APPLYING SCIENCE TO THE QUESTION OF MUSEUM CLIMATE

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ABSTRACT

An examination of the history and development of recommendations for the climate in museums reveals that there was minimal scientific support for the values and ranges that were selected. The small basis of research that existed was often extended to materials or objects to which it did not apply; decisions that were merely best guesses based on minimal evidence became set in stone; and the rationale for many decisions seems to have been forgotten or twisted around. Many recommendations were based on considerations other than permanence of the objects, such as mechanical limitations of HVAC systems, constraints imposed by the exterior climate or historic building regulations, or costs of implementation and maintenance. It is only relatively recently that research has provided a general scientific basis for determining appropriate values for the museum climate, especially the range in which temperature and relative humidity can be safely allowed to vary. Because the results of this research differed from what had become climatic dogma, it was criticized by some in the field. However, the results have stood up, with no substantive challenge to the data or conclusions, and are increasingly widely accepted.

THE NEED FOR ENVIRONMENTAL CONTROL IN MUSEUMS

The preservation of collections depends upon knowing how the materials and objects in the collection behave and how the environmental influences acting on them can be controlled to maximize their lifespan and chance of survival. Some aspects of preservation are obvious: fire, flood, pollution and earthquakes will damage or destroy most collections. It is obvious that such threats should be controlled, eliminated or minimized to the extent possible. Damage due to light and inappropriate values or ranges of temperature and relative humidity (RH) is often much slower and less dramatic, but nonetheless is also a serious problem. Light cannot simply be eliminated, since light is required to view objects and allow people to move about safely. The amount and type of radiation to which susceptible collections are exposed should be limited to the minimum amount and spectral range of visible light required to view an object. This is difficult to put into practice because of the variability in human vision, and the wide ranges of colour, contrast, and texture of objects, as well as sources of light. The determination of appropriate ranges of temperature and relative humidity (RH) is infinitely more complex still. Many more types of effects have to be considered since different materials may have quite different responses to specific values of, or changes in, temperature and RH. Climates that are appropriate for one type of material or object may be damaging for others. Both short term effects and long term aging processes must be taken into account. The maintenance of specific museum climates in general is an active, expensive, and time-consuming responsibility. An appropriate climate will contribute to the permanence of a collection, but maintaining a climate chosen on the basis of incorrect or incomplete information may be both damaging and wasteful of money and energy. This paper will examine the history of the museum environment, the ways in which museum climates have been chosen, the development of knowledge of how and why objects deteriorate, and how the present body of knowledge is being used in the determination of appropriate environments.

THE DEVELOPMENT OF MUSEUM CLIMATE SPECIFICATIONS

Objects originally were exposed to the same climate as humans. Aside from limited heating from fireplaces, it was neither technologically nor economically feasible to control the interior climate or do much more than store valuable objects in boxes or cases. The advent of industrial technology, central heating, and eventually air conditioning and humidity control made it possible to modify or produce interior environments that were either more uniform than, or different from, the exterior. Central heating without humidification, for example, was able to produce relative humidities lower than would have previously been experienced in interior living spaces. Extremely low RH can cause problems including the flaking of paintings, cracking and warping of wood, and loosening of furniture joints. While water washing of airflow systems was originally developed to remove dust and pollutants, it was recognized that it could also be used to control the RH and reduce problems associated with unhumidified central heating. The Boston Museum of Fine Arts installed

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a central heating, air washing, and humidification system in 1908, and after 2 years "found that the humidity best adapted for paintings and other works of art ranged from 55 to 60 percent" [1]. McCabe provided no information on any tests or results that led to this range, but the statement was highly influential in the development of environmental control in museums. The range appears frequently in subsequent recommendations, usually with no specifics as to how it was derived. Recommended temperatures varied, but were generally lower than would be considered today, and were often determined by the capacity of the heating systems. Then as now, though, any temperature recommended for the general museum climate had to be within the human comfort zone. The development of improved air conditioning systems led to its installation in a dozen museums in the US by 1941, including the National Archives and the Library of Congress [2].

The next major development occurred during World War II. During the war, the collections of the National Gallery in London were moved to caves in slate quarries in Wales. The natural conditions in the caves were cool and constant, but close to 100% RH. Such a high RH would have resulted in damage (mould, if nothing else), so simple heating was used to lower the RH. The target value chosen was 58%- the average RH in the National Gallery, as determined earlier by monitoring the weight of blocks of wood left for several months in the Gallery. Their average weight corresponded to the equilibrium moisture content at 55-60% RH [3]. The observation that flaking of the paintings stopped during storage in the constant environment of the caves was the primary impetus for the installation of air conditioning in the Gallery after the war. Interestingly, the specific RH chosen at the time for paintings (and, indeed, other objects in the collection as well as the library) was based on measurements of blocks of wood in the average RH in London, not on any research indicating that paintings were most stable or permanent under the chosen conditions. The conditions simply replicated the average RH in London, without the variations. In the absence of data to recommend any other climate, replicating the Gallery climate was less risky than choosing different conditions. However, there was nothing to show that these specific conditions or such narrow ranges were required or optimal, or that other conditions could not have been as, or more effective in reducing damage. The only real conclusion that could be drawn was that the quarry conditions were much better than the uncontrolled, greatly variable conditions of the un-airconditioned Gallery before the war. In part because of these results, the value of climate control in museums rapidly gained acceptance, and was often implemented using similar values. In 1960, the results of a survey of museums indicated a preferred range of RH values ranging from 40% to 70% RH, most within or overlapping the 50-60% range [4]. In the article, Plenderleith advocates a "zone of safety" of 50 to 60% RH, with 50% the lower limit to avoid dangerous desiccation (such as the supposed embrittlement of parchment) and 60% the upper limit to avoid mould growth. Plenderleith previously had used data on the seasoning of timber to argue for the 50% lower limit [5]. Again, little real data (such as data on the RH dependence of the stiffness of parchment) is presented to justify the various values in the survey or elsewhere. Even the statements that were made, such as those assuming embrittlement of organic materials below 50% RH, often had no basis in experiment. Practicality is evident in some cases. It is difficult and expensive to maintain high RH in winter in cold climates, and even if it can be achieved, condensation in the roof and exterior walls can cause serious damage to the building. Lower values of RH (as low as 25% in winter) eventually were adopted in the northern US and Canada, not because they were shown to be safe for collections, but because maintaining higher values in winter was difficult or impossible. This relates to the common belief that values other than the usual ones are OK if objects are "used to it", again with little real justification. (It should be noted here that most of the discussion relating to appropriate RH focuses on organic materials, since appropriate values of RH for inorganic materials are better defined and less controversial. There are some exceptions, such as weeping glass and ceramics containing deliquescent salts, for which appropriate environments are yet to be determined.)

The culmination of this process was the publication of *The Museum Environment* [6] by Garry Thomson of the Scientific Department of the National Gallery, London. To a greater extent than any previous publication, *The Museum Environment* examined the available scientific evidence and made an attempt to derive appropriate values and allowable ranges, rather than simply draw conclusions based on vague, unsupported, or questionable statements. Thomson, evidently more than anyone else, was aware of the lack of relevant knowledge, and qualifies many of his statements. While he does recommend taking into account the type of collection and local climate when determining what conditions to maintain, his recommendation for typical museums was 55% RH. The value of 55% RH was chosen to a great extent because it is the midpoint of what he considered a safety zone between 40%

RH (embrittlement) and 70% RH (mould growth), rather than because of any evidence indicating that 55% RH is an optimal value. (Later research by the present authors showed that the common perception that organic materials embrittle below 40% RH has little basis in fact). There was plenty of evidence that extremes of relative humidity cause damage, but little to indicate how much the climate could be allowed to vary without causing damage. Thomson suspected that there was a threshold variation below which damage did not occur, but not enough information to determine what the threshold range was. He qualifies his recommendations by stating quite explicitly: "The tolerance usually quoted of ±4 or 5% RH is based more on what can be expected of an air-conditioning plant than on what exhibits can actually stand without deterioration, which is not known in any detail." In other words, RH control was based on what was possible, not what was required, simply because at the time it was not known how closely the RH had to be controlled to eliminate damage. The threshold limit of fluctuation below which damage did not occur had not been determined, so the least risky course (at least in terms of the safety of the objects) was to control the RH as tightly as possible. An obvious implication is that when information regarding allowable fluctuations becomes available, these values should be reconsidered. Unfortunately, Thomson's book seems to have been quoted (or misquoted) more often than it has been read or understood. When asked why the RH has to be maintained within ±4 or 5% RH, a typical response is that *The Museum Environment* says that is what is required to keep the objects from falling apart.

Thus, while there had certainly been serious attempts to determine the effects of climate on museum objects, the climate specifications typically used in museums for temperature, RH, and allowable RH fluctuation ultimately seem to derive from three basic bits of data- the human temperature comfort zone; the average RH in the National Gallery, London, as determined by weighing blocks of wood; and the practical mechanical limitations on RH control in museums. The climate recommendations thus "derived" have since been extended, solidified, and modified with little more justification. The temperature values are probably the least controversial, since for practical reasons general exhibit spaces must be maintained within the human comfort range regardless of any effect on permanence. Storage is a different matter, and beyond the scope of this article. There is little evidence that 55% RH is optimal for blocks of wood, and no more evidence for the extension of this value to paint, paper, parchment, textiles, photographs, bone, etc. As Thomson stated, his specified variations of ±4% or 5% RH were determined by mechanical limitations. Predictably, the incorrect interpretation "more constant is better" has led to the philosophy that if ±5% is good, then ±2% is better- or at least it won't hurt. Never mind that maintaining such narrow ranges is expensive and impractical if not impossible, and standard methods of measurement of RH have uncertainties greater than the specified ranges [7].

REQUIREMENTS FOR CONTROL OF THE MUSEUM CLIMATE

There are three fundamental steps in controlling the museum climate:

1. Determine the effects of the environment on materials and objects.
2. Set specifications based on the results of Step 1, taking into account the type of collection, the building and the local climate and economics.
3. Maintain and monitor the environment based on the results of Step 2.

Unfortunately, there has been a lot more effort put into Steps 2 and 3 than Step 1. Thomson acknowledged as much when he said "…we have to erect this framework of preventive conservation before rather than after our research has reached a dignified level of completion." [6]. Specifying climate control requirements and telling the engineers to implement them is easier by orders of magnitude than the research required to justify the specifications. Monitoring the environment is also straightforward, and with modern sensors, data logging equipment and computer processing has become routine. The hard part of Step 3 is the implementation of climate specifications. This is especially true when they are too strict, ignore factors such as local climate, can potentially damage the building, or their implementation is too expensive in terms of equipment, personnel, energy, repair and maintenance.

One of the first indications that physical damage to museum objects due to environmental effects might be quantifiable and predictable was a paper presented at the 1982 meeting of the IIC. In it, the engineering concept of finite element analysis (FEA) was shown to be applicable to the complex layered structures of paintings, and to predict patterns of damage that matched observed damage [8]. One of the authors, Marion Mecklenburg, later joined the Conservation Analytical Laboratory (CAL, later SCMRE, at present MCI) of the Smithsonian Institution, where complementary environmental research was proceeding.

The first indication that research was being conducted at the CAL that could lead to rational and justified specifications for the museum climate was a lecture presented at a national meeting of the American Chemical Society [9]. In this presentation, the effects of specific environments, as well as changes in environments, on different types of materials of museum objects were discussed. Topics included changes in reaction rates, critical values of RH, and changes in dimension and physical and mechanical properties for various types of materials. The critical remaining problem, though, was the determination of allowable limits of variation in the environment. Other papers followed, expanding on the theme of determining environmental effects on the chemical, physical, and mechanical properties of the materials of museum objects, and applying this data to predict the behavior of complex objects [10-16]. Research was conducted on the effect of temperature and relative humidity on important degradation processes, and tests conducted to determine the physical response of a wide variety of materials to changes in temperature and relative humidity. The effects of aging processes (chemical reactions) on physical properties and responses were also examined. Extensive experimentation showed that tensile tests and dimensional temperature and moisture isotherms were related to the changes in restrained materials subject to changes in temperature and RH (the museum path), and could be used in predictive modeling using FEA [17]. In other words, measurements of the dimensional response of individual materials to environmental changes can be combined with the results of standard mechanical testing to predict stresses and strains induced in composite objects by environmental changes. Computer modeling approaches were developed that could take the data for individual materials and predict the behavior of composite objects. Most importantly, these models could predict when changes in a component of an object exceeded the elastic (reversible) limits. All materials can reversibly sustain some stress and strain, and it is only when these limits are exceeded that permanent change or damage such as warping or cracking occurs. Modeling showed how much change in climate was required to produce irreversible changes, and consequently how much change could be allowed without damage. Significantly, this approach predicted not just ultimate failure, but the onset of any irreversible physical change.

Within this allowable range of RH that does not produce short term physical damage, permanence can be optimized by choosing conditions (or more precisely, a range of conditions) that minimize long term processes and chemical reactions and that are feasible and economical to maintain. Within a range determined by minimizing physical damage, the climate can be adjusted seasonally to minimize expense, maintenance, and other problems, while still respecting the need to preserve the collection. For example, maintaining cooler and drier conditions during winter can offset the effects of slightly warmer and more humid conditions during summer (as long as these changes are kept within the overall safe range).

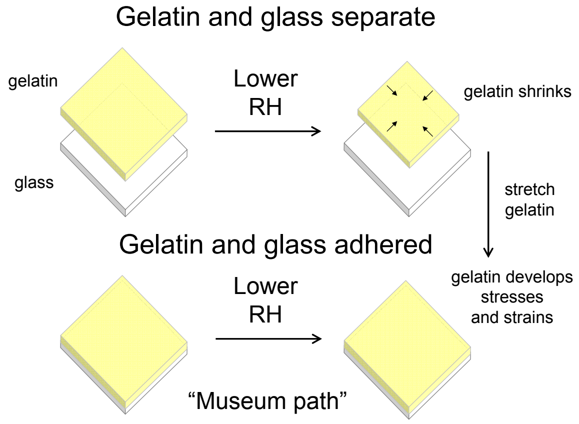

Figure 1. Extreme environmental changes cause damage due to the differential expansion and contraction of materials. If the RH around a free gelatin layer is lowered, it shrinks and no strains or stresses are generated. If it is adhered to a glass plate that does not respond to RH changes, however, it cannot shrink because the glass is stiffer, stronger, and thicker. Stresses and strains develop in the gelatin even though there is minimal dimensional change. The glass plate develops little strain (its size is minimally different from a free glass plate) but develops stresses equal and opposite to those in the gelatin layer. This example demonstrates why the stress-strain behaviour and dimensional response to RH change of the individual materials must be known to predict the behaviour of an object, and why dimensional measurements alone cannot be used to determine the state of an object or to predict behaviour.

In 1994, a press release from the Smithsonian Institution announced that scientists at the CAL (Mecklenburg, Tumosa, Erhardt, and McCormick-Goodhart) had developed new guidelines for the museum climate based on their research [18]. Combining previous and ongoing environmental research with computer modeling, it became possible to predict irreversible changes (damage) due to fluctuations in the climate. The scientists were now able to develop rational guidelines that took into account environmental effects on chemical, physical and mechanical properties of materials. The primary advance was in being able to predict how much environmental fluctuation was required to force a component of an object beyond its

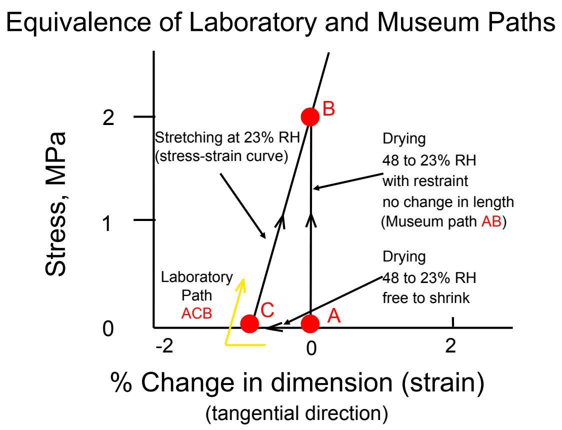

Figure 2. Point A represents a free material (such as wood) in an unstressed state. If the material is restrained while the RH is lowered, the dimension remains the same but stresses develop due to the force required to keep it from shrinking. The development of stress in moving from point A to point B is what can occur in a composite object exposed to RH fluctuations, the "museum path" AB. If the material is allowed to freely shrink during the RH change, no stresses develop in moving from point A to point C. If the material is then stretched to its original size (CB), it develops stresses equal to those generated in the restrained material. Dimensional change due to RH changes (AC) and stress-strain behaviour (CB) can be measured in the laboratory, and the laboratory path ACB used to predict the effects of RH changes in the museum. If the dimensional change CA during the stress strain measurement is within the elastic limit of the material, the process is reversible and there is no permanent change or damage.

elastic (reversible) limit, and therefore the range which did not produce irreversible changes (figures 1 and 2). Using worst case examples such as an RH responsive material adhered to a non-responsive material (e.g. gelatin on glass plate photographic negatives) that was allowed to fully respond to a possible change in RH or temperature, they could calculate conservative allowable ranges for general collections. In general, the allowable range for an object (or collection) is determined by the most responsive component material present. The guidelines provided safe ranges in which mechanical and physical damage was prevented and slower processes such as chemical deterioration could be minimized. Significantly, the results showed that moderate fluctuations within the range 50 +15% RH were safe. The results were published in a paper presented at a meeting of the International Institute for Conservation [19]. The reaction to this challenge to current dogma was immediate. Numerous critical letters and comments appeared, but these tended to have no more substance than what the previous specifications had been based on. There has been no substantive challenge to the basic data, interpretation, theory, or conclusions used to derive the guidelines. Subsequent papers have refined and expanded the guidelines and the science behind them [20-30].

The allowable fluctuation of temperature or RH varies with the starting setpoint, because the responsiveness of materials varies with temperature and RH. For general collections, variations within the range 30% to 60% RH are mechanically safe. The temperature is usually determined by human comfort considerations, but should be maintained above 13°C to stay above the temperatures at which some materials such as acrylics undergo phase transitions and become brittle. Within this range of mechanical safety, long term chemical stability is usually enhanced by cooler and drier conditions. There are exceptions to these recommendations. For example, photographs generally should be kept in cold storage. Metal objects should be kept in the dry end of the recommended range. Severely degraded materials, objects with weak or degraded adhesives (especially veneers and inlays), or objects such as drums and Japanese screens with pre-existing stresses should be kept in more stable environments. Display cases and storage cabinets alone or with buffering agents (which can be other hygroscopic objects) provide an extra degree of protection against RH fluctuations. Current environmental guidelines at the Smithsonian call for 45 ±8% RH and 70 ±4 F (approximately 21 ±2°C), values which are well within the already conservative generally allowable ranges.

RESULTS

The new guidelines are increasingly widely accepted, and have been adopted in a number of museums and institutions. Because the new guidelines are more flexible and allow a wider range of environmental conditions, implementing them is simpler, less expensive, and less time consuming. For example, the costs of construction of the Udvar-Hazy Center annex to the National Air and Space Museum of the Smithsonian Institution were reduced by approximately $10,000,000 (10%) when the new guidelines were incorporated into the planning. Energy costs have also been reduced. Ongoing implementation of the new guidelines in Smithsonian museums resulted in cost savings of $2.7 million in just the second half of 2006 (out of $32 million total energy costs for all of 2006), and $1.5 million in the first quarter of 2007. The savings were achieved because the building managers

"were able to run smaller or fewer boilers during summer, secure or setback air handling equipment during unoccupied periods, raise chilled water supply setpoints, lower heating water boiler supply setpoint, reduce boiler pressure, secure outside air and exhaust during unoccupied periods, minimize OA intake, raise space temperature setpoints, raise AHU discharge temperatures, secure terminal reheat/fan-coils, secured reheat pumps, etc." [31]

In addition to the cost savings, the new guidelines also help preserve the historic buildings of the Smithsonian Institution which are an integral component of the collections. There have been no reports of damage to the collections due to implementation of the new guidelines.

Conclusions

Early specifications for the museum climate were based on little evidence, illogical and unfounded interpretations of what evidence was available, and extensions to materials, objects and situations not covered even by the minimal evidence available. Nevertheless, the recommendations became fixed and inflexible. Eventually, research resulted in the development of more rational guidelines for the museum climate. While entrenched thinking (or lack of it) has persisted, the new guidelines have gained wide acceptance.

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