

Cold Storage of Cultural Artifacts

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1 – Introduction - Need for Cold Storage

Cold storage will prolong the life of all cultural materials. It is commonly used with photographic prints, film and videotape to decrease the rate of

- Dye fading or dye loss (color fading in dark storage)
- Acetate film base deterioration (Vinegar Syndrome)
- Nitrate base deterioration
- Deterioration of Resin Coating on prints (20 years to cracking, introduced approx. 1970)
- Yellowing of fiber based papers (most stable print base, but will yellow in 200-500 years)
- Inkjet dyes and pigments (colorants) on all paper and plastic media (base)
- Hydrolysis of binder (Sticky Shed Syndrome) in the magnetic layer of videotape

Cold storage will not harm materials as long as the cooling and warming is done in a controlled manner. Commonly, this done with the moisture content of the materials being held stable inside a sealed bag. Warm-up can occur in the open if the material is warmed only through a limited range, such as in an anteroom from 55°F to 70°F, to a main Active cold storage vault. Although possible it is more dangerous than warming slowly (in a Styrofoam cooler) in a sealed package.

The secret of safe cold storage is cooling in a sealed bag or container.

Moisture content is an intrinsic property to a material that is directly influenced by the humidity in the surrounding air, and secondarily, by temperature. In a sealed container, moisture content will not change, because it has nowhere to go.

Paper, film-based materials and videotape can have a significant improvement of life when in cold storage. However, the temperature of the storeroom can limit access (its colder than normal) and generally curtails browsing the collection because materials are in sealed bags. Thus, longevity is favored while access is sacrificed. If, as part of the storage protocol, images are digitally captured, access is maximized along with longevity. The downside of course, is the time it takes to make even basic digital images can render a project so time consuming that it is prohibitive expensive.

The variables are weighed during the planning stages of a project. Cold storage will prolong the life of partially-deteriorated materials almost indefinitely. Limiting access by sealing a collection in bags will slow the use of a collection. This could lead to the collection becoming less valued in the hierarchy of value an institution places on a collection and thus decreasing funds for its management. Ironically, color storage could decrease the value of a collection due to limited access. Taking the time to capture images or adequately describe the collection could save a collection from slow oblivion.



Figure 14. CMI-packaged negatives in our walk-in freezer.



Figure 1a, b & c: (a) on left shows a typical temperature controlled room inside a larger room; (b) center, shows material seal in bags (from Bigelow, 2004) in a temperature controlled room; (c) right shows one of several possible 20'x7.5' x 7.5' refrigerated storage containers (220v 30A 1-phase) that can be quickly purchased new or used, or rented nationwide.

Humidity-controlled vaults are generally found desirable for B&W and color print collections (including prints made on inkjet printers from digital files); where direct access is a the primary use criteria.

The more economical cold storage system is **Passive** cold storage. Passive vaults rely on sealed packages to control the relative humidity (moisture content) of materials in a freezer of three basic configurations. The job of the freezer is to create cold, while the sealed package controls humidity. Thus, the humidity control is passive. These types of vaults are generally found to be the desirable solution for film collections.

The newest alternative freezer is the new or used walk-in refrigerated storage container, which are 7.5' x 7.5 square in cross-section and approximately 20 or 40 feet long; yielding approximately 1000 ft³ or 2000 ft³ internal storage space. The cheap and cheerful option is the home or commercial freezer box, usually containing 20 ft³. Also in common use, is the ubiquitous food freezer common to every fast-food restaurant; they range in size from 500 to 2000 ft³.

An **active** vault is one where the humidity (relative moisture content) is controlled by the HVAC system. The advantage is that access is far less limited because materials are stored relatively freely in cabinets, drawers or boxes. This system is much more expensive to build and run, and, it is generally operated at high temperatures to allow daily human access. As a result, it does not increase the life of an artifact as much as the use of the common passive freezer system. A feature found in mat active systems is an anti-room operated at about 20 degrees below room temperature, so that materials can be staged out for the vault on a routine basis. This vault type is often used for color transparency or color print storage.

Table 1: Comparison of Cold Storage Vault Types

Type	Cost to Build	Cost to Run	Degree of Preservation	Degree of Accessibility
Active - Humidity Controlled Vault	Expensive	Expensive	Not as cold	High
Passive - Sealed pkg on shelves in Freezer	4-20 times less	½ to 4x less	Highest Possible	4-8 Hr Warm-up
Passive - Sealed Cabinets in Freezer	2-10 times less	½ to 4x less	Highest Possible	4-8 Hr Warm-up

Frozen storage in sealed packages or cabinets, within commercial or upright freezers, is safer and far more economical, but is not as accessible or user friendly as humidity controlled vaults. There are two classes of cultural materials that often do not need direct access because they are not immediately human readable: film and videotape. Only experienced workers can get useful visual information from a negative, especially color negative with their orange mask, and a machine must be used to playback videotape. Most libraries require 1-2 weeks' notice to view motion pictures or video.

Color slides are human readable, but their size requires a lightbox and loupe. This makes slides less accessible than prints, which are generally viewed at arm's length. Prints are generally held in purpose-built humidity-controlled vaults, because immediate direct access by curators or designers is considered highly desirable.

Prints and large format transparencies are immediately human readable. It is common for one to walk into a vault, look for a print thorough drawers, boxes or cabinets, make a selection for study, examination, loan or exhibition and cycle that materials out to the room temperature environment. This is the virtue of the complex and expensive active humidity-controlled storage vaults. Such vaults often have a higher temperature anteroom that facilitates the quick unsealed warm-up period.

If a collection is cataloged and there is an image-base for the materials, direct access is not necessarily required for human readable media, and even prints. The user could easily view prints online and wait the warm-up period for access to the materials, in the afternoon, or the next morning.

2 - Basic Chemistry of Cold Storage for Organic Materials – Generic Cultural Artifact

Organic materials are those that contain carbon in a molecular chain. In museums, archives and libraries this includes paper, polymers in plastic films and adhesives (videotape), gelatin and related materials such as parchment, animal feathers and skins. As a group they have generic organic behavior, see Table 1 below. When a specific material is studied, such as cellulose acetate by IPI, then information that is more precise becomes available. IPI has researched and produced publications that have specific storage predictions based on cold storage of (1) acetate film, **IPI Storage Guide for Acetate Film**, James Reilly, 1993, Rev. 1996 and (2) color film, **Storage Guide for Color Photographic Materials**, James Reilly, 1998.

An IPI report on magnetic tape preservation can be found online in their final report too the NEH: **The Preservation of Magnetic Tape Collections: A Perspective**, 2006, by Jean-Louis Bigourdan, James M. Reilly, Karen Santoro, Gene Salesin http://www.imagepermanenceinstitute.org/shtml_sub/NEHTapeFinalReport.pdf. A 1995 report on videotape by John Van Bogart: **Magnetic Tape Storage and**

Handling, a Guide for Libraries and Archives, can be found at http://www.clir.org/PUBS/reports/pub54/2what_wrong.html.

2.1 - Generic Organic Materials

A spokesman for IPI announced at the 2007 AIC-PMG Winter Meeting (GEH) that the life of cellulose nitrate film ranges from 50 to 500 years. Based on early findings, and certain assumptions, it had been said that nitrate film base would fail in 50-60 years.

The following data, for generic organic materials, is a reasonable assessing the effects of cold storage on nitrate film base. Work done by IPI and Mark McCormick-Goodhart (Smithsonian) on the cold storage of generic organic materials, suggests that the improvements in lifetime listed below will result from storage at the following conditions.

Table 2: Effects of Cold Storage on Generic Organic Materials

85°F at 80% yields	1/7-times improvement of lifetime
85°F at 60% yields	1/4-times improvement of lifetime
75°F at 60% yields	1/2-times improvement of lifetime
70°F at 50% yields	1 times improvement of lifetime
60°F at 50% yields	2 times improvement of lifetime
60°F at 40% yields	4 times improvement of lifetime
40°F at 40% yields	8 times improvement of lifetime
40°F at 30% yields	18 times improvement of lifetime
-4°F at 40% yields	380 times improvement of lifetime
-4°F at 25% yields	690 times improvement of lifetime
-15°F at 40% yields	10000 times improvement of lifetime
-15°F at 25% yields	12500 times improvement of lifetime
-20°F at 30% yields	13000 times improvement of lifetime
-25°F at 40% yields	13500 times improvement of lifetime
-25°F at 30% yields	14000 times improvement of lifetime

Note that both temperature and humidity have an influence on longevity; both change in the table above. Temperature obviously influences the energy level, the higher the energy the faster process will proceed; higher temperatures always increase the rate of deterioration. Humidity in air influences the moisture content of materials, increasing or decreasing the amount of water available for reaction. Water will soften and swell, and often react with the various polymers in film and prints. Chemical reaction with water can only decrease system entropy (degree of order), thus more water in a system increases the overall state of deterioration.

2.2 - Videotape

The carrier in videotape is generally polyester plastic, but paper and metal were early prototypes (1928: paper audio tape, 1952: BBC's Vera used 2" metal video tape; and in 1954: RCA was the first to use a plastic base successfully). Thus, videotape differs from film in that the base is stable, while the binder of the magnetic layer creates the problem. The polyurethane binder, used for the magnetic pigment in the magnetic layer, which is coated on the plastic base, suffers from hydrolysis chain scission. It is sensitive to water content and humidity. Lower than normal humidity is considered desirable and cool (above freezing) storage is recommended.

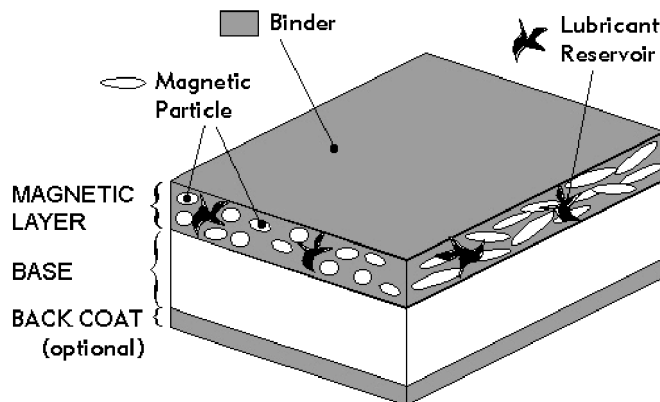


Figure 2: Image taken from *Magnetic Tape Storage and Handling, A Guide for Libraries and Archives* (1995) John Van Bogart, found at http://www.clir.org/PUBS/reports/pub54/2what_wrong.html.

In approximately 1972-5, some magnetic tape manufacturers (possibly only one, but distributed to others) included a compound that forms tiny white crystals when taken below freezing; thus frozen storage is not recommended. There have been no reports that the white crystals cause harm, but with the current state of understanding, frozen storage is not recommended. The general conundrum with videotape is that extended life will be possible, but playback equipment may not.

There is evidence that frozen storage in a vault with unregulated humidity pulls water from videotape over time, as does freeze-drying. This would suggest damaged video tape could be rejuvenated by frozen storage in an unregulated freezer. Here is an excellent topic for research.

Quoted from the IPI Report (2006) referenced above **The Preservation of Magnetic Tape Collections**; p.12 in PDF:

"Today the preservation strategy for magnetic tape collections consists of just a few possible actions, none of which actually addresses the challenge of preserving a large quantity of material that is likely to become obsolete over time. Proper storage at a cool temperature and low RH improves binder stability. ISO provides temperature and RH guidelines for long-term storage of magnetic tape." Footnote: ISO 18923: 2000, Imaging Materials—Polyester-base magnetic tape—Storage practices, (Geneva: International Organization for Standardization, 2000).

The other issue with videotape is that it is not human readable. Videotape requires an electronic device for playback. After about 1998-2000, DVDs took over the commercial movie market and videocassette recorders (VCR) have been on the decline. During the 1980s, the sales of new professional $\frac{3}{4}$ " U-Matic video tape recorders (VTR) were discontinued. By 2000 most professional VHS, S-VHS and BetacamSP video tape recorders (VTR) had been discontinued. In about 20-30 years VTR and VCR devices will be very rare. The last source of professionally serviced historic video equipment went out of business in early 2008 (The Broadcast Store). Prolonged storage of videotape at frozen conditions may preserve the videotape for 500 to 5000 years, but devices to play videotape back may be so rare that their use may be difficult to impossible. Migration to new digital video formats must be done over the next 30 years while VTR and playback units are still available and serviceable.

Storage at 40-50°F and 25-40%RH is the common recommendation. The use of sealed polyethylene bags in a refrigerator set to 40-45°F would be an excellent solution. It would be desirable to lower the relative humidity (moisture content) of the videotapes to 25-40% using a good dehumidifier, before sealing in bags. Follow the bagging recommendations at the end of this essay.

2.3 - Nitrate Base Film

There have not been the in depth reports on the deterioration and cold storage of nitrate base film as there are for acetate-base film. Therefore, the data above on generic organic materials is used to describe their performance in cold storage.

Table 3: Effects of Cold Storage on Nitrate Base Film

70°F at 50% yields	1 time improvement of lifetime
70°F at 30% yields	1.7 times improvement of lifetime
40°F at 30% yields	18 times improvement of lifetime
-4°F at 30% yields	580 times improvement of lifetime
-15°F at 40% yields	11650 times improvement of lifetime
-25°F at 40% yields	13500 times improvement of lifetime

It was assumed until recently that nitrate base films would have a life of 20 to 60-80 years. IPI (3/07 PMG Winter Meeting) recently announced that the life of cellulose nitrate film will range from 50 to 500 years, rather than their previous series of informal predictions that nitrate film would have a 20-60 year lifetime. This earlier prediction had prompted many cultural professional to identify and destroy nitrate film. In addition, nitrate film does not give off explosive or flammable vapors. The vapor, at its worst, is dilute nitric acid, mixed with degrading gelatin (animal skin, sinew and bones).

Numerous workers, in survey after survey, have shown that much of the nitrate film found today (made 1889 and 1951) is largely still in L2 to L3 condition, showing only yellowing and silvering-out (image silver migrated to the surface). Thus, film that is now 57 to 117 years old, is still in fair to good condition.

Experience has shown that the average life for an "early-failure" nitrate film species was about 45-60 years. This "early failure" cohort has been found to be about 10-15% of collections held in storage; estimates [here is another topic for research]. Only small portions (5-10%) of nitrate collections remaining on the west coast, after early failure specimens have been found and isolated, are now

degraded to the L4-L5 state (brown, distorted and sticky) within 60-80 years of their manufacture. Some of this film is now unusable or has been prematurely destroyed (culled by mistake). Most extant nitrate film, about 80% of most collections, is now about 80-115 years old. Most of this film is still in the L2 state, showing only yellowed and minor silvering-out, still quite usable. Many workers agree, much of the early nitrate film (sheet and roll) is still in very usable condition.

That portion of the whole universe of nitrate film produced (production 1889 to 1948-52) that has failed early, is estimated to be about 10-25 % of medium-sized collections. That is, the 10-25% of the nitrate film universe has already reached its final stages of deterioration, L4, L5 & L6. Most of these "blocks of stuck-together negatives" have been set aside as unusable, culled or destroyed by Fire Marshals.

2.4 - Acetate Base Film

The progression of the acetate deterioration has two stages (a) initiation and (b) autocatalytic. The following graph is from James Reilly, **IPI Storage Guide for Acetate Film**, 1993, p13.

The **initiation stage** takes about 40 years, at a normal rate of progression. Using the IPI, A-D Strips, the rating is from 0.0 A-D (blue) to 1.5 A-D (green edges). The "Free Acid" content is from 0.05 (new) to 0.49 (A-D 1.5) in the initiation stage.

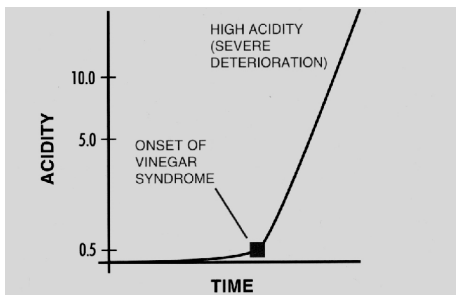


Fig. 17 Time-versus-acidity curve for acetate film. The autocatalytic part of the curve occurs at about 0.5 free acidity, the point chosen as the basis for predictions of the onset of vinegar syndrome in the Guide.

Figure 3: Two-stage deterioration of acetate base, taken from Reilly, "IPI Storage Guide for Acetate Film" (1993).

When the free acid content is high enough, 0.5, the acid in the film further catalyzes deterioration without being consumed, and remains available to do further damage. This stage is referred to as the **autocatalytic phase** and is far faster than the earlier phase. IPI, A-D Strips, can be used to evaluate the condition based on the acid in the air surrounding the film. The A-D Strip value for autocatalytic phase runs from A-D 1.5 (medium green) to 3.0 (yellow), the highest the strips can measure. The amount of **free acid** in the film during the relatively short autocatalytic phase runs from 0.5 to 10, and sometimes even higher. The yellow color of the IPI A-D Strips reaches its maximum at a free acid content of 3.0. More acid can be generated beyond L3, but the state mostly unusable (L5 or L6). The autocatalytic stage often progresses in a very short period, 5-15 years depending on storage conditions and inherent vice in the film. There have been reports that the final phase can proceed very quickly, days, week or months, but this has not been confirmed in documented reports. Word-of-mouth descriptions of "open to examine one day and a short time later the materials are found in an advanced state of deterioration," abound.

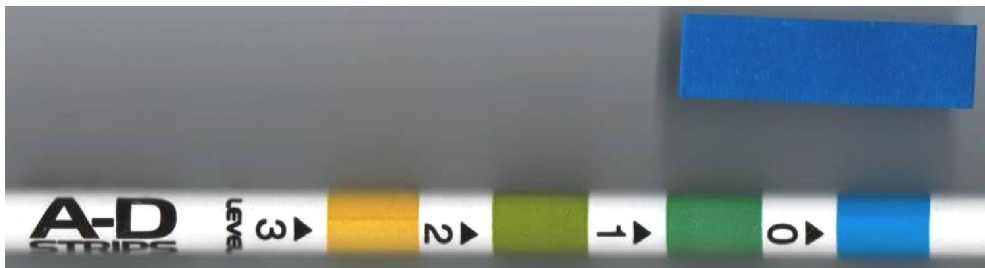


Figure 4: Image of the A-D Strip, upper right, and the tools used to judge color after exposure to the acetic acid in the head space around the artifacts made with cellulose acetate.

In sub-zero cold storage (-15°F at 30-40% RH) that short period (5-15 year) can be increased approximately 2000 times longer, up to 30,000 years. A 2000-times improvement may seem an overly large increase, until one calculates that (1) the "current" state of degradation of the material now (1.5 A-D value or 0.5 Free Acidity) and (2) the decrease in extended lifetime caused by "time out of storage" (it must be assumed that there will be some use of items in storage); see the TOS section below.

Acetate-base film will become almost unprintable in 45-100 years. Even though the long-lived silver-gelatin emulsion will last 200+ years, the acetate base can cause premature failure for some cohorts in 45 years.

It has been found, however, in surveys of several west coast collections, that only a small portion of the acetate-based materials actually follows the IPI predictions of failure in 45-60 years. The

percentage of collections actually showing the "predicted" behavior is 10-20%. Most of these collections have about 80% of the acetate-based collections showing L2-L3 behavior. If the artifacts are held at cool or cold conditions, their lifetime will improve substantially.

Table 4: Effects of Cold Storage on Acetate Base Film with TOS mixed in for comparison

Lifetime for New Film, Years	Storage Conditions
45	70°F at 50%RH
175	55°F at 40%RH
1900	30°F at 30%RH (storage in a refrigerator, above freezing)
1600	30°F at 30%RH + 5 days-time-out-of-storage/year (5 days TOS a yr)
31,500	* 0°F at 30%RH (using home-upright freezer)
1900	* 0°F at 30%RH + 5 days-time-out-of-storage/year (5 days TOS a yr)
110,000	-15°F at 30%RH (using home-upright or commercial freezer)
1900	-15°F at 30%RH + 5 days-time-out-of-storage/year (5 days TOS a yr)

* Reminder: 0°F = -18°C; 32°F = freezing = 0°C

2.5 - Color Film and Prints-- Based on Color Dyes

Color photographic materials always use color dyes, be it on acetate film base, or as a positive image on paper (fiber) or resin coated (RC), supports. It is the dyes that are the subject of this Color section.

Using data from Kodak and other manufactures supplied to Wilhelm (1993) the following data, Table 4, has been generated; actual behavior will have many variables. The most significant variable would be storage, until rehoused in a cultural institution.

For the early to middle era slide films (1938-88) Kodachrome slide film has the best life in dark storage -- about 50-66 years, before significant color shift (fading of one dye). For modern slide films (1980-1995) that are to be projected, Fujichrome Velvia film has the longest life -- 5.3 hours. Fujichrome Velvia has one of the shortest lifetimes in dark storage, about 15-20 years, in a class that can have 200+ lifetimes.

Ektachrome slide film (the pre-1988 formulation, E3 & E4), the type held in most collections, has a very poor life of 14 - 46 years. Modern Ektachrome slide film (1988 to present, E5 & E6) has a life of 105-250 years. Moreover, most of these films are 20-40 years old so they have lost much of their usable life. Many show some color shift (minor to noticeable), the loss of blue and yellow dye intensity leading to a magenta cast.

Table 5: Estimated Lifetime of Color Film, Acetate Base, either Transparency or Negative

Years in Dark Storage, for 20% Dye loss*	Color Film Type
16	Kodak Royal Gold 100 RA Negative
38	Kodak VPS Vericolor Negative
12	Kodak 6011 Vericolor Internegative
14	Kodak 5035 CII Kodacolor Negative
16	Kodak Royal Gold 200 RB Negative
12	Kodak 4112 Vericolor Internegative
35	Kodak 5093 Kodacolor CL 200 VR 200 Negative
38	Kodak Gold 400 Negative
20	Kodak Royal Gold 25 RZ Negative
20	Fuji HR 1600 (1984) Negative
15	Agfa XR 1000 Negative
220	Kodak 5025 Ektachrome Transparency (64X, EPX)
220	Kodak 5075 Ektachrome Transparency (400X, EPL)
40	Kodak 6121 Ektachrome Transparency Duplicating
105	Kodak 6036 Ektachrome Transparency (200, EPD)
35	Kodak 5071 Ektachrome Duplicating
105	Kodak 5056 Ektachrome Elite 200 post 1988
105	Kodak 5076 Ektachrome 200 ED (daylight)
66	Kodak Kodachrome 1938-1988
20	Kodak Eastman Color Reversal Movie (estimate)

2.6 – B&W and Color Print (Fiber and RC paper base) Materials

Color prints have significantly less life than B&W prints. Fiber based B&W are said to have a life of 300-500 years. On resin coated (RC) base, B&W prints have a life of only 20 years because the resin coating cracks due to the inclusion of titanium dioxide. The TiO₂ acts as a free radical, facilitating UV-light induced degradation the polymer coating; premature deterioration of an otherwise stable plastic.

Color based RC materials cannot do better than B&W, thus color RC prints only have a 20 year lifetime. The best chromogenic paper, Fuji Crystal Archive has a predicted life of 45-60 years on display and several decades in the drawer (dark storage).

Table 6: Estimated Lifetime of Color Print Materials, on Fiber or RC Base

Years in Dark Storage*	Color Print Material Type
50	Fiber based Chromogenic prints, often Kodak or Agfa brand
20	Resin coated Chromogenic prints, usually Kodak brand
150	Fuji Crystal Archive print (45-60 years on display)
400-800	Kodak Dye Transfer (30-50 years on display)
100	Fujichrome, 1986-92, polyester base
500+	Cibachrome, 1980-91, polyester base
500+	Ilfochrome Classic, 1991-Pr, polyester base
20?	Polaroid (Polacolor, 2 & ER: 1963, 75, 80-Pr and SX-70: 1972, 75-Pr)
0.5- 200	Digital prints 1990-Pr (6 mos. to 3 years with some notable exceptions)
100-200	Archival Digital prints 1998-2003 (40-100 years on display)
150-250**	Archival Digital prints 2004-Pr (60-250 years on display)
3-5	Color photocopies (actually, longevity unknown)

* Lifetime when new; most artifacts will already be 20 to 45 years old; end point not defined, probably 20-30% loss.

** When dark storage research has been completed for the 2004-2008 era pigment-based inks, the lifetime will increase. Yellowing of the paper base will always be the weakest link. In a 2007 study by Robin Myers <http://www.rmimaging.com/information/neutral_references.html>, UV-brighteners were found in most premium Epson papers and many other coated papers, when they fade the paper will look more yellow because the brighteners fluoresce blue.

2.7 - Predicting Extended Life of Color Film in Cold Storage

Using the Reilly (1998) color dye fading data, which was calculated base on a 30% loss of the least stable dye, IPI predicts an average life of 40-45 years for early-1990 color materials. Based on the types of color films commonly held at cultural institutions (see above and below), and assuming that the average age of creation was 1987 (about 25 years ago), the lifetime of the average color film is about 25 years.

Table 7: Effects of Cold Storage on Color Dyes (includes TOS for comparison)

Years of Life	Storage Conditions
25	70°F at 50%RH
75	55°F at 40%RH
70	55°F at 40%RH with 5 days-time-out-of-storage a year
170	45°F at 40%RH
125	45°F at 40%RH with 5 days-time-out-of-storage a year
1300	30°F at 30%RH
375	30°F at 30%RH with 5 days-time-out-of-storage a year
30,000	0°F at 30%RH
490	0°F at 30%RH with 5 days-time-out-of-storage a year
160,000	-15°F at 30%RH
550	-15°F at 30%RH with 5 days-time-out-of-storage a year

Taking account of time out of storage (TOS), the optimistic "lifetime" numbers drop dramatically. If we assume 5 days time-out-of-cold-storage every year, storage at -15°F at 30%RH becomes about 550 years. Five days time-out-storage out of storage is the time it takes to have a duplicate negative or print made locally, or, to acquire a good scan. Two months is approximately the time it takes to send a group of negatives away for duplication or scanning; this is 5 days TOS over twelve years (5 x 12 = 60), assuming a 2-300 year lifetime.

2.8 - Color Film Fading: Predicting Lifetimes

There are few natural aging of film studies (Anderson & Ellison, 1992: 12 years of natural aging) that cover 40 years of data for the dark storage of film. Predictions can only be calculated from accelerated aging studies at elevated temperature (Kodak, 1988; Wilhelm 1993 and Reilly, 1998).

The average color film is expected to fade, in museum storage conditions, in about 40-45 years. The films with the longest relative stability are the Kodachrome 25, 64 & 200 (K-14) transparency films; later Kodachrome II (C-41) has less stability. Kodak Kodachrome and Ektachrome slide films manufactured after 1988 are predicted by Kodak to last 185-220 years in cold storage. Projection of the slide will lower its fading rate dramatically, years to hours.

According to Reilly (1998), Kodachrome (1938-Pr) film will fade to 30% single dye loss in 40-50 years. According to Kodak data (1988), a density loss of 10% will occur in 50 years, and to 30% loss of one dye, in 100 years. A 10% loss is acceptable fading, but 30% of a single dye loss is very bad. Thus, it should be assumed that post-1938 Kodachrome has a useful life of 50-66 years. Based on this prediction other color films can have their behavior predicted with a fair amount of accuracy.

Table 8: Estimated Lifetime of Color Transparency Film on Acetate Base

Type	Wilhelm 20% Loss	Kodak 20% Loss	Predicted Lifetime at Museum Conditions
Ilfochrome Micrographic M & P	2555 days		290 years*
Kodachrome (post-1938, K-14)	580 days	30-115 years	66 years
Kodachrome (K-12)	580 days	30-115 years	66 years
Average transparency film rating from Reilly (1998)			40 years
Ektachrome (6121 dup: E6)	225 days	25-45 years	35 years
Ektachrome (160T E6)	225 days	25-45 years	35 years
Ektachrome (5071 dup E6)	225 days	25-45 years	35 years
Ektachrome (5017/6117 & 5018/6118)	225 days	25-45 years	35 years
Ektachrome (5036 E6)	225 days	25-45 years	35 years
Fujichrome (general)	185 days		21 years
Fuji Velvia	135 days		15 years
PolarChrome Instant	90 days		10 years
Kodachrome II (C-41)		14 years	heavily faded
Ektachrome (E1-3)		14 years	heavily faded
Ektachrome (5038 E4)		14 years	heavily faded

* Anderson & Ellison, *Natural Aging of Photographs*, JAIC 31:2, 213-223, 1992

Kodak, *Image-Stability Data: Kodak Kodachrome Films*, Kodak Publication E-105, 1988

Reilly, *Storage Guide for Color Photographic Materials*, 1998, IPI

Wilhelm & Brower, *The Permanence and Care of Color Photographs*, 1993, Preservation Publishing Co

Wilhelm (1993) and Kodak (1988) predict that Ektachrome class of films resists fading about 2-3 times less than the Kodachrome class of slide films. Kodachrome from the 1935-40 era have very poor fading properties. Kodachrome from the 1938 to 1961 era have much-improved fading properties over the first release Kodachrome films, on the order of 30-110 years. Kodachrome II and -X films (1961-74) have about a half the stability of modern post-1988 Kodachrome. The Ektachrome films will fade in a range of about 16-25 years for an average 20 years; based on pp189-194 in Wilhelm & Brower (1993) and Kodak (1988).

Unfortunately, Wilhelm used a single temperature when performing his accelerated aging tests, so he could not use the Arrhenius-plot method to project actual performance at lower temperatures. Kodak (1988) data does use the Arrhenius-plot method. Both groups of data, Kodak and Wilhelm (data), reflect the actual behavior of Kodak color films.

3 - Cold Storage - Cool vs Cold vs Frozen

There are two types of cold storage vaults (1) Active - humidity-controlled cold vaults and (2) Passive - where materials are sealed in packages within freezers. In the first, the artifact is easy to access, at a moment's notice, but is many times (10-20) more expensive. The second method is far less expensive, but requires more time for access and warm-up.

Cool = 45-60°F

Cold = 38-45°F

32°F = Water Freezes

Frozen = +25 to -25°F

Active humidity-controlled vaults cannot be cooled to as low a temperature as commercial freezers, thus they are often referred to as cool and cold storage vaults.

Passive systems in commercial freezers (walk-in food storage "boxes") or consumer upright frost-free freezers require breaking the collection into small units, sealed bags. Commercial freezers (Bally Box type) are capable of 15-25° below zero (-25°F) or lower. Upright home-style freezers generally have a range of 25° F above zero (+25°F/-4°C), to zero degrees (0°F/-18°C), but not below zero. Small, under the counter sub-zero freezers are available for under \$1000, but larger units run several thousand dollars for 20-40 ft³ upright boxes. Obviously, the lower the temperature achieved the longer the lifetime enhancement.

3.1 -Active vs Passive Vaults

The Corbis-Bettmann Archives has invested in sub-zero passive storage (2004) using a sealed package system designed by Mark McCormick-Goodhart http://www.wilhelm-research.com/pdf/WIR_IST_ColdStorage/WIR_ISTpaper_2004_04_HW.pdf.

The Vancouver City Archives has developed a passive vault for their film collections. The process is detailed in the publication **Cold Storage of Photographs at the City of Vancouver Archives**, Guidebook from Canadian Council of Archives, Sue Bigelow (2004) which can be found at <http://www.wilhelm-research.com/canada/ccoa.html>. Must reading from anyone planning a purpose-built passive vault.

The National Geographic Society has an immense slide collection in several active vaults scattered throughout their many buildings, with more planned, based on comments from NGS Conservation Staff (2006). Other active vault users in Washington, DC, are the Library of Congress and the National Archives and Record Administration (NARA). There several more in NYC including the Museum of Modern Art. Curators, registrars and staff in institutions that have large photographic print and transparency collections favor active systems. Active systems are complex and expensive but they provide direct access through an abutting "cool room" that is held at a warmer temperature, regulated to the humidity to rooms not controlled by the vault but by building HVAC. Warm up can be just a few hours in well-designed systems. It is rumored that the vaults at the institutions mentioned cost over \$5 million.

Table 9: Estimated Costs Passive or Active Systems

Cost	Size	Type of Cold Storage	Conditions
\$300,000	20'x 20'	Active Vault -- Humidity Controlled	38°F and above
\$30,000	20'x 20'	Passive Vault -- Walk-in Food Freezer	-25 to -15°F, sub-zero
\$800	20 ft ³	Passive Freezer -- Frost-free Upright	0°F passive
\$600	6 ft ³	Passive Freezer -- Frost-free Upright	-25°F passive

3.2 - Active Vault

The active vault is the early style of cold storage vaults. The design fills the needs of large institutions where the cold storage vault was designed and built to facilitate a specific curatorial mission. The room(s) have temperature and humidity systems, maintaining conditions just above freezing at 38-40°F. In active vaults, the cold air must be humidity controlled because the moisture in the artifacts is based on the moisture content of the surrounding air. A stable moisture content, creates a stable size is based on the swelling caused by water. As humidity varies, so do the dimensions of the artifact. This is the basic precept for all preservation control measures.

In the humidity-controlled vault design, the desired traits of convenience and accessibility has been "traded for" high system complexity and cost with an overall decrease in artifact longevity. The convenience and accessibility help curators and workers who want instant access to specific transparencies or prints at a moments notice. For institutions with deep pockets and collections in good condition, these trade-offs seem reasonable.

Many Curators desire direct access to their artifacts without waiting for a 4-24 hour warm-up period. Direct access requires that the artifacts readily available in unsealed cabinets or boxes ready for retrieval and viewing at any time. Human comfort and mechanical logistics dictate that cold [38-40°F] or cool anteroom temperatures [45-60°F] be used in the walk-in humidity-controlled vaults, rather than frozen conditions [+25 to -25°F] used in high longevity film storage systems.

In many humidity-controlled vault installations there is also a viewing room that is maintained at a higher, but still cool, temperature at the identical humidity. This allows artifacts in the cold vault to be moved, still unwrapped, to a more comfortable space while maintaining artifact moisture content. In a cool room, the user needs only a modest sweater or light coat while viewing artifacts directly, all

without a warm-up period. With a short warm-up within many anterooms the materials can be moved directly into the standard museum environment $70^{\circ} \pm 5^{\circ}$ at $50\% \text{ RH} \pm 10\%$.

3.3 - Passive Vault

Food cold storage freezers operate at a fairly stable low RH by default; they are not humidity controlled. These vaults are called “passive” in the preservation field because the relative humidity (RH) of the air in the vault is not directly controlled by the freezer equipment. The humidity of the artifacts is passively controlled by the sealed bags, or gasketed cabinets, within the vault, where the moisture content can not change with the sealed bag regardless of the temperature. Passive systems can operate at much lower temperatures, extending the lifetime of its artifacts while also lowering the cost of operation. Finally, artifacts in seal bags or gasketed cabinets cannot be harmed by a system malfunction, external flood or excess water from a fire.

A passive vault operated at 0°F (-18°C) will cost about $\$1.25/\text{ft}^3/\text{yr}$ (2006) for electricity. A passive vault running frozen, between -15°F to -25°F , will cost about $\$2\text{-}3/\text{ft}^3/\text{yr}$ (2006).

The Wilhelm Imaging Research $15' \times 15' \times 7'$ passive vault in Grinnell, IA cost approximately $\$550$ to operate in 2004, where electricity cost was $\$0.63/\text{kwh}$. The passive vault runs at about a third, to a quarter, the cost of humidity-controlled systems.

A humidity-controlled vault running at $38\text{-}40^{\circ}\text{F}$ will cost about $\$4\text{-}6/\text{ft}^3/\text{yr}$ to operate. A $15' \times 15' \times 7'$ vault will cost approximately $\$4000$ to operate in 2006 in the Bay Area where electricity cost $\$0.75\text{-}0.85/\text{kwh}$; the operating cost would be $\$5.50/\text{ft}^3/\text{yr}$.

The standard $38\text{-}40^{\circ}\text{F}$ humidity-controlled (active) vault will have

- **1/38th (2.6%) the preservation effect of a sub-zero vault (0°F to -25°F)**
- **cost 4-5 times as much to build**
- **cost about 3-6 times more to run**

A passively controlled 0°F vault of the same size, will cost one quarter the amount to build (including the cabinets) and produce a 30-300 times improvement in stability, while affording more protection against equipment failure, acts of nature and fire damage.

3.4 - Cold Storage of Small Quantities

A Sears' auto-defrost, 20 ft^3 cu ft, upright freezer ($\$800$ delivered) can be used for storage at about 0°F . They also sell right off the store floor, a series of smaller chest-type manual-defrost freezers, ranging in size from 4 to 8 ft^3 (large TV in size) that can be used for smaller collections, priced from $\$180\text{-}\350 . The larger [20 ft^3] upright will cost about $\$50\text{-}\$100/\text{yr}$ ($\$3.75/\text{ft}^3$) and the smaller boxes will cost about $\$35\text{-}\$60/\text{yr}$ ($\$2.38/\text{ft}^3$).

Stand-alone freezers have similar operating cost to the active humidity-controlled vaults, due to the lack of economy of scale for the freezers. A passive vault would run at about a third to a quarter the cost of operating upright freezers or active vaults.

Certain upright freezers (low temp freezers) are capable of -25°F , but the “affordable” versions of this technology are the smaller under-counter size holding 4-6 ft^3 , rather than the 20 ft^3 of the normal 0°F upright http://www.cooler-store.com/summit_upright_freezer_under_counter_1090_prd1.htm and http://www.cooler-store.com/summit_upright_freezer_low_temperature_1147_prd1.htm. The purchase cost is about $\$1000$, with $\$100\text{-}\$125/\text{yr}$ to operate. Larger $20\text{-}70 \text{ ft}^3$ low temperature upright self-contained freezers can be purchased for $\$4\text{K}\text{-}\12K . Installing a walk-in (Bally Box type) low temperature freezer makes better sense if portability is not an issue.

3.5 - System Costs Small Active Vault and a Small Passive Freezer System

A local institution built a small humidity-controlled vault ($10' \times 10' \times 7'$ H) for $\$180\text{K}$. If a cool (55°F) anteroom was added, the project cost would increase by $\$60\text{K}\text{-}\120K . This particular vault would hold about 200,000-250,000 film artifacts at about $\$0.80$ to $\$1.50$ each. The yearly utility cost would be $\$2000\text{-}\3000 , or $\$4/\text{ft}^3/\text{yr}$ to operate.

The basic upright freezer [20 ft^3] can hold about 20,000 packaged negatives, and will cost $\$1000$ for everything including packaging, or about $\$0.05$ per film artifact. At $\$100$ per year, operation is about $\$5/\text{ft}^3/\text{yr}$.

Table 10: Summary of Basic Passive and Small Active Cold Storage

	Size	Build	Negatives	Real Estate	Electricity	Yearly Cost
Basic Up-right Freezer	20 ft^3	$\$1000$	20,000	$\$0.05$	$\$5/\text{ft}^3/\text{yr}$	$\$100$
Small Active Vault	700 ft^3	$\$200,000$	250,000	$\$0.80$	$\$4/\text{ft}^3/\text{yr}$	$\$3000$

The comparison is between (a) \$0.05 per item for sealed package frozen storage and (b) \$0.8 to 1 per item for a humidity-controlled vault. Besides the 20-times cost increase premium for the convenience of direct artifact access, the longevity of artifacts held at the "cold conditions" will have about 40-300-times less permanence than those held under frozen (25°F to -25°F) conditions. In addition, when a humidity-controlled vault fails, the results can be mold growth, envelopes stuck to the gelatin emulsion or high temperature base deterioration.

3.6 - Modes of Failure in Active and Passive Systems

In a sealed package, within a commercial freezer, the slow warm up to room temperature at constant moisture content is the only adverse outcome from a passive freezer system failure. Slow warm-up at constant moisture content is an intended procedure. When storage is parceled out into separate 20 ft³-upright freezers, only the one unit that failed, not all the freezers, will cause problems.

The resolution of the problem will require replacing only one freezer at about \$800. On the other hand, a diagnostic visit for a custom-built active humidity-controlled vault will cost \$1-3K, excluding parts and installation labor, which could run several thousand dollars more.

Table 11: Estimated Construction and Running Costs

Temperature	Improvement	Construction Cost	Running Cost
70°F Humidity-controlled room	normal rate	\$5K - \$10K	\$4-6/ft ³
40°F Humidity-controlled	9 times normal rate	\$80K - \$320K	\$25/ft ³
0°F Passive Freezer	350 times normal rate	\$800 - \$4K	\$20/ft ³
4°F Humidity-controlled	350 times normal rate	\$140K - \$250K	\$37/ft ³
0°F Passive Vault	350 times normal rate	\$20K - \$40K	\$13/ft ³
-15°F Passive Vault	2000 times normal rate	\$20K - \$40K	\$20/ft ³
-25°F Passive Vault	2500 times normal rate	\$20K - \$40K	\$25/ft ³
-25°F Passive Freezer	2500 times normal rate	\$600	\$25/ft ³

In upright freezers, equipment failures do not result in high humidity, pooled liquid water or a high internal temperature. The moisture content of the materials is contained in the sealed package. The materials will remain stable because the moisture has no place to escape and any stray liquid water is sealed out of the bag. The only issue in a freezer failure, is a slow warm-up to "as sealed" conditions.

The "high temperature" failure mode is not possible in upright frost-free freezers, as shown in <http://www.appliance411.com/faq/howdefrostworks.shtml>. The "how it works" URL shows that excessive high temperature build up due to freezer defrost coil overheat, has been designed out of the system using a series of elements that require multiple element failures for system failure. In an integrated system, such as a commercial upright freezer, multiple element failures generally cause a full system failure. The relevant design elements are: (a) specific fault-proof circuits [power for heater coil through compressor], (b) limited duration event timer [30-minute heater cycle] and (c) mechanical thermostats. Thus, failure of the defrost thermostat in an upright freezer will not result in internal overheating. The failure of the compressor will also prevent energizing of the defrost heater element. The refrigeration process may fail, but the artifacts are sealed in bags at constant moisture content as the cabinet slowly warms to room temperature, over several tens of hours. Any liquid water that may show up from melting ice will be sealed out of the bags.

In humidity-controlled walk-in vaults, where massive sub-systems are often interconnected rather than integrated, due to their sheer scale, the loss of one subsystem can lead to overheating of the vault room. Overheating can have two outcomes (1) very high temperature or (2) elevated temperature resulting in humid air or liquid water. Liquid water can condense on cool artifact surfaces when humid air is created and artifacts are still below the dew point of the surrounding warmer air. The presence of liquid water will often lead to mold growth. Very high temperature over prolonged periods can also lead to faster deterioration of the film base, or dyes in color film.

For mold to grow, mold spores must settle on the artifact (going on all the time) either before or after the critical event. When the liquid evaporates from the growth media (paper or gelatin), the moisture content and pH may reach a critical point where mold will grow.

Overheating could be designed out of walk-in vault system with sufficient engineering experience. However, each of these \$500,000 to \$1,500,000 systems is a custom design. Thus, system integration relies on the refrigeration system experience of the designer, who probably has not designed, built or troubleshot one of these rare systems.

Warming within a humidity-controlled vault cannot be designed-out, only closely monitored and alarmed. In events where monitoring fails, water problem are inevitable. Mold growth can result, but

often, the adverse outcome is sticking of the envelopes to the gelatin side of the film or glass plate. The fact that each artifact is unprotected in a humidity controlled vault, not in a sealed package, means that each can be harmed in any adverse water-based event.

3.7 - Gasketted Cabinets for Passive Vaults

Passive cold storage vaults require some sort of "sealed" system. Sealed cabinets are one option. The cost of sealed cabinets range from

- \$1500 for a basic seal 6'x3'x14" standing storage cabinet with shelves
- \$2500 for a 3' deep by 4' wide by 36" tall large flat material cabinets
- \$3000+ for sealed flat-file storage cabinets



Figure 5: Gasketed cabinets by Viking Metal Cabinet <<http://www.vikingmetal.com/mus/search/348.html>>.

The humidity of the air in the vault can fluctuate due to the opening and closing of the primary vault access door and time of the year. The gasketed cabinets and sealed bags maintain a stable humidity environment.



Figure 12. Freezer sharing work space.



Figure 13. Freezer showing taped seams, alarm panel (read light).



Figure 14. CMI-packaged negatives in our walk-in freezer.



Figure 23. Cabinet loaded with 48 boxes.

Figure 6: The walk-in vault built at the City of Vancouver Archives showing both sealed packages stored on metal shelves and un-seal boxes stored in gasketed cabinets. Images have been taken from Sue Bigelow's 2004 report "Cold Storage of Photographs at the City of Vancouver Archives," Guidebook from Canadian Council of Archives, which can be found at <http://www.wilhelm-research.com/canada/ccoa.html>.

3.8 - Freezer Kits

Metal Edge sells Safe-Care Image Archive Freezer Kits (800-336-4847) that consist of 2 heavyweight Ziploc bags (polyethylene) and a tan acid-free/buffered board box, with instructions for use. The cardboard box acts as the moisture sink and buffer; it is very high quality. Equilibrate the materials at 65-75°F and 45-55% RH, for about a week before sealing materials in the bag and placing in the sealed unit in the freezer. The bags can simply be removed from the freezer and allowed to warm up for 4-8 hours, while remaining sealed. For more degraded materials, and larger amounts, a slower warm-up procedure should be followed, see below.

3.9 - Bags for Cold Storage

Average sized bag will hold about

- 2-4, 500-1500 ft reels per bag, with ample matboard, blotters or quality cardboard
- 50-200 sheets of 4 x 5 film in acid-free envelopes
- 50-100 sheets of 8 x 10 film in acid-free envelopes

- 10-20 slide protector pages (200-400 slides) per bag (double-bagged Ziploc bags)
- 6-12 video cassettes per bag, with ample matboard, blotters or quality cardboard
- 4-8 boxes of microfilm per bag
- Glass plates don't lend themselves to bag storage; use suspension boxes in large custom bags

See Gaylord Catalog (800-448-6160) and IMPAK Corp for ready-made bags and Metal Edge Inc. catalog (800-862-2228) for Freezer Kits.

Marvelseal 360 is a metalized polyethylene and polypropylene barrier film that is heat-sealable. It has a Nylon exterior that is slightly tougher than the **Marvelseal 470**. **Escal bag material** is a newer product that is clear. I have not used Escal, but it is getting favorable reviews. It is 4 times the cost of Marvelseal, but it's clear so you can see labeling inside; search online for sources.

A professional bag sealer should be chosen because the width of the seal is about 1/2", rather than the 1/8"-seam found in refrigerator bag sealers. The Futura Portable heat sealer, Barrier model, can be purchased for about \$65 from (a) Audion Packing Aids Corp, San Rafael (415-454-4868), (b) one of the online suppliers of bagging supplies such as IMPAC Corp <http://www.sorbentsystems.com/footsealer.html> or (c) the conservation materials supplier selling the Marvelseal products.

Add 2-3 sheets of good-quality buffered 4-ply matboard (or 3/16" of buffered blotters, 4-5 sheets) to each bag as a moisture sink. See the University Products (800-336-4847) catalog for cut-sizes of matboard. Materials should be labeled on the exterior of the storage bags. A label with actual contents is very helpful, but a unique number that is referenced in a nearby paper cataloged or online database is more efficient. The materials should be held in a controlled room that has a stable relative humidity, such as 45-55% for about 1-2 weeks before they are sealed into the storage bags. This will increase the life substantially over the average 65% RH conditions found in the Bay Area.

3.10 - Warm-Up Process

When photographic materials are taken out of cold storage they must be allowed to warm to room temperature in a sealed bag before they are exposed to the unlimited water content of a room. Allow 4-12 hours for the "average" bag to adjust back to room condition before cutting the seal (or opening the Ziploc bag), when held in a thermal barrier holder such as a Styrofoam cooler. Longer is required if there is a great deal of air, or film, in the bag. The bag should be warmed in a Styrofoam cooler to prevent temperature gradients. The Styrofoam "cooler's" thermal barrier prevents rapid warming of the bagged materials.

Shorter warm-up times can be used for tightly-conforming bags holding relatively small amounts of materials. The bag will need to sit on a rack in a well ventilated room. There will always be concern about warming too fast, but a 2-4 hour warm-up can be used in critical situations. The Styrofoam cooler method is recommended and preferred.

3.11 - Time Out of Storage (TOS)

Time out of storage (TOS) will decrease the useful life of materials in cold storage. IPI sells materials to figure TOS for (1) color film and (2) cellulose acetate base film. Basically, 5-days TOS per year (for sub-zero storage conditions) lowers life by 90% -- $0.1 \times \text{years} = \text{years with TOS}$. If the useful life starts at 1000 years it becomes 100 years, when using sub-zero cold storage with 5-days TOS/yr.

Time out of storage of 5 days means the following:

- (1) Someone requests a slide on Monday
- (2) Its taken out of the freezer for the 6-12 hour warm Monday evening
- (3) The user gets back to the slide Tuesday
- (4) They copy or use it on Wednesday
- (5) They give it back to the operator on Thursday
- (6) Sometime on Friday the operator reseals the slide's package and gets it back into the freezer

All this assumes that the work area has consistent temperature and humidity, not requiring a preconditioning period.

4 - Moisture Content and Relative Humidity in Cold Storage

Materials have a specific water content that is based on the humidity in the surrounding air. The equilibrium moisture content is the amount of water that a material will hold in equilibrium with the relative humidity of (stable) air. If the relative humidity of the surrounding air changes, the moisture content of the material will come into equilibrium with the new RH of the air.

The moisture content of cellulosic materials and gelatin at 50% RH is on the order of 5-8% of their gross weight. Most cellulose-based materials reach about 90% of equilibrium with the relative

humidity in air within 10-60 minutes, assuming a reasonable movement of air around the artifact. Complete (100%) equilibrium takes longer.

Roll film and tightly packed negatives-in-envelopes take longer, days or weeks, to reach equilibrium in the center of the pack. If a material is sealed in a bag or cabinet within cold storage the moisture content of the material remains almost the same as when it was at room conditions. The artifact's solids are holding much more water by weight than the air surrounding it. Because the artifact holds so much more water than air, the material buffers the air. The air is almost inconsequential as long as some cellulosic materials are present. That is, the solid controls the gas (air) within the bag or sealed cabinet. This is why matboard, acid-free blotters or acid-free envelopes are recommended when sealing film into bags for cold storage.

In a frozen state, it has been shown, materials hold their moisture content, and, even slightly increase their moisture content. All materials will decrease in size very slightly when cooled, and will increase when warmed. The significant point is that the sealed artifact is stable, because it maintains a stable moisture content.

Upon cooling, air surrounding a material in a sealed bag will decrease its relative humidity. This is because materials hold "very" slightly more water at low temperature, than at room temperature. Thus, the material draws moisture from the air into its solid. Materials hold less water at elevated temperature, because the gas molecules are more energetic and move away from the solid slightly more when at higher temperature. This is counter-intuitive to most museum professionals. They know that air holds more water at higher temperature and less water at lower temperatures.

If the relative humidity in a bag or cabinet is 50% RH, at room temperature, then that same air will be 35% relative humidity at -15°F (-26°C). The small amount of air in the bag (or gasketed cabinet) has lower relative humidity, but the moisture content of the solid increases slightly, the equilibrium remains virtually the same.

When the bag or cabinet is returned to room temperature, the moisture content (weight of water relative to the weight of the solid) of the material is the same as when it started, because no moisture could escape. The relative amount of moisture in the air has changed, but the absolute moisture content remains the same. The relative humidity in the bag or cabinet never condensed at dew point (on a cooler surface) because the amount of water in the "air" was limited by bag.

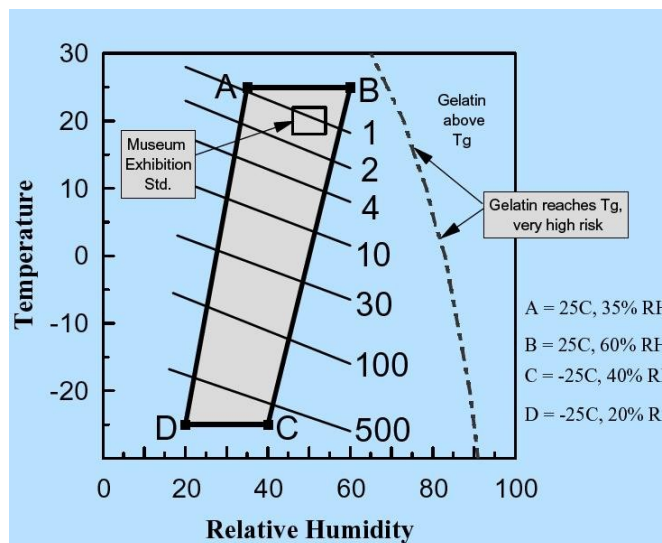


Figure 7: Trapezoid ABCD shows the safe zone for the cold storage of photographic materials, from work by Mark McCormick-Goodhart.

4.1 - Constant Moisture Content Trapezoid

In Figure 7, the trapezoid labeled **ABCD** describes the boundaries of acceptable moisture content condition between room storage (top of trapezoid) and "cold storage" conditions (bottom of Trapezoid). The room conditions are 35-60 %RH, at between 65-76° F, and 20-40 % RH at -25°F, at the bottom of the trapezoid.

All photographic material must be equilibrated in air that falls within the range of 35-60 %RH at 65-76°F room conditions, prior to bagging and cold storage. Equilibration can take 1 hour for single

items, to several weeks, for blocks of negatives in envelopes held in a dense group, in larger boxes. When the materials are frozen, they will stay within the ABCD trapezoid, because the moisture content at equilibration will be held constant by the constraints of the storage bag or gasketed cabinet.

Figure 6 was taken from: McCormick-Goodhart, M. *The Allowable Temperature and Relative Humidity Range for the Safe Use and Storage of Photographic Materials* in Journal of the Society of Archivists, Vol. 17, No. 1, 1996 pp 7-21. It can be obtained from SCRME, Information Services, Smithsonian Institution, 301-238-1240 Suitland, MD: Item #12891, where he did the work, or you can download his articles on cold storage from the Wilhelm Imaging Research website http://www.wilhelm-research.com/pdf/WIR_ISTpaper_2004_04_MMGWIR_ISTpaper_2004_04_MMG_HW.pdf.

If a material's temperature and humidity are kept inside the solid trapezoid found in McCormick-Goodhart's graph marked "Figure 4," the materials will follow line, **H-I**, and will remain completely safe during the cooling down and warming up process. This is accomplished if a material is sealed within a bag, or gasketed cabinet, at 35-62% RH at between 65-75°F and, and then cooled to its "cold" storage conditions. The materials must also warm-up while sealed in the bag; the "sealed in" moisture content remains constant eliminating stress during warming and preventing condensation because the solid overwhelms the water content of the air.

16 M. H. McCormick-Goodhart

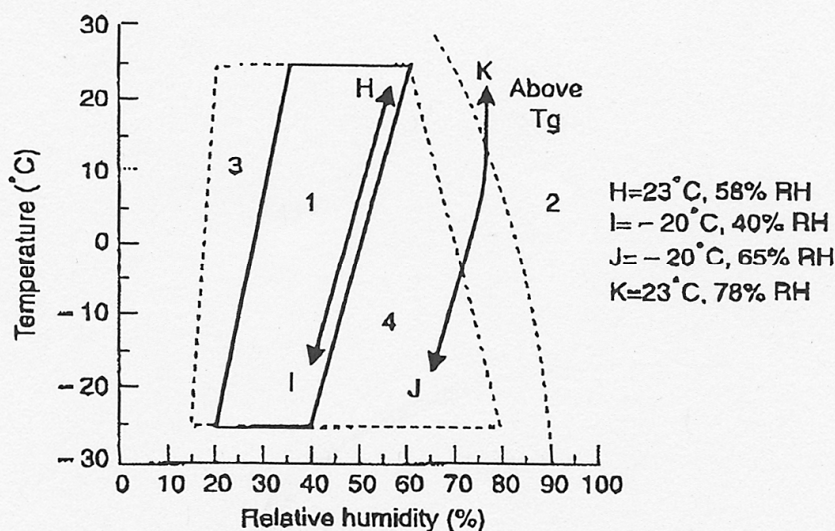


FIGURE 4. Microclimate response of confined photographic films and papers.

Figure 7: Figure 4 from "The Allowable Temperature and Relative Humidity Range for the Safe Use and Storage of Photographic Materials" by McCormick-Goodhart, p16.

If the material is removed from the bag, while still cold, it will follow the line **J-K**, which is outside the trapezoid. There will be two major results: (a) the materials could cross over the glass transition temperature (T_g) allowing the material to undergo an unacceptable size change (damage due to stress) and (b) condensation will form on the surface of the materials due to the massive amount of water in the surrounding air. Most new materials can tolerate a small number of these bad T_g -cycles, but damage can occur at any time.

4.2 - Physical Effects of Freezing

We often think of foods in the freezer when we think of putting cultural materials into cold storage. Most foods held in the freezer (except things such as grains, nuts and dry pasta) have a large **free water** content. Free water freezes and expands when frozen. We see the free water as ice crystals sealed in the food bags within the freezer. Water present in large proportions, on the order of 20-100% by weight of the solid is free water. Meat has quite a bit of free water.

Water in cellulose and gelatin at 50% RH is on the order of 5-8% of the solid; there is no free water in paper at 50% RH. Water held in materials at 50% relative humidity is adsorbed onto the surface of the solids as bound water. Bound water merely goes along with the other atoms in the materials as they increase and decrease in size with changes in temperature. On the other hand, free water

freezes and expands when frozen, causing damage to thin cell membranes in formerly living materials e.g., meat. The comparison between freezing meat and freezing film is not valid. There is no free water in film at normal room conditions.

Every time we fly, we move in a complex metal, plastic, glass, paint and rubber structure from -70°F (when flying at a 35-40,000 feet cruising altitude) back to 72°F at ground level when it lands. This is a change of 100°F. The composite structure of the airplane moves through the air at 400-600 mph, traverses massive temperature and pressure change, all without the paint peeling or plastic and glass cracking.

4.3 - System Design

Each system has to be designed specifically for the space in which it will be used. The variables are:

- (1) **Vault room or freezer compartment**
- (2) **Temperature**
- (3) **Sealed storage device (bags or cabinets)**
- (4) **Materials to be stored (film, prints or other artifacts)**
- (5) **Fire Protection requirements (local rules)**

In practice, local fire rules or requirements are often the most difficult problems. For the construction and installation of a nitrate film cold storage vault at the Oakland Museum, the fire issues were the most difficult to resolve. For nitrate vaults, a cinderblock room needed to be built around the standard modular freezer-room components. The Fire Marshal required that the vault must have sprinklers above the modular room, that would keep the freezer-room exterior cool in the event of a fire within.

For the cold storage of normal film, a modular commercial freezer can be located in any larger room with no extra internal or external fire protection than that required within the specific building. A freezer project needs an experienced conservator as a consultant, who knows photographic materials and the range of cold storage options.

5 - Storage Materials and Solutions

Devices for storage (high priority items should be foldered singly; low access items can be stored several to a folder, interleaved)

- **acid-free folders (Metal Edge)**
- **oversized folders made from acid-free/buffered paper (Permalife in Gaylord)**
- **oversized folders made from acid-free/buffered Tan Barrier Board (Gaylord)**
- **standard-sized large folders made from acid-free/buffered paper (Metal Edge)**
- **L-sealed Mylar folders of various sizes (Metal Edge)**
- **Mylar Document Protectors (Gaylord)**
- **Self-made Mylar folders made from Mylar (0.003-0.005" thick) on the roll**

Foldered paper-base materials can be held in boxes such as

- **Acid-free/buffered Archival Record Storage Cartons (gray corrugated, Gaylord)**
- **Archival Document Cases (Tan, Lignin-free, Gaylord)**
- **Drop Front Storage Boxes (Metal Edge, Tan)**

Bulk materials unsorted and unfolded

- **Bulk materials in acid-free/buffered Archival Record Cartons (gray corrugated, Gaylord)**
- **Bulk materials in Standard Record Storage Boxes (Metal Edge, Tan, buffered)**
- **Within intellectual groups in Archival Document Cases (Tan, Lignin-free, Gaylord)**

Books, pamphlets and notebooks can be held in

- **Archival Document Cases of various sizes (tan, lignin-free, Gaylord) within Document Preservation Binders (Gaylord)**
- **within Case Binders (Gaylord) using Glue-in attachment**
- **Individual Book Boxes (Metal Edge)**
- **Corrugated Book Storage Boxes (Metal Edge)**

5.1 - Inner Housing – sleeves or interleaving

Inner housings protect the surface of a print or negative from damage when in a storage container. All historic images need surface protection such as sleeves, four-flap folders, page protectors (virgin polyethylene or poly propylene), or, single folders made from acid-free unbuffered paper, Permalife™ paper (with low buffering level), acid-free glassine or polyester (Mylar).

Sleeves: All the existing glassine and clear sleeves (Kodak triacetate) should be replaced with acid free paper envelopes, polyester sleeves or 4-flap paper folders.

Interleaving: Original prints held in groups within a single folder should be interleaved with some sort of acid free material such as acid-free glassine, Permalife™ paper or unbuffered acid-free tissue.

Glassine is generically my choice because it has minimal texture, is easy to handle, is translucent and is now acid free (started about 20 years ago).

Older glassine can be very acidic and should be eliminated from all collections. Buffered (with excess calcium carbonate) materials are often not recommended for the storage of photographic materials. The concern is that in a flood, the extra alkalinity dissolved in the water can soften gelatin more than just neutral or acidic water.

6 - Other Resources

Sue Bigelow, Art Conservator, ***Cold Storage of Photographs at the City of Vancouver Archives***
<http://www.cdnCouncilarchives.ca/Storage%20%20English.pdf>. How-to Manual.

David Horvath ***The Acetate Negative Survey*** (1987) final report to the National Museum Act (funder) can be found at <http://library.louisville.edu/library/ekstrom/special/AcetateNegativeSurvey.pdf>

Mark McCormick-Goodhart, ***On the Cold Storage of Photographic Materials in a Conventional Freezer Using the Critical Moisture Indicator (CMI) Packaging Method***, 2003, http://www.wilhelm-research.com/subzero/WIR_ISTpaper_2004_04_MMG_%201.pdf.

Mark McCormick-Goodhart and Henry Wilhelm ***The Design and Operation of a Passive Humidity-Controlled Cold Storage Vault Using Conventional Freezer Technology and Moisture-Sealed Cabinets***, 2004, http://www.wilhelm-research.com/subzero/WIR_ISTpaper_2004_04_MMG_%201.pdf.

Henry Wilhelm and Carol Bower ***The Permanence and Care of Photographs*** (1993) 758 pp
http://www.wilhelm-research.com/pdf/HW_Book_758_Pages_HiRes_v1a.pdf also individual chapter downloads; chapter on cold storage.

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Albumen Photography Website in 2000) <http://albumen.conservation-us.org>
VideoPreservation Website in 2007 <http://videopreservation.conservation-us.org>