Environmental assessment and condition survey

A strategic preservation plan for DFI's motion-picture film collections

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Faced with the challenge of preserving its collections, the Danish Film Institute Film Archives, with encouragement from the Ministry of Culture, has in recent years initiated a total change of its preservation strategy and has taken steps to improve the storage conditions of its collections. Toward this end, the DFI awarded a contract to the Image Permanence Institute (IPI) at Rochester Institute of Technology, Rochester, New York for the purpose of formulating a preservation strategy for extended-term storage of its motion-picture film collections.[1]

The DFI film archive currently faces a crucial situation in which their aging film collections not only have outgrown the original storage facility but also have started to display various forms of decay associated with the poor environmental conditions in which they are stored.[2] Studies on film stability have demonstrated that the quality of the storage environment and the current condition of the collection materials must be known before it is possible to determine a best-fit strategy for ensuring the future of film collections. By initiating this investigation, implementing a wide-ranging environment assessment, and performing a film condition survey, DFI has embarked on what promises to be a productive undertaking.

IPI's role in this project has been to analyze the environmental data collected by DFI, review its current plans, and propose further actions. To achieve these goals IPI's time-weighted preservation index (TWPI) and mold risk factor were used as evaluation models. These, together with IPI's Climate Notebook software, provided basic information on storage quality.

The assessment of current storage conditions and evaluation of the state of preservation of the collections done during the project demonstrated the need for a new special archive. This paper discusses the data developed during the project and describes the environments that will be necessary to preserve the film archive's collections for an extended time period. This paper proposes a methodology that can be applied to more than just the specific challenges faced by DFI. Using basic information and existing assessment tools as described in the following text, a sound preservation strategy can be designed for any film collection.

ORIGIN, COLLECTION SIZE, AND FILM MATERIALS

As early as 1910, films were donated to the Royal Danish Library that currently represent the oldest movies in DFI's collections and constitute the core of materials on which the collections were built. Over the years, the collections have grown to include about 30,000 titles or around 200,000 film containers, and they are still growing. Because of DFI's history and continuing expansion, its collections include a wide variety of film material types. The collections encompass both early and contemporary cinema and include all types of motion-picture materials produced during the evolution of cinema technology. Film on nitrate base makes up a significant portion of the holdings–an estimated 10% (camera negatives and prints included). Black-and-white and color films, film on acetate base, and, more recently, film on polyester base constitute the bulk of the holdings. The collections can be further grouped as preservation materials (masters) or prints. Masters can be any type of material, including negatives, duplicate positives, and archival prints. Like many film archives in the world, DFI is at a crossroads, where the need to protect the collections from intensive use collides with efforts to develop tools, such as an on-line catalog, that will increase interest in the collections and potentially increase their use. In this situation, preserving original materials, or masters, becomes an even more urgent objective.

STORAGE FACILITIES

Since the 1960s, the DFI film collections have been stored in former fortifications that have been transformed into a series of climate-controlled cells. Today, all films on nitrate support and some prints on acetate base are stored in Bagsværd Fort. Starting in January 2000, preservation materials and a portion of the prints collection on safety base were transferred to Naverland, Glostrup, where they are stored in a new cold room. This recent move was prompted by the deterioration of the storage conditions at Bagsværd Fort and marked a new phase in preservation planning for the film archive collections.[2]

Bagsværd Fort

In the 1960s, the conversion of the fortifications into film storage facilities appeared to be an adequate solution. Typically, these types of constructions offered good thermal insulation that buffered outside temperature swings and were already conveniently broken up into small units providing individual storage spaces. These features made such spaces suitable for storing relatively small quantities of highly flammable nitrate film in each unit. At that time, the rehabilitation of the fort into a film archive was completed by the installation of a climate-control system designed to maintain a temperature of around 12°C and a relative humidity of 50% RH. At that time, the project satisfied the requirements for film preservation, as they were understood in the 1960s. Assessment of the situation forty years later calls into question the efforts made in earlier years. The deterioration of the storage conditions at Bagsværd Fort has become a critical issue, as described by Johnsen.[2] Obvious manifestations of deterioration caused by high humidity can be observed today throughout the building. Examples are deteriorating plaster, mold growth on the walls and on cardboard boxes, and rusting metal cans. Over the years, because the space

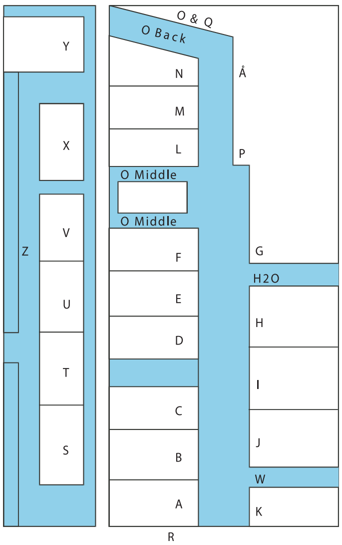


Figure 1. Map of storage areas evaluated in Bagsværd Fort.

could not accommodate the continuing growth of the collections, film materials had to be stored in uncontrolled spaces. It is likely that these storage pockets were exposed to drastic environmental changes and high humidity levels. But there are problems with storage quality inside the climate-controlled vaults as well. Signs of high humidity are noticeable in those spaces, and high RHs have been measured. A previous survey determined that the existing climate-control equipment was forced to function beyond its operating range. Padfield discussed this point in detail in an earlier report [3] and demonstrated that, as used, the equipment could not have properly controlled the humidity level inside the vault and failed to provide cool storage at moderate RH.

Cold Room at Naverland, Glostrup

In 1999, a 600-square-meter cold room was constructed to serve as temporary storage space until new storage facilities became available. This space was built using insulating panels assembled to provide an enclosed "envelope" within the existing structure of an industrial building. Four cooling units and one dehumidification unit using desiccants are installed, maintaining the environment at 5°C, 35% RH. Since January 2000, film materials on safety support (preservation materials and prints) have been moved from Bagsværd Fort into this cold room. This operation signifies a transition toward optimum storage conditions. There is no doubt that cold storage will greatly extend the useful life of the film collections; simple calculation demonstrates how cost-effective such an approach is in the long term, compared to the cost of restoration or duplication of degraded films. Although the existing cold room is in principle a good response to the storage problems facing DFI, it is not and was not intended as the sole solution. A single room, because of its structure, its one type of climate, and its size, cannot accommodate the diversity of materials, mass of film, variety of uses, and specific environmental needs of many different material groups. To date, only masters on acetate and polyester base have been transferred to this cold space. Nitrate masters, primarily for safety reasons but also for lack of space, cannot be removed from Bagsværd. Only a portion of the prints has been relocated to the cold room. That said, the availability of the cold room and the transfer of the film archive staff to Naverland marked the first step toward effective preservation of the DFI film collections.

ENVIRONMENTAL ASSESSMENT

Since December 1999, the film archive staff has monitored the environmental conditions in storage areas in both Bagsværd and Naverland, Glostrup. IPI's mission was to collect, reassemble, and analyze the large number of temperature and RH data sets produced by the film archive between December 1999 and March 2001 for most of the test sites. A one-year history of the storage conditions in twenty-nine test locations was compiled. Temperature and RH data were interpreted using Climate Notebook, a software tool for environmental assessment being developed at IPI. This software provides a way to document, understand, and quantify the quality of any storage environment in relation to the type of materials stored therein. Analysis consisted of both interpretation of raw temperature and RH data sets and the use of the time-weighted preservation index (TWPI) and the mold risk factor, two concepts introduced by IPI. Table I summarizes the results by storage location. (The identification codes are those used at the film archive and can be found in Figure 1).

Location	Materials	Climate Control	Avg. T (°C)	Avg. % RH	TWPI (years)	Mold Risk Factor
Bagsværd A	Nitrate masters	Yes	8	59	147	0
Bagsværd B	Nitrate masters	Yes	8	62	133	0
Bagsværd C	Acetate prints	Yes	9	63	107	0
Bagsværd D	Nitrate prints	Yes	9	60	138	0
Bagsværd E	Nitrate prints	Yes	9	64	114	0
Bagsværd F	Nitrate prints	Yes	9	62	120	0
Bagsværd G	Acetate masters	Yes	6	68	150	0
Bagsværd H2O	Acetate prints (shorts and documentaries)	No	9	81	67	35.3
Bagsværd H	Acetate masters	Yes	9	60	127	0.58
Bagsværd I	Acetate masters	Yes	10	64	107	0
Bagsværd J	Acetate masters	Yes	11	48	142	0
Bagsværd K	Acetate masters		11	66	86	0
Bagsværd L	Nitrate masters (National Museum)	Yes	7	77	101	5.6
Bagsværd M	Nitrate prints	Yes	6	77	120	0
Bagsværd N	Acetate special collection	Yes	8	73	96	2.3
Bagsværd O middle	Acetate prints	No	9	73	89	2.9
Bagsværd OE	Acetate prints, stills, photo albums	No	13	64	71	0
Bagsværd OE back	Acetate prints, technical collection	No	12	60	82	0
Bagsværd P	Acetate (shorts and documentaries)	Yes	6	71	139	0
Bagsværd R	Acetate prints (shorts and documentaries)	No	14	61	62	0.2
Bagsværd S	Acetate masters	Yes	10	72	85	12.2
Bagsværd T	Acetate masters	Yes	10	69	90	0
Bagsværd U	Acetate masters	Yes	10	73	75	11.4
Bagsværd V	Acetate masters	Yes	9	75	80	9.4
Bagsværd W	Acetate masters and prints	No	12	72	68	1.5
Bagsværd X	Acetate prints	Yes	9	78	77	15.2
Bagsværd Y	Mixed acetate materials	No	9	76	82	2.2
Bagsværd Z	Acetate prints	No	11	68	79	0
Naverland, Glostrup	Acetate masters and prints	Yes	5	32 33	523 518	0

Table I. Locations, materials, and comparison of average temperature, average RH, TWPI, and mold risk factor.

TEMPERATURE AND RH

Environmental monitoring produced a series of temperature and RH data sets that reflect the climate conditions of the twenty-nine storage locations selected for testing. These data are fundamental for quantifying the quality of these storage spaces using the TWPI model and mold risk factor. Table I indicates the types of materials that have been or still are stored in each identified space and reports average temperature, average RH, TWPI, and mold risk factor. Figures 2 and 3 compare the average values of temperature and RH. The materials stored in Bagsværd were kept at cool to cold storage temperatures – i.e., between 6°C and 14°C. Most locations in Bagsværd displayed high humidity levels of 60% RH and above. It was expected that a condition assessment of film kept under those conditions would uncover numerous problems such as biological decay. In contrast with storage conditions at Bagsværd, average conditions at Naverland are cold and moderately dry (5°C, 30% to 35% RH).

PI and TWPI Analysis

The temperature and RH data sets recorded at the film archive show that the environmental conditions indeed fluctuated during the monitoring period. We may assume that the data give a fairly clear picture of the changing climate conditions experienced by the film collections over the past decades. It is difficult enough to know how static conditions affect film collections, but it is even harder to know the impact of changing conditions. To do this, PI (preservation index) and TWPI (time-weighted preservation index) must be used.

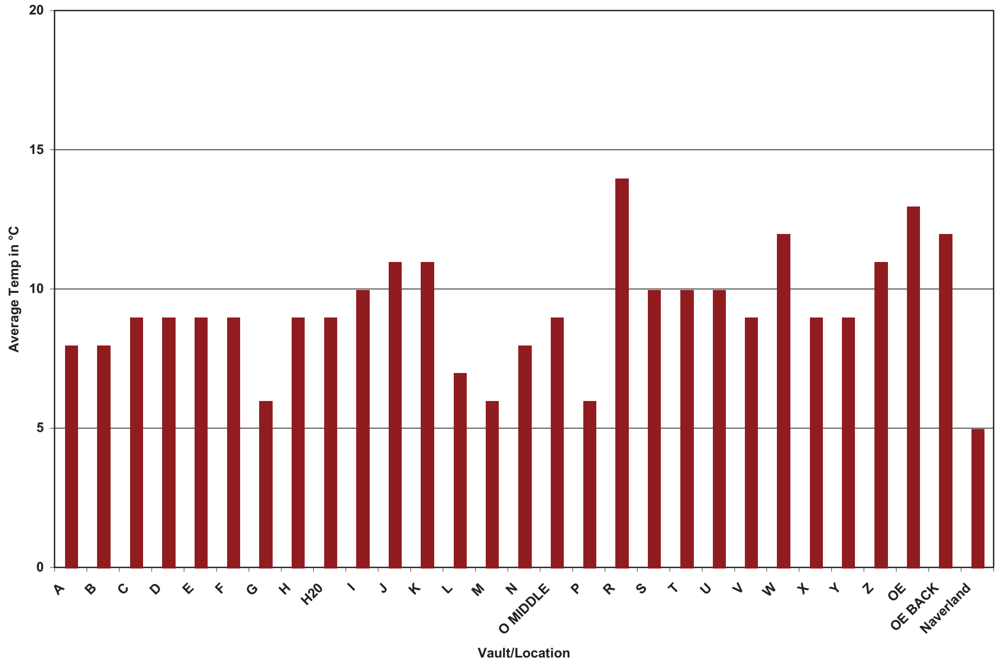


Figure 2. Comparison of average temperatures for twenty-nine locations monitored from December 1999 to March 2001.

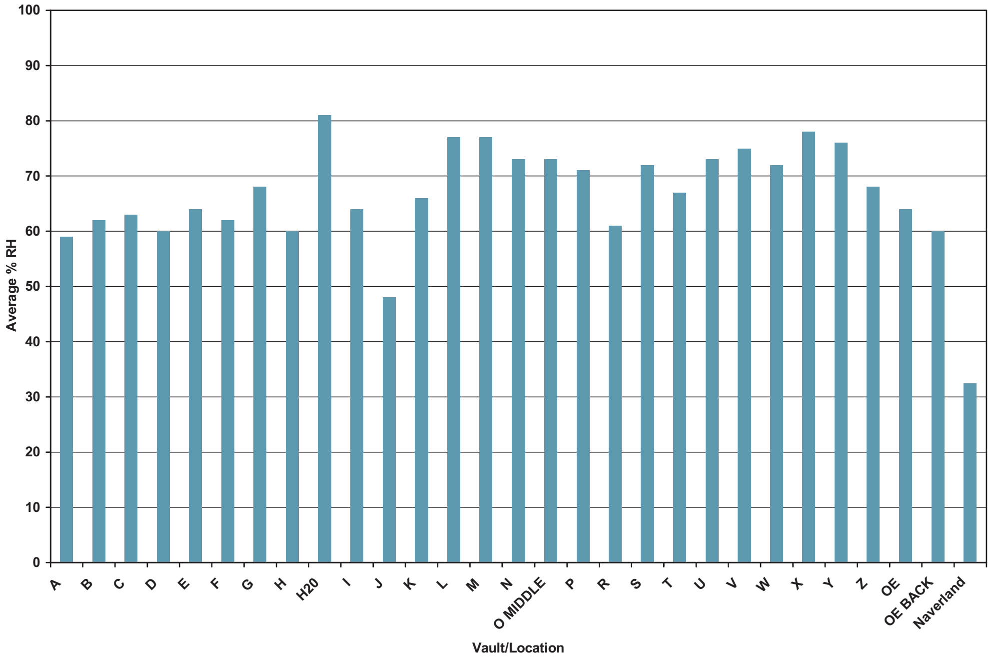


Figure 3. Comparison of average RHs for twenty-nine locations monitored from December 1999 to March 2001.

PI and TWPI analysis starts with temperature and RH data collected over time. PI values are predictions of life span in years of vulnerable organic materials and are based upon experimental data obtained under accelerated conditions. PI gives a quantitative evaluation of how a particular temperature-RH combination affects decay rate. An environment characterized by high temperature and high humidity will greatly reduce the life span of acetate base film through chemical degradation and will have a very low PI value. An environment providing cold temperature and low RH will maximize the chemical stability of photographic film and will have a high PI value.

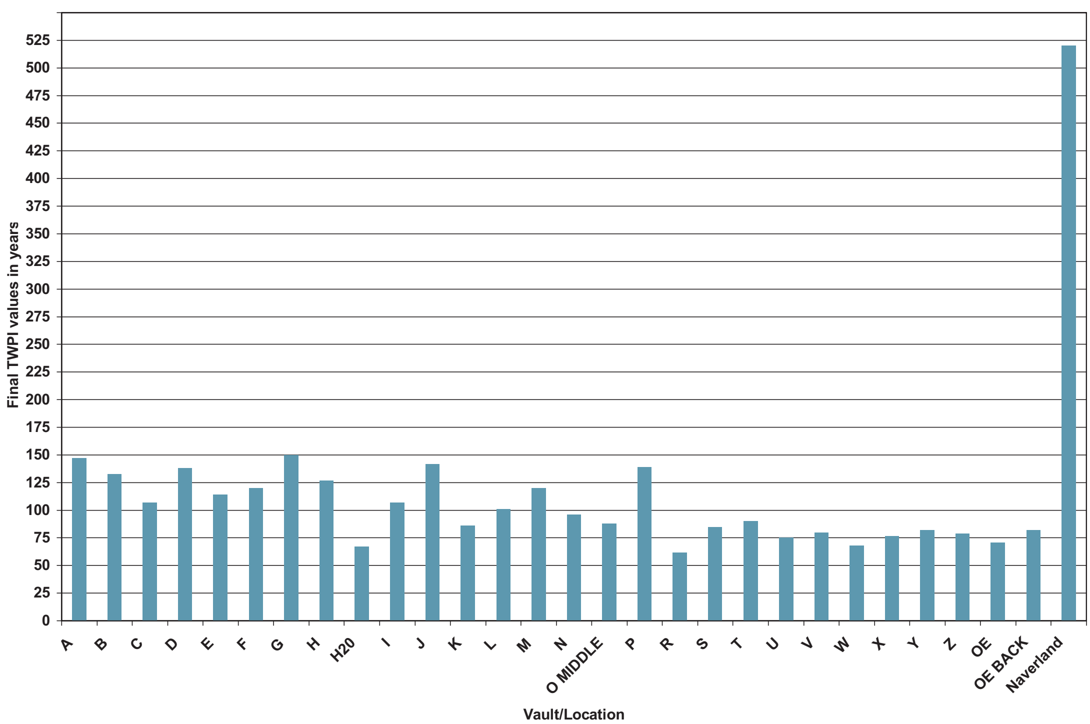
TWPI is an average of changing PI values over time. TWPI reflects the fact that chemical deterioration proceeds more rapidly under warmer conditions and higher RH than it does under colder and drier conditions. It also reflects the fact that poor climate conditions have a greater impact on longevity than good conditions. The reason is simple: chemical decay may slow down under proper storage, but it can never be reversed. TWPI values characterize the quality of storage (higher values mean higher quality) and provide an estimated life span for newly processed film materials. Thus, TWPI provides a measurement of the efficacy of any storage environment to preserve chemically unstable materials. The theory and calculation methods behind TWPI have been described in detail in earlier publications.[4]

IPI has produced two tools that use this computational method to translate raw temperature and RH records into PI and TWPI: the Preservation Environment Monitor™, or PEM, and Climate Notebook™, software currently in development. Climate Notebook was used for computation in this project. The results obtained for each test location are included in Table I. Figure 4 compares final TWPI values (as of the end of the monitoring period) for the twenty-nine test sites. These results made it possible to rank the locations according to their TWPI–i.e., how effectively they can postpone chemical decay of organic materials.

Bagsværd Fort–Final TWPI

If we assume that the climate data recorded at Bagsværd Fort reflect the prevailing conditions, we can conclude that about half of the newly processed acetate film or color film materials stored in those spaces will deteriorate significantly in less than 100 years. The rest probably will not last more than 150 years without significant degradation. Figure 4 indicates that TWPI values at Bagsværd vary between 62 years and 147 years. This indicates that the quality of these environments is not high enough to achieve extended-term (i.e., 500 years) storage of fresh photographic films. Interpretation of the results indicates that although the storage temperatures are relatively low, the sustained high RH levels significantly reduce their benefit. This conclusion is true for stability of both film support (nitrate and acetate) and color

Figure 4. Environmental assessment. TWPI values calculated for the storage locations in Bagsværd Fort and Naverland, Glostrup.



dyes. The stability of these major components of photographic film is strongly influenced by temperature and moisture.

Naverland, Glostrup–Final TWPI

TWPI analysis based on the temperature and RH data collected in two locations in the cold room indicate that film stored in this space could have a significantly greater life expectancy than film stored at Bagsværd. Calculations based on the environmental data produced final TWPI values greater than 500 years. These values demonstrate that the Naverland cold room could improve the chemical stability of photographic film by at least a factor of 3.5 to 8, depending on the Bagsværd location used for comparison.

ENVIRONMENTAL NEEDS OF FILM COLLECTIONS

Because TWPI values represent the overall effect of storage conditions on film chemical stability, this approach makes it possible to quantitatively assess various storage areas and rank them according to the life span they can provide to collection materials. TWPI analysis shows that the quality of the environment in the colder and drier climate-controlled Naverland cold room is markedly superior to that in the Bagsværd storage areas. It should be noted that TWPI analysis uses newly processed film as a reference; the final analysis of storage requirements must integrate the fact that the goal is to preserve not only fresh materials but also older films, which comprise a major part of the collections. The latter are likely to be either already decaying or approaching the early stages of decay and will require more stringent climate conditions than newly processed films to achieve a similar life span. Other categories of decay, such as physical deterioration and biological decay, must be addressed separately.

MOLD RISK FACTOR

Studies have demonstrated that, regardless of the species, mold growth is strongly dependent on temperature and RH. For this project, Climate Notebook was used to determine the mold risk factor for the twenty-nine test locations. Using environmental data, Climate Notebook derives a single value ? the mold risk factor ? that indicates the likelihood and severity of mold growth on susceptible collection materials. This model is based on the principles that mold growth occurs at an optimum temperature (as temperature rises or falls from this optimum point, the rate of mold growth slows down) and that it is stimulated by high humidity. The model assumes that mold grows in two stages: germination of spores and active growth (when the mold becomes visible and destructive). Climate Notebook works through temperature and RH data and determines whether conditions are favorable to encourage the germination of mold spores. It does this by calculating a running sum that represents cumulative progress toward germination. The sum starts at 0. When it reaches 1, germination occurs. If conditions remain favorable for mold, the sum is continued. For example, a prolonged damp period could run the cumulative sum up to 5 or 6 (meaning five or six times the minimum germination time), which would signal a severe mold outbreak. Because the conditions for germination and the complexity of the biological mechanisms vary widely according to species, this is only an approximate growth model.

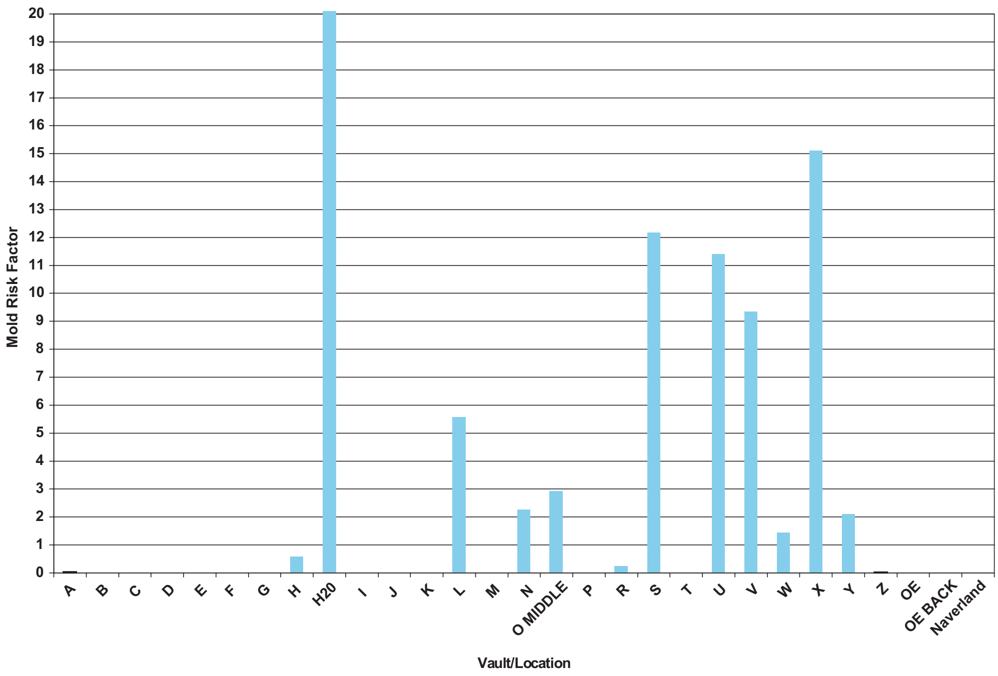


Figure 5. Environmental assessment. Mold risk factors determined for storage locations in Bagsværd Fort and Naverland, Glostrup.

Figure 5 presents a mold risk factor comparison. Ten locations are identified as having a mold risk factor higher than 1. Five of these locations had a mold risk factor greater than 5. Some of these storage locations had no climate control (see Table I) and displayed obvious mold growth on film boxes and walls. These ten locations had an average RH above 70%; RH in some cases was as high as 80%. Environmental data indicated long periods at sustained high RH ? highly favorable conditions for biological decay. It should be noted however, that while the relatively low temperature (6°C to 14°C) maintained in the storage areas contributed to the high RH, it discouraged the growth of mold, which commonly germinates at around 29°C. In the end, however, ten out of the twenty-nine locations tested presented a high risk of biological decay.

CONDITION ASSESSMENT OF THE FILM COLLECTIONS

In order to evaluate the state of preservation of the DFI collections, film archive staff performed a survey based on a stratified random sampling, which included films on nitrate support, shorts and documentary films, preservation materials on acetate base, prints on acetate base, and magnetic sound tapes. The methodology and results obtained during the condition survey were reported by DFI film archive.[5] The film archive has put forth considerable effort to achieve a detailed picture of the state of their collections. There is no doubt that all the criteria used for the survey are important in the management of the film collections. However, IPI analysis is confined to the types of decay that are related to storage conditions and does not cover types of degradation that are likely to be caused by handling, use, or other external factors.

NITRATE BASE FILM–CONDITION SURVEY

Typical signs of nitrate base decay such as base discoloration, acrid odor, brittleness, and base decomposition were observed during the inspection. These indicate that chemical deterioration has started, and that 21% of the DFI sample is in advanced stages of decay, based on the brittleness of the films. Earlier film stability studies have revealed that chemical decay of nitrate base generates acid, causes base discoloration and shrinkage, and increases the brittleness of the plastic. The measurement of base shrinkage is a good indicator of film condition and of potential duplication problems. Of the films measured, about 35% of the DFI test sample displayed shrinkage of 1% to 2%. Although some permanent dimensional changes are due to the loss of residual solvent from the film base, this shrinkage is more indicative of chemical decay of the nitrate base. As early as the 1930s, shrinkage determinations were used as criteria for prioritizing films for reprinting. Today, the challenge facing the film archive is to adopt a balanced approach between providing proper storage to minimize further decay and prioritizing duplication. The condition survey findings suggest that, if storage conditions stay as they are, 55% of the nitrate base collections (i.e., about 11,000 cans) should be duplicated.[5] On the other hand, if climate conditions were improved, this number could be reduced and the need for immediate duplication could be postponed. Table II summarizes the major findings from the film archive inspection and emphasizes the multiple advantages of providing proper storage for the nitrate film collections.

Decay Signs	Extent of Decay	Cause	How to Control It
Base shrinkage	35% of the films present between 1% and 2% shrinkage. 1% of the films presents more than 2% shrinkage.	Base chemical decay causes base discoloration, excessive shrinkage, deformation, brittleness, and base decomposition.	Nitrate chemical stability is highly variable; however, it is strongly influenced by climate conditions. Cold temperatures and low RH have great potential to maximize nitrate chemical stability.
Base yellowing	10% to 20% of the films		
Base brittleness	About 20% of the films		
Base decomposition	About 5% of the films		
Silver mirroring	Less than 4% of the films	Silver oxidation is caused by oxidizing compounds (e.g., nitrate degradation byproducts) and promoted by moisture.	Maintain RH below 50% and minimize the presence of oxidizing compounds to reduce the risk of silver image oxidation.
Ferrotyping	More than 10% of the films	High moisture content causes gelatin to be more susceptible to softening and flowing	Keeping RH at moderate or low levels eliminates the risk of ferrotyping.

Table II. Major signs of decay identified during the survey and how to control the problems.

Acetate Base Film–A-D Strip Testing

The two key principles involved in the preservation of acetate film collections grew out of film stability studies conducted at IPI: First, monitoring the acid content of film makes possible the detection of early signs of acetate degradation. Second, the current condition of the film must be known in order to implement the most efficient preservation strategy for the collection.

Monitoring the acid content of acetate film over time reveals the current condition of the film and, ultimately, the remaining useful life of the film. The relationship between the film acid content and time is shown in Figure 6. Because one of the primary byproducts of acetate degradation is acetic acid, the level of acidity in film is the best way to characterize its condition or state of decay before the appearance of such visible signs as physical property changes, which occur only after film, is already very acidic. Figure 6 also indicates that the degradation process of acetate base collections may be described as *slow* during the induction period and as *fast* beyond the so-called autocatalytic point. This is very important, because it illustrates the fact that beyond

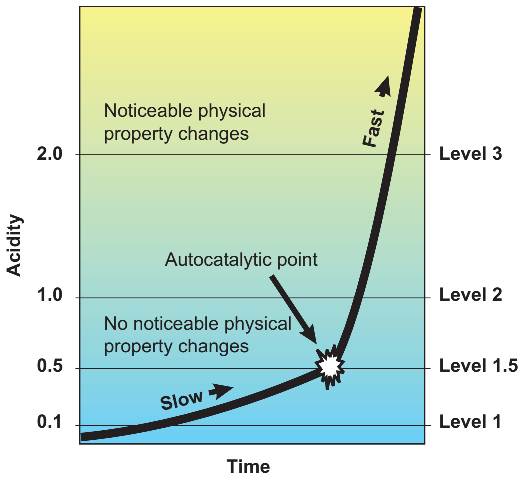


Figure 6. Relationship between film free acidity, film condition, and A-D Strip levels. Free acidity is expressed in milliliters of 0.1M NaOH per gram of film.

the autocatalytic point it is more difficult to extend the useful life of acetate materials. This means that film in poor condition will require more stringent climate conditions (i.e., a colder and drier environment) than film in better condition to achieve a similar life span.

This underscores the importance of knowing the condition of a film collection when deciding on a strategy that will meet the needs of the institution. In the quest for support of such efforts as improving storage conditions or prioritizing the preservation of information recording materials through duplication, the state of preservation of collections must be considered. A-D Strips were developed for just this purpose. The utility of the strips is based upon the fact that acidity increases during the base degradation process. The strips contain an acid-base indicator that provides an indirect method for quantifying the condition of a film by changing color in relation to the acid content of the film. This technology was used for the DFI survey. The relationship between A-D Strip levels, acid content, and film condition is illustrated in Figure 6.

Acetate Base Film–Condition Survey

The extent of vinegar syndrome was evaluated by random sampling for three groups of films: the shorts and documentary films, and feature film masters and prints. A-D Strip testing results are reported in Table III. The data indicate that 60% to 80% of the films tested displayed signs of base chemical decay (A-D Strip level 0.5 and above). Data also indicate that most of the films displaying signs of base deterioration are still in the first phase of chemical degradation (A-D Strip level 0.5 to 1.5). At this stage the rate of decay is still comparatively slow and the acid content in the film is still below the autocatalytic point (A-D Strip level 1.5). Based on this fact, we can conclude that these acetate base collections could achieve a long, useful life if stored properly. Further inspection of the shorts and documentary film collections identified other significant manifestations of decay such as dye fading, silver attack, mold growth, and ferrotyping. Table IV reports some of the data developed by the film archive and indicates ways to control those types of decay. Such approach again emphasizes the importance of climate control in extending the useful life of photographic film.

A-D Strip Levels	**A-D Strip Results in %**		
	Shorts and Documentaries	**Feature Films**	
		Masters	**Prints**
0	39	25	20.5
0.5	26	69	67
1	34	6	12
2 - 3	1	0	0.5

Table III. A-D Strip testing results for acetate film collections (i.e., shorts and documentaries and feature film masters and prints).

Decay Signs	**Extent of Decay**	**Cause**	**How to Control It**
Vinegar syndrome	60% of the films displayed signs of vinegar syndrome. Most films have not reached the autocatalytic point.	Acetate film base by nature is prone to chemical decay. The rate of decay is strongly influenced by temperature and RH.	Cold temperatures and low RH have great potential to optimize chemical stability of acetate film base and color dyes. Maintaining RH below 50% would minimize the risk of silver image oxidation.
Dye fading	About 45% of the films displayed severe dye fading.	Color dyes are inherently prone to fading. Rate of decay is dependent upon temperature and RH, and is accelerated by acids (e.g., byproducts of acetate film base degradation).	
Silver mirroring	About 5% of the films	Silver oxidation is caused by oxidizing compounds and promoted by moisture.	
Mold growth	About 14% of the films	Biological decay. Promoted by warm and humid environments	Avoid high RH and control temperature.
Ferrotyping	About 15% of the films	High moisture content causes gelatin to be more susceptible to softening and flowing at certain temperatures.	Controlling RH to moderate or low levels eliminates the risk of ferrotyping.

Table IV. Major signs of decay identified during the survey of shorts and documentaries and how to control the problem.

OPTIMIZING FILM LONGEVITY

Tables II and IV indicate that many of the stability problems observed during the condition survey are caused by adverse environmental conditions. Conversely, it is recognized that providing proper storage minimizes many of the problems commonly encountered in film collections. Decay such as mold growth and ferrotyping can be avoided by keeping the RH at moderate levels. Keeping the RH below 50% can also minimize silver oxidation. For those types of decay, a limited maximum RH is an effective preservation strategy. Environmental assessment indicated that these requirements are not met at Bagsværd. In fact, the evaluation of the mold risk factor confirmed the visual observation of mold growth and identified ten zones at high risk. Chemical decay, such as nitrate and acetate deterioration and color dye fading, is known to occur under any storage conditions. Nitrate decomposition, vinegar syndrome, and dye fading are inherent to the nature of film components and are ongoing processes. The fact that the rate of these chemical reactions is strongly influenced by temperature and RH provides a key to understanding how to control them. The relationship between climate conditions and nitrate and acetate base decay and color dye fading have been quantified.[6,7] With this information it is possible to recognize inadequate storage conditions and to increase the longevity of film materials. TWPI analysis, used to evaluate the risk of chemical decay throughout the DFI film archive storage locations indicated that a newly processed acetate base film would be significantly deteriorated in less than 150 years if kept in any of the Bagsværd locations. The cold room at

Types of Decay	Signs of Decay	How Bagsværd Fort Storage Contributes to Decay
Nitrate base decay	Yellowing, brittleness, base decomposition, shrinkage, deformation.	TWPI analysis indicates that storage quality cannot fulfill long-term preservation objective (maximum TWPI=150 years). Also, nitrate stability is highly variable; DFI collections are already displaying signs of aging. Duplication is recommended for 35% to 45% of the films tested (shrinkage >1%.)
Vinegar syndrome	A-D Strips show that about 60% of shorts and documentaries on acetate base, and at least 75% of feature films tested display early signs of decay.	TWPI analysis indicates that current conditions cannot fulfill long-term preservation objectives for chemically unstable film base (maximum TWPI=150 years). Acetate base degradation has already started for a large portion of the collection. These films need even more stringent climate conditions. Under current conditions, already degrading film will have a short remaining life span.
Dye fading	45% of shorts and documentaries are affected by severe dye fading.	Stability of color dyes is strongly dependent on temperature and RH. Effects have been quantified.7 Bagsværd does not provide the required temperature and RH to achieve extended-term storage.
Silver oxidation	Silver mirroring	Both contaminants and high humidity promote silver oxidation. Keeping RH below 50% would minimize problem. High RH levels were found.
Mold growth	Mold growth seen on walls and containers and found during condition inspection. About 14% of shorts and documentaries show signs of biological decay.	Mold risk factor analysis shows that risk for biological decay is very high for a number of locations (see Table I).

Table V. Major decay observed during the inspection of the collections and its relationship to storage conditions in Bagsværd Fort.

Naverland, Glostrup is the only storage area that would provide a life expectancy of 500 years for newly photographic film. It should be re-emphasized that the historic films that give such high value to the collections require even better storage conditions than fresh film to achieve the same life span. Data analysis shows that the collections will remain at risk as long as they are stored in Bagsværd. The lack of reliable and efficient climate control equipment and the structural deterioration at Bagsværd Fort make this site unsuitable for DFI's preservation needs.

Table V illustrates the disparity between the Bagsværd storage environment and the conditions needed to effectively stabilize the aging DFI collections for an extended period. That said, optimizing the longevity of a given film collection means determining suitable storage conditions for maximizing film stability. Climate condition requirements may vary depending on materials, their current state of preservation, and the goals of the institution.

Optimizing Nitrate Film Stability

Stability studies on nitrate film indicate that the behavior of nitrate base is highly variable.[8] The life expectancy at room conditions of some nitrate samples has been estimated to be as short as ten years; other samples have been predicted to last longer than triacetate base film. (Anecdotal evidence in the field demonstrates that nitrate film can outlast acetate film.) Nevertheless, nitrate stability is strongly influenced by storage conditions.

IPI's nitrate film stability studies have helped to define new storage recommendations. The most recent data based on five and a half years of sample incubations at moderately accelerated temperatures (e.g., 50°C) led IPI to recommend environments of –10°C, 20%-50% RH or 2°C, 20%-30% RH for optimizing the longevity of nitrate film in good condition.[9] These recommendations are based on experimental results such as those illustrated in Figure 7, an Arrhenius-type plot for toughness of nitrate film. These data indicate that films in condition similar to that of the one represented in Figure 7 should be undamaged after a period of at least 500 years, if kept at -10°C, 20%-50% RH. These conditions are beneficial to most nitrate film, but their effect on actively degrading nitrate film has not been quantified. IPI studies have indicated, however, that the higher the current acidity of nitrate base is, the lower its extrapolated longevity will be.[8]

Unfortunately, film acidity values are not available for the DFI nitrate collections. Because the only reliable acidity test for nitrate film is destructive, such information could not be determined during the condition survey. Although the time predictions illustrated in Figure 7 were based on the incubation of the least stable of a group of nitrate base films, that film had relatively low acidity and satisfactory toughness values and was not brittle. The results of the DFI inspection contain plenty of evidence to indicate that, as expected, chemical decay has already started. Surveyors found base discoloration and significant shrinkage; 20% of the DFI nitrate film samples also displayed brittleness. These facts and the age of the collection signify that more stringent storage conditions than those mentioned above may be required to reach DFI's preservation objectives. Based on the IPI study, an environment of -5°C, 20%-

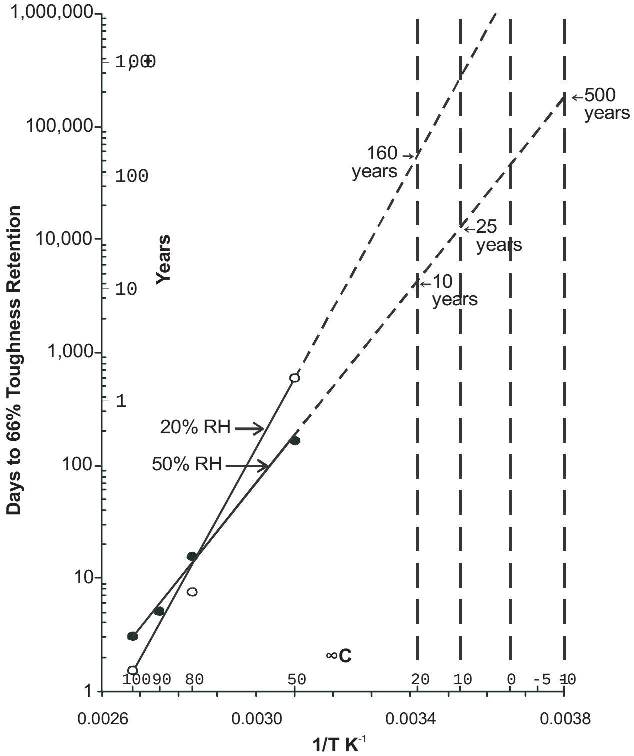


Figure 7. Arrhenius-type plot for toughness of cellulose nitrate film with acidity value of 0.1. Film samples preconditioned to 21°C and indicated RH and heated in sealed bags.

30% RH should extend the life span of the DFI collection. It is recognized that only a limited number of films were used for the IPI study; however, this is the only information of this nature that exists at the present time. Figure 7 indicates that even colder temperatures should further increase nitrate longevity, but it also must be conceded that predictions at very low temperatures cannot be considered quantitative because the extrapolations are greatly extended. However, it is believed that an environment of -5°C, 20-30% RH should meet at least the 500-year-life-span objective for the DFI collections and allows time to identify film at risk and earmark it for duplication. Based on the collection condition evaluation, IPI recommends more stringent climate conditions than those recommended in the ISO standard.[10]

Optimizing Acetate Film Stability

The condition surveys conducted on shorts and documentaries and feature film masters and prints showed that from 60% to 80% of the films have started to decay, depending on the group (see Table III). They also indicated that, for the most part, vinegar syndrome was limited to levels below the autocatalytic point (i.e., the point at which the rate of degradation increases greatly). This information is pertinent to the optimization of DFI collection longevity. The remaining useful life of acetate base material is dependent on (1) its current state of decay, and (2) climate conditions, which strongly influence the rate of further chemical deterioration. An acetate film considered to be actively degrading (A-D Strip level 2) is still duplicable and retains all of its original information. As time passes, the film reaches a critical state of decay. Soon after the film reaches this point (A-D Strip level 3), information may be lost because the film becomes damaged and difficult to duplicate due to excessive shrinkage. Recent data indicate that excessive shrinkage can be related to high acidity levels. It has also been reported that acid loss from decayed acetate film causes a significant increase of shrinkage.[11] Consequently, it is important to estimate the remaining useful life of acetate films, based on their storage conditions and their current state of preservation, as shown in Table VI. The table compares fresh film to film displaying an A-D Strip level of 1.5—that is, at the autocatalytic point_and reports rough estimates, based on accelerated-aging tests, of the times required for acetate films to achieve an acid content of 1 (A-D Strip level 2). Table VI also compares the worst and the best conditions in Bagsværd Fort (locations R and G, respectively), the conditions in the Naverland cold room, and cold storage conditions above and below freezing temperature. The time estimates in Table VI indicate that it is possible to significantly increase the life span of acetate base films that have already started to chemically decay.

	Estimated Time to Reach Acidity of 1 (A-D Strip level 2) Based on Average Temperature and RH Conditions				
	Vault R **14°C, 61%RH**	**Vault G** **6°C, 68% RH**	**Cold Room, Naverland** **5°C, 35% RH**	**Cold Storage** **2°C, 20-30 %RH**	**Storage at Subfreezing Temperature** **-5°C, 20-30%RH**
Fresh Acetate Film	75 years	190 years	500 years	>1000 years	>2000 years
Degrading Acetate Film (A-D Strip level of 1.5)	<15 years	<50 years	<200 years	<350 years	>500 years

Table VI. Estimates of time for fresh and already degrading acetate films to reach an acidity level of 1 (A-D Strip level 2) based on various storage situations.

Cold temperature markedly increases the stability of both fresh and actively degrading film. Acetate film displaying an A-D Strip level of 1.5 or below could have a useful life greater than 500 years if stored at -5°C, 20-30% RH. Based on the condition profile of the DFI collections, such an environment should extend the useful life of most of the acetate materials beyond 500 years.

DFI collection materials displaying A-D Strip levels 2 or 3 should be in limited number, according to the recent film archive survey. Once identified, however, these films in a more advanced state of decay could benefit from colder temperatures while waiting to be duplicated. Data developed at IPI indicate that the use of low temperatures (-15°C) can stop the generation of acid by degrading film (at least for six and a half years, the length of the experiment to date), while storage at room temperature (20°C) accelerates the chemical decay of acetate film base.[11,12] The discovery during this survey of a few materials in an advanced state of decay suggests that the collection may contain other individual films in a similar state of decay (A-D Strip levels 2 and 3). These materials could also be stabilized at -15°C before eventually being duplicated.

Color Dyes

The cold environments proposed above for optimizing the stability of acetate film base would also benefit the stability of color dyes. Severe dye fading was recorded during the DFI survey. This type of decay poses a major threat for the collections. Data published in the *Storage Guide for Color Photographic Materials* demonstrates that an environment of -5°C, 20-30% RH, as recommended for acetate base film, would greatly improve the stability of color dyes.

PRESERVATION STRATEGY

This project has made it possible to describe the situation faced by DFI in more concrete terms than ever before. First, DFI film collections will stay at risk for as long as they are housed in the existing storage conditions at Bagsværd. The environmental assessment conducted during the survey demonstrated that the film will continue to decay at an unacceptable rate in that location. Second, the condition survey highlighted the fact that nitrate base decay and the first stages of vinegar syndrome are affecting the DFI collections, and that some of the collections display severe dye fading. The survey results suggest that immediate duplication is already advisable for 55% of the nitrate films tested, and that most of the nitrate may have to be duplicated within the next 25 years if collections are kept in the current Bagsværd environments. The acetate film collections are in fair to good condition in terms of vinegar syndrome. However, A-D Strip testing indicated that acetate base chemical decay has already started and will progress at an unacceptable rate for as long as materials are stored at Bagsværd. Within 50 years, a portion of the acetate collections may be actively decaying, and duplication will be advisable. This situation calls for an environment-based strategy to stabilize the condition of all DFI film collections and reduce the need for a large-scale duplication program.

Storage Environments

The diversity of film materials in the DFI collections and their various states of preservation require several different special environments that address the needs of nitrate film, acetate film, and color materials. Table VII provides recommendations for storing (1) masters and prints on nitrate support, (2) masters on acetate support, (3) masters and prints in an advanced state of acetate base decay, and (4) print collections on safety base. The basis for the recommended environments of -5°C, 20-30% RH and -15°C, 20-50% RH is described above. The second set of conditions is recommended for acetate in an advanced state of decay (A-D Strip levels 2 and 3). These conditions should stabilize materials awaiting duplication.

Although prints on acetate support and in color are affected by their storage environment in the same way that master materials are, it could be argued that because they may be periodically accessed their stability will be significantly reduced. The impact of the time spent out of storage on film stability has been quantified for acetate film base and color dyes.[6,7] The data indicate that the benefits of cold storage can be drastically reduced or even cancelled out if film is frequently removed from storage. Ten days each year out of cold storage can speed dye fading by a factor of 5. Acetate base stability is similarly affected by time spent out of storage. Frequent access is also likely to promote mechanical deterioration, which reduces the life span of the prints. Based on an average of ten days spent out of storage each year, predicted times to reach 30% dye fading would be similar whether using an environment of -5°C, 20%-30% RH or 5°C, 20%-30% RH. Therefore, an environment like the current one in the cold room at Naverland 5°C, 35% RH is a reasonable compromise. The management of the prints collection should include regular testing for vinegar syndrome and color dye fading in order to monitor the condition of the collection over time and identify the prints in need of reprinting or duplicating.

DFI's requirements for preservation and access call for several new climate-controlled storage spaces as indicated in Table VII. Important aspects such as temperature tolerances, allowable temperature and RH fluctuations, monitoring of environmental conditions, impact of time out of special storage, and cold-storage handling practices were discussed in IPI's project report to DFI and in other publications.[1,9, 13]

Materials	Recommended Environments
Masters and prints on nitrate support	-5°C, 20-30% RH
Masters on acetate support	-5°C, 20-30% RH
Masters or prints in advanced state of decay (A-D Strip levels 2 and 3)	-15°C, 20-50% RH
Print collections on acetate support and color films	5°C, 35% RH

Table VII. Environments recommended for DFI's film collections.

Minimizing the Risk of Contamination

The potential for contamination of fresh films by already degrading films is a recurrent concern for film archivists. Since it was discovered that the decay process has started in the DFI collections, it seemed prudent to monitor the air quality. Air contamination by degrading film is an even greater concern when 100% of the air is recirculated inside the storage space with no air filtration to reduce the concentration of any acidic vapors. This is the case in the Naverland cold room. Laboratory testing conducted at IPI has indicated that there is a relationship between A-D Strip levels and the concentration of acidic vapors in the air. Table VIII shows this relationship. Air quality was evaluated by exposing A-D Strips throughout the Naverland cold room three weeks prior to color evaluation. None of the strips displayed a color change. Based on this observation, we can assume that the quality of the air inside the room is satisfactory and the risk of contamination is low. Similar tests conducted in other facilities have indicated that acetate collections in good to fair condition (A-D Strip levels 0 and 1) stored at cold temperatures do not cause the presence of high concentrations of degradation byproducts in the air. However, it is advisable to include the possibility for air-quality control in planning a new storage facility. Once actively degrading films (A-D Strip levels 2 and 3) have been identified, they can be isolated either by placing them in sealed microclimates (using molecular sieves inside the environments is an option) or by moving them to a separate storage space. Nevertheless, an environment of -15°C, 20%-50% RH must also be provided in order to stabilize decaying materials.

A-D Strip Levels	Acetic Acid (ppm)
1	1 to 2
1.5	3 to 5
2	6 to 8
2.5	18 to 20

Table VIII. A-D Strip levels as they relate to the concentration of acetic acid vapor in the air, in ppm. Relationship defined in laboratory by estimating the concentration of acetic acid inside pouches containing films at various stages of degradation using both Draeger diffusion tubes and A-D Strips. Tests were conducted at temperatures ranging from 0°C to 5°C.

Monitoring the Condition of Acetate Film Collections

Because the decay process is autocatalytic (see Figure 6), assessing the condition of acetate base collections is often recommended. Once vinegar syndrome has begun, further decay will occur at an ever-faster rate. For this reason, rechecking the collection condition using the same testing method is advisable. When film is stored at cold temperatures, significant changes in film condition should be extremely slow; therefore, it should not be necessary to recheck the collection any more often than every 25 years or so. If acetate masters are stored at -5°C, 20-30% RH or colder, condition reassessment with A-D Strips will not likely indicate any significant changes for many decades.

This may not be the case for frequently accessed materials, however. The DFI prints collection is frequently accessed. While this may negatively affect its longevity, each accession may also be regarded as an opportunity. As discussed earlier, the useful life of film materials is reduced by the amount of time they spend out of cold storage. However, accessing the materials provides the opportunity to routinely evaluate their physical and chemical condition. It is recommended that, when accessed, acetate films be tested with A-D Strips and that color films be evaluated for dye fading. Done routinely, this continuing condition evaluation would benefit the collections by identifying individual acetate films that are close to or already in critical condition (A-D Strip testing levels 2 or 3). This approach is suggested here because, over the years, it would produce an overview of the evolution of collection condition and might help to isolate individual items in trouble. Recommended minimum exposure times for A-D Strip testing are reported in Table IX for the recommended cold environments as well as for room temperature. No matter how often the collections are periodically tested, condition survey results should be used to target groups of materials that may eventually benefit from further testing.

Temperature	Minimum Exposure Time
Room	24 hours
5°C	3 weeks
-5°C	6 weeks

Table IX. Recommended minimum exposure times for A-D Strips, based on temperature in testing area and moderate RH from 30% to 50% RH.

Prioritizing Acetate Film for Duplication

Duplication has been an essential part of preserving motion-picture film collections for many years. The cost of duplication is high, however, and it has been demonstrated that storage at subfreezing temperatures is an efficient approach to stabilizing films.[11,12] It is also true that the more advanced the chemical decay is, the more likely it is that the film is approaching the end of its useful life. Recent data indicate the correlation between acid content in the film and the risk of excessive shrinkage that may further compromise the possibility for duplication.[11] Therefore, periodic A-D Strip testing should be done to identify individual films or pockets of films within large collections that are most at risk. These would be films that indicate A-D Strip levels 2 and 3. Such films should be stored in an environment of -15°C, 20%-50% RH while waiting for duplication. Using this approach, the films in the worst condition can be identified and duplicated first.

CONCLUSION

Both the inadequacy of the existing storage facility at Bagsværd Fort and the dependence on low storage temperatures for maximizing photographic film stability led to a strategic plan for a new DFI film archive that includes several special environments. The plan was developed to respond specifically to the critical situation faced by the Danish Film Institute. It is believed, however, that the methodology developed during this project can be used to address the concerns of any film archives.

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