

ENVIRONMENTAL REQUIREMENTS FOR MUSEUMS

by

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Abstract

Museums represent a unique class of indoor environments with environmental control requirements that are quite different than traditional occupant-based buildings. As caretakers of cultural and natural artifacts, museums and archives often contain irreplaceable objects. In situations where environments for artifacts are not correctly maintained and controlled, permanent damage can result. A greater understanding of the role that environmental factors play in the preservation of artifacts would help to specify a heating, ventilation and air-conditioning (HVAC) system that meets the special requirements of museums.

Five main factors are generally responsible for the deterioration of artifacts: light, temperature, relative humidity, pollution and biological attack. Damage from light can be limited or prevented through the use of UV filters and indirect lighting. Fluctuations in both temperature and relative humidity should be minimized. Although recommended set points for temperature and relative humidity are material dependent, temperature should be maintained in a range between 59-77 °F with relative humidity between 35-60%. Concentrations of pollutants should be minimized to prevent the formation of harmful acids, which weaken materials.

An environmental survey performed at the Field Museum of Natural History in Chicago, IL indicated that the temperature in certain areas often exceeded the recommended upper limit of 77 °F. Relative humidity was poorly controlled and the central heating caused

relative humidities as low as 10% during winter in certain areas of the building. It is very likely that these extremely low relative humidities are a primary cause of damage to the artifacts.

Exhibition cases which house artifacts for display provide a layer of protection between the microenvironment within the case and the fluctuations in temperature, relative humidity and pollutant concentration in the Museum macroenvironment. An infiltration model of an exhibition case was developed and validated, in order to calculate the number of air changes a case undergoes in a day. The results indicate that tighter exhibition cases provide greater protection against fluctuations. Cases should therefore be constructed with less than one air change per day.

The most obvious solution to the environmental control problems within the Field Museum is a complete retrofit and renovation of the building's HVAC system. To alleviate the severely dry conditions in the Museum during winter until a new HVAC system is installed, any existing humidification equipment must be serviced, cleaned and activated. Obvious leaks in the building perimeter through emergency doors or non-operational windows should be sealed to limit the infiltration of unconditioned outdoor air. The relative humidity of the space can be increased by a few percentage points by reducing the space temperature set point to 68°F in the winter.

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Nomenclature

HVAC	heating, ventilation and air conditioning
K_{cap}	moisture capacitance
$k_{\text{diff,CO}_2}$	exchange rate coefficient for CO_2
M_{air}	mass of air in display case
\dot{m}_{bar}	mass flow due to change in barometric pressure
MW	molecular weight
N_{air}	air changes per day
P_{bar}	barometric pressure
R	gas constant for air
RH	relative humidity
T	temperature
V_{case}	volume of display case
ω	humidity ratio
Ω	equilibrium moisture content

CHAPTER 1

Introduction

1.1 Background and Motivation

Museums represent a unique class of indoor environments with environmental control requirements that are quite different than traditional occupant-based buildings. As caretakers of humanity's cultural heritage and the diversity of life found on our planet, museums and archives often contain priceless artifacts that are irreplaceable. In situations where environments for artifacts are not correctly maintained and controlled, permanent damage can result. A factor that further complicates environmental control issues for museums is the potential inconsistency between temperature and relative humidity requirements that best preserve the artifacts and those that maximize the comfort of building occupants. A greater understanding of the role that environmental factors play in the preservation of artifacts is an essential requisite to establishing specifications for a heating, ventilation and air-conditioning (HVAC) system that can cost-effectively operate to meet the special needs of museums.

1.1.1 The Field Museum

The research project was initiated to better understand the requirements of a new HVAC system upgrade proposed at the Field Museum of Natural History in Chicago,

Illinois. In addition, Field Museum staff expressed an interest in studying possible causes of and contributors to damage of certain exhibits. In particular, the mount of a wild Somalian Ass on display had developed a large tear on its rump that was particularly noticeable during the winter season. As the animal is an endangered species, it is unlikely that a replacement hide would be available at any time in the future so prevention of future damage is very important. In addition, the method of mounting the animal was unique to the taxidermist and the mount is now considered a work of art. Figure 1.1 contains a photo of the display case, while Figure 1.2 presents a close up of the tear, which was roughly 6-8 inches in length during the month of April 1999. In addition, teeth and shells located in the Zoology department have experienced cracking and breakage while undisturbed in storage. Determining the cause of such damage and making suggestions for remediation were the primary goals of this project.



Figure 1.1 Photo of the wild Somalian Ass mounts.



Figure 1.2 Close-up image of the tear in Somalian Ass mount.

The experimental phase of this work was carried out on-site at the Field Museum in Chicago. The Museum was founded in 1893 and is one of the largest natural history museums in the world with one million square feet of floor space housing a collection of over 20 million specimens and cultural objects. The mission statement of the Museum is extensive, encompassing its educational and research capabilities to link the past with the present, and help provide a greater understanding of the Earth and the creatures that inhabit it. More specifically, “the Museum holds encyclopedic collections of biological and geological specimens and cultural objects as the data needed to understand the nature of - and conditions affecting - environmental and cultural change. (<http://www.fmnh.org>).” These collections are held in trust for future generations and are the focus of conservation and preservation efforts.

The Museum moved to its current building, located on the lakefront museum campus of the Chicago Park District, in 1921 and contains an expansive central hall, called Stanley Field Hall, of approximately one million cubic feet stretching the entire length and height of the building as shown in Figure 1.3. The estimated heating and cooling costs for the facility are on the order of two millions dollars a year. Large exhibition halls open off this main hall on two levels. All of these public areas are interconnected; only two of the 34 exhibit halls are discrete spaces (Sease, 1991). Controlling the conditions of the indoor environment to the requirements that simultaneously satisfy the artifacts, staff and visitors in such an old building poses significant challenges.



Figure 1.3 Picture of Stanley Field Hall, which is the main central hall of the Museum.

1.2 Discussion of Environmental Factors for Preservation

Deterioration of artifacts could be attributed to several things: repeated mechanical stress of the object due to an uncontrolled environment, chemical deterioration, and biological attack. Light, temperature, relative humidity and pollution are all potential adversities that could contribute to degradation. Each factor will be discussed, in brief, in the following sections. For more extensive and/or specific information, the reader is referred to the full bibliography listed in Appendix A.

1.2.1 Mechanical Stress

1.2.1.1 Temperature and Relative Humidity

A large percentage of objects on display and in storage in museums are of a biological nature, either of plant or animal origin, such as textiles, wood, leather and other animal hides. Such materials are generally hygroscopic, meaning that they can adsorb and desorb water. An example of this behavior is shown in Figure 1.4 where the equilibrium moisture content of wood is plotted as a function of the relative humidity for 60°F and 120°F. As the moisture content of the air increases so will the moisture content of the wood after a sufficient period of time elapses for the wood to reach equilibrium. Temperature has little effect on the moisture uptake characteristics of wood as evident by the similarity of the two curves.

If unrestrained, the specimen will tend to dimensionally expand with the adsorption of water and shrink with the desorption of water. The effect of moisture content on dimensional change, expressed in terms of normalized length, is illustrated in Figure 1.5 for

cottonwood. In a similar manner, many materials also respond to changes in temperature, shrinking with decreases in temperature and expanding with increases in temperature.

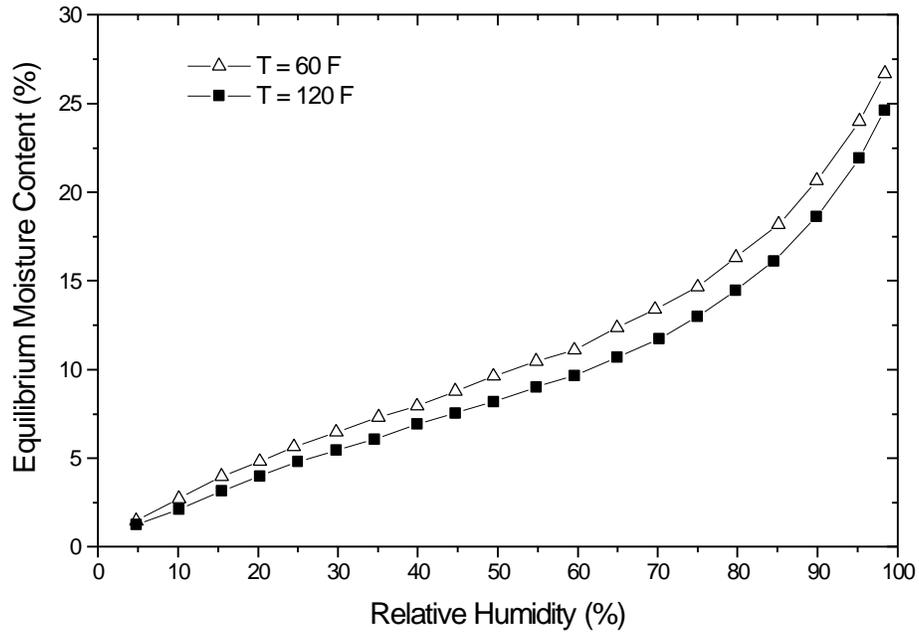


Figure 1.4 Equilibrium moisture content of wood versus relative humidity at 60°F and 120°F from Rose (1994).

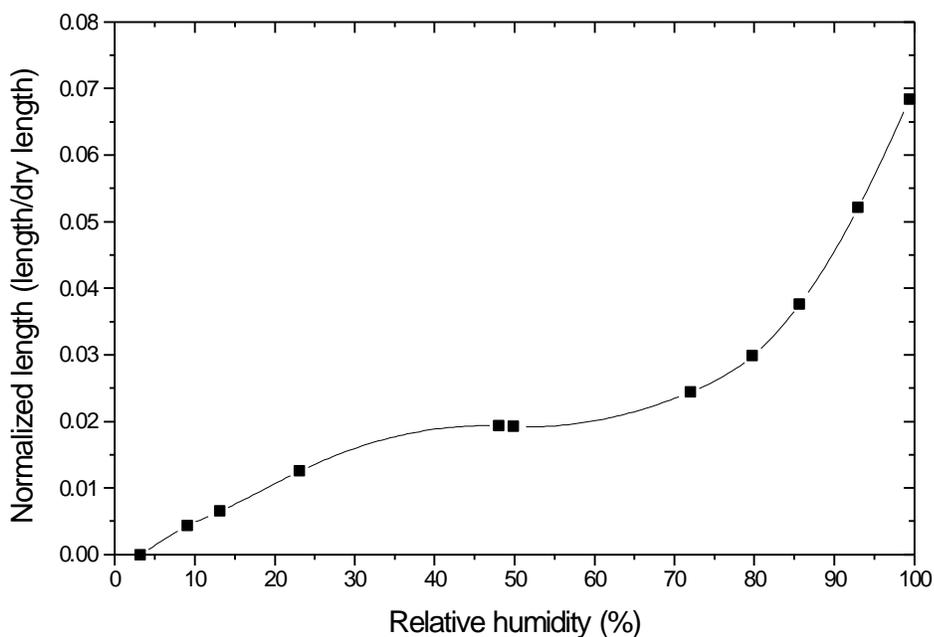


Figure 1.5 Swelling isotherm for cottonwood at 22°C from Mecklenburg et al. (1994).

Once the material is rigidly held and prevented from expanding or shrinking with changes in temperature or relative humidity, stress accumulates and can lead to damage or mechanical failure manifested by cracking, splitting, tearing, flaking or warping. Figure 1.6 presents stress as a function of temperature and relative humidity for rabbit skin glue to illustrate this increase in stress with decreases in temperature and relative humidity. The maximum stress due to cooling is at least an order of magnitude less than that due to desiccation. A similar proportion was found for wood where a 10% change in relative humidity caused a 0.45% change in length when a 5°C change in temperature caused a 0.02% change in length (Thomson, 1986). As a result, temperature fluctuations are generally less of a problem (Thomson, 1986 and Michalski, 1994a); relative humidity variations have a much greater impact on artifacts.

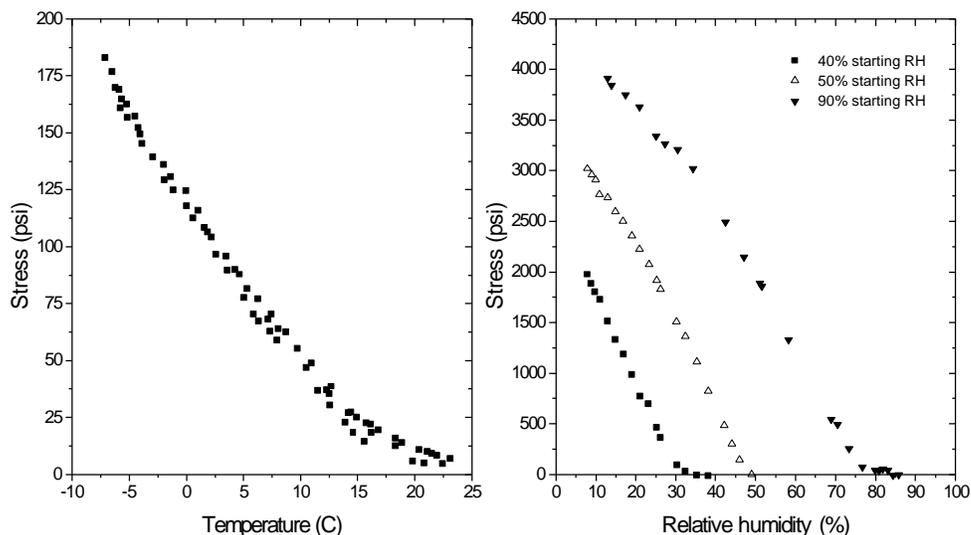


Figure 1.6 Stress development in restrained rabbit skin glue with decreasing temperature (left) and decreasing relative humidity (right) from Mecklenburg et al. (1992).

Knowledge of the mechanical properties of the cultural objects, such as strength and stiffness, can help in understanding the objects' response to changes in temperature and relative humidity as well as specify the range of allowable fluctuations in temperature and relative humidity before damage occurs. Such research has been accomplished in the past 10-15 years by scientists at the Smithsonian Institution for a large number of different materials such as wood, glue and artists' paints (Mecklenburg, 1991, Mecklenburg et al., 1992, Erlebacher et al., 1992, Mecklenburg and Tumosa, 1993 and Mecklenburg et al., 1995a). For example, their extensive work with different types of wood indicates that the typical strain at which yielding, or permanent damage, occurs is 0.004 (Mecklenburg et al., 1995b). In fact, this strain threshold of 0.004 is consistent for a wide variety of polymeric materials (McCormick-Goodhart et al., 1997). Based on such experimental data and using

finite element modeling techniques, plots which graph the allowable RH fluctuations versus relative humidity have been constructed for a variety of different woods. An example of such a plot is shown in Figure 1.7 for ash. The shape of the curve is fairly standard for many of the woods in that the maximum allowable fluctuations occur in the range of 35%-60% relative humidity while dropping off at lower and higher values.

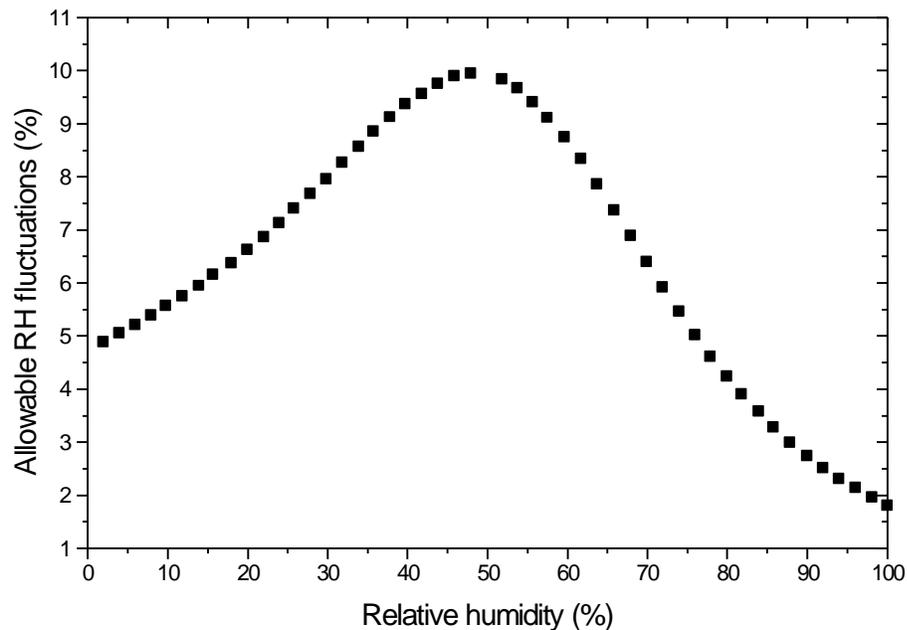


Figure 1.7 Allowable RH fluctuations versus ambient RH for fully restrained ash in the tangential direction from Mecklenburg et al. (1992).

Within the allowable RH range, the deformations and induced stress are within the elastic range of the material so that no permanent damage results. It is important to note that these types of graphs are generated assuming the worst possible conditions, i.e. that the specimens are fully restrained and are allowed to fully respond to the change in ambient relative humidity. In practice, these conditions are rarely met all at once so that the range of allowable RH fluctuations would be greater.

It is also important to note that although many organic materials exhibit the same general behavior in response to changes in relative humidity, the exact magnitudes are material dependent. To reduce damage from mechanical stress, specifying RH fluctuation guidelines for a general collection consisting of a wide variety of organic materials is, at best, a compromise. The work done by the Smithsonian Institution suggests that relative humidity fluctuations within the range of 35% to 65% would result in little to no mechanical damage (Erhardt et al, 1997, Erhardt and Mecklenburg, 1994, Tumosa et al., 1996 and Erhardt et al., 1995). However, particularly fragile objects or previously damaged objects should be maintained in a stable microenvironment where the fluctuations are limited to $\pm 5\%$ or less.

1.2.1.2 Light

Damage can occur from the heating effect of incident light with wavelengths in the infrared (IR) range. Localized heating of the air and materials can lead to the evaporation of water and dehydration of the material. Repeated cycles of desiccation can affect the appearance of textiles and also the mechanical strength. To limit damage due to localized IR heating, lamps and other light sources should be positioned at a sufficient distance from the object or placed in a location to produce indirect lighting.

1.2.2 Chemical Deterioration

1.2.2.1 Temperature

The temperature at which the materials are stored or displayed directly affects their rate of chemical decomposition. As an example, consider the generic bimolecular reaction of substance A combining with B to form substances C and D:



Taking the forward reaction only, the rate of decrease of substance A is proportional to the concentrations of substances A and B, as well as the rate coefficient of the reaction, k , as expressed by Equation 1.2.

$$\frac{d[A]}{dt} = -k[A] \cdot [B] \quad (1.2)$$

The rate coefficient, k , can be expressed in Arrhenius form as shown in Equation 1.3:

$$k = A \exp\left(\frac{-E_a}{R_u T}\right) \quad (1.3)$$

where A is termed the pre-exponential factor, E_a is the activation energy, R_u is the universal gas constant and T is the temperature at which the reaction takes place. A and E_a are empirical parameters that vary depending on the reaction being considered. Thus for a given reaction and activation energy, increasing the temperature increases the rate coefficient and therefore the rate at which A is consumed.

The chemical deterioration of paper has been the most widely studied and the benefits from lowering the temperature are clearly seen; it has been shown that rates of paper degradation often behave according to the Arrhenius equation, Equation 1.3 (Erhardt, 1991). For example, the useful life of acidic paper can be doubled by lowering the temperature from 68° F to 60°F while held at constant relative humidity (Banks, 1999 and Thomson, 1986).

The process of cellulose and protein chain aging is chemical in nature and involves numerous reactions (Erhardt, 1991, Erhardt and Mecklenburg, 1994 and Bresee, 1986). Reducing the temperature would slow all of the reactions. However, for articles on display the minimum temperature is often restricted to the comfort zone of museum visitors. For

objects in storage lower temperatures may be more feasible. For particularly susceptible objects, such as photographic materials, cold storage greatly prolongs their lifetime.

1.2.2.2 Relative Humidity

Many deterioration mechanisms for cellulose and protein involve chemical reactions with water (Hansen et al., 1992 and Erhardt and Mecklenburg, 1995). A common damaging reaction is hydrolysis, where the long chains of cellulose and proteins are broken up into smaller chains through chemical interaction with water. As a result, structural changes occur within the material and generally the strength decreases. For paper, the lifetime can be roughly doubled by lowering the RH from 50% to 25% (Banks, 1999). For collagen, a complex triple strand of proteins that makes up a large percentage of skin (Hansen et al., 1992), gelatinization also occurs, where the organized molecular bonds between strands are broken. Both of these reactions dominate when the relative humidity is over 40% (Erhardt and Mecklenburg, 1995 and Hansen et al., 1992).

An additional chemical reaction known as cross-linking can occur if the relative humidity drops below 25-30%. Figure 1.8 contains the moisture isotherm for cotton at 25°C which also shows how the water is absorbed. From 0-20% relative humidity, most of the water absorbed by the fiber is “bound” water, meaning that water is chemically bound within the long chains of cellulose and protein. Above roughly 30%, water is sorbed on hydrophilic sites and held through capillary action on the surface of the polymer. If the specimen is severely desiccated below 30%, bound water begins to leave the molecule, leaving highly reactive sites open. The long chains of molecules then become attracted and bound to each

other through these sites, causing a decrease in overall strength of the material. Thus for molecular stability, at least 25% relative humidity should be maintained.

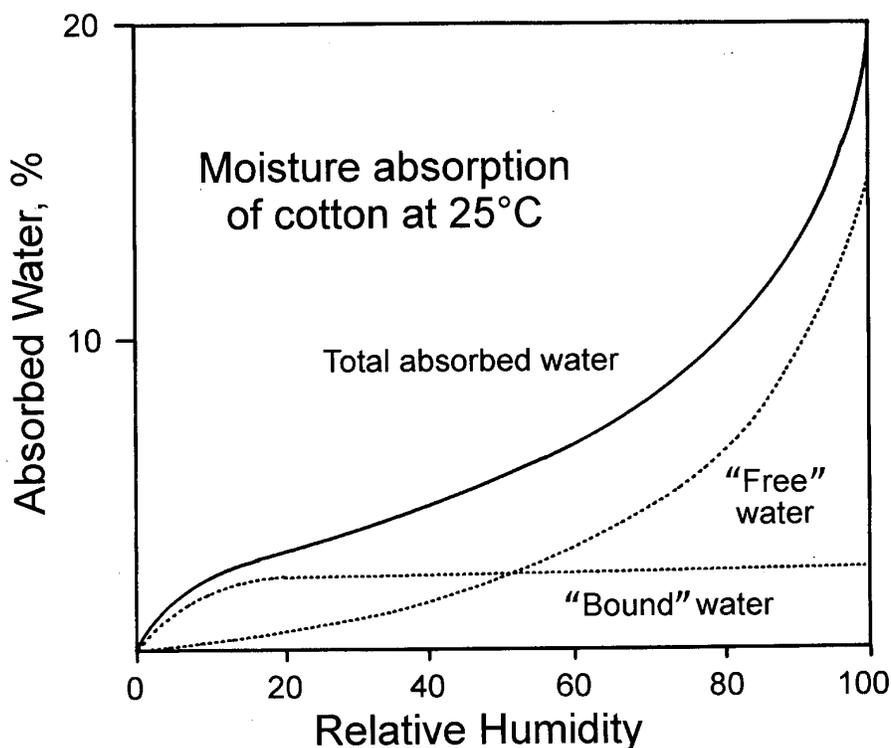


Figure 1.8 The moisture isotherm for cotton, showing the absorbed water versus relative humidity. The dashed lines indicate the different types of absorbed water contributing to the total amount (Mecklenburg and Tumosa, 1999).

1.2.2.3 Pollution

Air contains several substances that are harmful to organic and inorganic materials. Three of the most dangerous are sulfur dioxide (SO_2), oxides of nitrogen (NO_x) and ozone (O_3). Sulfur is a trace constituent commonly found in coal and diesel fuel and enters the atmosphere when the petroleum products are burned. It combines with oxygen and forms sulfur dioxide. Once in the air, sulfur dioxide is photochemically oxidized to sulfur trioxide

which readily forms sulfuric acid in the presence of water vapor (Thomson, 1986). The process of sulfuric acid formation is illustrated in Equation 1.4.



Oxides of nitrogen are also formed in large quantities during combustion processes. Nitrogen (N_2) combines with oxygen at high temperatures to form nitric oxide (NO) and nitrogen dioxide (NO_2) among other oxides, which are generally referred to as NO_x . NO_2 combines with water vapor found readily in air to form nitrous acid (HNO_2) and nitric acid (HNO_3) per the following reaction:



The nitrous acid is further oxidized by air to form more nitric acid.

Ozone can be formed by two processes: one occurring naturally in the upper atmosphere and the other through a complex series of reactions initiated by sunlight and the presence of nitric oxide (NO). The latter process accounts for the large concentration of ozone present in urban areas and contributes to urban smog.

The sulfuric and nitric acid and ozone can considerably damage artifacts. Some of the most common effects are the discoloration of dyes in textiles and fabrics (Salmon and Cass, 1993, Thomson, 1986, and Grosjean et al., 1991). The compounds also result in the hydrolysis of cellulose and proteins, leading to a weakening of the material (van Soest et al., 1984). As a result, reducing the concentrations of these pollutants to levels as low as possible is highly recommended.

1.2.2.4 Light

Although light is necessary for the viewing and enjoyment of cultural artifacts, it must be regulated to prevent unnecessary damage to materials. In particular, organic substances such as textiles, paper, leather, silk and wool are vulnerable to light whereas inorganic objects like metal, stone and ceramic are largely unaffected. Two wavelength-dependent mechanisms responsible for light damage are photolysis and photo-oxidation.

Photolysis occurs when photons of high energy are absorbed by the material resulting in the breakage of chemical bonds between atoms. This results in permanent, often deleterious, molecular changes which can affect the structural strength and integrity of the material. The wavelengths responsible for this type of damage are in the near and far ultraviolet (UV) range. Photo-oxidation damage occurs when light in the near UV (310-400 nm) initiates chemical reactions in the presence of oxygen. The result is often embrittlement, discoloration or the fading of certain dyes.

Although damage occurs at all wavelengths, steps can be taken to limit the damage without compromising the viewing experience of the museum visitor. The most effective method of removing UV light is through the use of special filters. Ordinary window glass filters wavelengths smaller than 310 nm but additional filters may be needed, especially on fluorescent light bulbs. Limiting the intensity of incident light is also desirable to minimize damage from visible wavelengths. 50 lux is recommended for light sensitive materials and 150-200 lux for less sensitive materials or general exhibition (Thomson, 1986 and Weiss, 1977). An additional option for reducing exhibit illumination is to turn off lights when the museum is closed or the exhibit is not being viewed. For example, exhibit halls or cases

could use motion detectors to illuminate objects when visitors enter the area and shut them off when they leave.

1.2.3 Biological Attack

1.2.3.1 Temperature and Relative Humidity

Mold and fungal activity can severely damage a collection by weakening the material through consumption of the artifact. Bacteria feed on the organic materials leading to discoloration as a by-product of the microbial metabolism. High temperatures and relative humidities encourage the growth of mold. Below an RH of 70%, mold spores are largely inactive. Stagnant air and temperatures above 80°F should also be avoided.

1.3 Guidelines for Environmental Factors

In summary, the temperature for storage and display of artifacts should be kept stable to minimize mechanical stresses within materials and it should be kept low to decrease the rate of chemical reactions and reduce the likelihood of mold activity. However, the comfort of the museum visitor places a practical lower limit on the temperature in the exhibition area. In display areas it seems reasonable to aim for a temperature of 68°F in the winter and 74°F in the summer.

Specifications for relative humidity are more difficult to make based on the wide range of materials present and the simultaneous considerations of chemical deterioration and mechanical stress. Figure 1.9 compiles the material dependent relative humidity recommendations considering all damage-inducing factors (Erhardt et al., 1997).

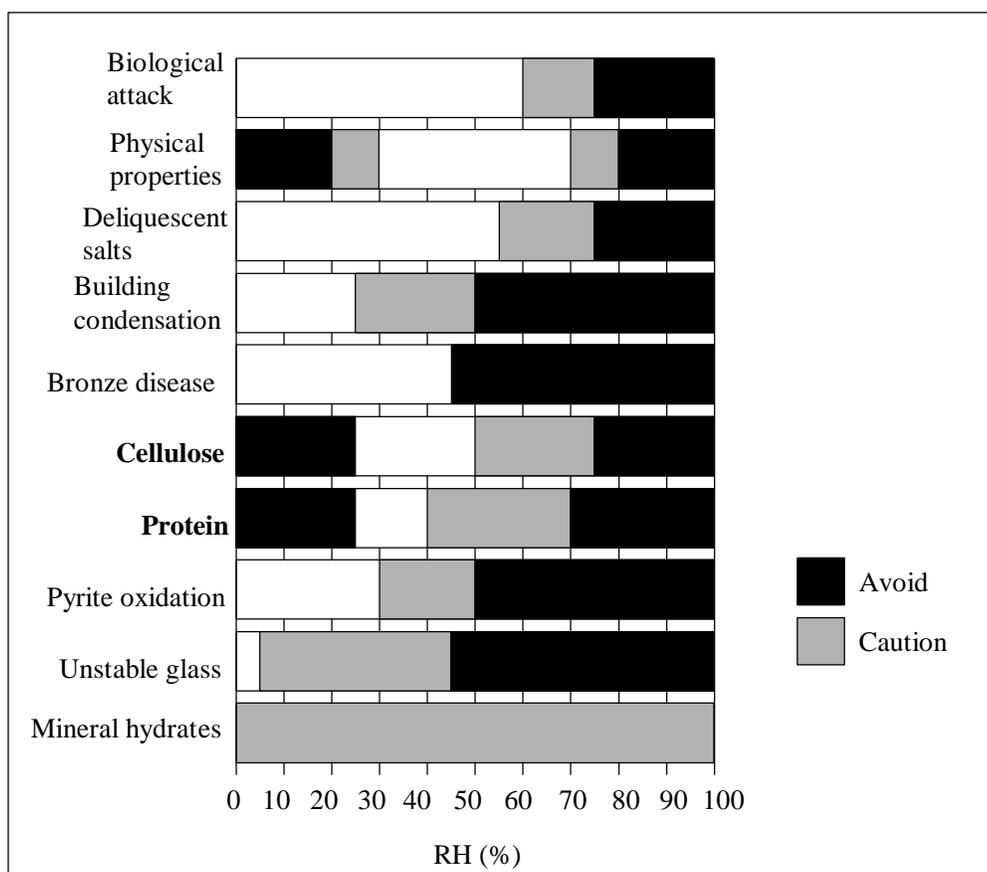


Figure 1.9 Ranges of relative humidity suggested by consideration of various factors (Erhardt et al., 1997).

Pyrite oxidation, unstable glass, mineral hydrates and deliquescent salt requirements were not discussed here but can be found in Thomson (1986), Erhardt et al. (1997), and Ryan et al. (1993). The upper and lower RH bounds for cellulose and protein are chemically limited by the hydrolysis and cross-linking reactions respectively. Bronze disease is corrosion of metals and occurs due to the presence of water (Thomson, 1986). Physical properties refer to the mechanical characteristics of materials and the range where RH fluctuations are generally considered to cause elastic, and therefore non-damaging, dimensional changes.

The 1999 ASHRAE Applications Handbook includes a chapter on museums and archives and its recommendations for temperature and relative humidity set points and allowable fluctuations in general museums are detailed in Table 1.1. The recommended relative humidity set point is 50% while the temperature can be set between 59°F and 77°F. The table illustrates that a range of control is available with varying consequences on artifact lifetime.

Table 1.1 Recommended temperature and relative humidity fluctuation limits for a general collection museum.

CLASS OF CONTROL	SHORT FLUCTUATIONS	SEASONAL ADJUSTMENT IN SET POINT	COLLECTION RISK (from mechanical damage)
Precision control No seasonal changes	RH: $\pm 5\%$ T: $\pm 4^\circ\text{F}$	RH: none T: $\pm 9^\circ\text{F}$	None to most artifacts
Precision control Seasonal changes	RH: $\pm 5\%$ T: $\pm 4^\circ\text{F}$	RH: $\pm 10\%$ T: Summer: $+9^\circ\text{F}$ Winter: -18°F	Small to none depending on artifact vulnerability
Precision control Some gradients Winter setback	RH: $\pm 10\%$ T: $\pm 9^\circ\text{F}$	RH: $\pm 10\%$ T: $< 86^\circ\text{F}$ Decrease to maintain RH control	Moderate to none depending on artifact
Prevent all high risk extremes	RH: 25% - 75% T: rarely over 86°F ; usually below 77°F		High to low risk

Pollution concentration recommendations come from Thomson (1986) and suggest that sulfur dioxide be reduced to less than 4 parts per billion (ppb), oxides of nitrogen to less than 6 ppb and ozone to less than 1 ppb. For comparison with actual recorded values, data from the Illinois EPA 1998 Annual Report are listed in Table 1.2, which contains outdoor ambient levels of SO₂, NO₂ and O₃ from a monitoring station situated at the Chicago

Transport Authority building on 320 S. Franklin, which is located within two miles of the Field Museum.

Table 1.2 Maximum and annual average concentrations of SO₂, NO₂ and O₃ for ambient air in metropolitan Chicago in 1998.

SUBSTANCE	SHORT TERM HIGHS	LONG TERM HIGHS	ANNUAL AVERAGE
O ₃	92 ppb (1 hour)	79 ppb (8 hour)	-
SO ₂	120 ppb (3 hour average)	41 ppb (24 hour average)	5 ppb
NO ₂	112 ppb (1 hour)	68 ppb (24 hour)	32 ppb

1.4 Scope of Current Research

The specific objectives of this project were to:

- conduct a literature review of the causes of damage to artifacts and resulting environmental requirements for museums;
- assess the current level of environmental control in the Field Museum;
- determine the interaction between the Museum macroenvironment and the microenvironment of key display cases;
- recommend short and long-term remediation solutions for control problems.

The results of the literature search are detailed above in Sections 1.2 and 1.3 and highlight the various causes of damage to artifacts as well as summarize the most current recommendations for temperature and relative humidity set points for artifacts in general exhibition. The long term environmental monitoring plan is presented in Chapter 2 and the

results are shown in Chapter 3. A model of an exhibit display case is developed in Chapter 4 and the results indicate the level of interaction of the case microenvironment with the museum macroenvironment. Short and long-term remediation solutions are put forward in Chapter 5 with overall conclusions and recommendations for future work presented in Chapter 6.

CHAPTER 2

Environmental Monitoring Plan

2.1 Purpose of Environmental Monitoring Plan

One of the primary goals of this research project was to document temporal environmental conditions at critical locations within the Field Museum over an extended period of time (i.e. one year). Critical locations included:

- Locations where visible damage to artifacts had occurred;
- Locations in storage areas with suspected poor environmental controls;
- Storage areas with recently renovated environmental controls;
- Newly purchased cases designed to passively control humidity;
- Common areas in the facility.

Dry bulb temperature and relative humidity were measured at fifteen-minute intervals. Concentration of carbon dioxide (CO₂) was simultaneously measured inside and outside certain cases to ascertain the level of interaction between the microenvironment within the cases and the macroenvironment of the museum. In addition, a video camera was installed within the Somalian Ass case to gather time-lapse images of a sizeable tear in the hide on the rump of the mount. Linking the video images with the temperature/humidity

history in the case may provide evidence to support or refute possible hypotheses to explain the root cause of the mammal mount degradation. By gathering data over an extended period of time, a better assessment of the performance of environmental control systems can be made on both a short-term (day-to-day), intermediate (week-to-week) and long-term (season-to-season) basis. The process of monitoring environmental conditions during both heating and cooling seasons was especially important to gauge the operability of these mutually exclusive systems.

2.2 Parameters Monitored

2.2.1 Temperature and Relative Humidity Measurements

Dry bulb temperature and relative humidity were simultaneously monitored with a Hobo Pro data logger (Onset Computer Corporation), shown in Figure 2.1. The unit can store up to 32,645 measurements with sampling intervals ranging from 0.5 seconds to 9 hours, allowing for long term data logging.

The temperature sensor consists of a thermistor with a range from -22°F to 122°F , a resolution of 0.05°F and accuracy of $\pm 0.3^{\circ}\text{F}$. The relative humidity is determined from a humidity-sensing polymer with a range from 0% to 100% (non-condensing) and an accuracy of $\pm 3\%$. The sampling interval for the temperature and relative humidity measurements was initially once every four minutes during the first two months of monitoring to gather information about short-term environmental transients. The sampling interval was later increased to once every fifteen minutes after realizing that the time constant for the temperature and relative humidity instrument is rated to be less than 30 minutes.



Figure 2.1 The Hobo Pro data logger used for monitoring temperature and relative humidity.

2.2.2 Carbon Dioxide Measurements

The concentration of carbon dioxide was monitored with a Vaisala, Inc. GMW21 CO₂ transmitter, which is shown in Figure 2.2. The sensor uses a non-dispersive infrared (NDIR) beam to determine the concentration of CO₂ in air. The measuring range is 0-2000 ppm with a rated accuracy of $\pm 1\%$ full-scale plus 1.5% of the reading. The output signal of the CO₂ transmitter was digitized and stored by a Hobo H8 external channel data logger (Onset Computer Corporation) with a sampling frequency of three minutes.

2.2.3 Video Camera Monitoring

A 1/3 inch black and white CCD camera (Panasonic, model WVBP334) with zoom lens was installed in the Somalian Ass case in April 1998. The camera signal output was connected to a time-lapse, high-density videocassette recorder (Panasonic, model AG-6740).

One frame was recorded every three minutes with the intent of photo-documenting any visible changes in the large tear in the hide of the mount over long periods of time.



Figure 2.2 Vaisala GMW21 carbon dioxide transmitter used to monitor carbon dioxide concentrations within the Museum.

2.3 Locations Monitored

Four display cases, two storage areas, an entrance hallway and the roof of the Museum were monitored. The locations, along with the monitored parameters, are summarized in Table 2.1 and shown in Figure 2.3 and Figure 2.4.

Table 2.1 List of the locations monitored within the Museum.

LOCATION	PARAMETERS MONITORED	STARTED LOGGING
Lions of Tsavo case Inside case Outside case (Rice Hall)	T, RH, CO2 T, RH, CO2	Dec. 1998 Dec. 1998
Somalian Ass case Inside case Outside case (Hall 21)	T, RH, CO2 T, RH, CO2	Feb. 1999 Dec. 1998
Watering Hole Diorama Inside diorama Behind diorama	T, RH T, RH	Dec. 1998 Dec. 1998
Chinese case Inside case Outside case	T, RH T, RH	Dec. 1998 Dec. 1998
Anthropology storage Storage 1 (#1) Storage 2 (#2)	T, RH T, RH	Dec. 1998 Dec. 1998
Zoology storage Storage 1 (#1) Storage 2 (#2) Cabinet 1 (#1A) Cabinet 2 (#2A)	T, RH T, RH T, RH T, RH	Dec. 1998 Dec. 1998 Sept. 1999 Sept. 1999
Hall 13	T, RH	Dec. 1998
Roof of Museum	T, RH	Dec. 1998

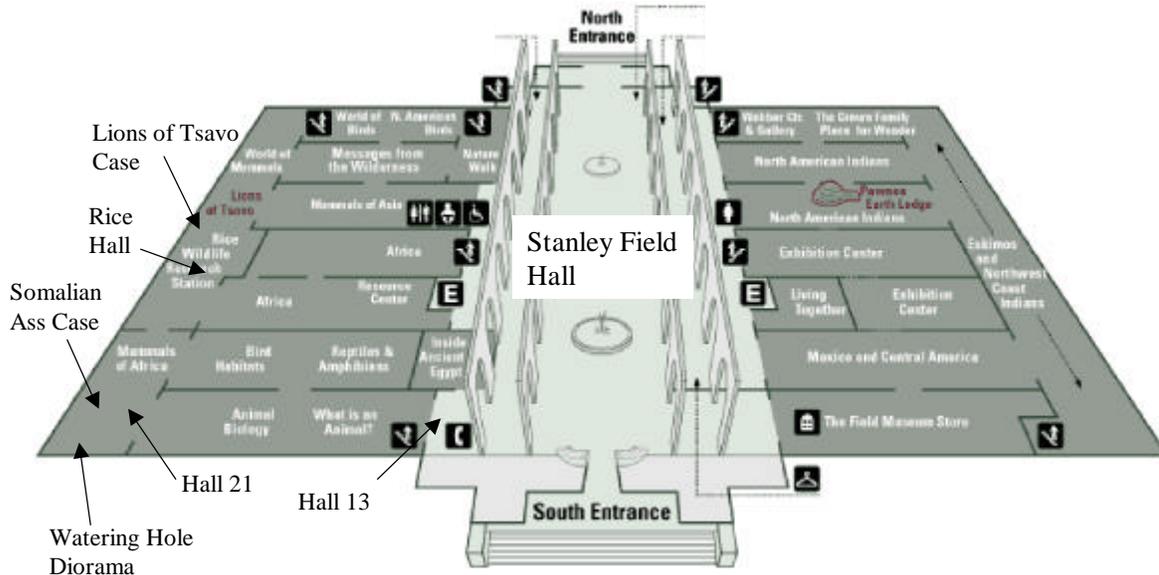


Figure 2.3 Ground floor layout of the Field Museum highlighting the locations for environmental monitoring (www.fnmh.org).

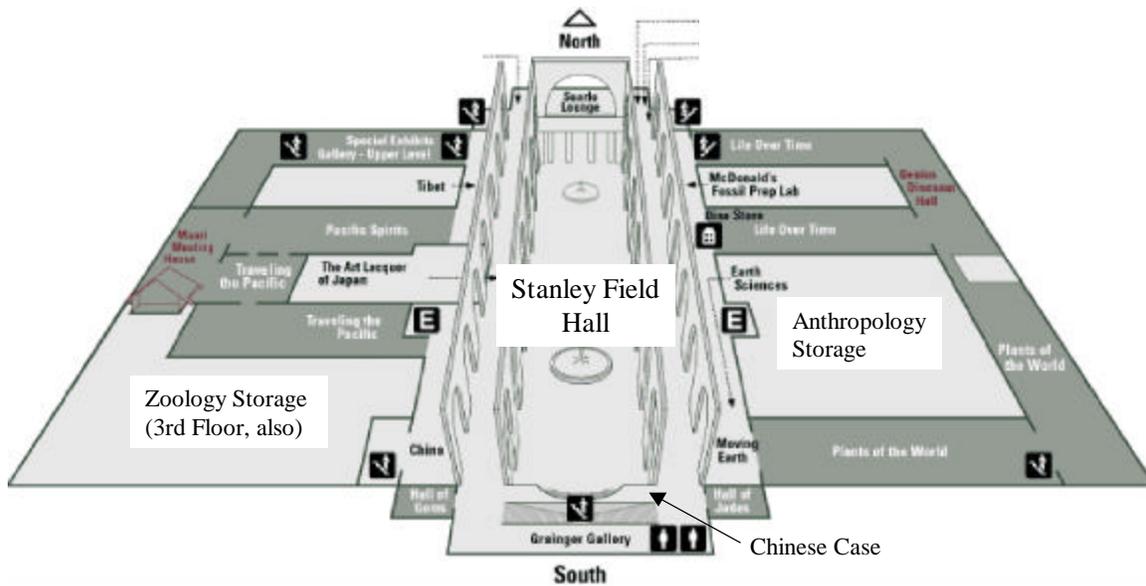


Figure 2.4 Second floor layout of the Field Museum highlighting the environmental monitoring locations (www.fnmh.org).

2.3.1 Description of Monitored Areas

A brief description of the size, construction and access to the cases will be given as an example of typical cases within the Field Museum. The storage areas of the Zoology and Anthropology departments will also be described.

2.3.1.1 Lions of Tsavo Case

The Lions of Tsavo case contains two lions mounted for display. The case is roughly the shape of a rectangle with the following dimensions (in feet): 10'H x 14'W x 10'D. The case is constructed from wood and the contents viewed through a 7'H x 14'W plate glass window. The front of the case faces an open area called Rice Hall, which is often used for luncheons and other special events. The back of the case defines the wall for a small utility area that serves as a buffer space between the Lion case and the west outer wall of the Museum. Access to the case is achieved through a small 3'W x 3'H hinged door in the utility room. Three 40-watt fluorescent tubes provide lighting for the Lions. The layout of the case is shown in Figure 2.5. One temperature and relative humidity logger, along with a CO₂ sensor, was placed inside the case as shown in Figure 2.6 where the Lions are visible in the foreground the photo. The data obtained from these loggers will be referenced as "Inside Lion". Another set of monitoring devices was placed on top of the case to monitor the conditions in Rice Hall and the data will be referred to as "Outside Lion".

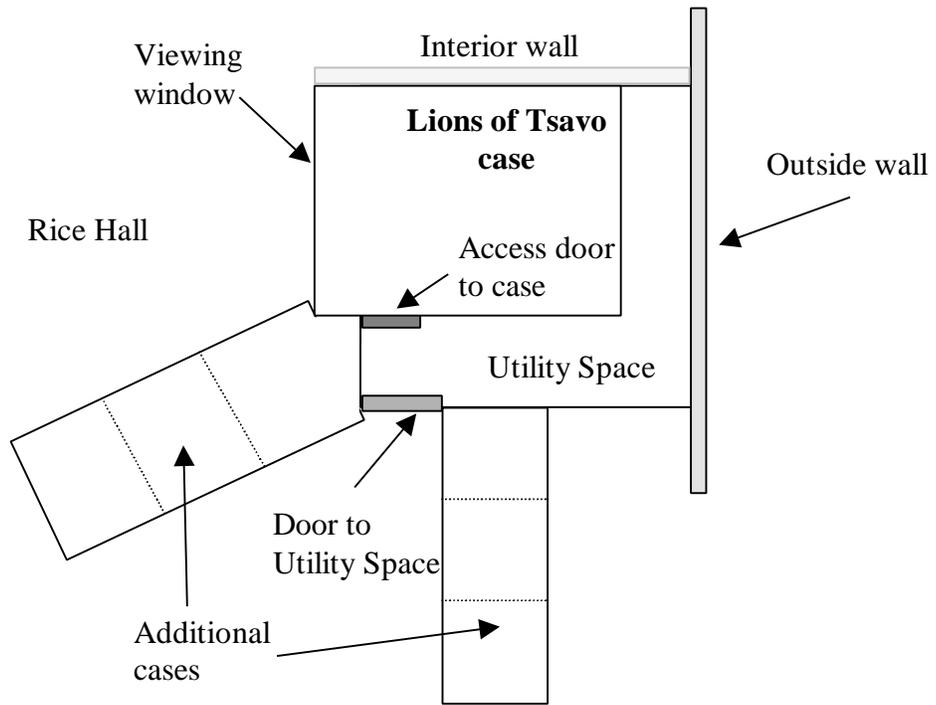


Figure 2.5 Layout of the Lions of Tsavo case.



Figure 2.6 Photo of the interior of the Lions of Tsavo case, showing the temperature and relative humidity logger in the foreground and the animal mounts in the background.

2.3.1.2 Somalian Ass Case

The Somalian Ass case is one of four group display cases, freestanding within one of the smaller exhibit halls, namely Hall 21. Four wild ass mounts are on display in the case

and viewable from two sides through plate glass. The dimensions of the case are 11'H x 14'W x 13'D. Four 40-watt fluorescent tubes provide lighting for the case contents. A 1'H x 2'W access door was cut into the top wood molding of the case and a small shelf installed to hold the sensors and provide a location to mount the video camera. A diagram of the case is shown in Figure 2.7. "Inside Somalian Ass" will refer to data obtained from the loggers placed inside the case, while "Outside Somalian Ass" will refer to data from the loggers placed on top of the case to monitor Hall 21. Figure 2.8 contains a photo of the case, showing the four animal mounts. Visible in the upper portion of the photo is the shelf supporting the camera as well as the other environmental monitoring equipment.

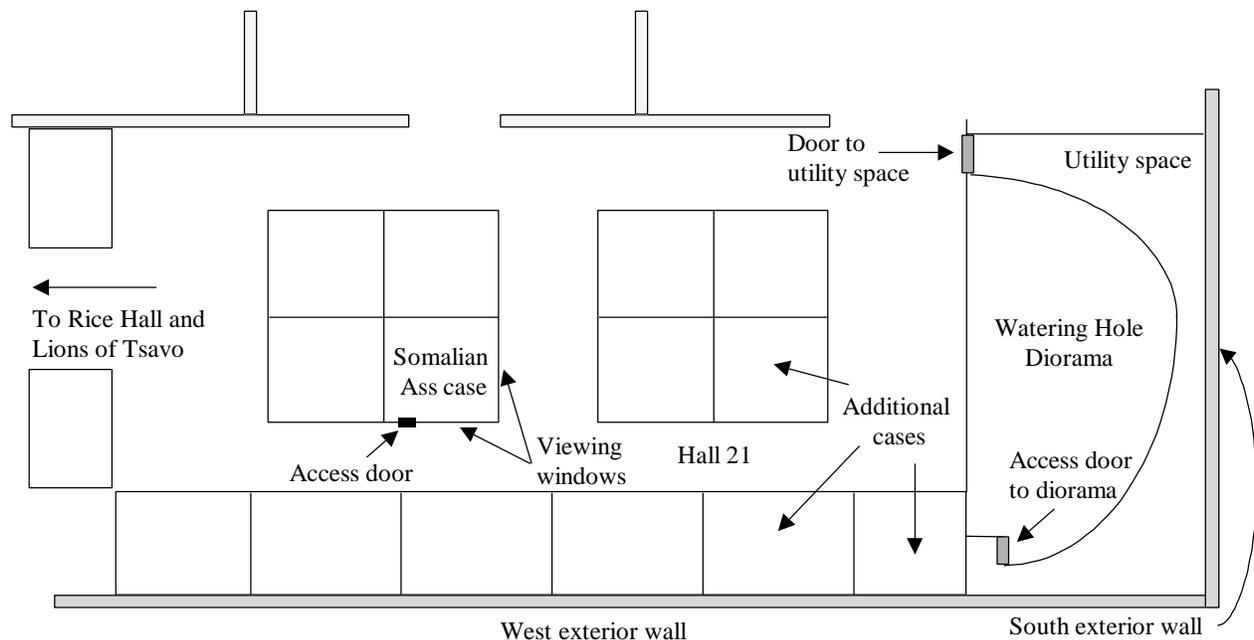


Figure 2.7 Layout of Somalian Ass case and the Watering Hole diorama.



Figure 2.8 Photo of the contents of the Somalian Ass case, highlighting the location of the T/RH and CO₂ loggers, along with the camera.

2.3.1.3 Watering Hole Diorama

The watering hole diorama is a much larger case with several different types of animals on display, including giraffes and hippos. The front of the case is made of plate glass and the rest is a combination of wood and fiberglass. Similar to the Lions of Tsavo case, the watering hole diorama shares its back wall with a utility and electrical space, which separates it from the south outer wall of the Museum. Access to the contents is achieved through a small 2’W x 3’H wooden door. The layout of the diorama can be seen above in Figure 2.7. “Inside Watering Hole” will refer to data from the loggers placed inside the diorama, while “Behind Watering Hole” will refer to data from the loggers placed in the utility space. The loggers placed outside the Somalian Ass case also serve to monitor the

area outside the Watering Hole diorama since both display cases are located in Hall 21 and are within 20 feet of each other.

2.3.1.4 Chinese Case

The Chinese case is much smaller than the above mentioned cases and displays smaller objects, such as wood and ivory figurines. It is a freestanding case with approximate dimensions (in feet) of 5' H x 1.5'D x 8'W. It was constructed within the past three years and uses a silica gel desiccant called ArtSorb (Fuji Silysia Chemical, Ltd.), which is stored within adjoining drawers, to help maintain a desired relative humidity for the contents. A photo of the case is shown in Figure 2.9. Data taken from the logger placed inside the drawer will be referenced as “Inside Chinese” while “Outside Chinese” will refer to data from the logger placed on top of the case.



Figure 2.9 Photo of the Chinese case.

2.3.1.5 Anthropology Storage

The artifacts of the Anthropology department are stored in large rooms with rows of open shelving, as shown in Figure 2.10. The contents are organized by geographical location so that a variety of materials, such as textiles, wood and metals, are stored openly together. Lighting is provided on an as-needed basis by UV-filtered fluorescent tubes. Two adjacent rooms were monitored and will be referred to as Anthropology #1 and Anthropology #2.



Figure 2.10 Photo of the Anthropology storage area, showing textiles laying on tables in foreground and shelving in the background.

2.3.1.6 Zoology Storage

The Zoology storage consists of both a working area and a series of storage cabinets. Hides and coverings of a vast number of animals are generally stored within metal cabinets with approximate dimensions of 59”W x 40”H x 38”D and shown in Figure 2.11. The cabinets are stacked two high and in a long row on rails so that rows can be collapsed,

providing access to one row at a time. Rubber gaskets are placed all along the doors to the cabinets, thus providing a more complete seal. For scientific study, the animals are taken from the storage cabinets and placed on workbenches where they can be more easily examined. Two general areas of Zoology were monitored, one on the third floor of the Museum and the other on the second floor mezzanine directly below the third floor location. Initially only the temperature and relative humidity of the work areas were recorded, with Zoology #1 referring to the third floor location and Zoology #2 to the mezzanine location. At a later date, the inside of the metal storage cabinets were also monitored with Zoology #1A referring to a cabinet on the third floor located closely to Zoology #1, and Zoology #2A referring to a cabinet on the mezzanine located closely to Zoology #2.



Figure 2.11 Photo of a typical storage cabinet in the Zoology department.

2.3.1.7 Entryway

One temperature and relative humidity logger was placed in Hall 13, which is located on the ground floor facing Stanley Field Hall, the main central hall of the Museum. It is also located near the south entrance of the Museum, where large amounts of unconditioned air can enter the building as visitors and staff enter and leave the building. Data from this location will be referred to as “Hall 13”.



Figure 2.12 Photo of Hall 13 with the location of the T/RH logger highlighted.

2.3.1.8 Roof of the Museum

A final temperature and relative humidity logger was placed on the east side of the roof of the Museum to provide information on the air entering the HVAC system. The

logger was placed underneath air intake ducting to partially shield it from the elements. This location will be referred to as the “Roof”.

CHAPTER 3

Temperature and Relative Humidity Results**3.1 General Overview**

The results of the long-term temperature and relative humidity data logging for the storage and display areas will be presented and discussed. The results are summarized in a table of the winter and summer, high and low temperatures and relative humidities. Hourly averaged data are then presented for comparisons of locations within the museum as well as for comparisons during different times of the year. Psychrometric charts of a typical winter and summer day are shown to illustrate the conditioning of outdoor air by the HVAC system of the Museum. An analysis of the fluctuations in a day, week, and month for the different monitoring locations is then presented.

3.2 Typical Winter and Summer Values

Table 3.1 and Table 3.2 contain the temperature and relative humidity extremes with corresponding monthly ranges for a winter and summer month, respectively. January and July were chosen as they were the coldest and hottest outdoor months of the year. The winter data inside the Somalian Ass case comes from the month of February as the T/RH logger was not installed until then.

Table 3.1 Temperature and relative humidity highs and lows for the month of January.

LOCATION	T_{AVE} (°F)	T_{HI} (°F)	T_{LO} (°F)	RH_{AVE} (%)	RH_{HI} (%)	RH_{LO} (%)
Roof	26.0	54.9	-4.9	81	100	52
Anthro#1	73.4	74.5	71.1	46	51	40
Anthro#2	66.1	68.3	64.7	33	42	31
Zoo#1	79.1	83.7	75.2	15	27	8
Zoo#2	75.7	80.6	71.2	15	27	9
Inside Chinese	71.6	75.9	66.9	21	29	17
Outside Chinese	72.1	76.3	67.9	20	33	14
Inside S. Ass	81.5*	83.2*	80.2*	21*	22*	20*
Outside S. Ass	80.9	83.7	79.1	15	28	10
Inside Lion	71.8	73.5	69.6	22	26	17
Outside Lion	71.8	74.7	69.6	20	34	12
Inside Water	72.4	75.4	69.3	25	28	22
Behind Water	71.6	77.0	66.5	24	38	17
Hall 13	73.0	79.9	68.8	20	33	11

* Data are from month of February

Table 3.2 Temperature and relative humidity highs and lows for the month of July.

LOCATION	T_{AVE} (°F)	T_{HI} (°F)	T_{LO} (°F)	RH_{AVE} (%)	RH_{HI} (%)	RH_{LO} (%)
Roof	82.0	111.5	62.1	69	100	20
Anthro#1	70.7	72.1	68.2	52	62	49
Anthro#2	71.2	72.5	69.1	51	64	45
Zoo#1	71.0	74.4	68.4	61	76	46
Zoo#2	70.9	73.4	68.5	58	78	46
Inside Chinese	75.8	77.6	74.3	45	49	42
Outside Chinese	75.5	79.4	72.7	51	63	44
Inside S. Ass	77.0	79.1	74.8	33	37	29
Outside S. Ass	75.7	78.0	73.5	51	65	38
Inside Lion	72.1	75.7	70.0	50	54	45
Outside Lion	70.9	75.4	68.1	54	64	43
Inside Water	80.9	84.2	79.2	50	57	46
Behind Water	82.0	85.4	79.2	47	59	34
Hall 13	71.9	74.9	70.0	58	70	47

The tables highlight several facts concerning the hourly-averaged data. Spatial variations in temperature and relative humidity exist throughout the Museum. In general, neither temperature nor relative humidity are controlled to the recommended standards presented in Chapter 1. The more dangerous infractions, in terms of artifact lifetime, are: 1) the high temperatures in the Somalian Ass area and Zoology storage, 2) the extremely low relative humidities in winter throughout most of the monitored areas, 3) high relative humidity in the Zoology area during the summer and 4) the wide range and corresponding large fluctuations of relative humidity at each location throughout a month. These data are discussed in more detail below.

3.3 Hourly-Averaged Data

The temperature and relative humidity as a function of time are presented for each monitored location. The data were originally acquired in 15 minute intervals but were averaged to obtain hourly values. With the exception of the Museum roof data (i.e. outdoor conditions), all the plots are shown with the same scaling to allow for comparison between locations. The temperature and relative humidity extremes for the entire data history are also identified on each graph along with the day and hour at which they occurred. Table 3.3 lists each location presented along with the period of environmental monitoring.

3.3.1 Storage Areas

The environmental conditions for the Anthropology and Zoology storage areas are shown in Figure 3.1 through Figure 3.12. These two areas represent the extremes in environmental control currently available at the Museum, where Anthropology is maintained

with fairly tight control and Zoology with little control over temperature and no control over relative humidity.

Table 3.3 Monitoring locations with start and stop date of data acquisition.

LOCATION	STARTED LOGGING ON	ENDED LOGGING ON
Anthropology #1	12/18/98	8/17/99
Anthropology #2	12/18/98	8/17/99
Zoology #1	12/18/98	11/4/99
Zoology #2	12/18/98	11/4/99
Zoology #1A	8/17/99	11/4/99
Zoology #2A	8/17/99	11/4/99
Inside Chinese case	12/18/98	11/4/99
Outside Chinese case	12/18/98	11/4/99
Inside Somalian Ass case	2/18/99	11/4/99
Outside Somalian Ass case	12/18/98	11/4/99
Inside Lions of Tsavo case	12/18/98	11/4/99
Outside Lions of Tsavo case	12/18/98	11/4/99
Inside Watering Hole diorama	12/18/98	11/4/99
Behind Watering Hole diorama	12/18/98	11/4/99
Hall 13	12/18/98	11/4/99
Roof	12/18/98	11/4/99

Anthropology #1 is controlled more closely to the temperature and relative humidity set points of the storage area, which are 72°F±2°F and 50%±5%, respectively, than Anthropology #2. The temperature history for Anthropology #1, shown in Figure 3.1, suggests that set point is actually 73°F. This discrepancy between desired and actual set point may be due to a difference in calibration between the T/RH loggers and the thermostat of the storage area. During the heating season, roughly from 12/18/98 through 5/1/99, the relative humidity set point of Anthropology #1 appears to be 45% before rising to 50% during the summer cooling season. Except for some brief daily excursions, the relative humidity range stays within ±5% of the set point as presented in Figure 3.2. However, it

seems to be more difficult to control the humidity in the area during the winter months than during the summer months as evidenced by the reduced variation in both temperature and relative humidity after May 1. The sharp fluctuations in relative humidity on a nearly daily basis from mid-January to early April are partially due to the lack of control in temperature, which is seen to jump back and forth between 71°F and 74°F.

Anthropology #2, which is separated from Anthropology #1 by a wall, exhibits less daily variability in both temperature and relative humidity but is centered about values different than the above specified set points. Temperature ranges around 65°F in winter and spring then climbs to 72°F in summer while the relative humidity is about 35% in the winter before rising to 50% in the summer. The lower relative humidity of Anthropology #2 compared to Anthropology #1 during the winter months reveals that less humidification of the supply air is provided for that area.

Zoology #1 and #2 behave very similarly to each other over the period of data acquisition, as seen in Figure 3.5 through Figure 3.8. The variations in both the temperature and relative humidity traces are severe on both short and long time scales. In the winter, Zoology #1 is generally one to two degrees hotter than Zoology #2. This situation occurs because Zoology #1 is one floor above Zoology #2. Temperature fluctuates are less in Zoology #2 than Zoology #1 due to the construction of Zoology #2, which resulted in poor airflow distribution and thus stagnant air. The relative humidity traces are nearly identical, with a minimum of about 10% occurring in early January and a maximum of approximately 65% in the beginning of August. It is these very low relative humidities that are most likely causing the damage seen in teeth and shells in this area (Williams, 1991). The anisotropic nature of teeth results in the buildup of stress during desiccation resulting in cracking and

breakage. The monthly relative humidity average, shown in Figure 3.6 overlaid in a thick line, resembles a sinusoid in its progression from low values in the winter to high values in the summer and back. This average RH curve is typical for the inside of the Museum, as will be shown in the following figures. The low moisture content of the outside air in winter and high moisture content in the summer cause this behavior.

Figure 3.9 through Figure 3.12 present the temperature and relative humidity measurements made inside the metal storage cabinets in Zoology. The temperatures measured inside and outside the storage cabinets follow identical trends. The interior measurements exhibit less variation and often do not reach the same level of extreme temperatures. The major difference between the interior and exterior cabinet environment is seen in the relative humidity traces. The inside relative humidities are nearly flat and in no way appear to respond to the dramatic changes that are occurring in the workspace area. From September 1, 1999 to November 1, 1999, the average RH in Zoology #1 drops from 50% to 25%. In the same span of time, the RH in Zoology #1A dropped from roughly 38% to 36%. The sharp downward spike in the RH history for Zoology #1A seen around October 22 is most likely due to the cabinet door being opened for some period of time as the RH drops to the level recorded outside the cabinet. The behavior of the relative humidity inside the cabinets is most likely due to the extreme tightness of the cabinets as well as to the presence of hygroscopic materials (hides and furs) which adsorb and desorb water. This adsorptive capacitance of organic materials will be further addressed in Chapter 5.

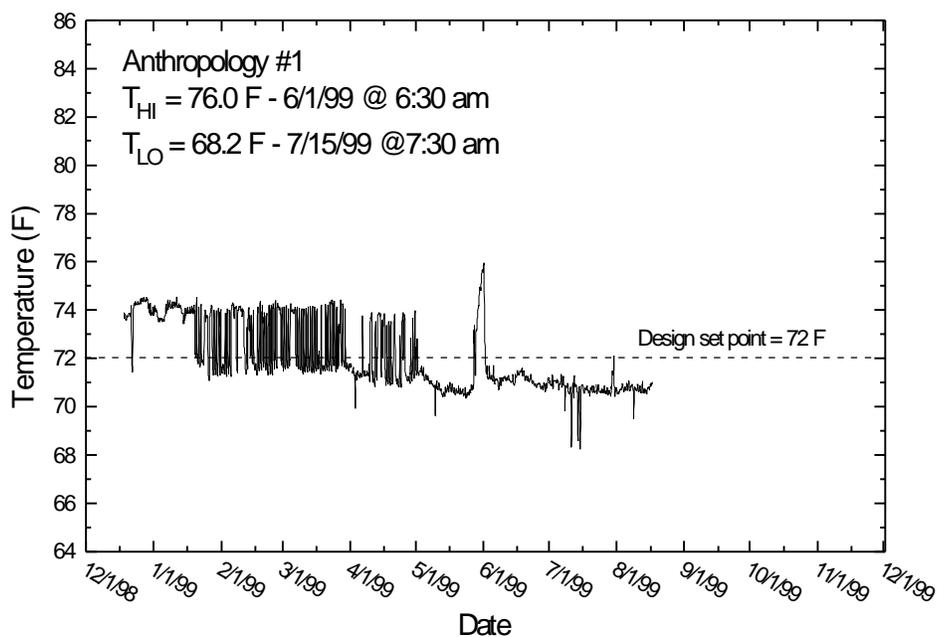


Figure 3.1 Temperature history for Anthropology #1 storage area.

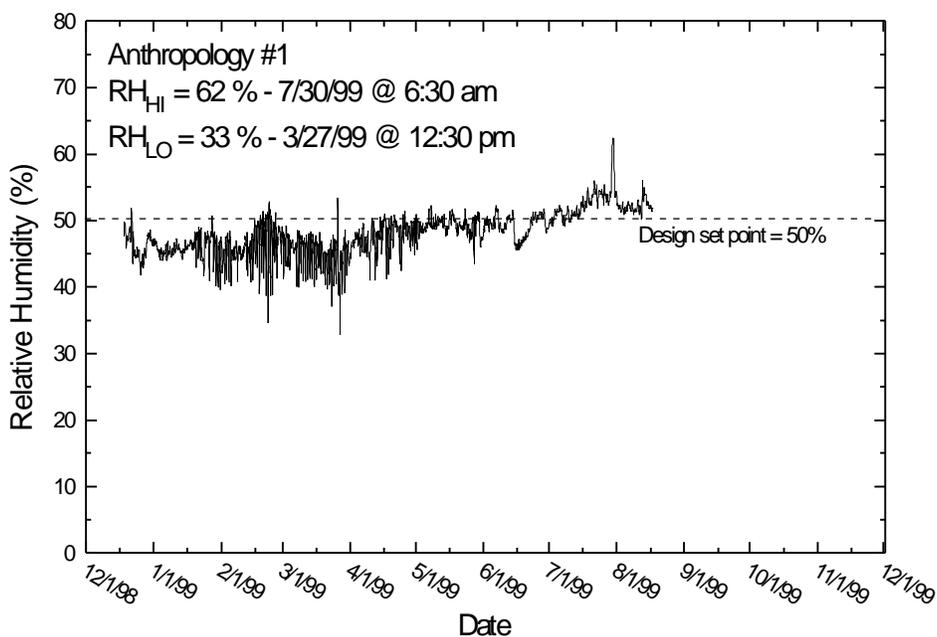


Figure 3.2 Relative humidity history for Anthropology #1 storage area.

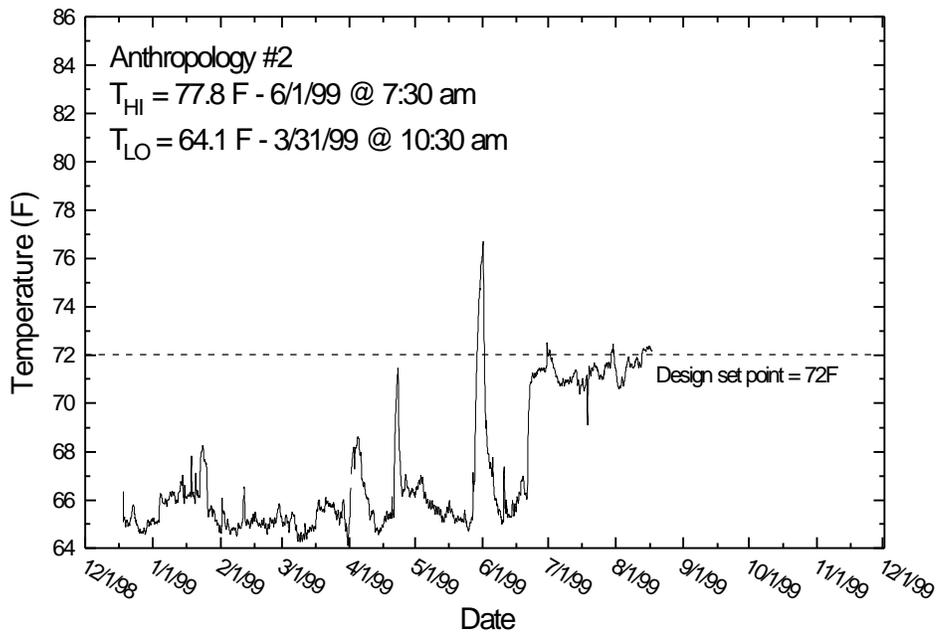


Figure 3.3 Temperature history of Anthropology #2 storage area.

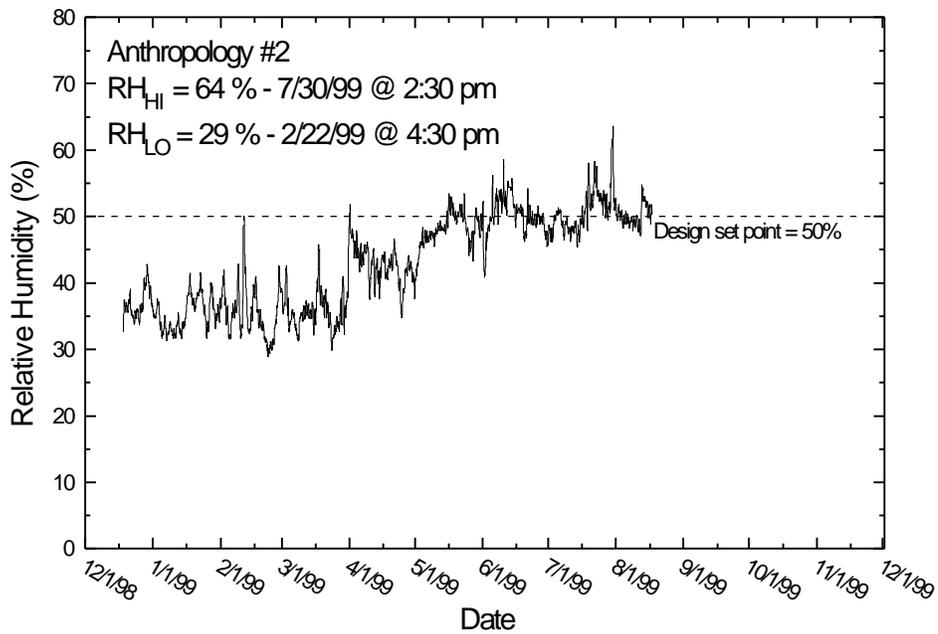


Figure 3.4 Relative humidity history for Anthropology #2 storage area.

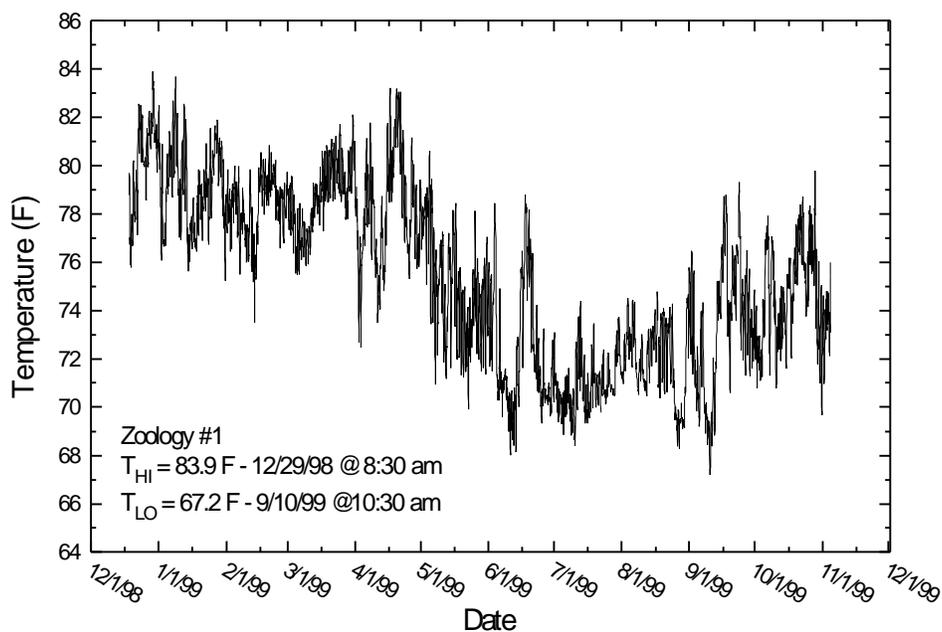


Figure 3.5 Temperature history for Zoology #1 storage area.

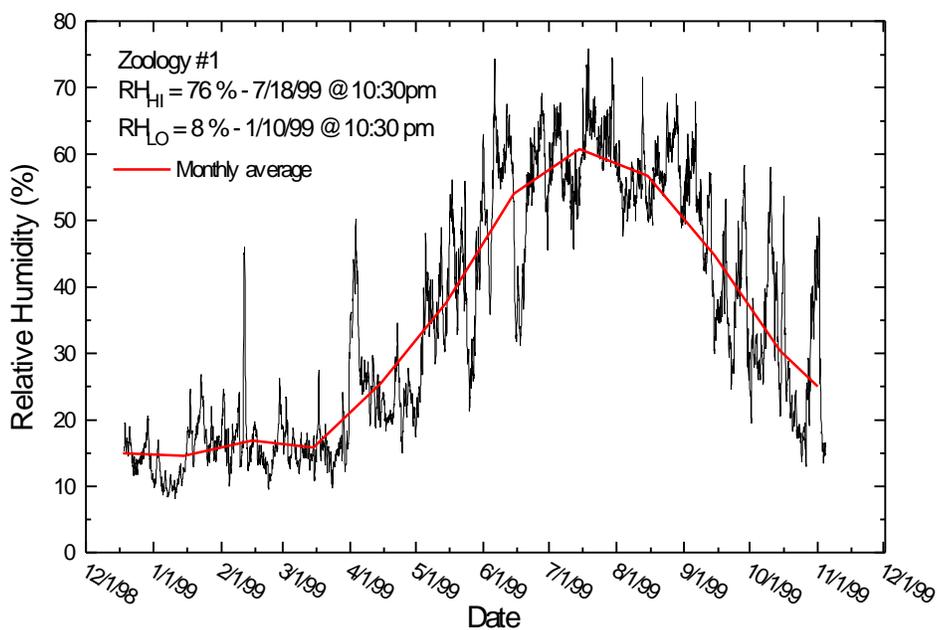


Figure 3.6 Relative humidity history for Zoology #1 storage area with monthly RH average superimposed.

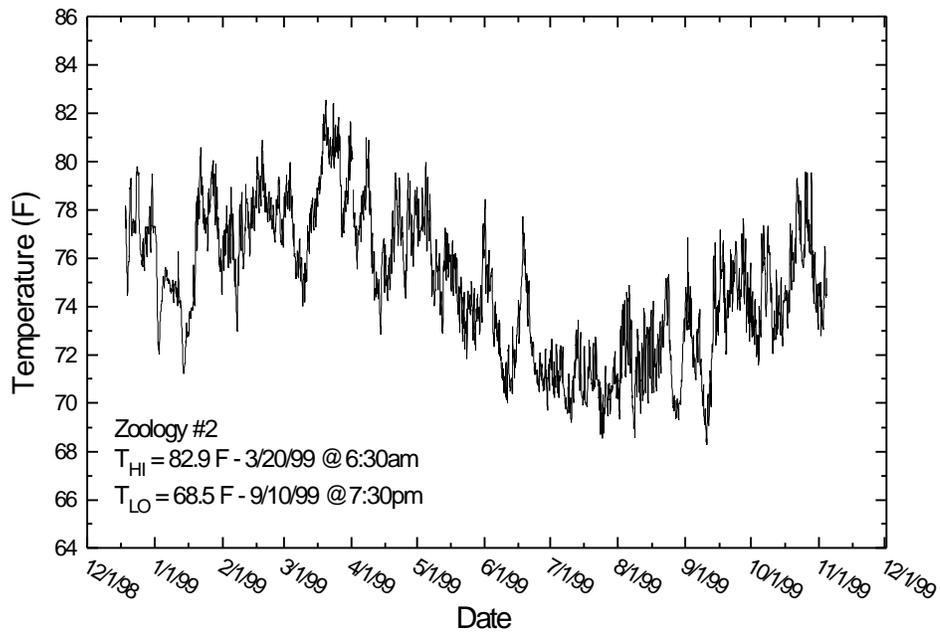


Figure 3.7 Temperature history for Zoology #2 storage area.

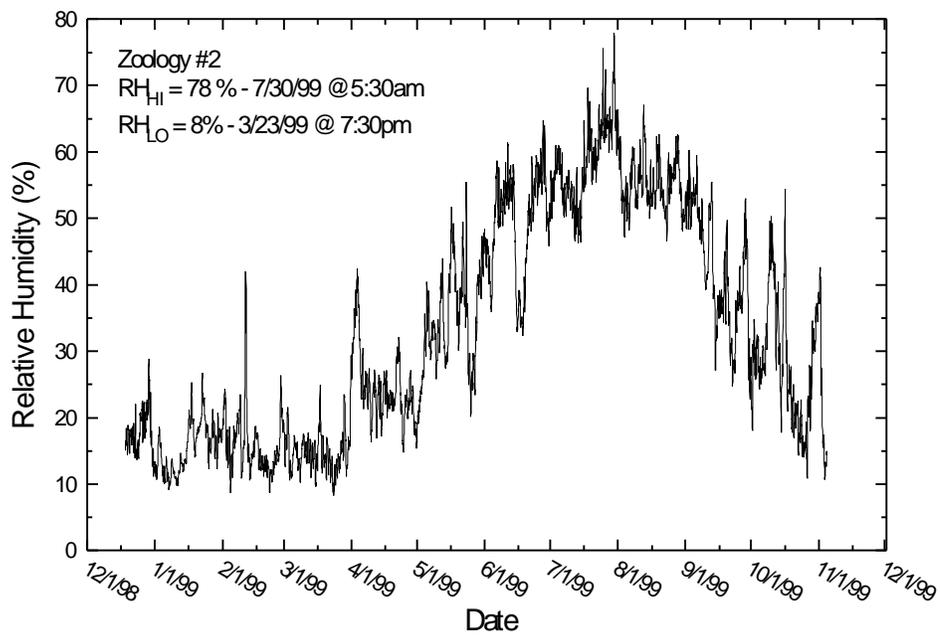


Figure 3.8 Relative humidity history for Zoology #2 storage area.

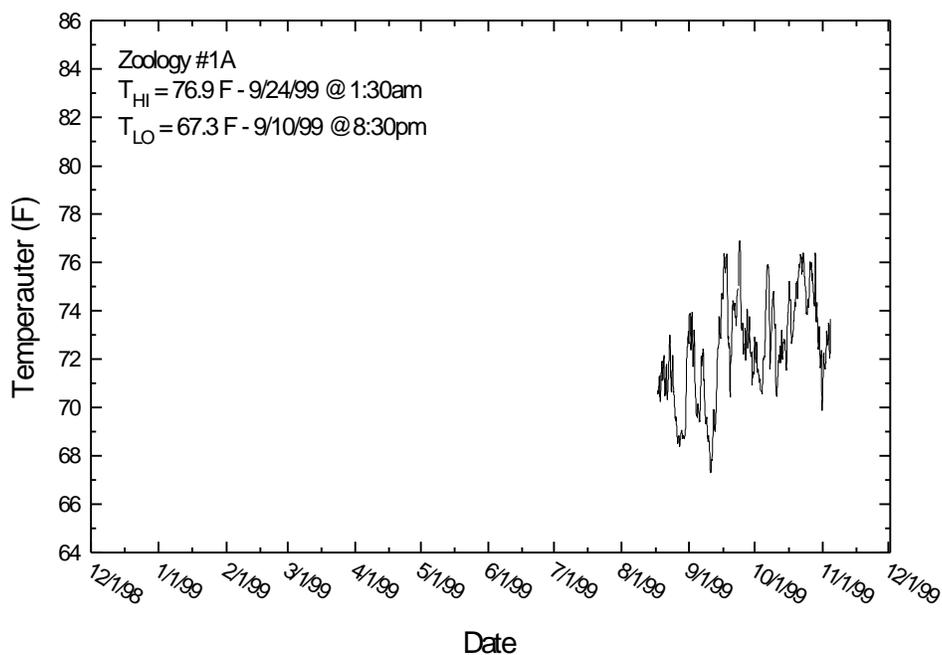


Figure 3.9 Temperature history for Zoology #1A – storage cabinet.

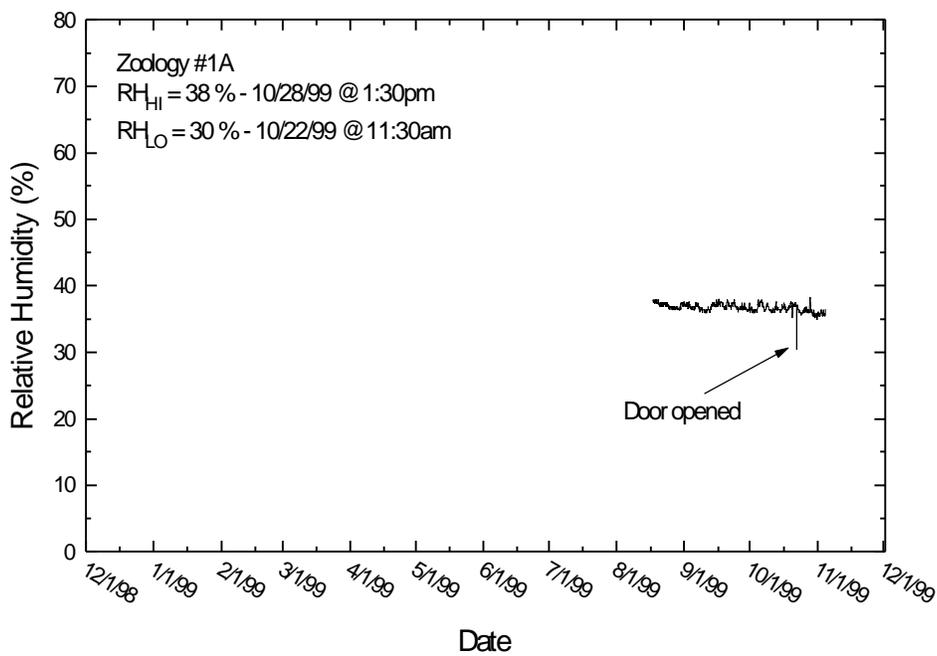


Figure 3.10 Relative humidity history for Zoology #1A – storage cabinet.

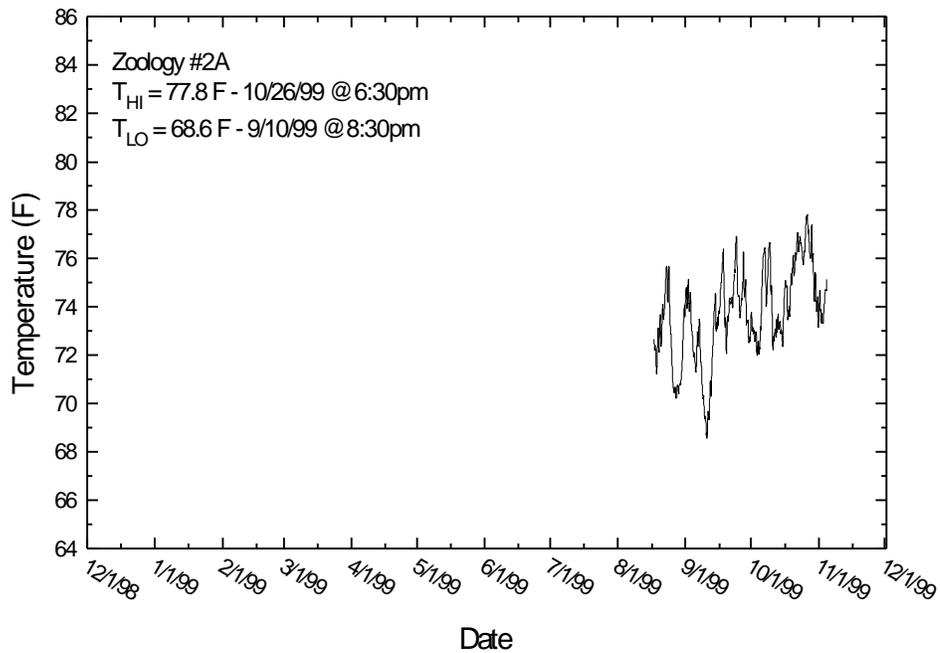


Figure 3.11 Temperature history for Zoology #2A – storage cabinet.

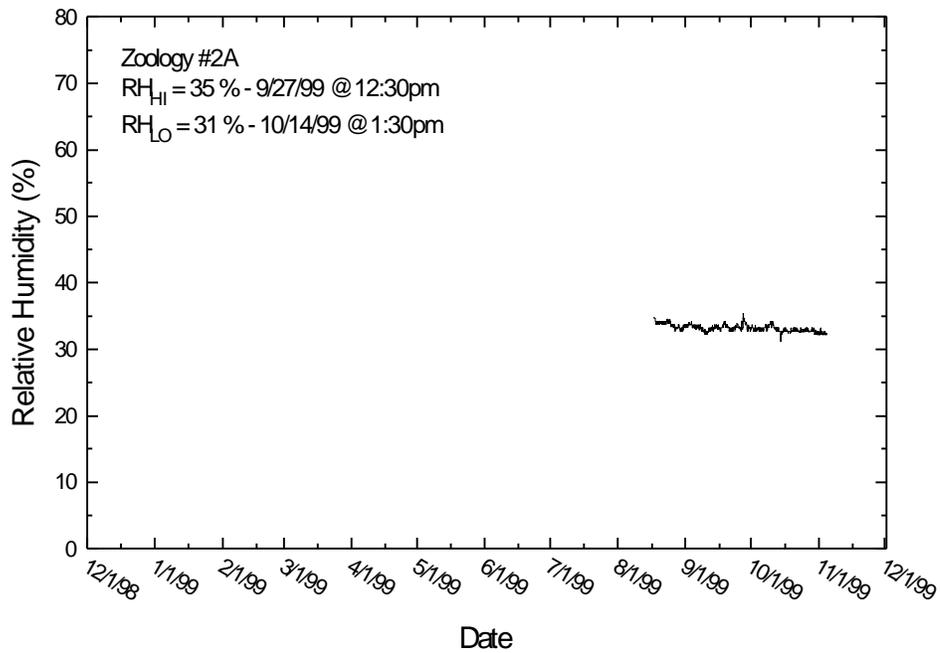


Figure 3.12 Relative humidity history for Zoology #2A – storage cabinet.

3.3.2 Display Areas

Figure 3.13 through Figure 3.29 contain the temperature and relative humidity histories for inside and outside the four display cases examined: the Chinese case, the Somalian Ass case, the Lions of Tsavo case and the Watering Hole diorama. Notice that the general shape of the relative humidity curve for both the inside and outside of all the cases follows the same sinusoidal-like shape evident for Zoology #1 storage.

For each of the four cases, the fluctuations in relative humidity (and to a lesser degree temperature) inside the cases are reduced compared to that measured outside each case. The Somalian Ass case exhibits the highest level of fluctuation reduction, followed by the Watering Hole and Lions of Tsavo with the Chinese case showing the least amount of fluctuation reduction. These differences in behavior inside the case are due to differences in case tightness and air exchange rate, which will be discussed further in Chapter 4. For the Somalian Ass case, short-term fluctuations on the order of both a day and a week have been eliminated inside the case, whereas for inside the Lions of Tsavo and Watering Hole cases, the fluctuations on the order of a day are removed. The Chinese case initially shows little attenuation of relative humidity inside the case, with only the most extreme excursions eliminated. However, starting around June 1 and for the duration of the summer, the fluctuations are greatly reduced and then increase once autumn begins.

As mentioned in Chapter 2, the Chinese case is a new addition to the Museum. It was discovered to be poorly sealed as is attested by its behavior from mid-December to late May as well as the degree to which the RH inside the case follows that measured outside the case. In mid-May, steps were taken to reseal the case, resulting in improved performance during the summer. In addition to tightening the case, a passive desiccant is used to help maintain

the case interior RH to 45%. However, the desiccant seems to be doing little to prevent the downward plunge in RH as autumn moves towards winter. Figure 3.17 contains the relative humidity history for outside the Chinese case along with the desired case interior set point of 45%. From the figure, one can see that for roughly 9 months of the year, the desiccant inside the case will have to desorb water in order to maintain the interior RH at 45%. Only during the summer months from June to September does the desiccant adsorb moisture. As a result, if a sufficient amount of desiccant is not used it will have to be reconditioned at least once a year for moisture addition so that the desired set point can be maintained throughout the heating season. Another option is simply to use more desiccant to control the interior space.

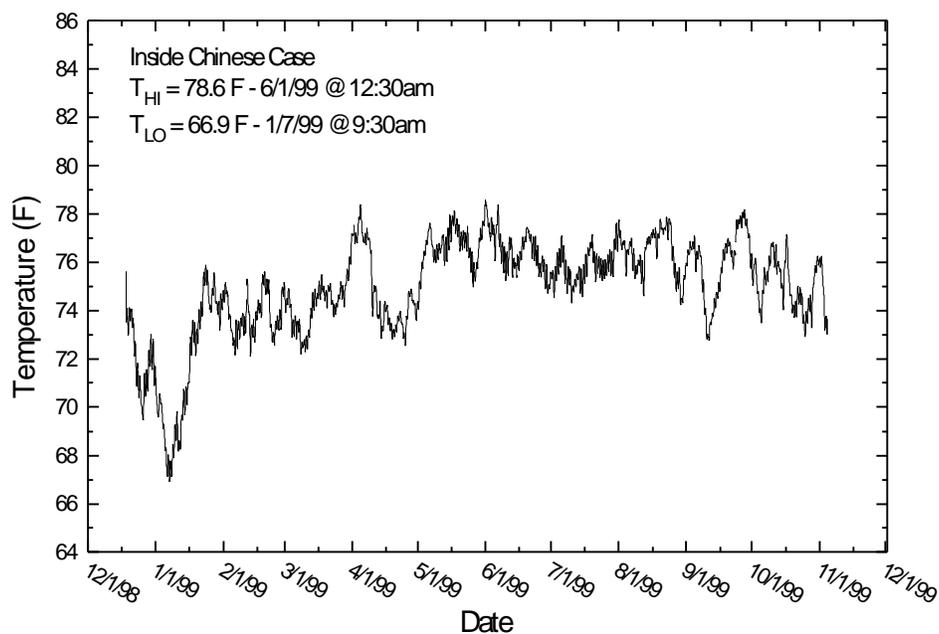


Figure 3.13 Temperature history for inside the Chinese case.

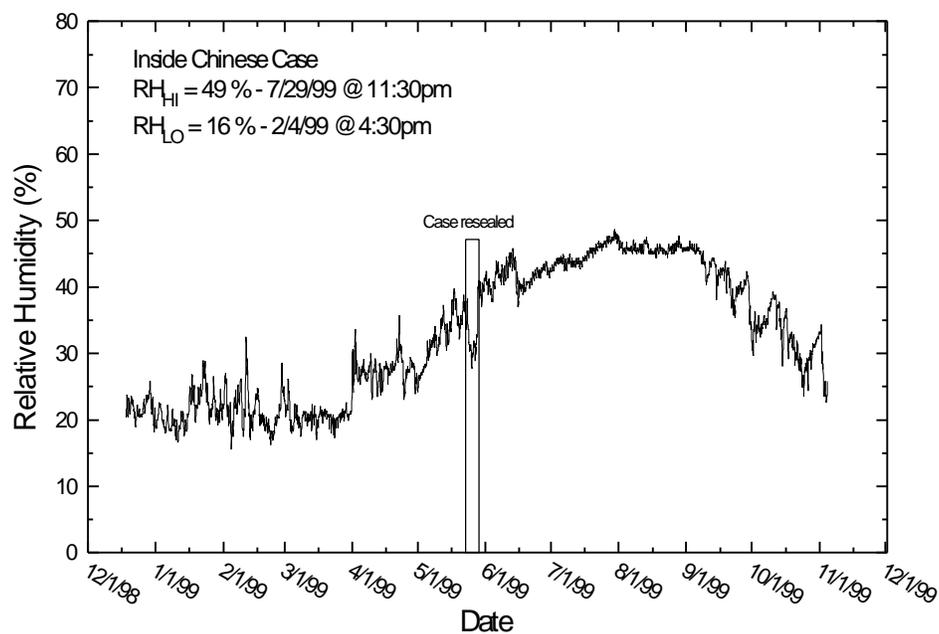


Figure 3.14 Relative humidity history for inside the Chinese case.

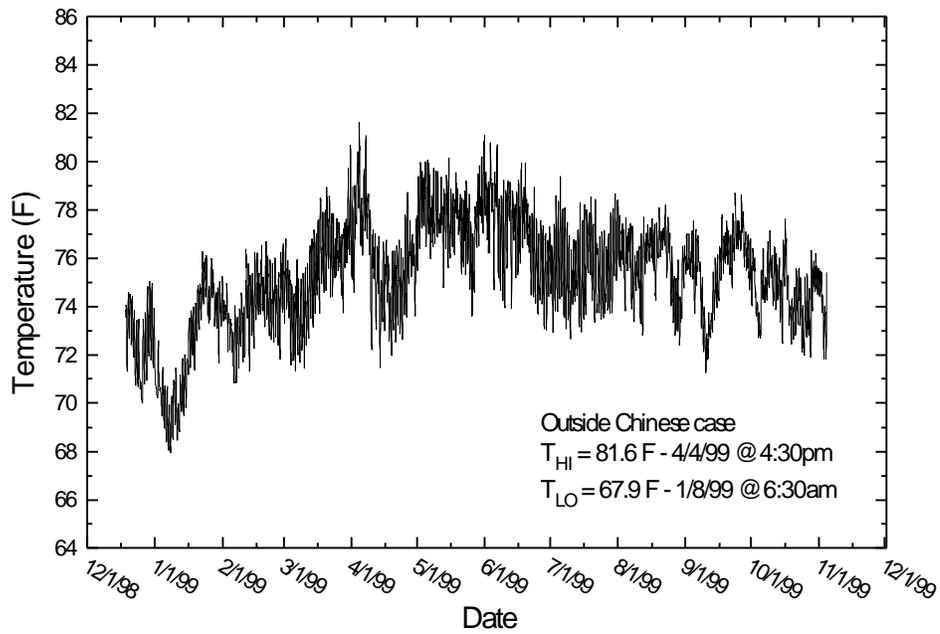


Figure 3.15 Temperature history for outside the Chinese case.

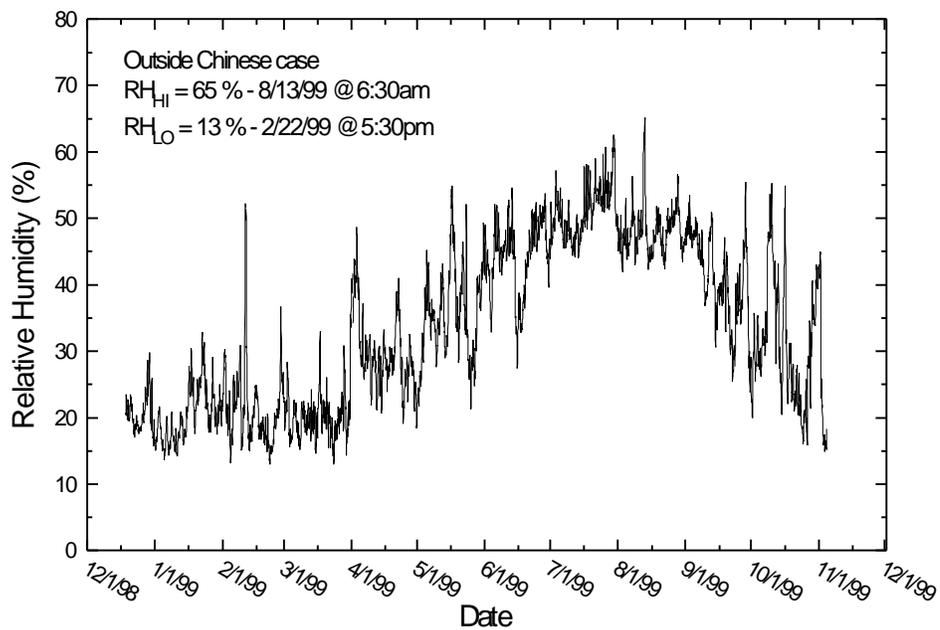


Figure 3.16 Relative humidity history for outside the Chinese case.

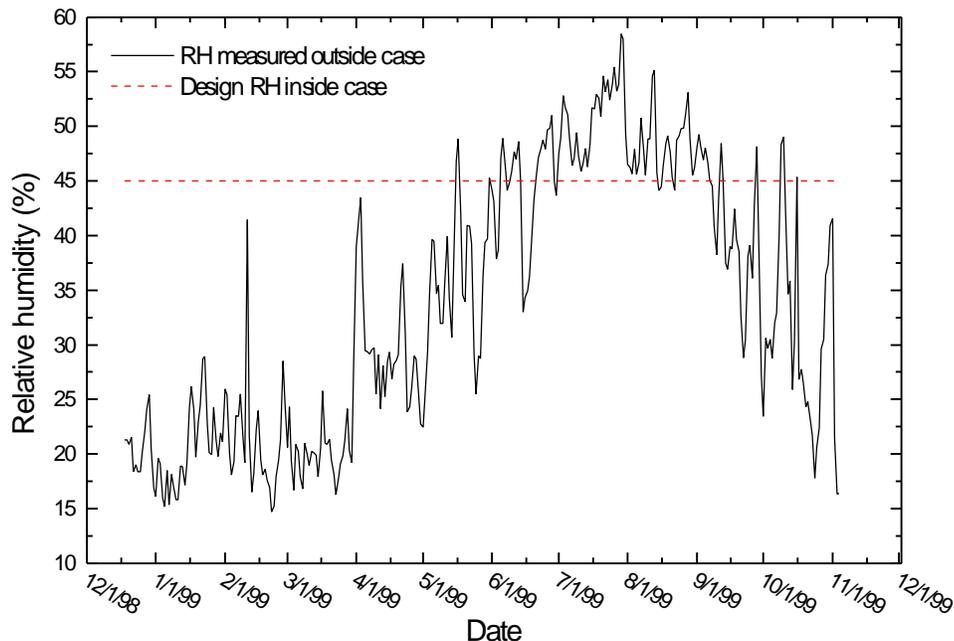


Figure 3.17 Measured relative humidity outside the Chinese case and the desired set point of 45% inside the case to illustrate the desorption and adsorption time periods available.

It is also interesting to note the different temperatures recorded for Hall 21 and Rice Hall, which contain the Somalian Ass, Lions of Tsavo and Watering Hole areas, since the cases are located in reasonably close proximity to each other within the Museum. For the entire monitoring period, the temperature recorded in Hall 21 (outside the Somalian Ass case) is higher than that recorded in Rice Hall (outside the Lions of Tsavo case). In winter, the temperature difference ranges from 3°F-10°F, with Hall 21 averaging around 81°F and Rice Hall averaging between 72°F and 75°F. This temperature difference is most likely due to poor air circulation from Rice Hall to Hall 21, which occurred only through a 7 ft x 6 ft doorway in the wall separating the halls. In addition, an air distribution diffuser opens to the Lion area, leading to better mixing of the air and therefore more moderate temperatures.

Even though the T/RH logger in Hall 21 is also considered to be the outside logger for the Watering Hole diorama, the temperature inside the diorama more closely follows that measured behind the diorama in the utility space. The temperature history behind the diorama is different than that measured out in the display area because the exterior wall is next to the utility space as was shown in Figure 2.6. Since the spaces behind the diorama and in front of the diorama are only connected through a small 1-ft x 2-ft grate in an access door, little mixing of the air occurs. The diorama has more surface area facing the utility area behind it; therefore, its temperature is similar to that measured behind it. Similarly as was shown in Figure 2.5, the Lions of Tsavo case also has a utility space behind it that borders an exterior wall but the interior temperature of the case follows that measured outside the case in Rice Hall. Unlike the Watering Hole diorama, the utility area behind the Lion case is in good communication with the area in front of the case through a six foot clearance all around the case, as the walls do not reach entirely to the ceiling.

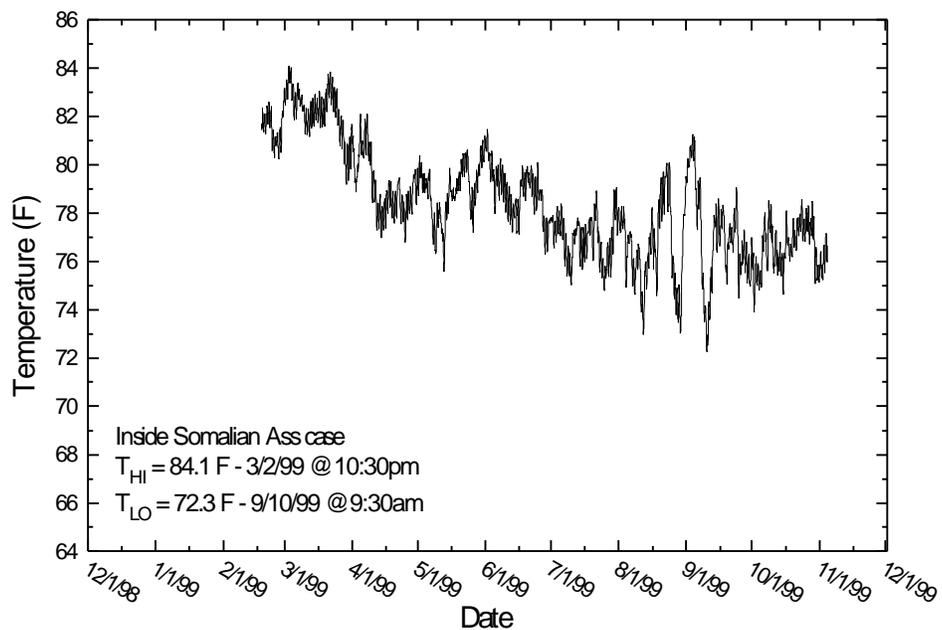


Figure 3.18 Temperature history for inside Somali Ass case.

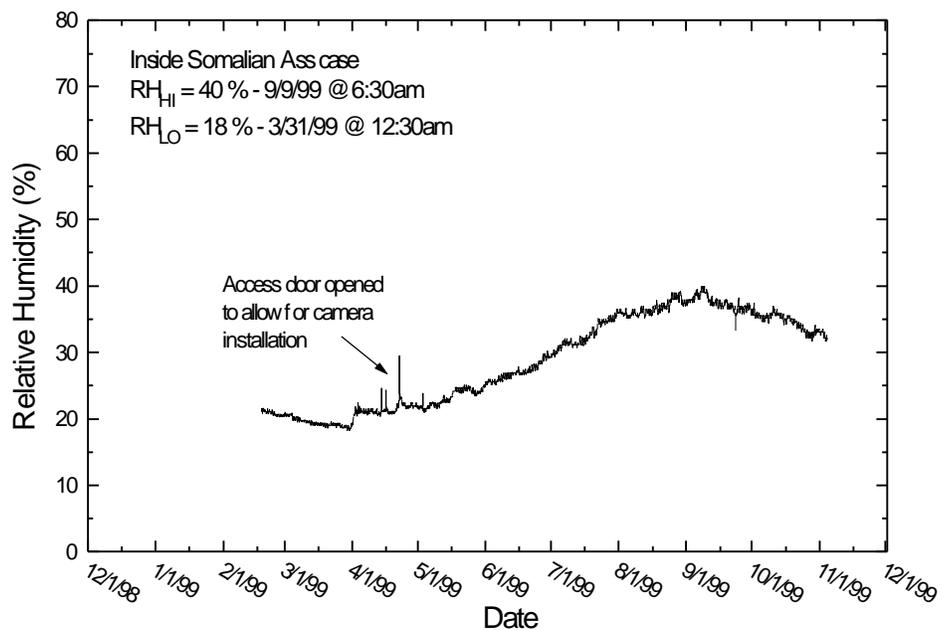


Figure 3.19 Relative humidity history for inside Somali Ass case.

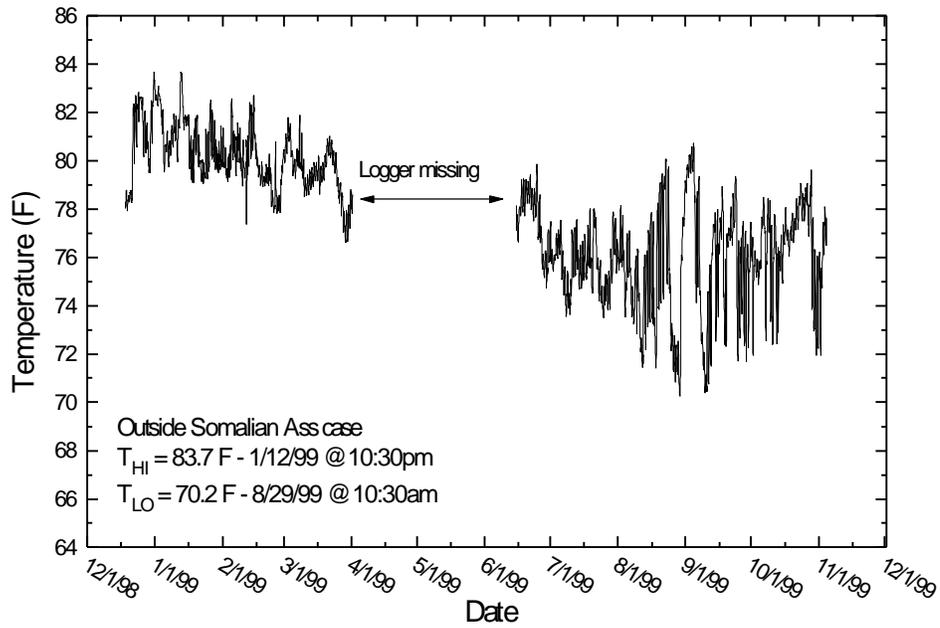


Figure 3.20 Temperature history for outside Somalian Ass case.

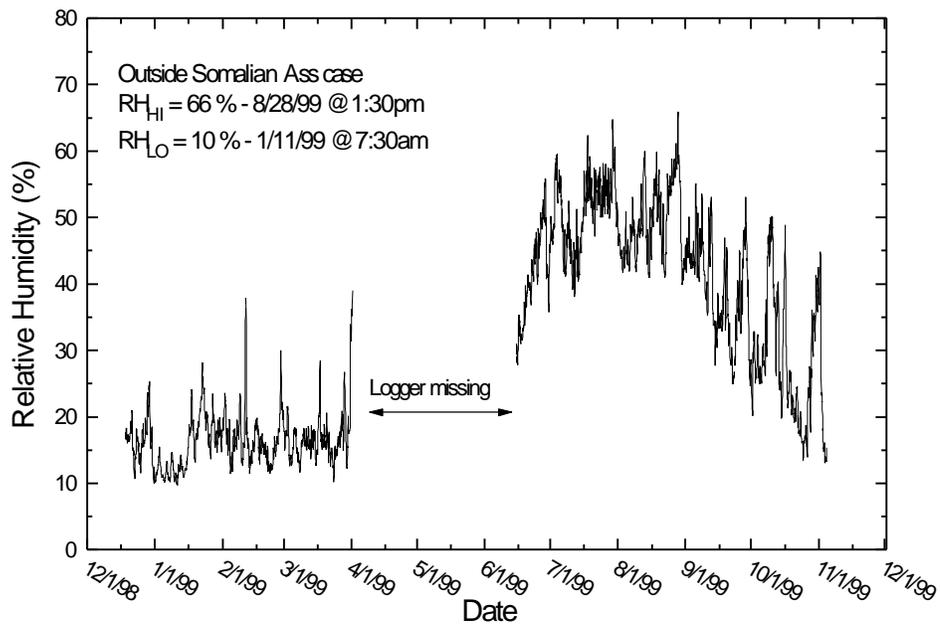


Figure 3.21 Relative humidity history for outside Somalian Ass case.

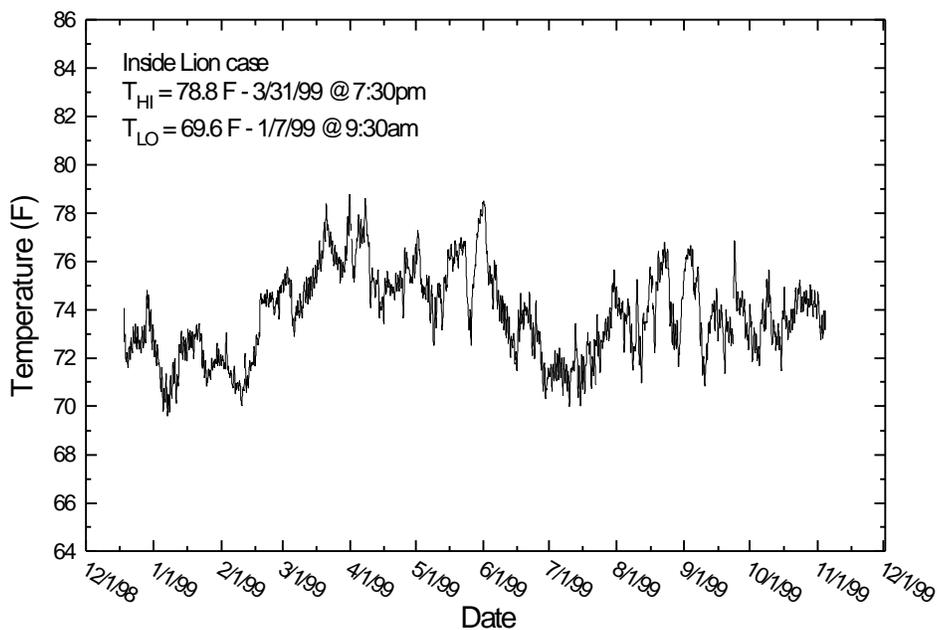


Figure 3.22 Temperature history for inside Lions of Tsavo case.

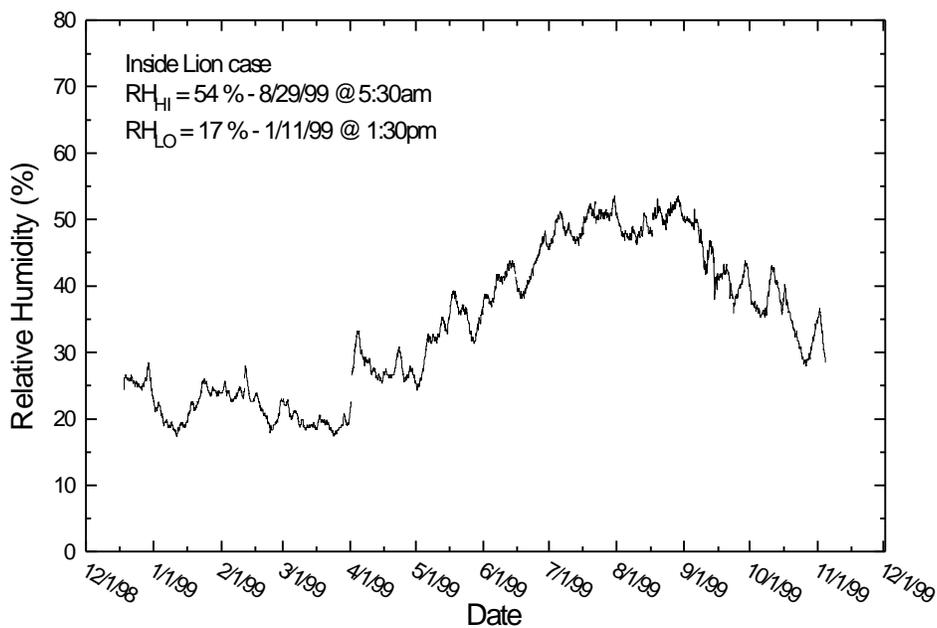


Figure 3.23 Relative humidity history for inside Lions of Tsavo case.

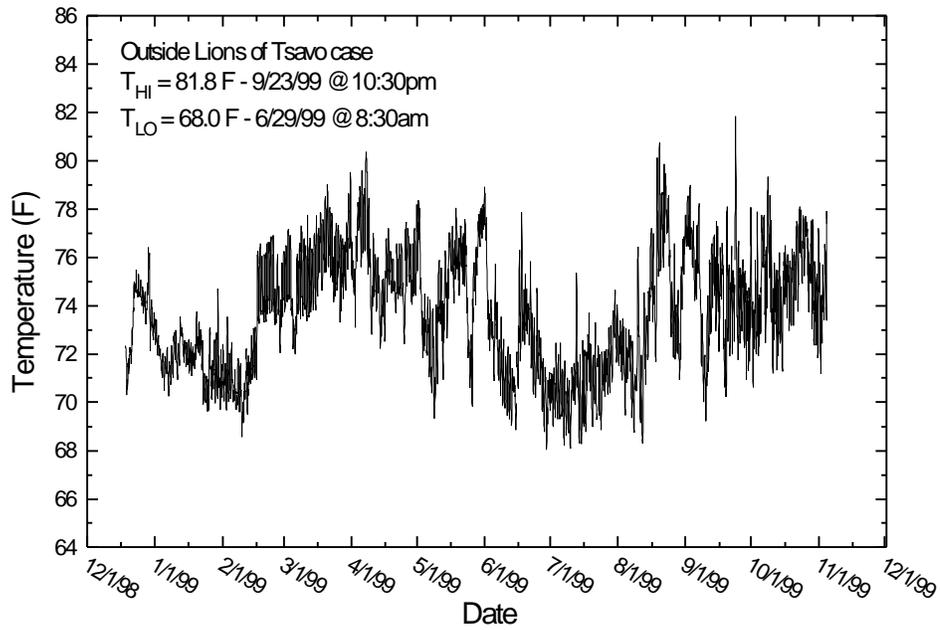


Figure 3.24 Temperature history for outside the Lions of Tsavo case.

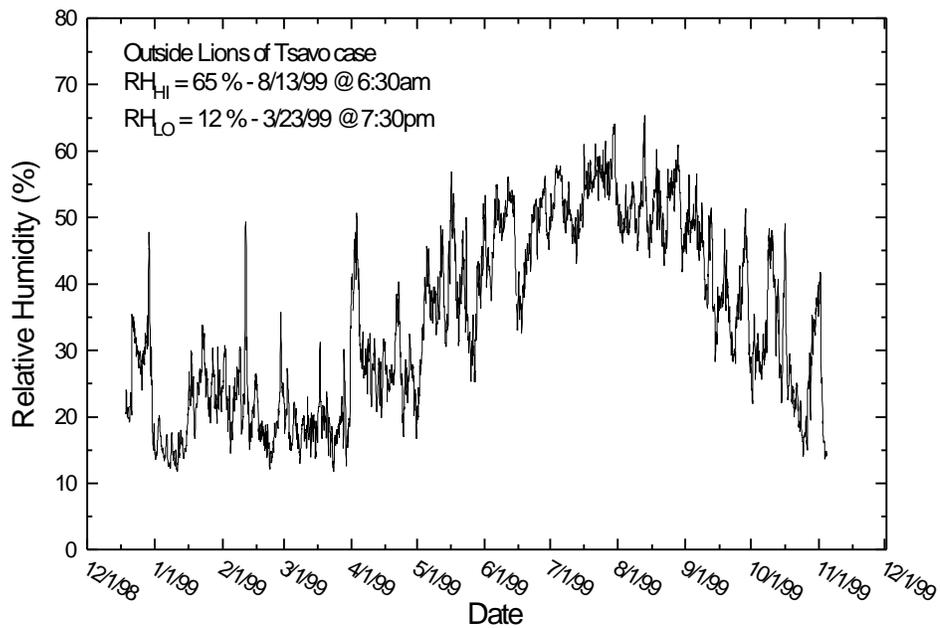


Figure 3.25 Relative humidity history for outside the Lions of Tsavo case.

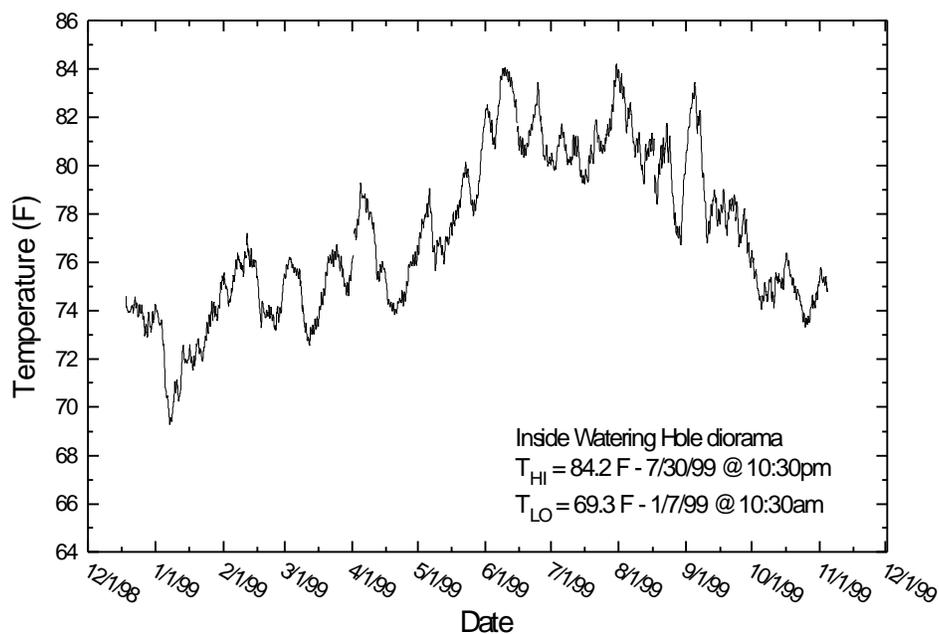


Figure 3.26 Temperature history for inside the Watering Hole diorama.

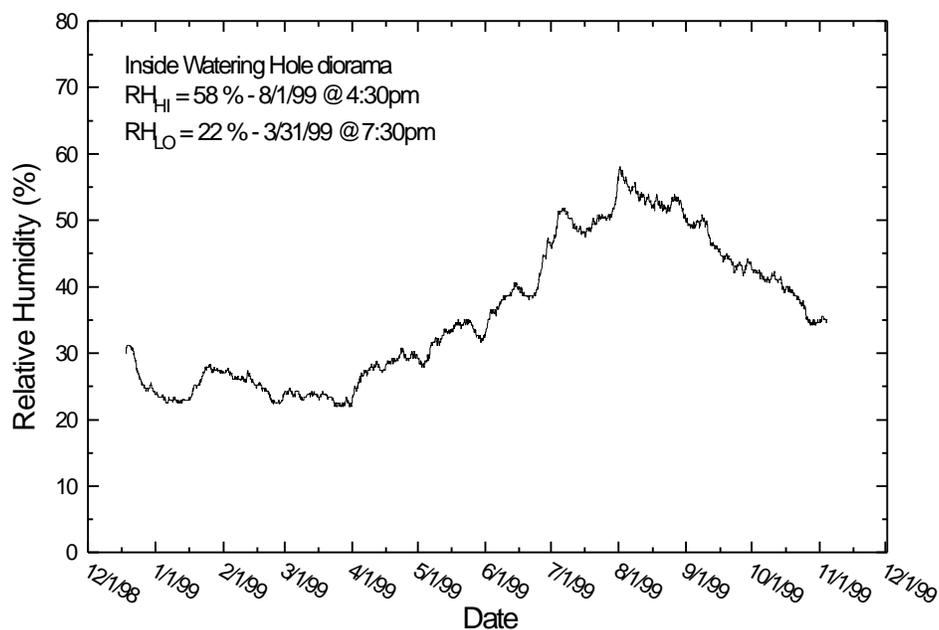


Figure 3.27 Relative humidity history for inside the Watering Hole diorama.

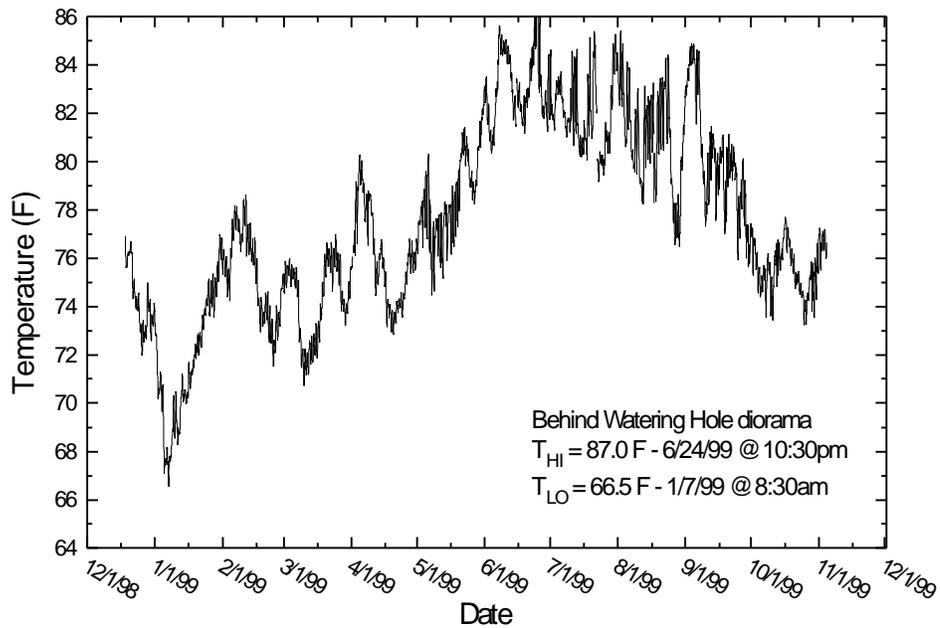


Figure 3.28 Temperature history for behind the Watering Hole diorama.

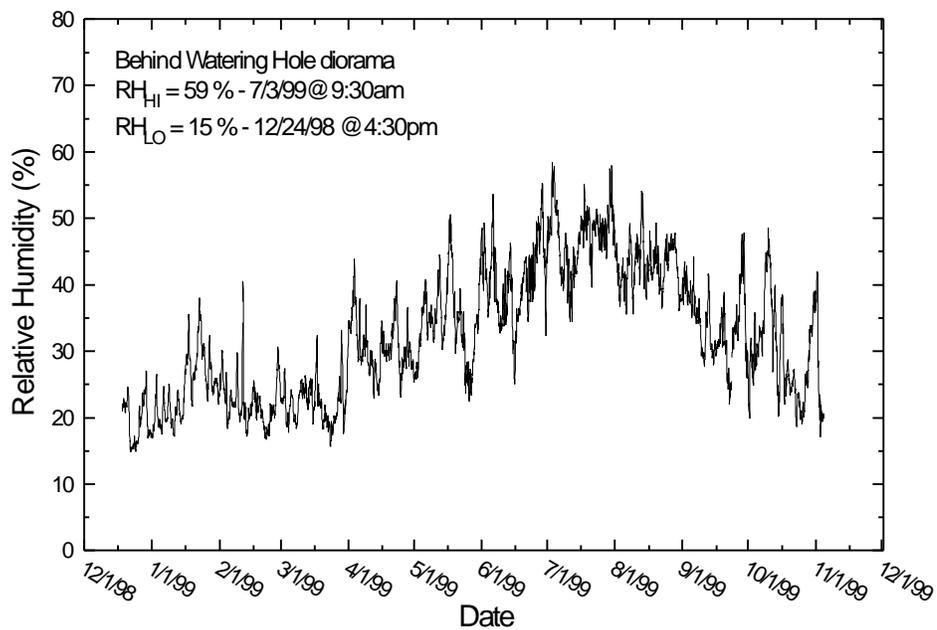


Figure 3.29 Relative humidity history for behind the Watering Hole diorama.

3.3.3 Entryway and Roof

The temperature and relative humidity of Hall 13 as a function of time are shown in Figure 3.30 and Figure 3.31. The temperature trace is very similar to that recorded outside the Chinese case due to the proximity of both locations to the large central hall of the Museum, Stanley Field Hall, as was shown in Figure 2.1. The relative humidity is like that seen in the Zoology storage area, with lows around 10% and highs around 65%.

Figure 3.32 and Figure 3.33 present the temperature and relative humidity histories of the rooftop location of the Museum. Overlaid on the temperature plot in Figure 3.32 is the humidity ratio of the outside air, which is lowest in the winter time and increases towards summer to a peak around early August. The relative humidity fluctuates greatly due to the large fluctuations in temperature and moisture content.

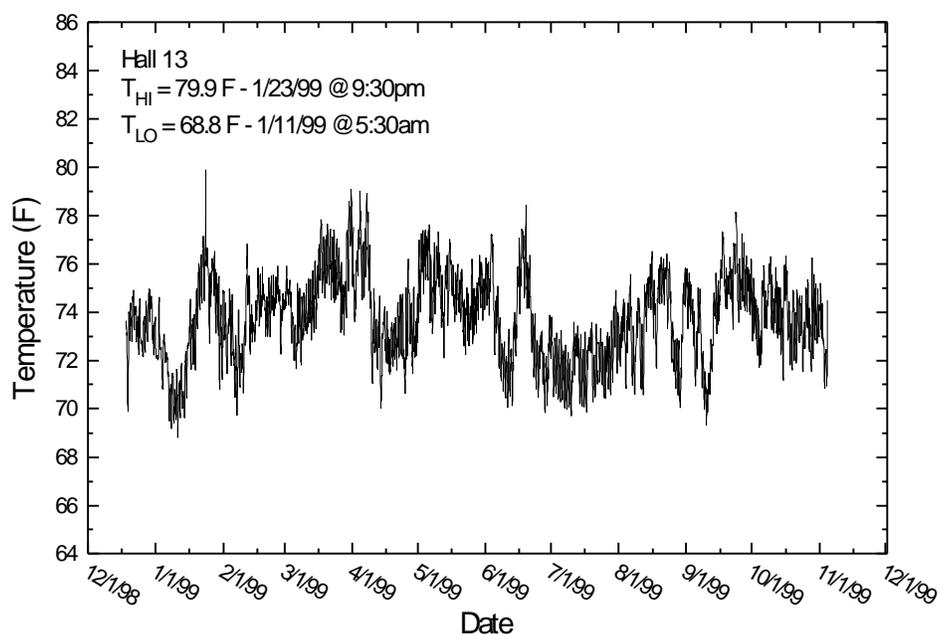


Figure 3.30 Temperature history for Hall 13.

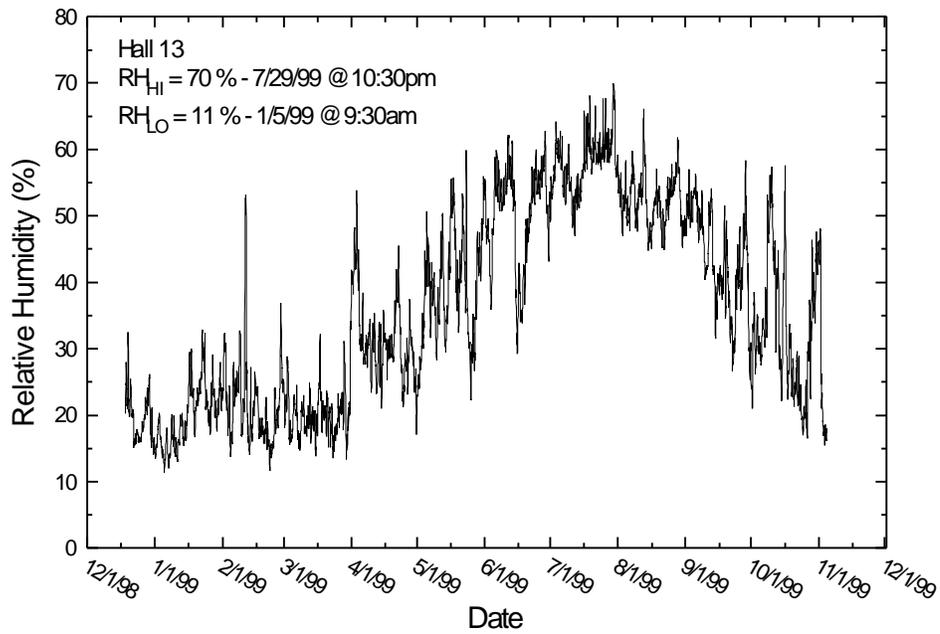


Figure 3.31 Relative humidity history for Hall 13.

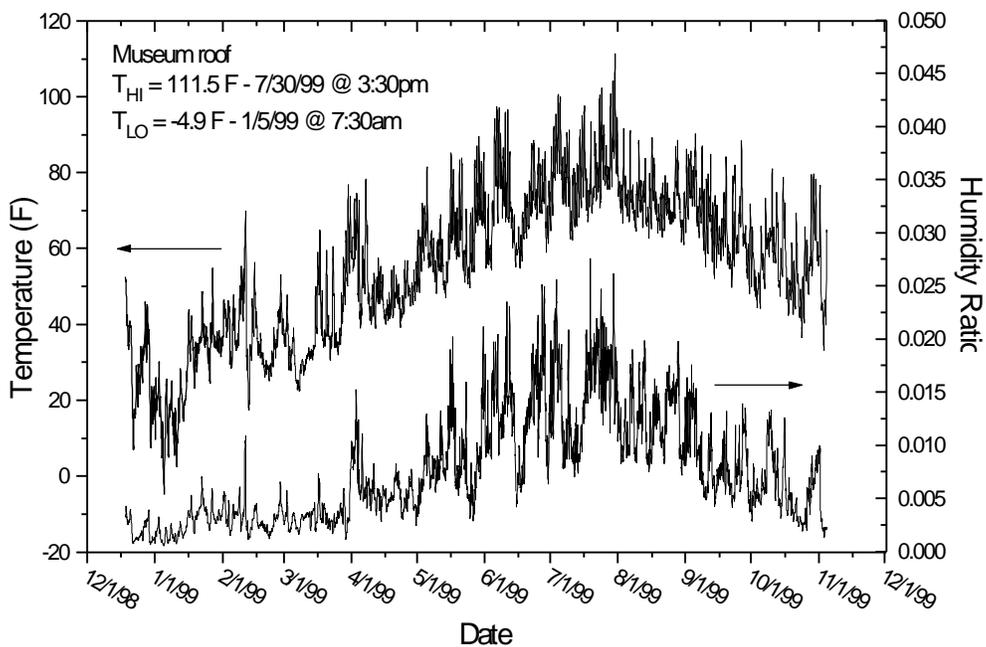


Figure 3.32 Temperature and humidity ratio history for the Museum roof.

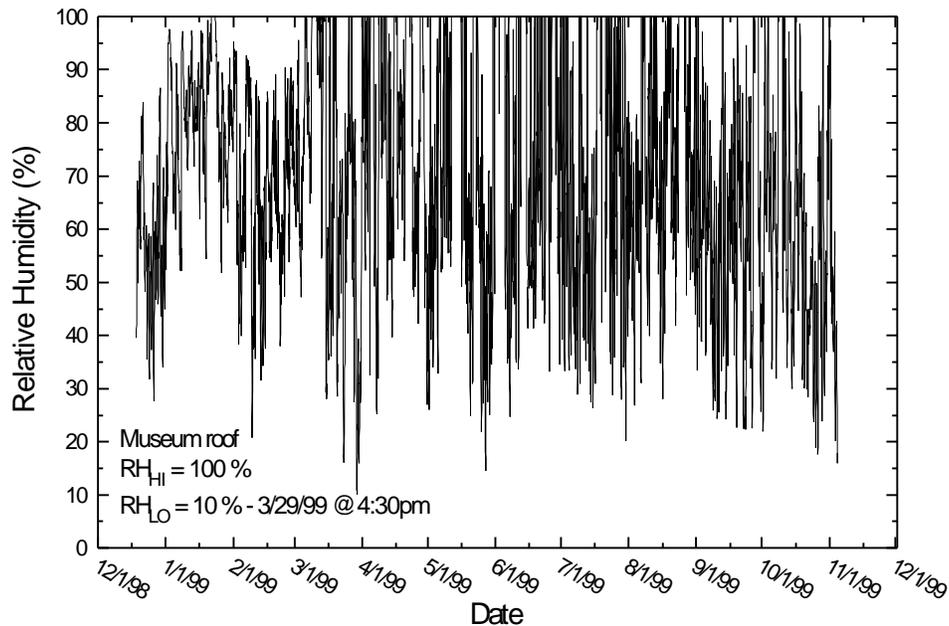


Figure 3.33 Relative humidity history for the Museum roof.

3.4 Psychrometric Charts

Plots of the typical operating points during the winter and summer are shown on the psychrometric charts in Figure 3.34 and Figure 3.35. For the day of February 18, 1999, the average outdoor air temperature was hovering around freezing with a relative humidity of about 70%. The humidity ratio of the outside air, the air in Zoology and outside the Somalian Ass case are nearly identical, indicating that air serving these zones is not humidified and the sensible heating alone causes the relative humidity inside the building to plummet. Anthropology storage, as was previously seen in Figure 3.2 and Figure 3.4, can provide humidification to the supply air such that the RH is much closer to the desired set point of 50%. Inside the Somalian Ass case, the RH is higher than that outside of the case due to two factors: 1) the tightness of the case which decreases the air exchange rate between

the case microenvironment and the Museum macroenvironment and 2) the hygroscopic nature of the displayed animals, which desorb water to prevent a severe drop in RH. The hygroscopic response of the case contents is discussed in more detail in Chapter 5.

For July 22, 1999, the outdoor air is nearly saturated with a temperature close to 80°F. The air conditioning system of the Museum cools the incoming air to about 55°F while decreasing its moisture content. The sensible heating loads of the building increase the temperature to that shown in the figure. Once again the RH inside the Somalian Ass case is lower than its surroundings due to case tightness and the contents absorbing moisture from the air.

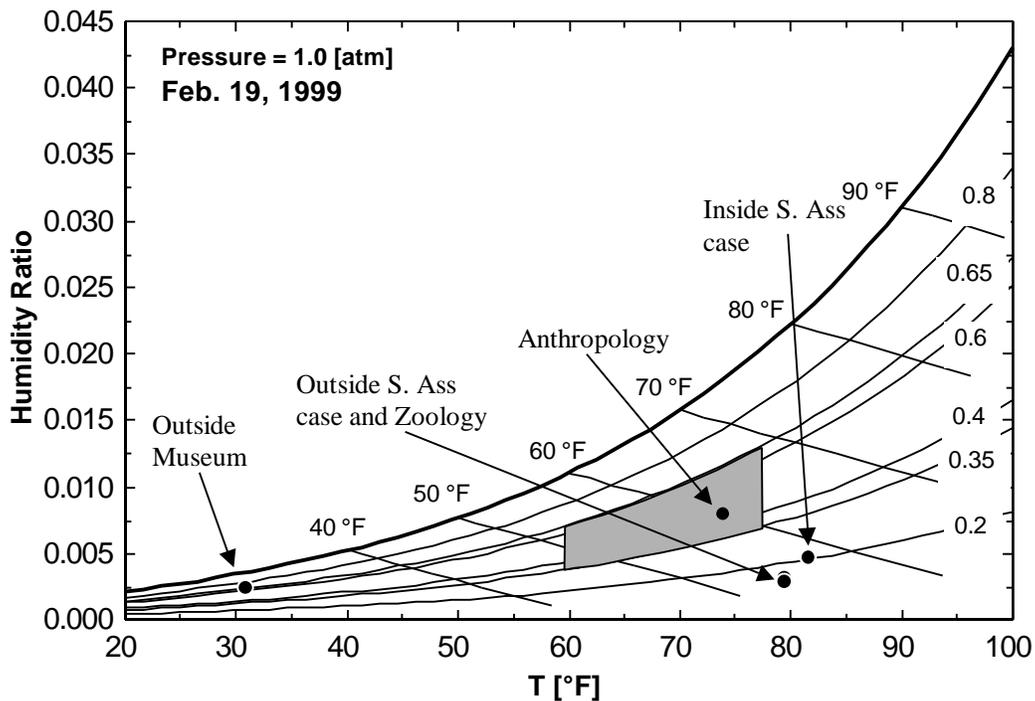


Figure 3.34 Psychrometric plot of the outdoor air and locations within the Museum in winter. The ASHRAE recommendations for the T and RH ranges are highlighted in gray.

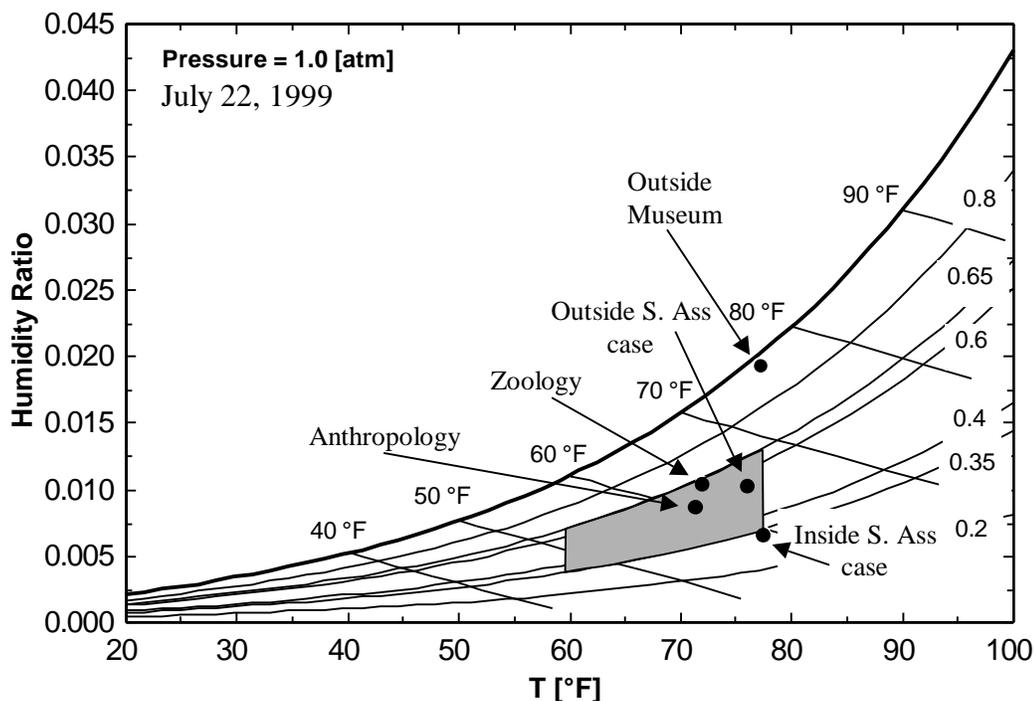


Figure 3.35 Psychrometric plot of outside and inside the Museum in summer. The ASHRAE recommendations for the T and RH ranges are highlighted in gray.

3.5 Temperature and Relative Humidity Fluctuations

Figure 3.36 and Figure 3.37 illustrate the variability of relative humidity and temperature for all the examined areas. The range of relative humidities and temperature for each day, week and month of logging were calculated, averaged, and plotted. As shown, the building and HVAC system provide a considerable level of protection from the variation that occurs in the outside conditions. Cases further reduce the RH range to less than 3% on a daily basis. Anthropology storage has the next best performance with an average RH range of less than 5%. The remainder of the locations, namely Zoology, Hall 13 and the areas outside of the cases, has an average RH range of approximately 10%. The trend that the

insides of the cases are most protected from fluctuations in RH and that Zoology has the largest RH range is repeated for the weekly and monthly time frames. The average daily temperature ranges show a similar trend, however the range for the different locations are more similar over long periods of time. The mechanical stresses that may be induced from these small changes in temperature are probably not damaging in and of themselves. The lack of temperature control is more serious through its effect on relative humidity, which can induce much greater stress.

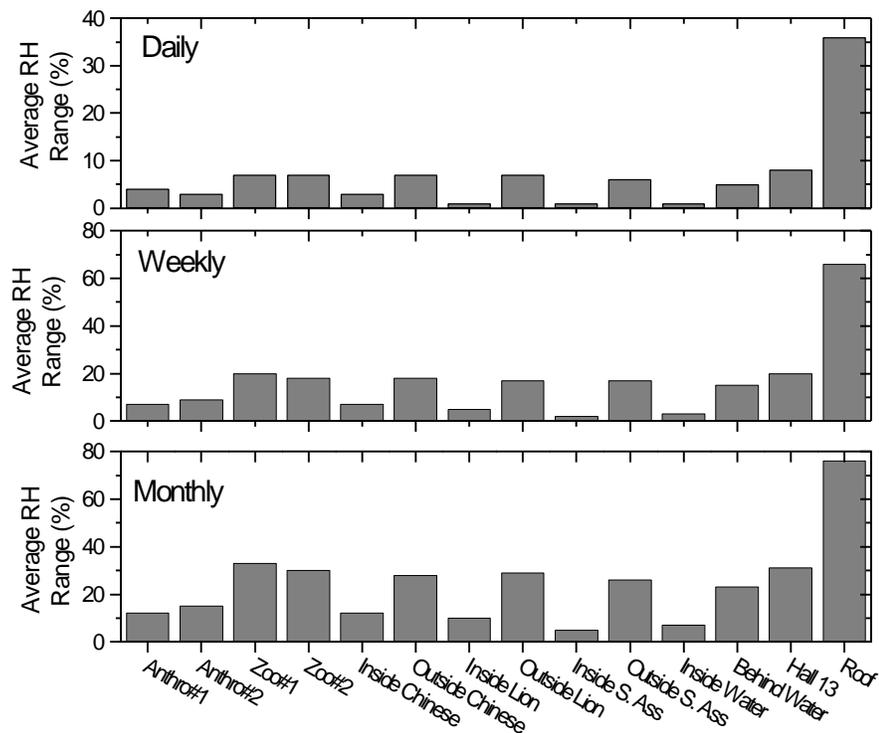


Figure 3.36 Average daily, weekly and monthly RH range for monitored locations.

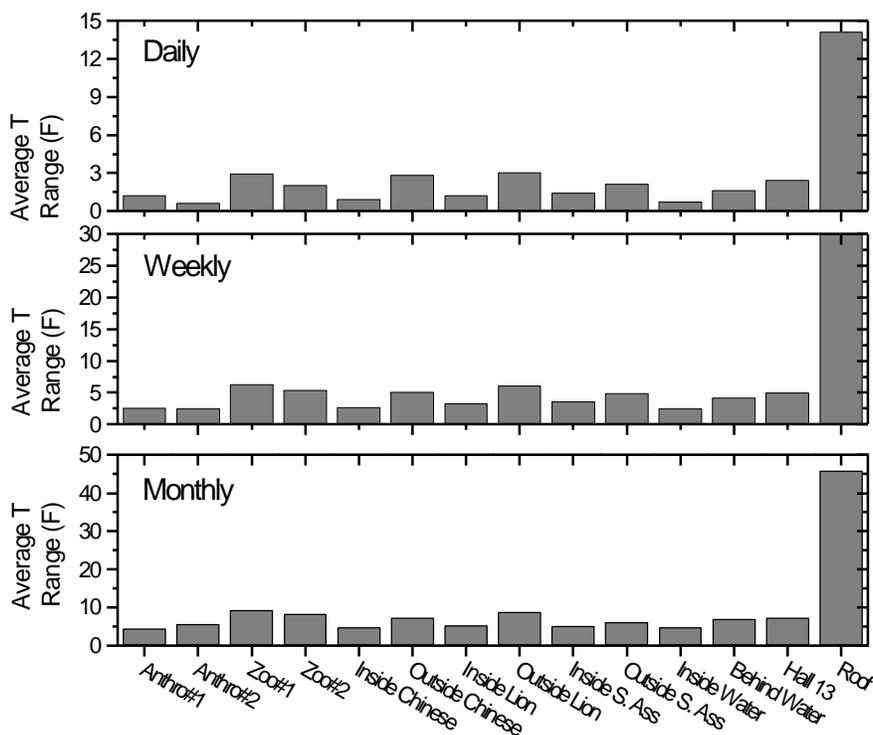


Figure 3.37 Average daily, weekly and month T range for monitored locations.

Figure 3.38 through Figure 3.41 plot the daily, weekly and monthly RH ranges as a function of time for the Chinese, the Somalian Ass, the Lions of Tsavo cases and the Watering Hole diorama in order to more closely compare the inside versus the outside conditions. For each case and all times, the inside of the cases experiences lower fluctuations than the outside of the cases. As was mentioned before in discussion of Figure 3.14, the RH inside the Chinese case nearly matches the outside RH range due to poor sealing of the case. The RH range drops from above 5% to below 5% once the case had been tightened after mid-May before increasing once again in September and October. The occasional spikes seen in Figure 3.39 for the Somalian Ass case are due to the access door being opened for an extended period of time.

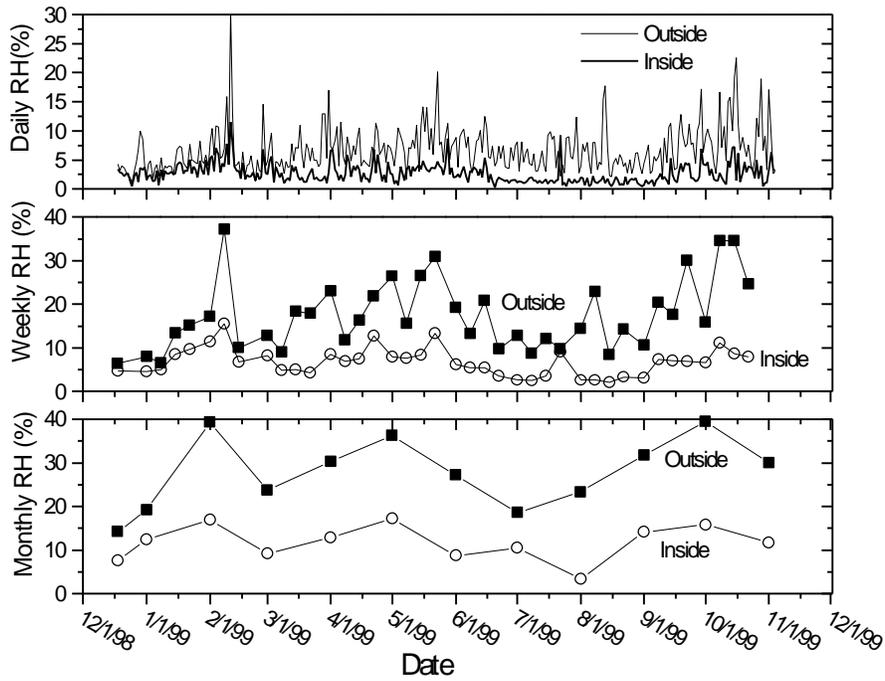


Figure 3.38 Daily, weekly and monthly range values for relative humidity inside and outside the Chinese case.

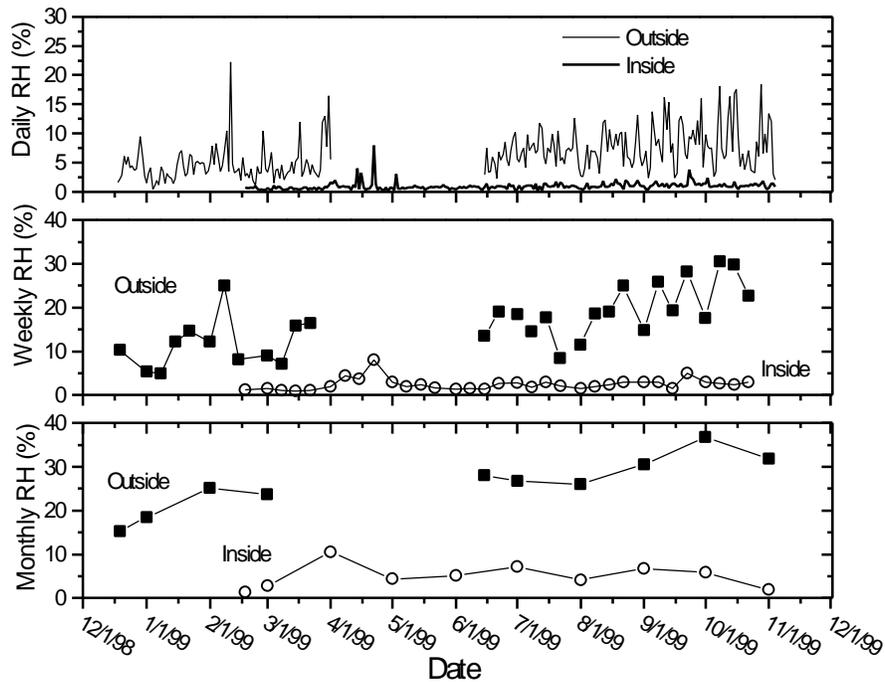


Figure 3.39 Daily, weekly and monthly range values for relative humidity inside and outside the Somalian case.

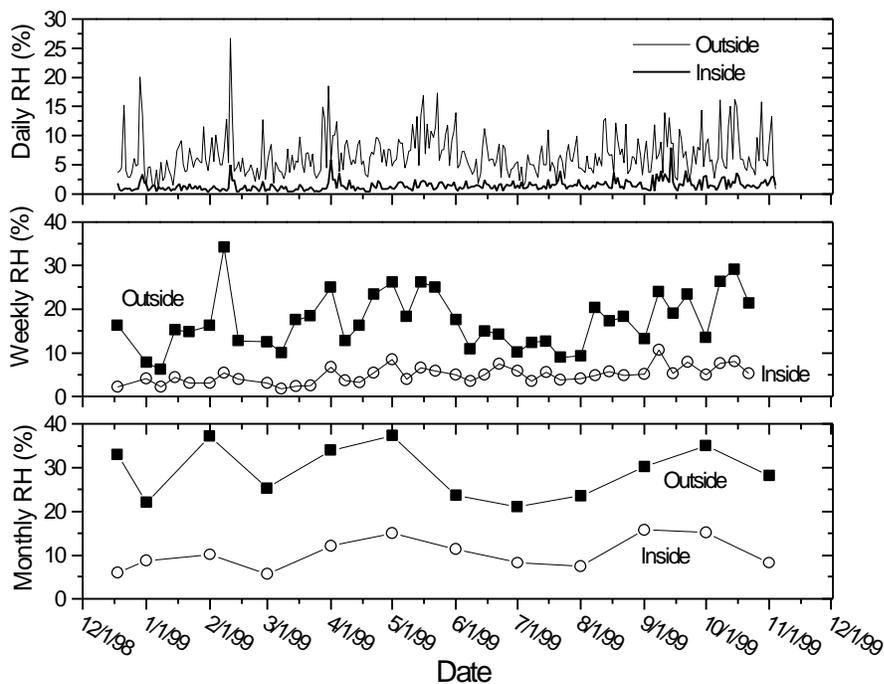


Figure 3.40 Daily, weekly and monthly range values for relative humidity inside and outside the Lions of Tsavo case.

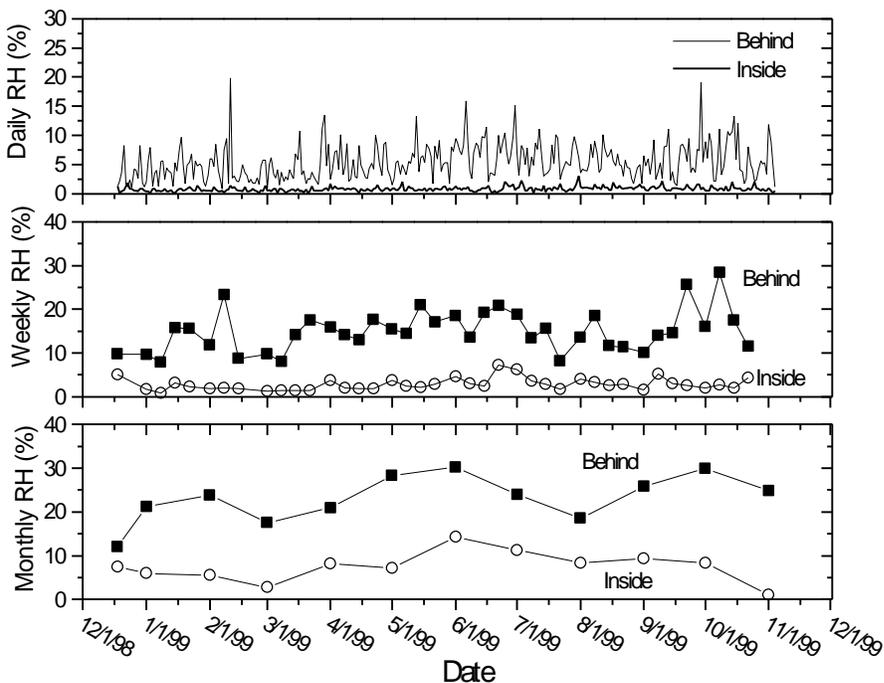


Figure 3.41 Daily, weekly and monthly range values for relative humidity inside and behind the Watering Hole diorama.

Figure 3.42 contains the average day-to-day, week-to-week and month-to-month variations for the different locations monitored in the Museum. The bar graphs were constructed by first finding the average relative humidity for the day, week or month and then finding the absolute value of the difference between the average for a day (week or month) and the average for the previous day (week or month). The day-to-day, week-to-week and month-to-month fluctuations were then averaged over the time period available. Ideally, the day-to-day fluctuations should be small. If there were a seasonal adjustment of the relative humidity set point, this gradual variation would appear in the week-to-week and month-to-month averages. A typical example of such a control scheme would allow the RH set point to be 35% in the winter and 55% in the summer. In general, the maximum adjustment recommended is $\pm 10\%$ (ASHRAE Applications Handbook, 1999). In that instance, the month-to-month RH variations should not exceed 5%. As expected, the Zoology work area has the worst performance over all time scales. For the day-to-day fluctuations, the cases do a good job of minimizing the variation, but as the time scales increase, the difference between inside and outside the cases decreases. Due to the renovated environmental controls in the Anthropology storage area, it was possible to maintain the RH set point over both the heating and cooling seasons with little month-to-month variation.

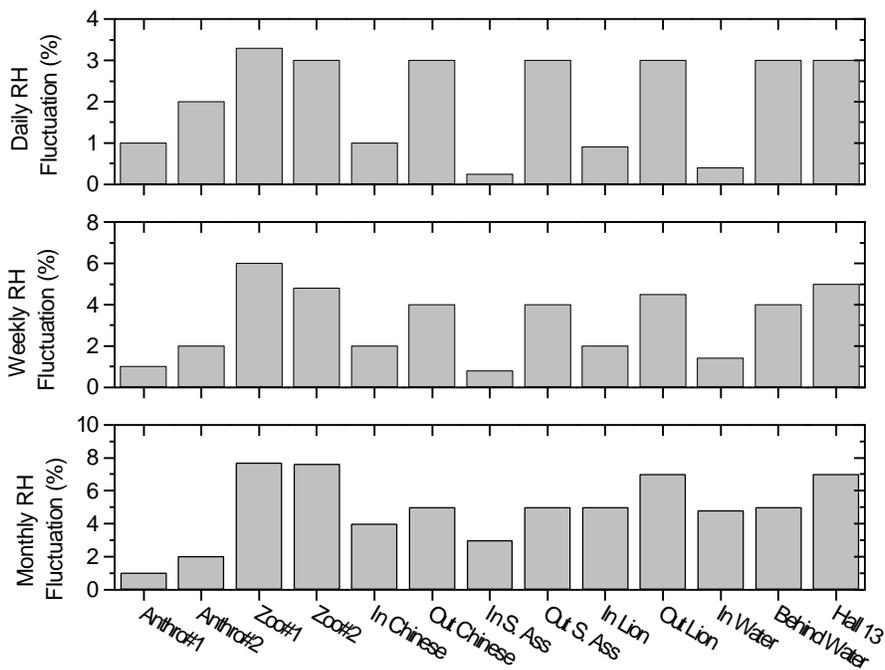


Figure 3.42 Average day-to-day, week-to-week and month-to-month fluctuations for the locations monitored within the Museum.

3.6 Conclusions

The long term environmental monitoring of the 13 different locations within the Museum reveals that there is inadequate temperature control and little to no humidity control in some parts of the building. The HVAC system in Anthropology storage manages to maintain the relative humidity close to the set point of $50\% \pm 5\%$ for most of the year, although spatial variations do exist for both temperature and relative humidity. The working area of Zoology experiences the worst control of any of the areas monitored. The central heating of the outdoor air in winter time results in a relative humidity less than 20%, which is much lower than that recommended in Chapter 1. The use of desiccant to provide passive

RH control in the Chinese case was not effective for long periods of time and steps should be taken to either increase the amount of desiccant used or to recondition the desiccant at the start of the winter heating period.

The use of cases for the display of objects is very beneficial to protect the contents against fluctuations in relative humidity and temperature. As a result, cultural artifacts should be stored and displayed in cases, where possible. In addition, the cases used should be tight. However, though the fluctuations of RH are reduced to acceptable levels, the absolute level of relative humidity is still much too low in the winter and steps should be taken to provide humidification of the supply air.

CHAPTER 4

Model of Exhibition Cases**4.1 Purpose of Model**

A dynamic mass exchange model of the exhibition cases is developed in this chapter. A series of experiments using carbon dioxide as a tracer gas were performed to determine model parameters for each of two different exhibition cases. The mass exchange model of the cases estimates the exchange by leakage or infiltration between the contents of an individual exhibition case and the environment surrounding the case, i.e. the Museum indoor environment. A calibrated mass exchange model allows levels of airborne or gas phase pollutant concentrations within the case microenvironment to be estimated knowing the pollutant concentration in the macroenvironment (i.e. the Museum).

4.2 Case Infiltration

The microenvironment of an exhibition case interacts with its surrounding macroenvironment by the following three mechanisms: gas diffusion through openings, gas permeation through porous surfaces, and infiltration of air (Michalski, 1994b). Diffusion is driven by differences in concentration of the particular gas and is considered the dominant mechanism of exchange (Thomson, 1977, Brimblecombe and Ramer, 1983 and Michalski,

1994b). Vapor permeation, particularly that of water, can be neglected since most of the Museum cases are made of glass and 0.5-1 inch thick varnished or painted wood, which have water vapor permeances close to zero (Michalski, 1994b). Infiltration is driven by differences in pressure and can be caused by changes in barometric pressure, which leads to barometric pumping of the case, or from the ventilation system, which can also drive flow through cracks and holes in the exhibition case envelope. Infiltration due to the operation of the building ventilation system can be difficult to determine since knowledge of the air velocities around the case as a function of time and of the case construction, particularly the number and size of the cracks and holes, is needed.

The total exchange rate can be determined by two methods: monitoring the amount of water in a case or using a tracer gas. Thomson placed a graduated cylinder of water in a small exhibition case within a controlled room and monitored the water level as a function of time (Thomson, 1977). Michalski filled small jars (50 cm^3) halfway with water and monitored their weight change with time (Michalski, 1994b). For slightly larger cases ($40.6 \times 40.6 \times 39.4 \text{ cm}$), the weight of suspended desiccant was monitored to determine the leakage rate. Brimblecombe and Ramer used carbon dioxide gas as a tracer gas to determine the leakage rates of $180 \times 60 \times 60 \text{ cm}$ cases (Brimblecombe and Ramer, 1983). CO_2 was added to the cases and its concentration was monitored as a function of time. The resulting exponential decay of CO_2 concentration yielded the leakage rate of the case. A similar procedure was applied to exhibition galleries in the Metropolitan Museum of Art using CO_2 or helium as a tracer gas (Barrette, 1984).

4.2.1 Description of Current Experiments

Experiments were performed to determine the gas exchange rates of the Somalian Ass and the Lions of Tsavo cases. Since the cases are large (on the order of 30 m^3) and contain hygroscopic materials with unknown capacities and rates for water absorption, monitoring the change in air moisture content inside the case is insufficient to allow estimates of case exchange rates. As a result, the tracer gas method was used. Carbon dioxide was chosen because sensors are commercially available to monitor its concentration and it poses no threat to fragile cultural objects. In addition, CO_2 is a natural by-product of human metabolism and fluctuates on a daily basis due to the presence of visitors and staff in the museum. The procedure used for determining the leakage rates of the two cases is outlined in the following paragraph.

One CO_2 sensor and one T/RH logger are placed in the case and another set is placed outside of the case in a location that will not be disturbed or breathed on, which would bias the CO_2 sensor. The CO_2 concentration in the case is then increased to 2000 ppm or higher by discharging a small cylinder of pure CO_2 inside the case. This process is known as “loading” the case. The goal in loading the case is to raise the tracer gas concentration to a level significantly higher than that in the surrounding environment. The CO_2 concentration in the Museum typically fluctuated between 500-1200 ppm. The volume of the case is needed to calculate the necessary volume of CO_2 added to achieve the target concentration, namely 2000 ppm. A flow meter is used to ensure that the correct mass of CO_2 is added. The case is then closed and the concentration monitored over time as it decays to the ambient level. The acquired CO_2 concentration data inside and outside the case as a function of time,

along with the ambient T/RH recordings are used to estimate unknown parameters in the mass exchange model for the exhibition cases.

4.2.2 Case Model to Determine Exchange Rates

The case leakage model includes two dominant mechanisms for gas exchange: diffusion and barometric pumping. Equation 4.1 presents the mass balance which states that the time rate of change of mass of CO₂ inside the case is due to CO₂ diffusing in (or out) of the case plus CO₂ which is carried in (or out) of the case due to barometric pumping.

$$M_{air,in} \frac{d[CO_{2,in}]}{dt} = \underbrace{k_{diff,CO_2} ([CO_{2,out}] - [CO_{2,in}])}_{diffusion} + \underbrace{\dot{m}_{bar} [CO_{2,*}]}_{barometric\ pumping} \quad (4.1)$$

The in and out subscripts refer to inside and outside the case, respectively. Mass flow is defined as positive for flow entering the case. The units of mass were kilograms, CO₂ concentration was measured in ppm, and hour was used as the unit of time. From dimensional analysis, k_{diff,CO_2} , which is the diffusional mass exchange rate, has units of kilograms per hour. \dot{m}_{bar} is the time rate of change of the mass of air inside the case and is a function of the barometric pressure and the temperature inside the case with units of kilogram per hour:

$$\dot{m}_{bar} = \frac{dM_{air,in}}{dt} = \frac{d\left(\frac{P_{bar} V_{case}}{RT_{in}}\right)}{dt} \quad (4.2)$$

CO_{2,*} is CO_{2,in} if \dot{m}_{bar} is negative, indicating that air is flowing out of the case, or CO_{2,out} if \dot{m}_{bar} is positive, which means that air is flowing into the case. The concentration inside the

case can be predicted by approximating Equation 4.1 with finite differences and solving for $CO_{2,in}^+$ as a function of the previous time step:

$$CO_{2,in}^+ = CO_{2,in,old} + \frac{\Delta t}{M_{air,in,old}} \left(k_{diff,CO_2} ([CO_{2,out,old}] - [CO_{2,in,old}]) + \dot{m}_{bar} [CO_{2,*,old}] \right) \quad (4.3)$$

The “+” superscript refers to the current time step and the “old” subscript refers to the previous time step. Equation 4.2 can also be approximated by a finite difference and is represented in Equation 4.4:

$$\dot{m}_{bar} = \frac{\Delta M_{air,in}}{\Delta t} = \frac{1}{\Delta t} \left(\left(\frac{P_{bar} V_{case}}{RT_{in}} \right)^+ - \left(\frac{P_{bar} V_{case}}{RT_{in}} \right)_{old} \right) \quad (4.4)$$

The time step used for the calculations was one hour. Records reported every three hours of the barometric pressure were obtained from the National Climatic Data Center for the O’Hare Airport. The barometric pressure data was linearly interpolated to obtain estimates of hourly pressures between measurements. The field-measured CO_2 concentration data inside the case are used to initialize the prediction with an initial value of $CO_{2,in,old}$. The value of k_{diff,CO_2} is then varied until the predicted concentration of CO_2 inside the case matches the actual measured concentration as closely as possible during the case loading experiment. This matching is achieved by minimizing the sum of the squares of the differences between the predicted and measured CO_2 concentration values inside the case. The final value of k_{diff,CO_2} is then used to calculate the number of air changes that the case undergoes in a day through the following equation:

$$N_{air} = \frac{k_{diff,air}}{?_{air,in} V_{case}} \cdot 24hr / day \quad (4.5)$$

where $k_{diff,air}$ is determined from Graham's Law of diffusion (Brimblecombe and Ramer, 1983) as

$$k_{diff,air} = k_{diff,CO_2} \sqrt{\frac{MW_{CO_2}}{MW_{air}}} \quad (4.6)$$

4.3 Results of Tracer Gas Experiment

The CO₂ loading experiment was performed under two separate occasions, once in July and once in September, for both the Somalian Ass and Lions of Tsavo cases. The July and September experiments were initiated on July 22, 1999 and September 25, 1999, respectively. The time interval shown for each case varies depending on when the case interior CO₂ concentration dropped below the upper limit of the CO₂ sensor (i.e. 2000 ppm). The mass exchange rate constant, k_{diff,CO_2} , found for each of the cases is then tested on additional data to ensure that the fitted constants are valid.

4.3.1 Somalian Ass Case

4.3.1.1 July Experiment

The acquired CO₂ concentration data averaged over one hour increments are shown in Figure 4.1 for the Somalian Ass case for the period of July 24 through July 31. The concentration inside the case was elevated in excess of 2000 ppm on July 22 and decreased to 2000 ppm by 7:30 p.m. on July 24, which is the start of the displayed data. The inside concentration gradually decayed to approximately 1000 ppm at the end of the seven day period. The concentration of CO₂ outside of the case fluctuates diurnally due to the generation of CO₂ by people inside the building. As visitors and staff enter the Museum

during the day, the concentration level of CO₂ increases, peaking in mid to late afternoon before decreasing during the closing hours of the Museum when occupancy is at a minimum.

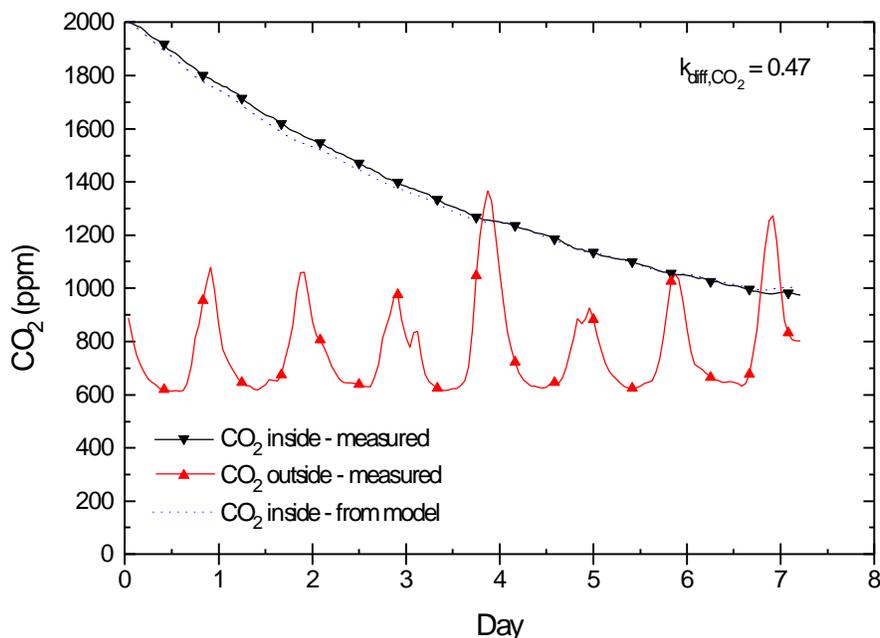


Figure 4.1 Carbon dioxide concentration measured inside and outside the Somalian Ass case, along with inside concentration of CO₂ as calculated from Equation 4.3 for the July experiment, 7/24/99-7/31/99.

The predicted CO₂ concentration inside of the case is superimposed on the actual data in Figure 4.1. As shown, the calculated values of the interior CO₂ concentration match quite closely with that actually measured. The value of $k_{\text{diff,CO}_2}$ found to give the best fit was 0.47 (kg/hr) which resulted in an average of 0.28 air changes per day. It is important to note that the CO₂ concentration inside the case barely responds to the diurnal fluctuations of CO₂ outside of the case, thus providing a qualitative measure of case tightness.

The time history of the barometric pressure for the July experiment is shown in Figure 4.2, along with the corresponding percent change in air mass inside the case due to

changes in barometric pressure and temperature inside the case. Very little flow is driven in or out of the case due to the pressure changes. As a result, diffusion dominates the air exchange mechanisms between the case and its surroundings, which is in agreement with previously published work (Thomson, 1977, Brimblecombe and Ramer, 1983, and Michalski, 1994b).

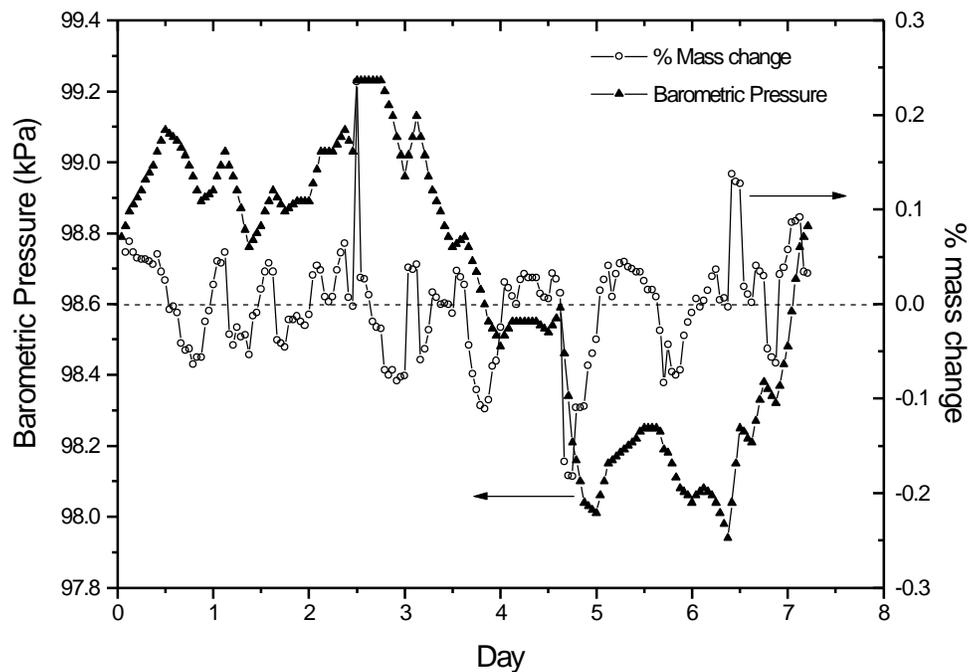


Figure 4.2 Barometric pressured measurements and calculated percent change of air mass inside the case due to changes in barometric pressure for July experiment in the Somalian Ass case.

Figure 4.3 plots the measured carbon dioxide data along with the calculated values of concentration inside the case with barometric pumping set to zero. There is very little difference in the general behavior of the calculated CO_2 concentration trace and the values are only slightly different than those shown in Figure 4.1, with a maximum difference of 25

ppm. Even though the effect of barometric pumping was found to be small, it is retained as a component of the model.

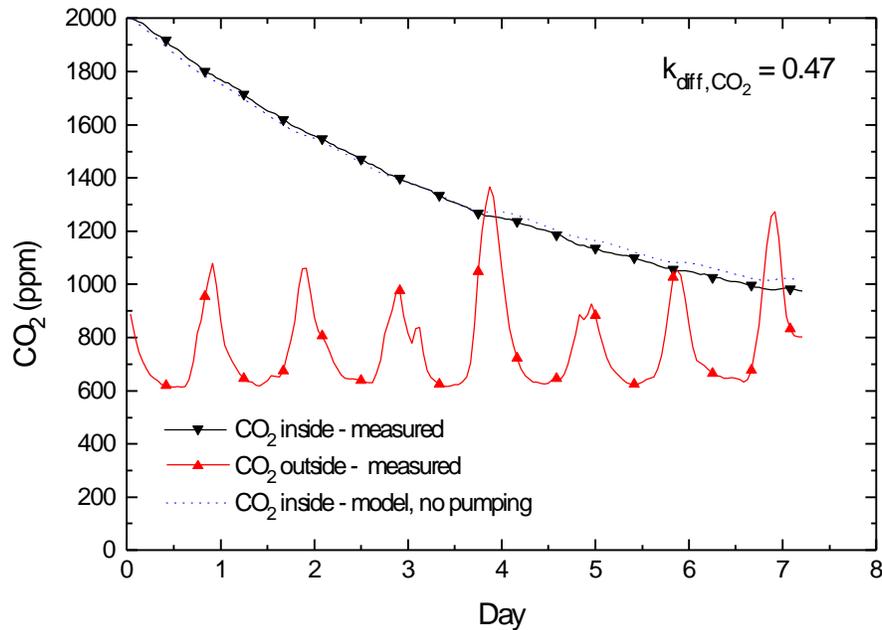


Figure 4.3 Carbon dioxide concentration measured inside and outside the Somalian Ass case, along with inside concentration of CO₂ as calculated from Equation 4.3 while setting \dot{m}_{bar} to zero.

4.3.1.2 September Experiment

To increase confidence in the calculation of air exchange rate for the Somalian Ass case, the CO₂ loading experiment was repeated in September. Data starting at 9:30 p.m., September 29 are shown in Figure 4.4. The actual values of CO₂ concentration inside and outside are plotted along with the calculated concentration values from the model. Once again, the agreement between the measured and calculated concentration inside the case is quite good with a resulting $k_{\text{diff,CO}_2}$ of 0.50 (kg/hr) and an average of 0.30 air changes per

day. This value represents a 6.4% increase in $k_{\text{diff},\text{CO}_2}$ from the July experiment but within experimental error calculated in Section 4.3.3.

The average CO_2 concentration in Hall 21 seems to have decreased by roughly 200 ppm from the July experiment to the September experiment. This apparent decrease was most likely due to differences in instrumentation offset since different sets of CO_2 sensors were used for each experiment. Calibration checks were made with 1000 and 300 ppm calibration gas (CO_2 in nitrogen) before and after each experiment and the concentration records were adjusted so that the inside and outside concentrations agreed with each other.

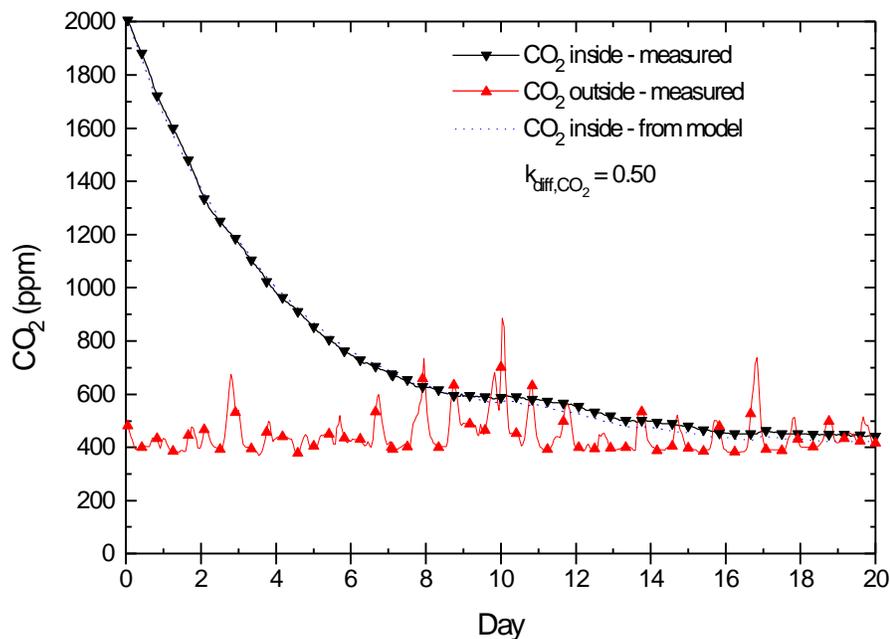


Figure 4.4 Carbon dioxide concentration measured inside and outside the Somalian Ass case, along with inside concentration of CO_2 as calculated from Equation 4.3 for the September experiment, 9/29/99-10/19/99.

4.3.1.3 Model Validation

Carbon dioxide measurements from the week of September 1, 1999 were used to independently validate the $k_{\text{diff},\text{CO}_2}$ fitted from the CO_2 loading experiments. The data

record starts at 12:30 am on September 1, 1999 and lasts until midnight of September 7, 1999 and is shown in Figure 4.5. The average $k_{\text{diff},\text{CO}_2}$ from the July and September experiments was used resulting in a value of 0.485. The agreement between the measured data and the model predicted data is good with a maximum difference of roughly 20 ppm.

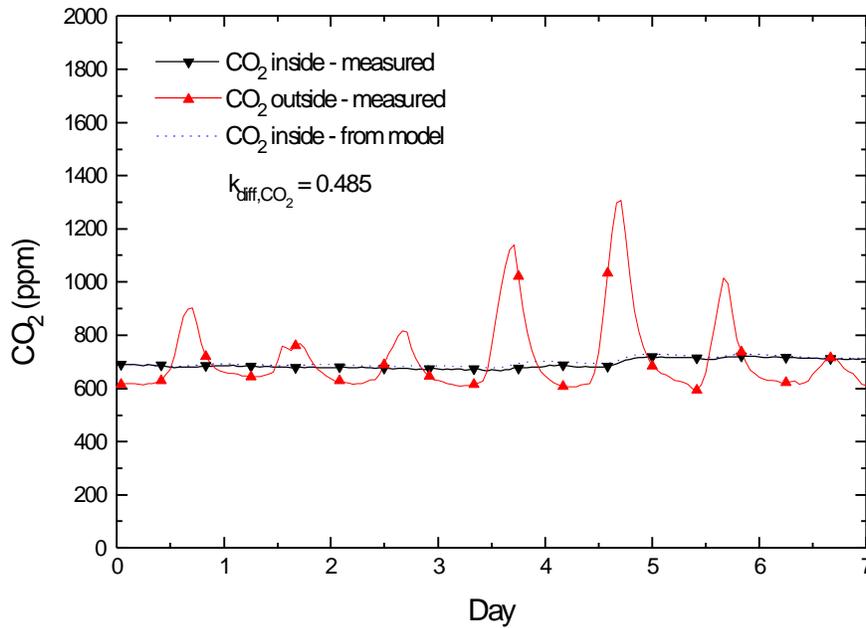


Figure 4.5 Carbon dioxide concentration measured inside and outside the Somalian Ass case, along with inside concentration of CO₂ as calculated from Equation 4.3 for the first week of September, 9/1/99-9/6/99.

4.3.2 Lions of Tsavo Case

4.3.2.1 July Experiment

The measured and calculated CO₂ concentrations for inside and outside the Lions of Tsavo case are presented in Figure 4.6. The data presentation starts at 6:30 p.m. on July 22 and lasts until the end of July 31. The concentration inside of the case decayed relatively quickly from 1660 ppm to approximately 825 ppm in just over a 36 hour period.

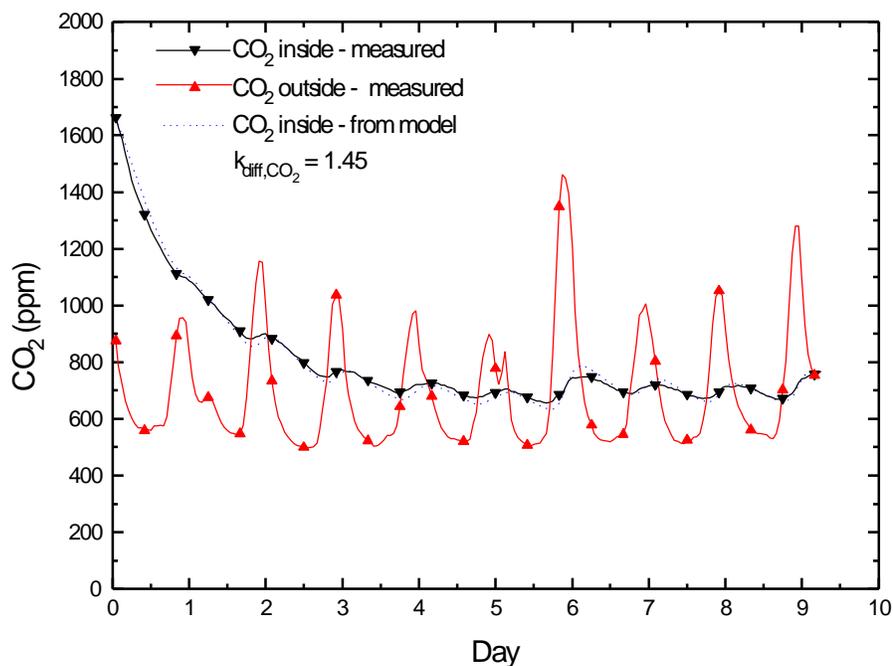


Figure 4.6 Carbon dioxide concentration measured inside and outside the Lions of Tsavo case, along with inside concentration of CO₂ as calculated from Equation 4.3 for the July experiment, 7/22/99-7/31/99.

The value of $k_{\text{diff},\text{CO}_2}$ found to give the best fit was 1.45 (kg/hr) which resulted in an average of 1.1 air changes per day. In comparison with the Somalian Ass case, the Lions of Tsavo case has a considerably higher leakage rate. Evidence for this high exchange rate is that the inside concentration level responds, albeit in a dampened fashion, to the daily fluctuations in CO₂ outside the case during the decay period. The difference in tightness between the cases is most likely due to construction of the access door, especially for the Lions of Tsavo case, where a gap of approximately one centimeter exists between the door and its frame along the bottom.

4.3.2.2 September Experiment

Figure 4.7 contains the measured and model-calculated CO₂ concentrations for inside and outside the Lions of Tsavo case from the CO₂ loading experiment in September. The data presented are from 1:30 p.m., September 25 throughout midnight, October 11. The initial case interior concentration drops from 2000 ppm to roughly 1000 ppm in 2 days, yielding a $k_{\text{diff,CO}_2}$ of 1.25 and an average of 0.94 air changes per day.

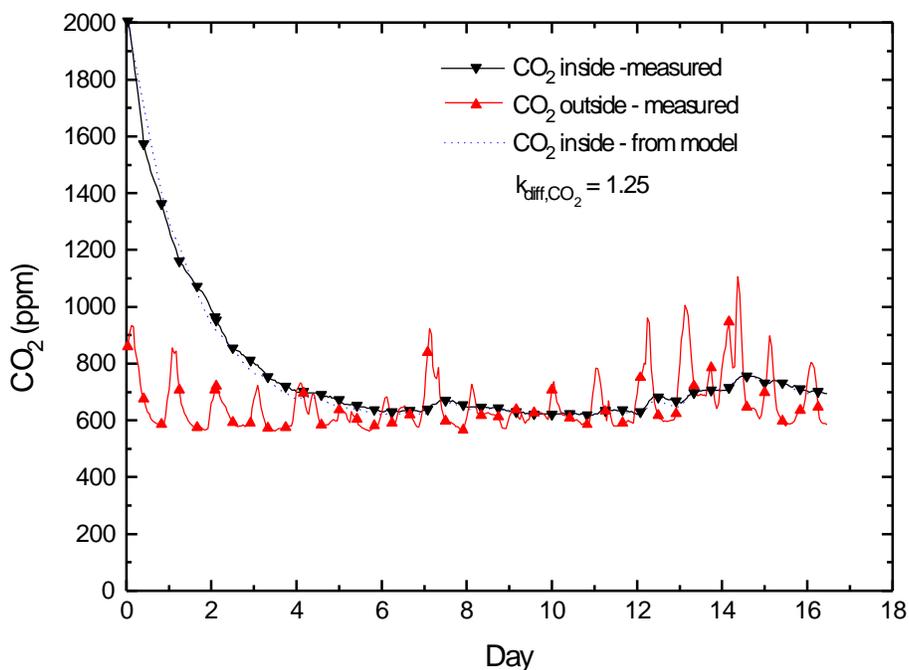


Figure 4.7 Carbon dioxide concentration measured inside and outside the Lions of Tsavo case, along with inside concentration of CO₂ as calculated from Equation 4.3 for the September experiment, 9/25/99-10/11/99.

This is a 14% decrease in $k_{\text{diff,CO}_2}$ from the July experiment and could be due to experimental error but might also be due to the fact that during the September experiment the edges of the access door were taped with duct tape, which would reduce the crack size

available for diffusion. However, additional CO₂ loading experiments should be performed to confirm this hypothesis.

4.3.2.3 Model Validation

Carbon dioxide measurements from the week of July 14, 1999, were used to validate the parameter, $k_{\text{diff},\text{CO}_2}$, of the Lions of Tsavo case fitted from the CO₂ loading experiments. The data record starts at 12:30 am on 7/14/99 and lasts until midnight of 7/20/99 and is shown in Figure 4.8. $k_{\text{diff},\text{CO}_2}$ was set equal to 1.25 as from the July experiment since the access door was taped in a similar manner. The fit between the actual data and that from the model is not as good as was seen with the Somalian Ass case since differences on the order of 50 ppm are visible. A possible reason for the poorer agreement between the measured and model-predicted values for inside the Lions of Tsavo case may be that there is another mechanism of infiltration unaccounted for in the model which becomes significant for cases which are not as tight. Infiltration due to pressure differences caused by the ventilation system may be a factor for the Lions case due to its close proximity to one of the air distribution ducts.

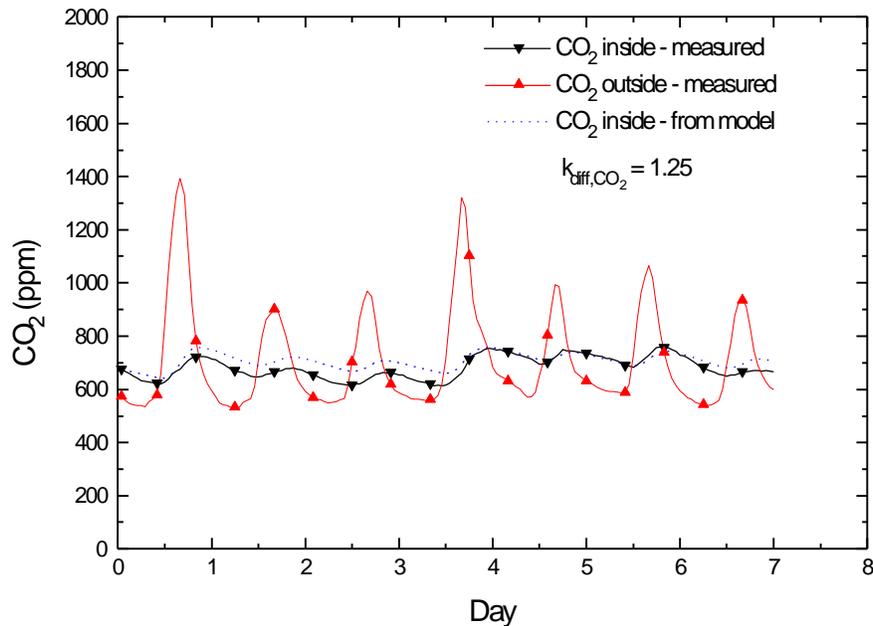


Figure 4.8 Carbon dioxide concentration measured inside and outside the Lions of Tsavo case, along with inside concentration of CO₂ as calculated from Equation 4.3 for the week of 7/14/99-7/20/99.

4.3.3 Error Analysis for Tracer Gas Experiments

The calculation of the exchange constant, $k_{\text{diff},\text{CO}_2}$, was subject to experimental errors in the measurement of CO₂ as well as errors in the determination of the volume of the display cases.

To determine the effect that instrumentation error had on the value of $k_{\text{diff},\text{CO}_2}$ and the resulting calculation of average number of air changes in a day, N_{air} , the measured concentration data inside and outside the Somalian Ass case was varied by the rated accuracy of the CO₂ sensors. As a worst case example, the measured CO₂ data for outside the case were increased by 50 ppm while the inside values were decreased by 50 ppm. The model was then run to find the new best fit $k_{\text{diff},\text{CO}_2}$. The model results are shown in Figure 4.9 and

the values for k_{diff,CO_2} and N_{air} are tabulated in Table 4.1. Both the exchange rate constant and the number of air changes in a day increase by 17%. For this reason, it is important that stable and accurate CO_2 sensors are used and their calibration checked before and after tracer gas experiments.

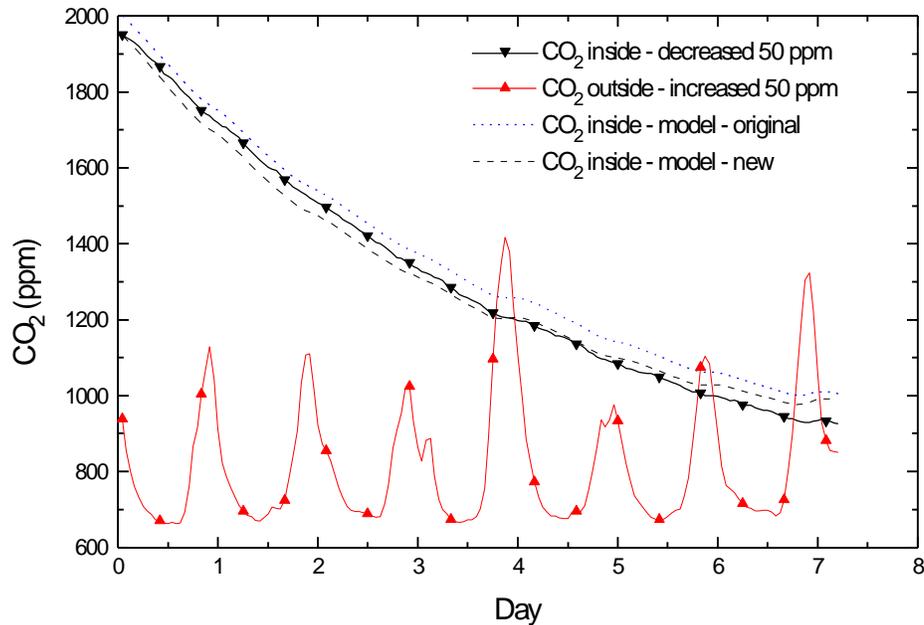


Figure 4.9 Measured inside and outside CO_2 concentrations varied by 50 ppm and the resulting effect on the model data for the July experiment data for the Somalian Ass case.

Table 4.1 Effect of CO_2 sensor accuracy on the exchange rate constant, k_{diff,CO_2} , and the number of air changes in a day, N_{air} .

CONDITION	k_{diff,CO_2}	N_{air}
Original data	0.47	0.284
Increasing outside CO_2 by 50 ppm and decreasing inside CO_2 by 50 ppm	0.55	0.332

Although the dimensions of the Somalian Ass and Lions of Tsavo case are known, the exact volume of the animals on display within the cases is not. The infiltration model

was developed and run with rough estimates of air volume within the case with 75% and 85% air in the Somalian Ass and Lions of Tsavo cases, respectively. An analysis was run for the Somalian Ass case using the results from the July experiment where the percent volume of air in the case was varied by $\pm 10\%$ from the original 75%. The results are shown in Figure 4.10 and the resulting values for $k_{\text{diff},\text{CO}_2}$ and the average air changes, N_{air} , are summarized in Table 4.2. Even though the values of $k_{\text{diff},\text{CO}_2}$ vary by $\pm 13\%$ as the volume is varied by $\pm 10\%$, there is very little change in the average number of air changes in a day. The relative insensitivity of N_{air} to changes in volume is due to the fact that the air volume is used to calculate $k_{\text{diff},\text{CO}_2}$ then divided out to determine N_{air} .

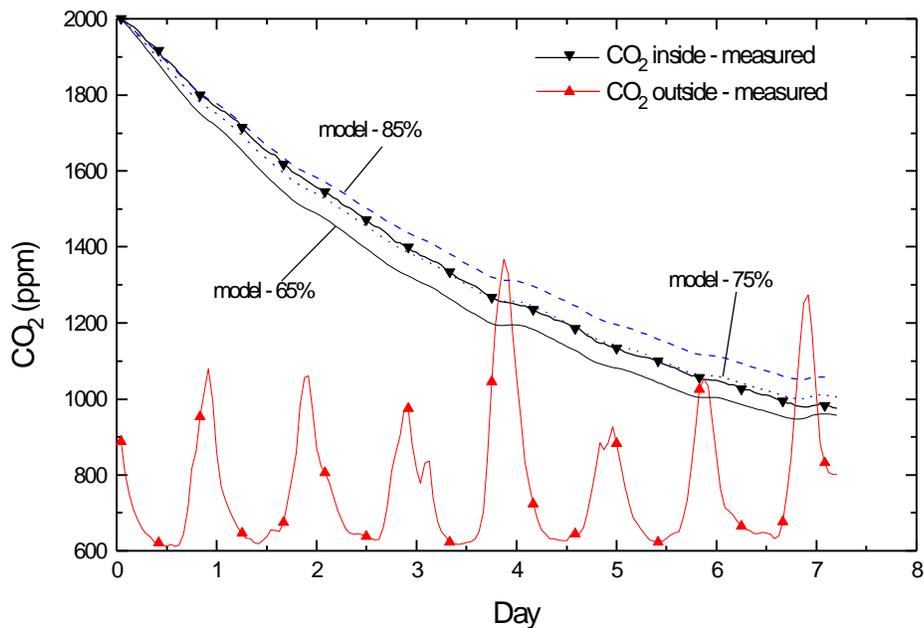


Figure 4.10 Measured and calculated values of CO₂ concentration outside and inside the Somalian Ass case for the July experiment for variations in percent air volume of the case.

Table 4.2 Variation of $k_{\text{diff,CO}_2}$ and N_{air} with variation in percent air volume of the Somalian Ass case.

VOLUME % AIR	$k_{\text{diff,CO}_2}$ (kg/hr)	N_{air} (per day)
75%	0.47	0.284
85%	0.53	0.282
65%	0.41	0.285

4.4 Pollutant loading

As discussed in depth in Chapter 1, artifacts are vulnerable to a number of airborne gases, in particular ozone, oxides of nitrogen and sulfur dioxide. With the Museum's proximity to Lake Shore Drive, a major thoroughfare in Chicago, as well as to extensive parking lots nearby, these gases could be present in high and destructive levels within the Museum. Studies done in museums have shown that the ratio of indoor to outdoor concentration of pollutants can vary between 10-80% depending on the construction of the building and the HVAC system used to condition it (Hackney, 1984, Druzik et. al., 1990, Ligocki et. al., 1993 and Hisham and Grosjean, 1991). Tighter buildings with more modern systems had the lowest ratio while older buildings and their mechanical systems experienced the highest ratio. No such study has yet been carried out in the Field Museum but based on the age of the building and the ventilation system, controlled and uncontrolled infiltration rate of outside air can be assumed to be high. For the following argument, the worst case scenario of 100% indoor to outdoor pollutant ratio will be assumed.

Since diffusion dominates the infiltration rate of cases as measured by the tracer gas experiments in the Somalian Ass and Lions of Tsavo cases, the results can be used to estimate the amount of pollutants within the cases. As seen with the CO₂ measurements, the

cases act to buffer the inside concentration of CO_2 such that the levels inside the case can be approximated by the daily average carbon dioxide concentration seen outside of the cases. Ozone exhibits diurnal concentration fluctuations since its production is largely dependent on sunshine. For this reason, ozone levels are more of a concern in the summer than in the winter. Sulfur dioxide concentrations peak at various times depending on the location of coal-burning industries in the region and the wind speed and direction.

Average annual values of SO_2 and NO_x for 1998 and hourly data for O_3 , SO_2 and NO_x during July 1999 were obtained from the Environmental Protection Agency (EPA) (Swinford, 1999) for a monitoring station located within one mile of the Field Museum. Using the infiltration model previously developed, the concentrations of the three pollutants within the Somalian Ass case are estimated from the data. The exchange rate constants for each of the molecules was determined by applying equations analogous to Equation 4.5 but with the corresponding molecular weights of SO_2 , O_3 and NO . Case interior concentrations of the pollutants were found by applying Equation 4.3 and replacing CO_2 with each pollutant.

Figure 4.11 presents the results for NO_x for the Somalian Ass case for the same time interval as the July experiment, July 24, 1999 through July 31, 1999. The starting NO_x concentration for the case interior was taken to be the arithmetic average from 1998, which was 0.032 ppm. Different NO_x traces are plotted for different values of air changes per day. As expected, the lower the number of air changes per day, the less responsive the interior concentration is to exterior pollutant fluctuations. However, even with a very tight case, the average inside concentration of NO_x will be nearly equal to the outside concentration average. The case merely protects the contents from large fluctuations in pollution. For NO_x , some sort of filtration system, either within the case (Grosjean and Parmar, 1991) or in

the HVAC air intake system, would have to be used to decrease the average concentration to recommended levels.

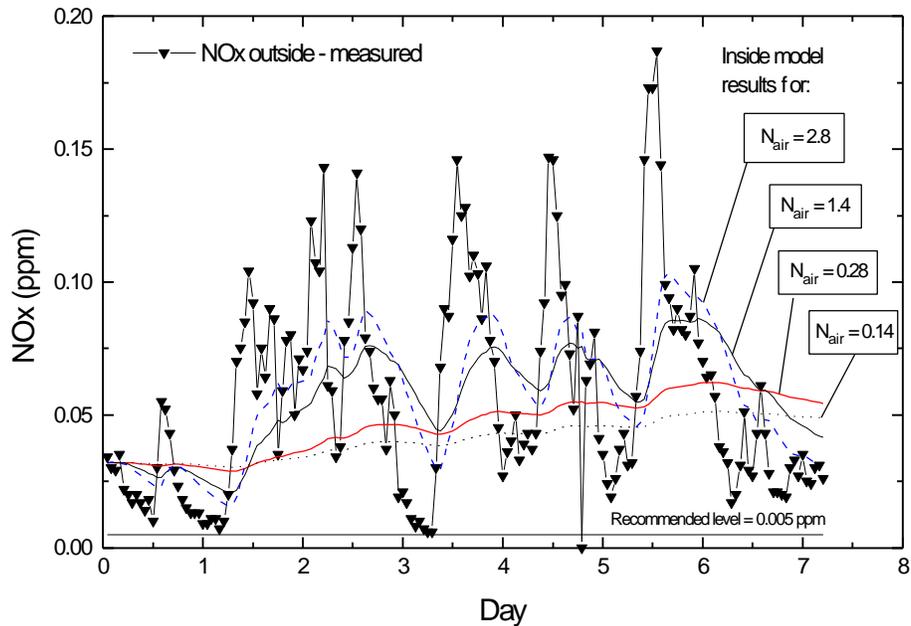


Figure 4.11 Estimated case interior concentrations of NO_x for different air changes per day for the Somalian Ass case during the July experiment.

Figure 4.12 presents similar data for SO₂ where the 1998 average and corresponding starting point for the model prediction was 0.005 ppm. It is possible that this week of data of SO₂ is not representative of the highest fluctuations but the natural levels are low enough that even cases with air changes on the order of 1.4 can maintain the recommended SO₂ level of 0.004 ppm without filtration.

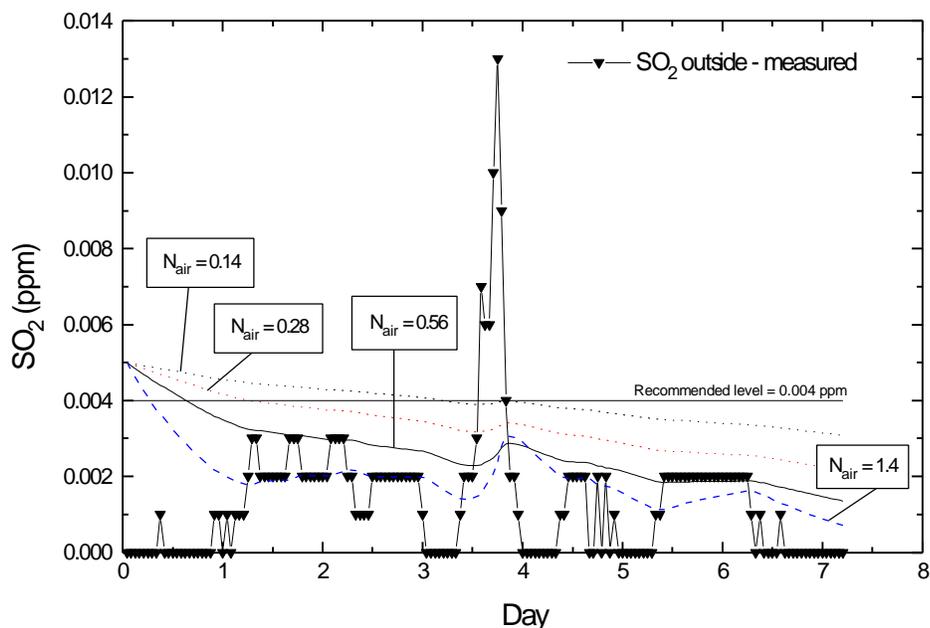


Figure 4.12 Estimated case interior concentrations of SO₂ for different air changes per day for the Somalian Ass case during the July experiment.

Ozone data is presented in Figure 4.13. Since ozone production is mostly a problem between April and October, an annual mean for the concentration was not available. The starting point for the model prediction was taken to be the average of the measured outdoor concentration data for the week examined. The average was 0.1685 ppm. Cases with 0.5 air changes per day or less are recommended since they maintain the interior concentration close to the outdoor average. The average is slightly higher than the maximum recommended level of 0.013 ppm so filtration might be required, especially during the summer months when ozone production is greatest.

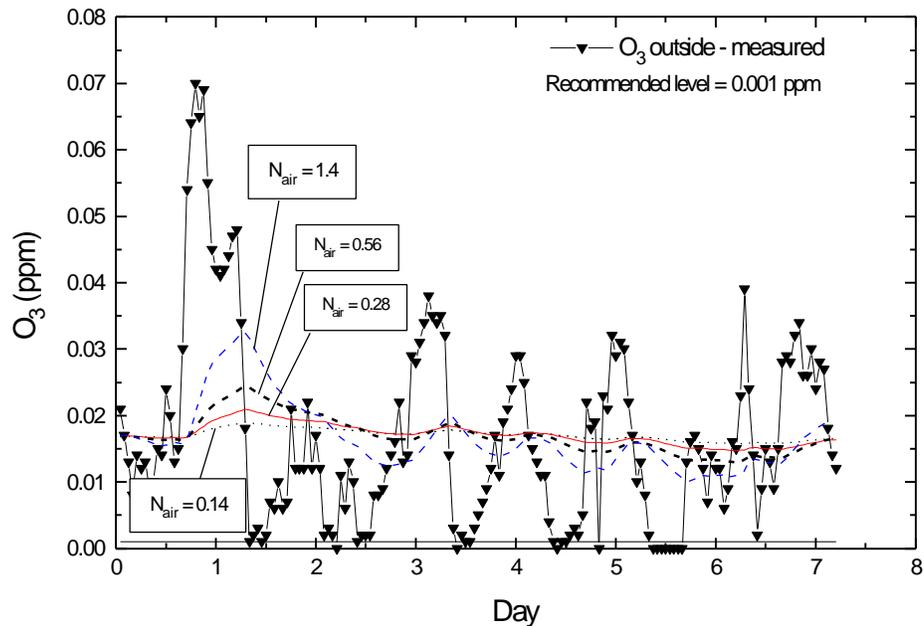


Figure 4.13 Estimated case interior concentrations of O_3 for different air changes per day for the Somalian Ass case during the July experiment.

4.5 Conclusions

A procedure has been developed for assessing the tightness of cases by monitoring the decay in concentration of carbon dioxide inside a case. An exchange rate constant for the case can be determined by applying the CO_2 concentration data, temperature and relative humidity data taken inside and outside the case to a predictive model. The model accounted for diffusional and barometric pumping effects. The results indicated that diffusion dominated the air exchange mechanisms between of the case microenvironment and the Museum macroenvironment.

The Somalian Ass case is roughly three times tighter than the Lions of Tsavo case with an average number of air changes per day of 0.3 and 0.9, respectively. This difference

in tightness was most likely due to differences in case construction, especially in the construction of the access door to each case.

Pollutant data was obtained from the EPA for a location near the Museum and case interior concentration of pollutants was estimated using the infiltration model. The results indicate that in addition to protecting case contents from fluctuations in relative humidity, as was shown in Chapter 3, cases can be an economical way of protecting artifacts from fluctuations in airborne pollutants. However, it seems that even with tight cases the ambient levels of NO_x and O_3 are high enough to recommend the use of a filtration system to achieve the desired low levels of pollution. An indoor survey of the pollutant levels should be made since the building may provide enough protection.

CHAPTER 5

Case and Remediation Recommendations
5.1 Introduction

The infiltration model developed in Chapter 4 will be extended to predict the humidity ratio and relative humidity within a case. The model results can then be used to specify the level of control needed in the Museum macroenvironment to maintain the case microenvironment within the recommended relative humidity fluctuations. Additional suggestions for the remediation of the relative humidity problems will also be addressed.

5.2 Water model of display case

The development of a model to predict the humidity ratio within a case starts in the same manner as that developed for infiltration in Chapter 4. The time rate of change of the humidity ratio within the case is due to water diffusing into or out of the case plus water that is carried in or out of the case due to barometric pumping plus the adsorption or desorption capacity of the case contents. This relationship is expressed in Equation 5.1.

$$M_{air,in} \frac{d\mathbf{w}_{in}}{dt} = \underbrace{k_{diff,H_2O} (\mathbf{w}_{out} - \mathbf{w}_{in})}_{diffusion} + \underbrace{\dot{m}_{bar} \mathbf{w}_*}_{barometric\ pumping} - \underbrace{k_{cap} * M_{contents}}_{adsorption / desorption} \frac{d\Omega}{dt} \quad (5.1)$$

where $M_{air,in}$ is the mass of the air inside the case in kilograms, w_{in} is the humidity ratio within the case, w_{out} is the humidity ratio measured outside the case, w^* is w_{in} if \dot{m}_{bar} is negative and w_{out} if \dot{m}_{bar} is positive. The units of humidity ratio are kilograms of water per kilograms of dry air. k_{diff,H_2O} , with units of kg/hr, is calculated by applying Graham's Law (Equation 4.5) with the appropriate molecular weight of water, with k_{diff,CO_2} , which was determined from the procedure outlined in Chapter 4. $M_{contents}$ (kg) is the dry mass of the case contents, such as the mounted animals on display, and k_{cap} can be considered as a constant governing the mass transfer of water between the air and the contents within a case. Ω is the equilibrium moisture content (kg of water per kg of dry material) of the hygroscopic material within the case and can be mathematically represented as a function of relative humidity by Equation 5.2 which is representative of wool and other biological materials (Jurinak and Mitchell, 1984). The function represented by Equation 5.2 is shown in Figure 5.1.

$$\Omega = 0.33 \cdot \left(\frac{1}{5} \tan \left(\frac{RH - 0.43194}{0.4395} \right) + 0.3 \right) \quad (5.2)$$

Since both k_{cap} and $M_{contents}$ are unknown, they can be lumped into one unknown constant called K_{cap} (kg) and Equation 5.1 can then be rewritten as

$$M_{air,in} \frac{dw_{in}}{dt} = \underbrace{k_{diff,H_2O} (w_{out} - w_{in})}_{diffusion} + \underbrace{\dot{m}_{bar} w^*}_{barometric\ pumping} - \underbrace{K_{cap} \frac{d\Omega}{dt}}_{adsorption/desorption} \quad (5.3)$$

The humidity ratio within the case can be predicted by representing Equation 5.3 with a first-order finite difference scheme and solving for w_{in} as a function of time:

$$w_{in}^+ = w_{in,old} + \frac{\Delta t}{M_{air,in}} \left(k_{diff,H_2O} (w_{out,old} - w_{in,old}) + \dot{m}_{bar} w_{old,*} - K_{cap} \Delta \Omega \right) \quad (5.4)$$

$$\text{where } \Delta \Omega = \Omega^+ - \Omega_{old} \quad (5.5)$$

The “old” subscript refers to parameters from the previous time step and the “+” superscript refers to the current time step. Increments of one hour were used as the time step.

To determine the value of $\Delta \Omega$, two assumptions were made: 1) the organic material in the case is in equilibrium with the air in the case at the beginning of the model prediction and 2) the organic material reaches equilibrium with the air at the end of each time step. Therefore, the relative humidity of the case at time zero determines the initial starting point on the Ω curve shown in Figure 5.1 so that

$$\Omega_{old} = f(RH_{in,old}) = f(w_{in,old}) \quad (5.6)$$

$$\Omega^+ = f(RH_{in}^+) = f(w_{in}^+) \quad (5.7)$$

Equation 5.4 is then iteratively solved for w_{in}^+ .

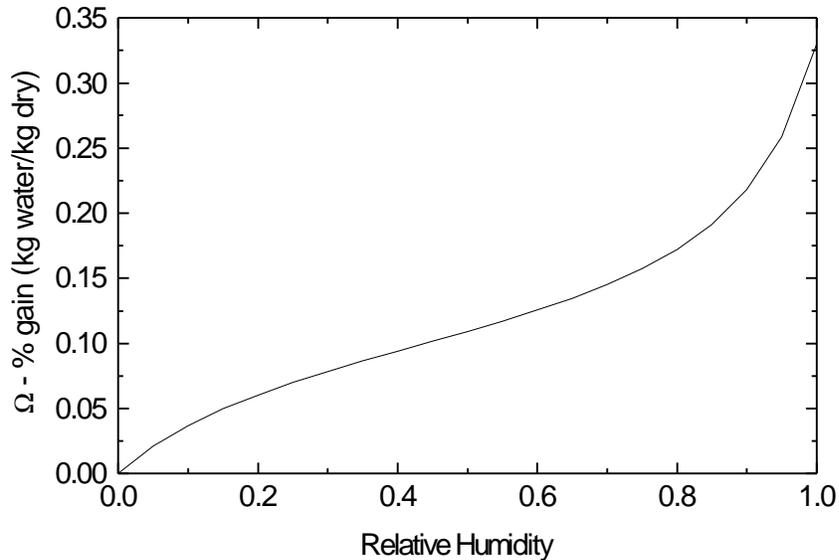


Figure 5.1 Equilibrium moisture content isotherm for wool, as represented by Equation 5.2.

5.3 Results of water model

The water model was applied to the same data sets that were used to determine the exchange rate constant, $k_{\text{diff,CO}_2}$, in Chapter 4 for the Somalian Ass and Lions of Tsavo case.

5.3.1 Somalian Ass case

The July experiment lasted from 7:30 p.m. on July 24, 1999 until midnight on July 31, 1999. The September experiment began at 9:30 p.m. on September 29, 1999 and terminated at midnight on October 19, 1999. The average water capacitance constant, K_{cap} , fit from these two data sets was then applied to a third data set starting on September 1, 1999 and lasting until midnight of September 7, 1999.

The results of the model for each of the periods are presented in Figures 5.2 through Figure 5.4. The fitted values of K_{cap} are summarized in Table 5.1. The high level of agreement between the predicted humidity ratio and that actually measured suggests that the assumption of equilibrium between the animal mounts and the air is valid. The values of K_{cap} determined from the July and September experiments are of the same order of magnitude; however, the K_{cap} from July is nearly twice that fitted from the September experiment. As will be shown in Section 5.3.4, the predicted humidity ratio is fairly insensitive to the exact value of K_{cap} as long as the order of magnitude is correct.

Table 5.1 Summary of exchange rate constants and capacitance constants for the Somalian Ass case.

DATA SET	$k_{\text{diff,CO}_2}$	K_{cap}
July experiment	0.47	183
September experiment	0.50	101
1 st week of September	0.485	142

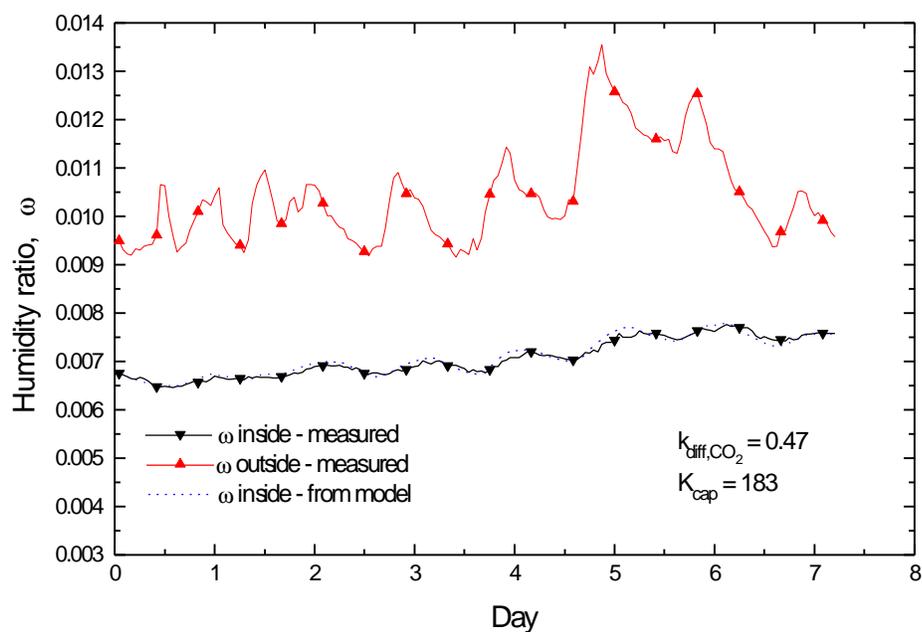


Figure 5.2 Measured humidity ratios inside and outside the Somalian Ass case, along with the calculated values of humidity ratio inside the case from Equation 5.4 for the July experiment, 7/24/99-7/31/99.

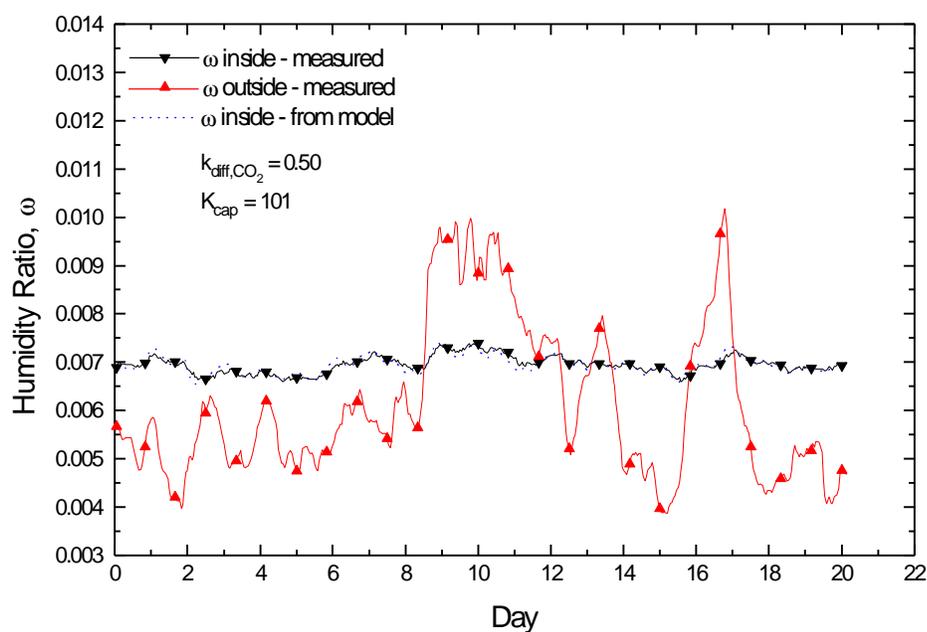


Figure 5.3 Measured humidity ratios inside and outside the Somalian Ass case, along with the calculated values of humidity ratio inside the case from Equation 5.4 for the September experiment, 9/29/99-10/19/99.

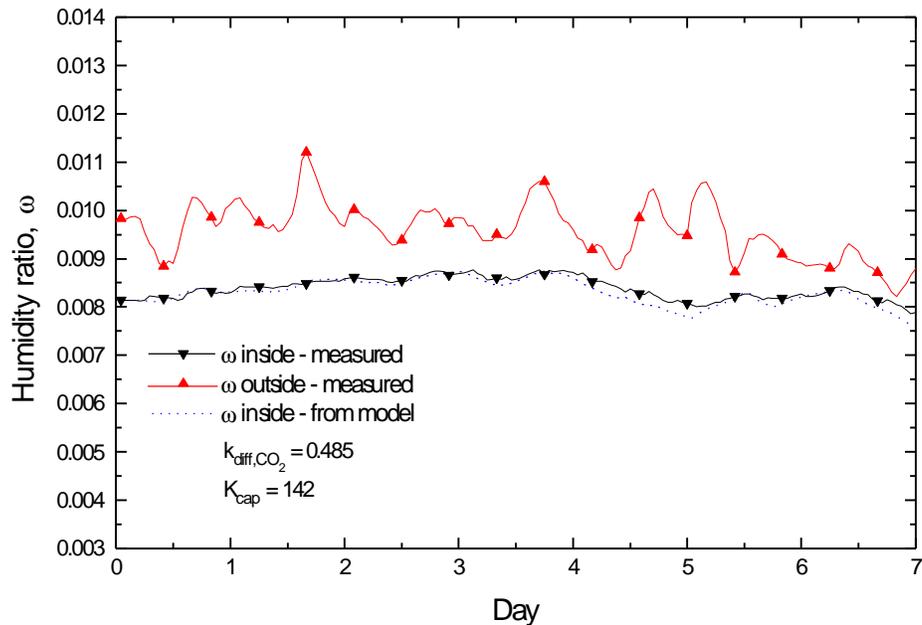


Figure 5.4 Measured humidity ratios inside and outside the Somalian Ass case, along with the calculated values of humidity ratio inside the case from Equation 5.4 during the first week of September, 9/1/99-9/6/99.

5.3.2 Lions of Tsavo case

The July experiment lasted from 6:30 p.m. on July 22, 1999 until midnight on July 31, 1999. The September experiment began at 1:30 p.m. on September 25, 1999 and terminated at midnight on October 11, 1999. The average water capacitance constant, K_{cap} , fit from these two data sets was then applied to a third data set that started on July 14, 1999 and ended on July 20, 1999.

Figures 5.5 through Figure 5.7 present the model results for each of the time periods. Table 5.2 lists the fitted values of K_{cap} . Once again the fitted constant, K_{cap} , from July is nearly two times the magnitude of that fitted from the September data. In comparison with the Somalian Ass case, the fits between the model-calculated and measured values of w_{in} are

not as good. This poorer fit may suggest that the equilibrium assumption is not always valid due to the higher number of air changes per day or, as was suggested in Chapter 4, that an additional mechanism of infiltration, such as flow driven by differences in density, is significant in less tight cases. However, the model does predict the humidity ratio within the experimental error as will be discussed in Section 5.3.3.

Table 5.2 Summary of exchange rate constants and capacitance constants for the Lions of Tsavo case.

DATA SET	$k_{\text{diff,CO}_2}$	K_{cap}
July experiment	1.45	64
September experiment	1.25	34
3rd week of July	1.45	49

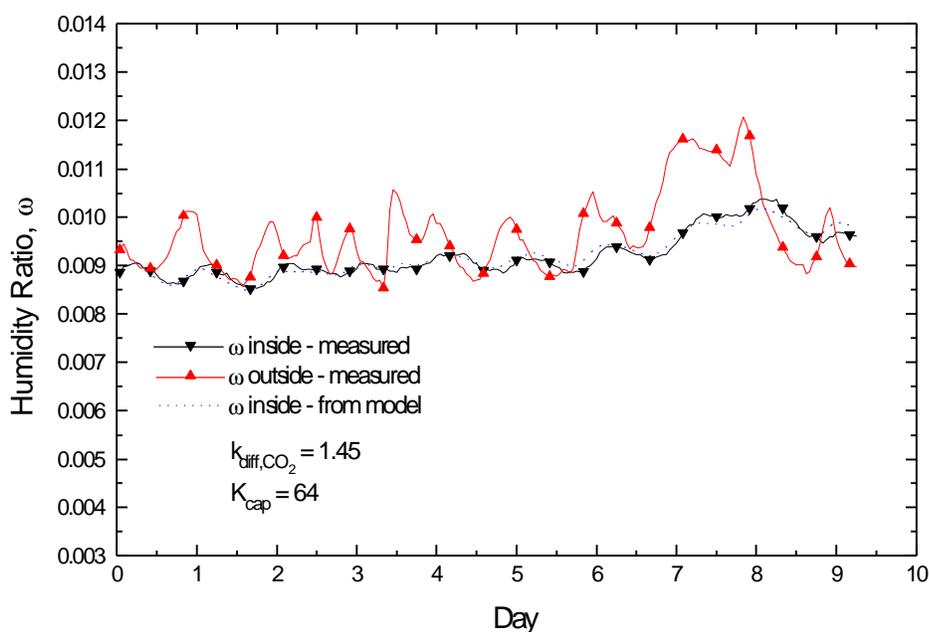


Figure 5.5 Measured humidity ratios inside and outside the Lions of Tsavo case, along with the calculated values of humidity ratio inside the case from Equation 5.4 for the July experiment, 7/22/99-7/31/99.

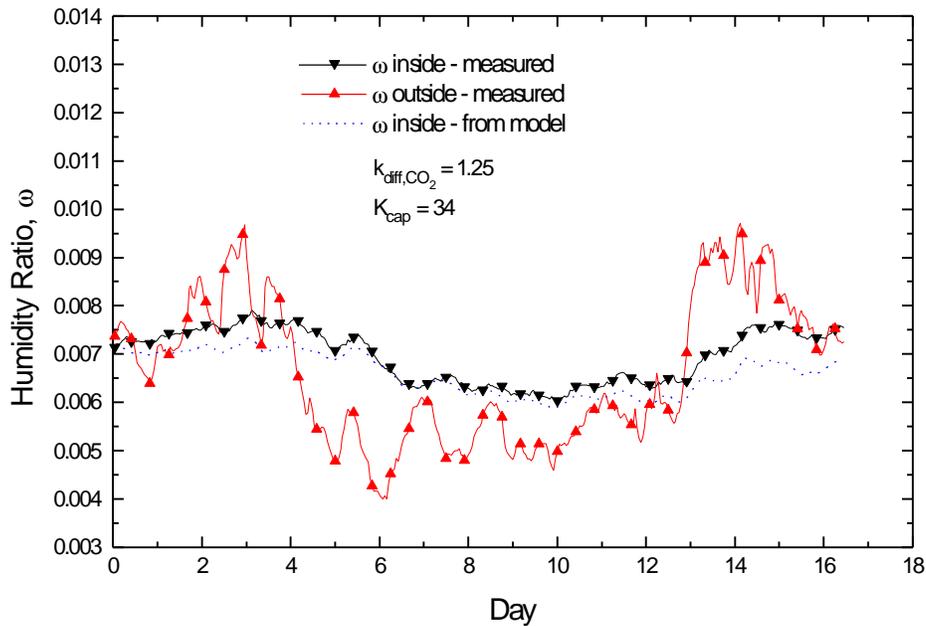


Figure 5.6 Measured humidity ratios inside and outside the Lions of Tsavo case, along with the calculated values of humidity ratio inside the case from Equation 5.4 for the September experiment, 9/25/99-10/11/99.

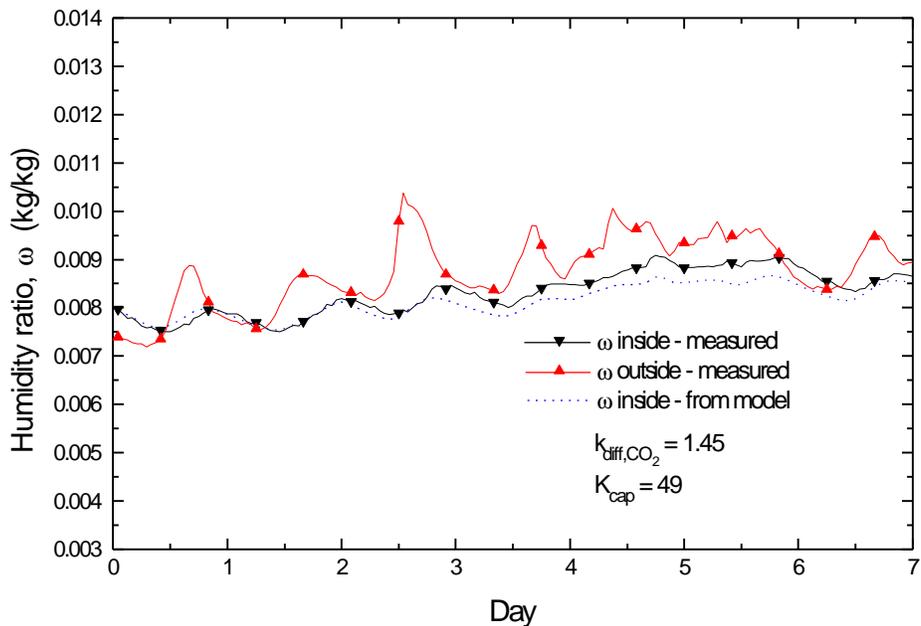


Figure 5.7 Measured humidity ratios inside and outside the Lions of Tsavo case, along with the calculated values of humidity ratio inside the case from Equation 5.4 for the third week of July, 7/14/99-7/20/99.

5.3.3 Error analysis

The reported measured values of the humidity ratio are subject to the experimental accuracy of the instrumentation used to measure the temperature and relative humidity. To determine the error in the humidity ratio values of the previous sections, the relative humidity measurements used in the calculations were varied by $\pm 3\%$ for the Somalian Ass case data from 7/24/99 through 7/31/99. The results are shown in Figure 5.8 and indicate that the $\pm 3\%$ accuracy in relative humidity corresponds to an approximate experimental error of $\pm 10\%$ for the measured values of humidity ratio inside and outside the cases.

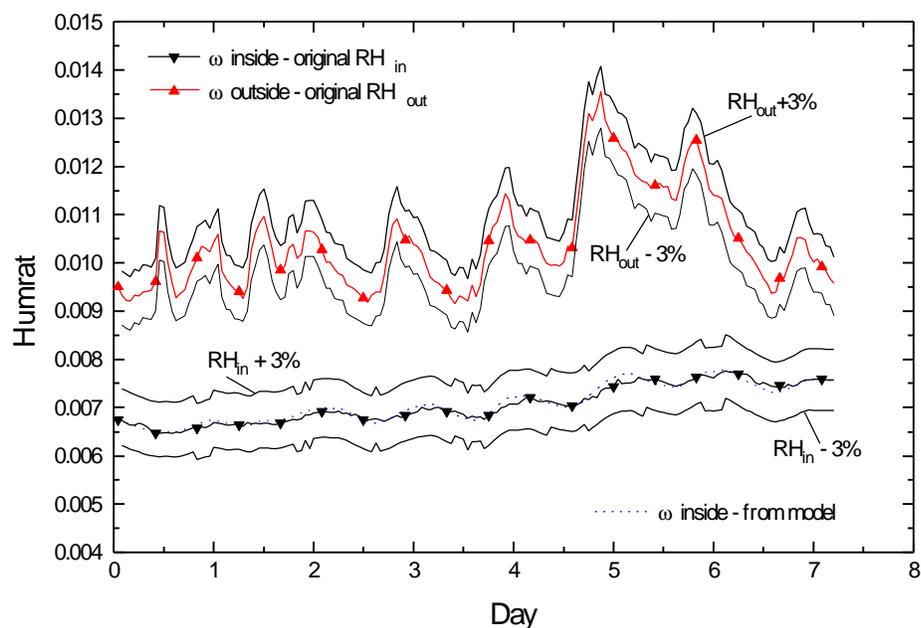


Figure 5.8 Effect of relative humidity sensor accuracy on the reported values of humidity ratio inside and outside the Somalian Ass case for the time period between 7/24/99 – 7/31/99.

5.3.4 Long Term Model Validation

The water model was tested for both the Somalian Ass and Lions of Tsavo cases for a period of one week, shown above in Figure 5.4 and Figure 5.7 respectively. The model was able to predict the humidity ratio inside the cases within the estimated error over a short period of time. Additional validations were performed to check the water model over a much longer period of time. A period of four months was chosen, starting with July 1 1999 and ending on October 31 1999. This span of four months includes the high relative humidities of the summer time as well as the swing to low relative humidities as winter heating is turned on in late September. The fitted parameters, $k_{\text{diff,CO}_2}$ and K_{cap} , used for each case are the averages found from the July and September experiments and listed in Table 5.3.

Table 5.3 $k_{\text{diff,CO}_2}$ and K_{cap} used for validation of water model over a period of four months, July 1 though October 31 1999.

CASE	$k_{\text{diff,CO}_2}$	K_{cap}
Somalian Ass case	0.485	142
Lions of Tsavo case	1.35	49

The results for the Somalian Ass case are shown in Figures 5.9 and 5.10, which plot the predicted humidity ratio and the resulting predicted relative humidity as a function of time. Figures 5.11 and 5.12 contain the results for the Lions of Tsavo case. For the most part, the water model is able to predict the humidity ratio and corresponding relative humidity inside the case within the experimental error of $\pm 10\%$ discussed in Section 5.3.3. Although the predicted humidity ratio does not always follow abrupt changes in moisture content actually measured, the model adequately captures the general trend of decreasing relative humidity exhibited with the transition from summer to winter.

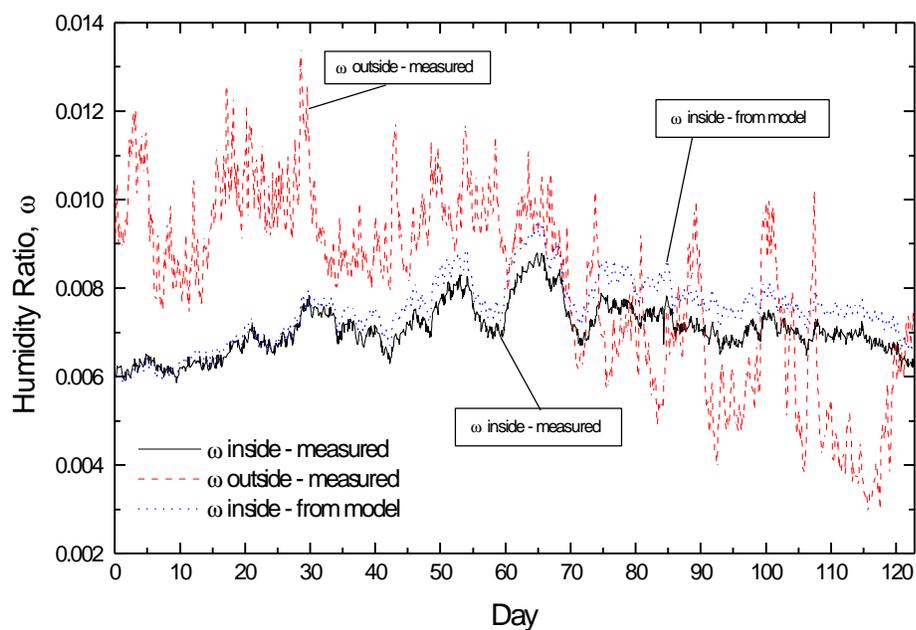


Figure 5.9 Measured humidity ratios inside and outside Somalian Ass case, along with the calculated values of humidity ratio inside the case from Equation 5.4 for four months, July 1 through October 31 1999.

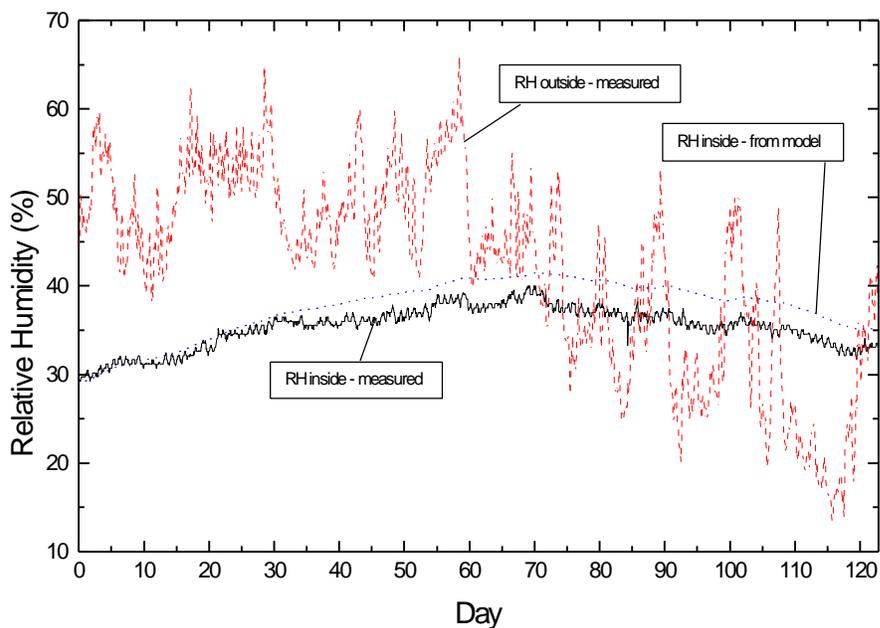


Figure 5.10 Measured relative humidities inside and outside Somalian Ass case, along with the calculated values of relative humidity for four months, July 1 through October 31 1999.

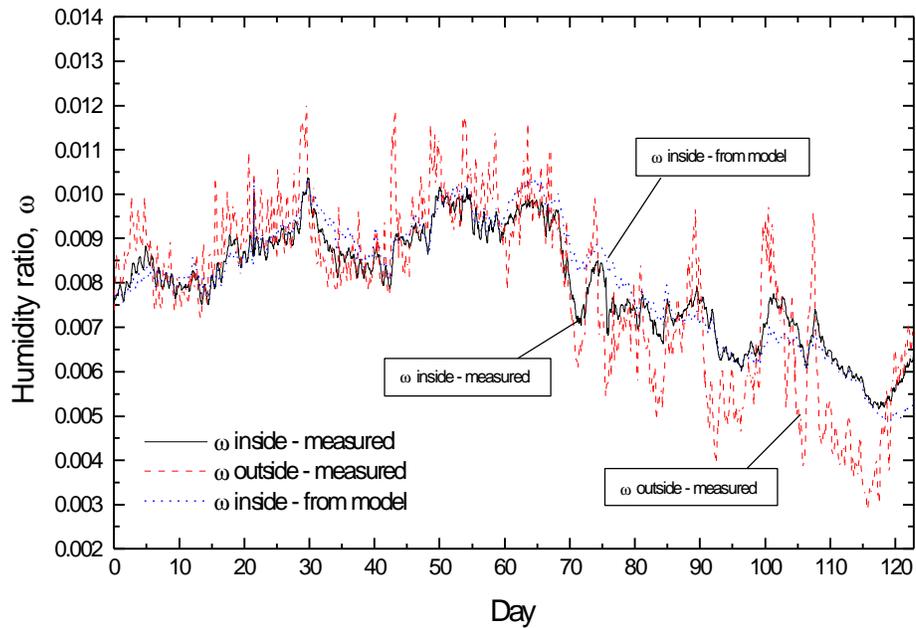


Figure 5.11 Measured humidity ratios inside and outside Lions of Tsavo case, along with the calculated values of humidity ratio inside the case from Equation 5.4 for four months, July 1 through October 31 1999.

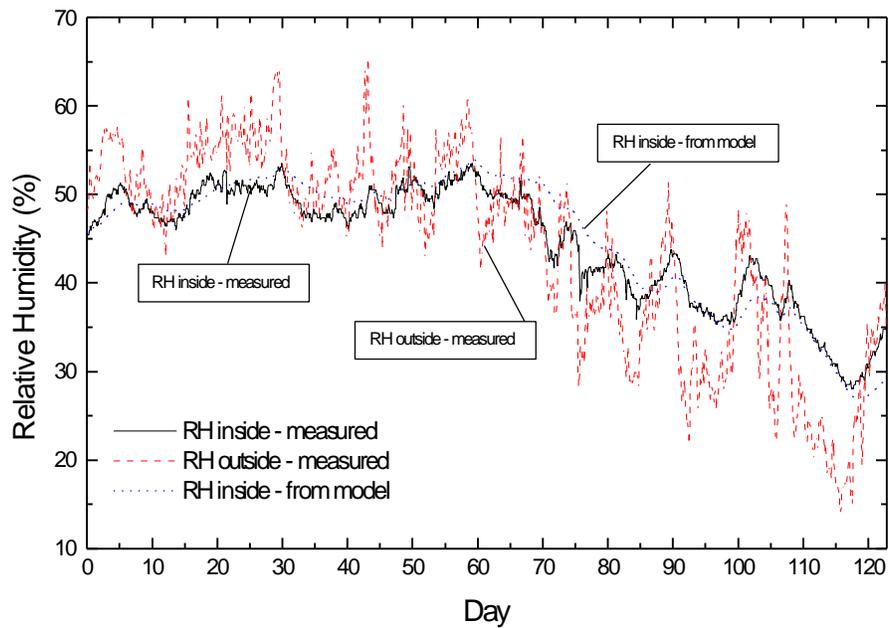


Figure 5.12 Measured relative humidities inside and outside Lions of Tsavo case, along with the calculated values of relative humidity for four months, July 1 through October 31 1999.

5.3.5 Sensitivity analysis

To determine how sensitive the water model is to the values of $k_{\text{diff,CO}_2}$ and K_{cap} , a sensitivity analysis was performed on the July data set for the Somalian Ass case. K_{cap} and $k_{\text{diff,CO}_2}$ were each varied by $\pm 50\%$ from their best-fit values of 183 and 0.47, respectively. The effect of varying K_{cap} on the predicted case interior humidity ratio is shown in Figure 5.13 while Figure 5.14 shows the effect of varying $k_{\text{diff,CO}_2}$. Halving or doubling K_{cap} has little effect on the resulting predicted data. This insensitivity to the moisture capacitance is due to the fact that the change in moisture content, $\Delta\Omega$, is very small so that only orders of magnitude changes in K_{cap} affect the model-predicted values of w_{in} .

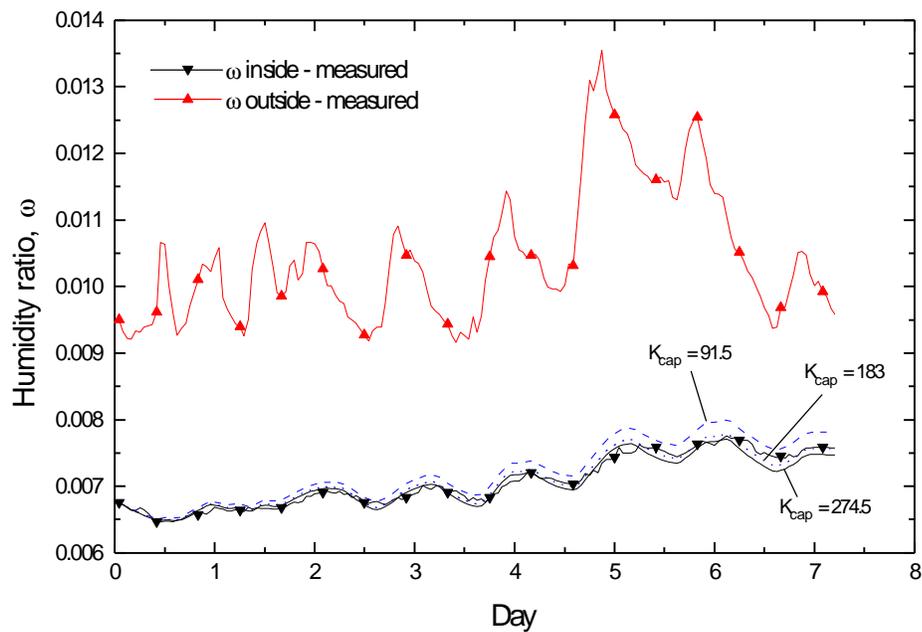


Figure 5.13 Variation of predicted humidity ratio inside the Somalian Ass case for different values of K_{cap} .

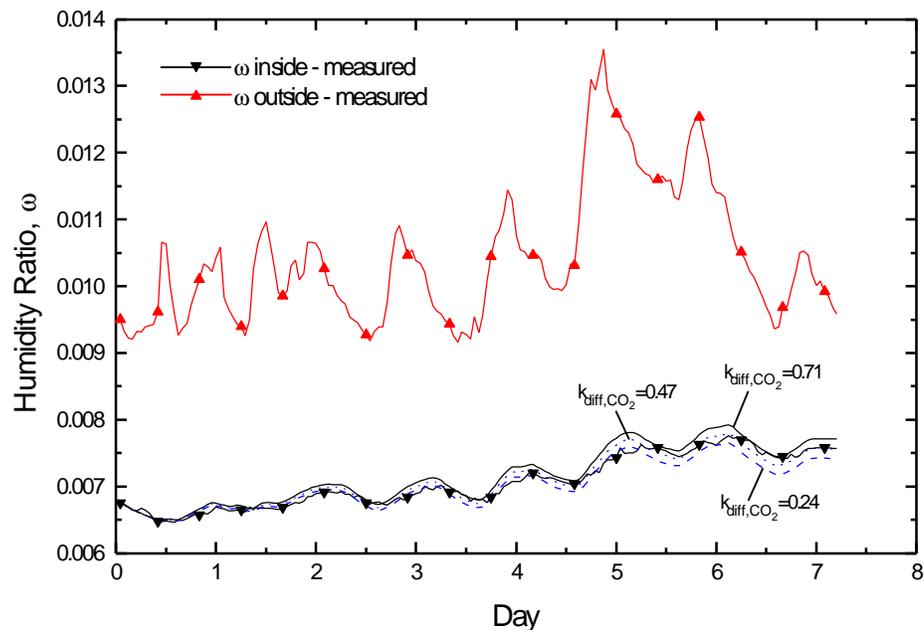


Figure 5.14 Variation of predicted humidity ratio inside the Somalian Ass case for different values of $k_{\text{diff},\text{CO}_2}$.

Variations in $k_{\text{diff},\text{CO}_2}$ have little effect on the predicted humidity ratio because of the iterative nature of the solution. $\Delta\Omega$ is directly related to the value of $k_{\text{diff},\text{CO}_2}$ so that as $k_{\text{diff},\text{CO}_2}$ increases, so does $\Delta\Omega$. As a result, the humidity ratio prediction is largely insensitive to changes in either fitted parameter.

5.3.5.1 Experimental Recommendations

From the development of Equation 5.3, K_{cap} is directly related to the mass of dry hygroscopic material inside the display case, M_{contents} . It seems unlikely that there are nearly 200 kilograms of sorbing material in the Somalian Ass case. To verify the water model developed in this chapter as well as the values of the fitted parameter, K_{cap} , a procedure similar to the CO_2 loading experiment could be performed. A known quantity of steam could

be added to a case and the humidity ratio inside and outside monitored with time. With the water vapor exchange rate constant, $k_{\text{diff,H}_2\text{O}}$ determined from the CO₂ loading experiment, diffusion of water vapor out of the case could be accounted for. From the measured humidity ratio in the case, the amount of water $\Delta\Omega$ adsorbed by the hygroscopic materials could also be estimated, so that the value of K_{cap} could be more accurately approximated. The experiment would also help to verify whether the hygroscopic materials are in equilibrium with the air inside the case.

5.4 Recommendations for case tightness

The developed water model will be used to estimate the level of control needed by an HVAC system to maintain the case contents within $\pm 5\%$ of the desired RH set point. Assume that an HVAC system has been installed in the Museum that can provide good temperature control and humidification of the air space to within $\pm 10\%$ of the relative humidity set point. How tight does a case need to be so that the internal fluctuations are limited to $\pm 5\%$? A simulation was carried out for the Somalian Ass case using generated relative humidity values for outside the case. The water model was run with different values of air changes per day to predict the resulting relative humidity within the case. The relative humidity outside the case was constructed from a sinusoid with different amplitudes and periods and represented by Equation 5.8, where t is the time in hours. The different periods examined were 12, 24 and 48 hours.

$$RH_{out} = 10 \cdot \sin\left(\frac{2p \cdot t}{period}\right) + average \quad (5.8)$$

For the simulations, the average relative humidity outside the case was set to 45% and the temperatures inside and outside the case were held constant at 298 K so that the calculated RH fluctuations were not confounded by changes in temperature. Changes in barometric pressures were neglected. To isolate the effects of case tightness alone on reducing the relative humidity fluctuations, K_{cap} of the organic material within the case was initially set to zero.

Figures 5.15 through Figure 5.17 present the results of the water model with no capacitance for the three different periods of fluctuations, 12, 24 and 48. Five values of air exchange rates were examined: 0.28, 0.56, 1.4, 2.24 and 2.8 air changes per day. The number of air changes per day translated into cases that are 1, 2, 5, 8 and 10 times leakier than the Somalian Ass case. For the highest frequency fluctuations in the exterior relative humidity, a case can have as many as three air changes per day and still maintain the case interior RH to within $\pm 5\%$ of the average. As the period increases to 48 hours, tighter cases with air exchange rates of approximately one are required to maintain the desired RH range. With longer periods of fluctuations, the case interior has longer exposure time to the extremes in exterior RH, necessitating the use of tighter cases. A fairly tightly sealed case with 0.5 air changes per day can tolerate $\pm 10\%$ fluctuations with a period as great as seven days and maintain the interior to $\pm 5\%$.

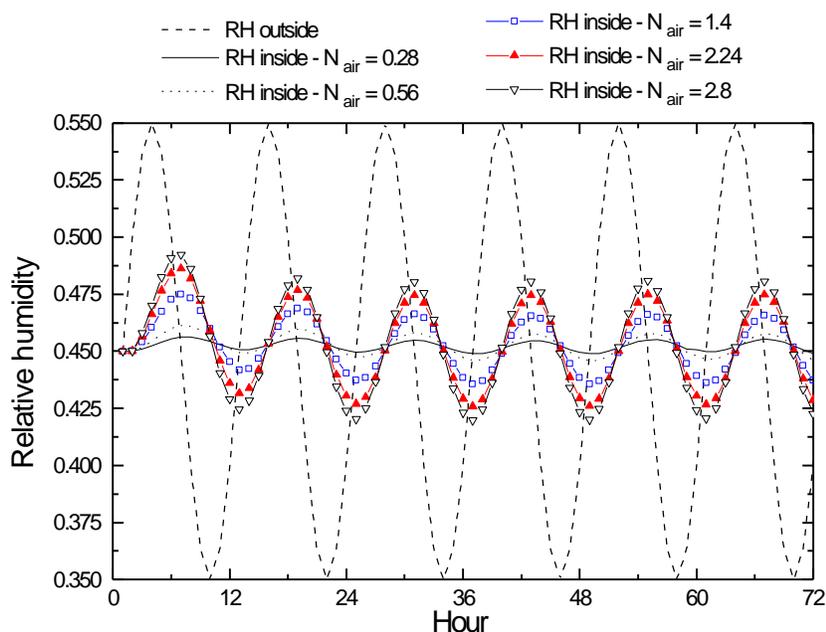


Figure 5.15 Prediction of case interior relative humidities for five different air exchange rates where the relative humidity outside the case fluctuates with a period of twelve hours. K_{cap} is equal to 0.

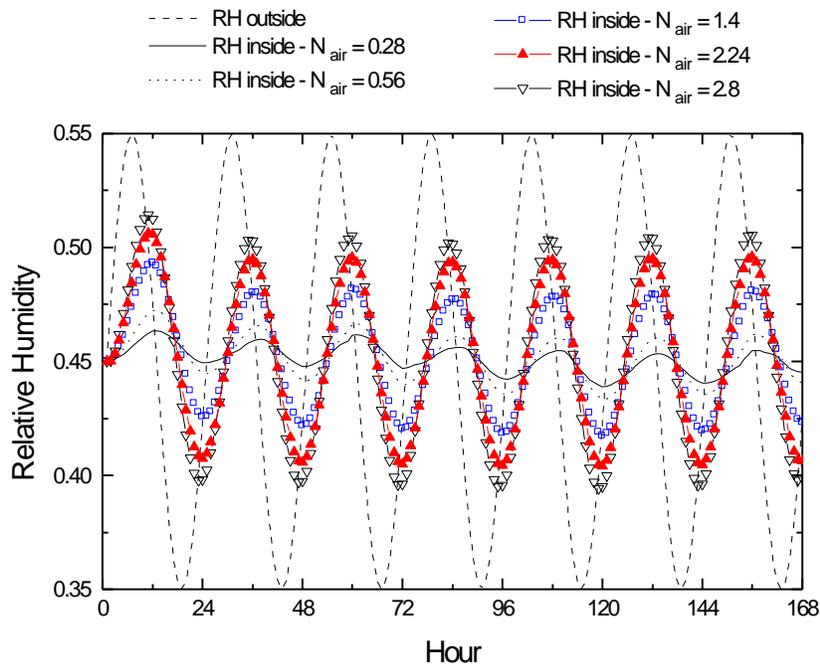


Figure 5.16 Prediction of case interior relative humidities for five different air exchange rates where the relative humidity outside the case fluctuates with a period of 24 hours. K_{cap} is equal to 0.

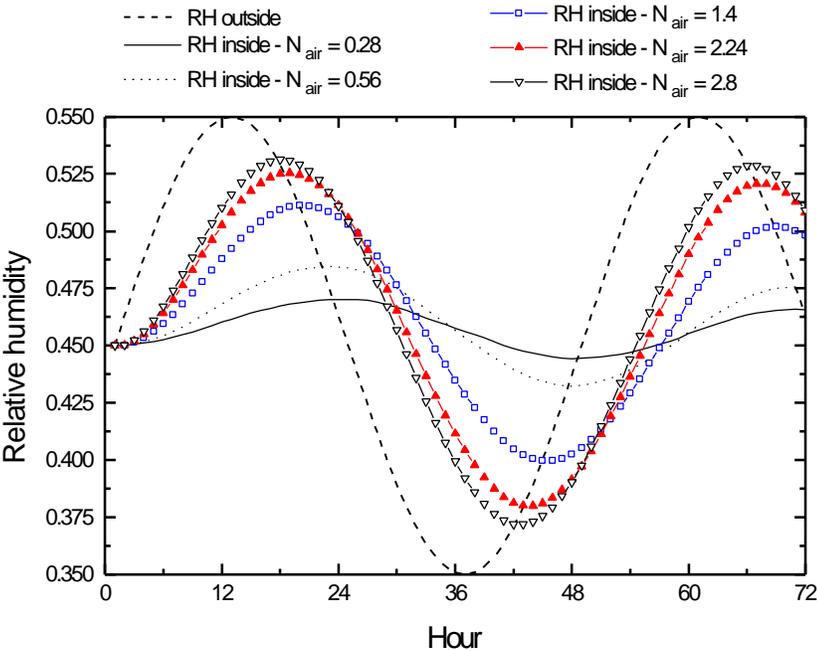


Figure 5.17 Prediction of case interior relative humidities for five different air exchange rates where the relative humidity outside the case fluctuates with a period of 48 hours. K_{cap} is equal to 0.

One recommendation for relative humidity control is to allow the RH within the building to float with the seasons. For example, the average relative humidity is allowed to drop to 45% in the winter and rise to 55% in the summer. An example of this gradual fluctuation in RH is shown in Figure 5.18 with a shorter-term fluctuation superimposed on it. The seasonal adjustment is a sine wave with a period of six months while the superimposed sine function has a period of 48 hours. By the end of the month, the average RH has increased to roughly 48% from 45%. The RH of the case interior matches the long-term variation but the case is able to damp out the short-term fluctuations.

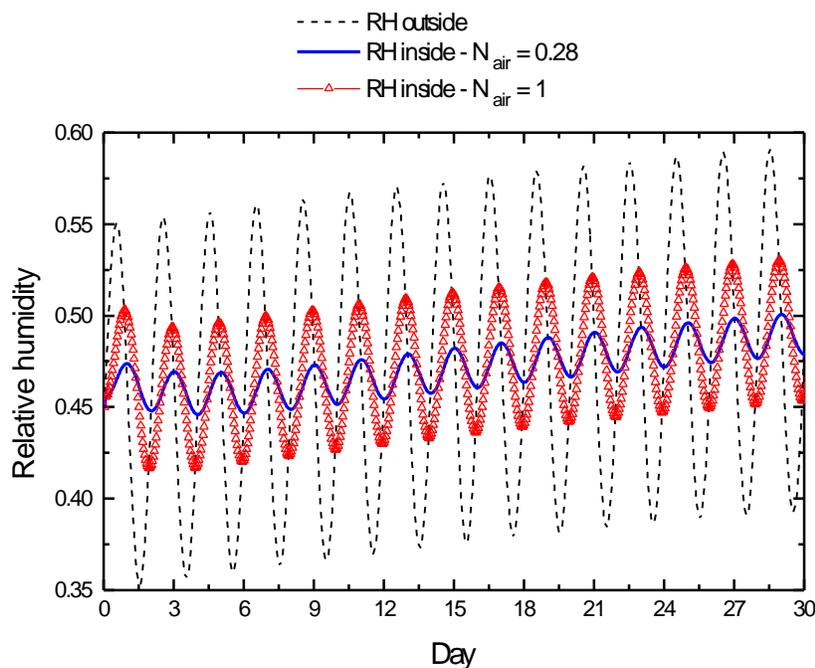


Figure 5.18 Prediction of case interior relative humidities for two different air exchange rates where the relative humidity outside the case fluctuates with a period of 48 hours about the average and the average fluctuates with a period of six months. K_{cap} is equal to 0.

In actuality, the fluctuation of the relative humidity with the cases will be less than that shown above in Figures 5.15-5.17 as can be seen in Figure 5.19, which includes the moisture capacitance, K_{cap} that was found for the Somalian Ass case. The organic materials on display act in a similar manner to silica gel and adsorb or desorb moisture with changes in relative humidity. However, it is this adsorption and desorption of water by the specimens that should be limited as it leads to dimensional changes. This is precisely why the relative humidity in the macroenvironment of the Museum must be controlled. To minimize the adsorption and desorption of water by the artifacts, the cases should be made as tight as possible with at most one air change per day. An additional benefit to using tight cases, as was just seen, is that the level of control needed for HVAC is greatly reduced. For cases

similar to that of the Somalian Ass, short-term, external fluctuations with a range of $\pm 15\text{-}20\%$ and a period of five days can be safely tolerated as long as the average RH is maintained at the desired set point.

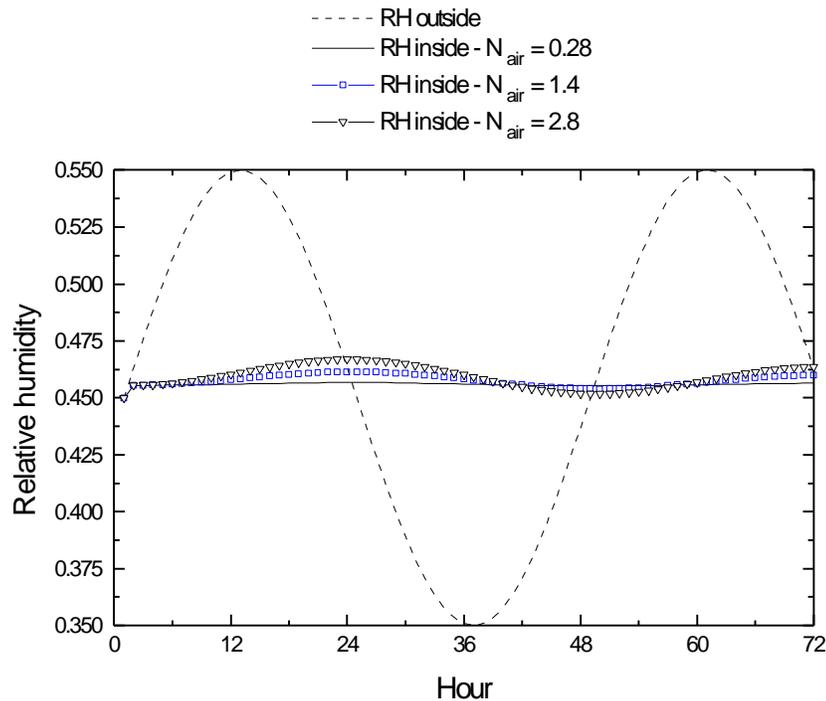


Figure 5.19 Prediction of case interior relative humidities for three different air exchange rates where the relative humidity outside the case fluctuates with a period of 48 hours. K_{cap} is equal to 183.

5.5 Remediation recommendations

From the temperature and relative humidity results presented in Chapter 3, the most important environmental problem that must be addressed is that of the extremely low relative humidities in the winter time. Based on the ASHRAE recommendations summarized in Chapter 1, a plan should be developed to improve the environmental conditions within the

Museum from merely preventing extremes to the establishment of year round stable conditions.

5.5.1 Long term remediation

5.5.1.1 Space conditioning

To preserve the contents of the Field Museum for decades to come, a long-term vision of prevention must be adopted. The installation of modern HVAC equipment, both in terms of primary systems such as hot and cold water supplies, as well as secondary systems such as improved air distribution systems, would provide Museum-wide temperature and relative humidity control for years to come.

An ideal system will have the flexibility to satisfy the varying environmental requirements of the diverse areas throughout the Museum. For example, storage areas such as Anthropology would need much tighter control of relative humidity fluctuations since the contents are largely stored on open shelving with no protection from storage cases or cabinets. In contrast to the storage areas, the exhibit hall areas where artifacts are stored in cases can tolerate a much greater amount of variability in macroenvironment relative humidity since the cases dampen the temperature and relative humidity variability seen within the case microenvironment.

Since large portions of the Museum's artifacts are maintained in storage, priority should be given to protecting these objects. Even in storage areas such as Zoology, which have tight cabinets that reduce temperature and relative humidity fluctuations, efforts should be made to maintain the average space RH at a minimum of $35\% \pm 5\%$ in the winter. Otherwise, the animal skins and other organic material in storage will desorb water in

response to low ambient relative humidities, causing dimensional changes and, depending on whether the specimen is restrained in any way, the buildup of mechanical stress

One control option that can be used for storage areas that do not see considerable or lengthy periods staff habitation is the use of humidistats in conjunction with thermostats to regulate the space temperature and humidity. Under this control scheme, relative humidity or dew point sensors are used to determine the relative humidity of the space. If the RH is below the desired set point, then the space temperature is allowed to drop and conversely, if the RH is above the desired set point, more reheat is used to raise the temperature of the space. The end result is that temperature of the space is allowed to float (within limits) in order to maintain the desired RH set point (Lafontaine and Michalski, 1984 and ASHRAE Applications Handbook, 1999).

Pressurization of the building would also be desirable to reduce the amount of uncontrolled infiltration in the summer. However, in the winter, it has been recommended that the museums in cold climates be maintained at slightly negative pressure during the winter (Hartman, 1996). For a building that maintains some level of humidification during the winter, the interior humidity ratio is higher than that outside. Imposing negative pressure on the building will reduce the amount of water migrating into the exterior walls, condensing and then eventually freezing, thus protecting the building envelope.

Once a system is installed that can provide adequate temperature and relative humidity control, steps should be taken to address pollution, fungi and mold problems. Active treatment of the incoming air, both to remove harmful chemicals and kill fungi, is recommended.

5.5.1.2 Case conditioning

Although the ArtSorb desiccant within the Chinese case appeared to be an ineffective means of controlling relative humidity for most of the monitoring period, the use of passive RH control can be an attractive option for smaller, tightly sealed cases that house objects which require a RH set point different from that of the macroenvironment. Thorough knowledge of the typical adsorption and desorption seasons must be known beforehand so that the correct amount of desiccant can be used to adequately control the relative humidity over a year.

The use of desiccants or saturated salt solutions in tight cases would decrease the amount of fluctuation control needed in a HVAC system (or for a small museum remove the need for an HVAC system altogether), reducing the capital cost of equipment as well as energy costs. However, due to the size and number of the cases in the Field Museum and the amount of desiccant that would be needed, it seems that passive RH control on a case by case basis would not be cost effective.

Other methods of controlling the relative humidity for a case or a series of cases have been developed which couple the aspects of both active and passive RH control. One such method that has been used in the Field Museum in the past is the implementation of active humidity control modules (Sease, 1991). The module consists of a small-scale mechanical control system, featuring a blower, a heat exchanger to keep the conditioned air at room temperature and a silica gel column to smooth out the humidity output of the humidifier and dehumidifier. The module is connected to each case with a system of plastic tubing, which is easy to install. Although the modules appeared to work satisfactorily for a period of years,

long-term maintenance problems prevented their continued use and expanded implementation throughout the Museum.

5.5.2 Short term remediation

In fact, the Field Museum is undergoing a major renovation, which will culminate in the complete replacement of the existing HVAC equipment. However, the equipment renovation is in the early stages of planning and will not be completed for another five to ten years. Short-term solutions are needed to help alleviate the relative humidity problems until the new HVAC system is fully operational.

5.5.2.1 Air supply humidification

Temperature is principally controlled within the Museum by two-pipe fan coil systems. In the summer, cold water runs through the fan coil units and the room air is cooled as it blown across them. A drainage system is provided for condensate that forms as the air is cooled. For the winter season, hot water runs through the fan coil units thus providing sensible heating of the air; however, no means of humidification is available with the system.

The Museum does have limited humidification capability in some of the air distribution supply system, which uses boiler steam for humidification. It is unlikely that the system has the capacity to provide the desired amount of humidification to raise the relative humidity to 45-50% through the exhibition areas but it might be possible to achieve a relative humidity of 30%. Surprisingly, this means of humidification is generally not used. Complaints on the odor of the air and high humidity levels at the air duct discharge result in the system being turned off. Steps should be taken to address and correct both of these concerns. The humidification system should be annually serviced and cleaned with

fungicides to kill off potential odor-producing molds and fungi. The use of a different water source for steam generation should be researched so that the amount of chemicals in the steam is minimized. The installation of additional fans to promote mixing of the fresh supply air would reduce local regions of high humidity and help distribute the moisture throughout the space.

5.5.2.2 Emergency door seals and thermostat location

On a recent visit to the Museum during a very hot and humid day in July, a visual survey of Hall 21 was made since that is one of the main problem areas. Adjacent to the exhibit hall is a stairwell and an emergency exit. Measurable infiltration of hot, humid air was occurring through the seals along the emergency exit door. A survey of the entire building should be performed to evaluate the seals of the doors and replace them if necessary to limit this infiltration of unconditioned air.

An additional survey should be performed within the Museum to locate, calibrate, and, if necessary, move the thermostats. For example, if the thermostat for Hall 21 were located near the stairwell and emergency exit, the unconditioned air would bias its temperature readings. Such a situation could in fact explain the behavior seen in Hall 21, which experiences high temperatures during the winter. Cold infiltration air would cause the thermostat reading to be low and indicate that additional heating is needed thus increasing the temperature of the space. Ideally, thermostats should be located on interior walls away from stairwells and regularly calibrated, so that they accurately control the temperature of the space.

5.5.2.3 Supply minimum outdoor air

Reducing the amount of outdoor air to the minimum recommended level for indoor air quality would benefit both the humidity and pollutant levels in the building. A lower outdoor air intake would reduce the amount of humidification needed to maintain the desired RH levels. In addition, the concentration of harmful pollutants that originate from outdoors and are delivered into the building would also decrease thus reducing or possibly eliminating the need for an active filtration system.

5.5.2.4 Decrease space set point temperature

For a given level of moisture content in air, increasing the temperature causes a decrease in relative humidity and vice versa. The relationship between relative humidity and temperature can be used to increase the space RH during the winter. From the results presented in Chapter 3, the average winter temperature appears to be around 74°F except in Hall 21 and Zoology, which experienced temperatures in excess of 80°F. If the temperature could be controlled to a lower set point, between 66-68°F, the relative humidity would increase by 2-10%. Not only would a lower temperature improve the relative humidity levels, it would also reduce the energy costs during the winter heating season.

5.5.2.5 Tighten cases

Tight display cases eliminate fluctuations in relative humidity and pollutants, thus protecting their contents from extremes in both parameters. A survey should be done of the existing cases and steps taken to tighten cases, where possible. Large cracks should be sealed and any access doors should be close fitting. It is neither desirable nor possible to

completely seal the cases, but reducing the number of air changes per day to less than 0.5 would be beneficial.

5.5.2.6 Removal of wall between Rice Hall and Hall 21

Comparison of the temperature and relative humidity between the Lions of Tsavo area, Rice Hall, and the Somalian Ass area, Hall 21, in Chapter 3 revealed that Hall 21 was roughly 5-8°F hotter than Rice Hall during the winter. This temperature difference resulted in a 3-5% lower RH in Hall 21 than Rice Hall. Based on these observations, the wall that separated the two spaces was removed on 8/10/99 to promote mixing between the two areas and reduce the temperature in Hall 21. Figure 5.20 presents the average daily temperature of the two areas during the two heating seasons that were recorded and shows that from December 12, 1998 through February 18, 1999 Hall 21 was roughly 8°F hotter than Rice Hall. After the wall was removed, the temperature difference between the areas was less than 2°F. Figure 5.21 presents the corresponding relative humidity for the two time periods. The initially large RH difference (~15%) from December 12, 1998 to the beginning of the month of January 1999 must be due to some source of humidification after which the difference decreases to 2-8%. After the wall removal the relative humidities are very similar.

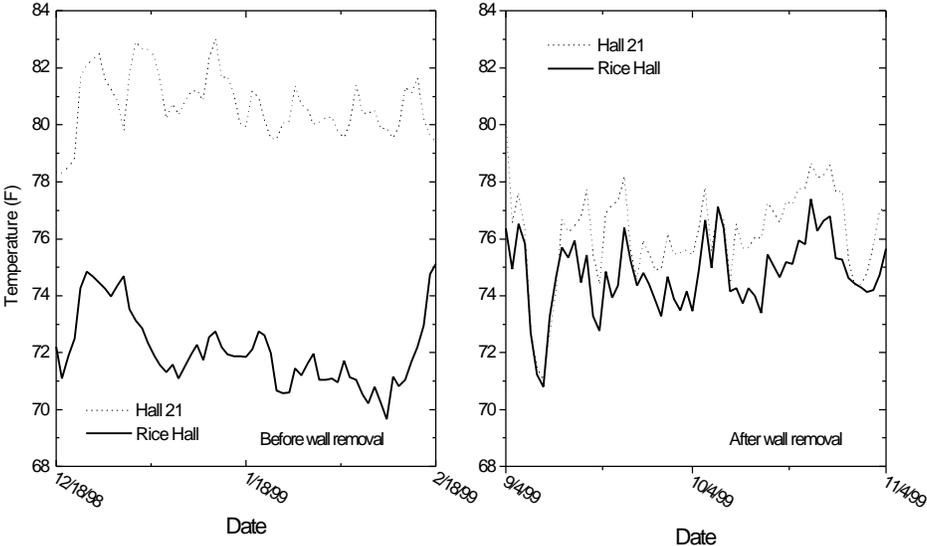


Figure 5.20 Temperature histories for Hall 21 and Rice Hall during two winter heating seasons.

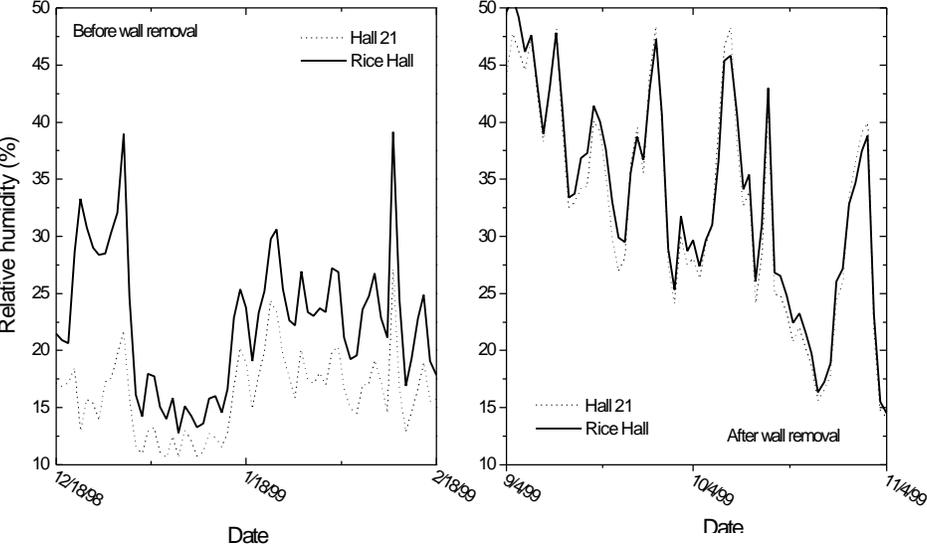


Figure 5.21 Relative humidity histories for Hall 21 and Rice Hall during two winter heating seasons.

5.6 Conclusions

The infiltration model developed in Chapter 4 was expanded to predict the humidity ratio values within the case where the isotherm for wool was utilized to represent the moisture-capacity characteristics of the animal mounts in the Somalian Ass and Lions of Tsavo cases. A simulation was then run with the model to determine the level of case tightness needed to maintain the contents to within $\pm 5\%$ of the average relative humidity of the space. Tighter cases can withstand greater external fluctuations as well as fluctuations with longer time periods. As a result, the HVAC system would not need to maintain very tight control, thus saving on capital and energy costs.

Short and long term remediation recommendations have been made to alleviate the low relative humidities experienced in exhibition hall and Zoology storage. The likelihood of damage occurring to the artifacts would be lessened if the relative humidity in the winter could be increased to at least 25-30%.

CHAPTER 6

Summary and Recommendations

6.1 Summary

This research project was undertaken to gain a better understanding of the causes of damage to cultural objects and to recommend environmental conditions for their storage and display. A literature review revealed that five main factors are mainly responsible for the deterioration of artifacts: light, temperature, relative humidity, pollution and biological attack. Damage from light can be limited or prevented through the use of UV filters and good exhibit design. Temperature and relative humidity are related and recommended set points for both parameters are material dependent. In general, relative humidity is the more harmful variable and also more difficult to control. For a general museum setting, fluctuations in both temperature and relative humidity should be minimized. Temperature can be maintained anywhere between 59-77°F depending on whether the area is for storage or display. Relative humidity should be maintained between 35-55%, although 45-50% is probably the best compromise across a wide variety of materials. Concentrations of pollutants should be minimized to prevent the formation of harmful acids, which weaken materials. Moderate temperatures and controlled relative humidity will limit the danger from biological agents such as fungi, mold and other pests.

An environmental survey was performed at the Field Museum of Natural History in Chicago, IL to evaluate certain areas which housed artifacts that displayed moderate to severe signs of deterioration. Temperature and relative humidity measurements were taken at fifteen minute intervals for almost eleven months in three exhibit cases and two storage areas. The results, which were presented in Chapter 3, indicate that the temperature in certain areas often exceeds the recommended upper limit of 77°F. Relative humidity is poorly controlled and the central heating causes relative humidities as low as 10% during winter in certain areas of the building. It is very likely that these extremely low relative humidities are a primary cause of damage to the artifacts.

Evaluation of the tightness of two display cases was performed through a procedure outlined in Chapter 4, which monitors the decay of carbon dioxide gas inside the case. An infiltration model of a case was developed and validated, so that the number of air changes a case undergoes in a day could be calculated. The model was then extended to predict the humidity ratio or relative humidity inside a case. Cases provide a layer of protection between the artifacts on display and the fluctuations that may occur in the Museum macroenvironment. Fluctuations in relative humidity, pollutants and to a lesser degree temperature are all buffered due to the presence of a case. The tighter the case, the greater the protection against fluctuations. One of the tighter cases in the Museum had an air exchange rate of 0.28 changes per day while the other experienced one air change per day. As a general recommendation, cases should be constructed with less than one air change per day.

To alleviate the severely dry conditions in the Museum during the winter until the new HVAC system is installed, any existing humidification equipment must be serviced,

cleaned and turned on. Obvious leaks in the building perimeter through emergency doors or non-operational windows should be sealed to limit the infiltration of unconditioned air. Reducing the space temperature set point will also serve to increase the corresponding relative humidity by a few percentage points.

6.2 Recommendations for future work

The long term monitoring plan of both the existing areas as well as of new locations should be continued within the Museum. Temperature and relative humidity in additional areas should be monitored in order to develop a complete understanding of the environmental conditions throughout the building. Travelling exhibit areas should be included in the plan to ensure that temporary displays are being maintained in an adequately controlled environment. In the Somalian Ass case, the video camera should be repositioned to obtain a better view of the tear in the rump of the mount. A direct correlation between tear size and the relative humidity within the case could then be developed.

The leakage rates of storage cabinets and additional display cases used throughout the Museum should be determined in order to characterize the level of protection available. Recommendations could then be made on a quantitative basis on whether cases should be tightened or storage cabinets replaced.

The Museum uses desiccant to passively control relative humidity in at least one case. Further studies should be performed to evaluate the performance of such systems so that optimal performance with minimum maintenance is achieved. Similarly, humidity modules mentioned in Chapter 5, which control the relative humidity of individual cases or a series of cases, warrant further investigation.

Since the Museum will eventually possess an HVAC system capable of controlling the temperature and relative humidity to the recommended set points, the other factors contributing to artifact damage must be investigated. An indoor air quality survey should be performed at various locations in the Museum to determine the concentrations of harmful pollutants, particularly of SO₂, NO_x and O₃. If the levels are above recommended levels, options for cost-effective means of filtering the air, either on an individual case basis or in the air intake system of the building, should be researched. In a similar manner, bioaerosol monitoring should be done to determine if excessive levels of mold and fungi are present in the building.

Appendix A

Contents

1. Bibliography of all works researched for project.

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Appendix B

Contents

1. EES program to predict CO₂ concentration and humidity ratio inside an exhibition case.

```

PROCEDURE FIND_CO2(mass, dCO_2, dm, k, CO2_in, CO2_out: total)
  {$ Function to calculate the inside co2 concentration taking into account pressure and
diffusion effects}

  IF (dm < 0) THEN

    total:=CO2_in+k/mass*dCO_2+dm/mass*CO2_in

  ELSE

    total:=CO2_in+k/mass*dCO_2+dm/mass*CO2_out

  ENDIF

END

"*****"

FUNCTION FIND_eq(RH)
  {$ Function to calculate the % gain in moisture of wool based on RH}

  w_max:=0.33

  w_star:=1/5*(tan((RH-0.43194)/0.43950))+0.3

  FIND_eq:=w_star*w_max

END

"*****"

FUNCTION FIND_wbar(dM, w_in, w_out)

  {$Function to determine which humrat is associated with the direction of barometric
pumping}

  IF(dM < 0) THEN

    FIND_wbar:=w_in

  ELSE

```

```

        FIND_wbar:=w_out

    ENDIF

END

"*****"

"Donkey case"

"Experimental data after pumping the CO2 inside the case to 2000 ppm"

"7/24/99 - 7/31/99"

Volume=0.75*(11*14*13*convert(ft^3, m^3))      "Volume of the display case
minus the contents"

R=R#/MM_air      "Specific gas constant for air"

MM_air=MOLARMASS(Air)

"Current time step assignments:"

hour2=lookup(TableRun#, 'hour1')

m_2=Volume/R*(lookup(TableRun#, 'P_bar')*convert(inHg,
kPa))/((lookup(TableRun#, 'T_in')+459.67)*convert(R,K))

P_atm=lookup(TableRun#, 'P_bar')*convert(inHg, atm)

P_kPa=lookup(TableRun#, 'P_bar')*convert(inHg, kPa)

T_in_K=(lookup(TableRun#, 'T_in')+459.67)*convert(R, K)

T_out_K=(lookup(TableRun#, 'T_out')+459.67)*convert(R, K)

RH_in=(round(lookup(TableRun#, 'RH_in')))/100      "!Make a fraction"

RH_out=(round(lookup(TableRun#, 'RH_out')))/100      "!Make a fraction"

"Assign previous time step parameters:"

```

```
m_1=Volume/R*(lookup(TableRun#-1, 'P_bar')*convert(inHg,
kPa))/((lookup(TableRun#-1, 'T_in')+459.67)*convert(R,K))
```

```
T_in_K_old=(lookup(TableRun#-1, 'T_in')+459.67)*convert(R, K)
```

```
P_kPa_old=lookup(TableRun#-1, 'P_bar')*convert(inHg, kPa)
```

```
DELTA m=m_2-m_1
```

```
cfm=DELTA m*VOLUME(Air,T=T_in_k,P=P_kPa)*convert(m^3/hr, ft^3/min)
```

```
Air_changes=k_co2*sqrt(MOLARMASS(CO2)/MOLARMASS(Air))/m_1*convert(
1/hr, 1/day)
```

```
percent_mass_change=DELTA m/m_1*100
```

```
"Calculate humrat taking into account changes in barometric pressure:"
```

```
ln_Psat_in=19.43753-5454.153*(1/T_in_K)
```

```
ln_Psat_out=19.43753-5454.153*(1/T_out_K)
```

```
Psat_in=exp(ln_Psat_in)
```

```
Psat_out=exp(ln_Psat_out)
```

```
Pvap_in=lookup(TableRun#, 'RH_in')/100.0*Psat_in
```

```
Pvap_out=lookup(TableRun#, 'RH_out')/100.0*Psat_out
```

```
{ w_in=0.622*Pvap_in/(P_kPa-Pvap_in)
```

```
w_out=0.622*Pvap_out/(P_kPa-Pvap_out)}
```

```
"Calculate humrat from EES thermo function:"
```

```
"!MEASURED values:"
```

```
w_in=HUMRAT(AirH2O,T=T_in_K,P=P_kPa,R=RH_in)
```

```

w_out=HUMRAT(AirH2O,T=T_out_K,P=P_kPa,R=RH_out)

"Predicting CO_2 concentration inside:"

k_co2=0.47          "0.47 was found to be the best fit"

CO2_out_old=lookup(TableRun#-1, 'CO2_out')

CO2_in=lookup(TableRun#, 'CO2_in')

DELTACO_2=lookup(TableRun#-1,          'CO2_out')-TableValue(TableRun#-1,
'CO2_calc')

CO2_calc_old=tablevalue(TableRun#-1, 'CO2_calc')

CALL  FIND_CO2(m_1, DELTACO_2, DELTAm, k_co2, CO2_calc_old,
Co2_out_old: CO2_calc)

dCO2_inside=CO2_calc-CO2_calc_old

"Predicting humrat inside, assuming its dominated by diffusion:"

k_water=sqrt(MOLARMASS(CO2)/MOLARMASS(H2O))*k_co2

w_out_old=tablevalue(TableRun#-1, 'w_out')      "!Measured value"

w_calc_old=tablevalue(TableRun#-1, 'w_calc')     "!Calculated value"

w_bar=FIND_wbar(DELTAm, w_calc_old, w_out_old)  "!Needed for the barometric
pumping part"

"Using w_in_new as driving potential - solves iteratively"

K_cap=183          "!183 was found to be best for this method"

DELTAhumrat=w_out_old-w_calc_old

```

$w_calc = w_calc_old + k_water/m_2 * DELTAhumrat + DELTAm/m_2 * w_bar -$
 $K_cap/m_2 * (DELTAomega)$

$DELTAomega = (Omega_new - Omega_old)$

$Omega_old = FIND_eq(RH_old)$

$RH_old = RELHUM(AirH2O, T=T_in_K_old, P=P_kPa_old, w=w_calc_old)$

$Omega_new = FIND_eq(RH_new)$

$RH_new = RELHUM(AirH2O, T=T_in_K, P=P_kPa, w=w_calc)$

$RH_calc = RELHUM(AirH2O, T=T_in_K, P=P_kPa, w=w_calc)$

"minimization of sum of squares to find best fit k_co2 and K_cap "

$SS = (CO2_calc - CO2_in) * (CO2_calc - CO2_in)$

$SS_water = (w_calc - w_in) * (w_calc - w_in)$

$N = 173$

$RMS = \sqrt{\text{sum}(\text{tablevalue}(i, 'SS'), i=2, N) / (N-2)}$

$RMS_water = \sqrt{\text{sum}(\text{tablevalue}(i, 'SS_water'), i=2, N) / (N-2)}$

$AVE_air_changes = \text{sum}(\text{tablevalue}(i, 'Air_changes'), i=2, N) / (N-1)$

Appendix C

Contents

1. Directory and contents of CD-rom. If there is no CD with the copy of the thesis, please contact: Solar Energy Laboratory, 1500 Engineering Drive, Madison, Wisconsin, 53706.

The main directories of the CD-rom are listed below with their contents and any other pertinent information.

Directory	Contents
\origin	Contains the graphics package, origin.exe, used to generate all of the plots in the thesis.
\endnote	Contains the reference program, endnote.exe, along with the library, museum.enl, which contains the complete annotated bibliography.
\bxcrpro4	Contains the program, BoxCarPro4, used to download the T/RH/CO ₂ sensors and also view the raw data files.
\research\rawdata	Contains the raw temperature, relative humidity and CO ₂ data taken from the Field Museum. Please read rawdatainfo.txt in the directory for more information.
\research\processed	Contains all of the hourly-averaged data and statistical data for all the different locations monitored in the Museum. Please read processed.txt in the directory for more information.
\research\Cprograms	Contains the C source code of the programs used to process the raw data. Please read Cprograms.txt in the directory for more information.
\research\pollution	Contains the 1997 and 1998 EPA Annual Reports for Illinois.
\thesis	Contains all the plots, EES files and origin files (*.org) used to generate the contents of the thesis.
\thesis\model	Contains the EES files used for the CO ₂ and humidity ratio prediction models.
\thesis\plots	Contains all of the origin plots (*.org).
\thesis\chapters	Contains all the word documents and pdf files of the finished thesis.
\thesis\epa	Contains pollution concentration data for the months of July and August 1999 for SO ₂ , NO _x and O ₃ from the CTA monitoring station in Chicago.
\thesis\presentations	Contains the PowerPoint file of the final defense presentation

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