curve was valid for a temperature differential from -20°C to 100°C. This data treatment was confirmed in the current study by evaluating a stack of photographic resin-coated prints under three temperature conditions: cooled from 50°C to 21°C and warmed from -16°C and 5°C to room temperature. The three sets of temperature data (Figure 17), translated into percent equilibration over time, gave very similar equilibration rates (Figure 18). This analytical approach was used to evaluate the thermal behavior and warm-up times of various configurations.

Results

Table I reports the results for various film formats, quantity of film, and packaging systems. The warm-up times listed were based on the lowest rate which is location-dependent (e.g., middle of the roll in the middle of a stack of cans). Typical enclosures have a relatively small effect on thermal equilibration rate. For example the equilibration rate of a 1000-ft. roll of motion-picture film, is not significantly altered by an enclosure made of metal or polypropylene. On the other hand, thermal equilibration rate is strongly altered by film mass, as we can see by comparing different roll lengths.

The thermal equilibration rate is much faster than the moisture equilibration rate. In most cases, photographic materials are thermally equilibrated within 6-12 hours of exposure to a new temperature condition. Although the materials may experience temperature changes (cooling, warming, fluctuations) within a short period of time, a study has shown that there were no practical risks caused by thermal shock or multiple freeze-thaw cycling [27].

Importance for cold storage

Thermal equilibration is of practical value for cold storage management. Since access to objects stored at low temperature might be needed on short notice, a risk of damage by water condensation exists. When an artifact is brought from cold storage into a warmer environment and its temperature is below the dew point of the air, moisture condenses on the outer surface (see Figure 19). To prevent this, two distinct methods are used.

First, it is possible to create a temperature-and humidity-controlled environment such that the temperature of the object is always above the dew point, normally by dehumidification of the air. This approach relies on the use of a climate-controlled staging room.

The second alternative relies on the use of moisture-proof packaging so that the moisture condensation does not affect the film. To eliminate the danger of condensation, it is not necessary to reach complete equilibrium with room temperature, but only to warm the film to a point above the dew point temperature (Figure 19). Based upon the percent equilibration rate, which is valid for a wide range of temperature differences, it is possible to determine the minimum warm-up time for specific configurations. This evaluation can be achieved by placing the critical dew point of the user’s environment on the percent equilibration curve. For example, the climate conditions 21°C, 50% RH have a dew point temperature of 10°C which corresponds approximately to 75% equilibration between freezer storage temperature (-20°C) and the user's room temperature (21°C). The minimum warm-up time can then be evaluated graphically (Figure 20). This method, based on empirical data, might be used to produce guidelines for cold storage handling procedures. To summarize, although dew point and percent equilibration can be used to estimate warm-up times, it must be emphasized that no valid estimate is possible without knowing the user's environment.

3. PRACTICAL SIGNIFICANCE

3.1. IMPLICATIONS AT ROOM TEMPERATURE

Vapor-permeable enclosures such as cardboard boxes do not buffer humidity changes. Short-term fluctuations (e.g., daily humidity cycling) are reflected in the RH of the microenvironment. In controlled-climate situations such permeable enclosures can be advantageous by keeping the object in equilibrium with the storage environment.

More tightly sealed enclosures such as metal or plastic containers postponed the attainment of an equilibrium with the surrounding air. Such enclosures can help attenuate short-term humidity fluctuation and seasonal drift.

The relationship between storage conditions and microclimate is not solely defined by the action of enclosures. Enclosed hygroscopic materials (e.g., photographic film, paper, cardboard) may regulate humidity changes inside their enclosures by exchanging a relatively small amount of water vapor.

In practical terms, the current recommended range of RH cycling for photographic film (±5% RH) may be unnecessarily tight [29]. A recent study [28] suggests that photographic materials can stay within a safety zone and undergo elastic and reversible physical changes caused by multiple temperature and RH cycling (e.g., from 35% to 60% RH at 25°C or from 20% to 40% RH at -20°C). The present study adds related information. Daily RH cycling (±10% and ±20% RH) indicate that tight enclosures very significantly narrow the range of humidity fluctuation experienced by the enclosed materials.

3.2. IMPLICATIONS AT LOW TEMPERATURE

For over 25 years, it has been recognized that low temperature extends the life expectancy of chromogenic materials [24]. Based on repeated and consistent recommendations [29] the implementation of cold storage is growing.

Regarding the use of low temperature storage, a common concern is the risk of water condensation when the photographic material is brought from low temperature into a warmer area. This problem can be addressed in two different ways:

a. Use of a staging room with climate conditions controlled so the film temperature is always above the dew point.

b. Use of moisture-proof packaging and a minimum warm-up time.

The second concern when photographic materials are kept at low temperature is the risk of moisture damage. When in equilibrium with any given RH conditions, photographic materials hold slightly more moisture at lower temperatures than at the same RH at higher temperature. A subsequent temperature increase (e.g., during transport) may make the gelatin binder more susceptible to physical damage (e.g., softening, ferrotyping, blocking) because it holds more moisture. This subject has been discussed in other publications [20, 21, 22, 30].

4. CONCLUSIONS

1. With the exception of completely permeable enclosures such as cardboard boxes, most enclosures retard the moisture conditioning rate. However, the thermal equilibration rate is relatively unaffected by enclosures.
2. Enclosures may moderate daily RH cycling and even seasonal drift depending on their moisture-buffering capacity.
3. New data on moisture conditioning and thermal equilibration rates of photographic film provide background information on the use of microenvironments.

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ABSTRACT

This is a tutorial paper which gives updated information on the factors affecting the moisture and thermal equilibration rates of photographic films. The effect of enclosures in buffering daily humidity cycling and long-term humidity changes was investigated primarily for film but results on book materials are also reported. The effect of temperature on moisture equilibration rates and on the moisture content-RH relationship for photographic material is also reported. The practical significance for cold storage is discussed.

Table I: Estimates of warm-up times to reach 50% and 90% thermal equilibration.

Material	Storage configuration	Time, hours	
		50%	90%
35mm motion-picture film on triacetate base	single 1000-ft. roll in metal can	3/4	3 1/2
	single 1000-ft. roll in plastic can	3/4	3 1/4
	stack of six 1000-ft. rolls in metal cans	1 1/2	7 1/2
	single 100-ft. roll in metal can	1/4	1 1/4
	single 100-ft. roll in cardboard box and low-density polyethylene bag.	1/3	1 1/4
	stack of six 100-ft. rolls in metal cans	1/2	2 1/3
4″ x 5″ sheet film on acetate butyrate base	stack of 500 sheet films in paper envelopes stored in metal box	2	6 1/4
	stack of 500 sheet films in polypropylene sleeves stored in metal box	2	6
3.5″ x 5″ resin-coated photographic print	stack of 1000 prints enclosed in drop-front cardboard box	1 1/3	4

Figure 1: Typical moisture equilibrium curves for the components of photographic products[19].

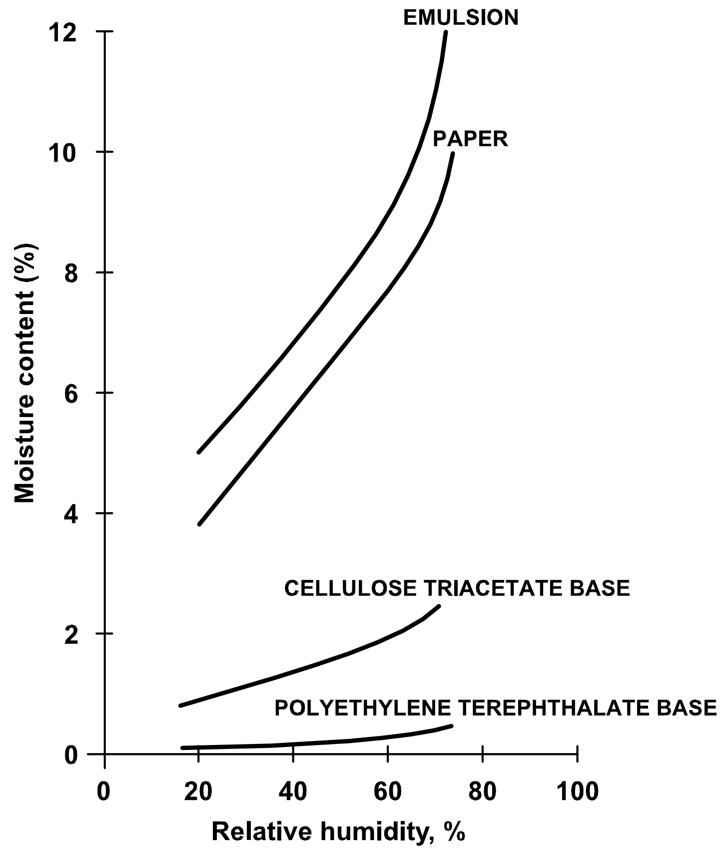

Figure 2: Moisture equilibration at 21°C for 100-ft. roll of 35mm motion-picture film enclosed in a cardboard box.

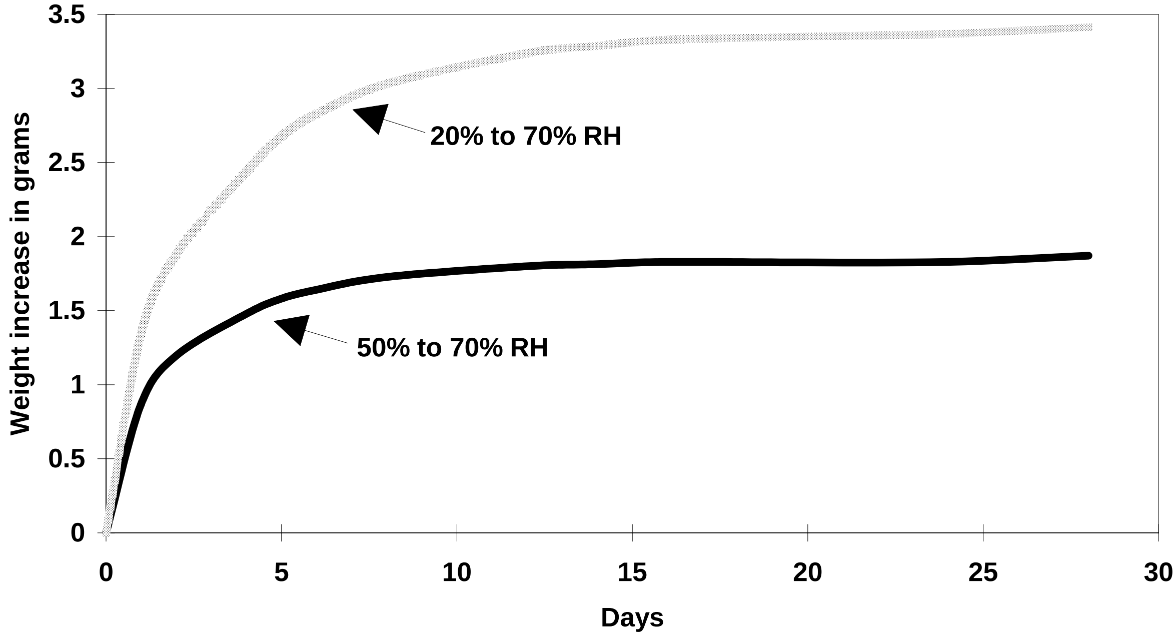

Figure 3: Moisture equilibration at 21°C for 100-ft. roll of 35mm motion-picture film enclosed in cardboard box.

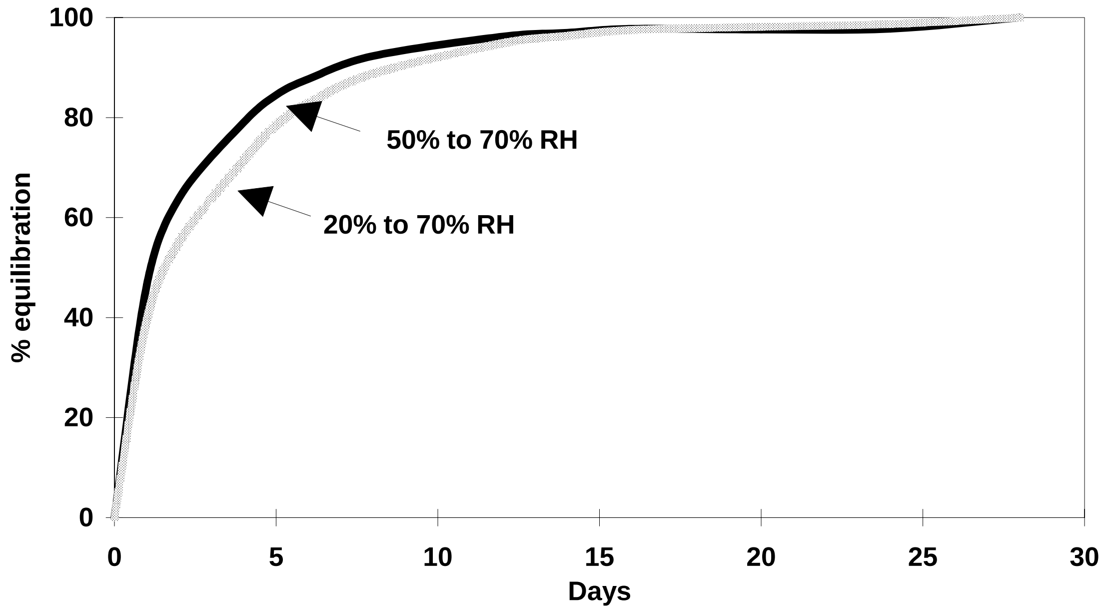

Figure 4: Moisture equilibration rate at 21°C from 20% to 50% RH for 100-ft. roll in various enclosures.

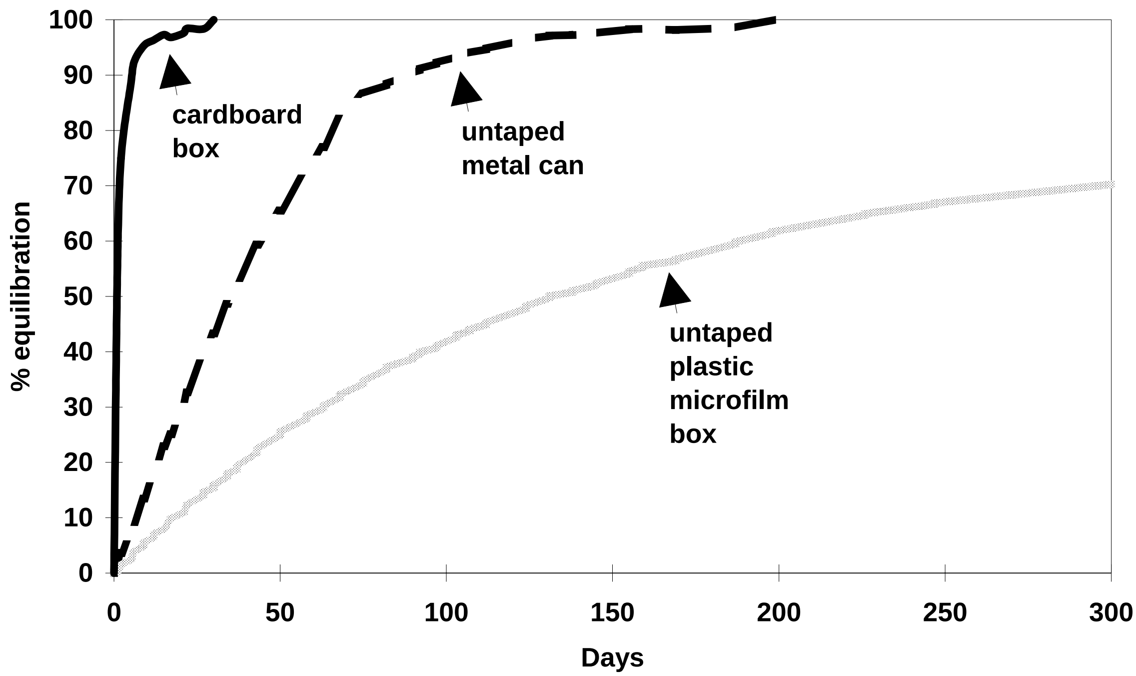

Figure 5: Rate of moisture conditioning for stack of 150 sheet films in cardboard and metal boxes. Film initially at 21°C, 20% RH and exposed to 21°C, 50% RH. Measurements made on inner sheets.

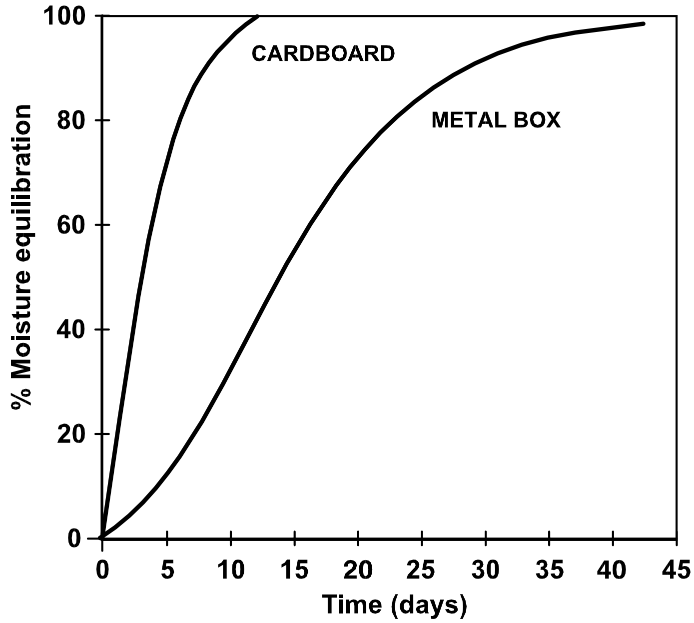

Figure 6: Moisture absorption and desorption half-times between 20% and 50% RH at 21°C for 100-ft. 35mm triacetate motion-picture film.

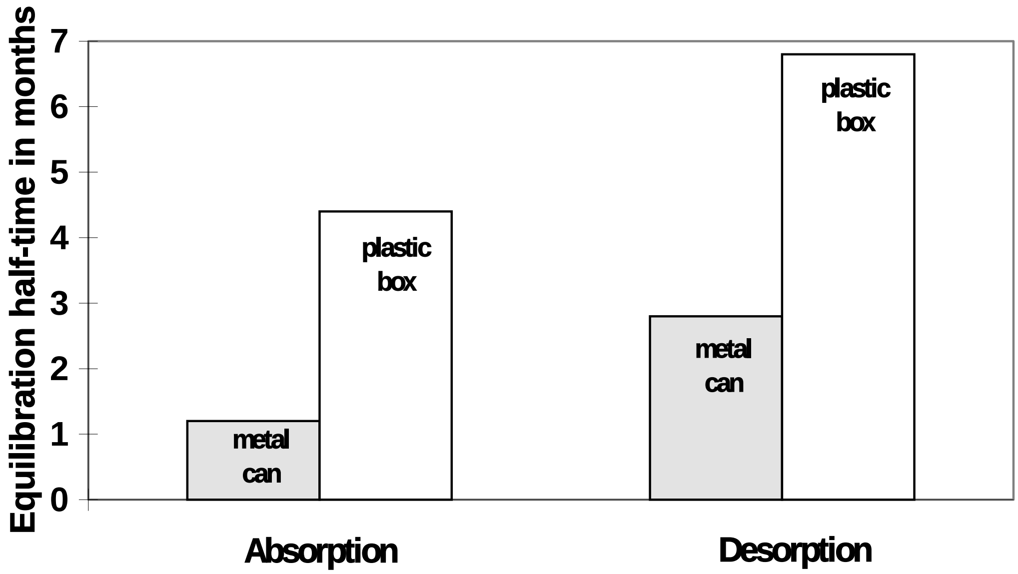

Figure 7: RH fluctuation inside various enclosures when exposed to daily 50%±10% RH cycling.

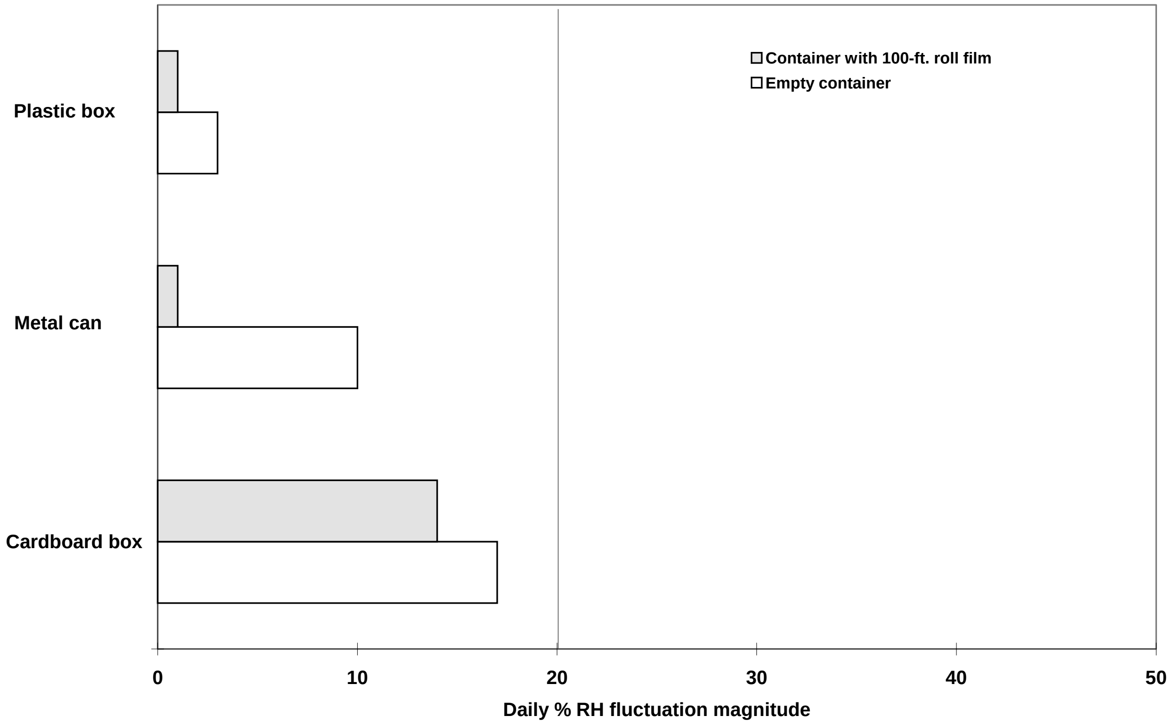

Figure 8: RH fluctuation inside various enclosures when exposed to daily 60%±20% RH cycling.

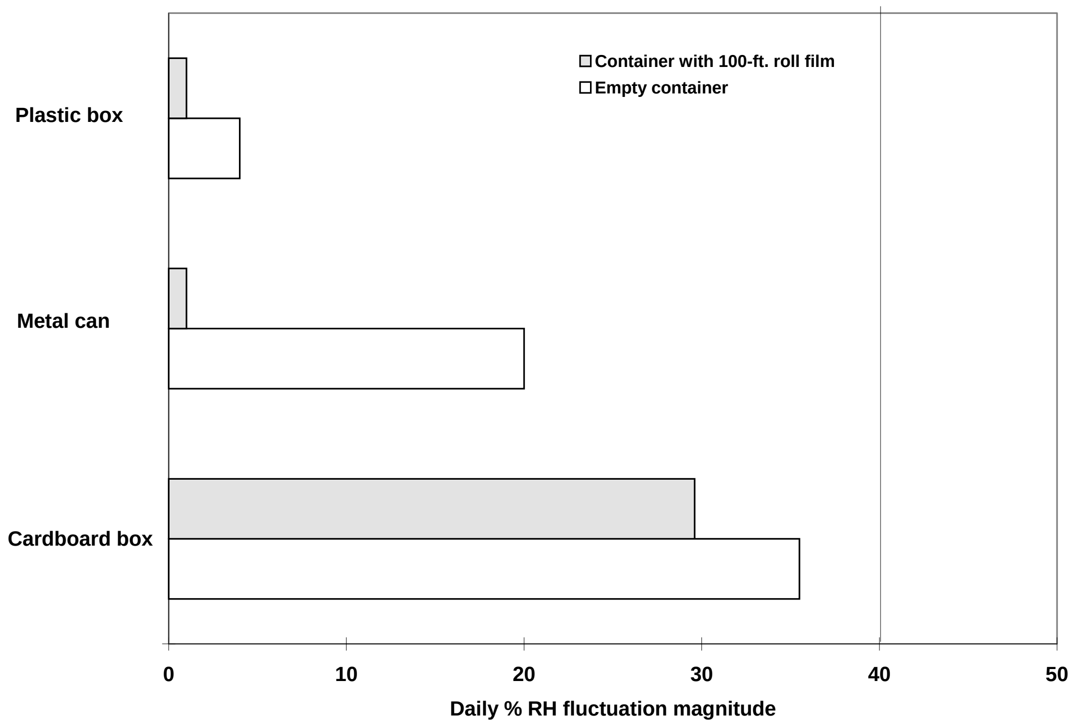

Figure 9: Impact of daily 50%±10% RH cycling on the microenvironment inside a cardboard document box at 21°C

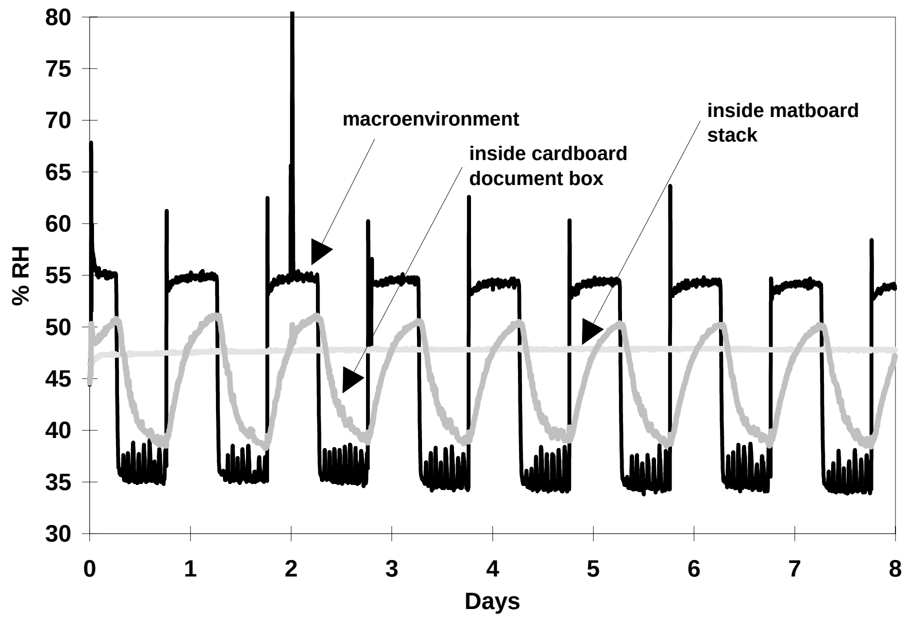

Figure 10: Impact of daily 50%+/-10% RH cycling on the microenvironment provided by a Solander museum case at 21°C.

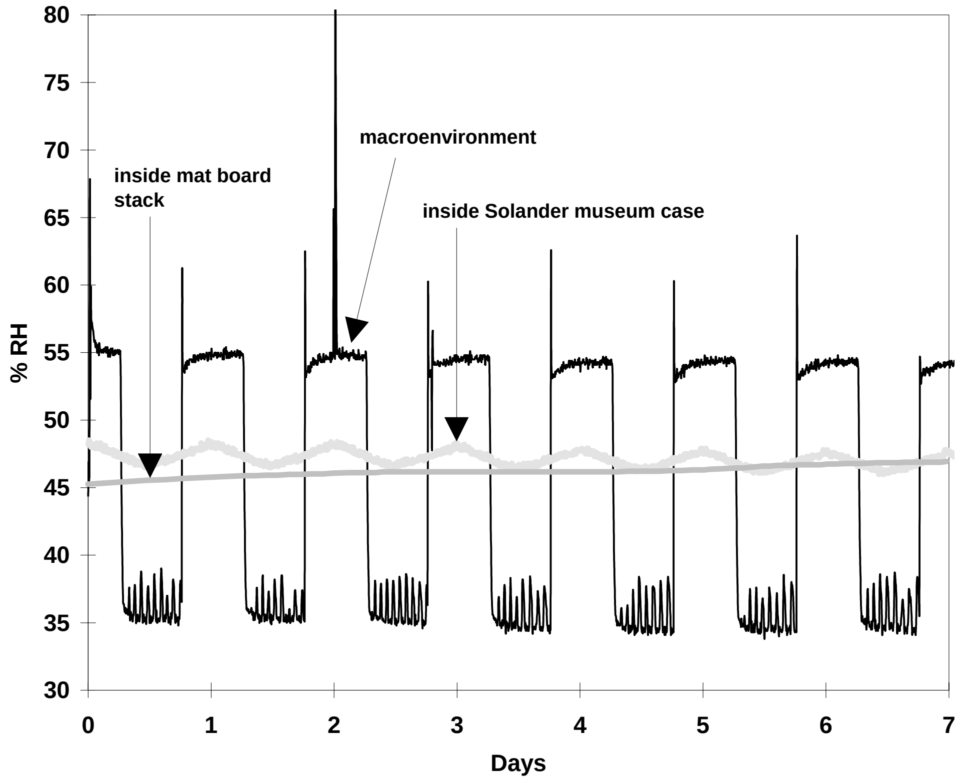

Figure 11: Effect of daily 60%±20% RH cycling on the core of a book at 21°C.

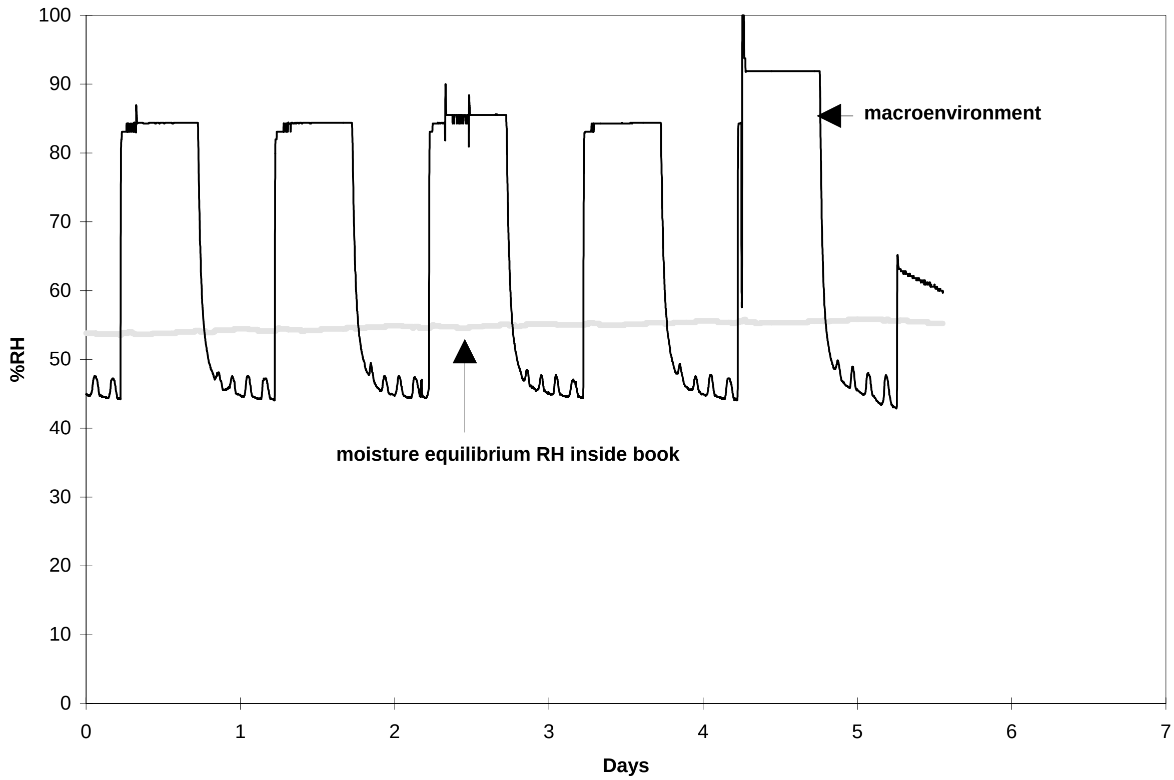

Figure 12: RH inside and outside a book during a three-month period at room conditions (IPI library).

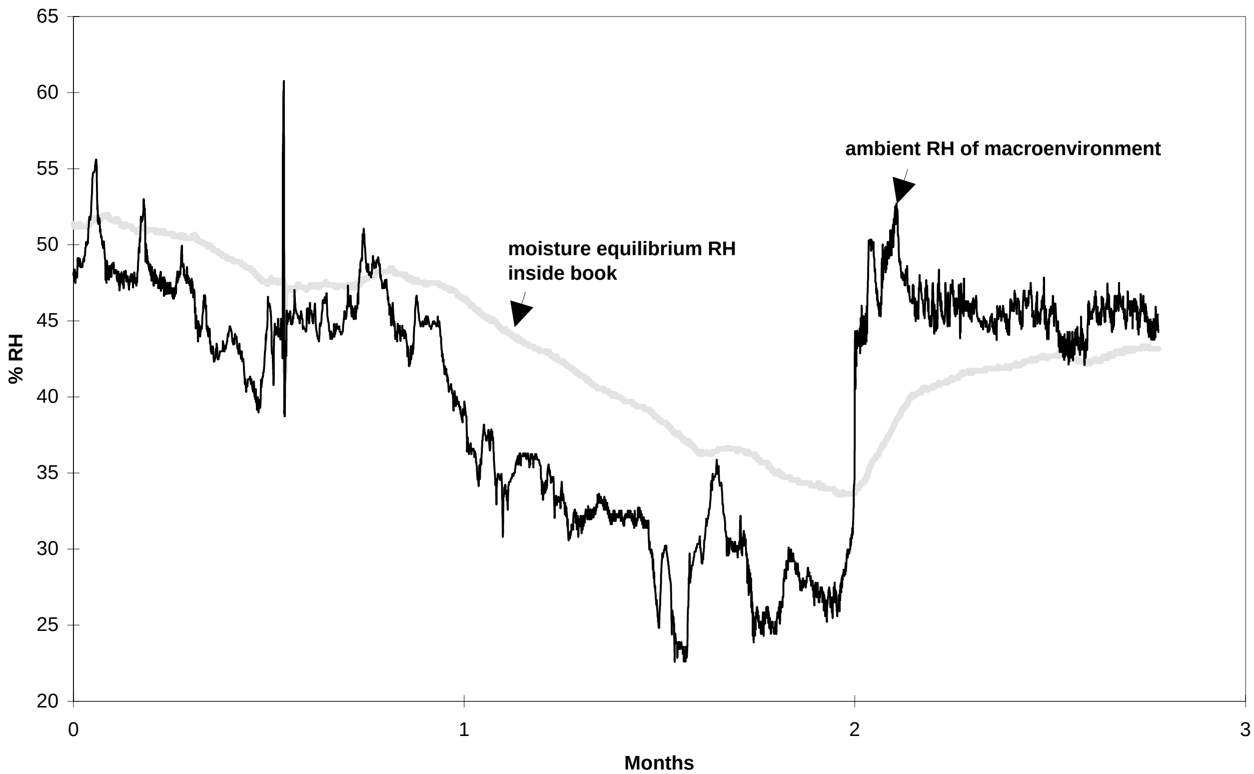

Figure 13: Impact of daily temperature cycling on the microenvironment inside a cardboard box containing matboard mounts.

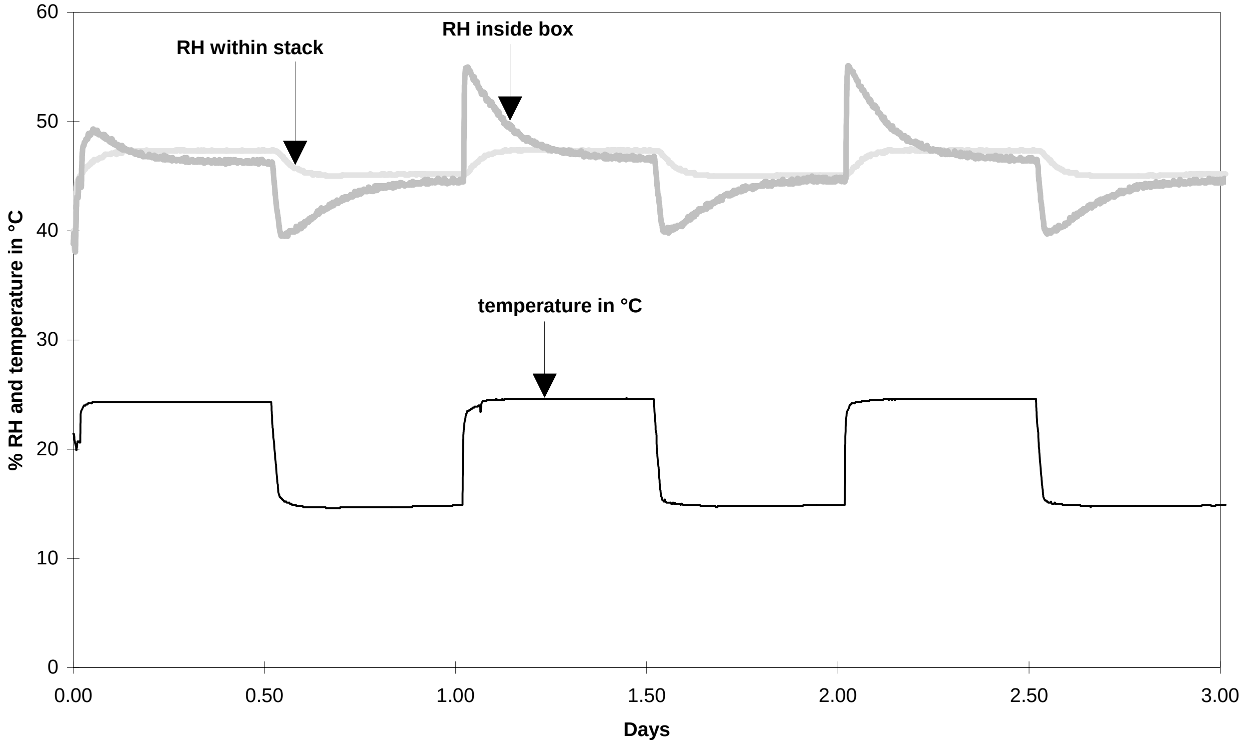

Figure 14: Rate of moisture conditioning for 35mm motion-picture roll in closed metal can. Film initially at 20% RH and exposed to 50% RH.

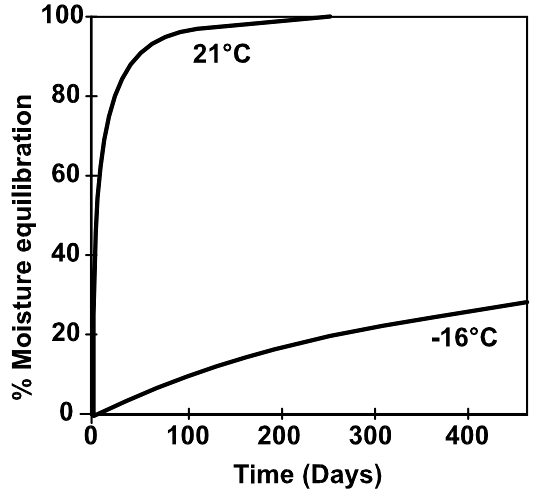

Figure 15: Moisture equilibration at -16°C inside frost-free freezer. Stack of 150 4" x 5" sheet films in paper envelopes inside cardboard box.

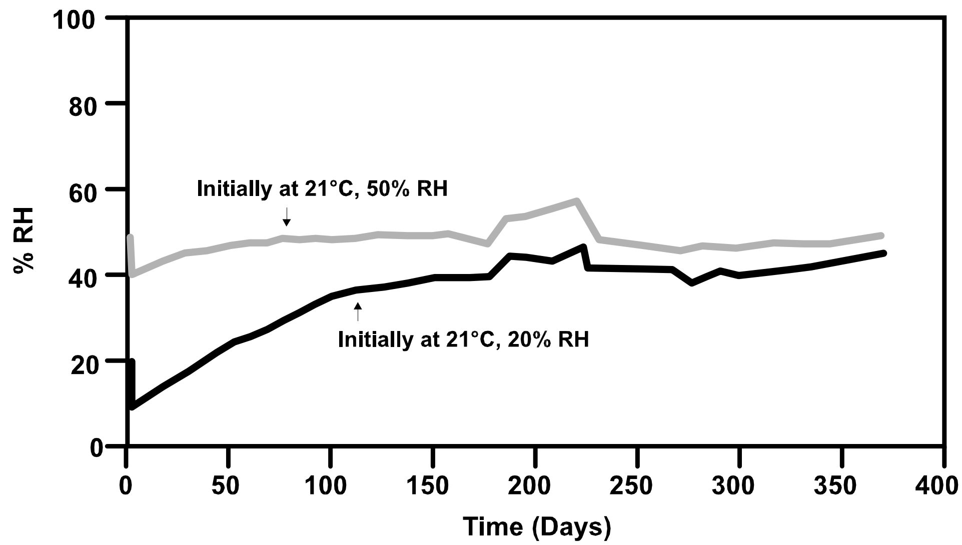

Figure 16: Effect of temperature on moisture equilibrium curve of 35mm motion-picture color film on cellulose triacetate base.

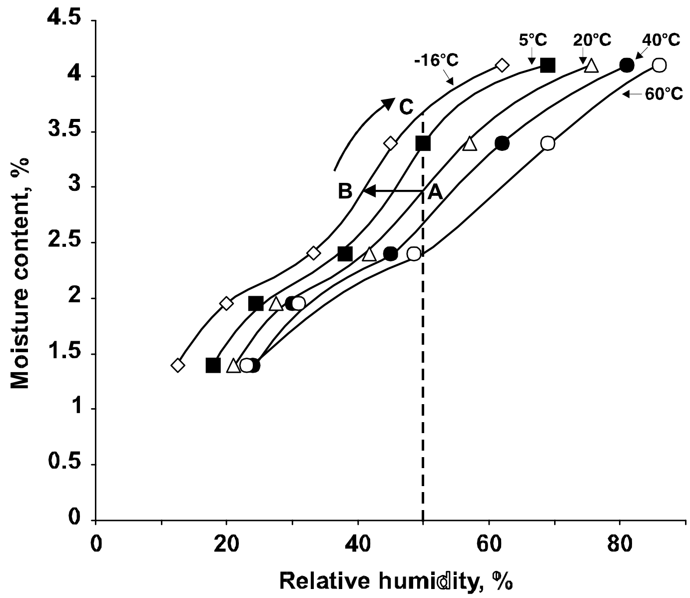

Figure 17: Thermal equilibration for a stack of 1000 3.5" x 5" resin-coated photographic prints enclosed inside a cardboard box. Temperature versus time.

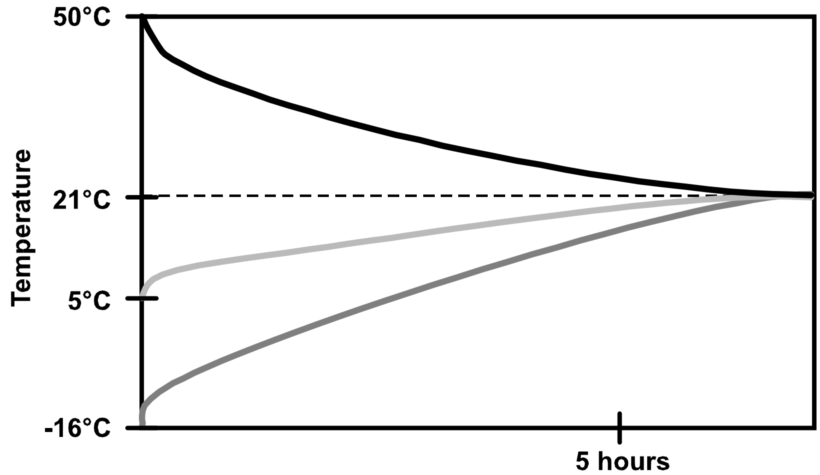

Figure 18: Thermal equilibration for a stack of 1000 3.5" x 5" resin-coated photographic prints enclosed inside a cardboard box. % equilibration versus time.

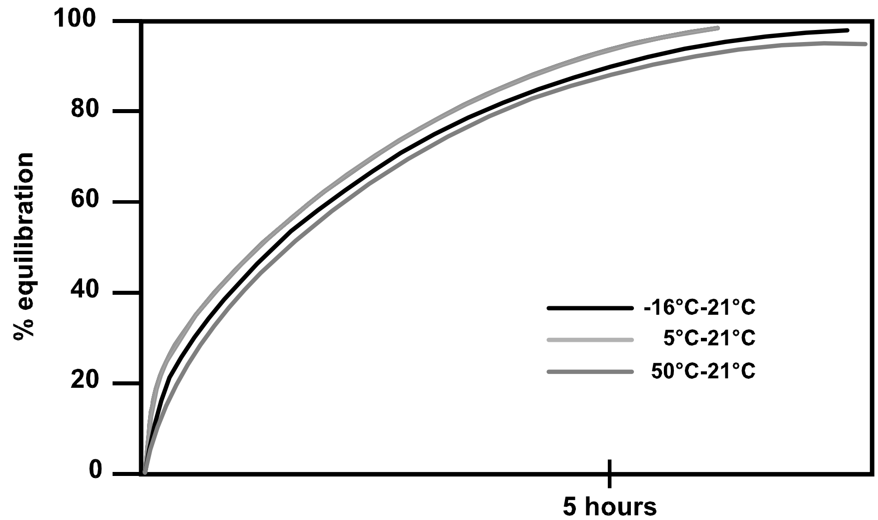

Figure 19: Thermal equilibration from cold storage to room temperature; temperature versus time.

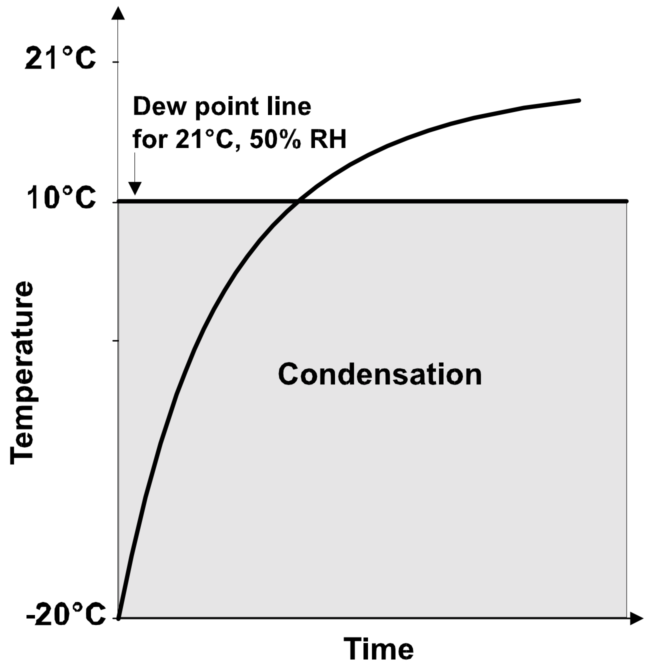

Figure 20: Thermal equilibration from cold storage to room temperature; % equilibration versus time.