IPI's Climate Notebook® Software for Environmental Analysis

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Abstract

Storage conditions play a critical role in determining the useful lifetime of electronic media and more traditional forms of information storage. Successful management of storage environments requires that the effects of temperature and RH conditions on the decay of collections be understood and controlled. The Image Permanence Institute (IPI) has developed algorithms that provide quantitative measures of the risk of three important kinds of decay: mold, dimensional change, and natural aging (spontaneous chemical change in organic objects). These algorithms operate on T and RH readings made over a period of time and provide integrated, single-value metrics of the "preservation quality" of a particular storage environment. IPI has incorporated the algorithms into a software product known as Climate Notebook®. This software is now in use in hundreds of museums and libraries worldwide. The approach has proven to be both practical and useful as a planning and evaluation tool for storage facilities.

Introduction

The useful life of all forms of information-recoding media is affected by storage conditions, especially temperature and relative humidity (RH).[1] For photographic prints, films, magnetic tape, CDs and DVDs environmental requirements for extended term keeping are specified in a number of ISO Standards.[2] Traditional archiving media such as paper, books, parchment, and papyrus are also very sensitive to storage conditions.[3] While there are a number of factors that can be included in a broad concept of storage environment, this paper deals only with temperature and RH. Light, air pollution, radiation, and vibration—when they are present—are important and deserving of attention. However, temperature and RH are usually the most fundamental factors to consider in environmental management. They are *always* present, they have far-reaching effects by themselves, and they act as enablers (or inhibitors) of damage by other factors such as light or pollutants.[4]

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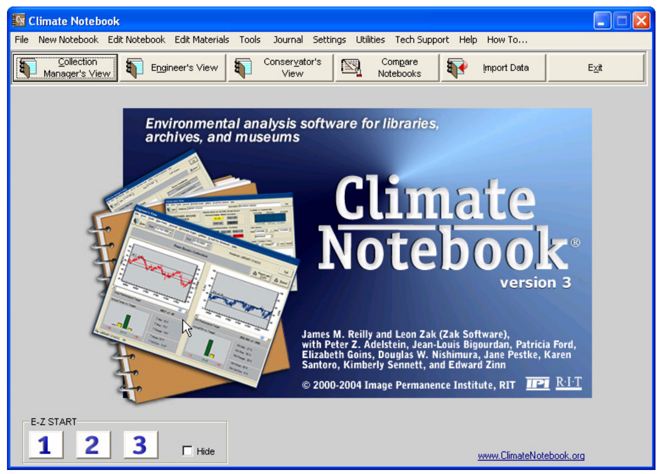

Figure 1. Main Screen of Climate Notebook software.

The issues and challenges involved in assessing and managing the storage climate for information media are similar to those for cultural property in general. The tasks break down into three areas: Data gathering, data analysis, and remedial action (if necessary). This paper is concerned with tools and approaches for data analysis. The tool described is an application software program for the MS Windows® operating system known as Climate Notebook. This software was created by the Image Permanence Institute with funding from the Division of Preservation and Access of the National Endowment for the Humanities, the Institute of Museum and Library Services, and from the Andrew W. Mellon Foundation. The analysis approaches developed by the Image Permanence Institute can be described as *performance-based* environmental assessment. Traditional approaches are based on maintaining specific targets for temperature and RH. Performance-based analysis deals with numerical estimates of the risks or benefits associated with a set of environmental conditions. Performance-based metrics quantify the effect of environmental conditions on promoting or retarding general modes of collection decay such as chemical change, mold growth, and physical changes. The analyst must know the nature of the objects stored in the environment in order to determine which types of decay—and therefore which of the performance-based metrics—are relevant to any given set of data.

Working with Environmental Data

In archival management, continuous monitoring is necessary. Building a permanent infrastructure of data gathering for ongoing environmental analysis is essential for an institution to care for its collections in a professional manner. It is the only way to ensure that the rate of collection decay is as slow as it can be, and that the investment in capital and operating costs for air conditioning is yielding a reasonable return. There are many ways to obtain the temperature and RH data. The most common sources are building automation computer systems and standalone dataloggers. Regardless of the origin of the data, there are certain practical considerations that make the analysis task difficult. One is the fact that environmental monitoring generates large quantities of data. Each location, if sampled for temperature and RH at half-hour intervals, generates 35,064 individual data points per year. The correct sampling interval for T and RH measurements is one that captures significant environmental events but does not slow down the analysis process with unnecessary repetition of similar readings. A common mistake among novice analysts is to set sampling intervals as short as one or two minutes, in the belief that more data is more information and better to be safe than sorry. The result is much wasted time waiting for data transfers, graphs to appear, etc. In all but the rarest cases, sampling intervals of 30 minutes to several hours capture the environmental events that are meaningful in collections preservation.

In larger institutions there often are dozens or even hundreds of monitoring locations. Simply to organize and manipulate such large data sets requires considerable effort. With a few exceptions, the software sold with building automation systems or standalone dataloggers was not designed for managing a continuous monitoring effort for multiple locations. IPI's Climate Notebook software includes a number of features that help organize and visualize large quantities of data from multiple locations. Rather than have a number of separate files containing data from a single location, Climate Notebook keeps all the data together in one file called a *notebook* file. The notebook file also holds information about the location, including a list object types stored there, location and logger descriptions, and target T and RH values. Climate Notebook also allows the user to define saved lists of locations that can be analyzed and viewed together. This feature is useful when a number of locations share similar collection contents, air handling systems, or geographic proximity. Reports and summaries can be constructed to reflect the administrative or physical relationships among locations.

Visualization and Basic Analysis

Basic analysis of environmental data deals with the raw temperature and RH readings. It can include tables of raw data, visualization of the data using graphs, and descriptive statistics such as mean, minimum, maximum, range, and standard deviation. Basic analysis can also include various methods for determining and visualizing when T and RH values exceed pre-established target limits, and by how much. Software tools for many of these basic analysis tasks are built into proprietary datalogger software or building management systems. Such analysis can also be done with general-purpose spreadsheet programs such as MS Excel® or with a variety of other statistical analysis software products.

IPI's Climate Notebook software offers very advanced capabilities for basic data analysis (all of the above-mentioned methods plus more), and also incorporates a number of features such as customizable default axis scaling and a powerful interface for manipulating time scales. Graphical presentations of data can efficiently communicate variations in magnitude, but they also can make small differences seem large and large differences seem small, depending on the axis scaling. This is a particularly difficult issue in analysis of environmental data because there is almost an automatic assumption that flat lines on graphs indicate a good environment for collection storage. Doubly incorrect analysis results when the easily seen variations (or lack of them) are taken as the primary indicator of preservation quality and when variations are either artificially enlarged or suppressed by inappropriate axis scaling on the graph.

Each of the three basic analysis techniques (graphs of T and RH, descriptive statistics, and comparisons to target values) are useful, and can—in certain limited situations—provide all the analysis necessary for determining what is right or wrong with a storage environment. The value of basic analysis is greatest in circumstances where there is a very clear and well-established sense of what the environmental conditions *should be*. Basic analysis is typically all that is needed for building operators and facilities managers. They have been given target values, and graphs and statistics tell them whether the targets are being met. When the targets are not met, they will have to adjust operating parameters or obtain new equipment.

From the preservation manager's perspective, basic analysis is less helpful because he or she is concerned not so much with whether the observed conditions stay within pre-defined targets, but with the impact of those conditions on the preservation or deterioration of collections. Deterioration mechanisms and their interactions with heat and moisture are complex and dynamic. Operating targets are simple and static. If the operating targets have been established through a process where the object-specific deterioration mechanisms have been understood and factored into an optimized set of desirable conditions, then the simple shorthand of basic analysis techniques may be sufficient. Unfortunately, such a thoughtful pedigree for operating norms is often assumed but seldom exists. More often than not, collections are diverse and targets (if they exist at all) have been set based on incomplete, incorrect, or outdated information "handed down" to facilities managers and preservation staff. In many institutions the operating norms have much more to do with human comfort complaints than the needs of collections.

Ironically, any attempt to go beyond a target-based analysis immediately places the analyst outside the realm of "facts" and into the murky world of "opinions," where any interpretation of conditions seems subjective and insubstantial compared to the weight of agreed-upon norms and long-established patterns. No wonder institute-ions do comparatively little environmental monitoring, despite the advent of much better data gathering technology—they simply lack the ability to draw meaningful conclusions from the data they collect. When conditions depart from target values they are unable to determine the degree of risk that results. They have no means to evaluate the preservation impact of conditions either in relative or absolute terms.

Performance-Based Environmental Analysis

The preservation manager needs analytical tools that can evaluate the quality of storage and display conditions in terms that are quantitative and directly related to the preservation or deterioration of collections. The Image Permanence Institute has been working for more than a decade to develop and refine such methods,[5,6] and incorporate them into its Climate Notebook software program. It has developed three generic analysis methods that relate to chemical change, mold growth, and dimensional change in organic objects. Table 1 gives an overview of the three main analytical approaches. The numerical metrics based on these approaches have a valuable role in both evaluating existing spaces and planning new ones. These metrics allow preservation specialists to specify the desired performance characteristics of new construction without limiting the options of architects and engineers or trying to second-guess how they might best be achieved.

The chief advantage of these metrics for "preservation quality" is that they allow for active management of storage conditions. Each of them yields numerical and continuous values by which both absolute and relative risks and benefits can be judged. Each refers to a specific type of deterioration and measures the combined effects of temperature and RH over time. To use the metrics in practice, it is best to monitor conditions for one full calendar year because the most important influences on environmental quality are seasonal. Analysis can be skewed if, for example, the data set has two summers and only one winter. It doesn't matter when during the calendar year the analysis begins or ends.

Once the Climate Notebook software has analyzed the data and calculated the metrics, the interpretation of them requires some additional information concerning the collection objects stored there. One needs to know what forms of deterioration are significant for the kinds of materials actually present in the environment (refer to the "Deterioration Problem Addressed" column of Table 1). For a research library collection, all three metrics are significant but the most important is Time-Weighted Preservation Index (TWPI) because it addresses environmental effects on the spontaneous chemical reactions that underlie the discoloration and weakening of paper. TWPI would also be the most important metric for color photograph collections because dye fading is a spontaneous chemical process whose rate depends on temperature and moisture content.

Table 1. Performance-Based Environmental Metrics

Analysis Method	Deterioration Problem Addressed	Basis for Analysis	Algorithm
Time-Weighted Preservation Index (TWPI)	Spontaneous chemical change leading to fading, embrittlement, yellowing	Generalized treatment of decay reaction kinetics	Integrates over time, weighting each time interval according to reaction rate
Mold Risk Factor (MRF)	Mold growth	Based on empirical studies of mold germination on food grains	Integrates over time, creates running sum of progress toward mold germination
Dimensional Change Metrics	Physical damage due to moisture absorption or desorption	Based on physical behavior of wood of "average species"	Estimates moisture content and dimensional changes over time

On the other hand, TWPI would *not* be significant for a collection of oak furniture because spontaneous chemical change (which occurs in oak as it does in all organic materials) would take many centuries to become a threat to the integrity of the object. Much more immediate for oak furniture is the threat arising from physical changes due to absorption and desorption of water. These can lead to warping, delamination of veneers, cracking and splitting. Thus the dimensional change metrics would be of much greater interest with a collection of furniture than it would with a collection of color slides. In all cases, it is necessary to know the general nature of the collections and their principal vulnerabilities in order to make good environmental assessments using the IPI metrics.

The performance-based environmental metrics incorporated into Climate Notebook cover natural aging (spontaneous chemical change), mold growth, and moisture-related dimensional changes in organic objects. While these are often very important considerations in preservation of collections, there are a number of other environmentally-induced deterioration processes for which quantitative metrics do not yet exist. Deterioration of metal objects through metallic corrosion is one example. However, field experience in more than 200 institutions has shown that performance-based assessment does provide insights that can be used to improve collection longevity and guide efforts to operate air conditioning systems more efficiently.

Time-Weighted Preservation Index (TWPI)

The TWPI metric is a generalized model of the kinetics of spontaneous chemical change in organic materials. It measures the combined effect of temperature and RH over time on the overall rate of natural aging. In recent years, a number of authors have discussed approaches to environmental assessment and preservation management from the point of view of a general treatment of decay reaction kinetics.[7] Sebera[8] was the first to describe how collection life, temperature, and RH could be inter-related using a kinetics model based solely on theory and assumptions about the likely activation energies of decay reactions. Others have combined models of chemical kinetics and physical behavior to define storage conditions.[9]

IPI's TWPI algorithm, published in 1995, is based on two key ideas: First, that the activation energies of decay reactions in organic materials are normally distributed, and hence the temperature dependence of decay reactions has a "sweet spot" at the mode of the normal distribution—this allows a general model to cover the behavior of most kinds of organic objects. Second, that an entire span of time can be broken into shorter intervals, the rate of reaction determined for that interval, and then all intervals can be combined into a single overall value that properly "weights" each interval to determine the overall average. Mark McCormick-Goodhart of the Smithsonian Institution was the first person to show how this could be done.[10] TWPI values have units of years and range from 1 to 9999. TWPI is a pseudo-lifetime, so a higher value means a longer life for collections. The annual TWPI of a typical office air-conditioned space is 50. A poor environment (an uncontrolled warehouse in St. Louis, for example) might have an annual TWPI of 20. The off-site library storage facilities recently constructed by the Library of Congress, Harvard University, and others have TWPI values greater than 200 years. To interpret TWPI values, first determine if the collection is at significant risk from fast chemical change. If so, a high TWPI is needed. Then consider the measured TWPI from the storage space, and act accordingly.

Mold Risk Factor (MRF)

The Mold Risk metric is based on published empirical studies of the effects of temperature and RH conditions on the germination of mold spores[11,12,13]. The studies were done on food grains inoculated with spores of common xerophilic mold species such as those in the *aspergillus* and *penicillium* genera. Food grains offer a very nutrient-rich substrate for mold, so modeling based on such studies presents a kind of worst case scenario in the sense that mold growth on less favorable substrates is not likely to occur any faster than it did on grain. Starting with the empirical data, IPI created a three-dimensional surface relating time to germination, temperature, and RH. From that surface a lookup table was constructed that contains germination times for any combination of temperature and RH. The algorithm for calculating Mold Risk takes each interval of time in the data set, looks up how long it would take for mold spores to germinate at those conditions (if in fact it ever would), and then calculates how much progress toward germination was made during that interval. For example, if during the first hour the conditions are such that mold would require 100 days to germinate, then during that hour the progress toward germination would be 1/100th times $1/24^{th}$, or = $1/2400^{th}$. The running sum from such calculations is the Mold Risk Factor (MRF). When the sum reaches 1.0, the model says that spores will have germinated and the mold is now in the active vegetative state.

The model further assumes that the conditions which favor progress of spores toward germination are approximately the same conditions that would sustain mold in the active vegetative state. So as long as conditions do not become unfavorable (dry out or get too warm or cold), the running sum continues to accumulate past 1.0. The higher the MRF goes, the more severe the mold outbreak is likely to be. When conditions do become unfavorable for 24 straight hours, the model assumes that the vegetative mold is no longer viable and the process "resets" again from spores. The MRF model is a simplified one that does not take into account such factors as pH of the substrate, light and air flow effects, and other known influences on the rate of mold growth. However, it is much superior to rules of thumb like "mold grows above 65% RH" because it can give warning of approaching mold problems before they become serious and can quantify the severity of the situation. Interpreting MRF values is relatively easy; the desired value is zero, indicating no chance for mold to grow. Values approaching 1.0 indicate a threat that merits action. When MRF values are 5 or greater, actively growing mold and consequent damage to collections is very likely. To put MRF values in some perspective, typical outdoor conditions have an annual MRF of 0.66 in Las Vegas, Nevada, while the MRF for Key west, Florida, is 12.94.

Dimensional Change Metrics

One of the most complex challenges for preservation managers is estimating the risk of physical damage caused by too high, too low, or too rapidly changing moisture content in collection objects. Organic materials such as wood, leather, paper, parchment, and plastics all absorb moisture to some degree. At low moisture contents these materials tend to contract and come become brittle, while at high moisture contents they tend to expand and become more flexible. Permanent damage results when dimensional changes cause tensile or compressive stresses to develop within the object, leading to cracks, tears, delamination, warping, sagging, or other kinds of deterioration. Recognition of this fact is the basis for the widely held perception that a good environment is a one with unvarying RH. While a steady RH does guarantee an unvarying equilibrium moisture content (EMC) for the objects, that alone does not prevent physical damage to the collections. One must also consider whether the EMC is too high or too low. Moreover, there is no special value to a steady RH condition in preventing chemical or biological deterioration. Much important research has been done in recent years by a team of scientists at the Smithsonian Institution to clarify the conditions under which susceptible objects (oil paintings, for example) are relatively safe from mechanical damage.[14]

In storage rooms and open spaces the amount of moisture contained in objects is determined by the relative humidity of the air. However, it usually takes some time—more than most people would imagine—for objects to attain full moisture equilibrium with their surroundings. It is especially important in this aspect of environmental assessment to consider moisture equilibrium relationships. The outer surfaces of objects are the first to "feel" a change in ambient RH. Moisture moves by diffusion into or out of the object to establish a new equilibrium condition. For books on a shelf or motion picture film on a reel this process takes three to six weeks to attain full equilibrium. Some objects take less time, others take more.[15] Climate Notebook allows the user to adjust the calculations relating to dimensional change to compensate for varying moisture equilibration times. The default is 30 days, which should be adequate for most collection objects.

Because there are a number of aspects to consider in assessing the risk of environmentally-induced dimensional changes, Climate Notebook uses five different numerical metrics, all of which are based on a simple idea: The behavior of a virtual (imaginary) block of wood. The metrics yield estimates of the equilibrium moisture content and dimensional changes that would be experienced by a transversely-sawn piece of wood of average species if it were stored in the environment where the T and RH data were gathered. By calculating what happens to the imaginary block of wood, the analyst can by inference estimate the effects of the conditions on other moisture-absorbing materials such as paper, leather, and parchment. The U.S. Forest Products Laboratory has published an equation that relates RH to equilibrium moisture content for wood of average species.[16] They also published an equation to determine % dimensional change from original size as a function of EMC. These equations were successfully used by Kosciewicz-Flemming and Pearce to model the behavior of cracks in a wooden cupboard door in a 17th-century Scottish building.[17] Climate Notebook uses the Forest Products Lab equations to derive numerical estimates of moisture content (Min, Max, and avg. EMC) and Dimensional Change (% DC Max, and Dimensional Change Index).

To use these metrics in practice, one needs to know the degree of vulnerability collections objects have to physical (mechanical) damage. For example, a rare book collection typically has high vulnerability due to the presence of vellum-covered wooden board bindings, and vellum leaves in loose or bound volumes. In such a case the analyst will consider all five dimensional change metrics, but especially important are the maximum % dimensional change and the minimum and maximum EMC estimates. The former is calculated by taking the difference between the most expanded state and the most contracted state and expressing that range as a percent of original size. The larger this value becomes, the greater the risk of object damage. Values of 1% or so are fairly representative of controlled conditions, while values greater than 2.5% suggest a dangerous degree of dimensional change. The Dimensional Change Index (DCI) metric indicates the RMS average (a kind of standard deviation) of dimensional change. The minimum and maximum EMC estimates are often very helpful in assessing environmentally-induced physical risks because they readily indicate situations where the risk arises from excessive dryness, dampness, or both.

Conclusion

IPI's Climate Notebook software has been proven through field testing and is now for sale to the public and in use in hundreds of institutions worldwide. Users report that it allows them to understand and manage storage environments in ways that have heretofore not been possible. It was created through a team effort among IPI staff and contractors. The algorithms and approaches were devised and implemented by this team, with special contributions from Leon Zak, Douglas Nishimura, Edward Zinn, Jean-Louis Bigourdan, Karen Santoro, Kim Sennett, Patti Ford, and James Reilly. The support of the Division of Preservation and Access, National Endowment for the Humanities, the Andrew W. Mellon Foundation, and the Institutue of Museum and Library Services is gratefully acknowledged. For more information about Climate Notebook, visit www.climatenotebook.org and www.imagepermanence institute.com.

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Biography

James M. Reilly, Director of Image Permanence Institute and professor in the Rochester Institute of Technology College of Imaging Arts and Sciences, graduated with a B. A. from Franklin and Marshall College in 1968 and an M. A. from the State University of New York at Buffalo in 1972. He continued his education in science at the Rochester Institute of Technology. He is well known for his research on the deterioration of nineteenth-century photographic prints, the effectiveness of storage enclosures for imaging materials, the major causes of image deterioration, and optimizing conditions in storage vaults. He is author of numerous publications, including Care and Identification of 19th-Century Photographic Prints, IPI Storage Guide for Acetate Film, and Storage Guide for Color Photographic Materials. He is a consultant to many museums and government agencies and is sought after worldwide as a teacher and seminar speaker. He is a member of IS&T.