A Comparison of the Efficacy and Costs of Different Approaches to Climate Management in Historic Buildings and Museums

David John Artigas
University of Pennsylvania,

A thesis in Historic Preservation Presented to the Faculties of the University of Pennsylvania in Partial Fulfillment of the Requirements of the Degree of Master of Science in Historic Preservation 2007.
Advisor: Michael C. Henry

A COMPARISON OF THE EFFICACY AND COSTS OF DIFFERENT APPROACHES TO CLIMATE MANAGEMENT IN HISTORIC BUILDINGS AND MUSEUMS

David John Artigas

A THESIS

In

Historic Preservation

Presented to the Faculties of the University of Pennsylvania in
Partial Fulfillment of the Requirements of the Degree of

MASTER OF SCIENCE IN HISTORIC PRESERVATION

2007

Advisor Michael C. Henry Lecturer in Historic Preservation University of Pennsylvania	Reader Richard L. Kerschner Director of Preservation and Conservation Shelburne Museum, Shelburne, Vermont

Program Chair
Frank G. Matero
Professor of Architecture
University of Pennsylvania

ACKNOWLEDGEMENTS

First I would like to thank Mr. Michael C. Henry; whose help and advice were of the utmost quality over the last year. I also would like to thank Mr. Richard L. Kerschner, who also offered invaluable help and advice. And Mr. Ernest A. Conrad provided substantial assistance, for which I am grateful.

Though they are not identified in this thesis, the Managers, Facilities Engineers, and other Staff of Sites A, B, C, D, and E provided the data used for this study. Without their help, this study would not have been possible. The have my eternal gratitude.

Mr. Shin Maekawa, Mr. Marion Mecklenburg, Mr. Peter Warner, and my Dad provided valuable information and assistance that helped me understand climate management equipment and the issues of climate management in heritage buildings. Mr. Edward Zinn, a representative of the Image Permanence Institute, provided a free copy of the Climate Notebook software, which was instrumental to the analysis of data from one of the sites of this study. They also have my gratitude.

I would like to thank Mr. Frank G. Matero, Dr. Randall F. Mason, and the Professors and Staff of the Graduate Program in Historic Preservation at the University of Pennsylvania, for teaching me a wonderful amount of knowledge in two short years.

Finally, I would like to thank all of my friends and classmates in the University of Pennsylvania's Historic Preservation program. Their friendship and support means the world to me.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 NEED FOR CLIMATE MANAGEMENT IN HISTORIC BUILDINGS AND MUSEUMS

For this thesis, *climate management* is defined as exerting some level of control over the indoor temperature and relative humidity (RH) by use of mechanical equipment. Materials react to their environment. They expand as the temperature increases and contract as the temperature decreases. As the relative humidity increases, many materials will adsorb water vapor, which will cause them to expand. As the relative humidity decreases, they will release moisture, causing them to contract. However, not all materials expand and contract at the same rate. Thus, stresses are created at the interfaces between materials, such as paint on wood or in the joints of a structure, as they push and pull against each other. Over time, these stresses can cause the deterioration of historic materials, whether they are a museum collection or the fabric of a historic structure.[1] To reduce this form of deterioration, preservationists must manage the indoor climate of their historic buildings and museums.

Another reason for climate management is to reduce mold growth. At high relative humidity, typically above 70% RH, mold grow is likely. If it is allowed to grow unabated, mold can destroy historic materials. Also, it has been found to cause numerous respiratory ailments.[2] However, some humidity is necessary to preserve historic fabric or a collection. If the relative humidity falls too low, typically below 30% RH, many

---

[1] David Erhardt and Marion Mecklenburg. "Relative Humidity Re-Examined," in *Preventive Conservation: Practice, Theory, and Research. Preprints of the Contributions to the Ottawa Congress, 12-16 September, 1994*, eds. Ashok Roy and Perry Smith. (London: The International Institute for Conservation of Historic and Artistic Works, 1994), 33.

[2] The Chicora Foundation. *Mold.* (2003). <http://www.chicora.org/mold.htm> (5 November 2006).

materials become brittle and fracture easily.[3] Other preservation issues are involved in climate management, such as the efflorescence of salts, the corrosion of metals, and the softening of adhesives; all of these issues are discussed in greater detail in *Chapter 3: Why Manage the Indoor Climate?*

1.2 ISSUES WITH CLIMATE MANAGEMENT IN HISTORIC BUILDINGS

The conventional specification for the indoor climate in a historic building or museum is 70°F ±2°F and 50% RH ±5% RH, year-round. This specification comes from the museum collections community, and is more the result of traditional practice than rigorous scientific analysis of the effects of the ambient environment on historic materials.[4] However, it usually does preserve materials very well. Maintaining such specific and tight controls on the indoor climate is very difficult as the outdoor conditions cycle through the seasons, especially in heritage buildings. It often requires complex and expensive air-conditioning and heating equipment, and, in historic buildings, historic fabric can be altered or destroyed as the equipment and services are installed. Also, the energy costs for these systems often are quite high.[5] Due to the equipment and energy costs necessary to maintain the conventional specification and the potential destruction of historic fabric, many historic sites feel that a proper climate management system is not possible in their site, so they do nothing and leave their historic materials vulnerable to the effects of unchecked moisture.

---

[3] Erhardt and Mecklenburg, "Relative Humidity Re-Examined," 34.

[4] J. P. Brown and William B. Rose. "Humidity and Moisture in Historic Buildings: The Origins of Building and Object Conservation." *APT Bulletin 27*, no. 3 (1996): 15.

[5] The conventional specification typically requires a site to spend $3/sq. ft./yr. on energy to operate the climate management system. Shin Maekawa, P.E., PhD, interview by author, 31 October 2006.

Recent research has challenged the necessity of the conventional specification. Conservators have investigated the effects of different setpoints and wider tolerances for the temperature and relative humidity; much of the current literature shows that many historic materials can survive quite well in climates that have different setpoints and wider tolerances for the indoor conditions.[6] Allowing a broader range of conditions permits a greater variety of climate management systems that can be less expensive to design and install, and may not require as much destruction of historic fabric. It is thought that these alternate climate management systems will have lower energy costs than a conventional system; however, the little published research on the topic does not always agree that alternative climate management systems and broader climate specifications lead to energy savings.

1.3 PURPOSE OF THIS THESIS

There are numerous ways to manage the indoor climate in a historic building or museums; however, there are few published resources that compare the different forms of climate management for preservationists to consult. The small amount of literature on the subject of alternative climate management systems often offers the general statements that a wider range of conditions will lead to energy savings, but data rarely is provided to support that statement. Also, while a few curators and conservators have published articles detailing the climate management system that were installed at individual sites, there is almost no literature that compares the bounds of temperature and relative humidity that reasonably can be achieved by different climate management systems.

---

[6] Erhardt & Mecklenburg, "Relative Humidity Re-Examined," 32-38.

This thesis will provide preservationists with one of the first resources to compare different climate management systems, both in terms of the level of environmental control they provide and their energy costs and consumption.

The hypothesis for this investigation is that a wider tolerance of the indoor temperature and relative humidity will result in lower energy costs and consumption than tight control over the indoor conditions. This study will attempt to determine if there is a mathematical relationship between energy expenditures and the level of environmental control in historic buildings and museums. Five historic sites and museums, each using a different climate management system, have provided information on their system and their energy costs, as well as monitoring data (a record of the indoor temperature and relative humidity) for one year. This data will be used to calculate the level of climate control vs. the energy costs for each site, and the level of control vs. the energy consumption. To control for different-sized buildings, the energy costs and consumption will be divided by the total floor area of the building. To control for differences in climate, the cost and consumption per square foot for each site will be divided by the number of degree days that the site experienced. Because the requirements of the climate management system change with the seasons, the analysis of the data is separated into three seasons: the heating season (winter), the cooling season (summer), and the mixed season (spring and fall), in which there often is a need for both heating and cooling. Then, weighted averages of the energy costs and consumption will be calculated to establish the annual energy expenditures versus the control of the indoor conditions. It is the author's hope that this study will lead to more historic sites and museums finding effective and affordable ways to manage their indoor climate, and that it will lead to further research in this area.

Two aspects of climate management and energy use in historic buildings and museums that this thesis will not cover must be identified. The first aspect is the building envelope. The building envelope is its first line of defense against the elements. How well the envelope is sealed will play a large part in determining how much moisture and heat migrate into and out of a building. An investigation of proper envelope design in historic buildings and museums would make an excellent research topic and should be considered by future researchers. The second aspect covers other actions sites can take to reduce their energy costs, such as changes to their lighting, fenestration, or operating hours. Climate management is only one part of a site's energy costs; an investigation into other cost-saving measures sites can take also would make an excellent topic for further research.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

The current literature concerning climate management in historic buildings and museums agrees that it is an important, and often expensive, aspect of preservation. However, there is some disagreement on the bounds of temperature and relative humidity (RH) that are proper for historic materials – whether these materials comprise the building fabric or a museum collection. *Chapter 3: Why Manage the Indoor Climate?* details more fully the effects of moisture on building materials and collections. This chapter addresses the conventional specifications for temperature and relative humidity that are found in the literature, and discusses recent literature that calls for different bounds of temperature and relative humidity. This chapter also will discuss the literature regarding issues relating to the installation of mechanical equipment in heritage buildings, and different climate management solutions that have been employed in heritage buildings and museums. Later chapters will discuss climate management equipment used to achieve the desired indoor conditions.

Before going further, it must be stated that this thesis is concerned only with different approaches to climate management through the use of mechanical equipment. The building envelope is the structure's first line of defense against the elements, and is an integral part of climate management. An analysis of how improvements to a building envelope can help manage the indoor climate in a historic building would make an excellent research topic; hopefully, such research will be performed in the future. In this thesis, the building envelope is discussed only relation to the level of environmental control that has been determined to be reasonable for a given building envelope construction.

2.2 CONVENTIONAL SPECIFICATION

The conventional specification for the indoor conditions in a historic building or museum in America is 70°F ±2°F and 50% RH ±5% RH (sometimes ±2% RH). It is found in many places in the literature, and still is recommended in many modern texts. This specification comes from the collections management community, and is based more on traditional practice than on rigorous scientific analysis. During World War II, the National Gallery of Art, in London, stored their paintings in underground quarries for safekeeping. Due to the subterranean location, it was easy to maintain a constant temperature and relative humidity of 63°F and 58% RH. They found that these conditions kept their paintings in remarkably good condition; so, after the war, the curators decided to create conditions in their museum that matched the conditions in the quarries as closely as possible. Due to the British climate and the limits of then-current mechanical equipment, the specification for their museums became 70°F and 55% RH[7] (in America, the climate led to the specification of 50% RH[8]); 70°F was chosen as the temperature specification mainly for human comfort, and not for preservation needs.[9] Because these conditions often preserve historic material very well, this specification

---

[7] Brown and Rose, "Humidity and Moisture in Historic Buildings," 15.

[8] Erhardt and Mecklenburg, "Relative Humidity Re-Examined," 32.

[9] Tadj Oreszczyn, May Cassar and Keith Fernandez. "Comparative Study of Air-Conditioned and Non Air-Conditioned Museums," in *Preventive Conservation: Practice, Theory, and Research*, eds. Ashok Roy & Perry Smith, 147.

became the norm for museums, and little research has been performed to determine if historic materials can survive in an environment of different conditions.[10]

Much of the literature notes that a stable temperature and relative humidity will help to preserve historic materials. Most materials expand and contract with changes in temperature and relative humidity, which places stress on the joints and the interfaces between materials and builds internal stresses, leading to deterioration.[11] The museum community determined that the tighter the tolerance on the indoor conditions, the lower these stresses would be. Therefore, the tight variances of ±2°F and ±5% RH were created. However, these limits were and are based upon the limits of mechanical equipment and the desire for constant relative humidity, not upon empirical investigations into how different materials react to changes in temperature and relative humidity.[12,13] A system that maintains a constant 70°F ±2°F and 50% RH ±5% RH often will be over-engineered to deal with rare extreme weather conditions, will be very expensive to design and install, will have high energy costs, and likely will require historic fabric to be altered or destroyed during its installation.[14]

Little research has been performed regarding the proper temperature and relative humidity in historic buildings, as opposed to museums. Instead, the specifications of the

---

[10] Erhardt and Mecklenburg, "Relative Humidity Re-Examined," 32.

[11] Ibid., 33.

[12] Brown and Rose, "Humidity and Moisture in Historic Buildings," 19.

[13] David Erhardt, Marion F. Mecklenburg, Charles S. Tumosa, & Mark McCormick-Goodhart. "The Determination of Allowable RH Fluctuations." *WAAC Newsletter* 17, no. 1 (1995). <http://palimpsest.stanford.edu/waac/wn/wn17/wn17-1/wn17-108.html> (12 October 2006)

[14] Ibid.

collections community (70°F and 50% RH) usually are recommended.[15] Historic buildings often were designed to adjust their indoor conditions to their outdoor environment, not to maintain constant indoor conditions. For instance, windows would be opened in the summer to allow natural ventilation to cool the inside, and the building's occupants would gather around the fireplace in the winter and leave much of the rest of the building unheated.[16] Vapor barriers and insulation had not been invented when these buildings were constructed; thus, moisture and heat migrate more easily through their walls.[17] In the past, there was no reserved space for the volume that modern mechanical systems require. Thus, they are difficult to fit in a historic building, and often are configured in such a way that regular maintenance is difficult.[18] The combination of these factors makes it very difficult to maintain the recommended constant indoor conditions as the outdoor conditions cycle throughout the day and throughout the seasons.

Unfortunately much of the literature still recommends that heritage buildings attempt to maintain a constant 70°F and 50% RH. In many texts it is noted that it may not be possible to do so in a historic building, but that is where the authors often stop. Very little of the literature takes the next step of determining what conditions are acceptable to maintain the health of historic building materials, and what conditions

---

[15] Richard L. Kerschner. "A Practical Approach to Environmental Requirements for Collections in Historic Buildings." *Journal of the American Institute for Conservation* 31, no. 1 (1992): 65.

[16] Nathan Stowlow. "The Preservation of Historic Houses and Sites: The Interface of Architectural Restoration and Collection/Display Conservation Principles," in *Preventive Conservation: Practice, Theory, and Research*, eds. Ashok Roy & Perry Smith, 116.

[17] Bernard M. Feilden. *Conservation of Historic Buildings*. (Boston: Butterworth-Heinemann Ltd., 1994), 172.

[18] Oreszczyn, Cassar and Fernandez, "Comparative Study of Air-Conditioned and Non Air-Conditioned Museums," 146.

reasonably can be achieved in historic buildings. Too often, historic site managers realize that their buildings never will be able to achieve constant conditions of 70°F and 50% RH year-round, so they do nothing, leaving their buildings vulnerable to the damaging effects of moisture. Or worse, they cause a great deal of destruction to the historic fabric of a building as they install insulation, vapor barriers, and mechanical equipment in an attempt to achieve a constant indoor environment.[19,20] Often, after undertaking the great expense, both in terms of funds and historic fabric that is necessary to establish the conventional specification, the site managers find that moisture is trapped in unexpected locations and accelerates the decay of the historic fabric. For example, condensation on the interior side of the fenestration and inside the walls during winter often is reported in historic buildings in temperate climates that have created an indoor climate of 70°F and 50% RH.[21,22]

Another issue in creating a constant environment of 70°F and 50% RH is the possibility that the historic fabric or collections have become seasoned to a different climate. Materials will adapt to their environment; subjecting them to a change in climate means that they likely will expand or contract with the change in temperature and relative humidity. This action places stress upon the joints and the interfaces between different materials. At times, site managers and curators have gone to great pains to

---

[19] Feilden, *Conservation of Historic Buildings*, 173.

[20] Stefan Michalski. "Relative Humidity: A Discussion of Correct/Incorrect Values," in *Preprints of the 10th Triennial Meeting, Washington, D.C., 22-27 August 1993*, ed. Janet Bridgland. (Paris: ICOM Committee for Conservation, 1993), 624.

[21] Kerschner, "A Practical Approach to Environmental Requirements for Collections in Historic Buildings," 65.

[22] Raymond H. Lafontaine. "Humidistatically Controlled Heating: A New Approach to Relative Humidity Control in Museums Closed for the Winter Season." *Journal of the International Institute for Conservation* 7, no. 1/2 (1982): 35.

establish the recommended constant indoor climate, only to find that it caused accelerated decay of the historic materials as they adjusted to the change in their environment.[23,24] Padfield[25] recommends that, rather than impressing the need for constant conditions of 70°F and 50% RH upon curators, architectural conservators should stress the need to understand how historic materials react to their environment and changes in their environment. Then the specifications for the indoor climate should be created.

Creating a constant indoor climate of 70°F and 50% RH also can be expensive in terms of energy. Though energy costs vary from region to region, the common estimate of the energy costs associated with this specification is $3 per square foot per year.[26] Also, the design and installation costs of the complex mechanical equipment that is necessary to achieve these conditions is quite high; in 1994, in Great Britain, the installation costs for this type of equipment were $3.00 – $4.50 per square foot[27] (no estimated installation costs for the United States were found). Also, the mechanical services can comprise as much as 90% of the lifetime cost of a building.[28] Museums and historic sites often have very tight budgets, thus the achievement of this type of climate management is difficult, or even economically impossible, to achieve.

---

[23] Garry Thomson. *The Museum Environment, 2nd ed.* (Boston: Butterworths, 1986), 89.
[24] May Cassar. *Environmental Management.* (New York: Routledge, 1995), 15.
[25] Tim Padfield. "The Role of Standards and Guidelines: Are they a Substitute for Understanding a Problem or a Protection Against the Consequences of Ignorance?" in *Durability and Change: Science, Responsibility and Cost of Sustaining Cultural Heritage*, eds. W. E. Krumbein, P. Brimblecombe, D. E. Cosgrove, and S. Staniforth. (New York: John Wiley and Sons, 1994). <http://www.natmus.dk/cons/tp/ppubs/dahlem.pdf> (31 October 2006).
[26] Shin Maekawa, Ph.D., P.E., interview by the author, 31 October 2006.
[27] Oreszczyn, Cassar and Fernandez, "Comparative Study of Air-Conditioned and Non Air-Conditioned Museums," 147. The currency was converted to United States Dollars from British Pounds using the exchange rate of 1 GBP = 1.5142 USD, and the area was converted to square feet from square meters.
[28] Ibid., 147.

The conventional specification has met with much criticism, aside from the high costs and the possible destruction of historic fabric. Barrette[29] states that "Even under the best of circumstances, no air-conditioning system would be capable of providing constant temperature and relative humidity day in and day out." Aside from the inevitable system malfunctions or power losses, research shows that the humidity sensors and humidistats used to control the climate management system cannot measure the indoor conditions that accurately. This inaccuracy is due to errors in the temperature measurement, air pressure and temperature fluctuations, and the measurement devices falling out of calibration.[30] A specification of ±5% RH actually can lead to indoor conditions of ±15% RH as the humidity sensors lose calibration.[31]

Another complaint is that, in the loaning of museum objects, the borrowing facility often is required to achieve indoor conditions of 70°F and 50% RH. The parent museum, due to the difficulty in accurately measuring the indoor conditions, seldom achieves that specification itself.[32] This situation either causes fewer objects to be loaned and shared with other communities, or objects to be transferred to an environment that is different from the one to which they have become seasoned (though, ostensibly, they are the same climate), possibly causing deterioration.

---

[29] Bill Barrette. "Climate Control: The Egyptian Galleries at the Metropolitan Museum of Art," in *Preprints of the 7th Triennial Meeting, Copenhagen, 10-14 September, 1984*, ed. Diana de Froment (Paris: ICOM Committee for Conservation, 1984), 84.17.7.

[30] Jonathan P. Brown. "Hygrometric Measurement in Museums: Calibration, Accuracy, and the Specification of Relative Humidity," in *Preventive Conservation: Practice, Theory, and Research*, eds. Ashok Roy & Perry Smith, 40.

[31] Murray Frost. "Working with Design Professionals: Preventive Conservators as Problem Solvers, not Problem Creators," in *Preventive Conservation: Practice, Theory, and Research*, eds. Ashok Roy & Perry Smith, 22.

[32] Jonathan Ashley-Smith, Nick Umney and David Ford. "Let's Be Honest – Realistic Environmental Parameters for Loaned Objects," in *Preventive Conservation: Practice, Theory, and Research*, eds. Ashok Roy & Perry Smith, 28.

2.3 ALTERNATE CLIMATE SPECIFICATIONS

Due to the high costs of maintaining a constant indoor environment of 70°F and 50% RH, the difficulty in doing so in a historic building, and the possibility of damage to historic fabric and collections caused by a change in their environment, recent research has investigated the effects of a broader range of temperature and relative humidity on historic fabric and collections. Other research has investigated whether a more easily obtained stable relative humidity that is different than 50% RH is better for historic fabric and collections than trying to force an environment of 50% RH. The hope is that allowing a wider range of indoor conditions will be less expensive to maintain, in terms of equipment and energy costs, and that it will require less destruction of historic fabric.

It must be stated that the architectural or collections conservator must be the one to recommend the proper indoor conditions for a building. However, as advocates for the preservation of the historic materials, they should be well versed in the current research on the proper conditions for the materials present at the site, and not dependant on traditional specifications simply as a matter of practice. The goal should not be to conform to an arbitrary ideal, but to create an environment that reasonably can be achieved in the building, protects the historic materials, and is affordable for the site's managers. The research presented here and in other sources should be considered when specifying the indoor conditions for a museum or a historic building.

For most materials, improper humidity levels cause far more deterioration than improper temperatures, as long as the temperature is not excessively high or low.[33]

---

[33] Lafontaine, "Humidistatically Controlled Heating," 36.

Therefore, much of the literature focuses on the proper relative humidity for different materials. Erhardt and Mecklenburg[34] have studied the effects of a wider range of relative humidity, and of changes in relative humidity, on materials. They investigated the effects of relative humidity on expansion and contraction, adhesive softening, salt deliquescence, condensation, metals corrosion, and organic materials. Erhardt and Mecklenburg found that different forms of deterioration occur at different levels of relative humidity for different materials, making it almost impossible to specify one value that will reduce all forms of decay. Also, they found that the tolerance of different materials changes as the relative humidity setpoint changes. For example, they found that rabbit-skin glue can withstand a variance of ±15 % RH at 50% RH, but only a variance of ±8% RH at 35% RH.[35] Taking all of their research into consideration, they did determine ranges for relative humidity that they recommend to control different forms of deterioration and to preserve different types of collections (see Figure 1). In short, for an active, mixed collection, Erhardt and Mecklenburg recommend that the indoor relative humidity be kept between 40 – 70% RH as the best compromise range when all forms of deterioration are considered. For archival storage, they recommend that the relative humidity be kept between 30 – 50% RH as the best compromise range.[36]

---

[34] Erhardt and Mecklenburg. "Relative Humidity Re-Examined," 32-38.
[35] Ibid., 34.
[36] Ibid., 37.

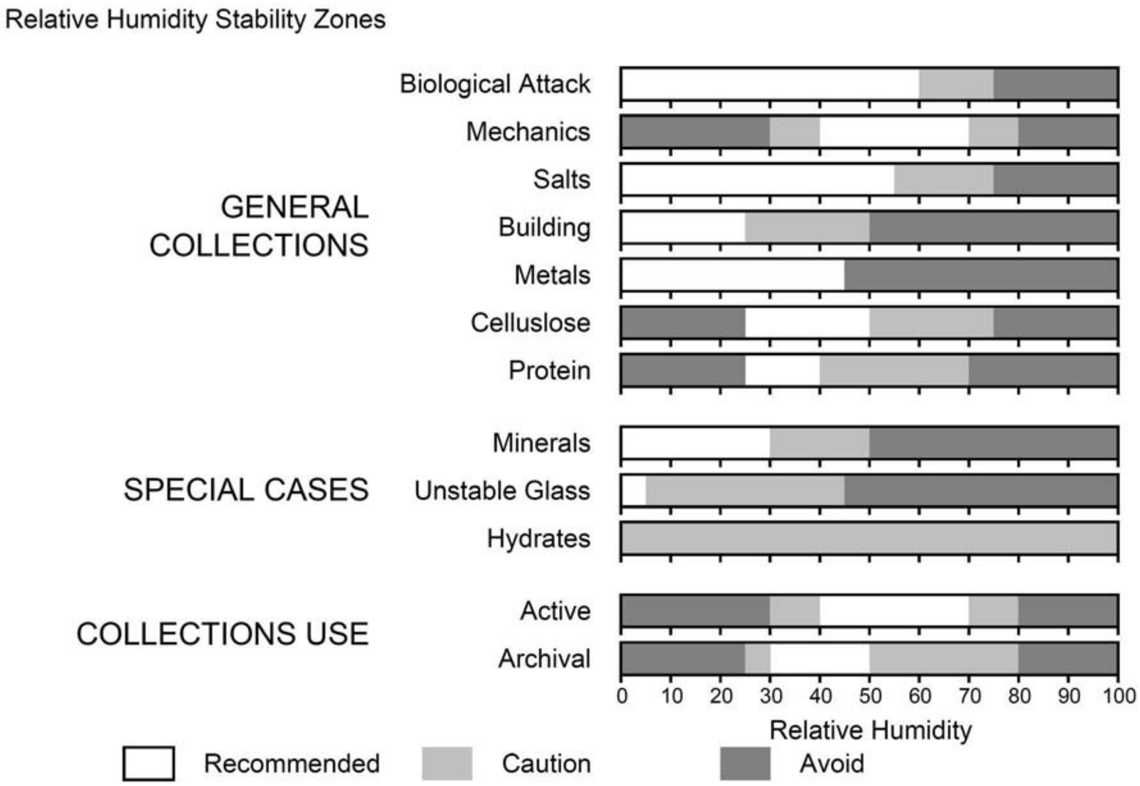


Figure 1: The Ranges of Relative Humidity Suggested by Consideration of Various Factors (recreated from: Erhardt and Mecklenburg, "Relative Humidity Re-Examined," 37).

It must be noted that Erhardt's and Mecklenburg's recommended specification of 40 – 70% RH, and the conventional specification of 50% RH, are meant to reduce mechanical deterioration, biological attack, and efflorescence. However, chemical degradation still is likely in this range.[37] To reduce chemical deterioration, the relative humidity should be kept below 30% RH; however, at that relative humidity many materials become unacceptably brittle.[38] There is no easy resolution to this conflict. The conservator and curator or site manager must determine what is best for the collection and specify the indoor conditions accordingly.

---

[37] Ibid., 37.
[38] Ibid., 34.

As most materials expand and contract with changes in the relative humidity, many authors state that a stable, achievable relative humidity is more important that the supposed ideal of 50% RH. As Reading[39] states, "For many museums these standards [70°F and 50% RH] are an impossible dream, so the approach must be an attainable stable target which can be maintained." The Smithsonian Museum recently abandoned the conventional specification, instead requiring conditions of 70°F ±4°F and 45% RH ±8% RH year-round. Due to the climate in Washington, D.C., it was determined that this specification is more easily obtained, and that it reduces the risk of condensation in the winter.[40]

Recently, researchers have studied the effects of letting the indoor conditions vary with the seasons. The daily fluctuations of the relative humidity are kept small, but the setpoint for the indoor relative humidity slowly rises and falls as the outdoor relative humidity rises and falls over the course of a year. In this approach, typically the indoor relative humidity setpoint is kept between absolute bounds, such as a range of 40 – 60% RH.[41] Conrad[42] states that all but the most delicate materials would survive well in such an environment. Bordass[43] claims that doing so is more energy efficient than maintaining constant conditions, but does not provide any data to support that claim.

---

[39] Alfred Reading. "Air-Conditioning, Energy Efficiency, and Environmental Control: Can All Three Co-Exist?" in *Museums Environment Energy*, ed. May Cassar. (London: HMSO, 1994), 40.

[40] Marion F. Mecklenburg, Charles S. Tumosa, and Alan Pride. "Preserving Legacy Buildings." *HVAC Retrofit – A Supplement to the ASHRAE Journal* (June, 2004): S19.

[41] Erhardt and others, "The Determination of Allowable RH Fluctuations."

[42] Ernest A. Conrad. "The Realistic Preservation Environment." (1999). <http://www.archives.gov/preservation/storage/realistic-preservation-environment.html> (18 October 2006).

[43] William T. Bordass. "Museum Environments and Energy Efficiency: Are Our Priorities Right?" in *Museums Environment Energy*, ed. May Cassar, 12.

The Shelburne Museum, in Vermont, has taken the approach of allowing the conditions to vary with the seasons in many of their buildings. In the buildings for which it is deemed appropriate for the collections, the relative humidity setpoint is 55% RH in the summer and 40% RH in the winter. Thus far, this method of climate management has preserved the historic materials located there very well.[44] The Canadian museum system also has adopted this approach. In their museums, the temperature setpoint varies from 65 – 72°F over the course of the year, and the relative humidity setpoint varies from 43 – 50% RH, with a ±10% RH daily fluctuation allowed.[45] After monitoring several historic sites in North America, Stowlow[46] also recommends allowing the indoor conditions to change gradually with the seasons: 19.5°C ± 1.5°C (67.1°F ±2.7°F) and 40% RH ±4% RH in the winter, and 24.5°C ± 1.5°C (76.1°F ±2.7°F) and 55% RH ±4% RH in the summer.

Other research into the necessary stability of the indoor relative humidity has investigated how large and how long a short term fluctuation must be to cause damage. Michalski[47] states that short periods of relative humidity as high as 90% RH typically are acceptable for "a day or two" and that fluctuations that last less than one hour should not

---

[44] Richard L. Kerschner. "Providing Safe and Practical Environments for Cultural Properties in Historic Buildings…and Beyond." Presented at the 20th Annual National Archives Preservation Conference, Beyond the Numbers: Specifying and Achieving an Efficient Preservation Environment. March 16, 2006. <www.archives.gov/preservation/conferences/2006/kerschner.pdf> (31 October 2006).

[45] Mecklenburg and others, "Preserving Legacy Buildings," S20.

[46] Stowlow, "The Preservation of Historic Houses and Sites," 120.

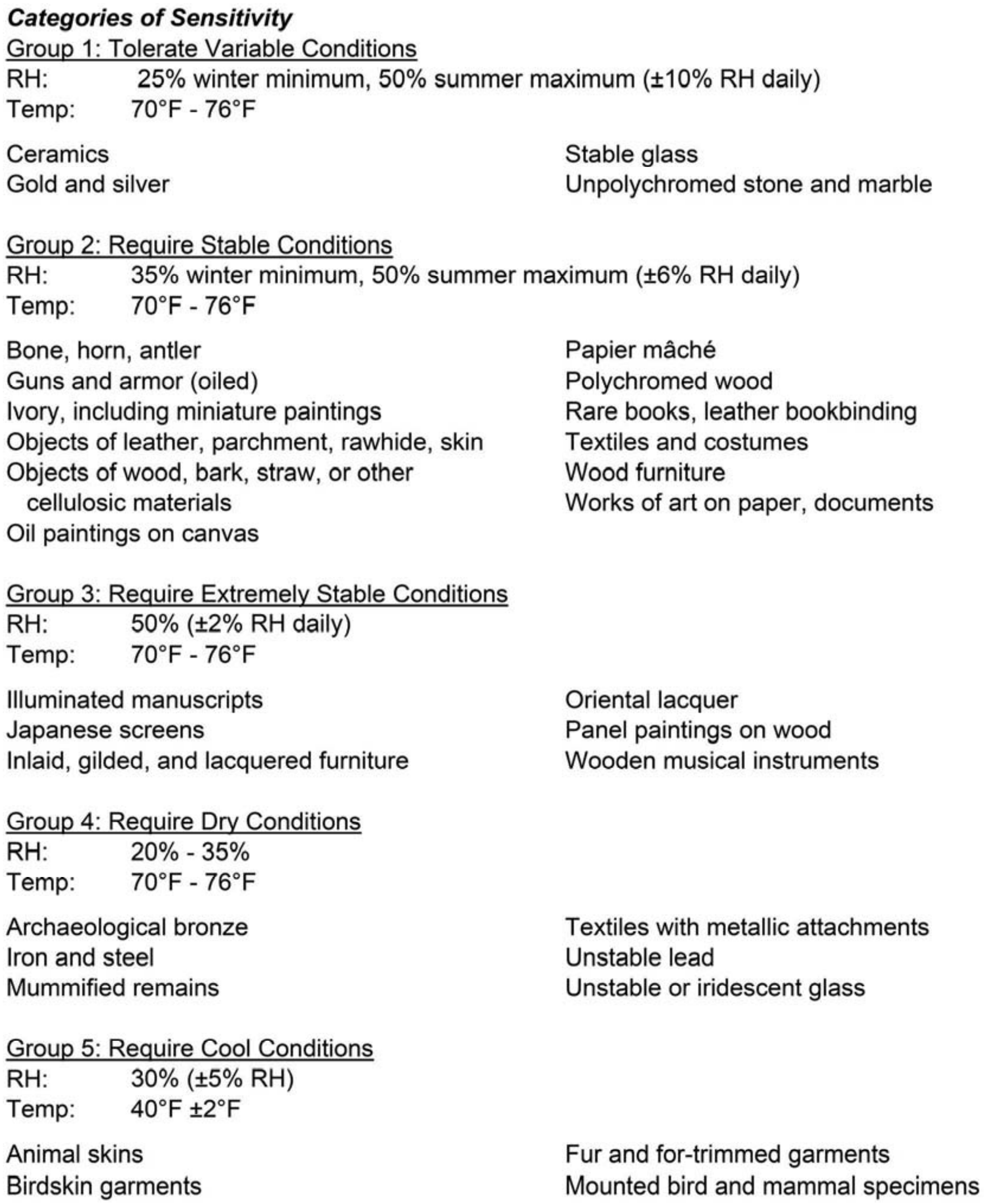
[47] Michalski, "Relative Humidity: A Discussion of Correct/Incorrect Values," 25, 626.

be a concern. Christoffersen[48] goes further, stating that "…there is no overwhelming evidence that a perfectly steady climate is necessary for the stability of the objects."

The Royal Ontario Museum[49] categorized materials based upon their sensitivity to daily relative humidity fluctuations (see Table 1). For the least hygroscopic materials, such as ceramics and glass, the Royal Ontario Museum recommends a daily fluctuation of ±10% RH. For materials that are less tolerant of changes in relative humidity, they recommend a daily fluctuation of ±6% RH. For extremely delicate materials, they recommend a daily fluctuation of ±2% RH. Other well known museums and museum systems have started to allow a greater tolerance of the indoor relative humidity. As stated previously, the Smithsonian Museum now specifies a tolerance of ±8% RH, and the Canadian Museum system now specifies a tolerance of ±10% RH. Padfield[50] states that "A variation of ±20% [RH] is unlikely to cause damage."

---

[48] Lars D. Christoffersen. "Resource Saving Storage of Historic Material," in *Preprints of the 10th Triennial Meeting, Washington*, D.C., ed. Janet Bridgland, 601.
[49] Royal Ontario Museum. *In Search of the Black Box: A Report on the Proceedings of a Workshop on Micro-Climates Held at the Royal Ontario Museum, February 1978*. (Toronto: The Royal Ontario Museum, 1979), 37 – 39.
[50] Padfield, "The Role of Standards and Guidelines"



Categories of Sensitivity

Group 1: Tolerate Variable Conditions
RH: 25% winter minimum, 50% summer maximum (±10% RH daily)
Temp: 70°F - 76°F

Ceramics
Gold and silver
Stable glass
Unpolychromed stone and marble

Group 2: Require Stable Conditions
RH: 35% winter minimum, 50% summer maximum (±6% RH daily)
Temp: 70°F - 76°F

Bone, horn, antler
Guns and armor (oiled)
Ivory, including miniature paintings
Objects of leather, parchment, rawhide, skin
Objects of wood, bark, straw, or other cellulosic materials
Oil paintings on canvas
Papier mâché
Polychromed wood
Rare books, leather bookbinding
Textiles and costumes
Wood furniture
Works of art on paper, documents

Group 3: Require Extremely Stable Conditions
RH: 50% (±2% RH daily)
Temp: 70°F - 76°F

Illuminated manuscripts
Japanese screens
Inlaid, gilded, and lacquered furniture
Oriental lacquer
Panel paintings on wood
Wooden musical instruments

Group 4: Require Dry Conditions
RH: 20% - 35%
Temp: 70°F - 76°F

Archaeological bronze
Iron and steel
Mummified remains
Textiles with metallic attachments
Unstable lead
Unstable or iridescent glass

Group 5: Require Cool Conditions
RH: 30% (±5% RH)
Temp: 40°F ±2°F

Animal skins
Birdskin garments
Fur and for-trimmed garments
Mounted bird and mammal specimens

Table 1: Categories of Relative Humidity Sensitivity (recreated from: Royal Ontario Museum, *In Search of the Black Box*, 37-39).

In humid climates, site managers typically only have to worry about high humidity, and not low. At some sites in such locations, the managers have decided that their only real concern is to keep the indoor relative humidity below an upper bound, typically 70% RH to prevent mold growth. Hollybourne Cottage, in Georgia, has taken this approach. The historic building had been ravaged by high relative humidity. The architectural conservators decided that it would be more realistic simply to keep the relative humidity below 75% RH than it would be to create an indoor climate of 70°F and 50% RH. The system was able to keep the indoor relative humidity below 70% RH, which was found to successfully reduce the rate of deterioration of the building, and the system was far less expensive to design, install, and operate than a conventional system.[51]

As stated, one of the reasons to investigate alternate methods of climate control is to try to reduce the energy costs necessary to operate the machinery. Very little published information on this topic was found, and the data that has been published does not indicate that the broader specifications necessarily will lead to energy savings. Oreszczyn et al[52] state that reducing the temperature setpoint from 22°C (72°F) to 18°C (64°F) will reduce fuel costs by 25%, though it is not clear if this figure is simply an estimate or if it is based upon an empirical investigation. Similarly, another article states that there is an 8% drop in energy costs for every 1°C (2°F) drop in the heating setpoint.[53]

Ayres, Haiad, and Lau[54] created computer models of a museum in New York to analyze the costs associated with different specifications for the indoor conditions. According to their results, 50% RH is less expensive to maintain than are 40% RH or

---

[51] Shin Maekawa and Franciza Toledo. “A Climate Control System for Hollybourne Cottage, Jekyll Island Historic District, Georgia.” (2001). <http://www.getty.edu/conservation/publications/pdf_publications/iaq453.pdf> (7 October 2006).

[52] Oreszczyn, Cassar and Fernandez, “Comparative Study of Air-Conditioned and Non Air-Conditioned Museums,” 147.

[53] Tadj Oreszczyn, Tim Mullany and Caitriona NiRiain. “A Survey of Energy Use in Museums and Galleries,” in *Museums Environment Energy*, ed. May Cassar, 32.

[54] J. Marx Ayres, J. Carlos Haiad and Henry Lau. *Energy Conservation and Climate Control in Museums*. (Marina del Rey: The Getty Conservation Institute, 1988).

60% RH.[55] Also, they found that if the tolerance for the relative humidity is increased from ±2% RH to ±7% RH, there only is a slight reduction in energy use (for this part of the analysis the temperature was maintained at 72°F).[56] When they analyzed the effect of increasing the tolerance of the temperature from ±2°F to ±5°F, they again found only a small reduction in energy use (for this part of the analysis the relative humidity was held at 50% RH).[57] It must be stated that this study only was based upon a computer model, and not upon real-world data, and that they did not investigates the relationship between energy cost and changes in the tolerance of both temperature and relative humidity at the same time.

Mecklenburg[58] disagrees with the above conclusions regarding the energy costs versus the relative humidity tolerance in historic buildings and museums. After researching several different buildings at the Smithsonian Museum, he found that the energy costs decreased significantly as a wider range of relative humidity was allowed (see Figure 2). Mecklenburg claims that increasing the relative humidity tolerance from ±2% RH to ±7% RH will reduce energy costs by 55%.[59] Mecklenburg also stated that the Smithsonian's new specifications for the indoor climate (70°F ±4°F and 45% RH ±8% RH) resulted in \$3.2 million in energy savings in the last two quarters of 2006 and the first quarter of 2007.[60]

---

[55] Ibid., 4-44.

[56] Ibid., 4-53 – 4-54.

[57] Ibid., 4-53 – 4-54.

[58] Marion Mecklenburg, e-mail message to the author, 17 April 2007.

[59] Ibid.

[60] Ibid.

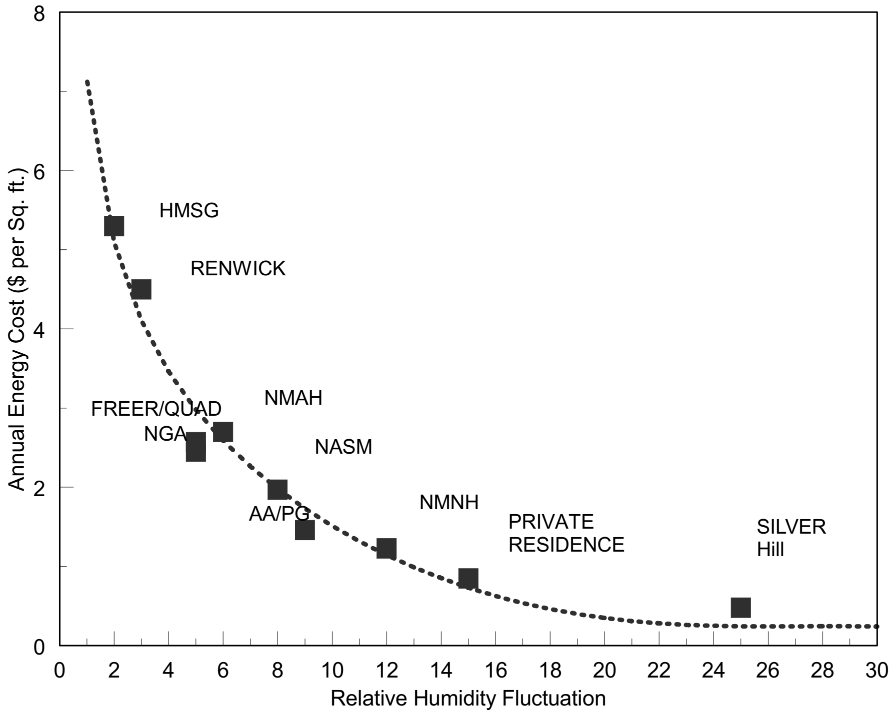


Figure 2: Smithsonian FY 1993 Energy Costs Correlated to Relative Humidity Control (source: unpublished, provided to the author by Marion Mecklenburg).

In 1994, an analysis of energy costs per square meter vs. type of collection for museums in Britain was published. The results of this analysis are presented in Figure 3. According to this chart, no real correlation can be drawn between the energy costs and the type of collection (for example, one museum with an “Industrial” collection had energy costs of £1/m^2, while another museum with an “Industrial” collection had energy costs of £10.50/ m^2). However, the authors did find that, generally, museums with a mixed or a fine art collection tended to have above-average energy costs.[61] Unfortunately, the authors did not provide any information on the types of climate management systems utilized in the museums, the specified indoor conditions of the museums, or the health of the collections. However, this research does show that the

---

[61] Oreszczyn, Mullany and NiRiain, “A Survey of Energy Use in Museums and Galleries,” 29.

costs of climate management can be difficult to predict, and that there are not many standard practices in designing climate management systems in cultural heritage buildings.

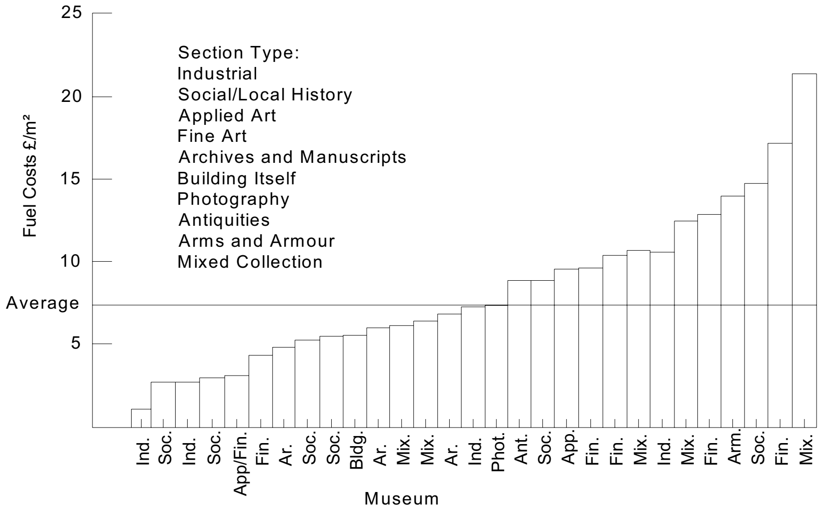
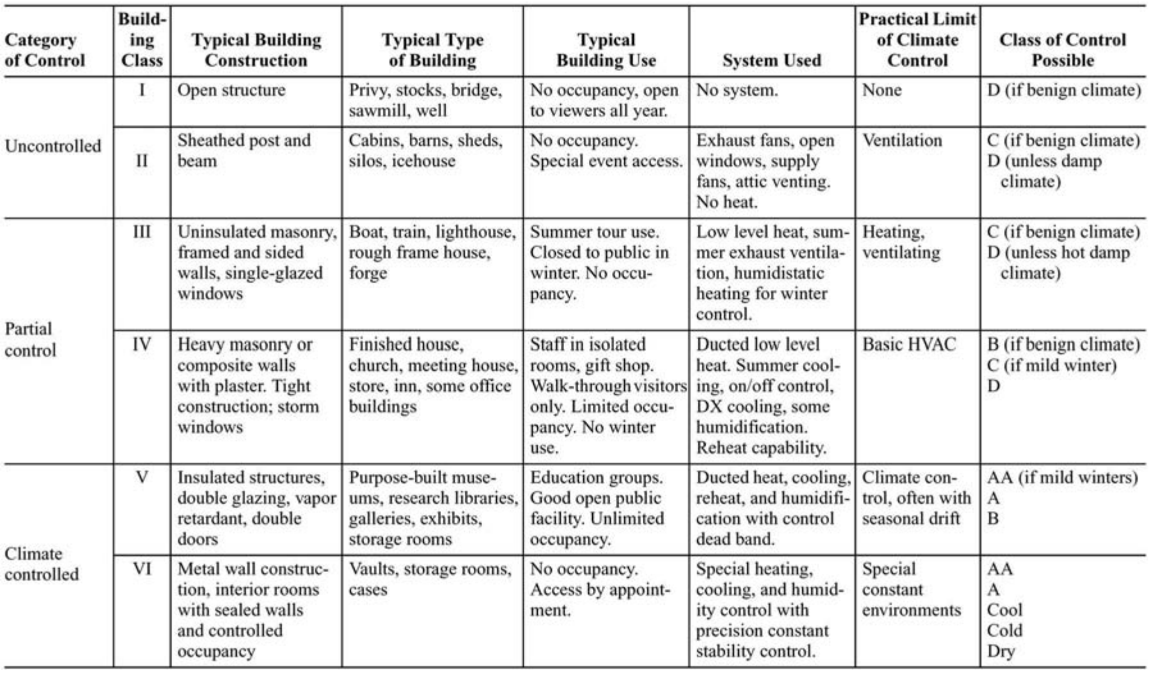


Figure 3: Plot of Fuel Costs for Climate Management by Museum Collection Type (recreated from: Oreszczyn, Mullany, and NiRiain, “A Survey of Energy Use in Museums and Galleries,” 29).

2.4 ALTERNATIVE CLIMATE MANAGEMENT SOLUTIONS

While the conventional specification allowed different climate management systems, the tight tolerance of the conditions meant that most of them would have the same basic components, and be costly to install and operate. Allowing a wider range of indoor conditions frees the curators and engineers to select from a wider variety of systems. A thorough explanation of some of the different climate management systems is presented in *Chapter 4: Climate Management Processes and Equipment*. Here, the current literature regarding the effectiveness, in terms of managing the indoor conditions, and energy costs associated with these systems will be presented. The proper climate management system for any site always will be a decision made by the site manager, the conservator, and the consulting engineer.

In the *ASHRAE Handbook – Applications*[62] are matrices that gives their recommended approach to climate management in historic buildings and museums based upon the building envelope (see Tables 2 and 3). These matrices provide the basic framework for specifying a climate management system for a cultural heritage building.

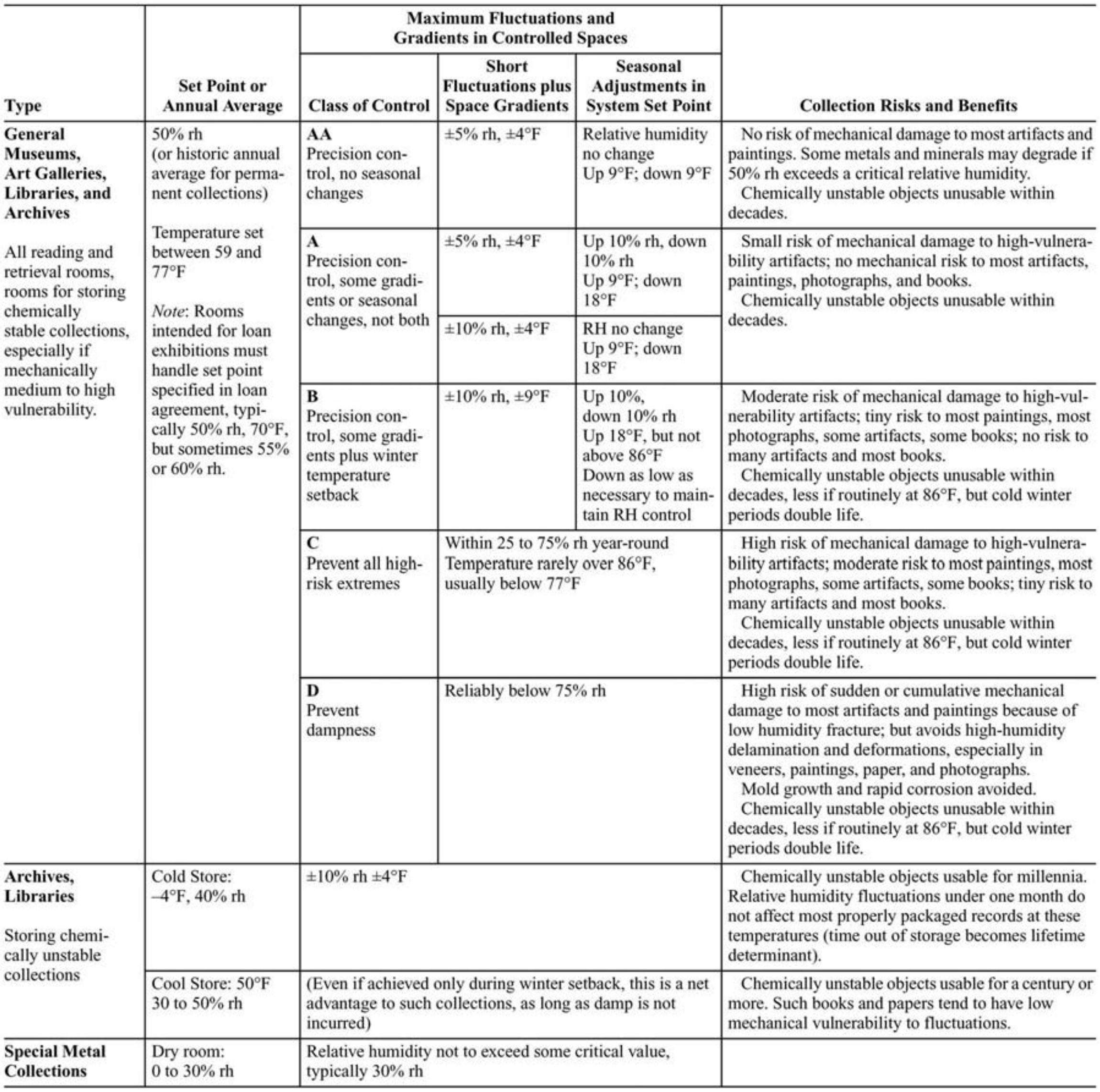


Category of Control	Building Class	Typical Building Construction	Typical Type of Building	Typical Building Use	System Used	Practical Limit of Climate Control	Class of Control Possible
Uncontrolled	I	Open structure	Privy, stocks, bridge, sawmill, well	No occupancy, open to viewers all year.	No system.	None	D (if benign climate)
	II	Sheathed post and beam	Cabins, barns, sheds, silos, icehouse	No occupancy. Special event access.	Exhaust fans, open windows, supply fans, attic venting. No heat.	Ventilation	C (if benign climate) D (unless damp climate)
Partial control	III	Uninsulated masonry, framed and sided walls, single-glazed windows	Boat, train, lighthouse, rough frame house, forge	Summer tour use. Closed to public in winter. No occupancy.	Low level heat, summer exhaust ventilation, humidistatic heating for winter control.	Heating, ventilating	C (if benign climate) D (unless hot damp climate)
	IV	Heavy masonry or composite walls with plaster. Tight construction; storm windows	Finished house, church, meeting house, store, inn, some office buildings	Staff in isolated rooms, gift shop. Walk-through visitors only. Limited occupancy. No winter use.	Ducted low level heat. Summer cooling, on/off control, DX cooling, some humidification. Reheat capability.	Basic HVAC	B (if benign climate) C (if mild winter) D
Climate controlled	V	Insulated structures, double glazing, vapor retardant, double doors	Purpose-built museums, research libraries, galleries, exhibits, storage rooms	Education groups. Good open public facility. Unlimited occupancy.	Ducted heat, cooling, reheat, and humidification with control dead band.	Climate control, often with seasonal drift	AA (if mild winters) A B
	VI	Metal wall construction, interior rooms with sealed walls and controlled occupancy	Vaults, storage rooms, cases	No occupancy. Access by appointment.	Special heating, cooling, and humidity control with precision constant stability control.	Special constant environments	AA A Cool Cold Dry

Table 2: ASHRAE Building Classification (source: ASHRAE, *2003 ASHRAE Handbook -- Applicatons*, 21.9).

---

[62] ASHRAE. *2003 ASHRAE Handbook – Applications*. “Chapter 21 – Museums, Libraries, and Archives.” Atlanta: ASHRAE, 2003), 21.8 - 21.9.



		Maximum Fluctuations and Gradients in Controlled Spaces			
Type	**Set Point or Annual Average**	**Class of Control**	**Short Fluctuations plus Space Gradients**	**Seasonal Adjustments in System Set Point**	**Collection Risks and Benefits**
General Museums, Art Galleries, Libraries, and Archives All reading and retrieval rooms, rooms for storing chemically stable collections, especially if mechanically medium to high vulnerability.	50% rh (or historic annual average for permanent collections) Temperature set between 59 and 77°F *Note*: Rooms intended for loan exhibitions must handle set point specified in loan agreement, typically 50% rh, 70°F, but sometimes 55% or 60% rh.	**AA** Precision control, no seasonal changes	±5% rh, ±4°F	Relative humidity no change Up 9°F; down 9°F	No risk of mechanical damage to most artifacts and paintings. Some metals and minerals may degrade if 50% rh exceeds a critical relative humidity. Chemically unstable objects unusable within decades.
		A Precision control, some gradients or seasonal changes, not both	±5% rh, ±4°F	Up 10% rh, down 10% rh Up 9°F; down 18°F	Small risk of mechanical damage to high-vulnerability artifacts; no mechanical risk to most artifacts, paintings, photographs, and books. Chemically unstable objects unusable within decades.
			±10% rh, ±4°F	RH no change Up 9°F; down 18°F	
		B Precision control, some gradients plus winter temperature setback	±10% rh, ±9°F	Up 10%, down 10% rh Up 18°F, but not above 86°F Down as low as necessary to maintain RH control	Moderate risk of mechanical damage to high-vulnerability artifacts; tiny risk to most paintings, most photographs, some artifacts, some books; no risk to many artifacts and most books. Chemically unstable objects unusable within decades, less if routinely at 86°F, but cold winter periods double life.
		C Prevent all high-risk extremes	Within 25 to 75% rh year-round Temperature rarely over 86°F, usually below 77°F		High risk of mechanical damage to high-vulnerability artifacts; moderate risk to most paintings, most photographs, some artifacts, some books; tiny risk to many artifacts and most books. Chemically unstable objects unusable within decades, less if routinely at 86°F, but cold winter periods double life.
		D Prevent dampness	Reliably below 75% rh		High risk of sudden or cumulative mechanical damage to most artifacts and paintings because of low humidity fracture; but avoids high-humidity delamination and deformations, especially in veneers, paintings, paper, and photographs. Mold growth and rapid corrosion avoided. Chemically unstable objects unusable within decades, less if routinely at 86°F, but cold winter periods double life.
Archives, Libraries Storing chemically unstable collections	Cold Store: −4°F, 40% rh	±10% rh ±4°F			Chemically unstable objects usable for millennia. Relative humidity fluctuations under one month do not affect most properly packaged records at these temperatures (time out of storage becomes lifetime determinant).
	Cool Store: 50°F 30 to 50% rh	(Even if achieved only during winter setback, this is a net advantage to such collections, as long as damp is not incurred)			Chemically unstable objects usable for a century or more. Such books and papers tend to have low mechanical vulnerability to fluctuations.
Special Metal Collections	Dry room: 0 to 30% rh	Relative humidity not to exceed some critical value, typically 30% rh			

Table 3: ASHRAE Recommended levels of Climate Control in Historic Buildings, Libraries, Archives, and Museums (source: ASHRAE, *2003 ASHRAE Handbook -- Applications*, 21.8).

Ventilation (exchanging indoor air for outdoor air) by use of fans often is employed in conjunction with other types of equipment, such as heating and cooling. However, by itself, it has been found to reduce the indoor relative humidity by as much as 10% RH.[63] Also, because the air is moving, it reduces the chance of mold growth, even when the relative humidity climbs above 70%.[64] Typically, a humidistat activates the fans when the outdoor relative humidity is lower than the indoor humidity. According to ASHRAE, this type of climate management is recommended for sheathed post and beam construction.[65] Also, a more complex climate management system could be designed to switch to only using ventilation when the outdoor conditions are favorable. For example, the climate management system in the Sainsbury Wing of the National Gallery is designed to use only ventilation when the outdoor conditions match the specified indoor conditions.[66] Due to the possibility of frost damage, Visser[67] recommends that ventilation not be operated when the outdoor temperature is below freezing.

Humidistatic heating (also called *humidistatically controlled heating* or *conservation heating*) relies upon psychrometrics to control the relative humidity of the air. In this approach, the air is heated only enough to attain a relative humidity that is considered safe for the historic materials (as the temperature of the air rises, the relative humidity decreases, and vice versa) with no concern for human comfort. Often, a humidistatic heating system also will use ventilation, because it needs good air

---

[63] Kerschner, "Providing Safe and Practical Environments for Cultural Properties in Historic Buildings…and Beyond."
[64] Ibid.
[65] ASHRAE, *2003 ASHRAE Handbook – Applications*, 21.8 - 21.9.
[66] Sean Ascough. "The National Gallery Sainsbury Wing Air-Conditioning System: A Combination of Close Control and Energy Efficiency." in *Museums Environment Energy*, ed. May Cassar, 51.
[67] Thomas D. Visser. "A Primer on Conservation Assessments and Emergency Stabilization for Historic Farm Buildings." *APT Bulletin* 25, no. 3/4 (1993): 67.

circulation to work well.[68] ASHRAE[69] recommends that humidistatic heating and ventilation be used in buildings of uninsulated masonry, framed and sided walls, and single-glazed fenestration. Because during the winter months in a colder climate the air often will not be heated to a level that is suitable for human comfort, this approach is suited best for buildings that are unoccupied during those months in colder climates.[70]

Some information has been published regarding historic sites and museums that are using alternate climate management systems. A humidistatic heating and ventilation system was installed in Hollybourne Cottage, in Georgia. It was designed to keep the indoor relative humidity below 70% RH and the indoor temperature below 30°C (86°F) by use of temperature sensors, humidistats, space heaters, and ventilation fans. No cooling equipment was installed. The equipment costs (including sensors) for this system were approximately 10 - 12% of the costs for a conventional air-conditioning system,[71] and the energy costs for this system are an average of $0.27 per square foot per year.[72] Because the system did not require ductwork or large mechanical equipment to be installed, there was very little alteration of the historic fabric.[73]

The Shelburne Museum, in Vermont, has been a leader in establishing cost effective ways to manage the indoor climate in museums and historic buildings. Using an expanded relative humidity guideline of 35 – 60% RH, they have installed a wall

---

[68] Raymond H. Lafontaine and Stefan Michalski. "The Control of Relative Humidity – Recent Developments," in *Preprints of the 7th Triennial Meeting, Copenhagen*, ed. Diana de Froment, 84.17.34.
[69] ASHRAE. *2003 ASHRAE Handbook – Applications*, 21.8 - 21.9.
[70] Kerschner, "Providing Safe and Practical Environments for Cultural Properties in Historic Buildings…and Beyond."
[71] Maekawa and Toledo, "A Climate Control System for Hollybourne Cottage, Jekyll Island Historic District, Georgia."
[72] Shin Maekawa, P.E., PhD, interview by the author, 31 October 2006.
[73] Maekawa and Toledo. "A Climate Control System for Hollybourne Cottage, Jekyll Island Historic District, Georgia."

mounted heater and a room air-conditioner in a 12 ft. x 30 ft. exhibition room in one historic building. The system is controlled by temperature and humidity sensors; in the winter, humidistatic heating is used to maintain a safe relative humidity, and in the summer, the air-conditioner is used to cool and dehumidify the space. The equipment for this simple system cost $1000 and it is able to keep the indoor relative humidity between 35 – 55% RH year-round.[74] No data was provided concerning the energy costs of this system, but they are quite low.[75]

Other buildings at Shelburne use a central climate management system much in the manner described above. During the summer, the central air-conditioning unit cools and dehumidifies the air (the specified conditions of the system were not given). In the winter, the system only uses humidistatic heating to maintain the proper indoor relative humidity.[76] Again, no energy costs for this system were provided.

In the past, other buildings at Shelburne used a variation of humidistatic heating in which historical weather data was used to determine the temperature setpoint necessary to maintain a safe relative humidity, rather than using humidity sensors to determine when the system should be activated. Such an approach has the advantages of using an existing heating system, and not requiring the purchase and calibration of expensive sensors. While this form of climate management can be a bit risky – the system reacts to historical data rather than its actual environment – it was effective in managing the

---

[74] Kerschner, "A Practical Approach to Environmental Requirements for Collections in Historic Buildings," 72.

[75] Richard L. Kerschner, Director of Preservation and Conservation, Shelburne Museum, written communication to the author, 27 February 2007.

[76] Kerschner, "Providing Safe and Practical Environments for Cultural Properties in Historic Buildings…and Beyond."

relative humidity in the buildings in which it was applied, and it was very inexpensive.[77] No data was provided regarding the energy costs of this system.

One drawback of these alternate climate management systems is that they may require greater attention from the site's or museum's staff. The historic materials must be observed closely for signs of deterioration, and the building must be inspected regularly for evidence of condensation. The controls often must be adjusted seasonally, which can be forgotten. While humidistatic heating can be effective, it also can mean that the building is too cold for human occupation in the winter.[78]

2.5 CONCLUSION

For decades, the preservation community prescribed the indoor conditions for heritage buildings and museums as 70°F ±2°F and 50% RH ±5% RH without considering how well other indoor climates preserve historic building fabric. As a result, sometimes historic fabric was removed or irrevocably altered as the sites' managers attempted to create these indoor conditions in buildings that never were meant to manage such a specific environment. Only recently have conservators began to research how well historic materials survive in other environments, either at a different setpoint for the temperature and relative humidity, or with a wider tolerance on the conditions, or both. While much research still needs to be done, the literature thus far indicates that many historic materials can tolerate both different setpoints and wider tolerances.

---

[77] Ibid.

[78] Kerschner, "A Practical Approach to Environmental Requirements for Collections in Historic Buildings," 72.

Allowing a wider range of indoor conditions potentially allows a site manager to select from a wider range of climate management systems, hopefully deciding upon one that requires little destruction of historic materials during installation. Unfortunately, a preservationist consulting the literature on this topic of alternative climate management systems will find very little published information. The little information that has been published indicates that smaller systems that allow a wider range of conditions preserve historic fabric very well and are less expensive than a conventional system.

One of the reasons to investigate alternate specifications for indoor conditions is the hope that they will lead to climate management systems that are less expensive to design, install, and operate. Though the modest amount of literature on the topic of alternate climate management systems states that they are less expensive, there is almost no published data to confirm that assertion. What little data that has been published does not always indicate that a broader range of indoor conditions will lead to equipment or energy savings. This area will benefit greatly from further research into the costs of these climate management systems in historic buildings and museums, such as the research that will be performed in this study.

CHAPTER 3: WHY MANAGE THE INDOOR CLIMATE?

3.1 EFFECTS OF TEMPERATURE AND RELATIVE HUMIDITY ON MATERIALS

The indoor temperature and changes in the indoor temperature have been shown to have an effect on the preservation of historic materials. Most materials expand with an increase in temperature, and contract with a decrease in temperature; these actions are called *thermal expansion and contraction*. Different materials expand and contract at different rates. Therefore, where there are interfaces between dissimilar materials, stresses can develop that may accelerate the deterioration of historic materials as the materials push and pull against each other.[79] Keeping the temperature as constant as is possible will reduce this form of decay. If the temperature falls too low, many organic materials become unacceptably brittle.[80]

The ambient temperature also has been shown to affect the rate of chemical reactions and biological growth that cause deterioration. Typically, chemical reactions are accelerated at warmer temperatures.[81] Also, mold grows at warmer temperatures, typically between 40 - 100°F.[82] When human comfort is not a concern, such as archival storage rooms, many authors recommend keeping the temperature as low as possible to reduce these deterioration mechanisms.[83,84] Unfortunately, for a historic building that is

---

[79] William B. Rose. "Effects of Climate Control on the Museum Building Envelope." *Journal of the American Institute for Conservation* 33, no. 2 (1994): 206.

[80] Lafontaine, "Humidistatically Controlled Heating," 36.

[81] Thomson, *The Museum Environment*, 45.

[82] U.S. Environmental Protection Agency. *Building Air Quality: A Guide for Building Owners and Facility Managers*. (Washington, D.C.: U.S. Government Printing Office, 1991), 141.

[83] William K. Wilson. *Environmental Guidelines for the Storage of Paper Records*, NISO Technical Report. (Bethesda: NISO, 1995), 1.

open to the public or a museum collection that is exhibited, the temperature usually must be kept warm enough to provide human comfort, typically around 70°F.[85]

Despite the deterioration mechanisms associated with temperature just described, most conservators note that the temperature alone usually is not responsible for the majority of the decay of historic materials. As long as the temperature does not become extremely high or low, and as long as the short term fluctuations of temperature are not extreme, most historic materials will not be affected greatly by their ambient temperature.[86] However, managing the indoor temperature still is of great importance in the preservation of historic materials, because the relative humidity depends on the temperature.

Before describing the importance of managing the relative humidity in preservation, the relationship between temperature and moisture in air must be understood. The relative humidity is the amount of water vapor in the air (called the air's *moisture content*) divided by the maximum amount of moisture the air can hold, expressed as a percentage.[87] The maximum amount of moisture the air can hold depends on the temperature – as the temperature increases, so does the maximum amount of moisture the air can hold, and vice versa.[88] Therefore, for a constant moisture content of the air, increasing the temperature will decrease the relative humidity. The relationship

---

[84] Kerschner, "Providing Safe and Practical Environments for Cultural Properties in Historic Buildings…and Beyond."
[85] ASHRAE. 2005 *ASHRAE Handbook – Fundamentals*. (Atlanta: ASHRAE, 2005), 8.12.
[86] Lafontaine, "Humidistatically Controlled Heating," 36.
[87] Gordon Van Wylen, Richard Sonntag and Claus Borgnakke. *Fundamentals of Classical Thermodynamics*. (New York: John Wiley & Sons, Inc., 1994), 499. Technically, the relative humidity is defined as the ratio of the partial pressure of water vapor in the air to the saturation pressure of the vapor at the same temperature. The definition given in the above text is a slightly simplified definition that works well in practical applications.
[88] Ibid., 498.

between air's temperature and moisture content is called *psychrometrics*, and is presented graphically in the *psychrometric chart* (see Figure 4). As an example, suppose that the air in a room is at 60°F and 70% RH. According to the psychrometric chart, this air will have a moisture content of 0.008 lb_{water}/lb_{air}. If the moisture content is kept constant and the air is heated to 70°F, the relative humidity falls to 49% RH, even though the moisture content of the air remains the same. Because the air's temperature increased, the relative humidity decreased.

If the relative humidity climbs to 100% RH, then the air is holding as much moisture as it possibly can.[89] As a result, some of the water vapor will begin to condense and become liquid water. Another way to think about it is at 100% RH the *dewpoint* is reached. The dewpoint is the temperature at which 100% RH, and therefore condensation, occurs.[90] Consider the air from the previous example at 60°F and 70% RH. For this air the dewpoint is 50°F. So, if the moisture content of the air is held constant and the temperature of the air falls to 50°F, the relative humidity will climb to 100% RH and condensation will occur. Or, if the air encounters a surface that is below the dewpoint, condensation will occur on that surface.

---

[89] Ibid., 498.

[90] Ibid., 498. This process assumes that the pressure of the air is kept constant.

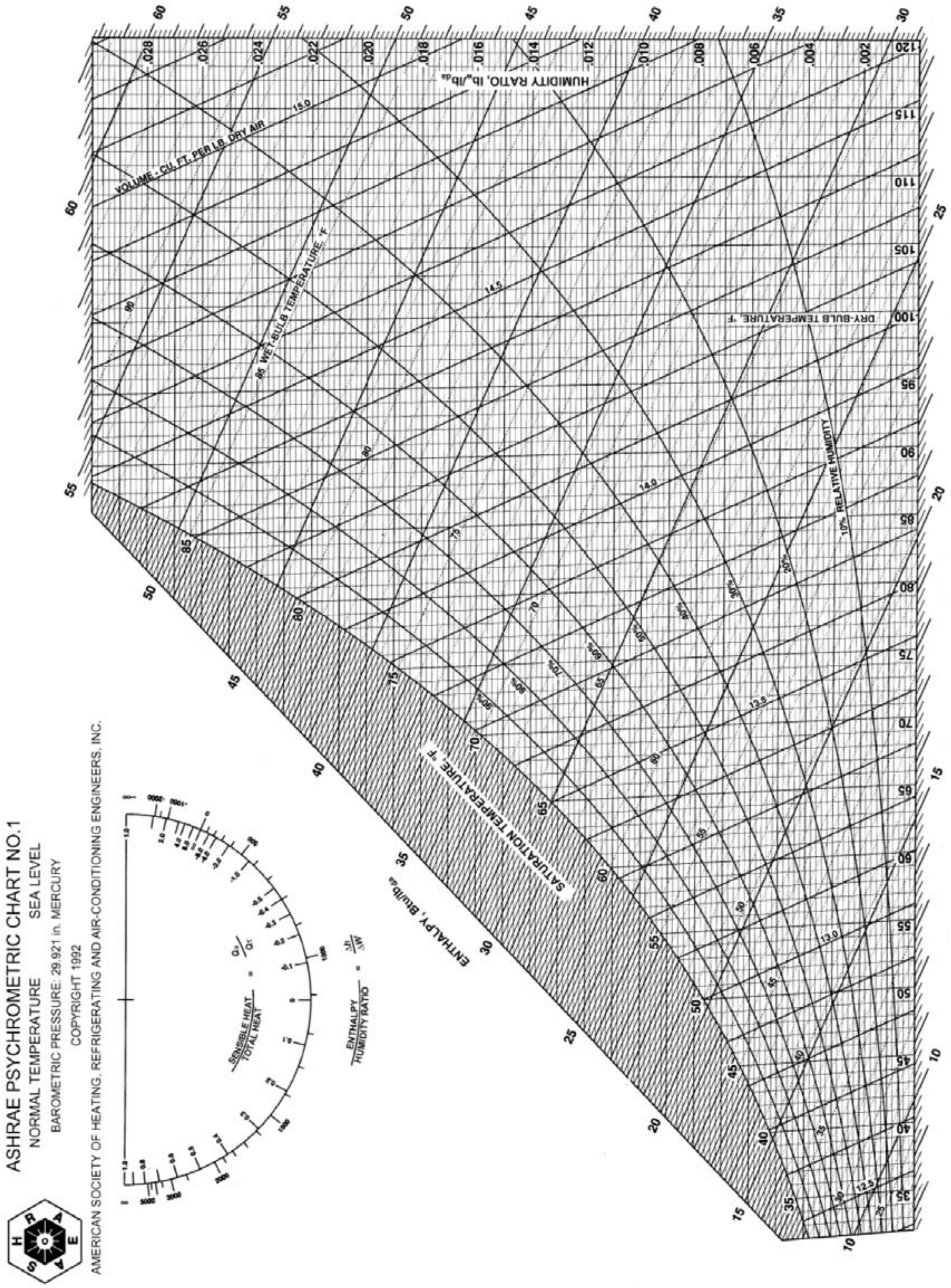


Figure 4: Psychrometric Chart (source: ASHRAE, *2005 ASHRAE Handbook -- Fundamentals*, 6.11).

The relative humidity has a significant effect on the conservation of historic fabric and is a major concern in historic preservation. Many materials will try to remain in equilibrium with the relative humidity of their environment. Materials that are *hygroscopic*, meaning that they are able to absorb and adsorb[91] moisture, will adsorb water vapor as the relative humidity increases and desorb water vapor as the relative humidity decreases as they try to remain in equilibrium with their environment.[92] As materials adsorb moisture they expand, and as they release moisture they contract. As with thermal expansion and contraction, different materials will expand and contract at different rates as they take in and release moisture, which will cause stresses in the interfaces between the materials.[93] Moisture expansion and contraction typically is much greater than thermal expansion and contraction, meaning that the stresses incurred due to changes in moisture will be much greater than those due to changes in temperature.[94]

Materials have an elastic range for stress and an inelastic range for stress. The inelastic range for stress always is greater than the elastic range. If the stresses incurred from moisture expansion and contraction are in the elastic range, the materials will return to their original form once the stresses are removed. If the stresses are in the inelastic range, the materials will be permanently deformed, even after the stresses are removed.[95] Recent research has shown that, for most materials, stresses that are kept in the elastic

---

[91] *Absorption* is the taking in of liquid water by a material; *adsorption* is the taking in of water vapor by a material.

[92] Rose, "Effects of Climate Control on the Museum Building Envelope," 203.

[93] Erhardt and Mecklenburg, "Relative Humidity Re-Examined," 33.

[94] Lafontaine, "Humidistatically Controlled Heating," 36.

[95] Erhardt and Mecklenburg. "Relative Humidity Re-Examined," 33.

range will not cause permanent harm, but stresses in the inelastic range will.[96] Because moisture expansion and contraction are cause by changes in the ambient relative humidity, theoretically conservators can control whether the stresses in the historic materials stay in the elastic range or move into the inelastic range by controlling the relative humidity. However, it is not that simple. Different materials have different ranges of elastic and inelastic stress. When that fact is coupled with the fact that different materials also expand and contract at different rates as they adsorb moisture, it becomes apparent that there is no single setpoint or variance for the relative humidity that will work for all of the materials in a historic building or museum.[97] Instead, conservators must consider the entire collection or building assembly and pick the relative humidity setpoint and variance based on what will best preserve the materials as a whole.

There are other concerns regarding relative humidity in the preservation of historic buildings and museum collections. If the relative humidity falls too low, many materials become unacceptably brittle and fracture easily.[98] As with the other forms of deterioration described here, the relative humidity at which different materials become brittle varies. However, research has shown that brittleness for most materials can be avoided if the relative humidity stays above 30% RH.[99]

Ambient water vapor also has an effect on deteriorating chemical reactions, such as the corrosion of metal. Typically, the higher the relative humidity, the greater the rate

---

[96] Ibid., 33.
[97] Ibid., 32.
[98] Ibid., 33.
[99] Ibid., 34.

of the reactions.[100] Therefore, to reduce these reactions, the relative humidity should be as low as possible. However, if the relative humidity is too low, there is a danger of the materials becoming too brittle.

The relative humidity also has a great effect on fungal growth. Mold, mildew, and other fungi can destroy historic materials.[101] It often attacks and seriously damages materials before it is noticed; Carll and Highley[102] note that mold can reduce the strength of wooden structural members by as much as 20% before there is visual evidence of fungal growth. Mold also has been linked to numerous respiratory ailments.[103] Fungal growth requires materials to have a minimum moisture content, below this threshold fungal growth will not occur.[104] As the moisture content of materials depends on the relative humidity, keeping the relative humidity below a certain value will keep the moisture content in the materials too low for fungal growth. Typically, this value is given as 70% RH, though fungi have been found to grow at lower relative humidity.[105] Some authors recommend that the relative humidity be kept below as 60% to avoid fungal growth.[106] Stagnant air also encourages mold growth,[107] though mold growth has been found on surfaces that experience high airflow.[108] Therefore, to combat fungal

---

[100] Thomson, *The Museum Environment*, 84.

[101] Samuel Y. Harris. *Building Pathology: Deterioration, Diagnostic, and Intervention*. (New York: John Wiley & Sons, Inc., 2001), 105.

[102] Charles G. Carll and Terry L. Highley. "Decay of Wood and Wood-Based Products above Ground in Buildings." *Journal of Testing and Evaluation* 27, no. 2 (1999): 155.

[103] The Chicora Foundation, *Mold*.

[104] Michalski, "Relative Humidity: A Discussion of Correct/Incorrect Values," 625.

[105] Ibid., 625.

[106] The Chicora Foundation. *Managing the Museum Environment*. (1994). <http://palimpsest.stanford.edu/byorg/chicora/chicenv.html> (31 October 2006).

[107] Ibid.

[108] Scott Graeme. "Moisture, Ventilation, and Mould Growth," in *Preventive Conservation: Practice, Theory, and Research*, eds. Ashok Roy & Perry Smith, 151.

growth, the relative humidity should be kept below a certain threshold and there should be proper ventilation.

Efflorescence also is affected by ambient water vapor. Efflorescence depends upon the moisture content of the materials, which, as stated, depends upon the relative humidity. For each salt, there is a value for the relative humidity below which it will not dissolve.[109] If the relative humidity fluctuates around this relative humidity value, the salts will deliquesce and crystallize as the relative humidity goes up and down.[110] To avoid this decay mechanism, the relative humidity should be kept as low as possible.[111]

Finally, the relative humidity must be managed to avoid condensation. As stated, if the dewpoint is reached, whether by increasing the moisture content of the air to 100% RH or lowering the air's temperature to the dewpoint, condensation will occur. In fact, condensation on cold windows during the winter was a common test for excess moisture in a building in times past.[112] Liquid water can be absorbed by historic materials and cause damage; the deterioration mechanisms of expansion and contraction, fungal growth, chemical reactions, and efflorescence also are accelerated by the presence of liquid water.[113,114] Controlling condensation in a historic building during the winter can be difficult, especially one that maintains 70°F and 50% RH year-round. The warm, moist indoor air will want to migrate to the outdoors (vapor transport mechanisms are

---

[109] Erhardt and Mecklenburg, "Relative Humidity Re-Examined," 34.
[110] Ibid., 34.
[111] Ibid., 34.
[112] Brown and Rose. "Humidity and Moisture in Historic Buildings," 13.
[113] Joseph Lstiburek and John Carmody. *Moisture Control Handbook: Principles and Practices for Residential and Small Commercial Buildings*. (New York: Van Nostrand Reinhold, 1993), 6.
[114] Sharon C. Park. "Holding the Line: Controlling Unwanted Moisture in Historic Buildings." National Park Service Preservation Brief #39. (1996). <http://www.cr.nps.gov/hps/tps/briefs/brief39.htm> (4 November 2006).

described in more detail in *Section 3.2: Vapor Transport Mechanisms and Sources of Moisture*); as it moves through the walls it will encounter internal surfaces that likely are colder than the dewpoint and condensation will occur inside the walls.[115]

So, in reviewing the effects of temperature and relative humidity on historic materials, it appears that a conservator must keep the temperature as low as possible to avoid chemical reactions and mold growth, keep it somewhat warm to avoid causing brittleness, it must always be kept above the dewpoint, and, if the building is open to the public, it must be kept warm enough for human comfort. The relative humidity must be kept as low as possible to avoid efflorescence and chemical reactions, high enough to avoid brittleness, low enough to avoid condensation in the winter, and lower than 70% RH to avoid fungal growth. Adding to the difficulty, different materials react to changes in temperature and relative humidity in different ways and at different rates. The contradictions in all of these constraints are apparent, leading to the conclusion that there is no single setpoint or variance for the temperature and relative humidity that will avoid all forms of deterioration. As Erhardt and Mecklenburg[116] state, "The optimal relative humidity is not a specific value upon which all considerations converge, but a range chosen as a compromise in an attempt to minimize the total effect of numerous reactions and processes." When determining the proper indoor temperature and relative humidity for a historic building or museum, a conservator must investigate the building materials or the collection thoroughly and consult the latest research to establish the conditions that will do the best job of preserving all of the materials.

---

[115] Padfield, "The Role of Standards and Guidelines."
[116] Erhardt and Mecklenburg, "Relative Humidity Re-Examined," 32.

Once the specification that will best preserve the historic materials has been established, there still is one concern. Materials become seasoned to their environment.[117] If the new specification for the indoor climate is greatly different from the existing conditions, the materials will experience a shock as they adjust to their new environment, moisture will be adsorbed or desorbed, leading to expansion or contraction.[118] To avoid this shock, Cassar[119] recommends changing the indoor environment slowly.

3.2 VAPOR TRANSPORT MECHANISMS AND SOURCES OF MOISTURE

Vapor transport mechanisms are the processes by which water vapor enters (*infiltrates*) or leaves (*exfiltrates*) a building. They are a function of thermodynamics (including psychrometrics and climate management systems) and building envelope design. Presented here will be a cursory explanation of the physics concerning why and how moisture enters and leaves a building.

Just as materials try to maintain equilibrium with their environment, the indoor space of a building tries to maintain equilibrium with the outdoors. Air tends to move from a warmer environment to a colder environment; this movement of air is called *natural convection*.[120] As the air moves, it takes the moisture that it holds with it. Warm air also rises inside the building; the buoyancy of warm air is called the *stack effect*.[121] As the air rises, the moisture it contains also rises. If it has no means of escape to the

---

[117] Cassar, *Environmental Management*, 15.
[118] Thomson, *The Museum Environment*, 89.
[119] Cassar, *Environmental Management*, 16.
[120] ASHRAE. 2005 *ASHRAE Handbook – Fundamentals*, 3.2.
[121] Ibid., 27.5.

outdoors, the warm moist air will collect at the underside of the roof of the building, and the moisture possibly will be adsorbed by the roofing materials or condense on them.

Also, water vapor tends to move from an area of high concentration to an area of low concentration; this process is called *diffusion*. The absolute moisture content of the air, not relative humidity, determines the direction of flow in diffusion.[122] Thus, it is possible that moisture will diffuse from an area of low relative humidity to high relative humidity if that area actually has a lower moisture content. This diffusion also can occur through building materials, not just through leaks in the assembly.[123]

Internal water vapor in a building has many sources: the ground, rain, the materials of and inside the building, mechanical systems, outdoor air, and human activities, such as bathing or cleaning.[124,125] Ground water can be absorbed in its liquid form by the building's foundation and walls through capillary rise. If there is not a vapor barrier between the interior surface of the walls and the interior space, the liquid water can evaporate into the interior.[126] Groundwater also can evaporate into the interior through the floor in a basement or through the ground in a crawl space if there is no vapor barrier covering the ground.[127] Conrad[128] states that "The odds are that the basement in an old home is the primary moisture engine [in the building]." Because these spaces

---

[122] Lstiburek and Carmody, *Moisture Control Handbook*, 43.
[123] Ibid., 43.
[124] Cassar, *Environmental Management*, 22.
[125] Feilden, *Conservation of Historic Buildings*, 169.
[126] John F. Straube. "Moisture, Materials, and Buildings." *HPAC Engineering*, April (2002): 40.
[127] Miimu Matilainen and Jarek Kurnistki. "Moisture Conditions in Highly Insulated Outdoor Ventilated Crawl Spaces in Cold Climates." *Energy and Buildings* 35 (2003): 176.
[128] Ernest A. Conrad. "The Dews and Don'ts of Insulating." *Old-House Journal* 24, no. 3 (1996), 41.

often are cool, the diffusion of moisture into them causes the risk of high relative humidity in these spaces.

Rainwater can infiltrate a building through poorly sealed seams or cracks in the roof and the walls of a building. It also can enter through the foundations. If it is not allowed to drain out of the building, this water can be absorbed by the building materials. This moisture can evaporate into the interior spaces and increase the indoor relative humidity.[129]

As stated previously, hygroscopic materials constantly are exchanging moisture with their environment in an attempt to maintain an equilibrium moisture content. An interesting situation may arise when the indoor relative humidity changes, but appears to remain stable. In this situation, it is possible that, as the indoor relative humidity falls or rises, the hygroscopic materials release or adsorb moisture as they attempt to maintain an equilibrium moisture content. Doing so may stabilize the indoor relative humidity. The materials act as a humidity buffer for the building, releasing or adsorbing moisture to keep the indoor relative humidity stable.[130] This process can make it difficult to determine if the historic materials are experiencing moisture expansion and contraction because the humidity sensors will indicate that the relative humidity is constant. However, if the mass of the historic materials is great, the individual materials may only

---

[129] Lstiburek and Carmody, *Moisture Control Handbook*, 46.

[130] Tim Padfield, Peder Bøllingtoft, Bent Esjøj and Mads Chr. Christensen. "The Wall Paintings of Gundsmøgle Church, Denmark," in *Preventive Conservation: Practice, Theory, and Research*, eds. Ashok Roy & Perry Smith, 96.

experience minimal expansion and contraction because the load is shared amongst them, and they actually will decrease the moisture load on the climate management system.[131]

For a building that is occupied, a certain amount of outdoor air must be brought into the space to keep the air fresh.[132] Also, it must expected that, no matter how hard one tries to make a building airtight, some outside air will infiltrate the building; old buildings especially are notorious for a lack of airtightness.[133,134] The outside air that purposefully is brought into the building (mechanical ventilation) or the outside air that infiltrates the building (natural ventilation) will contain moisture that will be added to the interior space.

Mechanical equipment, in the form of a humidifier, often is used to purposefully add moisture to the indoor spaces of a building. Remember that human comfort, and the preservation of the historic materials, requires the indoor relative humidity to be between 40 – 70% RH.[135] Imagine that the outdoor air has a temperature and relative humidity of 20°F and 50% RH. When the air is brought into the building, it will need to be heated to approximately 70°F for human comfort. According to the psychrometric chart, heating this air to 70°F will lower the relative humidity to 7% RH, which is both uncomfortable and dangerously low for the conservation of historic fabric and collections. To achieve a relative humidity in the safer range of 40 – 70% RH, a humidifier must be used to add moisture to the space.

---

[131] Ibid., 96.
[132] ASHRAE. *2005 ASHRAE Handbook – Fundamentals*, 27.1.
[133] Cassar, *Environmental Management*, 36.
[134] Park, “Holding the Line: Controlling Unwanted Moisture in Historic Buildings.”
[135] Erhardt and Mecklenburg, “Relative Humidity Re-Examined,” 37.

Human beings also add moisture to a building. Moisture is exhaled when breathing, and evaporates from the skin; on average, one person releases 40 ml of moisture per hour to the surrounding air.[136] Human activities, such as bathing, cooking, and cleaning, also add moisture to the indoor environment.[137]

3.3 CONCLUSION

The health of a historic building's fabric or a museum collection can be affected greatly by the indoor climate. While there is no setpoint for temperature and relative humidity that will avoid all forms of deterioration, some control over the climate often is necessary to conserve historic materials. To establish the range of conditions that best will preserve a historic building or a museum collection, a conservator must have a thorough understanding of the materials' properties and how they are affected by their ambient environment. Most likely, the setpoint and variance for the indoor temperature and relative humidity still will leave certain materials somewhat vulnerable to some of the decay mechanisms described here, but will do the best job of preserving the historic fabric as a whole.

In a sense, climate management is a necessary reaction to improper moisture levels in a building. The sources of moisture in a building vary; however, all of them typically are present in a building. Diagnosing the sources of moisture and its transport mechanisms can be difficult, for, as Lstiburek[138] states, "Water always changes its behavior, because its form is never constant. Evaporation, condensation, capillary

---

[136] Feilden, *Conservation of Historic Buildings*, 169.
[137] Lstiburek and Carmody. *Moisture Control Handbook*, 31-32.
[138] Joseph Lstiburek. "Investigating & Diagnosing Moisture Problems." *ASHRAE Journal*, December (2002): 36.

suction, gravitational flow, vapor diffusion and mass flow of moist air are all happening at the same time inside building cavities and inside materials." To design an effective climate management system for a building, a thorough investigation of the vapor transport mechanisms and the sources of moisture must be performed. Coupled with the conservator's assessment of the needs of the historic materials, this knowledge can lead to the development of an effective climate management solution for the historic building or museum.

CHAPTER 4: CLIMATE MANAGEMENT PROCESSES AND EQUIPMENT

4.1 INTRODUCTION

Prior to the development of mechanical cooling and heating equipment, architects designed their buildings to adjust to their environment in order to provide comfort to the buildings' inhabitants, and the buildings' inhabitants would adjust their behavior depending on the season. The fenestration would be placed to promote the natural flow of air through the building to provide fresh air and cooling during warm weather.[139] During the winter, the buildings' occupants would gather around fireplaces or stoves for warmth, while the rest of the indoor spaces remained cold.[140] With the development of mechanical cooling and heating equipment, mankind's expectations of indoor comfort changed, and whole-building cooling and heating became the norm. Now, some form of mechanical equipment often is used to exert some level of control over the indoor environment.

Before describing the climate management systems used by the sites studied in this thesis, the processes involved in climate management will be explained. Essentially, these processes are categorized as heating, ventilation, or cooling (air-conditioning) processes (hence the term *HVAC* – Heating, Ventilation, and Air-Conditioning). When control needs to be exerted over the relative humidity, humidification and dehumidification also are implemented. For ease of understanding, these processes will

---

[139] Tim Padfield. "How Air-conditioning Works," 1. <http://www.natmus.dk/cons/tp/aircon/aircon.pdf > (19 October 2006)

[140] Stowlow, "The Preservation of Historic Houses and Sites," 116.

be presented separately. It must be kept in mind that, for some processes, the physics behind them overlaps.

The following terms must be understood when reading this chapter: *Supply air* is air that is conditioned by the climate management system and distributed to the indoor spaces of a building. *Return air* is indoor air that is drawn back into the climate management system to be conditioned. *Exhaust* is indoor air that is released to the outdoors by the climate management system. *Outdoor air* is air from the outdoors that is brought into the climate management system to be conditioned and used as supply air.

Not all of the types of equipment described here are used by the sites included in this study; the information in this chapter only is presented as background information to illustrate how climate management is achieved.

4.2 COOLING PROCESSES AND EQUIPMENT

In order to lower something's temperature, whether it is a solid, liquid, or gas, heat must be removed from it, and transferred to something else. So, to cool the indoor environment of a building, heat that is inside must be transferred outside. More specifically, the heat of the indoor air must be transferred to the outdoor environment. There are several different types of mechanical equipment that will perform this heat transfer; an explanation of how each works would fill hundreds of pages. However, there are basic processes that they all use. These processes will be discussed in this section, as well as descriptions of the general types of equipment.

To transfer indoor heat to the outdoors, a medium must be used to absorb heat from the supply air. Typically, this medium either is a refrigerant or water. When the medium is a refrigerant, the system is called a *direct expansion* (often abbreviated *DX*) system.[141] This type of system commonly is found in applications of less than 75 tons[142] of cooling,[143] such systems commonly are used in homes and apartments. Without going into too much detail, this type of system works by causing the refrigerant to go through two different phase changes (a phase change is a change from one state of matter to another, i.e. solid to liquid, liquid to gas, etc.). During a phase change there is a large heat transfer. In this type of system, the refrigerant is converted from a liquid to a gas inside one coil of tubing (called the *evaporating coil*), and from a gas to a liquid inside another coil of tubing (called the *condensing coil*). During the liquid-to-gas phase change, an *air handler* blows the supply air over the evaporating coil; as the refrigerant evaporates inside the tubes it absorbs heat from the supply air, lowering the supply air's temperature.[144] The supply air then is delivered to the indoor spaces through ductwork. If, when it is being cooled, the supply air's temperature is lowered to the dewpoint, moisture in the air will begin to condense and fall out. Thus, this type of system also can be used to dehumidify the supply air.[145] Once evaporated, the gaseous refrigerant is compressed by a *compressor* then delivered to the condensing coil, which is located outside.[146] A fan blows air over the coil; the air absorbs heat from the refrigerant, causing it to become a liquid. After flowing through an expansion valve, the refrigerant

---

[141] William Bobenhausen. *Simplified Design of HVAC Systems*. (New York: John Wiley & Sons, Inc., 1994), 329.

[142] 1 ton of cooling = 12,000 Btu/hour of cooling.

[143] Peter Warner, a representative of The Trane Company, a manufacturer of HVAC equipment, interview by the author, 7 February 2007.

[144] Bobenhausen, *Simplified Design of HVAC Systems*, 329.

[145] Ibid., 320.

[146] Ibid., 329.

re-enters the evaporating coil to begin the cycle again.[147] Direct expansion air-conditioners typically require approximately 1.3 kW/(ton of cooling) in energy.[148]

The direct expansion system, described above, works well to cool the indoors in smaller applications. In larger applications, typically above 75 tons, chilled water often is preferred, as it is more efficient, and a larger scale typically makes it more cost-effective.[149] Also, chilled water systems give greater control over the dehumidification processes than direct expansion processes do.[150] For this type of system, the chilled water is carried through coils of piping inside either air handlers or *fan coil units*, both of which blow the supply air over the coils.[151] The chilled water absorbs heat from the supply air as the air is blown over the tubes, lowering the supply air's temperature.[152] The supply air then is delivered to the building, either by an air handler or fan coil units. An air handler uses ductwork to deliver the supply air to the building, whereas a fan coil unit is located inside the occupied spaces and delivers supply air directly to the indoor spaces. Again, if the supply air's temperature is lowered below the dewpoint, the air will be dehumidified because the moisture in the air will condense and fall out. The now-warmer water then flows into the *chiller*, where it is cooled again.[153] The chiller typically uses the direct expansion process described above to create the chilled water. In a chiller, the water flows over the evaporating coil; as the refrigerant inside the coil evaporates it

---

[147] Ibid., 329.
[148] Peter Warner, interview by the author, 7 February 2007.
[149] Ibid.
[150] Ibid.
[151] Bobenhausen, *Simplified Design of HVAC Systems*, 353.
[152] Dennis L. O'Neal and John A. Bryant. "Air-Conditioning Systems," in *Handbook of Heating, Ventilation, and Air-Conditioning*, ed. Jan F. Kreider. (New York: CRC Press, 2001), 4-35.
[153] Ibid., 4-31.

absorbs heat from the water, lowering the water's temperature to create chilled water.[154] This chilled water then flows back to the air handlers or fan coil units to be used to cool the supply air again. A chilled water system requires a pump to cause the water to flow through the system.[155] Chilled water systems have the advantage of being able to vary the temperature of the chilled water and its flow rate through the system. Thus, they are able to exert greater control over the indoor temperature and relative humidity than direct expansion air-conditioners can.[156]

When a chiller uses the direct expansion process to create chilled water, either outside air or water can be used to absorb heat from the refrigerant when it is inside the condensing coil. If air is used, a fan to blow the air over the coil is needed; such a device is called an *air-cooled chiller*.[157] If water is used, a separate piece of equipment, called a *cooling tower*, is used, and the chiller is called a *water-cooled chiller*.[158] A cooling tower produces water that is near the ambient wet-bulb temperature.[159] Rejecting heat from the refrigerant inside the condensing coil to water that is near the ambient wet-bulb temperature is more efficient than rejecting heat to air that is at the dry-bulb temperature.[160] An air-cooled chiller typically uses approximately 1.2 kW/(ton of cooling) in energy, while a water-cooled chiller typically uses less than 1 kW/(ton of

---

[154] Ibid., 4-31.
[155] Bobenhausen, *Simplified Design of HVAC Systems*, 164.
[156] Peter Warner, interview by the author, 7 February 2007.
[157] O'Neal and Bryant, "Air-conditioning Systems," 4-35.
[158] Ibid., 4-35.
[159] The *wet-bulb temperature* results from the evaporation of water off of the temperature sensor in a moving air stream. The *dry-bulb temperature* is simply the temperature of the air. Because the process of evaporation draws heat, the wet-bulb temperature always is lower than the dry-bulb temperature.
[160] Peter Warner, interview by the author, 7 February 2007.

cooling) in energy.[161] Therefore, in a larger application, the extra cost of the cooling tower may be offset by the savings from the increased efficiency of the process.

Another type of chiller, called an *absorption chiller*, also may be used, though it usually is found in very large applications, above 350 tons of cooling, where energy costs are high.[162] An absorption chiller uses a different substance as the refrigerant than does a direct expansion system, and does not use a compressor. In an absorption chiller, the refrigerant is carried in another fluid.[163] By the addition of heat, from combustion or electricity, the refrigerant is evaporated out of the carrying medium before entering the condensing coil, where it is condensed. At this point, the process mimics chillers that use the direct expansion process. The refrigerant flows into an evaporating coil, where it absorbs heat from the water to create chilled water.[164] The chilled water then is used to condition the supply air. Absorption chillers have the advantage of requiring less electrical energy than water-cooled or air-cooled chiller because they do not use a compressor. Also, as the size of the application increases, the efficiency of an absorption chiller increases. However, in order to be cost effective, they typically require low natural gas costs or a source of waste heat from something else that they can use to drive the process.[165]

There are advantages and drawbacks to each type of cooling system. A direct expansion air-conditioner is the simplest device, but it also is the least energy-efficient. Also, each condensing coil can serve only one evaporating coil. Therefore, for a larger

---

[161] Ibid.
[162] Ibid.
[163] O'Neal and Bryant, "Air-conditioning Systems," 4-44.
[164] Ibid., 4-44 – 4-45.
[165] Peter Warner, interview by the author, 7 February 2007.

building, several direct expansion air-conditioners may be needed to cool all occupied spaces. This type of system requires ductwork to be installed in the building, as well as tubing to carry the refrigerant from the outdoor condensing coil to the indoor evaporating coil and back (assuming the condensing coil and the evaporating coil are not packaged together as one unit). An air-cooled chiller is more energy-efficient that a direct expansion air-conditioner; however, it is a more complicated process requiring more mechanical equipment. A water-cooled chiller is more energy efficient than an air-cooled chiller, but it requires a cooling tower to service the condensing coil inside the chiller. An absorption chiller requires less electrical energy than the other types of chillers, but they are complex pieces of equipment that typically require large applications to justify their cost. For all types of chillers, tubing is necessary to carry the chilled water from the chiller to the air handlers or the fan coil units, and a pump is necessary to propel the water through the system. An advantage of a chilled water system is that one chiller can serve several air handlers or fan coil units. Also, if fan coil units are used, neither ductwork nor air handlers need to be installed, which are necessary for direct expansion air-conditioners to deliver supply air to the building. Another advantage of chilled water systems is they allow greater control over the indoor climate than do direct expansion air-conditioners.

4.3 HEATING PROCESSES AND EQUIPMENT

To heat the supply air for a building, heat must be transferred to the air from someplace else. There are several types of mechanical equipment for heating, each with its advantages and disadvantages. Again, a description and explanation of each type of equipment would fill hundreds of pages; instead, the basic processes that they use and the general categories of equipment will be presented.

For smaller applications in warmer winter climates, a *heat pump* may be appropriate. A heat pump simply is a direct expansion air-conditioner that is run backwards. Remember that the condensing coil rejects heat, and the evaporating coil absorbs heat. Therefore, the refrigerant is run backwards through the system, and what served as the evaporating coil for cooling now serves as the condensing coil for heating.[166] An air handler blows the supply air over the condensing coil. As the refrigerant condenses, it rejects heat to the supply air; the now warmer air proceeds through the ductwork to the indoor spaces of the building. The refrigerant then flows through the expansion valve into the evaporating coil (which served as the condensing coil during the cooling season), where it absorbs heat from outside air that is blown over the coil. Typically, heat pumps only can handle small heating loads;[167] if it is likely that the heating load will exceed the capacity of the heat pump, *electrical heating strips* often are placed inside the ductwork to handle the excess load. Heating strips create heat by passing electrical current through high resistance wires; as the supply air flows over the heating strips, they absorb heat from the wires.[168]

Also in applications with small heating loads or in small applications, electrical heating strips alone may be used to heat a building in winter. Because relatively little heat is produced relative to the amount of energy necessary to operate the system, the

---

[166] Vahab Hassani and Steve Hauser. "Thermodynamics and Heat Transfer Basics," in *Handbook of Heating, Ventilation, and Air-Conditioning*, ed. Jan F. Kreider, 2-6.

[167] Jan F. Kreider. "Heating Systems," in *Handbook of Heating, Ventilation, and Air-Conditioning*, ed. Jan F. Kreider, 4-20.

[168] Peter Warner, interview by the author, 7 February 2007.

form of heating is not reasonable for larger applications, as the energy costs would be quite high. Also, not enough heat is produced to make this type of heating practical in colder climates.[169] The advantage of both a heat pump and an electric heating system is that the capital expense for the equipment are quite low compared to more robust forms of heating.

For larger applications, some form of combustion typically is used to produce the heat energy that is necessary to heat the building. Several different types of mechanical equipment use combustion, the simplest of which is a *furnace*. There are several different designs for furnaces, but they all operate in the same way. Natural gas, liquid propane, or heating oil is ignited in a sealed metal container. A fan or air handler blows supply air over the hot container; as the air flows over the container it absorbs heat from the combustion process inside. The now warmer air then is delivered to the building through ductwork. The products of the combustion process are exhausted from the sealed container to the outdoors.[170]

Just as chilled water is used for large-application cooling in the summer, hot water is used for large-application heating in the winter. The water first circulates through a *boiler*. In the boiler, heat is produced by the combustion of natural gas, propane, or heating oil; this heat is transferred to the water to create hot water (note that, in a hot water system, the boiler does not actually boil the water).[171] The heat typically is transferred to the water in one of two ways. In one method, the combustion occurs inside

---

[169] Bobenhausen, *Simplified Design of HVAC Systems*, 273.
[170] Kreider, “Heating Systems,” 4-2.
[171] Ibid., 4-7.

sealed metal tubing, and the water flows around the tubes (called a *fire-tube boiler*). As the water flows around the tubes it absorbs heat from the combustion process.[172] The water then flows into tubing through which it is delivered to the building by the use of pumps.[173] The other method has the water flowing through tubes that are inside a chamber in which combustion takes place (called a *water-tube boiler*). The water absorbs heat from the combustion process occurring around the tubes.[174] The water then is delivered to the building through tubing, again, by the use of pumps.

There are several different methods by which the heat of the hot water is transferred to the supply air. The hot water may flow into air handlers which blow the supply air over the tubes; as the air flows over the tubes it absorbs heat from the water, then it is delivered to the building through ductwork. Or, the hot water may flow into fan coil units, in which a fan blows air over the tubing, arranged in coils, to absorb heat from the hot water. Because fan coil units are inside the occupied rooms of a building, the air flows from the hot water tubing directly into the indoor spaces; thus ductwork is not needed. Finally, the hot water may flow through *radiators* or *convectors*. Radiators and convectors are coils of hot water tubing that are located in the occupied spaces of a building; when they are located near the floor they often are called *baseboard heaters*. Radiators and convectors transfer heat directly to the interior spaces of a building by convection and by radiation instead of using a fan.[175] A newer approach is to run the hot water tubing underneath the flooring. The heat in the water is conducted and radiated

---

[172] Ibid., 4-7.
[173] Bobenhausen, *Simplified Design of HVAC Systems*, 260.
[174] Kreider, “Heating Systems,” 4-7.
[175] Bobenhausen, *Simplified Design of HVAC Systems*, 268.

through the floor to heat the building.[176] Because they are not forcing airflow through the building, radiators/convectors do not create drafts in the occupied spaces, making this type of application more comfortable for the building's occupants.[177] For all hot water systems, after the water has flowed through the air handler, fan coil unit, or radiator/convector, the water flows back into the boiler to be heated again.

In some applications, the boiler actually will boil the water to create steam. After the steam is created, the system functions much like a hot water system. The steam can be pumped to air handlers, fan coil units, or radiators/convectors; these pieces of equipment will transfer heat from the steam to the supply air or directly into the occupied spaces of the building in the same manner as hot water systems. Because steam is at a higher temperature than hot water, steam heating systems can handle higher heating loads than hot water systems can.[178] However, steam heating systems are more prone to leaking and typically require more maintenance than hot water systems do.[179] Also, more complex equipment is needed to separate the steam from the condensate that occurs inside the system.[180]

The type of heating system that is appropriate for a building is a function of the size of the application and the funds available to install and operate the system. A heat pump has the advantage of low equipment costs; because the exact same piece of equipment can provide direct expansion cooling in the summer and heating in the winter; a direct expansion air-conditioner/heat pump unit is only slightly more expensive than a

---

[176] Kreider, "Heating Systems," 4-26 – 4-27.
[177] Peter Warner, interview by the author, 7 February 2007.
[178] Kreider, "Heating Systems," 4-7.
[179] Peter Warner, interview by the author, 7 February 2007.
[180] Kreider, "Heating Systems," 4-9.

direct expansion air-conditioner by itself, and it does not require the extra mechanical equipment or the installation of tubing in the building that hot water and steam systems require. However, a heat pump would not be able to provide heating for a large building in a cold climate without high energy costs. An electric strip heating system also has low equipment costs, but can handle only a small heating load. A furnace can handle a larger heating load than a heat pump or electric heating strips, but is may not be as comfortable as hot water or steam systems because it can create drafts in the building. A hot water system can provide sufficient heating for a larger building in a cold climate and is more comfortable than a gas-fired furnace if radiators/convectors are used; however, it requires mechanical equipment to produce the hot water, and tubing to carry the hot water throughout the building. Steam heating systems can handle larger heating loads than hot water systems can, but the mechanical equipment is more complex and typically requires more maintenance.

4.4 VENTILATION

Ventilation is the circulation of fresh air into a building to replace stale air. It is an important part of maintaining the health of a building's occupants and users.[181] Ventilation also can help manage the indoor environment of a building. For instance, if the outdoor relative humidity is lower than the indoor relative humidity, the indoor air can be diluted with the drier outdoor air. Also, if the outdoor temperature is lower than the indoor temperature and there is a need for cooling, bringing in the cooler outdoor air will reduce the indoor temperature without the costs of operating the mechanical cooling

---

[181] Bobenhausen, *Simplified Design of HVAC Systems*, 94.

equipment. An *economizer* is a device connected to a cooling system that draws in cool outdoor air instead of running the system.[182]

In times past, buildings were designed to promote *natural ventilation*,[183] the exchange of air in the buildings openings that occurs naturally as a result of wind and temperature and air pressure differences.[184] Now, ventilation often is forced with mechanical equipment. In a historic building, a fan can be placed in an existing window, or, a new opening in the wall can be created for a fan. These fans will draw outdoor air into the building to freshen or dilute the indoor air. If a central cooling and/or heating system is used, the system typically will draw in outdoor air to mix with the return air (outdoor air that is mixed with return air is called *make-up air*[185]); this mixture then will be cooled or heated by the system and delivered to the building as supply air. At times, fans also are used to exhaust indoor air to the outdoors, such as in a kitchen or bathroom. Some buildings still rely on natural convection for their ventilation. A building that is not well-sealed and which has doors that constantly are being opened and closed may receive enough natural ventilation that mechanical ventilation is not necessary.[186]

4.5 HUMIDIFICATION PROCESSES AND EQUIPMENT

Humidification is the addition of water vapor to the air to increase the air's relative humidity. As stated in *Chapter 3: Why Manage the Indoor Climate?*, many historic materials will become brittle or begin to crack if the relative humidity falls below

---

[182] Peter S. Curtis. "Control Fundamentals," in *Handbook of Heating, Ventilation, and Air-Conditioning*, ed. Jan F. Kreider, 5-32.

[183] Padfield, "How Air-conditioning Works," 1.

[184] Bobenhausen, *Simplified Design of HVAC Systems*, 296.

[185] ASHRAE. *2005 ASHRAE Handbook – Fundamentals*, 27.2.

[186] Bobenhausen, *Simplified Design of HVAC Systems*, 95.

30% RH. Remembering psychrometrics, if a building is heated to a comfortable temperature in the winter (around 70°F), the relative humidity may fall far below the 30% RH threshold, causing damage to the historic fabric. A *humidifier* is used to add moisture to the indoor air in order to increase the indoor relative humidity to a level that the conservators have determined is safe for the historic materials. Humidifiers can be integrated into the central climate management system, or they can be stand alone units that are located inside the occupied spaces of the building.

There are five basic types of humidifiers. A steam humidifier boils water to create steam, which then flows into the indoor spaces.[187] An impeller humidifier has a rotating disc that throws water at a diffuser, which breaks the water into a mist that floats into the air.[188] An ultrasonic humidifier has a metal diaphragm covered with a thin film of water.[189] The diaphragm vibrates at an ultrasonic frequency, causing the water to float off as water vapor. An evaporative humidifier has a fan blow air through a water-soaked material.[190] The airflow causes the water to evaporate and enter the air stream. Because this type of humidifier causes evaporation, it has the side effect of cooling the air.[191] Finally, an atomizing humidifier has a fan blow air through a fine sheet of water. The air picks up the water as vapor.[192]

---

[187] Ellen M. Franconi and James B. Bradford. "Ventilation and Air Handling Systems," in *Handbook of Heating, Ventilation, and Air-Conditioning*, ed. Jan F. Kreider, 4-74.

[188] U.S. Environmental Protection Agency. "Indoor Air Facts No. 8: Use and Care of Home Humidifiers," (February, 1991). <http://www.epa.gov/iaq/pubs/humidif.html#Types%20of%20Humidifiers%20and%20Associated%20Pollutants> (3 March 2007).

[189] Ibid.

[190] Thomson, *The Museum Environment*, 96.

[191] Franconi and Bradford, "Ventilation and Air Handling Systems," 4-74.

[192] Ibid., 4-74.

4.6 DEHUMIDIFICATION PROCESSES AND EQUIPMENT

High indoor relative humidity is a common problem during the summer in air-conditioned buildings. Remember that mold growth is likely above 70% RH. Using psychrometrics, when warm air with a high moisture content is cooled and the moisture content does not change, the relative humidity increases. To address this problem, dehumidification often is used. As stated, the process of cooling the air can cause dehumidification if the air is cooled below the dewpoint, and some historic buildings and museums use the cooling equipment for dehumidification. However, it may be deemed necessary to use supplemental dehumidification; or, a site may not have cooling equipment, and a *dehumidifier* may be used.

There are two basic different types of dehumidifiers. A desiccant dehumidifier draws air through a desiccating material, which absorbs moisture from the air.[193] This approach has the drawback of particulate from the desiccant entering the air stream.[194] An alternative approach is to use a refrigerant dehumidifier, also called a hot-gas re-heat dehumidifier. A refrigerant dehumidifier uses the direct expansion process that was described earlier – there is a condensing coil, an expansion valve, an evaporating coil, and a compressor. When used for air-conditioning, the supply air is blown over the evaporating coil, which cools and dehumidifies the air. Outdoor air is blown over the condensing coil to draw heat from the refrigerant. When used for dehumidification, the supply air first is blown over the evaporating coil, again for cooling and dehumidification, then it blows over the condensing coil, which warms the air before

---

[193] Thomson, *The Museum Environment*, 97.
[194] Ibid., 98.

delivering it to the occupied spaces.[195] No outside air is used. This approach requires the condensate to be drained away from the evaporating coil, or a reservoir to collect the condensate which must be emptied periodically.

4.7 CONCLUSION

The basic processes and equipment for heating, cooling, ventilation, humidification, and dehumidification have been described. Any museum or historic site may use all of these processes, or only some, to mange the indoor environment. The selection of the equipment used is a function of the heating and cooling loads on the building, the needs of the collection or historic materials, available space for the equipment, and the funds available to purchase, install, and operate the equipment. This study will investigate sites where the climate management system ranges from no climate management at all, to a sophisticated system that uses all of these processes to maintain tight control over the indoor conditions.

---

[195] Ibid., 99-100.

CHAPTER 5: METHODOLOGY FOR THIS STUDY

5.1 PURPOSE AND HYPOTHESIS

As stated, the purpose of this study is to analyze different forms of climate management in historic buildings and museums to see if there is a mathematical relationship between the level of environmental control and the energy costs and consumption necessary to operate the climate management system in such buildings. The hypothesis is that allowing a wider range of indoor conditions will result in lower energy costs and consumption. Many authors make this claim, but few provide data to support their assertion (see *Chapter 2: Literature Review*).

This thesis will not attempt to compare the sites based upon whether or not their indoor environments are beneficial to the preservation of historic building fabric or a collection. Though recent research has shown that it often is not necessary to maintain tight control over the indoor environment (see *Chapter 2: Literature Review*), few researchers have taken the next step of investigating how much money and energy can be saved by allowing a wider range of indoor conditions. This thesis will be an early step in that direction.

5.2 SELECTION OF SITES

Thirteen historic sites and museums were contacted to ask if they would be willing to take part in this study. These thirteen sites represented a variety of climate management systems in a variety of building types. Some of the sites were comprised of multiple buildings using different forms of climate management, allowing them to serve as multiple sites. In order to minimize the influence of variation in climatic conditions between the sites, all but one of the sites that were contacted are located in either the mid-Atlantic or northeastern regions of the United States. To be able to determine the energy costs associated with the different climate management systems, it was necessary for the different buildings each to be on their own power meter and to have climate management systems that only serve that one building. It was intended that ten buildings in total would be investigated for this investigation. Of these thirteen sites, ten agreed to provide data and information. Two of these ten sites encompass multiple buildings, which would have lead to at least fifteen different buildings being available for study.

To perform the analysis of their indoor climate and energy costs and consumption, the sites needed to be able to provide monitoring data and energy bills for a twelve month period (the required data is described in more detail in the following section). Unfortunately, while these ten site managers were so kind as to offer to be a part of this thesis, two of the sites had power meters or climate management systems that served multiple buildings, two of them either did not perform monitoring of their indoor climate or lost their monitoring data, and one was not able to provide energy bills in the time available. Therefore, a total of five historic sites and museums are investigated for this thesis. These five sites represent a variety of climate management systems in different types of buildings, from one clapboard building that has no climate management at all to two sites that have sophisticated, yet different systems that attempt to maintain tight control over the indoor climate in modern, purpose-built museums. All sites are located either in the mid-Atlantic or northeastern region of the country, making it easier to control for the effects of the outdoor climate on the indoor conditions.

Financial data can be sensitive for any organization, so the anonymity of the sites and their managers is provided by referring to them by letter: Sites A, B, C, D, and E. Without the assistance of the sites' managers, facilities engineers, and other staff this study would not have been possible. They all have the author's utmost gratitude.

5.3 COLLECTION OF DATA AND INFORMATION

As stated, each site was asked to provide monitoring data and energy bills for a twelve month period. This length of time was selected because it covers all four seasons, and because one year's worth of data is manageable in the time provided for this study. The sites also were asked to provide the original construction dates of their buildings, the dates of any major alterations, the current function of their buildings, the construction of the building envelope, the total floor area of the building, their operating hours, and the type of climate management system they use.

All sites provided this information, but some were able to provide more detail than others. The descriptions of the sites in Appendices A, B, C, D, and E reflect the level of detail that the managers were able to provide. Also, different sites performed monitoring in different ways, some recorded the indoor conditions once every thirty minutes, some every hour, and some once per day. Most used data loggers, which record the temperature and relative humidity at set intervals, though one site recorded the data manually. Again, how each site monitored their indoor climate is explained in the chapter that specifically addresses that site.

The energy bills provided by the sites were both for electricity and, if applicable, the form of fossil fuel they used for heating – natural gas or heating oil. While each site was able to provide energy bills for a twelve month period, most sites were not able to exactly match the period of the provided monitoring data. Often, the two would be misaligned by one month, requiring certain assumptions and adjustments to be made regarding the energy costs and consumption for each site. In the appendices that detail each site individually, those assumptions and adjustments are explained. Only one site was able to provide the actual energy costs and consumption that specifically went to its climate management system; for the others, certain assumptions and adjustments were needed to estimate what percentage of their energy costs and consumption went to their climate management systems. Again, those assumptions and adjustments are explained in the appendices.

The number of heating degree days and cooling degree days for each month (referred to as the engineering climate data) for the period under consideration for each site were obtained from the National Climatic Data Center website.[196] Degree days are defined as the difference between a day's average temperature and 65°F. If the average temperature is below 65°F, the difference is called *heating degree day*s. If the average temperature is above 65°F, the difference is called *cooling degree days*.

---

[196] National Climatic Data Center website: http://www.ncdc.noaa.gov/oa/mpp/freedata.html

5.4 ANALYSIS OF DATA AND INFORMATION

5.4.1 Classification of the Buildings

ASHRAE has created guidelines for what form of climate management, and what bounds of temperature and relative humidity are reasonable for different types of buildings (see Tables 2 and 3). The first step in this analysis was to classify each building according to those guidelines. Doing so provided a rough framework for the indoor environment one reasonably could expect for each site.

5.4.2 Division of the Seasons

The engineering climate data was used to determine the duration of the seasons for each site. The term season does not refer to the typical winter, spring, summer, and fall, but to the heating, cooling, and mixed season. The heating season is comprised of the months in which there is a significantly higher number of heating degree days than cooling degree days, essentially, that it is cold outside and there is a need for heating. The cooling season encompasses the months in which there is a significantly higher number of cooling degree days than heating degree days; during these months it is hot outside, and there is a need for cooling. The mixed season is comprised of the months in which there are a significant number of heating and cooling degree days, indicating that there is a need for both heating and cooling during those months. The mixed season months typically occur in the spring and in the fall, when the outdoor climate is more dynamic.

Because some of the sites changed their form of climate management for the different seasons, or did not use any form of climate management during particular seasons, the monitoring data and energy costs and consumption were analyzed separately for each season. Analyzing the sites in this way revealed how the different forms of climate management perform during the individual seasons.

5.4.3 Analysis of the Indoor Climate Data

Most sites recorded the indoor conditions in more than one location in their building. To establish the average indoor temperature for a season, the average of all recorded values for the indoor temperature in all locations for that site for each season was calculated. The same procedure was used to calculate the average indoor relative humidity for each season. It must be understood that the calculations of the average indoor conditions are not weighted for the sizes of the different rooms in which the data loggers are located, and are meant to represent the indoor conditions solely for comparative purposes.

To establish the variance of the indoor conditions, the standard deviation of the entire indoor temperature or relative humidity record for each season was calculated. According to statistics, 95% of the data points in a record typically are within two standard deviations of the average value.[197] This distribution is illustrated in Figure 5. Taking 95% of the values to represent the variance of the indoor climate matches well with previously published recommendations. Cassar[198] states that 90% of the data for temperature and relative humidity should be considered representative of the indoor

---

[197] Stephanie Bell. *Measurement Good Practice Guide No. 11(Issue 2): A Beginners Guide to Uncertainty of Measurement*. (Teddington: National Physical Laboratory, 2001), 5.
[198] Cassar, *Environmental Management*, 70 – 71.

climate for a site, and Ashley-Smith, Umney, and Ford[199] assert that 95% of the data for temperature and relative humidity are indicative of a site's indoor climate. For both, the data points that are disregarded are on the extremely high or extremely low end. Because the recommendation of letting 95% of the recorded values represent the indoor climate elegantly equals two standard deviations, two standard deviations are used to determine the variance of the indoor conditions. Therefore, multiplying the standard deviation for the temperature or relative humidity by two gives the variance of the indoor conditions for a particular season.

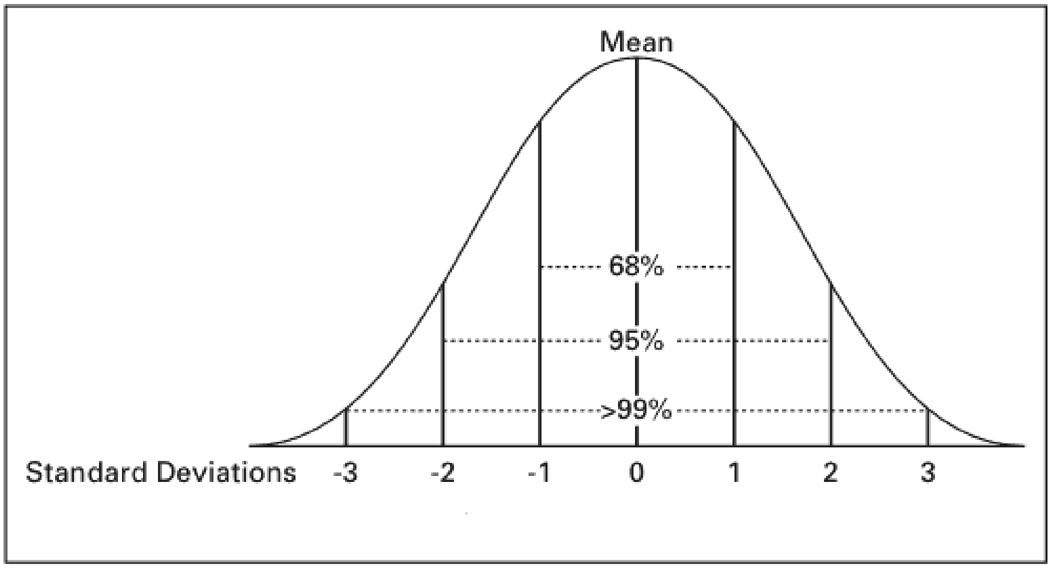


Figure 5: Normal Distribution with Standard Deviations (source: <http://homepages.ius.edu/JAKARNOL/T-102%20Lesson%208.2%20S'06_files/image016.gif> (17 April 2007)).

To establish the annual average indoor temperature or relative humidity, and the annual variance of those properties, the same procedure was used; however, in this case, the entire 12 month period's record for each site was used to calculate these values.

---

[199] Ashley-Smith, Umney and Ford. "Let's Be Honest – Realistic Environmental Parameters for Loaned Objects," 29.

5.4.4 Analysis of the Energy Expenditures for the Individual Sites

First, the energy costs and consumption of electricity and fossil fuels (when applicable) were totaled separately for each season. For each site, assumptions and adjustments were made to estimate the percentage of the total cost and consumption of electricity and fossil fuel that went to the climate management system. These assumptions and calculations varied for each site, and are explained fully in the appendices that analyze the sites individually.

Once the costs and consumption of electricity and fossil fuel that went to the climate management system for each season were calculated, these values were divided by the total floor area of the building to determine the cost and consumption of electricity and fossil fuel per square foot. As one would expect a larger building to use more energy than a smaller building, this action controlled for the differences in size between the buildings.

After the costs and consumption of electricity and fossil fuel per square foot for each season were calculated, these values were divided further by the total number of degree days divided by 100 for that season to determine the electricity and fossil fuel cost and consumption per square foot per 100 degree days. During the heating season, only the heating degree days were used for this calculation, and, for the cooling season, only the cooling degree days were used. For the mixed season, the total number of degree days, both heating and cooling, were used for this calculation, as it is expected that both heating and cooling would be used. If a site only used heating (i.e. no air-conditioning system to provide cooling) or only used cooling or ventilation (i.e. no heating system) during the mixed season, either only the heating degree days or the cooling degree days, respectively, were used for this calculation. Determining the energy costs and consumption per square foot per 100 degree days for the season controlled for the differences in outdoor climate that the sites experienced, and for differences in the lengths of the seasons.

To be able to compare the different site's energy consumption fairly, the fossil fuel consumption was converted to kilowatt-hours (kWh). The different conversion factors that were used for each fuel type are noted in the appendices that analyze the sites individually.

To determine the total cost for climate management for each season, the total costs of electricity and fossil fuel were added together. To determine the total cost per square foot, the cost of electricity and the cost of fossil fuel per square foot were added together. The total cost per square foot per 100 degree days was calculated by adding the costs of electricity and fossil fuel per square foot per degree day.

To determine the total energy consumption for climate management for each season the same procedure described above was used, substituting energy consumption for cost. To be able to combine the consumption for different forms of energy, the consumption in units of kWh was used.

5.5 COMPARATIVE ANALYSIS OF ALL SITES

First, the sites will be compared based upon their energy costs and consumption and the level of control over the indoor conditions they exerted for each individual season. For each season, four graphs will be created, which plot the following information for all five sites: 1) the energy costs per square foot versus the variance of the indoor temperature and relative humidity, 2) the energy consumption per square foot versus the variance of the indoor temperature and relative humidity, 3) the energy costs per square foot per 100 degree days versus the variance of the indoor temperature and relative humidity, and 4) the energy consumption per square foot per 100 degree days versus the variance of the indoor temperature and relative humidity. For all graphs, the energy cost or consumption is located on the y-axis and the variance of the temperature and relative humidity are located on the x-axis. On each graph, trendlines will be created to better illustrate the relationship between energy expenditures and the level of environmental control.

These four plots allow four different comparisons of the energy costs and consumption versus the level of environmental control for the sites of this study. It is likely that the greatest concern of site managers is the energy costs per square foot versus the level of environmental control, as they need to know what level of control they reasonably can afford. However, energy is charged at different rates in different locations; by providing the energy consumption per square foot versus the level of control, a more accurate appraisal of the energy expenditure for each site will be provided. This information can be used to determine the energy costs associated with a level of control for a given site by multiplying this value by the local rate at which energy is charged. Also, in an era where energy conservation is a major concern, the plot of energy consumption per square foot versus the level of control will reveal the energy savings that may result from allowing a greater variance of the indoor conditions.

By dividing the energy consumption and costs by the degree days each site experienced for each season, the differences in outdoor climates and the differences in the duration of the seasons are controlled. This analysis allows a more accurate comparison of the energy costs and consumption versus the level of control. The plots of the energy consumption per square foot per 100 degree days also allows a comparison of how much work the different systems had to perform to obtain their level of control. Again, this comparison will reveal the potential energy savings that may be possible by increasing the variance of the indoor conditions in a given climate.

The sites also will be compared on an annual basis. To obtain the data for the annual comparisons, weighted averages, based upon the duration of the seasons, of the energy costs and consumption will be calculated for each site. As explained earlier, the variance of the indoor conditions for each site will be based upon two standard deviations of each site's record of those properties for the entire twelve month period. While not giving an entirely accurate appraisal of the annual energy expenditures and level of control, these calculations do provide data that allow useful comparisons between the sites. Again, four types of graphs of the annual data will be created: 1) the energy costs per square foot versus the variance of the indoor temperature and relative humidity, 2) the energy consumption per square foot versus the variance of the indoor temperature and relative humidity, 3) the energy costs per square foot per 100 degree days versus the variance of the indoor temperature and relative humidity, and 4) the energy consumption per square foot per 100 degree days versus the variance of the indoor temperature and relative humidity. For the annual comparisons, graphs will be created that show the variance of the indoor temperature and relative humidity on the same graph, then graphs will be created that show only the variance of the indoor temperature or relative humidity. For the graphs that show only the variance of the temperature or relative humidity, the ASHRAE classes of control over these properties, shown in Table 3, will be displayed on the graphs to give an indication of the annual energy expenditures a site can expect to incur for a given ASHRAE class of control over temperature or relative humidity.

The four ways in which the annual data will be compared will allow the same comparisons as the graphs created for the individual seasons do, but here the comparisons are on an annual basis. To further clarify the relationship between energy costs and consumption, two more types of graphs will be created. These graphs will plot the normalized energy costs and consumption versus the variance of the temperature and relative humidity for each site. Again, graphs will be created that show the variance of the temperature and relative humidity together, and graphs will be created that show only the variance of the indoor temperature or of the relative humidity with the ASHRAE classes of control for these properties noted on the graphs. The data will be normalized by dividing the costs and consumption pre square foot for all sites by the costs and consumption for Site B. By normalizing the data, one can see the factor by which costs or consumption increase as the control of the indoor conditions becomes tighter, and the factor by which energy expenditures increase to obtain a higher ASHRAE class of control.

Finally, four graphs will be created for each site individually. As before, these graphs will plot: 1) the energy costs per square foot versus the variance of the indoor temperature and relative humidity, 2) the energy consumption per square foot versus the variance of the indoor temperature and relative humidity, 3) the energy costs per square foot per 100 degree days versus the variance of the indoor temperature and relative humidity, and 4) the energy consumption per square foot per 100 degree days versus the variance of the indoor temperature and relative humidity. However, unlike the other graphs, these graphs will show the data for all three seasons on one graph. By presenting the data in this way, one can easily see the seasons in which each site incurred the greatest energy costs and consumption, and in which seasons each site incurred the least energy costs and consumption. For a site manager in a building similar to one of these sites with a similar climate management system, these graphs will reveal the season in which he or she can expect the greatest and the least costs for a given level of control, and the season in which the climate management system must perform the most work to manage the indoor climate.

CHAPTER 6: COMPARISON OF ALL SITES

6.1 FORMAT FOR ANALYSIS

First, the sites included in this study will be compared for each individual season (heating, cooling, and mixed). As some of the sites altered their form of climate management depending upon the season, these seasonal comparisons will be instructive as to how the different forms of climate management performed regarding the level of environmental control they provided and the energy costs and consumption they required for each season. For each season, the sites will be compared based upon the following four criteria: 1) the energy costs per square foot versus the variance of the indoor temperature and relative humidity, 2) the energy consumption per square foot versus the variance of the indoor temperature and relative humidity, 3) the energy costs per square foot per 100 degree days versus the variance of the indoor temperature and relative humidity, and 4) the energy consumption per square foot per 100 degree days versus the variance of the indoor temperature and relative humidity. For all graphs, the energy cost or consumption is located on the y-axis and the variance of the temperature and relative humidity are located on the x-axis. The orange points and trendlines represent the variance of the indoor temperature, and the blue points and trendlines represent the variance of the indoor relative humidity. A horizontal black bar labeled with the site’s identification connects the variance of the temperature and the relative humidity for each site. Not that the vertical scales on the graphs change for each season to improve the legibility of the graphs.

The second part of this analysis will compare the sites based upon the annual energy costs and consumption versus the level of environmental control. To obtain the annual values for energy costs and consumption, weighted averages for each of these values will be calculated. As when the sites were compared for the individual seasons, for the annual comparisons the following four criteria will be used: 1) the energy costs per square foot versus the variance of the indoor temperature and relative humidity, 2) the energy consumption per square foot versus the variance of the indoor temperature and relative humidity, 3) the energy costs per square foot per 100 degree days versus the variance of the indoor temperature and relative humidity, and 4) the energy consumption per square foot per 100 degree days versus the variance of the indoor temperature and relative humidity. The layout of the graphs will be the same as when the sites were compared for each individual season. For the annual comparisons, graphs that plot the energy expenditures versus the level of control will be created that show the variance of the temperature or relative humidity individually, so that comparisons can be made to ASHRAE's classes of environmental control.

Third, the results for each site will be presented individually. The energy costs and consumption will be plotted against the variance of the indoor temperature and relative humidity, with all three seasons appearing on one graph. This analysis will show which season required the greatest energy expenditure for each site, and will compare the level of environmental control for each site for each season. For these graphs, a black bar connects the variance of the temperature and relative humidity for each season.

For all sites, the calculations of the variance of the indoor temperature and relative humidity and the energy costs and consumption are presented in Appendices A, B, C, D, and E. In this chapter, only the results of those calculations are discussed and analyzed.

The following points must be made regarding the variance of the indoor temperature and relative humidity discussed in this chapter. Site A only recorded the indoor conditions once per day during the period of this study. While the data do give some indication of the indoor climate, they do not include how the indoor environment of the site changes over the course of a day. In a building with no insulation, no vapor barrier, and with no climate management system, one would expect the indoor climate to change over the course of a day as the outdoor climate changes, giving a wider range of indoor temperature and relative humidity. By taking a reading only once per day, this wider range is not recorded, and it is likely that the variance for temperature and relative humidity presented here are smaller than their true values.

To some extent the same holds true for Site E, which also only recorded the indoor conditions once per day, as well as missing monitoring data for the month of February 2005 and several dates scattered throughout the year. However, Site E's buildings do contain insulation and a vapor barrier in the building envelope, and the climate management system is designed to maintain constant indoor conditions. Therefore, it is likely that the indoor environment of Site E did not vary as much from the data presented here as it did for Site A, but without an hourly record of the indoor climate it is impossible to know the true variance of the indoor conditions for this site.

6.2 THE HEATING SEASON

The indoor climate data and energy costs and consumption for the heating season for all sites are presented in Table 4. As explained in *Chapter 5: Methodology for this Study*, two standard deviations, representing 95% of the recorded values, were used to determine the variance of the indoor temperature and relative humidity. Remember that site A does not use any form of climate management, making its energy costs and consumption zero.

Variance, Costs, and Consumption for All Sites During the Heating Season

Site	Temperature Variance (°F)	Relative Humidity Variance (%RH)	Cost/ft^2	Consumption (kWh/ft^2)	Cost/(ft^2-100 degree days)	Consumption (kWh/(ft^2-100 degree days))
Site A	28	12	$0	0	$0	0
Site B	14	22	$0.26	6.6	$0.0058	0.14
Site C	12	24	$0.61	12.4	$0.011	0.22
Site D	4	10	$3.20	38.1	$0.059	0.70
Site E	4	6	$7.89	83.7	$0.13	1.4

Table 4: Variance, Costs, and Consumption for All Sites During the Heating Season.

Figure 6 displays the energy costs per square foot plotted against the variance of the indoor temperature and relative humidity for all sites during the heating season. The graph shows that as the variance of the indoor temperature or relative humidity became larger, the energy costs per square foot decreased exponentially.

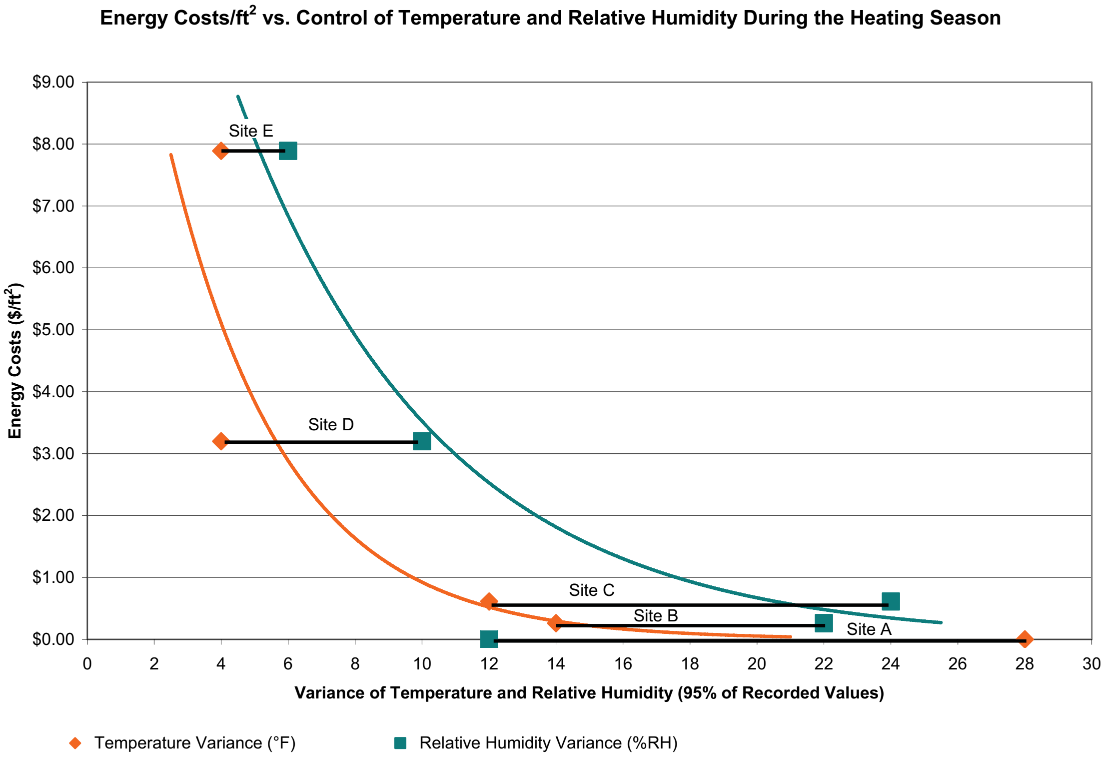


Figure 6: Energy Costs per Square Foot vs. Control of Temperature and Relative Humidity for All Sites During the Heating Season.

Figure 7 illustrates the energy consumption pre square foot plotted against the level of environmental control for all sites during the heating season. The result for this comparison closely mimics the plot of costs versus level of control. Again, the energy consumption decreased exponentially as the variance of the indoor conditions increased.

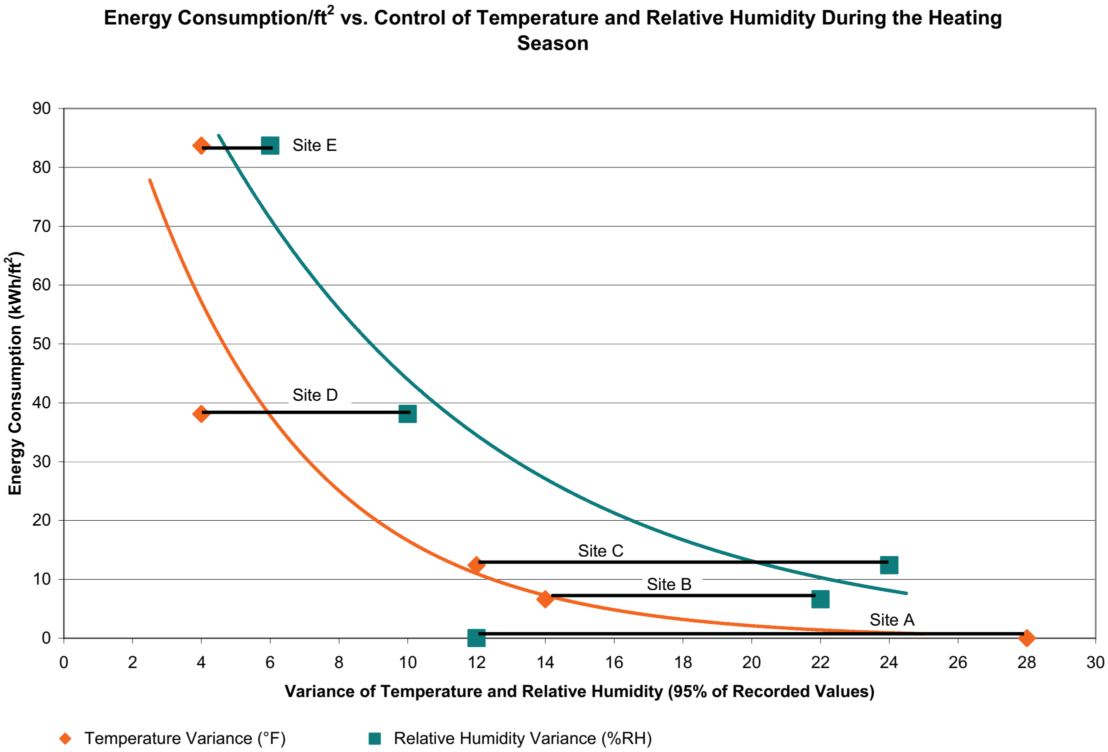


Figure 7: Energy Consumption per Square Foot vs. Control of Temperature and Relative Humidity for All Sites During the Heating Season.

To control for differences in outdoor climate, the energy costs and consumption per square foot were divided by the total number of heating degree days for the heating season, divided by 100. Figure 8 is a plot of the energy costs per square foot per 100 heating degree days versus the level of control for all sites during the heating season. Again, this plot shows that the energy costs of climate management decrease exponentially as the variance of the indoor temperature and relative humidity are made larger.

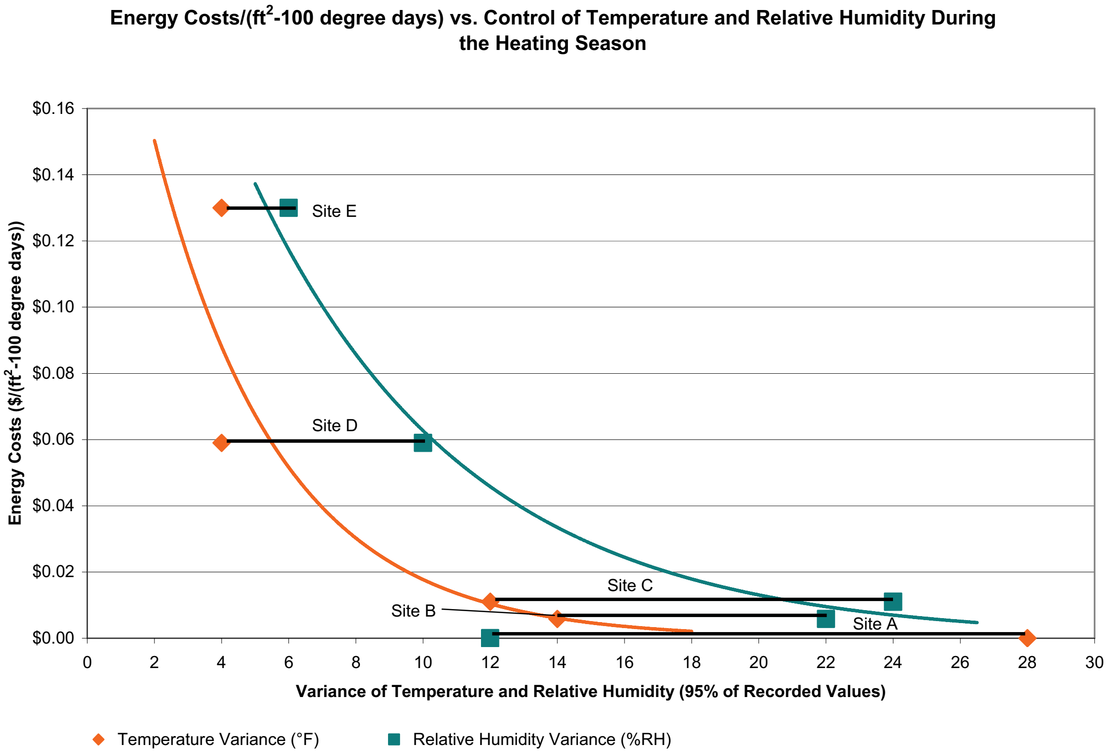


Figure 8: Energy Costs per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Sites During the Heating Season.

The last graph for the heating season, Figure 9, plots the energy consumption per square foot per 100 degree days against the level of environmental control for all sites for the heating season. This figure mimics the other graphs for the heating season, in that the energy consumption per square foot per 100 degree days decreases exponentially as the variance of the indoor conditions increases.

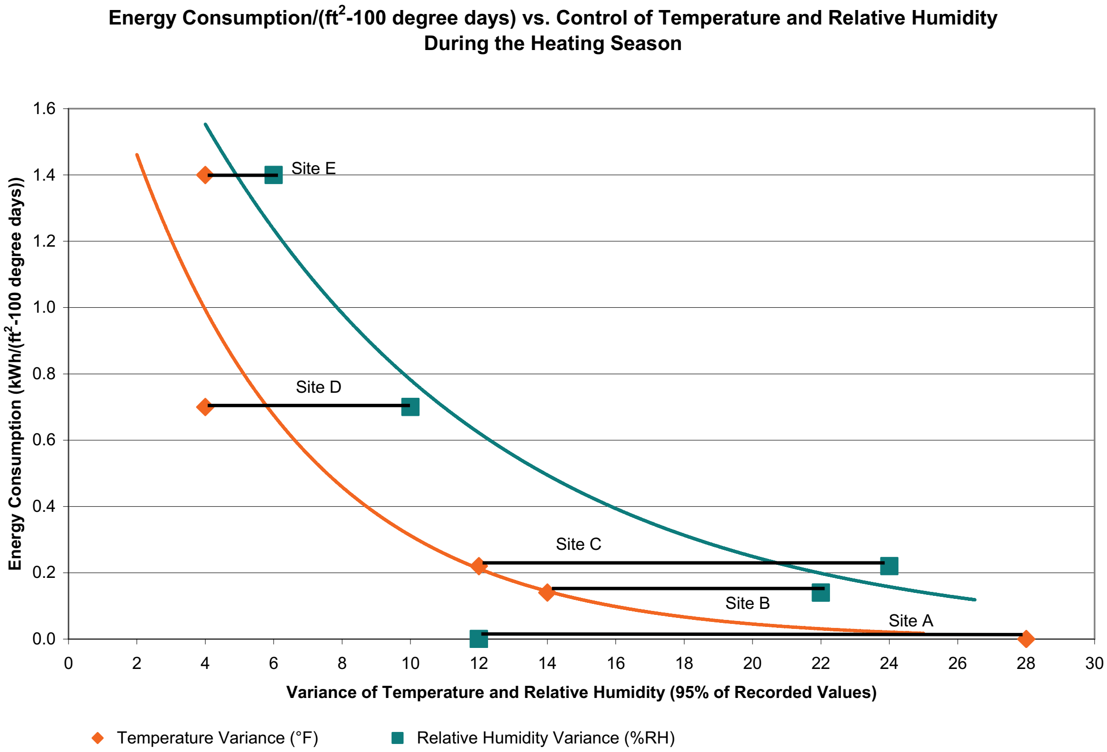


Figure 9: Energy Consumption per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Sites During the Heating Season.

Overall, the results for the heating season consistently indicate that there is an exponential relationship between the energy costs and consumption for climate management and the level of environmental control during the heating season. Across all four graphs, as the variance for the indoor conditions increase, the energy costs and consumption decrease exponentially. This result held true even after controlling for differences in the outdoor climate for each site.

An interesting comparison from these results is between Sites B and C, both of which only use heating in the winter. Though Site C spent more for energy and consumed more energy for every metric calculated, Site C had less control of the indoor relative humidity, but greater control of the indoor temperature. Perhaps this result comes from Site C operating their heating system for human comfort rather than to maintain a specific preservation environment, though two data points are not enough to make this claim with great confidence. Other factors could account for this difference, such as the fact that Site B uses heating oil for heat while Site C uses natural gas, or one building may allow more infiltration and exfiltration than the other.

An interesting observation is that Site A was the only site to exhibit a wider variance of the indoor temperature than of the indoor relative humidity. Because Site A is only one site and it only recorded the indoor conditions once per day it is difficult to make any broad conclusions regarding its indoor climate, but this result indicates that it may be possible that a site with no climate management will experience a greater temperature fluctuation than relative humidity fluctuation.

6.3 THE COOLING SEASON

Because Site A did not experience a true cooling season during the period of study, it is not included in this section. The indoor climate data and energy costs and consumption for the cooling season for all sites are presented in Table 5 Remember that Site C did not use any form of climate management during the cooling season, making its energy costs and consumption zero for this period.

Variance, Costs, and Consumption for All Sites During the Cooling Season

Site	Temperature Variance (°F)	Relative Humidity Variance (%RH)	Cost/ ft^2	Consumption (kWh/ft^2)	Cost/(ft^2-100 degree days)	Consumption (kWh/(ft^2-100 degree days)
Site A	*	*	*	*	*	*
Site B	12	18	$0.0030	0.042	$0.00036	0.0049
Site C	10	16	$0	0	$0	0
Site D	4	10	$1.43	17.2	$0.22	2.7
Site E	4	6	$3.10	35.7	$0.39	4.5

*Site A did not experience a cooling season during the period of this study.

Table 5: Variance, Costs, and Consumption for All Sites During the Cooling Season.

Figure 10 shows the energy costs per square foot plotted against the variance of the indoor temperature and relative humidity. Note that the costs per square foot for Site B appear to be zero on this graph, though Site B actually spent $0.0030.ft^2. As with the heating season, the energy costs decreased exponentially of the variance of the indoor conditions increased. When compared to the heating season, it is interesting to note that for all sites the energy costs pre square foot were much lower for the cooling season than they were for the heating season. Of course, to some extent, this result can be attributed to the fact that, for all sites, the cooling season was much shorter than the heating season.

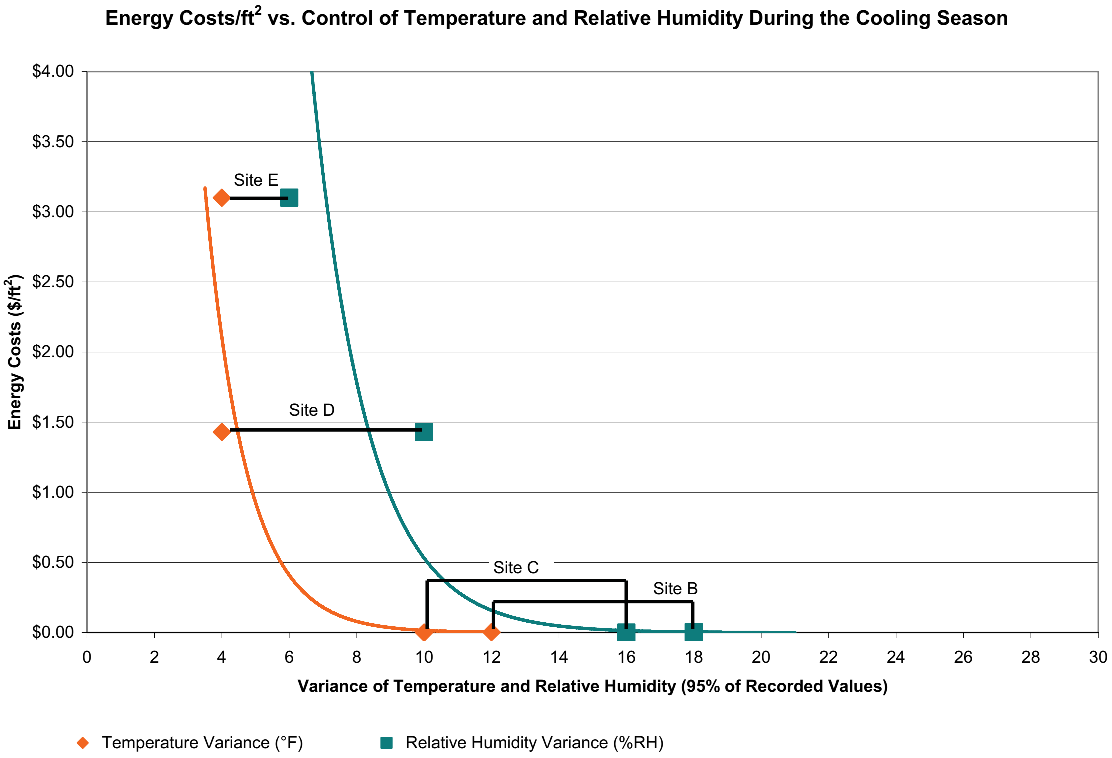


Figure 10: Energy Costs per Square Foot vs. Control of Temperature and Relative Humidity for All Sites During the Cooling Season.

Figure 11 is a plot of the energy consumption per square foot versus the level of control of the indoor environment for all sites during the cooling season. Note that Site B consumed 0.042 kWh/ft^2, though its consumption appears to be zero on this graph. Again, the energy consumption decreased exponentially as the variance of the indoor temperature and relative humidity increased. When compared to the heating season, all sites also consumed less energy per square foot during the cooling season.

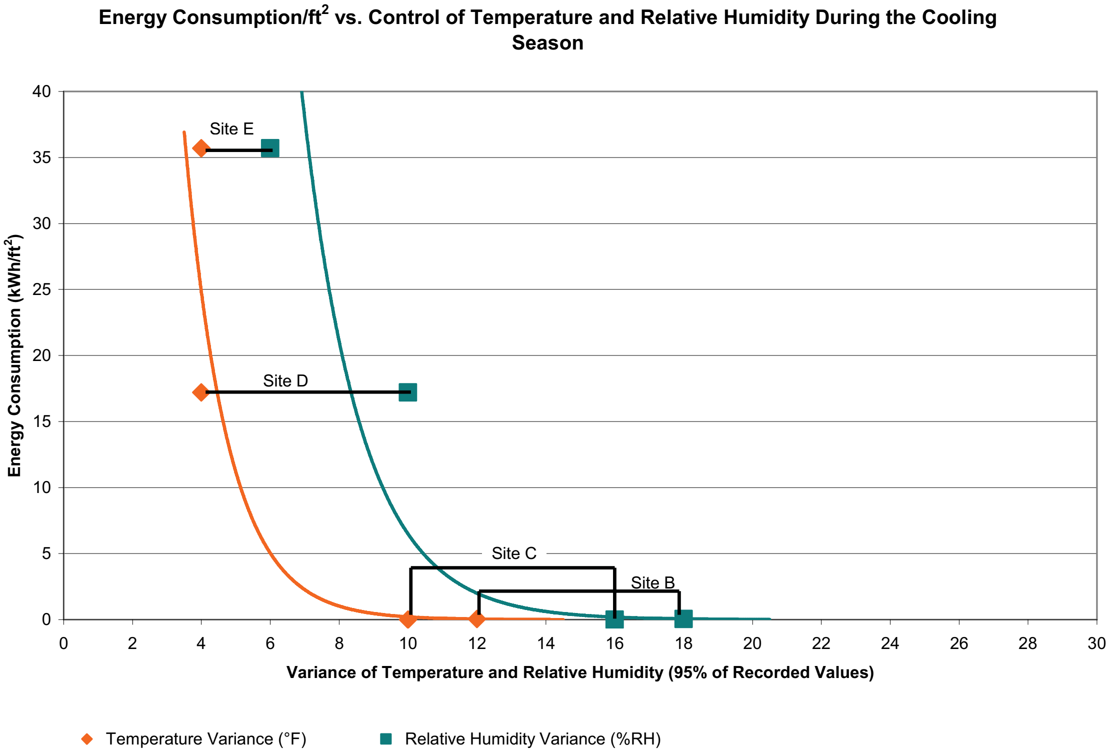


Figure 11: Energy Consumption per Square Foot vs. Control of Temperature and Relative Humidity for All Sites During the Cooling Season.

Figure 12 is a plot of the energy costs per square foot per 100 cooling degree days versus the level of control for the cooling season. Note that Site B spent \$0.00036/(ft^2-100 degree days), though its costs appear to be zero on this graph. Again, the energy costs decreased exponentially as the variance of the indoor temperature and relative humidity increased. This graph shows an interesting result when compared to the heating season. While the energy costs per square foot were greater for Sites D and E during the heating season, the energy costs per square foot per 100 degree days for the cooling season for these sites were greater, though each site maintained a similar level of control for both seasons. This result indicates that sites that maintain constant year-round indoor conditions will spend more for energy per degree day during the cooling season than they will during the heating season, indicating that the system has to perform more work to maintain the indoor climate. Site B, which only uses ventilation during the cooling season, spent less for energy during the cooling season than it did for the heating season.

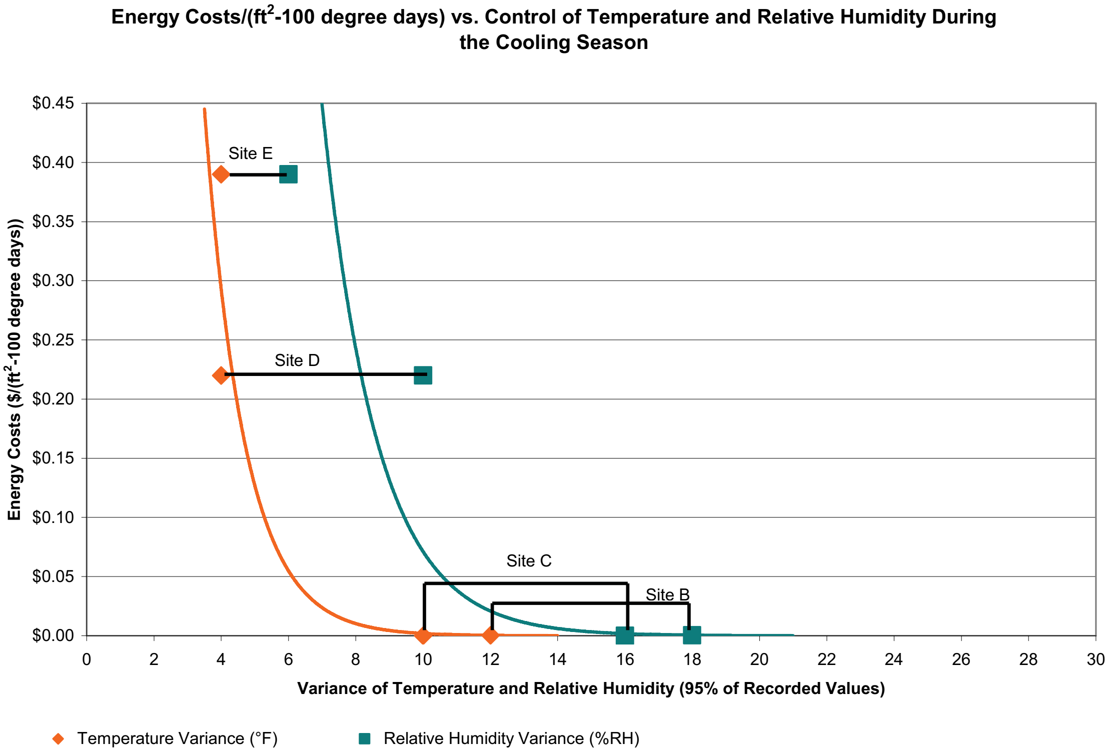


Figure 12: Energy Costs per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Sites During the Cooling Season.

Figure 13 shows the energy consumption per square foot per 100 cooling degree days plotted against the level of control for the cooling season for all sites. Note that Site B's consumption appears to be zero on this graph, though it actually was 0.0049 kWh/(ft^2-100 degree days). Again, the energy consumption decreased exponentially as the variance of the indoor conditions increased. Again, Sites D and E consumed more energy per square foot per 100 degree days during the cooling season than they did during the heating season, and Site B consumed less.

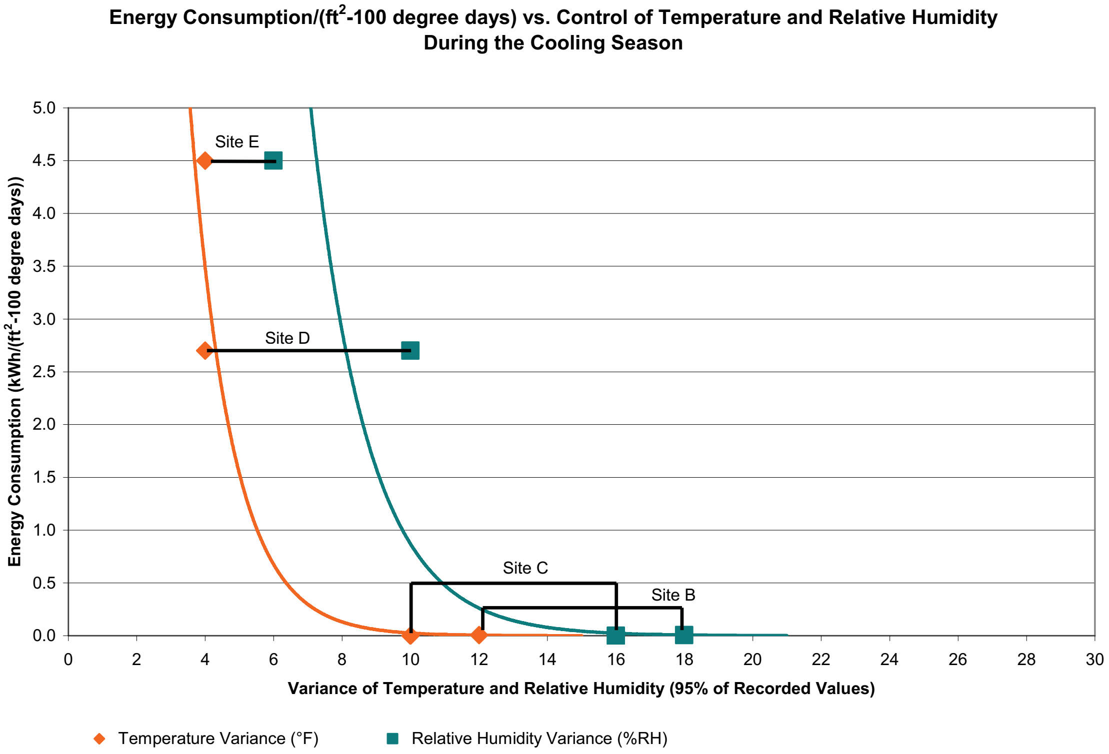


Figure 13: Energy Consumption per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Sites During the Cooling Season.

Overall, as with the heating season, the results displayed on all four graphs for the cooling season indicate that there is an exponential relationship between energy costs and consumption and the level of environmental control. Through all metrics used, the energy costs and consumption for climate management decrease exponentially as the variance of the indoor temperature and relative humidity increase.

Though the energy costs and consumption per square foot for Sites D and E were lower during the cooling season than they were during the cooling season, when divided by the number of degree days the energy consumption and costs during the cooling season were greater, though each site maintained a similar level of control for both seasons. For Site B, the costs and consumption always were lower during the cooling season. These results indicate that a site that attempts to maintain constant conditions will have a greater energy expenditure per degree day during the cooling season than they will during the heating season, and that a site that allows a wider range of conditions may be able to spend less per degree day during the cooling season.

Site C, which uses no form of climate management during the cooling season, maintained greater control over both the indoor temperature and the indoor relative humidity than did Site B, which uses ventilation for climate management during the cooling season. This result is interesting, because it suggests that no climate management is better than ventilation for the cooling season. However, one should not immediately jump to that conclusion, as many factors, such as differences in the outdoor climate, or the fact that Site B is a free standing building while Site C is a row house with adjacent houses on both sides, could account for this difference.

6.4 THE MIXED SEASON

The indoor climate data and energy costs and consumption for the mixed season for all sites are presented in Table 6. Remember that Sites A and C did not use any form of climate management during the mixed season, making their energy costs and consumption zero.

Variance, Costs, and Consumption for All Sites During the Mixed Season

Site	**Temperature Variance (°F)**	**Relative Humidity Variance (%RH)**	**Cost/ft^2**	**Consumption (kWh/ft^2)**	**Cost/(ft^2-100 degree days)**	**Consumption (kWh/(ft^2-100 degree days))**
Site A	12	14	$0	0	$0	0
Site B	10	18	$0.0090	0.26	0.0049	0.15
Site C	6	18	$0	0	$0	0
Site D	2	10	$0.41	4.7	$0.30	3.5
Site E	2	6	$1.04	10.3	$0.60	6.1

Table 6: Variance, Costs, and Consumption for All Sites During the Mixed Season.

Figure 14 is a plot of the energy costs pre square foot versus the level of environmental control for all sites during the mixed season. As occurred during the heating and cooling season, the energy costs per square foot decreased exponentially as the variance of the indoor temperature and relative humidity increased. When compared to the heating and cooling season, then energy costs per square foot for the mixed season were much less, which would be expected as the mixed season was the shortest season for all sites.

Figure 15 is a plot of the energy consumption per square foot versus the level of environmental control for all sites during the cooling season. As with the energy costs, the energy consumption per square foot decreased exponentially as the variance of the temperature and relative humidity increased. Again, the energy consumption per square foot for the mixed season was less than for the heating and the cooling seasons.

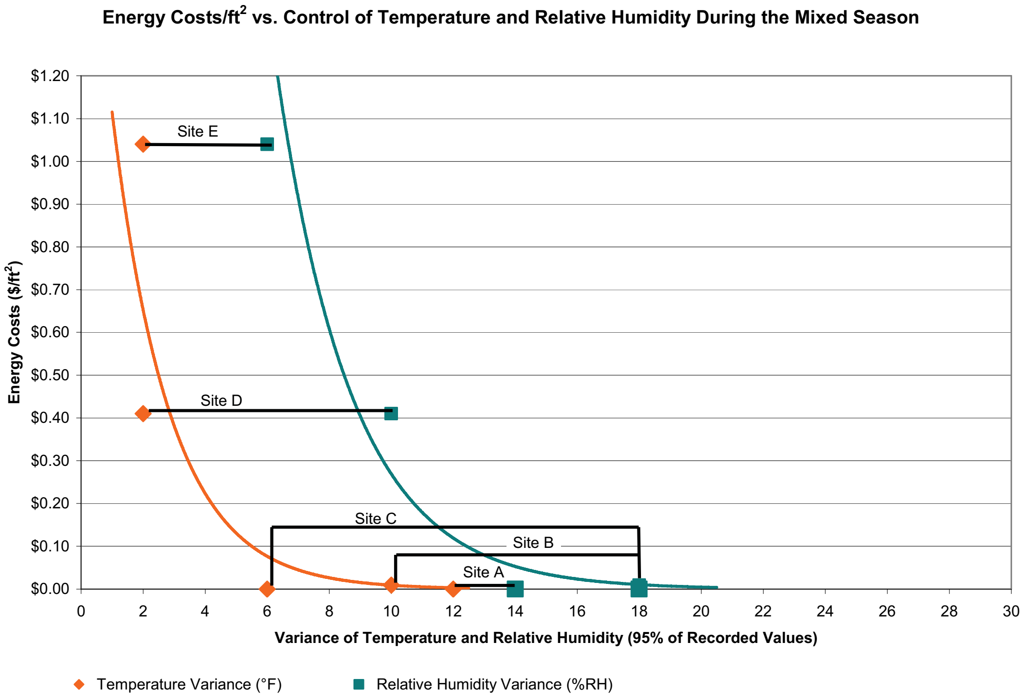


Figure 14: Energy Costs per Square Foot vs. Control of Temperature and Relative Humidity for All Sites During the Mixed Season.

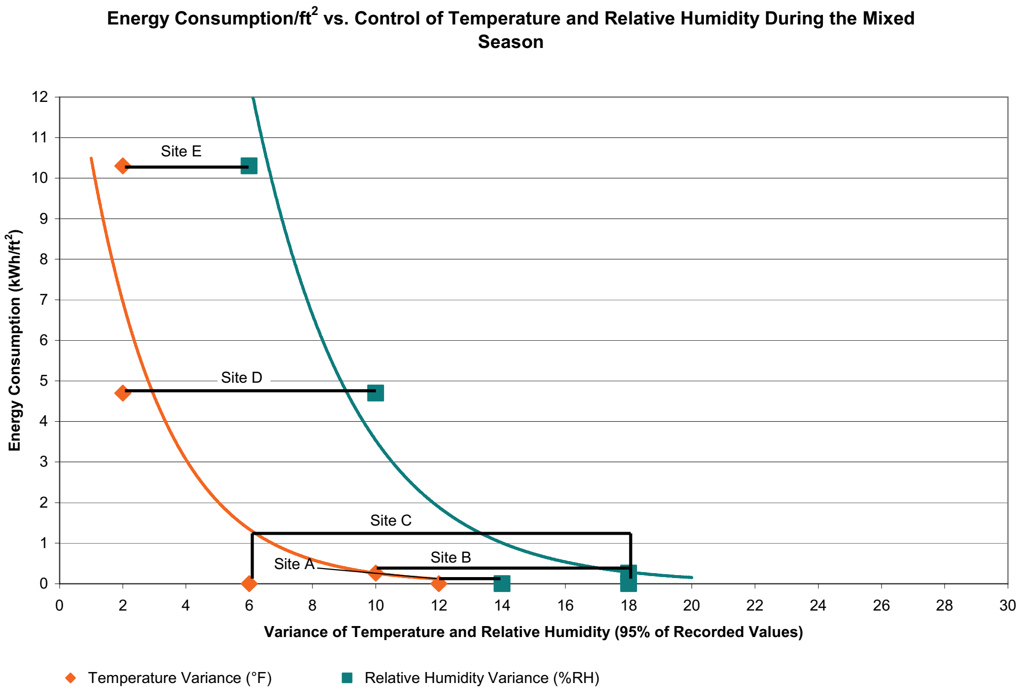


Figure 15: Energy Consumption per Square Foot vs. Control of Temperature and Relative Humidity for All Sites During the Mixed Season.

Figure 16 is a plot of the energy costs per square foot per 100 degree days versus the level of environmental control for all sites during the mixed season. This plot also illustrates that the energy costs decreased exponentially as the variance of the indoor temperature and relative humidity increased. This plot is interesting when compared to the analogous plots for the heating and cooling season. When divided by the degree days, Site D and Site E spent significantly more for climate management during the mixed season than for the heating and cooling seasons. As the mixed season has both heating and cooling loads, this result indicates that attempting to maintain constant indoor conditions as the outdoor conditions vary from warm to cold requires a greater energy expense than if the outdoor conditions are more stable (either all heating or all cooling loads). Site B, which is assumed to have alternated between heating and ventilation during the mixed season, also spent more per square foot-degree day during the mixed season than it did during the other two seasons.

Figure 17 shows the energy consumption per square foot per 100 degree days plotted against the level of environmental control. Again, the energy consumption decreased exponentially as the variance of the indoor temperature and relative humidity increased. When divided by the degree days for the mixed season, Sites B, D, and E all consumed more energy for climate management during the mixed season than for the other two seasons.

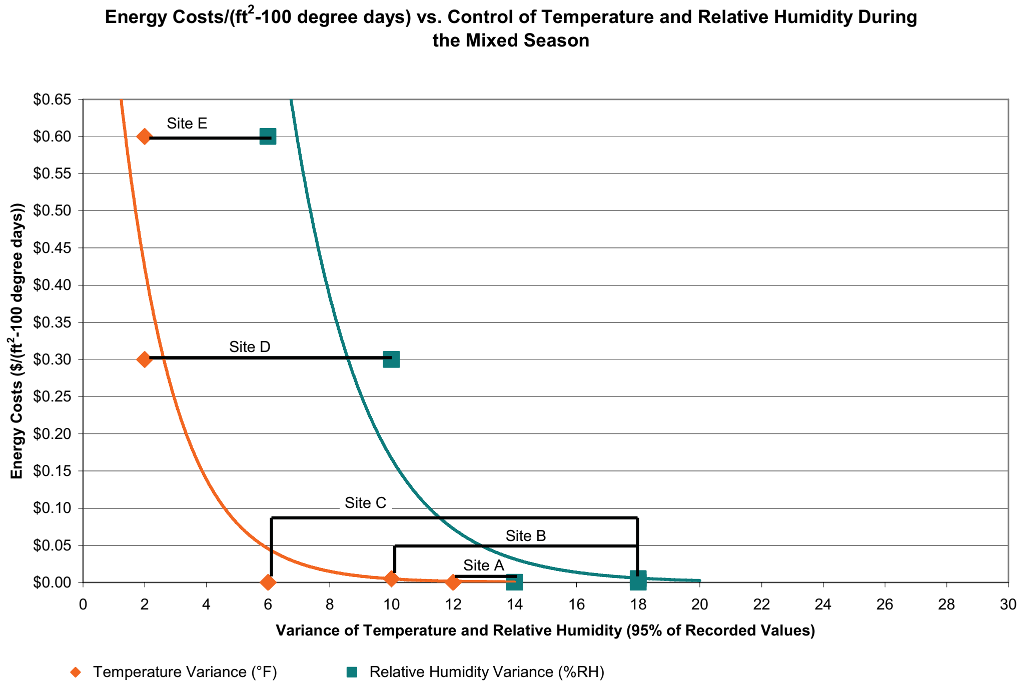


Figure 16: Energy Costs per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Sites During the Mixed Season.

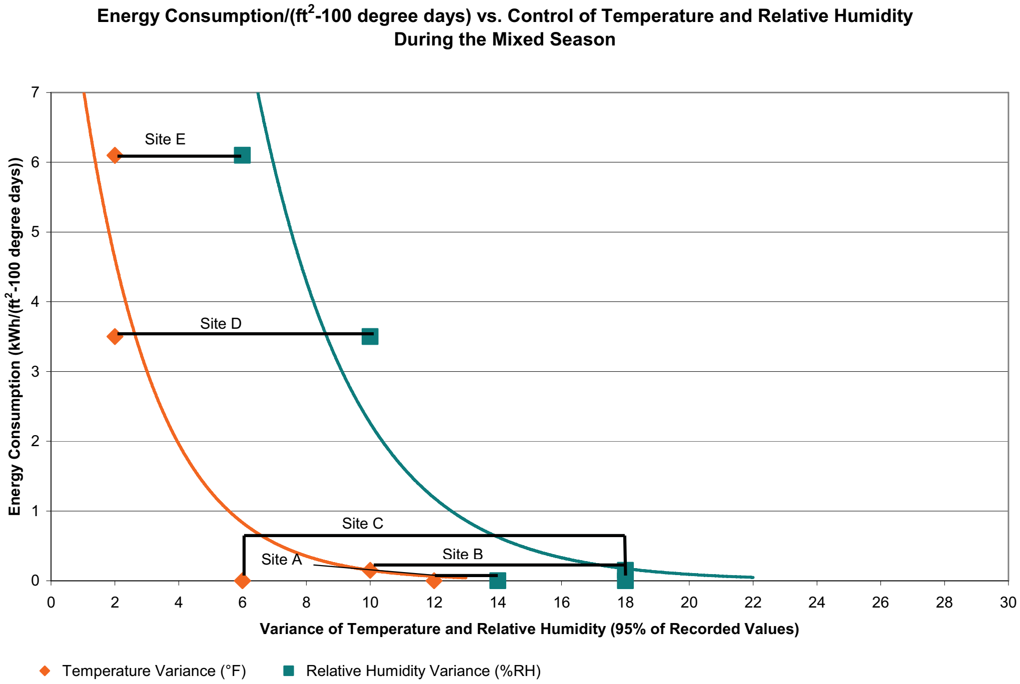


Figure 17: Energy Consumption per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Sites During the Mixed Season.

Overall, as with the heating and cooling seasons, the results displayed on all four graphs for the mixed season indicate that there is an exponential relationship between energy costs and consumption and the level of environmental control. Through all metrics used, the energy costs and consumption for climate management decreased exponentially as the variance of the indoor temperature and relative humidity increased. These results indicate that there is an exponential relationship between the energy expenditures for climate management and the level of control throughout the year.

The mixed season had the highest energy costs and consumption per square foot per 100 degree days when compared to the other two seasons. This result indicates that the energy expenditure per degree day for a site will be the highest during the mixed season, and that the mixed season will place the greatest strain on the climate management system.

Again, the comparison between Sites B and C is interesting. Site C, using no climate management, exhibited greater control over the temperature and equal control of the relative humidity when compared to Site B, which is assumed to have alternated between ventilation and heating during the mixed season. Again, this result would indicate that no using no climate management system will give greater control over the indoor conditions than using a simple system like Site B's, but one should not jump to this conclusion too readily. Again, the difference could have been caused by other factors, such as differences in the outdoor climate, or the fact that Site B is a free standing building while Site C is a row house with adjacent houses on both sides.

Though Site A, using no climate management system, displayed greater control over the indoor relative humidity than did Sites B and C, which used heating or ventilation, it must be remembered that Site A only recorded the indoor conditions once per day. It is likely that the indoor environment of Site A actually exhibited a greater fluctuation than the monitoring data indicates.

6.5 ANNUAL SITE COMPARISONS

To determine the annual level of environmental control and energy costs and consumption, weighted averages of those values from the seasonal data were calculated. While the weighted averages do not give a true assessment of the energy expenditures, this analysis does allow a useful comparison of the sites on an annual basis. Remember that Site A did not use any form of climate management at all, and that Site C only used climate management during the heating season. The annual data for all sites is located in Table 7.

Annual Data for All Sites (Weighted Averages for Costs and Consumption)

Site	Temperature Variance (ºF)	Relative Humidity Variance (%RH)	Cost/ft^2	Consumption (kWh/ft^2)	Cost/(ft^2-100 degree days)	Consumption (kWh/(ft^2-100 degree days))
Site A	34	16	$0	0	$0	0
Site B	13	19	$0.16	3.9	$0.0043	0.11
Site C	18	24	$0.41	8.2	$0.0072	0.14
Site D	4	12	$2.52	30.1	$0.12	1.4
Site E	4	6	$6.12	65.6	$0.24	2.6

Table 7: Annual Variance, Costs, and Consumption for All Sites (Weighted Averages for Costs and Consumption).

All graphs show either the energy costs or consumption plotted against the variance of temperature and relative humidity; for each of the four comparisons used in this study, the variance of both properties first is shown on the same graph, then on different graphs that also include the ASHRAE levels of environmental control for either the temperature or relative humidity. By placing the ASHRAE classes of control on each graph, one can see the annual energy costs and consumption associated with each class, as indicated by this study. From Table 3, ASHRAE class AA indicates ±4ºF and ±5% RH, class A indicates ±4ºF and ±5% RH or ±10% RH, class B indicates ±9ºF and ±10% RH, and class C indicates ±25% RH (class C does not include a variance of the temperature). The ASHRAE building class table (see Table 2) tells that classes of control A and B are appropriate for "purpose-built museums" in the climates typical of the sites in this study, and that class of control C is appropriate for uninsulated masonry or sheathed post and beam buildings.

Figure 18 has the annual energy costs per square foot plotted against the annual level of environmental control of both temperature and relative humidity. As this graph imitates the research performed by Mecklenburg regarding control of relative humidity, shown in Figure 2, Mecklenburg's data have been added to this graph for comparison (the gray data points and trendline).[200] Figure 18 shows that, on an annual basis, there is an exponential relationship between the energy costs for climate management and the level of control; as the variance of the indoor conditions increases the costs decrease exponentially. While Mecklenburg's data also show an exponential relationship between

---

[200] The Mecklenburg cost data has been adjusted for inflation using the conversion factor $1 = $1.27.

energy costs pre square foot and the level of control, his data also show tighter control of the indoor relative humidity at the high end of cost, and higher cost at the low end of control. This difference illustrates the difficulty in creating a reliable mathematical relationship between costs and level of control, and that study of many more sites is necessary to determine if a reliable mathematical model can be calculated.

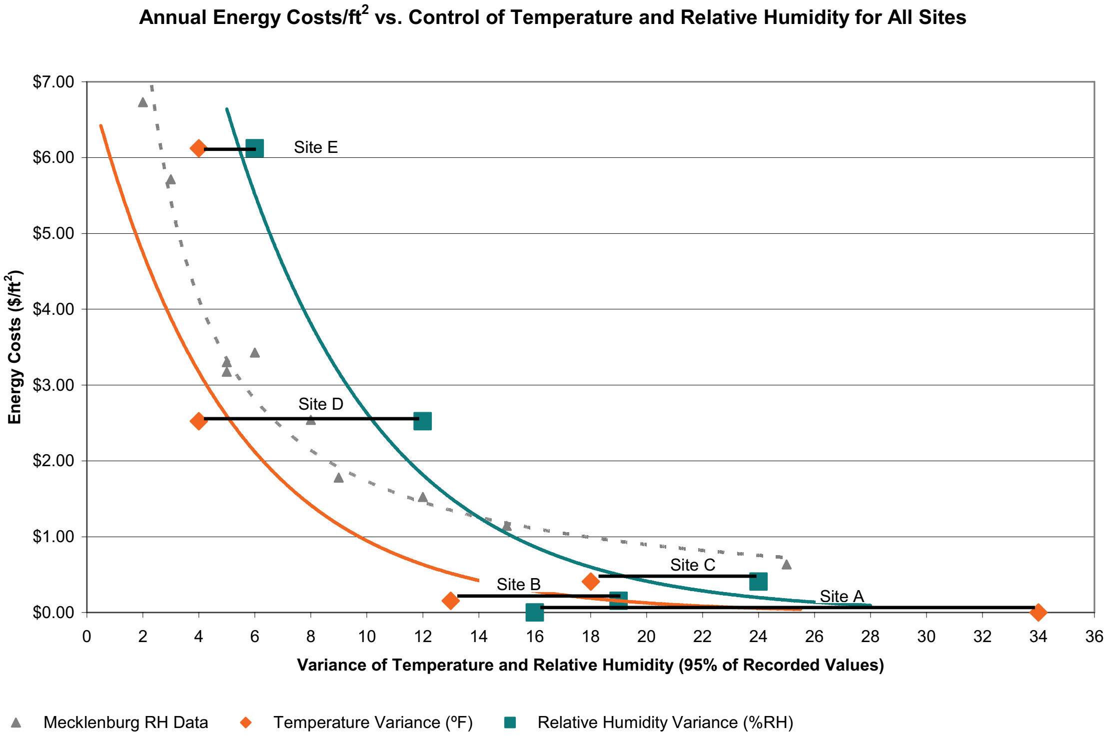


Figure 18: Annual Energy Costs per Square Foot vs. Control of Temperature and Relative Humidity for All sites, Including Previous Research By Mecklenburg

Figure 19 shows a plot of the annual energy costs per square foot versus the annual variance of the indoor temperature, as well as the ASHRAE classes of control of temperature. Figure 20 shows a plot of the annual energy costs per square foot versus the annual variance of the indoor relative humidity, as well as the ASHRAE classes of control of the relative humidity. Again, Mecklenburg's research has been reproduced on this graph for comparison.

Figure 21 is a graph of the annual energy consumption per square foot versus the level of environmental control for all sites. Again, the exponential relationship between energy consumption and the variance of the temperature and relative humidity is apparent. Figures 22 and 23 show the energy consumption per square foot plotted against the variance of either the temperature or the relative humidity, respectively, as well as the ASHRAE classes of control of those two properties.

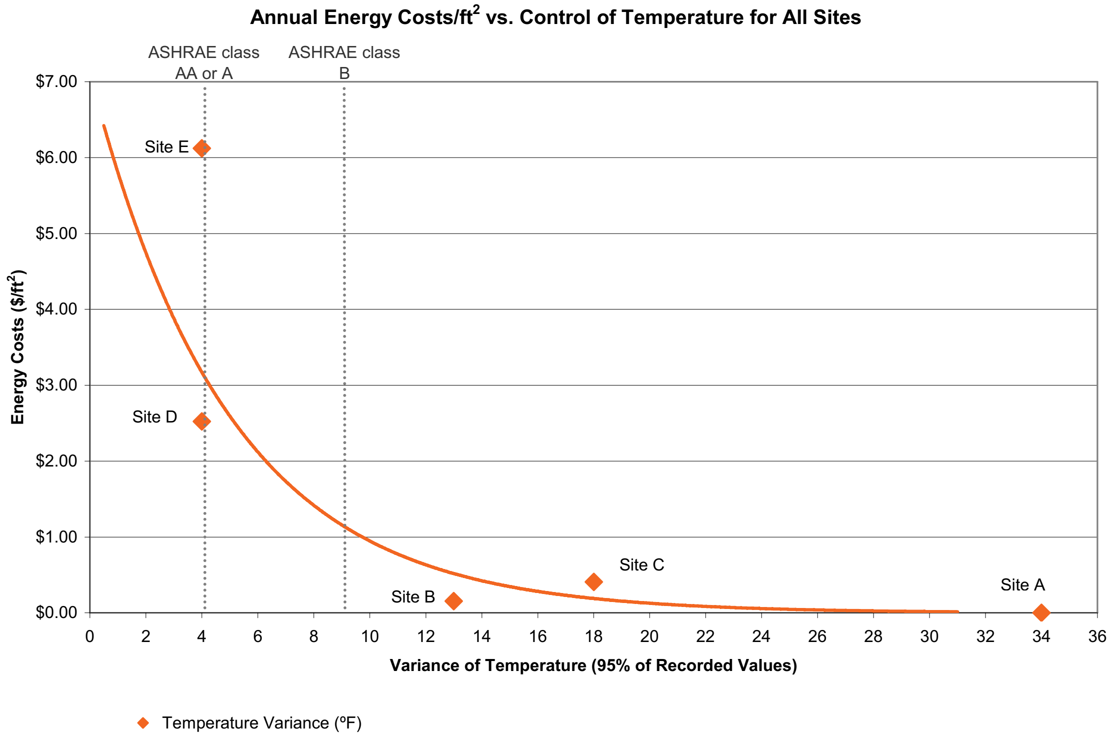


Figure 19: Annual Energy Costs per Square Foot vs. Control of Temperature for All Sites, Including ASHRAE Classes of Control.

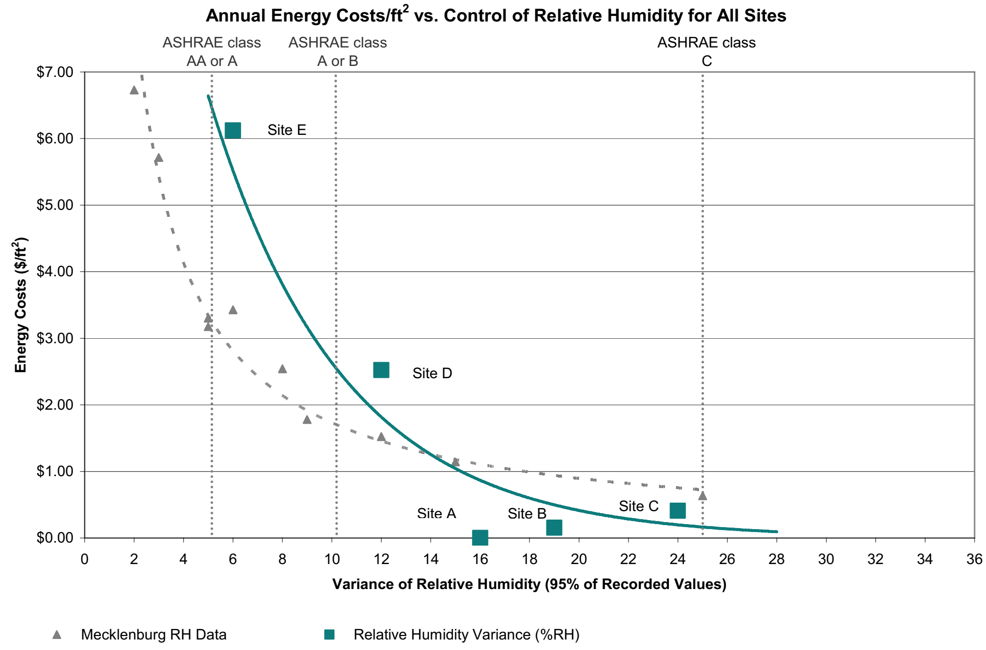


Figure 20:Annual Energy Costs per Square Foot vs. Control of Relative Humidity for All Sites, Including ASHRAE Classes of Control and Previous Research by Mecklenburg.

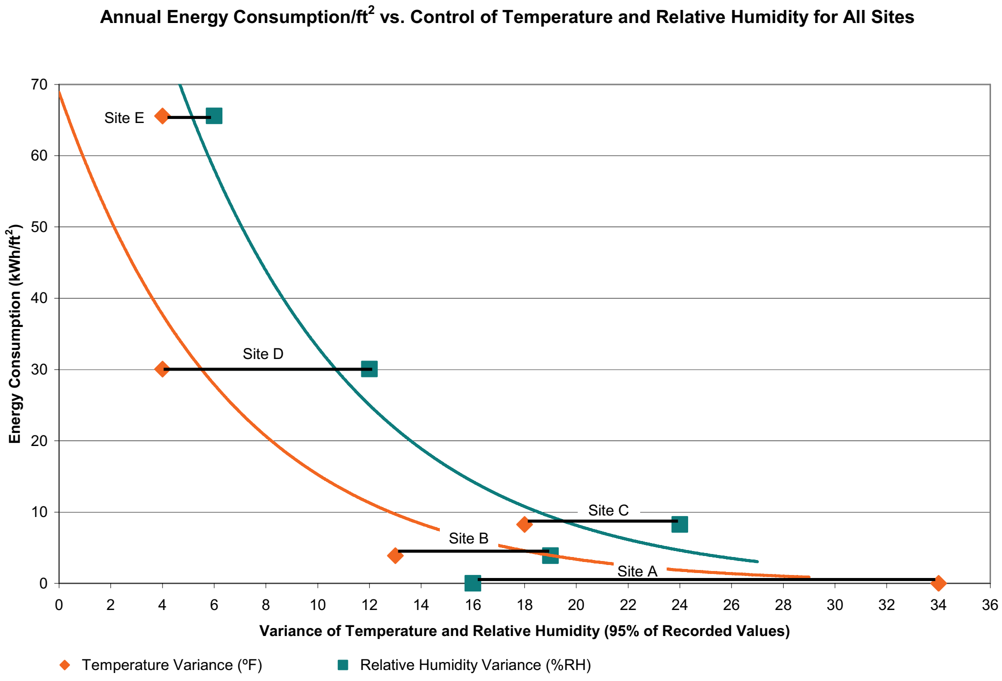


Figure 21: Annual Energy Consumption per Square Foot vs. Control of Temperature and Relative Humidity for All Sites.

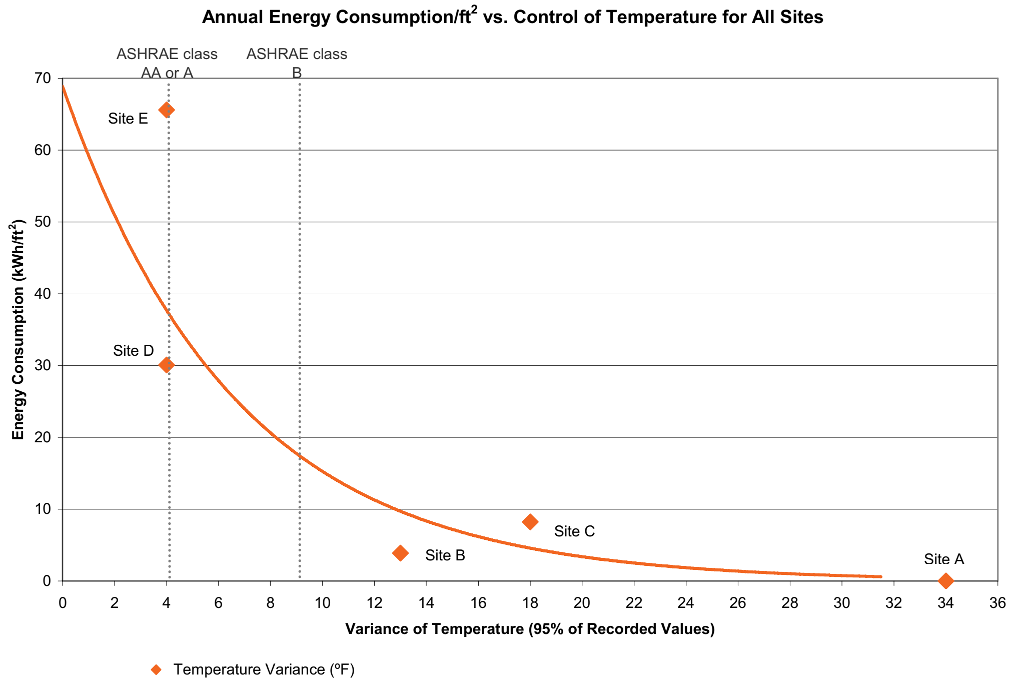


Figure 22: Annual Energy Consumption per Square Foot vs. Control of Temperature for All Sites, Including ASHRAE Classes of Control.

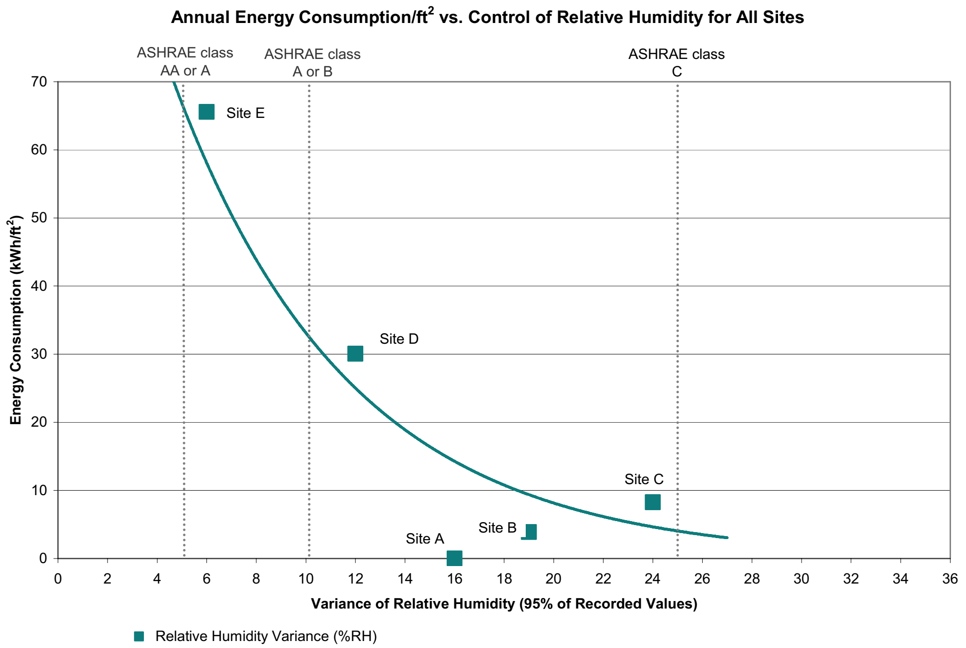


Figure 23: Annual Energy Consumption per Square Foot vs. Control of Relative Humidity for All Sites, Including ASHRAE Classes of Control.

The relationship of greater variance of the indoor conditions leading to an exponential reduction in energy costs and consumption also is revealed in Figures 24 and 25, which plot the annual energy costs per square foot per 100 degree days and the annual energy consumption per square foot per 100 degree days, respectively. Note that, on these two graphs, Sites A, B, and C are more closely bunched together at the bottom of the graph than they were on Figures 18 and 21, which do not control for the outdoor climate. This result indicates that, relative to each other, the climate management systems of Sites B and C did performed much less work per degree day than did Sites D and E to manage their indoor climates.

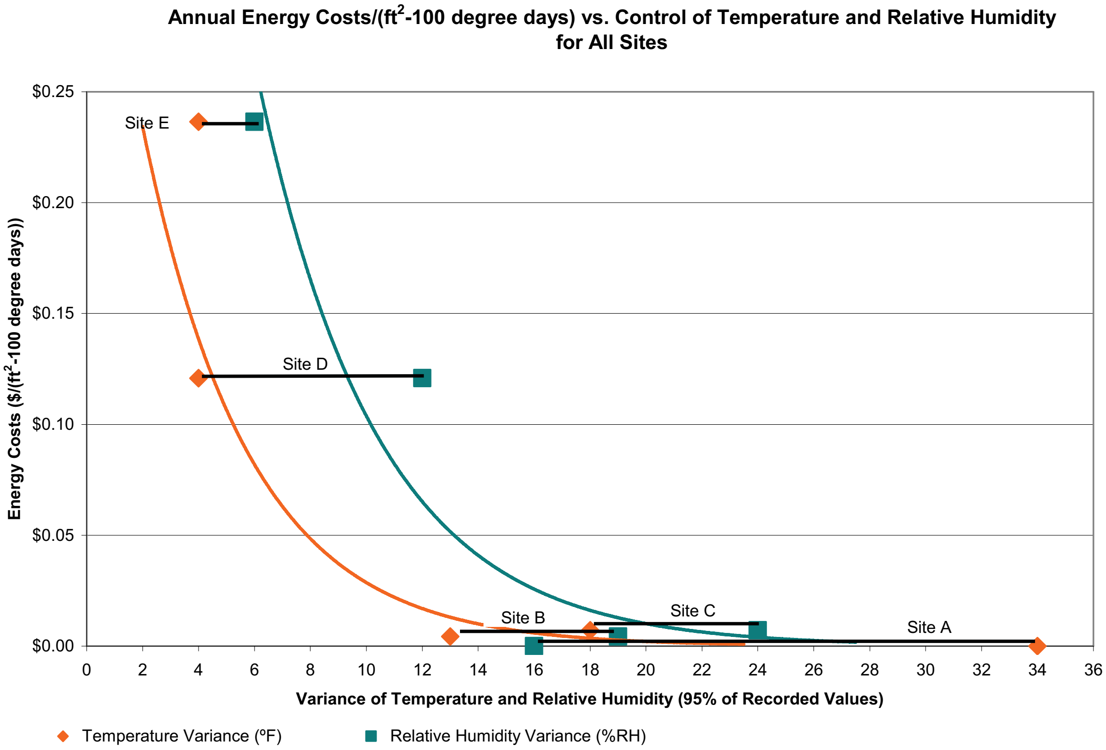


Figure 24: Annual Energy Costs per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Sites.

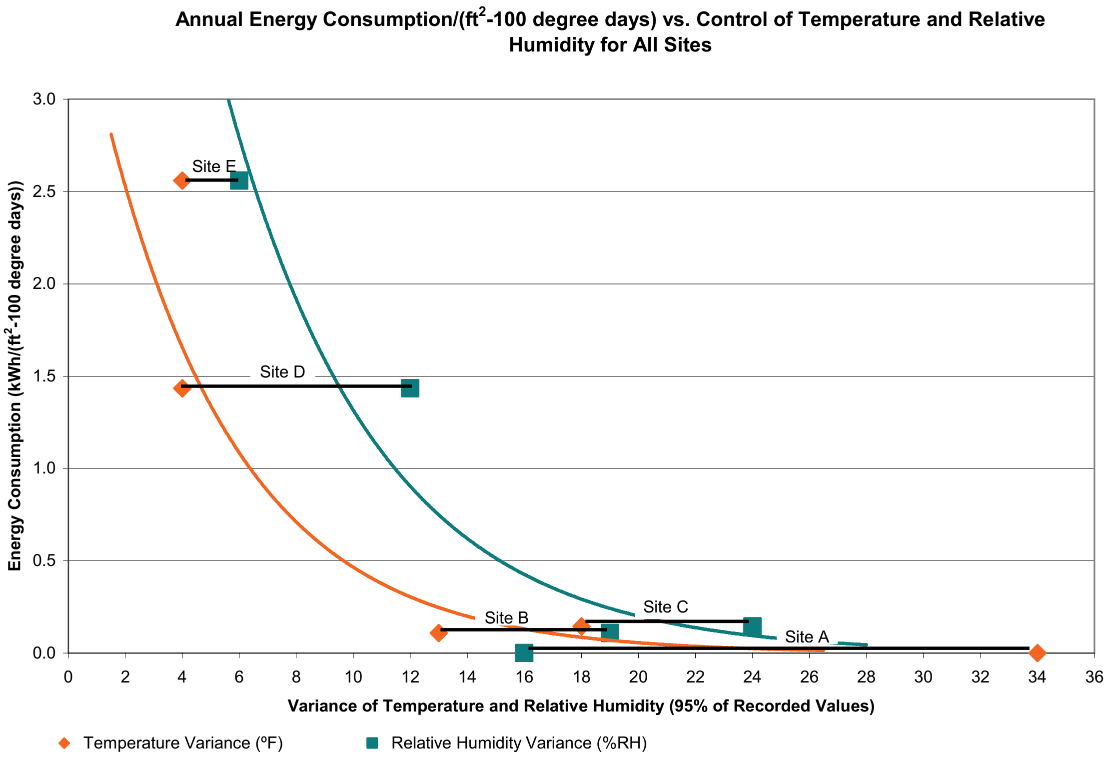


Figure 25: Annual Energy Consumption per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Sites.

Figures 26 and 27 show the annual energy costs per square foot per 100 degree days plotted against the variance of either the indoor temperature or relative humidity, as well as the ASHRAE classes of control. Figures 28 and 29 plot the annual energy consumption against the variance of either the indoor temperature or relative humidity, as well as the ASHRAE classes of control.

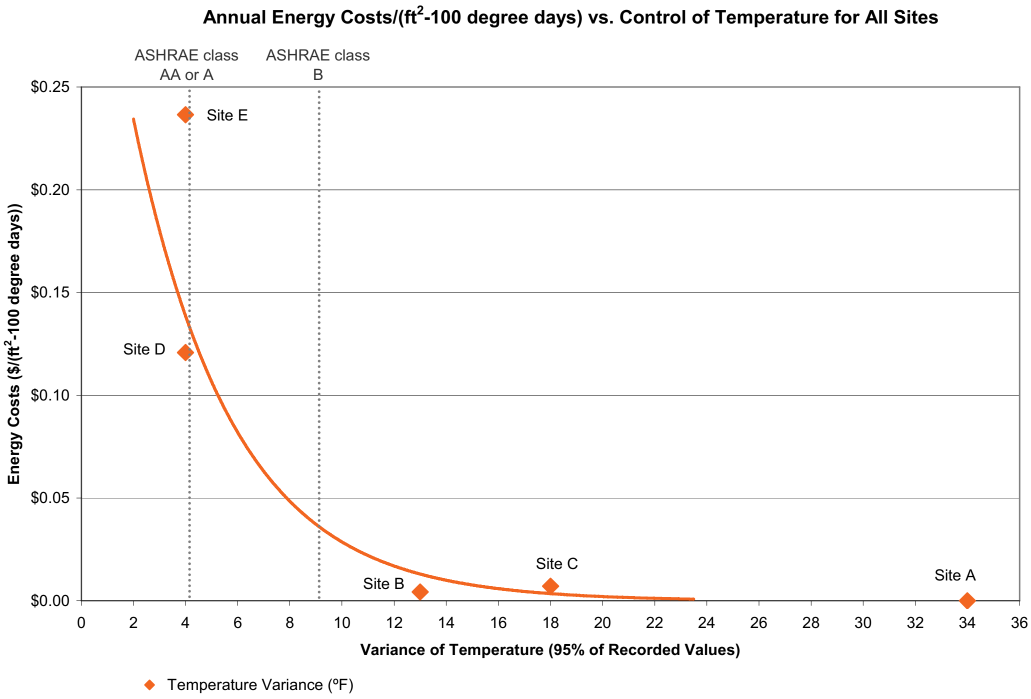


Figure 26: Annual Energy Costs per Square Foot per 100 Degree Days vs. Control of the Temperature for All Sites, Including ASHRAE Classes of Control.

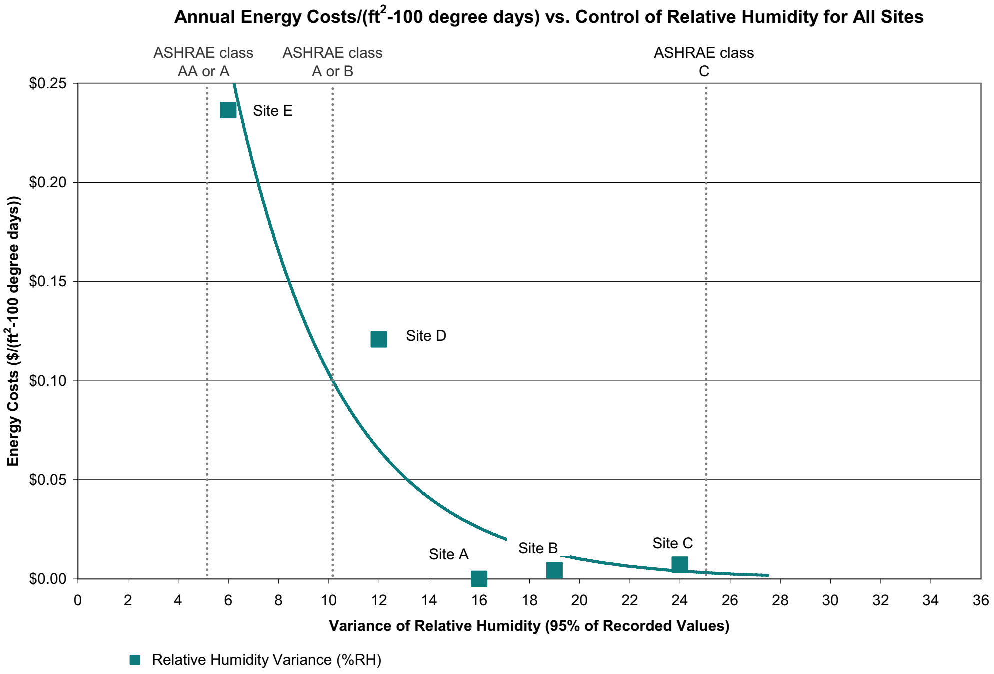


Figure 27: Annual Energy Costs per Square Foot per 100 Degree Days vs. Control of the Relative Humidity for All Sites, Including ASHRAE Classes of Control.

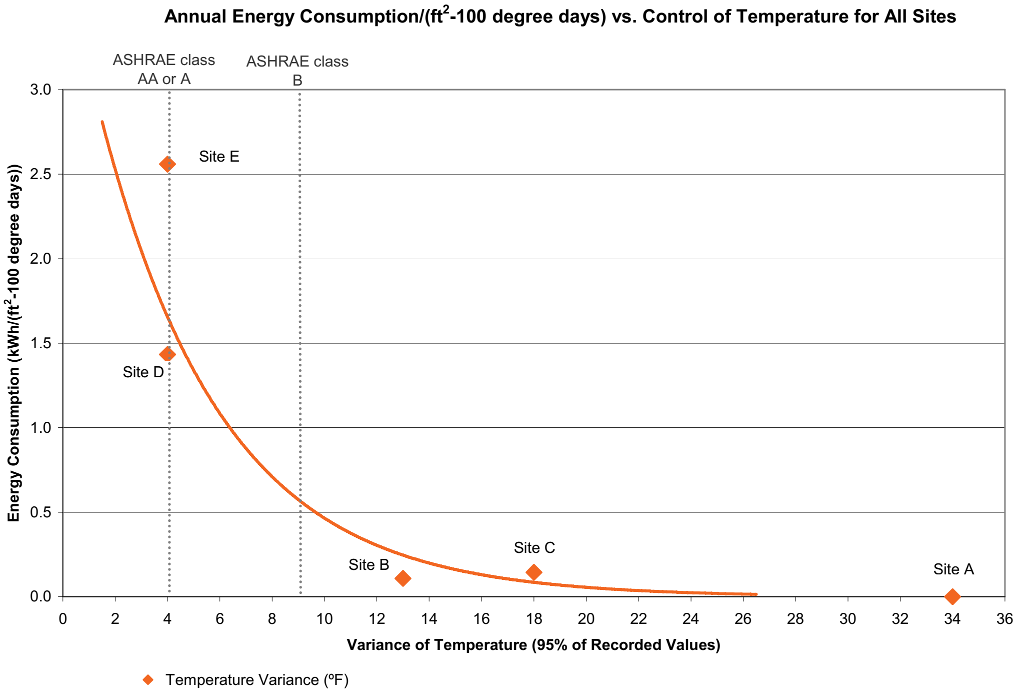


Figure 28: Annual Energy Consumption per Square Foot per 100 Degree Days vs. Control of the Temperature for All Sites, Including ASHRAE Classes of Control.

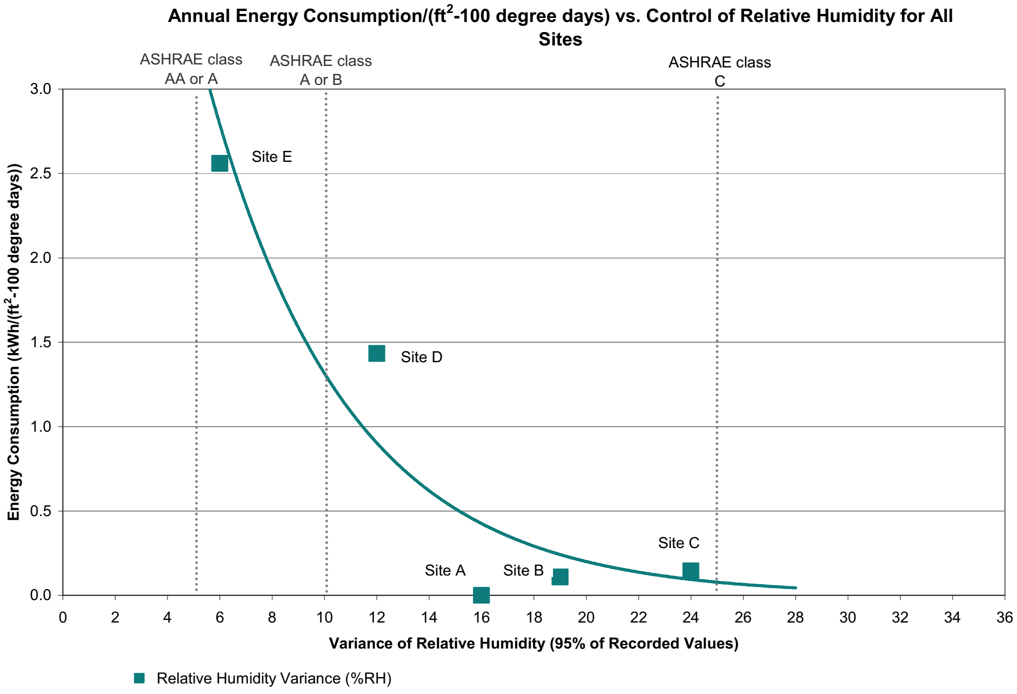


Figure 29: Annual Energy Consumption per Square Foot per 100 Degree Days vs. Control of the Relative Humidity for All Sites, Including ASHRAE Classes of Control.

The graphs that show the energy costs and consumption plotted against of the variance of the temperature or relative humidity individually display interesting results. Site E, while spending the most and consuming the most energy in all metrics used, exhibited the greatest control over the indoor conditions, and stayed within ASHRAE classes A or AA for control of the temperature and classes A or B for control over the indoor relative humidity. Site D, which also tries to maintain constant indoor conditions, spent and consumed less than Site E but more than the other three sites, while managing to stay within ASHRAE classes A or AA for control of the temperature, and at the low end of class C for control of the indoor relative humidity. Sites A, B, and C, which either operate simple systems or no system at all, had significantly lower energy expenditures that did Sites D and E. While consuming much less energy, Sites A, B, and C did not stay within either ASHRAE class of control for temperature, and all three stayed within class C of relative humidity control.

Two more types of graphs were created for this analysis. To better inform the comparison, the annual energy costs and consumption per square foot were normalized. To normalize the energy costs pre square foot, all values were divided by energy costs per square foot for the site that had the lowest non-zero costs, namely, Site B. The same was done for the annual energy consumption per square foot. This process reveals the factor by which the annual costs and consumption increased as the variance of the indoor conditions was made tighter. The normalized costs and consumption were plotted against the variance of the indoor conditions taken together, and against the variance of the temperature and relative humidity separately, again displaying the ASHRAE classes of control.

The normalized annual energy costs and consumption per square foot data are presented in Table 8. Figure 30 is a plot of the normalized annual energy costs per square foot versus the variance of the indoor temperature and relative humidity for all sites, and Figures 31 and 32 show the plots of the costs versus the variance of the temperature and relative humidity individually. These graphs show that Site C spent 2.6 times more for energy per square foot than did Site B for the year, even though Site C exhibited less control of the indoor conditions. Site D spent 16.2 times more for energy per square foot than did Site B, and exhibited control of the temperature that was 71% tighter than Site B and of the relative humidity that was 37% tighter. Site E spent 39.3 times more for energy per square foot than did Site B, and exhibited control of the temperature that was 71% tighter than Site B and of the relative humidity that was 68% tighter.

Normalized Annual Data for All Sites (Weighted Averages)

	Temperature Variance (ºF)	**Relative Humidity Variance (%RH)**	**Normalized Costs/ft^2**	**Normalized Consumption/ft^2**
Site A	34	16	0	0
Site B	13	19	1.0	1.0
Site C	18	24	2.6	2.1
Site D	4	12	16.2	7.7
Site E	4	6	39.3	16.9

Table 8: Normalized Annual Energy Costs and Consumption for All Sites.

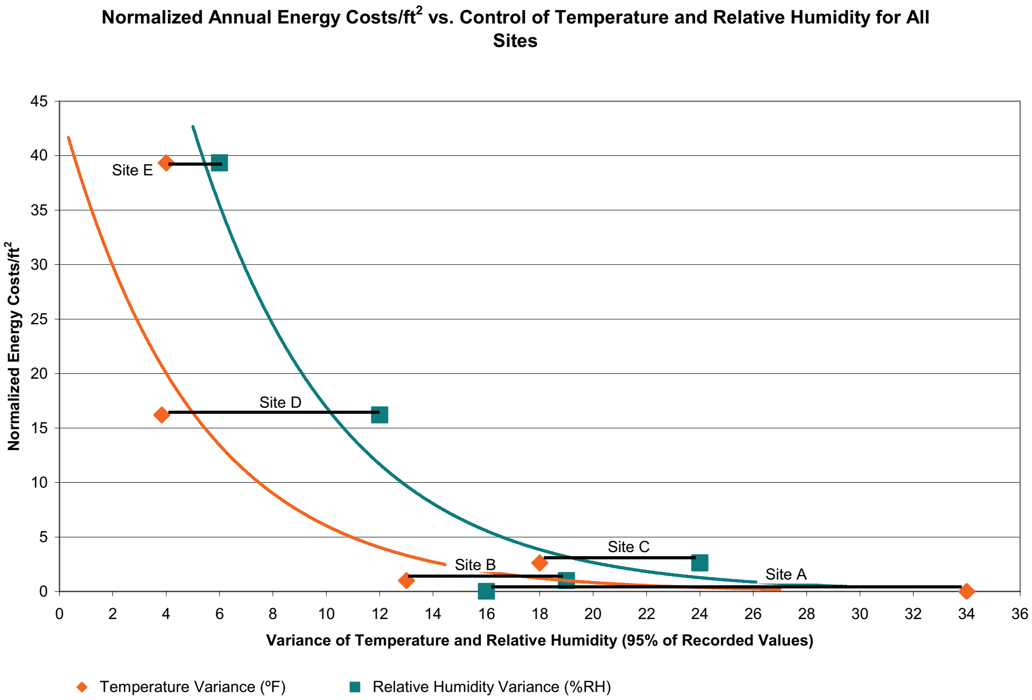


Figure 30: Normalized Annual Energy Costs per Square Foot vs. Control of Temperature and Relative Humidity for All Sites.

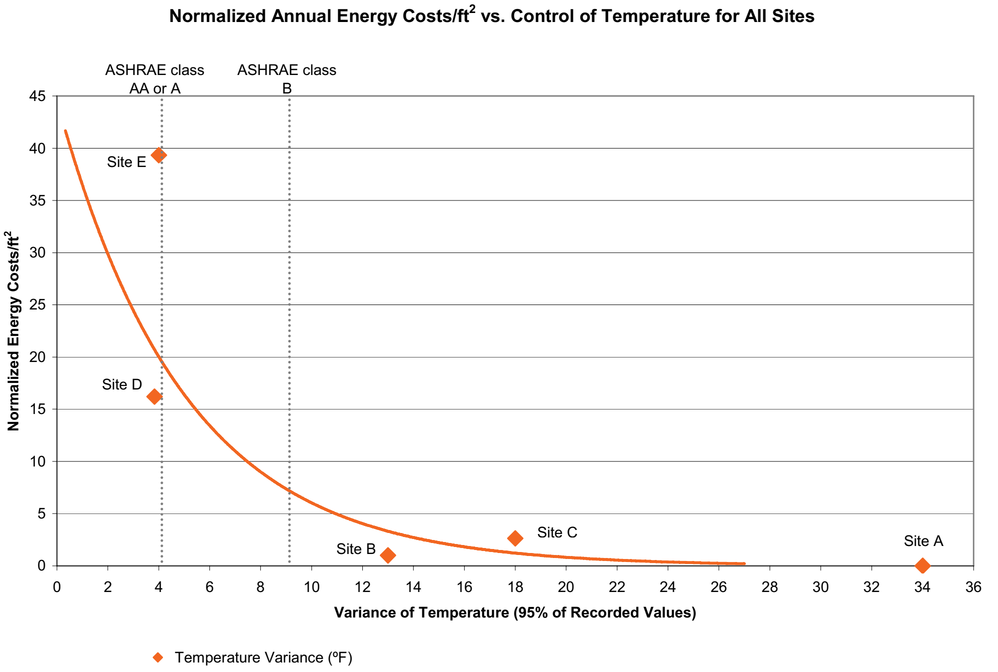


Figure 31: Normalized Annual Energy Costs per Square Foot vs. Control of Temperature for All Sites, Including ASHRAE Classes of Control.

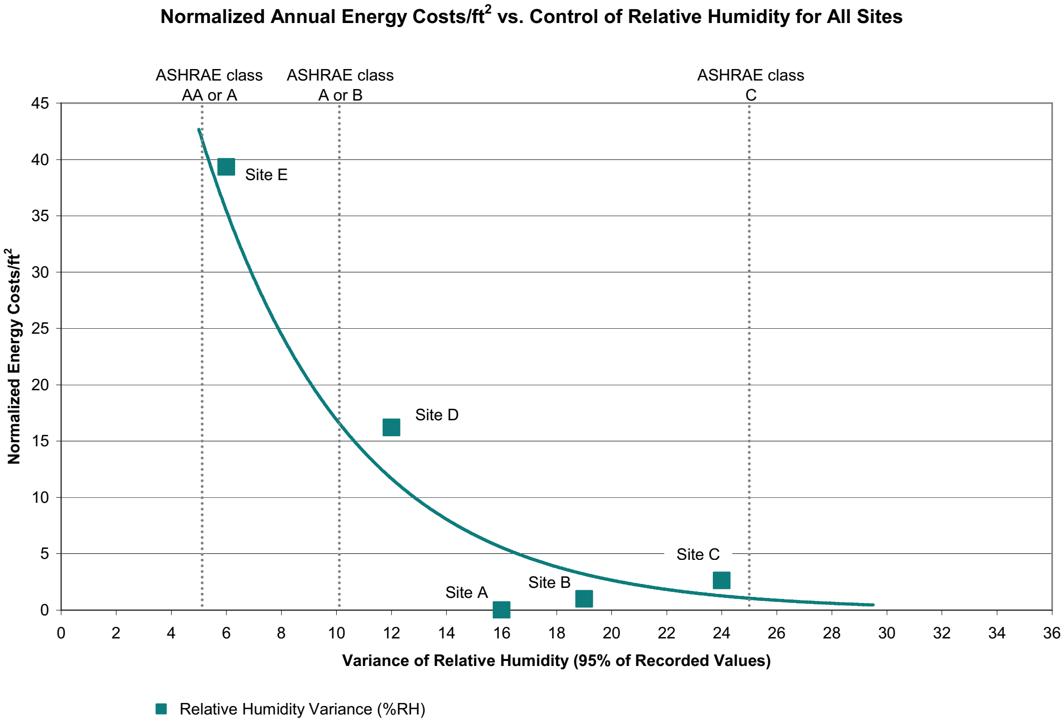
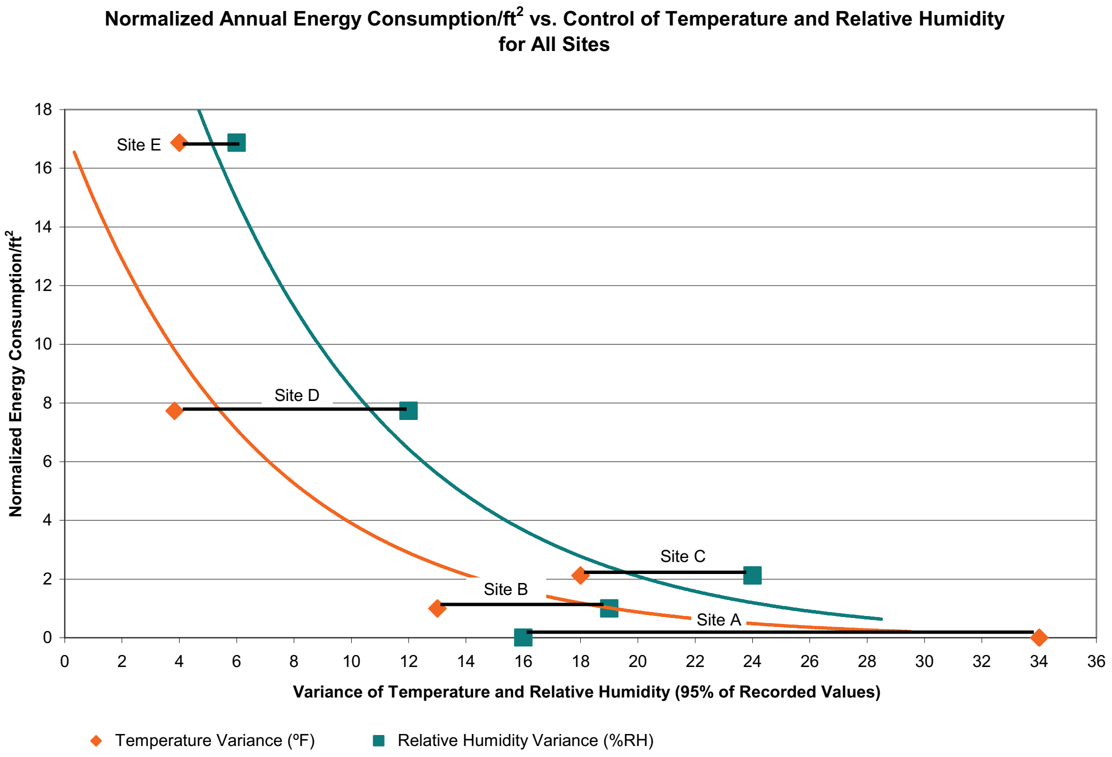


Figure 32: Annual Normalized Energy Costs per Square Foot vs. Control of Relative Humidity for All Sites, Including ASHRAE Classes of Control.

An interesting comparison is between Sites D and E, both of which attempt to maintain constant indoor conditions. Site E spent 2.4 times more for energy per square foot than did Site D, and achieve control of the temperature that was equal to that of Site D and control of the relative humidity that was 50% greater. By spending 2.4 times as much for energy as did Site D, Site E managed to remain in ASHRAE class A or B of relative humidity control.

Figure 33 is a plot of the normalized annual energy consumption per square foot versus the variance of the indoor conditions for all sites, and Figures 34 and 35 show the same plots for the variance of the temperature and relative humidity individually. From these graphs, one can see that the energy consumption per square foot did not increase by the same factors as the costs did as the variance of the indoor conditions decreased. For example, Site D’s energy costs per square foot were 16.2 times more than Site B’s, but the energy consumption per square foot was 7.7 times more. A similar result is found for Site E, which spent 39.3 times more for energy per square foot than did Site B, but consumed 16.9 times more energy per square foot. These results indicate that, for climate management, the type of system and the type of energy used, such as electricity, natural gas, or heating oil, will have a great effect on the energy costs of the system, and not just the level of control the system provides



Normalized Annual Energy Consumption/ft^2 vs. Control of Temperature and Relative Humidity for All Sites

Figure 33: Normalized Annual Energy Consumption per Square Foot vs. Control of Temperature and Relative Humidity for All Sites.

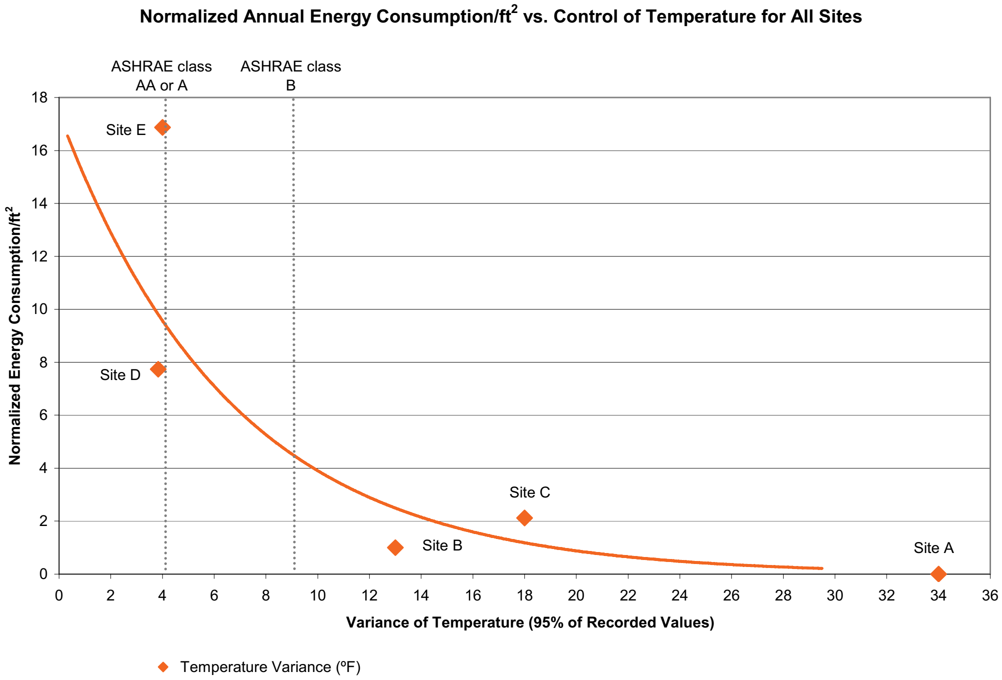


Figure 34: Normalized Annual Energy Consumption per Square Foot vs. Control of Temperature for All Sites, Including ASHRAE Classes of Control.

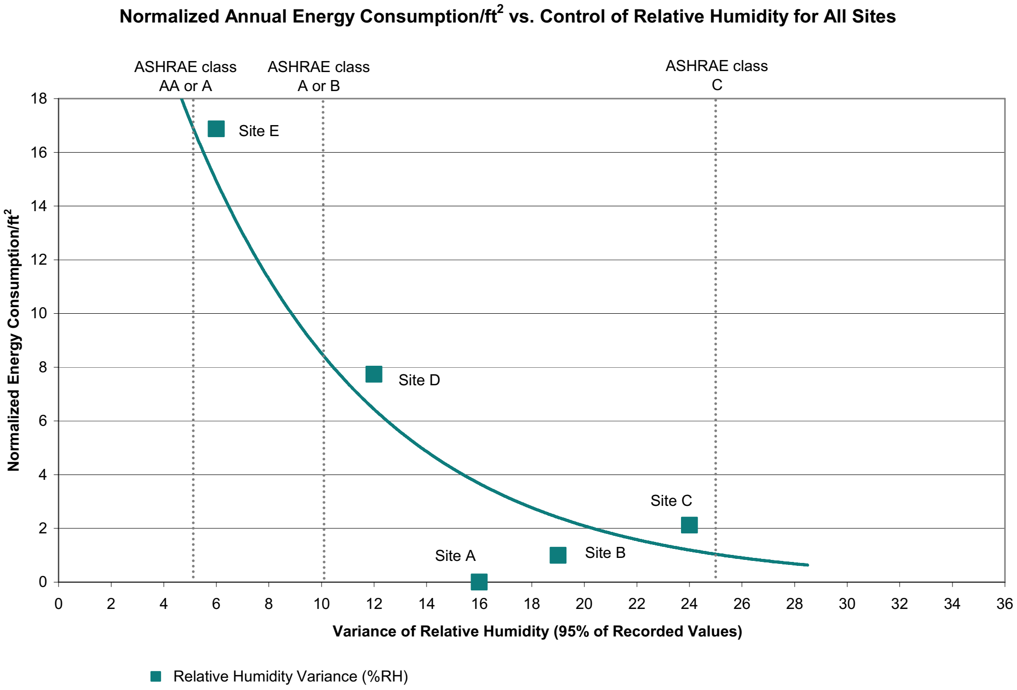


Figure 35: Normalized Annual Energy Consumption per Square Foot vs. Control of Relative Humidity for All Sites, Including ASHRAE Classes of Control.

6.6 INDIVIDUAL SITES

6.6.1 Site A

Because Site A does not use a climate management system, the energy costs and consumption for all seasons is zero. Figure 36 displays the variance of the indoor temperature and relative humidity for the heating and mixed seasons (Site A did not experience a cooling season). This graph shows that Site A experienced much greater variance of the indoor temperature during the heating season than during the mixed season, and similar variance of the indoor relative humidity during both seasons.

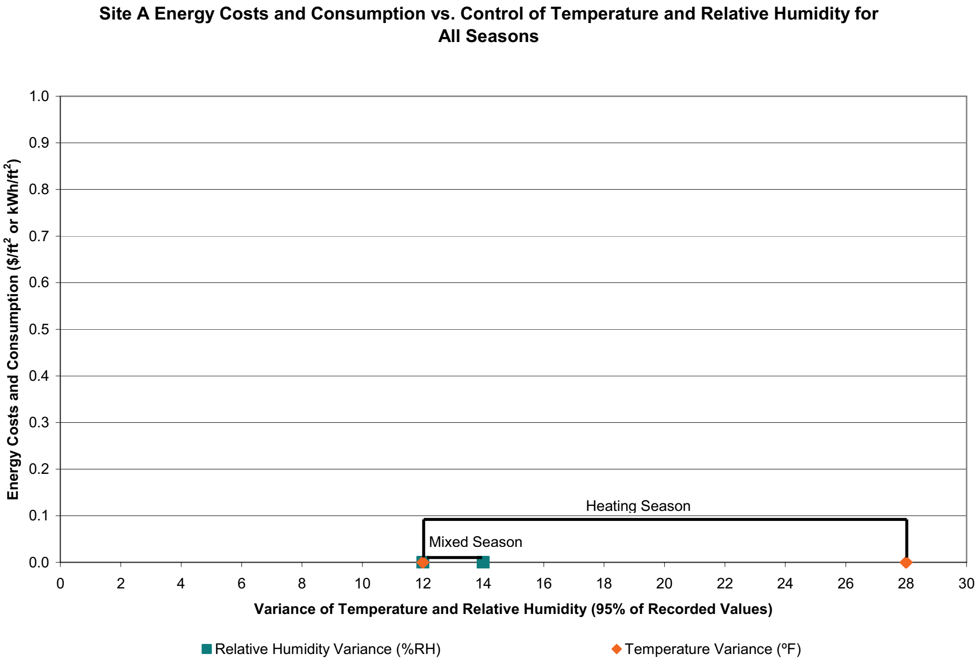


Figure 36: Site A Energy Costs and Consumption vs. Control of Temperature and Relative Humidity for All Seasons.

6.6.2 Site B

Figures 37 and 38 are plots of the energy costs per square foot and energy consumption per square foot for Site B for all three seasons, respectively. These graphs show that Site B spent the most and consumed the most energy per square foot during the heating season by a wide margin. Figures 39 and 40 are plots of the energy costs and the energy consumption per square foot per 100 degree days for Site B for all three seasons. These graphs show that Site B spent the most for energy per degree day during the heating season, but consumed the most energy per degree day during the mixed season, indicating that the system had to perform the most work per degree day during the mixed season. These graphs also show that Site B exhibited the greatest control over the indoor temperature during the mixed season, and the greatest control over the indoor relative humidity during the cooling season.

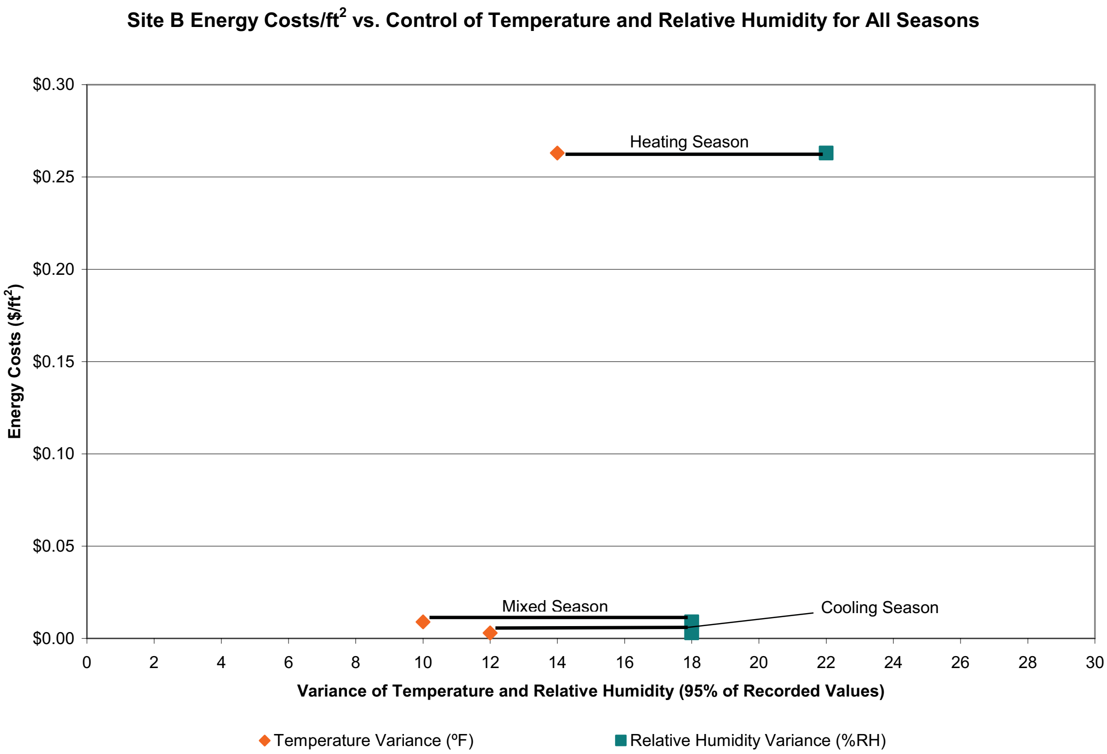


Figure 37: Site B Energy Costs per Square Foot vs. Control of Temperature and Relative Humidity for All Seasons.

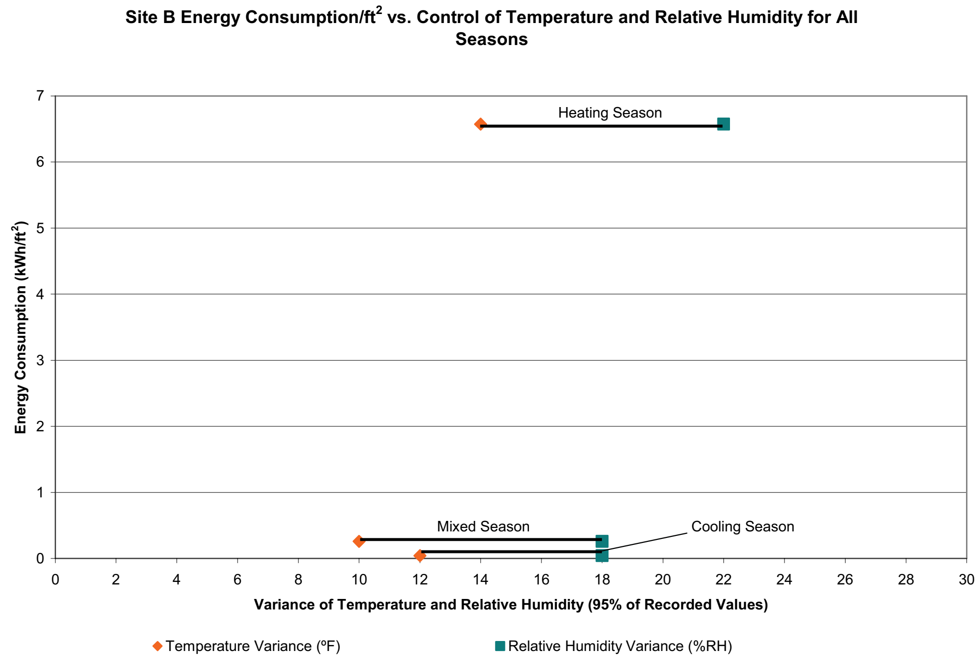


Figure 38: Site B Energy Consumption per Square Foot vs. Control of Temperature and Relative Humidity for All Seasons.

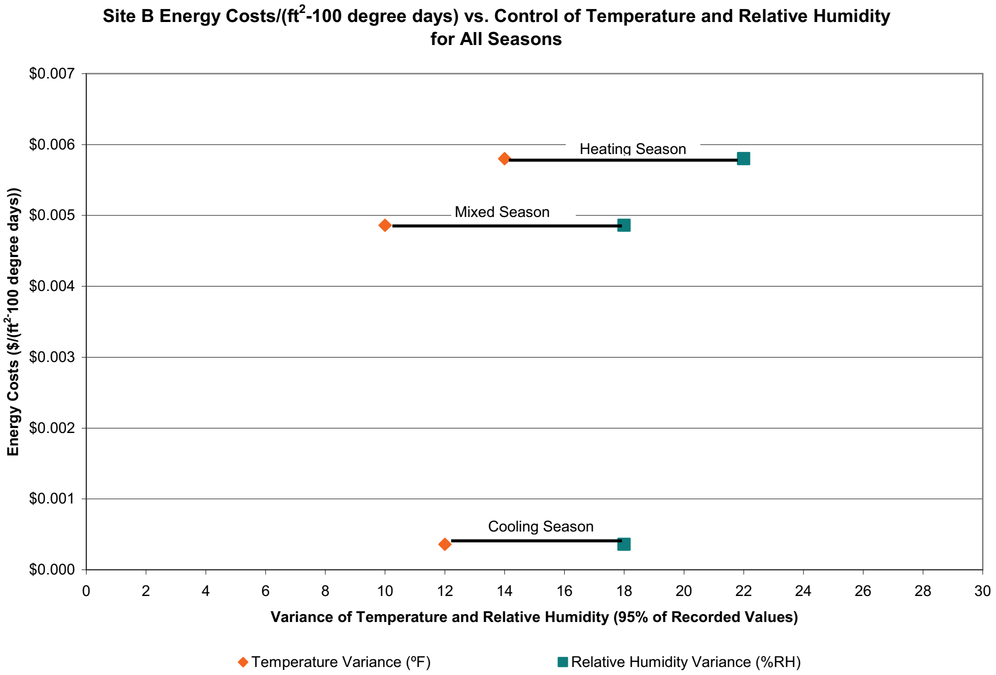


Figure 39: Site B Energy Costs per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Seasons.

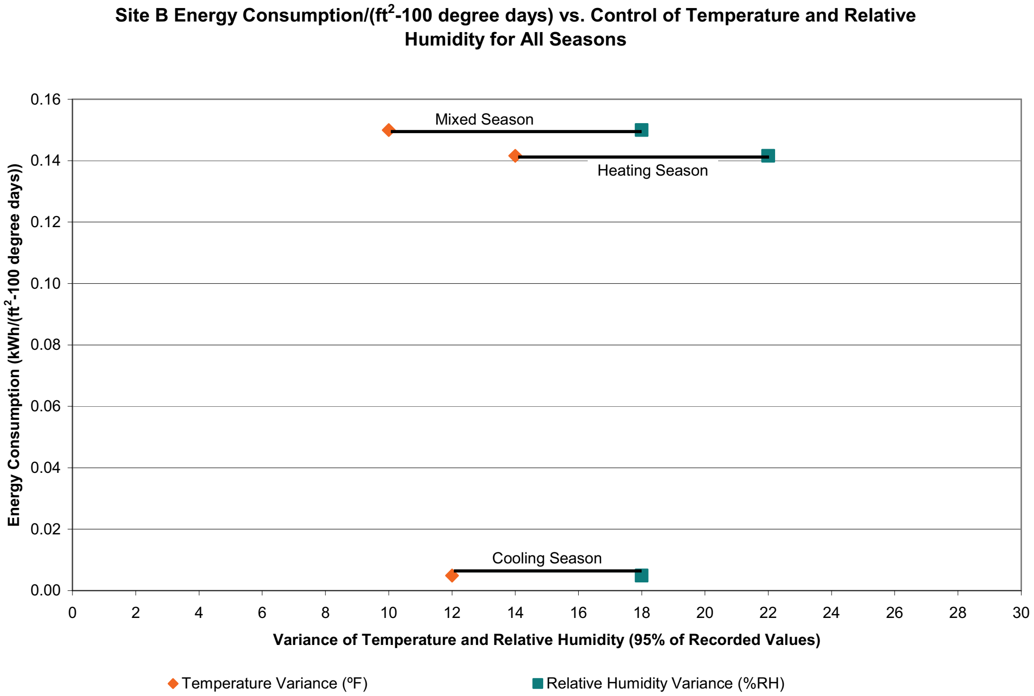


Figure 40: Site B Energy Consumption per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Seasons.

6.6.3 Site C

Figures 41 and 42 show the energy costs per square foot and the energy consumption per square foot plotted against the variance of the temperature and relative humidity for Site C for all three seasons, respectively. Because Site C only uses climate management during the heating season, the other two seasons have a cost and consumption of zero. The energy costs and consumption per square foot per 100 degree days versus the control of the indoor conditions are displayed on Figures 43 and 44, respectively. These graphs show that Site C exhibited the greatest control over the indoor temperature during the cooling season, and the greatest control over the indoor relative humidity during the mixed season. Interestingly, these are the seasons in which Site C does not use climate management. Perhaps Site C’s practice of heating the building for human comfort, rather than for preservation, during the heating season causes the site to have greater variance of the indoor conditions.

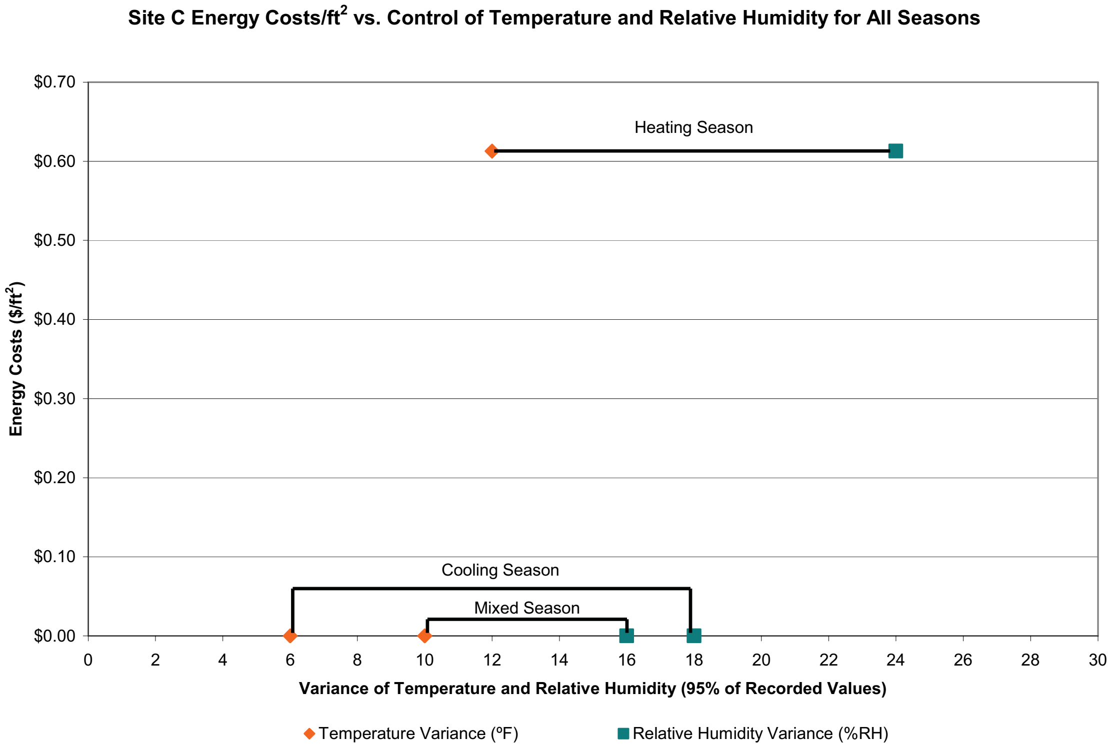


Figure 41: Site C Energy Costs per Square Foot vs. Control of Temperature and Relative Humidity for All Seasons.

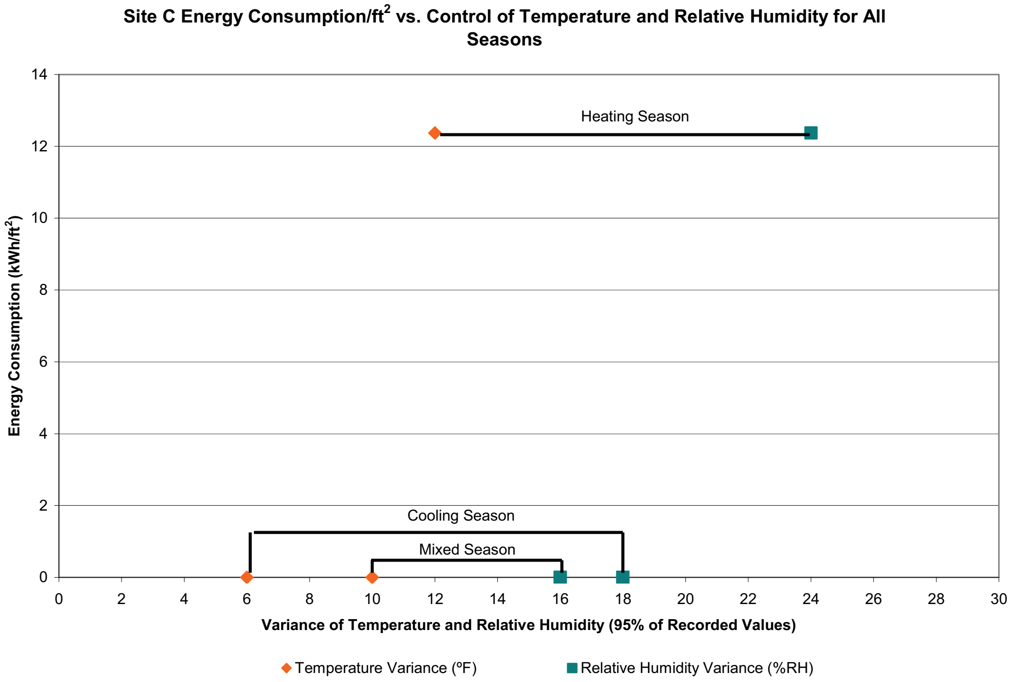


Figure 42: Site C Energy Consumption per Square Foot vs. Control of Temperature and Relative Humidity for All Seasons.

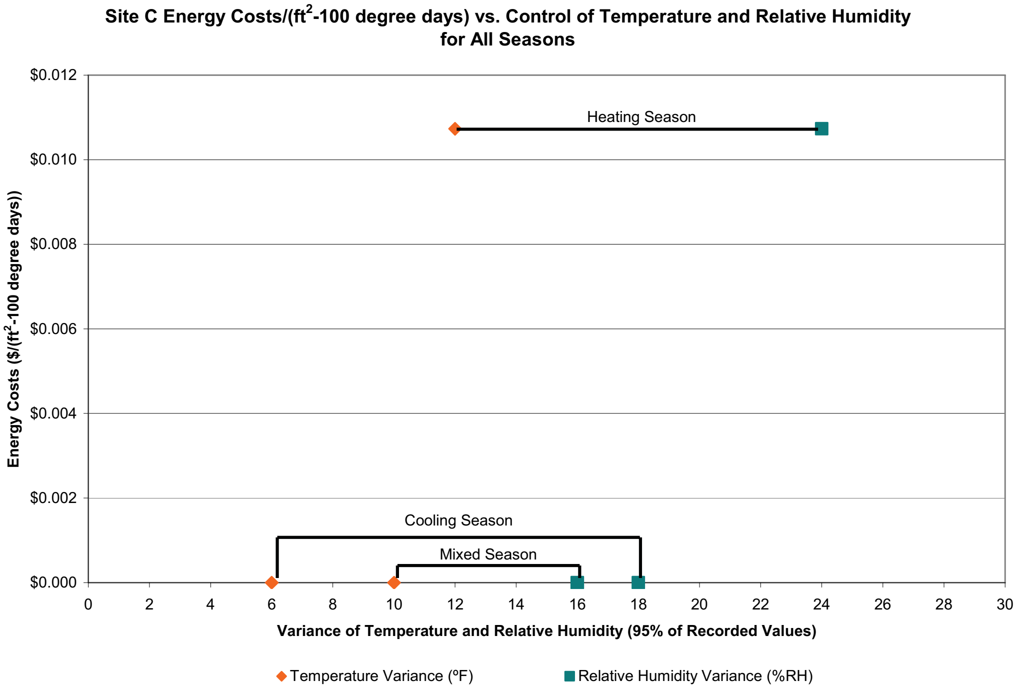


Figure 43: Site C Energy Costs per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Seasons.

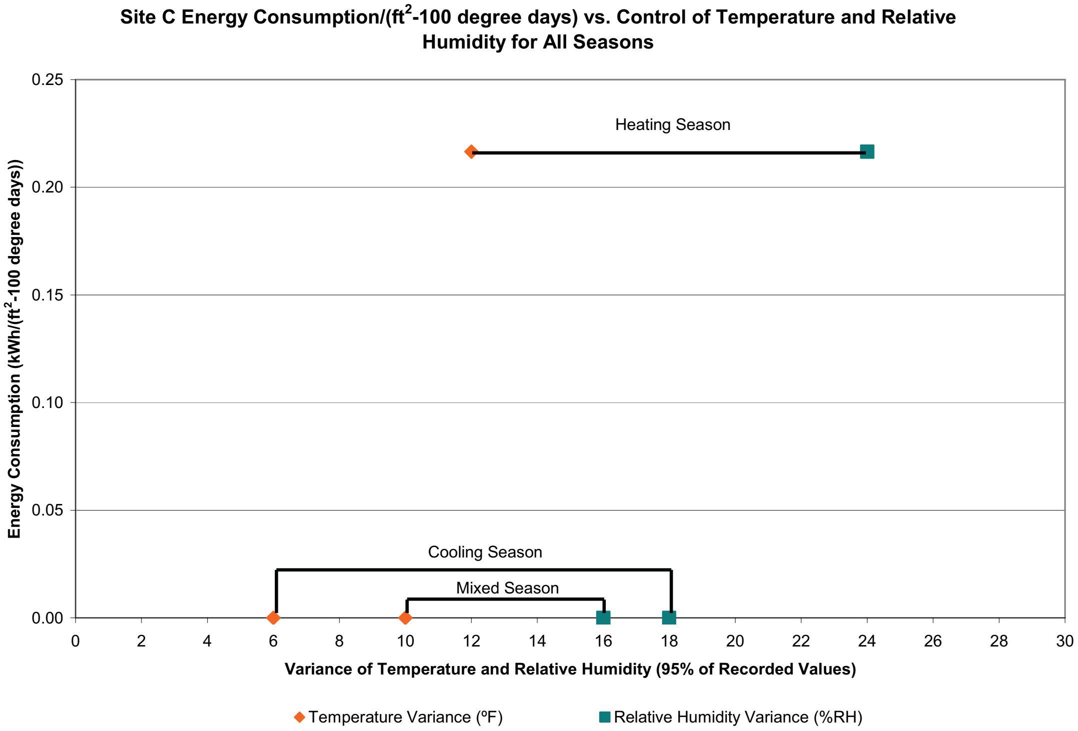


Figure 44: Site C Energy Consumption per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Seasons.

6.6.4 Site D

Figures 45 and 46 show the energy costs per square foot and the energy consumption per square foot plotted against the variance of the indoor temperature and relative humidity for Site D for all three seasons, respectively. These graphs show that Site D spent and consumed the most energy per square foot during the heating season. Figures 47 and 48 are plots of the energy costs and the energy consumption per square foot per 100 degree days versus the control of the indoor environment for Site D for all three seasons, respectively. These graphs show that Site D spent the most and consumed the most energy per degree day during the mixed season, indicating that the climate management system performed the most work for climate management during the mixed season. These graphs also show that Site D exhibited the greatest control over the indoor temperature during the mixed season, and exhibited an equal level of control over the indoor relative humidity for all three seasons.

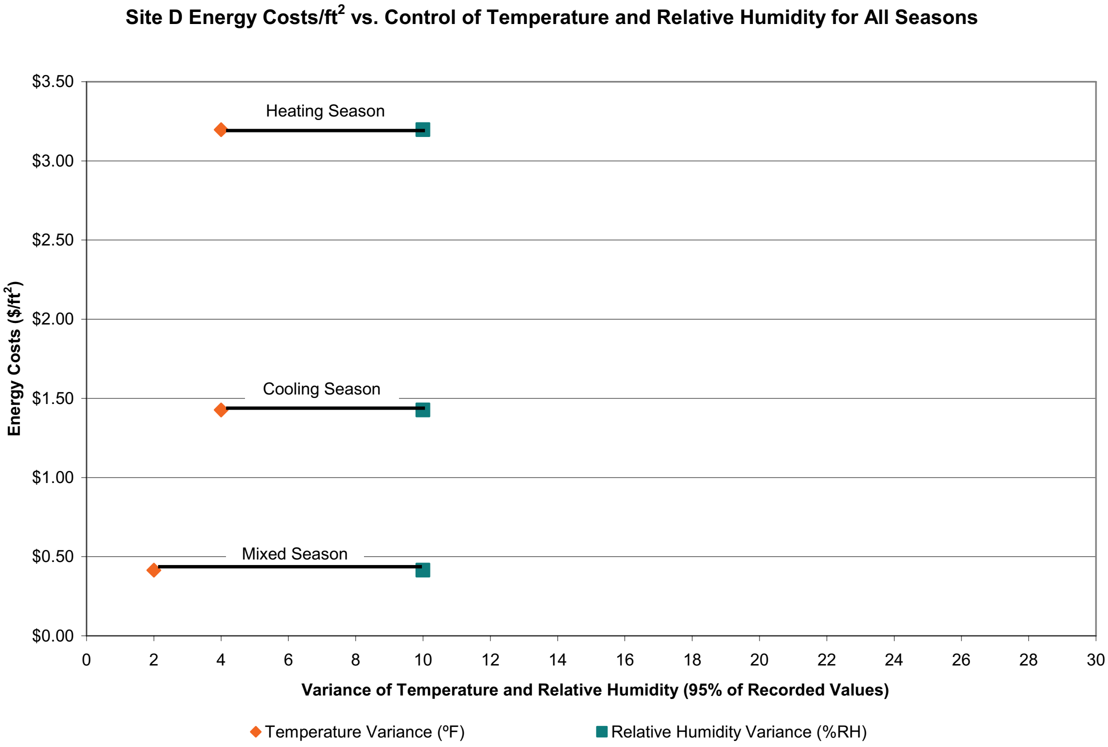


Figure 45: Site D Energy Costs per Square Foot vs. Control of Temperature and Relative Humidity for All Seasons.

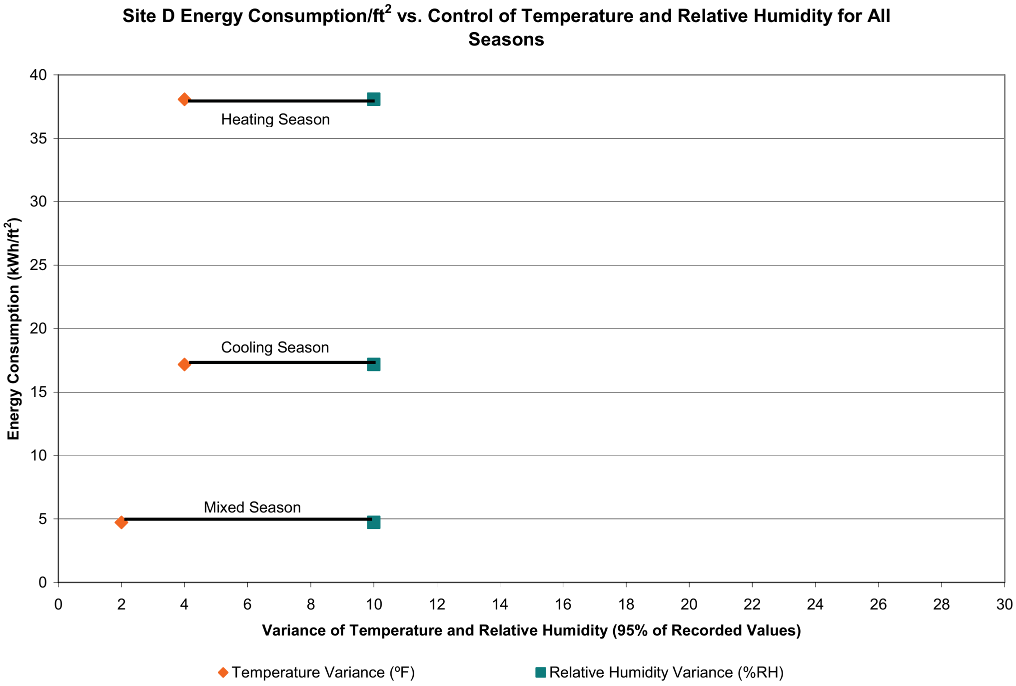


Figure 46: Site D Energy Consumption per Square Foot vs. Control of Temperature and Relative Humidity for All Seasons.

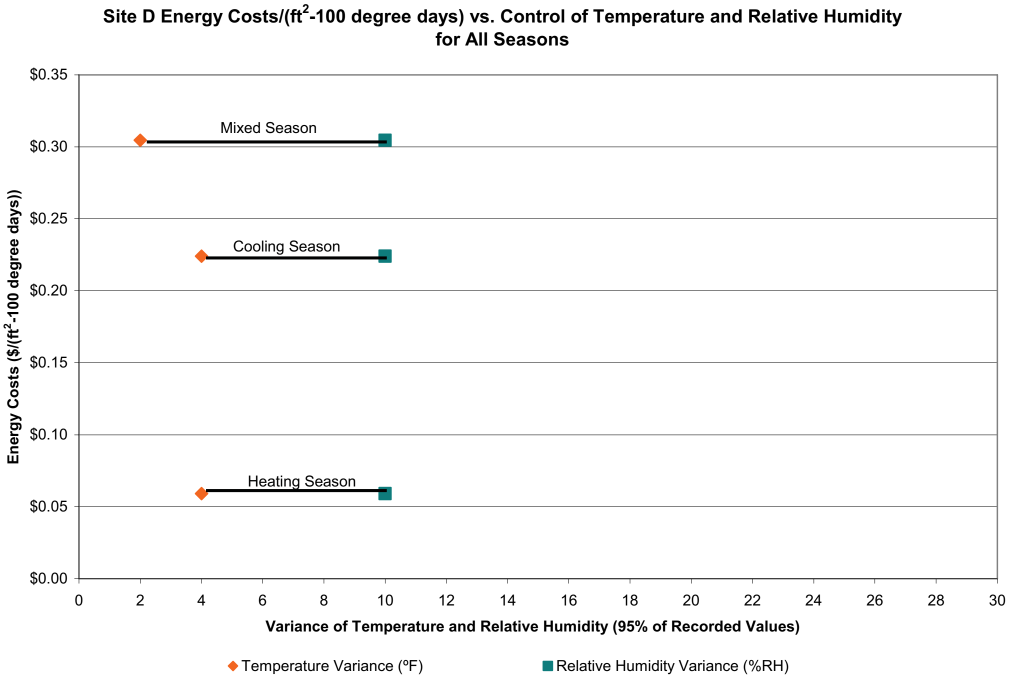


Figure 47: Site D Energy Costs per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Seasons.

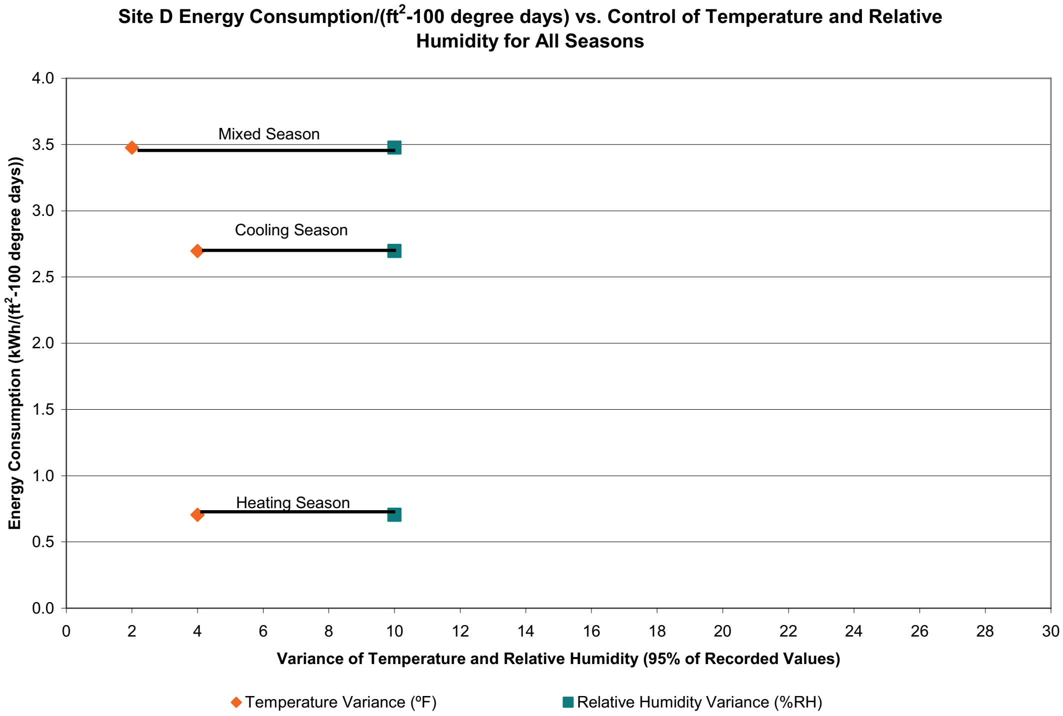


Figure 48: Site D Energy Consumption per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Seasons.

6.6.5 Site E

Figures 49 and 50 show the energy costs per square foot and the energy consumption per square foot plotted against the variance of the indoor temperature and relative humidity for Site E for all three seasons, respectively. These graphs show that Site E spent and consumed the most energy per square foot during the heating season. Figures 51 and 52 are plots of the energy costs and the energy consumption per square foot per 100 degree days versus the control of the indoor environment for Site E for all three seasons, respectively. These graphs show that Site E spent the most and consumed the most energy per degree day during the mixed season, indicating that the climate management system performed the most work for climate management during the mixed season. These graphs also show that Site E exhibited the greatest control over the indoor temperature during the mixed and cooling seasons, and exhibited an equal level of control over the indoor relative humidity for all three seasons.

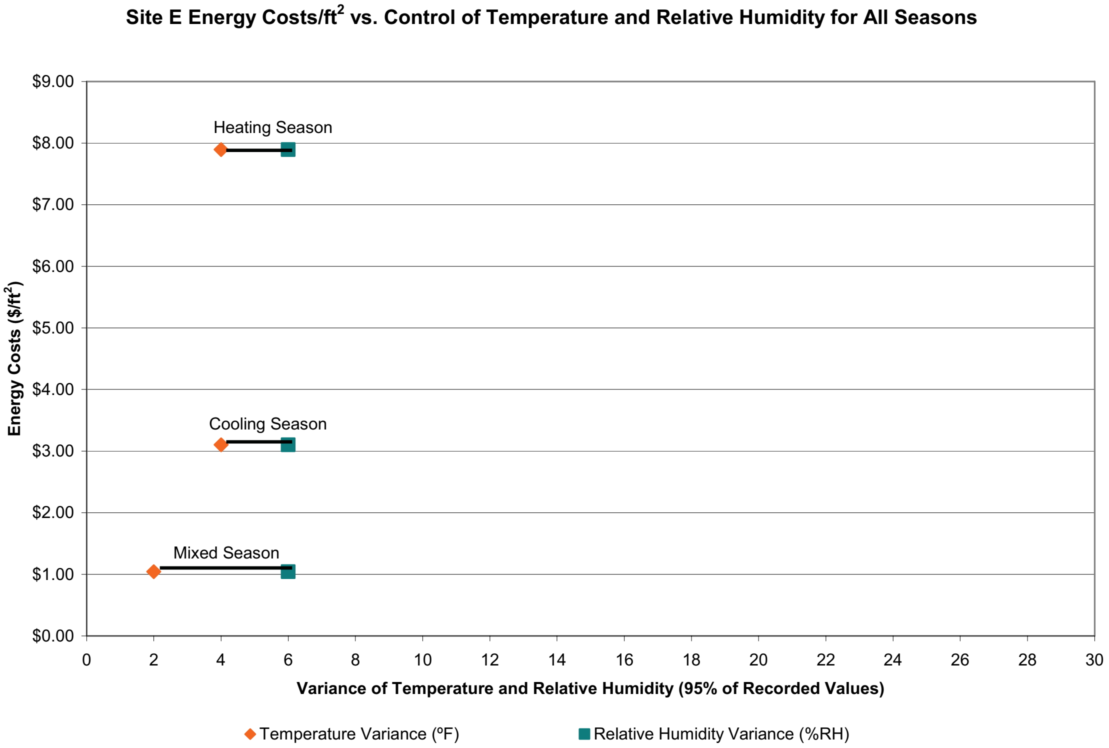


Figure 49: Site E Energy Costs per Square Foot vs. Control of Temperature and Relative Humidity for All Seasons.

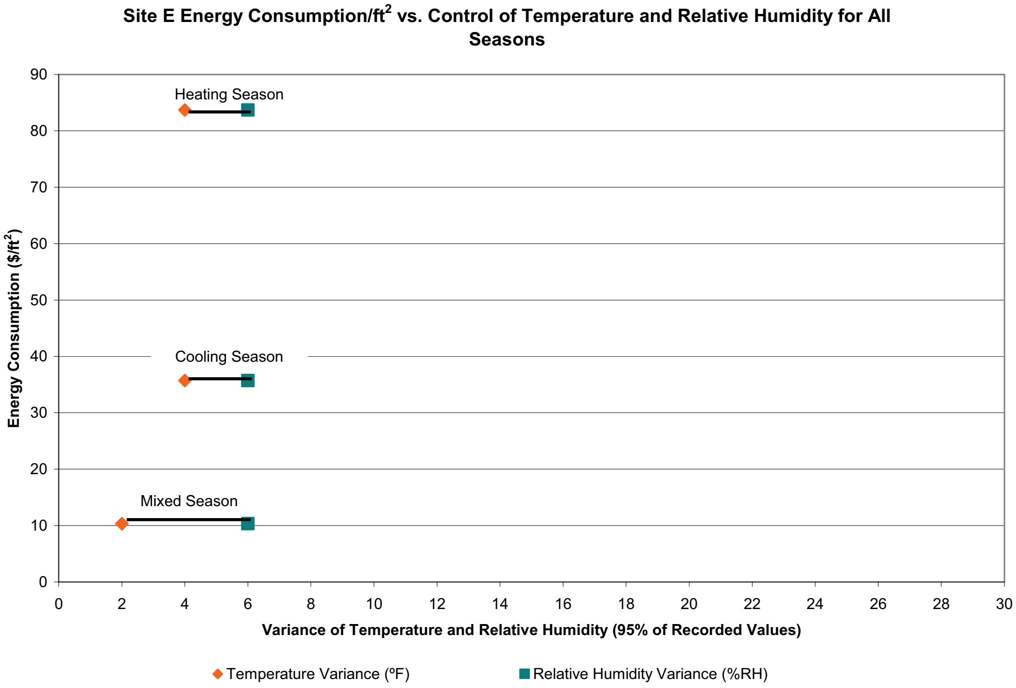


Figure 50: Site E Energy Consumption per Square Foot vs. Control of Temperature and Relative Humidity for All Seasons.

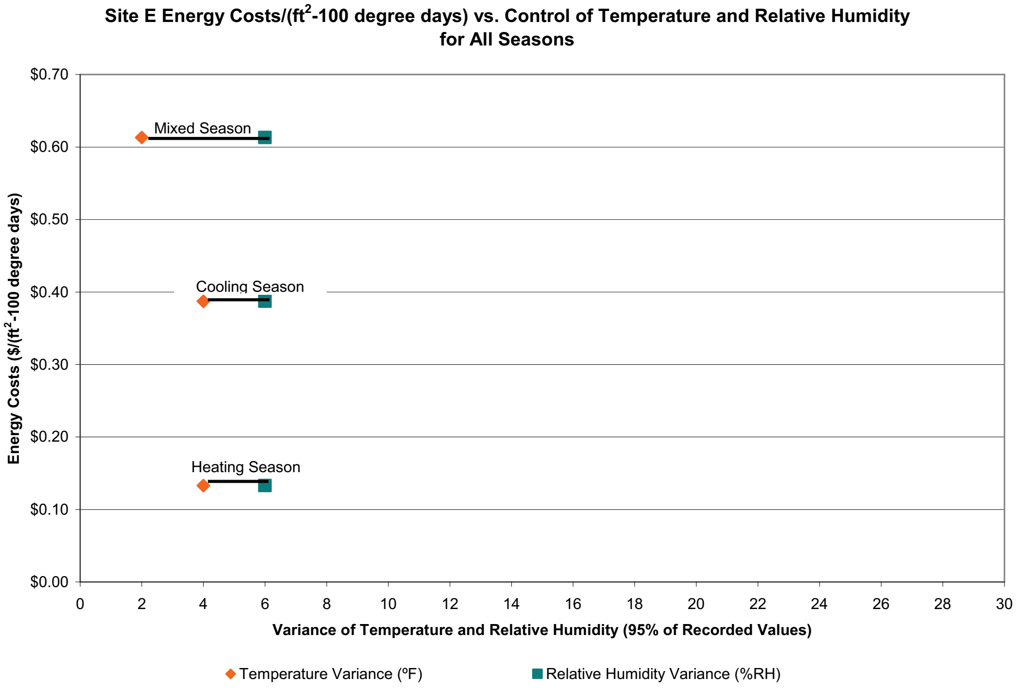


Figure 51: Site E Energy Costs per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Seasons.

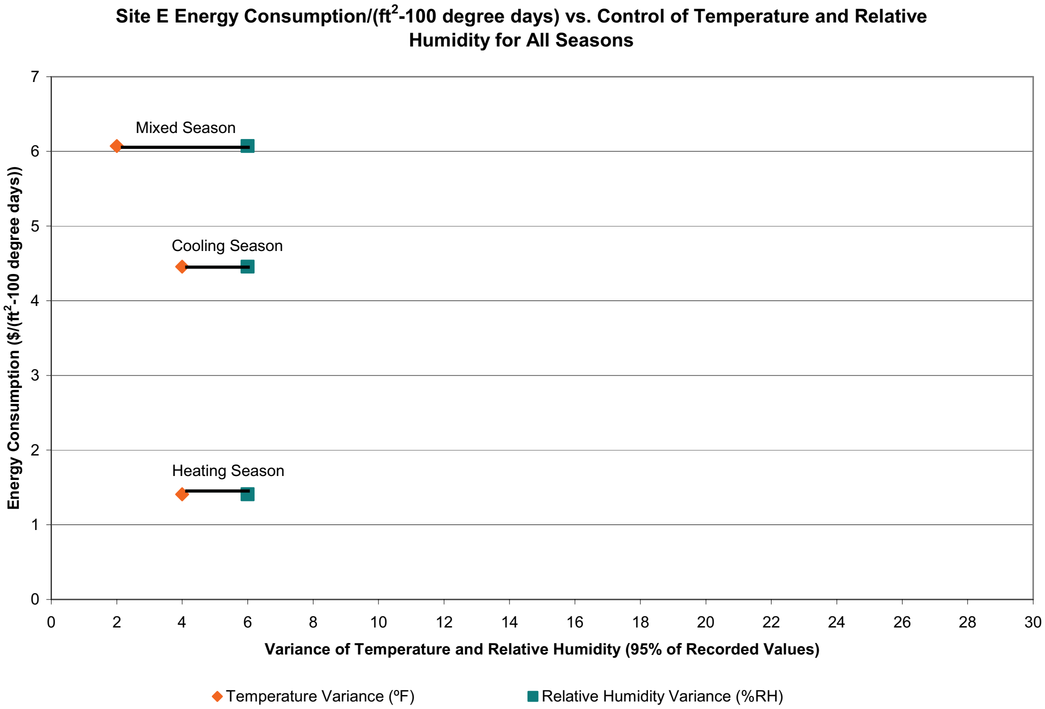


Figure 52: Site E Energy Consumption per Square Foot per 100 Degree Days vs. Control of Temperature and Relative Humidity for All Season.

CHAPTER 7: CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

7.1 CONCLUSIONS

This study began with the hypothesis that tighter control of the indoor temperature and relative humidity in historic buildings and museums requires the sites to spend more for energy and consume more energy to operate their climate management systems. Also, this thesis represents an early attempt to discover the energy costs and consumption that are associated with a given level of environmental control. While a study of five sites is not statistically robust enough to allow one to conclude with any certainty the mathematical relationship between energy costs and consumption and the level of environmental control, this study does give an indication of that relationship, and it serves as an early framework for future investigations into this area.

This study did not include the capital costs that are necessary to design, purchase, and install the climate management systems used by these sites. These costs can be significant, and will play a large role in a site manager's selection of a climate management system. Originally, this thesis intended to include those costs, but it was not possible to obtain the data in the time available. Therefore, only comparisons based upon the operating costs of the systems were made.

For all seasons, heating, cooling, and mixed, the hypothesis was supported. The results of this thesis show an exponential relationship between energy costs and consumption and the variance of the indoor temperature and relative humidity; as the variance increased the energy cost and consumption decreased exponentially. In other words, there is a diminishing level of control with increased energy costs and consumption. This exponential relationship held true for all analyses performed, including when the data were controlled for the size of the site and for the outdoor climate.

When the different seasons are compared, the two sites that try to maintain constant conditions, Sites D and E, had greater energy expenditures per degree day during the cooling season that they did during the heating season, indicating that their systems had to perform more work per degree day for cooling than for heating. For these two sites, the energy costs and consumption per degree day were greatest during the mixed season, indicating that their systems performed the most work per degree day to maintain their indoor environment during this season. While two sites are not enough to make broad generalizations, these results indicate that maintaining constant conditions places the most stress on the climate management system during the mixed season, and the least stress on the system during the heating season.

Unlike Sites D and E, Site B, which uses either heating or ventilation and allows greater variance of the indoor conditions, experienced lower energy expenditures per degree day during the cooling season than the heating season. This result indicates that simpler systems that allow a wider range of conditions will not incur greater stress during the cooling season than the heating season. However, Site B also had the highest energy expenditures per degree day during the mixed season, again indicating that the mixed season will place the greatest stress on a climate management system. Again, more systems and sites need to be studied to show if this trend can be considered generally true.

Site C, which uses heating for human comfort and not to maintain a preservation environment during the heating season, exhibited the least control over the indoor relative humidity during the heating season. Site C also had greater energy expenditures that Site B, which also uses heating, during this season. Two sites cannot be considered indicative of all sites, but these results hint that heating for human comfort results in less control of the indoor conditions, and costs more than heating for a preservation environment. Again, more study is necessary. Other interesting comparisons between sites B and C are for the cooling and mixed seasons, when Site C did not use any form of climate management, and Site B used either heating or ventilation. During these two seasons, Site C actually exhibited equal or greater control over the indoor conditions. However, the differences in the indoor conditions between the two sites may be the result of differences in the outdoor climate or the result of Site B being a free standing structure and Site C having adjacent buildings on two sides. More study of such sites with simple climate management systems is necessary.

The comparisons of the sites on an annual basis mimic the comparisons for the individual seasons. The graphs displaying the annual energy expenditures versus the level of control of temperature or relative humidity individually are reproduced here for reference (see Figures 53 – 56). Again, the results show that energy costs and consumption decrease exponentially as the variance of the indoor conditions increases. The results also generally confirm the class of control for different types of buildings set forth by ASHRAE, though Site D, which is a modern, purpose-built museum, did slightly stray outside the expected level of relative humidity control (classes AA, A, or B) for such buildings when the data were analyzed on an annual basis. When the annual energy costs and consumption were normalized, the results showed that a decreased variance of the indoor conditions caused the energy costs to increase at a faster rate than the energy consumption. This result indicates that the type of system used and the type of fossil fuel used will have a great effect on the energy expenditures. Again, more study is necessary to determine if this result generally holds true.

When compared to Mecklenburg's previous research in this area, it was found that his data showed a greater level of control at the high end of the costs than did the results of this thesis, and that his research showed a higher cost at the low end of control than did the results of this thesis. This discrepancy indicates that it is difficult to establish a mathematical relationship between energy costs and the level of control, and that more research in this area is needed. For both Mecklenburg's research and the results of this thesis, the relationship between energy costs and the level of control was found to be exponential.

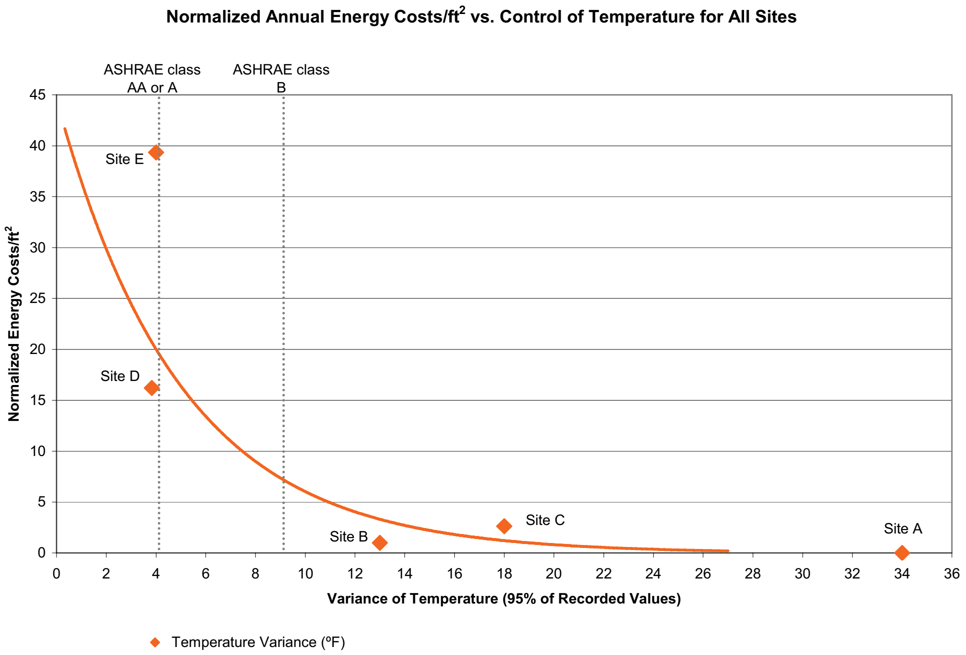


Figure 53: Normalized Annual Energy Costs per Square Foot vs. Control of Temperature for All Sites, Including ASHRAE Classes of Control.

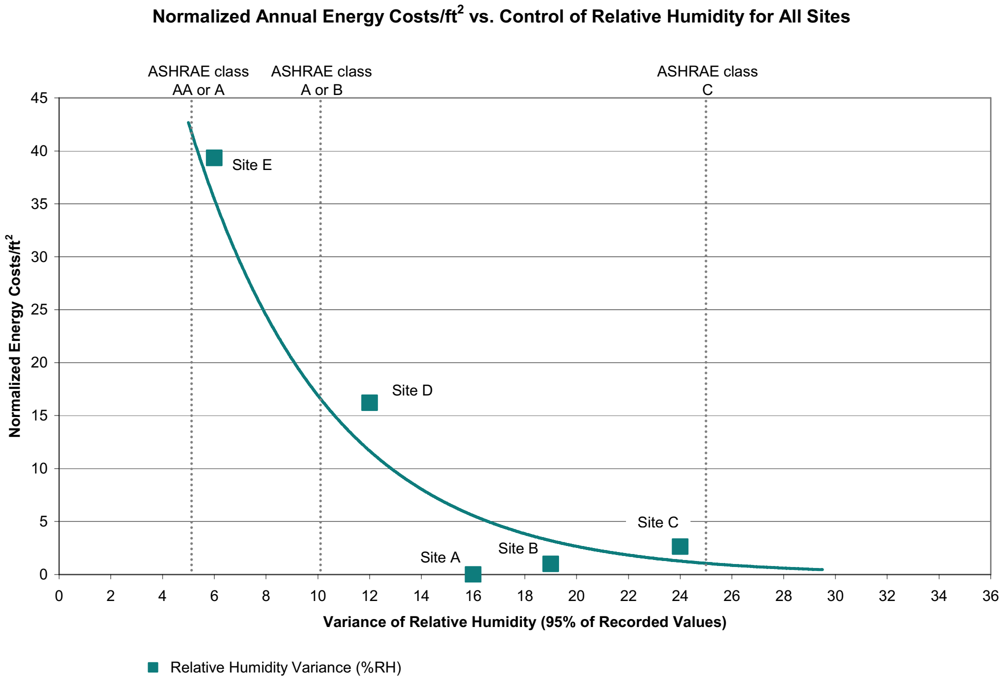


Figure 54: Normalized Annual Energy Costs per Square Foot vs. Control of Relative Humidity for All Sites, Including ASHRAE Classes of Control.

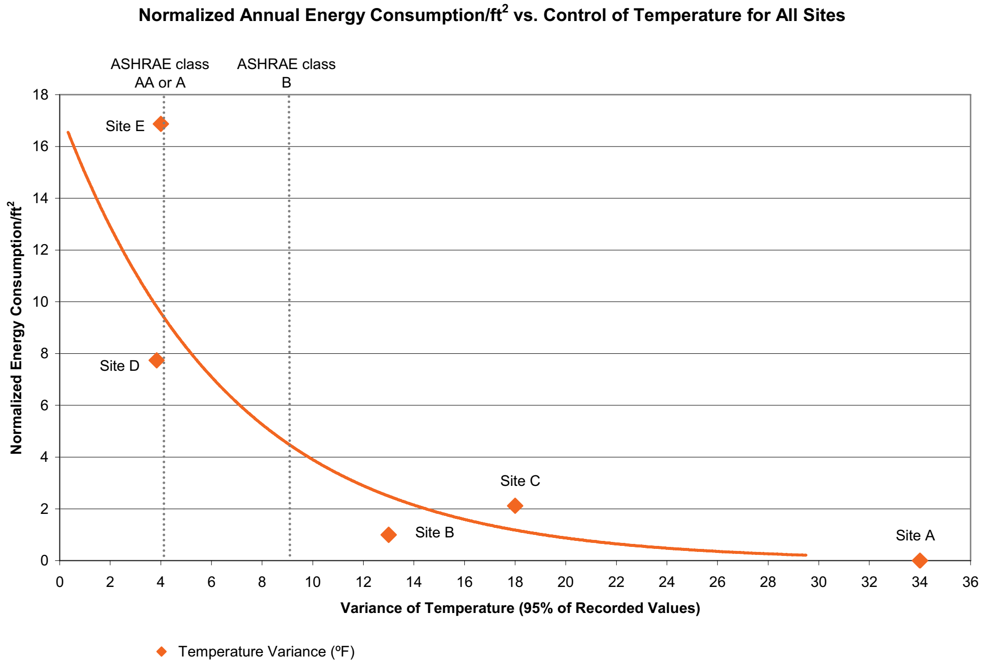


Figure 55: Normalized Annual Energy Consumption per Square Foot vs. Control of Temperature for All Sites, Including ASHRAE Classes of Control.

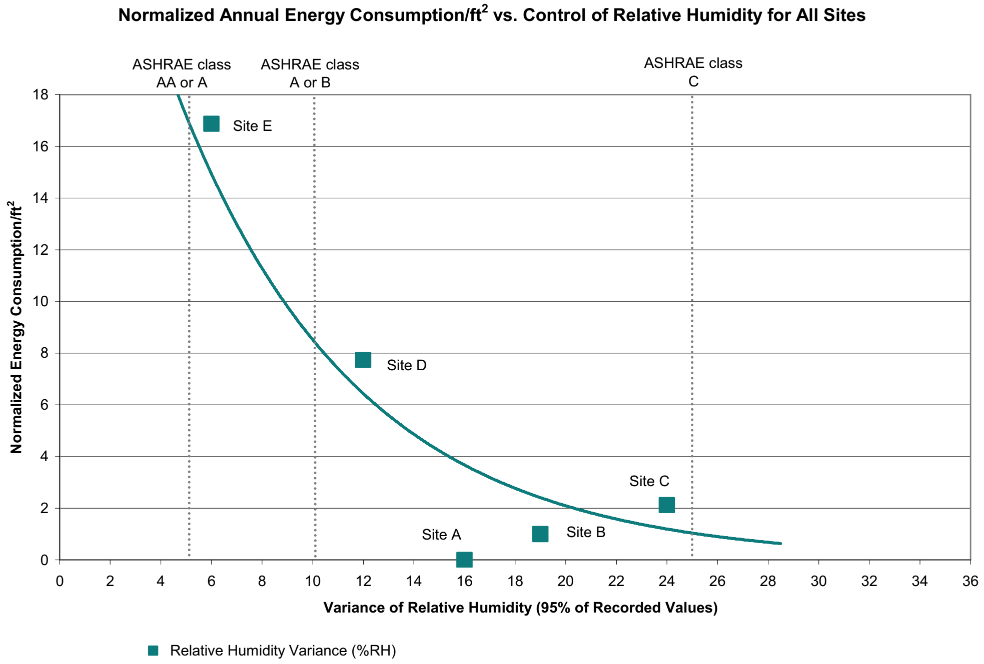


Figure 56: Normalized Annual Energy Consumption per Square Foot vs. Control of Relative Humidity for All Sites, Including ASHRAE Classes of Control.

These graphs also allow the calculation of the factors by which energy cost or consumption increase for the increasing levels of climate control set forth by ASHRAE. These comparisons can be difficult to understand, because ASHRAE sometimes lists more than one level of control for a given classification. Therefore, for ease of understanding, the variance associated with the different classes also is provided. From the results of this study, ASHRAE classes A or AA of control of the temperature (±4ºF) will cost 2.7 times more than Class B (±9ºF), and will consume 2.1 times more energy than class B. ASHRAE classes A or B of control of the relative humidity (±10% RH) will cost 16.1 times more than class C (±25% RH), and classes AA or A of control of the relative humidity (±5% RH) will cost 2.5 times more than classes A or B. Classes A or B of control of the relative humidity will consume 8.2 times more energy than class C, and classes AA or A of control of the relative humidity will consume 2.0 times more energy than classes A or B. These factors are presented in Tables 9 and 10.

Cost and Consumption Factors of Increasing Temperature Control

ASHRAE Class of Control	Cost Factor Increase Over Previous Level of Temperature Control	Consumption Factor Increase Over Previous Level of Temperature Control
C	N/A	N/A
B (±9ºF)	N/A*	N/A*
AA or A (±4ºF)	2.7	2.1

*ASHRAE does not list a variance for the temperature for class C

Table 9: Cost Factors of Increasing Temperature Control.

Cost and Consumption Factors of Increasing Relative Humidity Control

ASHRAE Class of Control	Cost Factor Increase Over Previous Level of Relative Humidity Control	Consumption Factor Increase Over Previous Level of Relative Humidity Control
C (±25% RH)	N/A	N/A
A or B (±10% RH)	16.1	8.2
AA or A (±5% RH)	2.5	2.0

Table 10: Cost Factors of Increasing Relative Humidity Control.

7.2 SUGGESTIONS FOR FURTHER RESEARCH

As stated, there are few published resources for site managers and engineers to consult when determining what type of climate management system or level of control is reasonable for a given site's budget and building construction. Most of the information regarding this area is scattered in the literature, making it difficult to find energy costs and consumption versus the level of environmental control. While this investigation is an early attempt to determine that relationship, the first recommendation for future researchers is to continue to study the relationship between energy expenditures and the level of environmental control. While a study of five historic sites and museums does give an indication of this relationship, a study of only five sites is not statistically robust enough to determine large-scale trends. A study of a greater number of cultural heritage buildings would provide a stronger statistical analysis of the relationship between energy use and the level of control.

The cost of energy to operate a climate management system is only one component of the cost for climate management. Funds also are required to retain a consulting engineer to design the system, to purchase and install the equipment, and to maintain the equipment. As stated, originally this study meant to include those costs in the analysis, but it was not possible to obtain all of that information from all of the sites included in this study in the time available. Future investigations in this area should include those costs, as they can be a large part of the cost of climate management in historic sites and museums.

For all but one site, it was necessary to estimate the proportion of the energy bills that went to the climate management system. While every attempt was made to make those estimates as close to the true value as possible, they still only are estimates. A better approach, though maybe not practical, is to connect a power meter or natural gas meter to the different components of the climate management system that will record their actual energy consumption. If heating oil is used, the exact amount of oil that feeds the furnace or boiler and when it is supplied should be recorded. Such an approach would provide a more accurate analysis of the energy costs and consumption of the climate management equipment.

The final recommendation for future research is to allow more time to collect data from the different sites. This study was completed over eight months, yet that was not enough time to obtain energy bills that completely reflect the period of the provided monitoring data, requiring assumptions to be made regarding the energy consumption of some of the sites for certain months. As this study required site managers to research their records in their free time, of which many of them had very little, it understandably took much longer than anticipated to obtain data.

In short, it is the author’s hope that this thesis will lead to more site managers, preservation engineers, and other preservation professionals investigating the relationship between energy costs and consumption and the level of environmental control those expenditures provide. This study presents one attempt at a framework for such an investigation, and it is hoped that future researchers will refine and improve it as they study this relationship. Doing so will help the preservation community as a whole find affordable ways to preserve the integrity of their historic materials for future generations.

BIBLIOGRAPHY

Ascough, Sean. "The National Gallery Sainsbury Wing Air-Conditioning System: A Combination of Close Control and Energy Efficiency." In *Museums Environment Energy*, Edited by May Cassar, 47-71. London: HMSO, 1994.

Ashley-Smith, Jonathan, Nick Umney and David Ford. "Let's Be Honest – Realistic Environmental Parameters for Loaned Objects." In *Preventive Conservation: Practice, Theory, and Research. Preprints of the Contributions to the Ottawa Congress, 12-16 September, 1994*. Edited by Ashok Roy and Perry Smith, 28-31. London: The International Institute for Conservation of Historic and Artistic Works, 1994.

ASHRAE. *2003 ASHRAE Handbook – Applications*. Atlanta: ASHRAE, 2003.

ASHRAE. 2005 ASHRAE Handbook – Fundamentals. Atlanta: ASHRAE, 2005.

Ayres, J. Marx, J. Carlos Haiad and Henry Lau. *Energy Conservation and Climate Control in Museums*. Marina del Rey: The Getty Conservation Institute, 1988.

Barrette, Bill. "Climate Control: The Egyptian Galleries at the Metropolitan Museum of Art." In *Preprints of the 7th Triennial Meeting, Copenhagen, 10-14 September, 1984*. Edited by Diana de Froment, 84.17.6-84.17.8. Paris: ICOM Committee for Conservation, 1984.

Bell, Stephanie. *Measurement Good Practice Guide No. 11(Issue 2): A Beginners Guide to Uncertainty of Measurement*. Teddington: National Physical Laboratory, 2001.

Bobenhausen, William. *Simplified Design of HVAC Systems*. New York: John Wiley & Sons, Inc., 1994.

Bordass, William T. "Museum Environments and Energy Efficiency: Are Our Priorities Right?" In *Museums Environment Energy*, Edited by May Cassar, 5-16. London: HMSO, 1994.

Brown, J. P. and William B. Rose. "Humidity and Moisture in Historic Buildings: The Origins of Building and Object Conservation." *APT Bulletin* 27, no. 3 (1996): 12-23.

Brown, Jonathan P. "Hygrometric Measurement in Museums: Calibration, Accuracy, and the Specification of Relative Humidity." In *Preventive Conservation: Practice, Theory, and Research. Preprints of the Contributions to the Ottawa Congress, 12-16 September, 1994*. Edited by Ashok Roy and Perry Smith, 39-43.

London: The International Institute for Conservation of Historic and Artistic Works, 1994.

Cassar, May. *Environmental Management.* London: Routledge, 1995.

Carll, Charles G. and Terry L. Highley. "Decay of Wood and Wood-Based Products above Ground in Buildings." *Journal of Testing and Evaluation* 27, no. 2 (1999):150-158.

The Chicora Foundation. *Managing the Museum Environment*. (1994). http://palimpsest.stanford.edu/byorg/chicora/chicenv.html. (31 October 2006).

The Chicora Foundation. *Mold.* (2003). http://www.chicora.org/mold.htm. (5 November 2006).

Chimack, Michael J., Christine E. Walker and Ellen Franconi. "Determining Baseline Energy Consumption and Peak Cooling Loads of a 107-Year Old Science Museum Using DOE 2.1E." Presented at the Seventh International IBPSA Conference, Rio de Janeiro, August 13-15, 2001, 196. http://www.simulationresearch.lbl.gov/dirpubs/BS01/BS01_191.pdf. (25 February 2007).

Christoffersen, Lars D. "Resource Saving Storage of Historic Material." In *Preprints of the 10th Triennial Meeting, Washington, D.C., 22-27 August 1993*. Edited by Janet Bridgland, 601-604. Paris: ICOM Committee for Conservation, 1993.

Conrad, Ernest A. "The Dews and Don'ts of Insulating." *Old-House Journal* 24, no. 3 (1996): 36-41.

Conrad, Ernest A. *The Realistic Preservation Environment*. (1999). http://www.archives.gov/preservation/storage/realistic-preservation-environment.html. (18 October 2006).

Curtis, Peter S. "Control Fundamentals." In *Handbook of Heating, Ventilation, and Air-Conditioning*. Edited by Jan F. Kreider, 5-1 – 5-46. New York: CRC Press, 2001.

Erhardt, David and Marion Mecklenburg. Relative Humidity Re-Examined." In *Preventive Conservation: Practice, Theory, and Research. Preprints of the Contributions to the Ottawa Congress, 12-16 September, 1994*. Edited by Ashok Roy and Perry Smith, 32-38. London: The International Institute for Conservation of Historic and Artistic Works, 1994.

Erhardt, David, Marion F. Mecklenburg, Charles S. Tumosa, & Mark McCormick-Goodhart. "The Determination of Allowable RH Fluctuations." *WAAC*

Newslatter 17, no. 1 (1995): 19-23. http://palimpsest.stanford.edu/waac/wn/wn17/wn17-1/wn17-108.html. (12 October 2006).

Feilden, Bernard M. *Conservation of Historic Buildings*. Boston: Butterworth-Heinemann Ltd., 1994.

Franconi, Ellen M. and James B. Bradford. "Ventilation and Air Handling Systems." In *Handbook of Heating, Ventilation, and Air-Conditioning*. Edited by Jan F. Kreider, 4-67 – 4-107. New York: CRC Press, 2001.

Frost, Murray. "Working with Design Professionals: Preventive Conservators as Problem Solvers, not Problem Creators." In *Preventive Conservation: Practice, Theory, and Research. Preprints of the Contributions to the Ottawa Congress, 12-16 September, 1994*. Edited by Ashok Roy and Perry Smith, 21-23. London: The International Institute for Conservation of Historic and Artistic Works, 1994.

Graeme, Scott. "Moisture, Ventilation, and Mould Growth." In *Preventive Conservation: Practice, Theory, and Research. Preprints of the Contributions to the Ottawa Congress, 12-16 September, 1994*. Edited by Ashok Roy and Perry Smith, 149-153. London: The International Institute for Conservation of Historic and Artistic Works, 1994.

Harris, Samuel Y. *Building Pathology: Deterioration, Diagnostic, and Intervention*. New York: John Wiley & Sons, Inc., 2001.

Hassani, Vahab and Steve Hauser. "Thermodynamics and Heat Transfer Basics." In *Handbook of Heating, Ventilation, and Air-Conditioning*. Edited by Jan F. Kreider, 2-1 – 2-75. New York: CRC Press, 2001.

Kerschner, Richard L. "A Practical Approach to Environmental Requirements for Collections in Historic Buildings." Journal of the American Institute for Conservation 31, no. 1 (1992): 65-76.

Kerschner, Richard L. "Providing Safe and Practical Environments for Cultural Properties in Historic Buildings…and Beyond." Presented at the 20th Annual National Archives Preservation Conference, Beyond the Numbers: Specifying and Achieving an Efficient Preservation Environment. March 16, 2006. www.archives.gov/preservation/conferences/2006/kerschner.pdf. (31 October 2006).

Kreider, Jan F. "Heating Systems." In *Handbook of Heating, Ventilation, and Air-Conditioning*. Edited by Jan F. Kreider, 4-1 – 4-29. New York: CRC Press, 2001.

Lafontaine, Raymond H. "Humidistatically Controlled Heating: A New Approach to Relative Humidity Control in Museums Closed for the Winter Season." *Journal of the International Institute for Conservation* 7, no. 1/2 (1982): 35-41.

Lafontaine, Raymond H. and Stefan Michalski. "The Control of Relative Humidity – Recent Developments." In *Preprints of the 7th Triennial Meeting, Copenhagen, 10-14 September, 1984*. Edited by Diana de Froment, 84.17.33-84.17.37. Paris: ICOM Committee for Conservation, 1984.

Lstiburek, Joseph. "Investigating & Diagnosing Moisture Problems." *ASHRAE Journal, December* (2002): 36-41.

Lstiburek, Joseph and John Carmody. *Moisture Control Handbook: Principles and Practices for Residential and Small Commercial Buildings*. New York: Van Nostrand Reinhold, 1993.

Maekawa, Shin and Franciza Toledo. "A Climate Control System for Hollybourne Cottage, Jekyll Island Historic District, Georgia." (2001). http://www.getty.edu/conservation/publications/pdf_publications/iaq453.pdf. (7 October 2006).

Matilainen, Miimu and Jarek Kurnistki. "Moisture Conditions in Highly Insulated Outdoor Ventilated Crawl Spaces in Cold Climates." *Energy and Buildings* 35 (2003): 175-187.

Mecklenburg, Marion F., Charles S. Tumosa, and Alan Pride. "Preserving Legacy Buildings." *HVAC Retrofit – A Supplement to the ASHRAE Journal*, June (2004): S18-S23.

Michalski, Stefan. "Relative Humidity: A Discussion of Correct/Incorrect Values." In *Preprints of the 10th Triennial Meeting, Washington, D.C., 22-27 August 1993*. Edited by Janet Bridgland, 624-629. Paris: ICOM Committee for Conservation, 1993.

O'Neal, Dennis L. and John A. Bryant. "Air-Conditioning Systems." In *Handbook of Heating, Ventilation, and Air-Conditioning*. Edited by Jan F. Kreider, 4-29 – 4-67. New York: CRC Press, 2001.

Oreszczyn, Tadj, May Cassar and Keith Fernandez. "Comparative Study of Air-Conditioned and Non Air-Conditioned Museums." In *Preventive Conservation: Practice, Theory, and Research. Preprints of the Contributions to the Ottawa Congress, 12-16 September, 1994*. Edited by Ashok Roy and Perry Smith, 144-148. London: The International Institute for Conservation of Historic and Artistic Works, 1994.

Oreszczyn, Tadj, Tim Mullany and Caitriona NiRiain. "A Survey of Energy Use in Museums and Galleries." In *Museums Environment Energy*, Edited by May Cassar, 17-37. London: HMSO, 1994.

Padfield, Tim. "How Air-conditioning Works." http://www.natmus.dk/cons/tp/aircon/aircon.pdf. (19 October 2006).

Padfield, Tim. "The Role of Standards and Guidelines: Are they a Substitute for Understanding a Problem or a Protection Against the Consequences of Ignorance?" In *Durability and Change: Science, Responsibility and Cost of Sustaining Cultural Heritage*. Edited by W. E. Krumbein, P. Brimblecombe, D. E. Cosgrove, and S. Staniforth. New York: John Wiley and Sons, 1994, 191-199. http://www.natmus.dk/cons/tp/ppubs/dahlem.pdf (31 October 2006).

Padfield, Tim, Peder Bøllingtoft, Bent Esjøj and Mads Chr. Christensen. "The Wall Paintings of Gundsmøgle Church, Denmark." In *Preventive Conservation: Practice, Theory, and Research. Preprints of the Contributions to the Ottawa Congress, 12-16 September, 1994*. Edited by Ashok Roy and Perry Smith, 94-98. London: The International Institute for Conservation of Historic and Artistic Works, 1994.

Park, Sharon C. "Holding the Line: Controlling Unwanted Moisture in Historic Buildings." National Park Service Preservation Brief #39. (1996). http://www.cr.nps.gov/hps/tps/briefs/brief39.htm. (4 November 2006).

Reading, Alfred. "Air-Conditioning, Energy Efficiency, and Environmental Control: Can All Three Co-Exist?" In *Museums Environment Energy*. Edited by May Cassar, 39-46. London: HMSO, 1994.

Rose, William B. "Effects of Climate Control on the Museum Building Envelope." *Journal of the American Institute for Conservation* 33, no. 2 (1994): 199-210.

Royal Ontario Museum. *In Search of the Black Box: A Report on the Proceedings of a Workshop on MNicro-Climates Held at the Royal Ontario Museum, February 1978*. Toronto: The Royal Ontario Museum, 1979.

Straube, John F. "Moisture, Materials, and Buildings." *HPAC Engineering*, April (2002): 37-46.

Stowlow, Nathan. "The Preservation of Historic Houses and Sites: The Interface of Architectural Restoration and Collection/Display Conservation Principles." In *Preventive Conservation: Practice, Theory, and Research. Preprints of the Contributions to the Ottawa Congress, 12-16 September, 1994*. Edited by Ashok Roy and Perry Smith, 116-122. London: The International Institute for Conservation of Historic and Artistic Works, 1994.

Thomson, Garry. *Museum Environment, 2nd ed.* Boston: Butterworth-Heinemann, 1986.

U.S. Environmental Protection Agency. *Building Air Quality: A Guide for Building Owners and Facility Managers*. Washington, D.C.: U.S. Government Printing Office, 1991.

U.S. Environmental Protection Agency. "Indoor Air Facts No. 8: Use and Care of Home Humidifiers." (February, 1991). http://www.epa.gov/iaq/pubs/humidif.html#Types%20of%20Humidifiers%20and%20Associated%20Pollutants (3 March 2007).

Van Wylen, Gordon, Richard Sonntag and Claus Borgnakke. *Fundamentals of Classical Thermodynamics*. New York: John Wiley & Sons, Inc., 1994.

Visser, Thomas D. "A Primer on Conservation Assessments and Emergency Stabilization for Historic Farm Buildings." *APT Bulletin* 25, no. 3/4 (1993): 64-69.

Wilson, William K. *Environmental Guidelines for the Storage of Paper Records, NISO Technical Report*. Bethesda: NISO, 1995.

APPENDIX A: SITE A – DESCRIPTION, DATA, AND RESULTS

A.1 DESCRIPTION OF SITE A

Site A is located in Vermont. It is a 1 ½ storey wood-frame building with clapboard siding, and faces west. The approximate year of construction of the building is 1832. The total floor area is 3843 ft^2, split between two levels. There is no vapor barrier or insulation in the wall envelope, but there is a plastic sheet ground cover over a dirt floor. Site A is a free-standing structure, and has fenestration on all four sides of the building. Originally a residence, Site A was moved from its original location to its present site and now houses a collection of carved and painted wooden artifacts that are on public display. The site is open to the public from the end of May to the end of October, and is closed during the other months. During the period of the year that visitors are allowed, the site is open from 10:00 AM – 5:00 PM daily.

A.2 SITE A – CLIMATE MANAGEMENT SYSTEM

Site A does not have any form of climate management. This site was included in this study to indicate what type of indoor environment one can expect in a building with a poorly-sealed envelope and no control exerted over the indoor climate.

Because the building is a wood-frame, clapboard building on the exterior and has plaster-lath walls on the interior, according to ASHRAE's building classification matrix this building is identified as building class III, for which they recommend heating and ventilation to manage the indoor climate. Using the recommended forms of climate management, the possible class of control listed is C, indicating that it is reasonable to attempt to maintain the temperature below 77°F and the relative humidity between 25 – 75% RH in the building (see Tables 2 and 3).

A.3 SITE A – PROVIDED DATA

Monitoring data was provided for the period of January 1997 to December 1997. The monitoring of the indoor climate is preformed by an electronic data logger that records the indoor temperature and relative humidity once pre day. It would be better to have the temperature and relative humidity recorded at least once per hour, because a measurement taken only once per day does not indicate how the indoor climate reacts to the cycle of outdoor temperature and relative humidity that occurs over the course of a day. However, because this study is dependent upon what the site managers can provide, it will have to suffice, and still will give some indication of the indoor climate of the building. Of course, because the building has no climate management system, the energy costs and consumption for climate management associated with this site are zero, so there was no need to provide energy bills.

A.4 SITE A – DIVISION OF SEASONS

By analyzing the engineering climate data[201] for the period of the monitoring data, the heating season for Site A lasted from January 1997 – May 1997, and from September 1997 – December 1997. During the summer months there actually were more heating degree days than cooling degree days, 207 to 182. Therefore, the months of June, July, and August 1997 will be treated as a mixed season, and not as the cooling season, as one

---

[201] Engineering climate data was downloaded from the National Climatic Data Center website: http://www.ncdc.noaa.gov/oa/mpp/freedata.html.

typically would expect for the summer months. The engineering climate data is presented in Table 11 and Figure 57.

Vermont Heating and Cooling Degree Days

Month - Year	Heating DD	Cooling DD
JAN 1997	1488	0
FEB 1997	1154	0
MAR 1997	1210	0
APR 1997	776	0
MAY 1997	493	0
JUN 1997	68	49
JUL 1997	46	75
AUG 1997	93	58
SEP 1997	265	4
OCT 1997	635	0
NOV 1997	964	0
DEC 1997	1262	0

Table 11: Engineering Climate Data for Site A (source: National Climatic Data Center).

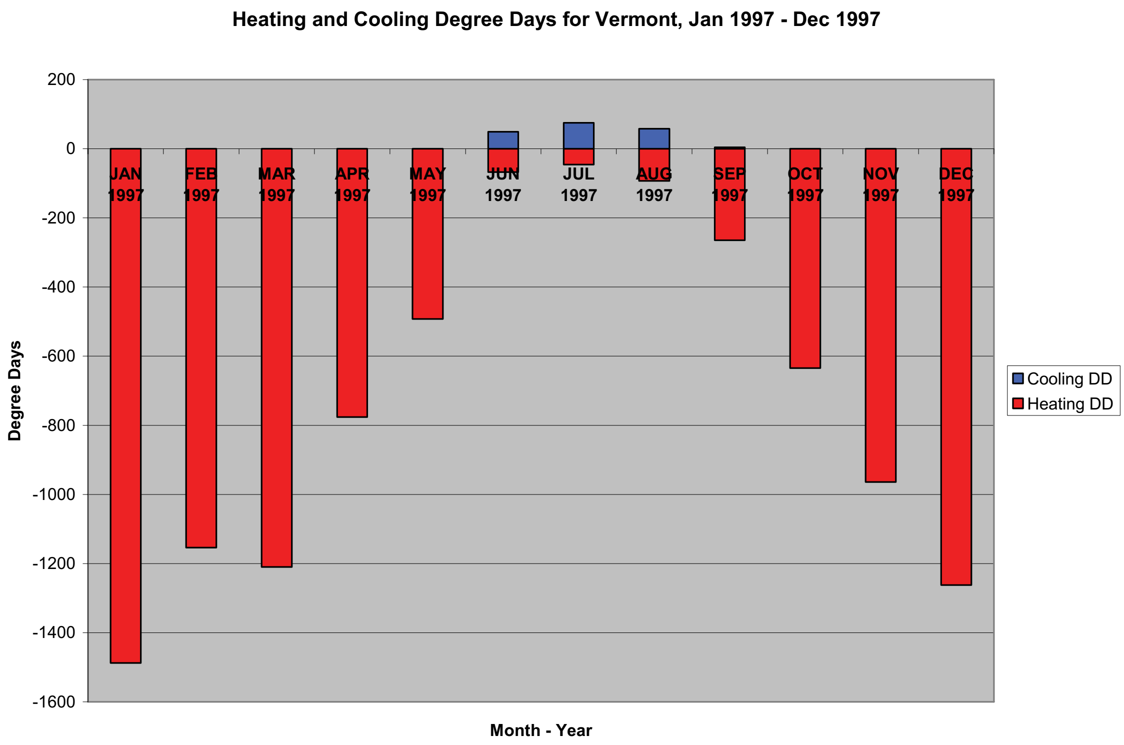


Figure 57: Graph of Heating and Cooling Degree Days for Site A.

A.5 SITE A – RESULTS FOR THE HEATING SEASON

A.5.1 Indoor Environment During the Heating Season

The heating season for Site A lasted from January 1997 – May 1997, and from September 1997 – December 1997. During the heating season there were 8247 heating degree days.

During the heating season, the average indoor temperature was 50°F. The standard deviation for the indoor temperature was 14°F, indicating a variance of the indoor temperature of 28°F. The average indoor relative humidity was 52% RH. The standard deviation for the indoor relative humidity was 6% RH, indicating that the variance of the indoor relative humidity was 12% RH. Therefore, Site A's indoor climate during the heating season for the period under consideration was 50°F ±28°F and 52% RH ±12% RH.

A.5.2 Energy Costs and Consumption During the Heating Season

Site A does not use any form of climate management; therefore, their energy costs and consumption for the heating season are zero.

A.6 SITE A – RESULTS FOR THE COOLING SEASON

According to the engineering climate data, Site A did not experience a true cooling season during the period under consideration; therefore, there is no analysis of the monitoring data for the cooling season.

A.7 SITE A – RESULTS FOR THE MIXED SEASON

A.7.1 Indoor Environment During the Mixed Season

The mixed season for Site A was the months of June – August 2002. Though these months typically are part of the cooling season, they were classified as mixed season months, as explained above. The number of heating degree days for Site A during June – August 2002 was 207, and the number of cooling degree days was 182.

During the mixed season, the average indoor temperature for Site A was 77°F. The standard deviation for the indoor temperature was 6°F, indicating that the variance of the indoor temperature was 12°F. The average indoor relative humidity was 61% RH. The standard deviation for the indoor relative humidity was 7% RH, indicating that the variance of the indoor relative humidity was 14% RH. Therefore, during the mixed season, Site A was able to maintain an indoor climate of 77°F ±12°F and 61% RH ±14% RH.

A.7.2 Energy Costs and Consumption During the Mixed Season

Site A does not use any form of climate management; therefore, their energy costs and consumption for the mixed season are zero.

APPENDIX B: SITE B – DESCRIPTION, DATA, AND RESULTS

B.1 DESCRIPTION OF SITE B

Site B is located in Virginia. The building is a 2 ½ storey limestone masonry structure, and faces south. The bottom story is one-half below grade. The original years of construction for the building are 1794 – 1797, with an addition constructed in 1815. The basement and main storey each have a floor area of 4480 ft^2, and the attic has a floor area of 980 ft^2, making a total of 9940 ft^2. The building envelope is comprised of load-bearing limestone masonry on the exterior and plaster-lath on the interior, no vapor barrier or insulation is present. Site B is a free-standing structure, and fenestration is present on all four sides of the building. Originally a residence, site B now functions as a house museum, and is open to the public April – October, and on selected weekends during November. When it is open, the hours of operation are 10:00 AM – 3:00 PM Monday through Saturday, and 1:00 PM – 4:00 PM on Sundays.

B.2 SITE B – CLIMATE MANAGEMENT SYSTEM

The climate management system at Site B is comprised of an oil-fired furnace (#2 fuel oil) that uses ductwork to deliver the hot air to the interior spaces during the heating season, and a ventilation fan that exhausts the indoor air and draws outdoor air into the building during the cooling season. No form of mechanical cooling is used in the building.

Because the building envelope is comprised of a limestone masonry exterior with plaster-lath interior walls, and no insulation or vapor barrier, it was placed in ASHRAE's building classification III, for which they recommend heating and ventilation to manage the indoor climate. Using the recommended forms of climate management, the possible class of control listed is C, indicating that it is reasonable to attempt to maintain the temperature below 77°F and the relative humidity between 25 – 75% RH in the building (see Tables 2 and 3).

B.3 SITE B – PROVIDED DATA

Monitoring data for Site B was provided for October 2002 – September 2003. The temperature and relative humidity were recoded in seven locations throughout the building once every 30 minutes by electronic data loggers. Also, an outdoor data logger recorded the outdoor temperature and relative humidity once every thirty minutes. The external data logger was not included in this study, as this study in concerned with the indoor environment only. The monitoring data that was supplied is incomplete. Some data loggers did not operate correctly at different points in time, and large amounts of data are missing. However, at least half of the data loggers were operating at any one time, giving some representation of the indoor climate for the full twelve month period.

The electricity bills were collected for the period of this study. These bills list both the electricity consumption (kWh) and the final dollar-amount costs. It must be noted that the electricity consumption for November 2002 was estimated. There is no way to know what percentage of the electrical energy bill was used for climate management, but certain assumptions can be made. The Engineer who designed the system related that it can be assumed that the oil-fired furnace consumes 0.56 kW of electrical power while operating, and that the system runs for 6 hours a day during the heating season. Multiplying these two values indicates that the furnace consumes an estimated 3.4 kWh of electrical energy per day. It is known that the ventilation fan used during the cooling season consumes 0.746 kW of electrical power when operating, and the Engineer who designed the system communicated that it is meant to run for 6 hours a day. Multiplying 0.746 kW by the assumed operating time of 6 hours per day, the ventilation fan consumed an estimated 4.5 kWh of electrical energy per day during the cooling season.

The heating oil bills for the period of this study also were provided; they list both the oil consumption (gallons) and the final dollar-amount costs. It will be assumed that all of the heating oil purchased by Site B was consumed by the climate management system. Because heating oil is delivered when required or ordered and can be stored before use, certain assumptions concerning the oil consumption must be made to determine how much oil was consumed during the periods that heating was required. During the coldest months of the heating season (November 2002 – March 2003), Site B purchased an average of approximately 280 gallons of oil per month. During this period there was an average of 793 heating degree days per month. 280 gallons divided by 793 degree days equals 0.35 gal./(degree day). Therefore, it will be assumed that Site B consumed approximately 0.35 gal./(degree day) when heating was required.

B.4 SITE B – DIVISION OF SEASONS

Site B provided monitoring data for the period of October 2002 – September 2003. By analyzing the engineering climate data[202] for this period, the heating season lasted from October 2002 – April 2003, and the cooling season lasted from June 2003 – August 2003. Because of the number of both heating degree days and cooling degree days during the months of May 2003 and September 2003, these months were classified as the mixed season. The engineering climate data is presented in Table 12 and Figure 58.

Virginia Heating and Cooling Degree Days

Month - Year	Heating DD	Cooling DD
OCT 2002	245	20
NOV 2002	592	0
DEC 2002	903	0
JAN 2003	1059	0
FEB 2003	861	0
MAR 2003	548	2
APR 2003	316	2
MAY 2003	138	42
JUN 2003	14	168
JUL 2003	0	324
AUG 2003	0	356
SEP 2003	39	126

Table 12: Engineering Climate Data for Site B (source: National Climatic Data Center).

---

[202] Engineering climate data was downloaded from the National Climatic Data Center website: http://www.ncdc.noaa.gov/oa/mpp/freedata.html.

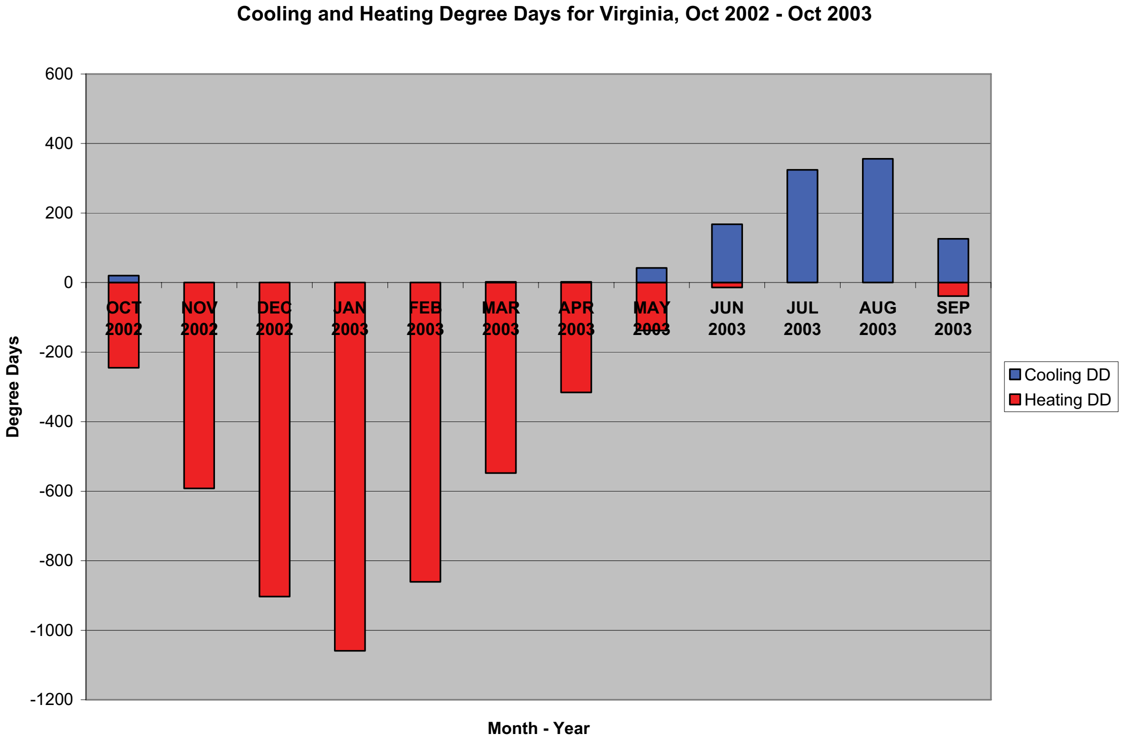


Figure 58: Graph of Heating and Cooling Degree Days for Site B.

B.5 SITE B – RESULTS FOR THE HEATING SEASON

B.5.1 Indoor Environment During the Heating Season

The heating season for Site B during the studied period lasted from October 2002 – April 2003. During this period there were 4524 heating degree days.

The average indoor temperature of all values recorded by Site B's data loggers during the heating season was 56ºF. The standard deviation of the entire temperature record during the heating season was 7ºF, indicating that the variance of the indoor temperature during the heating season was ±14ºF.

The average indoor relative humidity of all values recorded by Site B's data loggers during the heating season was 41% RH. The standard deviation of the entire relative humidity record was 11% RH, indicating that the variance of the indoor relative humidity during the heating season was ±22% RH.

Overall, during the heating season, Site B was able to maintain an indoor climate of 56°F ±14°F and 41% RH ±22% RH.

B.5.2 Energy Costs and Consumption During the Heating Season

As stated, the heating season for Site B lasted from October 2002 – April 2003. See Table 13 for a presentation of the monthly electricity charges for Site B for the heating season. During the heating season, Site B spent a total of $1814.19 for electrical energy, and consumed a total of 25,321 kWh of electrical energy. Assuming that the oil-fired furnace consumed 3.4 kWh per day of electrical energy during the heating season, the climate management system consumed an estimated total of 724.2 kWh, or 29% of the total consumption. Taking 29% of the total dollar-amount cost yields that Site B spent an estimated $526.12 for electricity to operate the furnace. When these values are divided by the floor area of the building (9940 ft^2), Site B spent \$0.053/ft^2 on electrical energy to operate the climate management system during the heating season, and consumed 0.073 kWh/ft^2 of electrical energy.

There was a total of 4524 heating degree days during the cooling season for Site B. Dividing the energy consumption and costs per square foot by the total number of heating degree days divided by 100 yields that Site B spent \$0.0012/(ft^2-100 degree days) on electrical energy, and consumed 0.0016 kWh/(ft^2-100 degree days) to operate the climate management system during the heating season.

Electricity Bill Data For Site B During the Heating Season

Bill Month	Total Charges	Estimated Charges for Climate Management (29% of Total Charges)	Total Energy Use (kWh)	Estimated Energy Use for Climate Management (kWh)	Notes
OCT 2002	$164.24	$47.63	2030	98.6	
NOV 2002	$166.79	$48.37	2263	105.4	Estimated Consumption
DEC 2002	$333.18	$96.62	4916	108.8	
JAN 2003	$359.21	$104.17	5420	98.6	
FEB 2003	$349.36	$101.31	4992	112.2	
MAR 2003	$256.04	$74.25	3255	98.6	
APR 2003	$185.37	$53.76	2445	102	
Total	**$1,814.19**	**$526.12**	**25321**	**724.2**	

Table 13: Electricity Bill Data For Site B During the Heating Season.

The heating oil bill data for Site B is presented in Table 14; this table lists all provided oil data, not just the data for the heating season. As explained above, it will be assumed that Site B consumed 0.35 gal./(degree day) for heating. This assumption indicates that Site B consumed approximately 1598 gallons of oil during the heating season. The heating oil supplier related that the oil cost was $1.31/gal.; therefore the oil had an estimated total cost of $2085.73 during the heating season. Dividing these values by the total floor area of the building yields that Site B spent $\$0.21/\text{ft}^2$ on heating oil for climate management during the heating season, and consumed 0.16 gal./ft^2 of heating oil. Dividing these values by the total number of degree days during the heating season divided by 100 indicates that Site B spent $\$0.0046/(\text{ft}^2\text{-100 degree days})$ on heating oil and consumed $0.0036\ \text{gal./(ft}^2\text{-100 degree days)}$ of oil.

Site B Complete Heating Oil Bill Data

Date	**Total Charges**	**Total Consumption (gal.)**	**Price/gal.**	**Total Consumption (kWh)**
11/8/2002	$141.35	108.3	$1.31	4380.2
12/4/2002	$261.96	200.7	$1.31	8117.4
12/23/2002	$285.45	218.7	$1.31	8845.4
1/13/2003	$288.19	220.8	$1.31	8930.4
1/29/2003	$350.05	268.2	$1.31	10,847.5
2/24/2003	$389.87	298.7	$1.31	12,081.1
3/17/2003	$223.45	171.2	$1.31	6924.3
6/4/2003	$150.62	115.4	$1.31	4667.4
Total	**$2,090.94**	**1602**		**64,793.7**

Table 14: Complete Heating Oil Bill Data Provided by Site B.

The heating oil consumption (gallons) was converted to kWh using the conversion factor 1 gal. #2 fuel oil = 40.4 kWh. This conversion gives a total energy consumption of 64,559 kWh in heating oil for the heating season. Dividing this value by the total floor area of the building yields that Site B consumed 6.5 kWh/ft^2 in heating oil. Further dividing by the total number of heating degree days divided by 100 indicates that Site B consumed 0.14 kWh/(ft^2-100 degree days) in heating oil during the heating season.

When the electricity and the heating oil costs and consumption are combined, Site B spent an estimated total of $2611.85 to operate the climate management system during the heating season, and consumed an estimated total of 65,283 kWh of energy. Dividing these values by the floor area of the building indicates that Site B spent $0.26/ft^2 and consumed 6.6 kWh/ft^2 to operate the climate management system during the heating season. Further dividing by the total number of heating degree days divided by 100 yields that Site B spent $0.0058/(ft^2-100 degree days) and consumed 0.0014 kWh/(ft^2-100 degree days) to operate the climate management system during the heating season (see Table 15).

Total Energy Costs and Consumption for Climate Management for Site B During the Heating Season

	Electricity	Heating Oil	Electricity + Heating Oil
Total Cost for Climate Management	\$526.12	\$2,085.73	**\$2,611.85**
Total Cost/ft^2	\$0.053	\$0.21	**\$0.26**
Total Cost/(ft^2-100 degree days)	\$0.0012	\$0.0046	**\$0.0058**
Total Consumption (kWh) for Climate Management	724.2	64,559	**65,283**
Total Consumption kWh/ft^2	0.073	6.5	**6.6**
Total Consumption kWh/(ft^2-100 degree days)	0.0016	0.14	**0.14**

Table 15: Total Energy Costs and Consumption for Climate Management for Site B During the Heating Season.

B.6 SITE B – RESULTS FOR THE COOLING SEASON

B.6.1 Indoor Environment During the Cooling Season

The cooling season for Site B during the studied period lasted from June – August 2003. During this period there were 848 cooling degree days. One of Site B's data loggers did not create a record of the indoor conditions throughout the cooling season, but there is at least some record of the indoor climate for the entire period from the other data loggers.

The average indoor temperature recorded by all of Site B's data loggers during the cooling season was 81ºF. The standard deviation of the entire temperature record for the cooling season was 6ºF, indicating that the variance of the indoor temperature was ±12ºF.

The average indoor relative humidity recorded by all of Site B's data loggers during the cooling season was 59% RH. The standard deviation of the entire relative humidity record for the cooling season was 9% RH, indicating that the variance of the indoor relative humidity was ±18% RH.

Overall, during the cooling season, Site B was able to maintain an indoor climate of 81°F ±12°F and 59% RH ±18% RH during the cooling season.

B.6.2 Energy Costs and Consumption During the Cooling Season

As stated, the cooling season for Site B lasted from June – August 2003. See Table 16 for a presentation of the monthly electricity charges for Site B for the cooling season. During the cooling season, Site B spent a total of $422.84 on electrical energy, and consumed a total of 5797 kWh in electrical energy. The lack of heating oil bills during the cooling season indicates that the heating system did not operate. It is known that the ventilation fan is specified as consuming 0.746 kW when operating, and that it was set to operate 6 hours a day, indicating that the fan consumed 4.5 kWh of electrical energy per day. This value yields an estimated total energy consumption of 414.0 kWh for climate management, or 7% of the total electrical energy consumption, during the cooling season. Taking 7% of the total energy costs yields an estimated $30.20 spent on electrical energy to operate the ventilation fan. When these values are divided by the total floor area of the building, Site B spent $0.0030/ft^2 on electrical energy during the cooling season to operate the climate management system, and consumed 0.042 kWh/ft^2 (see Table 17).

Electricity Bill Data For Site B During the Cooling Season

Bill Month	Total Charges	Estimated Charges for Climate Management (7% of Total Charges)	Total Energy Use (kWh)	Estimated Energy Use for Climate Management (kWh)
JUN 2003	$137.85	$9.84	1847	139.5
JUL 2003	$142.94	$10.21	1942	135.0
AUG 2003	$142.05	$10.14	2008	139.5
Total	**$422.84**	**$30.20**	**5797**	**414.0**

Table 16: Electricity Bill Data For Site B During the Cooling Season.

There was a total of 848 cooling degree days for Site B during the cooling season. Dividing the energy consumption and cost per square foot to operate the climate management system by the number of cooling degree days divided by 100 yields that Site B spent \$0.00036/(ft^2-100 degree days) and consumed 0.0049 kWh/(ft^2-100 degree days) during the cooling season for climate management (see Table 19).

Total Energy Costs and Consumption for Climate Management for Site B During the Cooling Season

	Electricity
Total Cost for Climate Management	**$30.20**
Total Cost/ft^2	**$0.0030**
Total Cost/(ft^2-100 degree days)	**$0.00036**
Total Consumption (kWh) for Climate Management	**414.0**
Total Consumption kWh/ft^2	**0.042**
Total Consumption kWh/(ft^2-100 degree days)	**0.0049**

Table 17: Total Energy Costs and Consumption for Climate Management for Site B During the Cooling Season.

B.7 SITE B – RESULTS FOR THE MIXED SEASON

B.7.1 Indoor Environment During the Mixed Season

The mixed season for Site B during the period under consideration was the months of May 2003 and September 2003. During these months there were 177 heating degree days and 168 cooling degree days.

The average of all recorded values of the indoor temperature for Site B during the mixed season was 71ºF. The standard deviation for all recorded values of the indoor temperature during the mixed season was 5ºF, indicating that the variance of the indoor temperature during the mixed season was ±10ºF.

The average of all recorded values of the indoor relative humidity for Site B during the mixed season was 63 % RH. The standard deviation for all recorded values of the relative humidity during the mixed season was 9% RH, indicating that the variance of the indoor relative humidity during the mixed season was ±18% RH.

Overall, during the mixed season, Site B was able to maintain an indoor climate of 71°F ±10°F and 63% RH ±18% RH.

B.7.2 Energy Costs and Consumption During the Mixed Season

As stated, for Site B the mixed season was comprised of the months May and September 2003. See Table 18 for a presentation of the monthly electricity charges for Site B for the mixed season. During the mixed season, Site B spent a total of $311.80 on electrical energy, and consumed 4202 kWh of electricity. As the mixed seasons involve both heating and cooling degree days, separating the electrical costs and consumption to operate both the oil-fired furnace and the ventilation fan will require some assumptions.

From the electrical energy costs described during the heating season, Site B consumed an estimated average of 0.16 kWh/(degree day) of electricity to heat the building. It will be assumed that this value also holds true during the mixed season, and it will be used to calculate the electrical energy consumption to operate the furnace during this season. Multiplying 0.16 kWh/(degree day) by the total number of heating degree days during the mixed season (177 heating degree days) yields that Site B consumed an estimated total of 28.3 kWh in electricity to operate the oil-fired furnace during the mixed season. 28.3 kWh is 0.7% of the total electrical consumption; taking 0.7% of the total cost for electricity during the mixed season yields that Site B spent an estimated total of $2.18 on electricity to operate the furnace during the mixed season (see Table 19).

Electricity Bill Data For Site B During the Mixed Season

Bill Month	Total Charges	Estimated Charges for Climate Management (7% of Total Charges)	Total Energy Use (kWh)	Estimated Energy Use for Climate Management (kWh)
MAY 2003	$180.24	$4.87	2452	64.4
SEP 2003	$131.56	$3.55	1750	45.9
Total	**$311.80**	**$8.42**	**4202**	**110.3**

Table 18: Electricity Bill Data For Site B During the Mixed Season.

The electrical energy consumption of the ventilation fan also must be estimated based upon some assumptions. From the electrical energy costs described during the cooling season, Site B consumed an average of 0.49 kWh/(degree day) to ventilate the building. It will be assumed that this value also holds true for the mixed season. Multiplying 0.49 kWh/(degree day) by the total number of cooling degree days for the mixed season (168 cooling degree days) indicates that Site B consumed an estimated total of 82.0 kWh to operate the ventilation fan during the mixed season. 82.0 kWh is 2% of the total energy consumption; taking 2% of the total electricity costs for the mixed season yields that Site B spent an estimated total of $6.24 on electricity to operate the ventilation fan (see Table 19).

Combining the electricity costs and consumption for both heating and ventilation gives an estimated total electricity cost of $8.42 and an estimated total electrical energy consumption of 110.3 kWh for the mixed season. Dividing these numbers by the total floor area gives an estimated cost of $\$0.00085/\text{ft}^2$ and an estimated consumption of 0.011 kWh/ft^2 of electricity to operate the climate management system during the mixed season. Further dividing these values by the total number of degree days, both heating and cooling (345 degree days total) divided by 100, indicates that Site B spent an estimated $\$0.00025/(\text{ft}^2\text{-100 degree days})$ for electricity to operate the climate management system during the mixed season, and consumed 0.0032 $\text{kWh}/(\text{ft}^2\text{-100 degree days})$ of electricity.

Previously, it was calculated that Site B consumed 0.35 gallons of heating oil per heating degree day during the heating season. It will be assumed that Site B also consumes 0.35 gal./(degree day) during the mixed season. Multiplying 0.35 gal./(degree day) by the total number of heating degree days (177 heating degree days) indicates that Site B consumed an estimated total of 62.0 gallons of heating oil during the mixed season, at an estimated total cost of $81.22. Dividing these values by the floor area of the building yields that Site B spent an estimated $\$0.0082/\text{ft}^2$ for oil during the mixed season, and consumed an estimated 0.0062 gal/ft^2. Further dividing these values by the total number of heating degree days divided by 100 indicates that Site B spent an estimated \$0.0046/(ft^2-100 degree days) for oil during the mixed season, and consumed an estimated 0.0035 gal/(ft^2-100 degree days).

When the oil consumption (gallons) is converted to kWh using the conversion factor 1 gal. #2 fuel oil = 40.4 kWh, Site B consumed an estimated total of 2505 kWh of energy in the form of heating oil during the mixed season. This values leads to Site B consuming an estimated 0.25 kWh/ft^2 in heating oil during the mixed season, and an estimated 0.14 kWh/(ft^2-100 degree days) in heating oil (see Table 19).

When the costs and energy consumption of electricity and heating oil are combined, Site B spent an estimated total of \$86.64 to operate the climate management system during the heating season, and consumed an estimated total of 2615 kWh. Dividing by the floor area, Site B spent an estimated total of \$0.0090/ft^2 for climate management during the heating season, and consumed an estimated total of 0.26 kWh/ft^2 of energy. Further dividing by the number of heating and cooling degree days, Site B spent an estimated \$0.0049/(ft^2-100 degree days) to operate the climate management system during the mixed season, and consumed an estimated 0.15 kWh/(ft^2-100 degree days) of energy (see Table 19).

Total Energy Costs and Consumption for Climate Management for Site B During the Mixed Season

	Electricity for Heating	**Electricity for Ventilation**	**Heating Oil**	**All Electricity + Heating Oil**
Total Cost for Climate Management	\$2.18	\$6.24	\$81.22	**\$89.64**
Total Cost/ft^2	\$0.00022	0.00063	\$0.0082	**\$0.0090**
Total Cost/(ft^2-100 degree days)	0.000064	0.00018	0.0046	**0.0049**
Total Consumption (kWh) for Climate Management	28.3	82	2,505	**2,615**
Total Consumption kWh/ft^2	0.0028	0.0082	0.25	**0.26**
Total Consumption kWh/(ft^2-100 degree days)	0.00083	0.0024	0.14	**0.15**

Table 19: Total Energy Costs and Consumption for Climate Management for Site B During the Mixed Season.

APPENDIX C: SITE C – DESCRIPTION, DATA, AND RESULTS

C.1 DESCRIPTION OF SITE C

Site C is located in Pennsylvania. It is a 2 ½ storey brick masonry building, and faces north. A basement also is present in the building, but the climate management system does not serve that space. The original year of construction is 1755, and an addition was built in 1850. The total floor area of the building is approximately 1650 ft^2, divided between the three floors. The building envelope is comprised of load-bearing brick masonry on the exterior and plaster-lath on the interior. No insulation or vapor barrier is present in the wall construction. Site C is a row house; there are adjacent buildings both to the east and to the west of Site C. Fenestration is present both on the north and south facades. Originally a residence, Site C now functions as a house museum, and is open year-round. March through October the site is open Monday – Saturday from 10:00 AM – 5:00 PM, and 12:00 PM – 5:00 PM on Sunday. November through February the site is open from Tuesday – Saturday from 10:00 AM – 5:00 PM, and 12:00 PM – 5:00 PM on Sunday.

C.2 SITE C – CLIMATE MANAGEMENT SYSTEM

Site C uses a gas-fired furnace and ductwork to distribute the warm air to the interior spaces to heat the building during the heating season, and no form of climate management during the cooling season, except for a window air-conditioning unit that is located in the office. The window unit was disregarded as it only provides cooling to one room of the building, and likely operates only sporadically when the room is in use.

According to the site's manager, the heating system is old and was designed mainly for human comfort, not to create an indoor environment conducive to the preservation of the historic fabric of the building.

Because Site C has a load-bearing brick masonry exterior, interior plaster-lath walls, and no insulation or vapor barrier, it was placed in ASHRAE building class III, for which they recommend heating and ventilation to manage the indoor climate. Using the recommended forms of climate management, the possible class of control listed is C, indicating that it is reasonable to attempt to maintain the temperature below 77°F and the relative humidity between 25 – 75% RH in the building (see Tables 2 and 3).

C.3 SITE C – PROVIDED DATA

Site C provided monitoring data for the period of February 2002 – January 2003. The temperature and relative humidity were recorded once every 30 minutes by electronic data loggers in six locations throughout the building, and in one external location. The external data logger was disregarded for this study, as this study is concerned with the indoor climate of the building only. Also, one of the data loggers was placed in the basement, which is not a climate-managed space in the building. That data logger also was disregarded.

The electricity bills were collected for the period of this study. The electrical energy bills include both the energy consumption (kWh) and the final dollar-amount of the charges. It must be noted that the electricity charges for May 2002 – December 2002 were estimated charges, meaning that the electricity supplying company did not charge the site for its actual energy consumption. Instead, they estimated the site's electricity use based upon historical data. Unfortunately, it was not possible to find the site's actual electrical energy consumption for this period. Therefore, for the purposes of this analysis, these estimated costs will be treated as the actual costs; but, it must be remembered that the data is not as reliable as the actual electricity costs would be. Also, electricity bills for December 2002 and January 2003 were not provided. Instead, bills for December 2001 and January 2002 were provided. Unfortunately this data will have to suffice, and it will be assumed that the energy costs and consumption for December 2002 and January 2003 approximately equal the energy costs and consumption for December 2001 and January 2002.

Unfortunately, there is no way to know what proportion of Site C's energy consumption was used by the climate management system. The exact model number of the gas-fired furnace was not provided, but it is known that the unit is available with fans for which the electrical energy consumption ranges from 0.149 kW – 0.56 kW. It will be assumed that Site C's furnace is equipped with the fan that consumes 0.56 kW of electricity. The amount of time each day the unit operated also is not known; it will be assumed that the furnace operated 6 hours per day. Therefore, it will be assumed that the gas-fired furnace consumed 3.4 kWh/day of electricity when it operated during the heating season.

The natural gas bills also were collected for the period under consideration. The bills list both the gas consumption (ccf) and the final dollar-amount costs. The gas bill for January 2003 was not provided, instead, the gas bill for January 2002 was given. Unfortunately, the gas bill for January 2002 will have to be substituted for the bill for

January 2003, with the assumption that the site would have consumed approximately equal amounts of natural gas during the two months. The gas bills indicate that Site C consumed an average of 8 ccf of natural gas during the months that the heating system was not operational. Therefore, it will be assumed that Site C uses 8 ccf of gas each month for purposes other than climate management, and 8 ccf will be subtracted from the gas consumption for each month that the system is operational.

C.4 SITE C – DIVISION OF SEASONS

By analyzing the engineering climate data[203] for the period of the monitoring data, the heating season lasted from February 2002 to May 2002, and from October 2002 to January 2003, and the cooling season lasted from June 2002 to August 2002. Due to the number of both heating degree days and cooling degree days during the month of September 2002, that moth was classified as the mixed season. The engineering climate data is presented in Table 20 and Figure 59.

Pennsylvania Heating and Cooling Degree Days

Month - Year	Heating DD	Cooling DD
FEB 2002	824	0
MAR 2002	765	0
APR 2002	386	0
MAY 2002	249	17
JUN 2002	15	160
JUL 2002	1	307
AUG 2002	3	297
SEP 2002	46	106
OCT 2002	414	0
NOV 2002	720	0
DEC 2002	1095	0
JAN 2003	1299	0

Table 20: Engineering Climate Data for Site C (source: National Climatic Data Center).

---

[203] Engineering climate data was downloaded from the National Climatic Data Center website: http://www.ncdc.noaa.gov/oa/mpp/freedata.html.

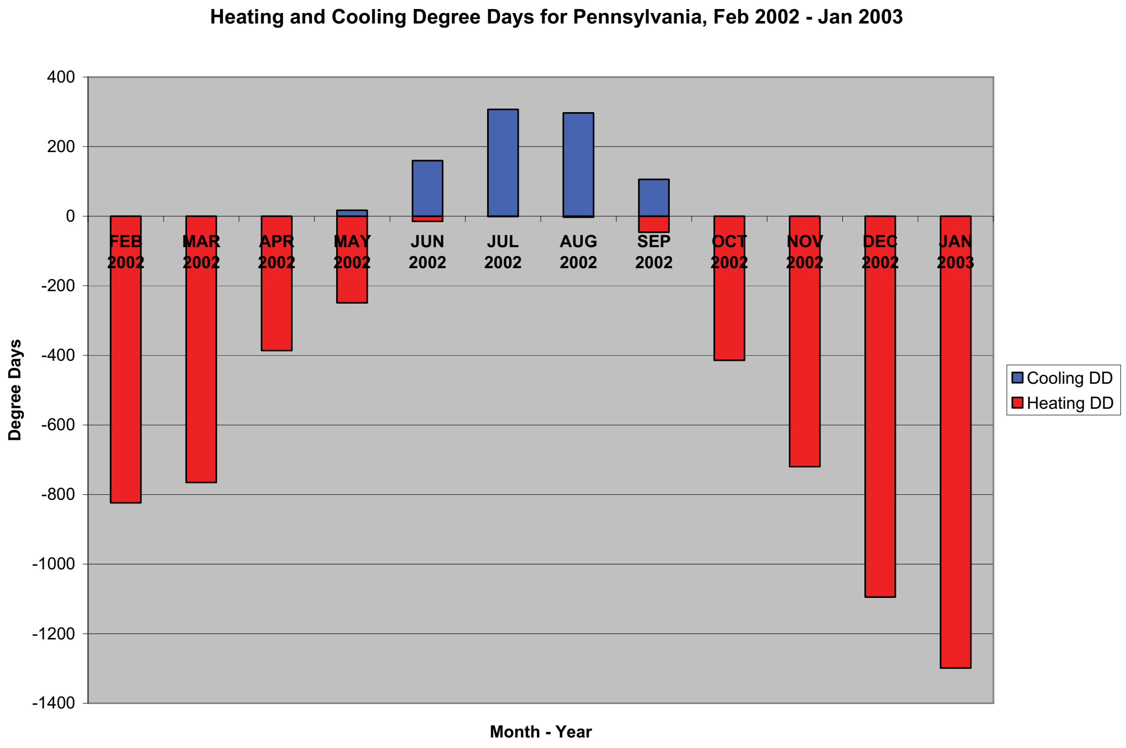


Figure 59: Graph of Heating and Cooling Degree Days for Site C.

C.5 Site C – Results for the Heating Season

C.5.1 Indoor Environment During the Heating Season

The heating season for Site C lasted from February 2002 to May 2002, and from October 2002 to January 2003. During this period there were 5752 heating degree days.

Taking the entire indoor temperature record during the heating season, the average indoor temperature was 65ºF. The standard deviation of the entire temperature record was 6ºF, indicating that the variance of the indoor temperature during the heating season was ±12ºF.

The average indoor relative humidity recorded in Site C during the heating season was 39% RH. The standard deviation of the entire relative humidity record was 12% RH, indicating that the variance of the indoor relative humidity during the heating season was ±24% RH.

Overall, during the heating season, Site C was able to maintain an indoor climate of 65°F ±12°F and 39% RH ±24% RH.

C.5.2 Energy Costs and Consumption During the Heating Season

As stated, the heating season for Site C lasted from February 2002 to May 2002, and from October 2002 to January 2003. As the only form of climate management used by Site C is a gas-fired furnace to provide heating, the natural gas bills indicate when the climate management system was operating. According to the natural gas bills, the heating system operated from February – April 2002, and from November 2002 – January 2003. Therefore, while the months of May and October 2002 are included in the heating season, the energy consumption and costs for these two months will not be included in this analysis, as the climate management system did not operate during these months.

See Table 21 for a presentation of the electricity charges for Site C during the heating season. During the heating season, Site C spent a total of $304.47 for electrical energy, and consumed 2124 kWh of electricity. Assuming that the climate management system consumed 3.4 kWh/day of electricity during the months it operated, the climate management system consumed an estimated 614.3 kWh of electricity during the heating season, or 29% of the total electrical energy consumption. Taking 29% of the total dollar-amount cost yields that Site C spent an estimated $88.30 for electrical energy to operate the climate management system during the heating season. Dividing these values by the total floor area of the building (1650 ft^2) yields that Site C spent an estimated \$0.053/ft^2 for electrical energy to operate the climate management system, and consumed an estimated 0.37 kWh/ft^2 of electricity during the heating season.

Electricity Bill Data For Site C During the Heating Season

Bill Month	Total Charges	Estimated Charges for Climate Management (29% of Total Charges)	Total Energy Use (kWh)	Estimated Energy Use for Climate Management (kWh)	Notes
DEC 2001*	\$46.23	\$13.41	320	104.1	
JAN 2002*	\$43.68	\$12.67	299	97.4	
FEB 2002	\$38.41	\$11.14	258	90.6	
MAR 2002	\$49.47	\$14.35	344	114.1	
APR 2002	\$90.94	\$26.37	666	100.7	Estimated Consumption
MAY 2002	\$81.31**	\$23.58	580	0	Estimated Consumption
OCT 2002	\$92.70**	\$26.88	679	0	Estimated Consumption
NOV 2003	\$35.74	\$10.36	237	107.4	Estimated Consumption
Total	**\$304.47**	**\$88.30**	**2124**	**614.3**	

Table 21: Electricity Bill Data For Site C During the Heating Season.

There were 5752 heating degree days during the studied period. Dividing the energy costs and consumption per square foot by the total number of degree days divided by 100 shows that Site C spent an estimated \$0.00093/(ft^2-100 degree days) for electricity to operate the climate management system, and consumed 0.0065 kWh/(ft^2-100 degree days) of electricity.

See Table 22 for a presentation of the natural gas bills during the heating season. During the heating season, Site C spent a total of \$993.68 for natural gas, and consumed

704 ccf (1 ccf = 100 cubic feet) of gas. When 8 ccf are subtracted from each month, Site C spent an estimated total of $925.92 on gas for climate management, and consumed an estimated 656 ccf of gas. When these values are divided by the total floor area of the building (1650 ft^2), Site C spent an estimated $0.56/$\text{ft}^2$ on gas for climate management, and consumed an estimated 0.40 ccf/ft^2 of gas. Dividing these values by the total number of heating degree days during the heating season divided by 100 yields that Site C spent $0.0098/($\text{ft}^2$-100 degree days) for gas to operate the climate management system during the heating season, and consumed 0.0069 ccf/(ft^2-100 degree days) of gas.

Natural Gas Bill Data for Site C During the Heating Season

Bill Month	Total Charges	Estimated Charges for Climate Management	Total Consumption (ccf)	Estimated Consumption for Climate Management (ccf)	Estimated Consumption for Climate Management (kWh)
JAN 2002*	$168.68	$157.18	147	139	4183
FEB 2002	$288.21	$268.56	97	89	2679
MAR 2002	$120.22	$112.02	109	101	3040
APR 2002	$89.67	$83.55	77	69	2077
MAY 2002	$26.12**	$0.00	8	0	0
OCT 2002	$26.49**	$0.00	8	0	0
NOV 2002	$118.80	$110.70	95	87	2618
DEC 2002	$208.10	$193.91	179	171	5147
Total	$993.68	$925.92	720	656	19,744

*This bill is substituted for January 2003

**Though a part of the heating season, the climate management system did not operate during these months; therefore, these charges are not included in the analysis

Table 22: Natural Gas Bill Data for Site C During the Heating Season.

The natural gas consumption (ccf) was converted to kWh using the conversion factor of 1 ccf = 30.097 kWh. This conversion gives a total energy consumption of 19,744 kWh in gas during the heating season. This value indicates that Site C consumed 12.0 kWh/ft^2 and 0.21 kWh/(ft^2-100 degree days) in gas for climate management during the heating season.

The total energy costs and consumption for climate management during the heating season are calculated by adding the costs and consumption for electrical energy and natural gas. Site C spent a total of $1014.22 and consumed a total of 20,358 kWh of energy for climate management during the heating season. Dividing by the floor area of the building indicates that Site C spent a total of $0.61/ft^2 and consumed a total of 12.4 kWh/ft^2 for climate management during the heating season. Further dividing these values by the total number of heating degree days divided by 100 yields that Site C spent a total of $0.11/(ft^2-100 degree days) and consumed a total of 0.22 kWh/(ft^2-100 degree days) for climate management during the heating season (see Table 23).

Total Energy Costs and Consumption for Climate Management for Site C During the Heating Season

	Electricity	Natural Gas	Electricity + Natural Gas
Total Cost for Climate Management	$88.30	$925.92	**$1,014.22**
Total Cost/ft^2	$0.053	$0.56	**$0.61**
Total Cost/(ft^2-100 degree days)	$0.00093	$0.0098	**$0.011**
Total Consumption (kWh) for Climate Management	614.3	19,744	**20,358**
Total Consumption kWh/ft^2	0.37	12.0	**12.4**
Total Consumption kWh/(ft^2-100 degree days)	0.0065	0.21	**0.22**

Table 23: Total Energy Costs and Consumption for Climate Management for Site C During the Heating Season.

C.6 SITE C – RESULTS FOR THE COOLING SEASON

C.6.1 Indoor Environment During the Cooling Season

The cooling season for Site C lasted from June 2002 to August 2002. During this period there were 764 cooling degree days.

Taking the entire indoor temperature record during the cooling season, the average indoor temperature was 80ºF. The standard deviation of the entire temperature record was 5ºF, indicating that the variance of the indoor temperature during the cooling season was ±10ºF.

The average indoor relative humidity recorded in Site C during the cooling season was 48% RH. The standard deviation of the entire relative humidity record was 8% RH, indicating that the variance of the indoor relative humidity during the cooling season was ±16% RH.

Overall, during the cooling season, Site C was able to maintain an indoor climate of 80°F ±10°F and 48% RH ±16% RH.

C.6.2 Energy Costs and Consumption During the Cooling Season

Site C does not use any form of climate management during the cooling season. Therefore, the energy costs and consumption for this period are zero.

C.7 SITE C – RESULTS FOR THE MIXED SEASON

C.7.1 Indoor Environment During the Mixed Season

The mixed season for Site C during the studied period was September 2002. During this period there were 46 heating degree days and 106 cooling degree days.

Taking the entire indoor temperature record during the mixed season, the average indoor temperature was 77ºF. The standard deviation of the entire temperature record was 3ºF, indicating that the variance of the indoor temperature during the mixed season was ±6ºF.

The average indoor relative humidity recorded in Site C during the mixed season was 51% RH. The standard deviation of the entire relative humidity record was 9% RH, indicating that the variance of the indoor relative humidity during the mixed season was ±18% RH.

Overall, during the mixed season, Site C was able to maintain an indoor climate of 77°F ±6°F and 51% RH ±18% RH.

C.7.2 Energy Costs and Consumption During the Mixed Season

The natural gas bills indicate that the climate management system did not operate during the mixed season. Therefore, the energy costs and consumption for this period are zero.

APPENDIX D: SITE D – DESCRIPTION, DATA, AND RESULTS

D.1 DESCRIPTION OF SITE D

Site D is located in Connecticut. It is a 1 storey modern museum gallery, and faces west. The building was constructed in 2002, and has a total floor area of approximately 10,000 ft^2. The building envelope for this building is complicated; the exterior skin is metal, backed by an air barrier, backed by plywood sheathing, backed by cinder block masonry, backed by batt insulation, backed by a vapor barrier, backed by plywood sheathing, which is backed by gypsum drywall, which forms the interior surface of the wall. Site D is a free standing structure, and fenestration is present on the north, west, and south facades. Also, skylights are used to provide interior illumination. The site is open to visitors all year long, from 10:00 AM – 5:00 PM Tuesday through Saturday, and 1:00 PM – 5:00 PM on Sunday. The building includes exhibition galleries, storage, a study center, a lobby, and a gift shop. The collection mainly consists of paintings.

D.2 SITE D – CLIMATE MANAGEMENT SYSTEM

Site D attempts to maintain a constant indoor climate of 69°F ±1°F and 45% RH ±5% RH. The climate management system is comprised of a direct expansion air-conditioner, two oil-fired (#2 fuel oil) hot water boilers, and steam humidifiers. The system uses an air handler, which conditions the air then delivers it to the indoor spaces of the building through ductwork. The system operates year-round; the air-conditioning provides cooling and dehumidification, then the hot water system re-heats the air to the proper temperature. The humidifiers then add moisture to the supply air stream to achieve the desired indoor relative humidity. To conserve funds and energy, the system uses an economizer, which can draw in outdoor air if it is of a suitable temperature to be used for climate management. Doing so reduces the cooling load on the equipment. The system also uses a hot-gas bypass system, which allows a tighter control on the supply air temperature.

The museum lobby and gift shop are heated by an oil-fired boiler that is separate from the two that service the gallery. This boiler also services another building on the site. The boiler feeds fan coil units that are located in the lobby and gift shop.

As a modern building specifically designed to function as a museum, Site C is placed in ASHRAE's building class V, for which they recommend ducted heat, cooling, reheat, and humidification. Because of the cold winter climate in Connecticut, Site D falls into ASHRAE's recommended climate classification B, indicating that it is reasonable to maintain an indoor temperature that is set between 59 - 77°F with a tolerance of ±9°F, and an indoor relative humidity of 50% RH ±10% RH (see Tables 2 and 3).

D.3 SITE D – PROVIDED DATA

Site D provided monitoring data for the period of January – December 2006. The indoor conditions were recorded once per hour in four different locations in the building.

Electricity bills were provided for the period of this study. These bills show both the total electrical energy consumption (in kWh) and the final dollar-amount costs. However, the bill for December 2005 was supplied instead of the bill for December 2006.

It will be assumed that the site consumed an approximately equal amount of energy in the two months, and the bill for December 2005 will be substituted for December 2006. Unfortunately, there is no way to determine what proportion of Site D's electrical consumption was used by the climate management system, so assumptions must be made. One study was found that calculated the proportion of total energy consumption for a museum that tries to maintain constant indoor conditions was found. This study determined 62% of total energy consumption went to climate management for the museum that was investigated; however, this museum was housed in a historic building, not a modern structure.[204] While one old museum cannot be considered representative of all modern museums, it is the only estimate that a review of the literature revealed, and it is instructive. Because one would expect a modern building to be more airtight and have better insulation than an old one, for this analysis it will be assumed that 55% of Site D's electrical energy consumption went to climate management.

Heating oil bills also were provided for the period of this study. These bills show both the heating oil consumption (in gallons) and the final dollar-amount cost. It will be assumed that all of the heating oil consumed by Site D was used by the climate management system. As stated previously, the lobby and gift shop of the building are serviced by a separate boiler, which also services another building on the site. This boiler services approximately 2000 ft^2 of Site D, or 20% of the total floor area. To approximate the total cost and oil consumption for Site D, first the cost and consumption for the

---

[204] Michael J. Chimack, Christine E. Walker and Ellen Franconi. "Determining Baseline Energy Consumption and Peak Cooling Loads of a 107-Year Old Science Museum Using DOE 2.1E." Presented at the Seventh International IBPSA Conference, Rio de Janeiro, August 13-15, 2001, 196. <http://www.simulationresearch.lbl.gov/dirpubs/BS01/BS01_191.pdf> (25 February 2007)

spaces served by the boilers dedicated solely to Site D will be calculated. These values then will be multiplied by 1.25 to give an approximation of the total oil consumption for the building.

In August, Site D entered into a contract for their heating oil needs, for which the total cost ($17,309.34) and amount of oil (6660 gal.) of the contract were provided, but not the time period, making it impossible to determine the oil consumption during the months of August – December. Therefore, the monthly average oil consumption calculated for the time before August, 881.9 gal./month, will be used to approximate the oil consumption for the months of August – December 2006. Also, the heating oil bill for January 2006 was not provided; for this month it also will be assumed that Site D consumed 881.9 gallons of heating oil.

D.4 SITE D – DIVISION OF SEASONS

By analyzing the engineering climate data[205] for the period of the monitoring data, the heating season lasted from January – May 2006, and from October – December 2006. The cooling season lasted from June – August 2006. Due to the number of both heating and cooling degree days that occurred during September 2006, this month is classified as the mixed season. The engineering climate data is presented in Table 24 and Figure 60.

At the time of this report, the number of heating degree days for December 2006 had not been published by the National Climatic Data Center. Therefore, the heating degree day data for December 2005 was substituted for December 2006, with the

---

[205] Engineering climate data was downloaded from the National Climatic Data Center website: http://www.ncdc.noaa.gov/oa/mpp/freedata.html.

assumption that there was an approximately equal number of heating degree days between the two months.

Connecticut Heating and Cooling Degree Days

Month - Year	Heating DD	Cooling DD
DEC 2005*	1016	0
JAN 2006	946	0
FEB 2006	980	0
MAR 2006	851	0
APR 2006	452	0
MAY 2006	224	11
JUN 2006	19	112
JUL 2006	0	324
AUG 2006	7	201
SEP 2006	105	31
OCT 2006	403	0
NOV 2006	535	0

*At the time of this paper The National Climatic Data Center had not published degree day data for December 2006. December 2005 is substituted instead.

Table 24: Engineering Climate Data for Site D (source: National Climatic Data Center).

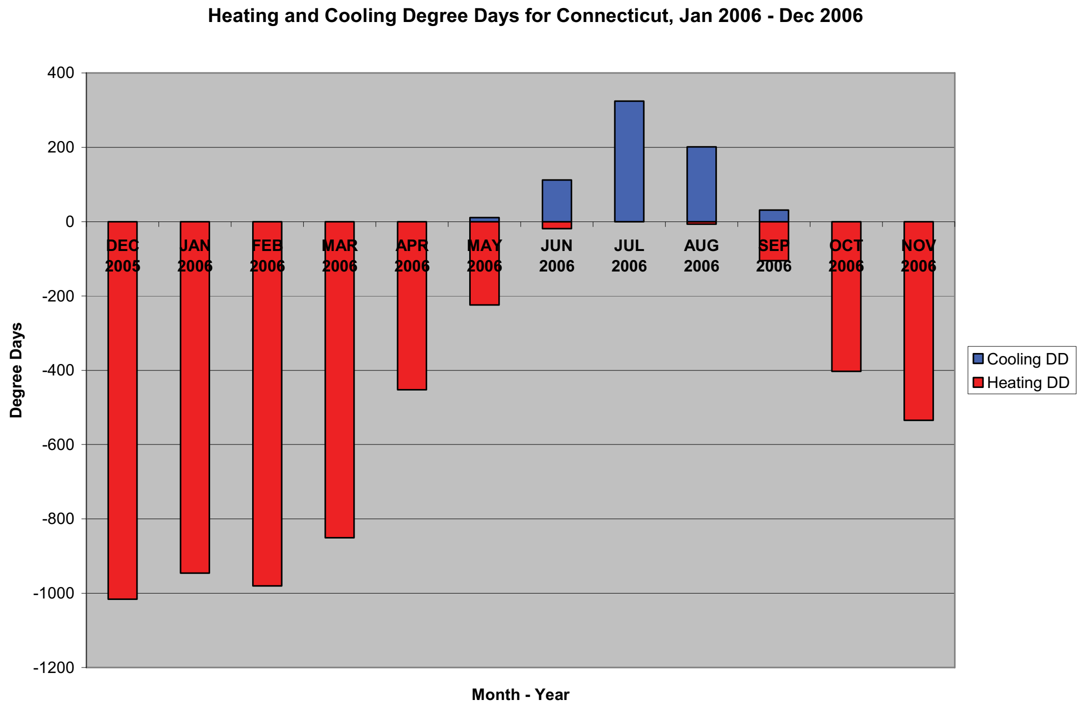


Figure 60: Graph of Heating and Cooling Degree Days for Site D.

D.5 SITE D – RESULTS FOR THE HEATING SEASON

D.5.1 Indoor Environment During the Heating Season

The heating season for Site D lasted from January – May 2006, and from October – December 2006. During this period there were an estimated 5407 heating degree days.

The average indoor temperature for the entire temperature record for the heating season was 70°F. The standard deviation for the entire temperature record was 2ºF, indicating that the variance of the indoor temperature during the heating season was ±4ºF.

The average indoor relative humidity for the entire relative humidity record for the heating season was 41% RH. The standard deviation for the entire relative humidity record was 5% RH, indicating that the variance of the indoor relative humidity during the heating season was ±10% RH.

Overall, during the heating season, Site D was able to maintain an indoor climate of 70°F ±4°F and 41% RH ±10% RH.

D.5.2 Energy Costs and Consumption During the Heating Season

As stated, the heating season for Site D lasted from January – May 2006, and from October – December 2006. See Table 25 for a presentation of the electricity bill data for the heating season. During the heating season, Site D spent a total of $29,908.96 for electrical energy, and consumed a total of 210,720 kWh of electricity. As explained previously, it will be assumed that 55% of the total energy consumption was used by the climate management system. This assumption indicates that Site D spent $16,449.93 for electrical energy and consumed 115,896 kWh of electricity to operate the climate management system during the heating season. Dividing these values by the total floor area of the building (10,000 ft^2) yields that Site D spent an estimated \$1.64/ft^2 for electricity to operate the climate management system during the heating season, and consumed 11.6 kWh/ft^2 of electricity.

There was a total of 5407 heating degree days for Site D during the heating season. Dividing the electrical energy costs and consumption per square foot by the total number of heating degree days divided by 100 indicates that Site D spent an estimated \$0.30/(ft^2-100 degree days) for electricity to operate the climate management system during the heating season, and consumed 0.21 kWh/(ft^2-100 degree days) of electricity.

Electricity Bill Data For Site D During the Heating Season

Bill Month	Total Charges	Estimated Charges for Climate Management (55% of Total Charges)	Total Energy Use (kWh)	Estimated Energy Use for Climate Management (kWh)
DEC 2005*	$3,298.55	$1,814.20	28880	15884
JAN 2006	$3,486.05	$1,917.33	24480	13464
FEB 2006	$3,582.88	$1,970.58	25600	14080
MAR 2006	$3,876.85	$2,132.27	26160	14388
APR 2006	$3,943.66	$2,169.01	27040	14872
MAY 2006	$4,166.85	$2,291.77	29280	16104
OCT 2006	$3,520.55	$1,936.30	22560	12408
NOV 2006	$4,033.57	$2,218.46	26720	14696
Total	$29,908.96	$16,449.93	210720	115896

*The electricity bill for December 2006 was not provided. The electricity bill for December 2005 has been substituted instead.

Table 25: Electricity Bill Data For Site D During the Heating Season.

The heating oil bill data for Site D for the heating season is presented in Table 26. The bill for the month of January 2006 was not provided; for this month it will be assumed that the site consumed 881.9 gal. of oil, based upon the average monthly consumption for February – July 2006. The price pre gallon will be assumed to be

$2.200, which was the price in February. As explained previously, because Site D entered into a contract for heating oil in August 2006 for which the monthly consumption is not available; it will be assumed that Site D consumed 881.9 gal./month from August – December 2006. The price of $2.599/gal. for this contract was provided by the site. Also, as explained previously, the total costs and consumption of heating oil will be multiplied by 1.25 to approximate the total oil cost and consumption for the building.

Site D Heating Oil Bill Data During the Heating Season

Bill Month	Total Charges	Adjusted Total Charges (125%)	Total Consumption (gal.)	Adjusted Total Consumption (125%) (gal.)	Price/ gal.	Adjusted Total Consumption (kWh)	Notes
JAN 2006*	$1,552.10	$1,940.13	705.5	881.9	$2.200	35,667.9	Assumed charges and consumption
FEB 2006	$1,136.90	$1,421.13	516.8	646.0	$2.200	26,127.8	
MAR 2006	$1,158.30	$1,447.88	526.5	658.1	$2.200	26,618.2	
APR 2006	$1,432.20	$1,790.25	651.0	813.8	$2.200	32,912.5	
MAY 2006	$1,640.77	$2,050.96	722.5	903.1	$2.271	36,527.3	
OCT 2006**	$1,833.59	$2,291.99	705.5	881.9	$2.599	35,667.9	Assumed charges and consumption
NOV 2006**	$1,833.59	$2,291.99	705.5	881.9	$2.599	35,667.9	Assumed charges and consumption
DEC 2006**	$1,833.59	$2,291.99	705.5	881.9	$2.599	35,667.9	Assumed charges and consumption
Total	**$12,421.05**	**$15,526.32**	**5238.8**	**6548.5**		**264,857.3**	

*Heating oil bills for January 2006 were not provided. The oil consumption is calculated based upon the average monthly consumption for February - July 2006, and the cost is based upon an assumed price of $2.200/gal.

**Site D entered into a contract for heating oil in August 2006. The oil consumption for these months is calculated based upon the average monthly consumption for February - July 2006. The cost of $2.599/gal. was given.

Table 26: Site D Heating Oil Bill Data During the Heating Season.

Using these assumptions, Site D spent an estimated total of $15,526.32 for heating oil during the heating season, and consumed an estimated total of 6548.5 gallons of oil. When divided by the floor area of the building, Site D spent an estimated \$1.55/ft^2 for heating oil during the heating season, and consumed an estimated 0.65 gal./ft^2 of oil. Further dividing these values by the total number of heating degree days divided by 100 indicates that Site D spent \$0.029/(ft^2-100 degree days) for heating oil during the heating season, and consumed 0.012 gal./(ft^2-100 degree days) of oil.

The heating oil consumption (gallons) was converted to kWh using the conversion factor 1 gal. #2 fuel oil = 40.4 kWh. This conversion gives an estimated energy consumption of 264,857 kWh in heating oil for the heating season. Dividing this value by the floor area yields that Site D consumed 26.5 kWh/ft^2 in heating oil. Further dividing this value by the total number of heating degree days divided by 100 indicates that Site D consumed 0.49 kWh/(ft^2-100 degree days) in oil during the heating season.

When the electricity and the heating oil costs and consumption are combined, Site D spent an estimated total of \$31,976.25 for climate management during the heating season, and consumed a total of 380,753 kWh of energy. Dividing these values by the floor area of the building indicates that Site D spent an estimated total of \$3.20/ft^2 for climate management during the heating season, and consumed an estimated total of 38.1 kWh/ft^2 of energy. Further dividing these values by the total number of heating degree days yields that Site D spent an estimated total of \$0.059/(ft^2-100 degree days) for climate management during the heating season, and consumed an estimated total of 0.70 kWh/(ft^2-100 degree days) (see Table 27).

Total Energy Costs and Consumption for Climate Management for Site D During the Heating Season

	Electricity	Heating Oil	Electricity + Heating Oil
Total Cost for Climate Management	$16,449.93	$15,526.32	**$31,976.25**
Total Cost/ft^2	$1.64	$1.55	**$3.20**
Total Cost/(ft^2-100 degree days)	$0.030	$0.029	**$0.059**
Total Consumption (kWh) for Climate Management	115,896	264,857	**380,753**
Total Consumption kWh/ft^2	11.6	26.5	**38.1**
Total Consumption kWh/(ft^2-100 degree days)	0.21	0.49	**0.70**

Table 27: Total Energy Costs and Consumption for Climate Management for Site D During the Heating Season.

D.6 SITE D – RESULTS FOR THE COOLING SEASON

D.6.1 Indoor Environment During the Cooling Season

The cooling season for Site D for the period of this study lasted from June – August 2006. During this period there were 637 cooling degree days.

The average indoor temperature for the entire temperature record for the cooling season was 69ºF. The standard deviation for the entire temperature record was 2ºF, indicating that the variance of the indoor temperature during the cooling season was ±4ºF.

The average indoor relative humidity for the entire relative humidity record for the cooling season was 48% RH. The standard deviation for the entire relative humidity record was 5% RH, indicating that the variance of the indoor relative humidity during the cooling season was ±10% RH.

Overall, during the cooling season, Site D was able to maintain an indoor climate of 69°F ±4°F and 48% RH ±10% RH.

D.6.2 Energy Costs and Consumption During the Cooling Season

As stated, the cooling season for Site D lasted from June – August 2006. See Table 28 for a presentation of the electricity bill data for the cooling season. During the cooling season, Site D spent a total of $12,027.22 for electrical energy, and consumed a total of 80,480 kWh of electricity. Assuming that 55% of the total electrical energy consumption went to the climate management system, Site D spent an estimated total of $6,614.97 on electrical energy for climate management during the cooling season, and consumed an estimated total of 44,264 kWh of electricity. Dividing these values by the total floor area of the building yields that Site D spent an estimated $0.66/ft^2 for electrical energy to operate the climate management system during the cooling season, and consumed 4.4 kWh/ft^2 of electricity.

Electricity Bill Data For Site D During the Cooling Season

Bill Month	Total Charges	Estimated Charges for Climate Management (55% of Total Charges)	Total Energy Use (kWh)	Estimated Energy Use for Climate Management (kWh)
JUN 2006	$3,726.04	$2,049.32	25,120	13,816
JUL 2006	$4,327.24	$2,379.98	29,120	16,016
AUG 2006	$3,973.94	$2,185.67	26,240	14,432
Total	**$12,027.22**	**$6,614.97**	**80,480**	**44,264**

Table 28: Electricity Bill Data For Site D During the Cooling Season.

There was a total of 637 cooling degree days for Site D during the cooling season. Dividing the electrical energy costs and consumption for Site D during the cooling season by the total number of cooling degree days divided by 100 indicates that Site D spent an estimated \$0.10/(ft^2-100 degree days) for electricity to operate the climate management system during the cooling season, and consumed an estimated 0.69 kWh/(ft^2-100 degree days).

The heating oil bill data for Site D during the cooling season is presented in Table 29. As explained previously, it will be assumed that Site D consumed 881.9 gallons of oil during August 2006, and that multiplying the total oil cost and consumption shown in the bills by 1.25 is necessary to approximate the cost and consumption for the whole building. This assumption leads to an estimated total cost of \$7,653.11 for heating oil during the cooling season, and an estimated total oil consumption of 3152.4 gallons of oil. Dividing these values by the floor area indicates that Site D spent an estimated \$0.77/ft^2 for heating oil during the cooling season, and consumed an estimated 0.32 gal./ft^2 of oil. Further dividing these values by the total number of cooling degree days divided by 100 yields that Site D spent an estimated \$0.12/(ft^2-100 degree days) for oil during the cooling season, and consumed an estimated 0.049 gal./(ft^2-100 degree days) of heating oil.

The heating oil consumption (gallons) was converted to kWh using the conversion factor 1 gal. #2 fuel oil = 40.4 kWh. This conversion gives an estimated energy consumption of 127,499 kWh in heating oil during the cooling season. Dividing this value by the floor area indicates that Site D consumed 12.7 kWh/ft^2 in oil during the heating season. Further dividing by the total number of cooling degree days divided by

100 yields that Site D consumed 2.0 kWh/(ft^2-100 degree days) in oil during the cooling season.

Site D Heating Oil Bill Data During the Cooling Season

Bill Month	Total Charges	Adjusted Total Charges (125%)	Total Consumption (gal.)	Adjusted Total Consumption (125%) (gal.)	Price/gal.	Adjusted Total Consumption (kWh)	Notes
JUN 2006	$2,393.96	$2,992.45	1018.7	1273.4	$2.350	51,502.3	
JUL 2006	$1,894.93	$2,368.66	797.7	997.1	$2.375	40,329.2	
AUG 2006*	$1,833.59	$2,291.99	705.5	881.9	$2.599	35,667.9	Assumed charges and consumption
Total	**$6,122.48**	**$7,653.11**	**2521.9**	**3152.4**		**127,499.3**	

*Site D entered into a contract for heating oil in August 2006. The oil consumption for this month is calculated based upon the average monthly consumption for February - July 2006. The cost of $2.599/gal. was given.

Table 29: Site D Heating Oil Bill Data During the Cooling Season.

When the electricity and the heating oil costs and consumption are combined, Site D spent an estimated total of $14,268.08 for climate management during the cooling season, and consumed an estimated total of 171,763 kWh of energy. Dividing these values by the total floor area of the building indicates that Site D spent an estimated total of $1.43/ft^2 for climate management during the cooling season, and consumed an estimated total of 17.2 kWh/ft^2 of energy. Further dividing by the total number of cooling degree days divided by 100 shows that Site D spent an estimated total of $0.22/(ft^2-100 degree days) for climate management during the cooling season, and consumed an estimated total of 2.7 kWh/(ft^2-100 degree days) of energy (see Table 30).

Total Energy Costs and Consumption for Climate Management for Site D During the Cooling Season

	Electricity	Heating Oil	Electricity + Heating Oil
Total Cost for Climate Management	\$6,614.97	\$7,653.11	**\$14,268.08**
Total Cost/ft^2	\$0.66	\$0.77	**\$1.43**
Total Cost/(ft^2-100 degree days)	\$0.10	\$0.12	**\$0.22**
Total Consumption (kWh) for Climate Management	44,264	127,499	**171,763**
Total Consumption kWh/ft^2	4.4	12.7	**17.2**
Total Consumption kWh/(ft^2-100 degree days)	0.69	2.0	**2.7**

Table 30: Total Energy Costs and Consumption for Climate Management for Site D During the Cooling Season.

D.7 SITE D – RESULTS FOR THE MIXED SEASON

D.7.1 Indoor Environment During the Mixed Season

September 2006 is classified as the mixed season due to the number of both heating degree days and cooling degree days that occurred during that month. During September 2006 there were 105 heating degree days and 31 cooling degree days.

The average indoor temperature for the entire temperature record for the mixed season was 70°F. The standard deviation for the entire temperature record was 1ºF, indicating that the variance of the indoor temperature during the mixed season was ±2ºF.

The average indoor relative humidity for the entire relative humidity record for the mixed season was 47% RH. The standard deviation for the entire relative humidity record was 5% RH, indicating that the variance of the indoor relative humidity during the mixed season was ±10% RH.

Overall, during the mixed season, Site D was able to maintain an indoor climate of 70°F ±2°F and 47% RH ±10% RH.

D.7.2 Energy Costs and Consumption During the Mixed Season

As stated, the mixed season for Site D occurred during the month of September 2006. See Table 31 for a presentation of the electricity bill data for the mixed season. During the mixed season, Site D spent a total of $3,364.57 for electrical energy, and consumed a total of 21,120 kWh of electricity. Assuming that 55% of the total energy consumption went to the climate management system, Site D spent an estimated total of $1,850.51 for electrical energy to operate the climate management system during the mixed season, and consumed an estimated total of 11,616 kWh for climate management. Dividing these values by the total floor area of the building indicates that Site D spent an estimated $0.19/ft^2 on electricity to operate the climate management system during the mixed season, and consumed 1.2 kWh/ft^2 of electrical energy.

Electricity Bill Data For Site D During the Mixed Season

Bill Month	**Total Charges**	**Estimated Charges for Climate Management (55% of Total Charges)**	**Total Energy Use (kWh)**	**Estimated Energy Use for Climate Management (kWh)**
SEP 2006	$3,364.57	$1,850.51	21120	11616
Total	**$3,364.57**	**$1,850.51**	**21120**	**11616**

Table 31: Electricity Bill Data For Site D During the Mixed Season.

There were totals of 105 heating degree days and 31 cooling degree days for Site D during the mixed season. Taken together, there was a total of 136 degree days during the mixed season. Dividing the electrical energy costs and consumption per square foot by the total number of degree days divided by 100 yields that Site D spent \$0.14/(ft^2-100 degree days) for electricity and consumed 0.85 kWh/(ft^2-100 degree days) of electrical energy to operate the climate management system during the mixed season.

The heating oil bill data for Site D during the mixed season is presented in Table 32. As explained earlier, it is assumed that Site D consumed 881.9 gallons of heating oil at a cost of \$2.599/gal., leading to an estimated total cost of \$2,291.99 for heating oil during the mixed season. Dividing these values by the floor area of the building yields that Site D spent an estimated \$0.23/ft^2 for heating oil during the mixed season, and consumed an estimated 0.088 gal./ft^2 of oil. Further dividing by the total number of degree days divided by 100 indicates that Site D spent an estimated \$0.14/(ft^2-100 degree days) for heating oil during the mixed season, and consumed an estimated 0.065 gal./(ft^2-100 degree days) of oil.

The heating oil consumption (gallons) was converted to kWh using the conversion factor 1 gal. #2 fuel oil = 40.4 kWh. This conversion gives an estimated energy consumption of 35,668 kWh in the form of heating oil during the mixed season. Dividing this value by the floor area of the building indicates that Site D consumed an estimated 3.6 kWh/ft^2 in the form of oil during the mixed season. Dividing this value by the total number of degree days divided by 100 yields that Site D consumed an estimated 2.66 kWh/(ft^2-100 degree days) in the form of heating oil during the mixed season.

Site D Heating Oil Bill Data During the Mixed Season

Bill Month	Total Charges	Adjusted Total Charges (125%)	Total Consumption (gal.)	Adjusted Total Consumption (125%) (gal.)	Price/gal.	Adjusted Total Consumption (kWh)	Notes
SEP 2006	$1,833.59	$2,291.99	705.5	881.875	$2.599	35667.9	Assumed charges and consumption
Total	**$1,833.59**	**$2,291.99**	**705.5**	**881.9**		**35,667.9**	

Table 32: Site D Heating Oil Bill Data During the Mixed Season.

When the costs and consumption of both electricity and heating oil are combined for the mixed season, Site D spent an estimated total of $4142.50 for climate management, and consumed an estimated total of 47,284 kWh of energy. Dividing these values by the floor area of the building shows that Site D spent an estimated total of $0.41/ft^2 for climate management during the mixed season, and consumed an estimated total of 4.7 kWh/ft^2 of energy. Further dividing by the total number of degree days indicates that Site D spent an estimated total of $0.30/(ft^2-100 degree days) for climate management during the mixed season, and consumed an estimated total of 3.5 kWh/(ft^2-100 degree days) of energy (see Table 33).

Total Energy Costs and Consumption for Climate Management for Site D During the Mixed Season

	Electricity	Heating Oil	Electricity + Heating Oil
Total Cost for Climate Management	$1,850.51	$2,291.99	**$4,142.50**
Total Cost/ft^2	$0.19	$0.23	**$0.41**
Total Cost/(ft^2-100 degree days)	$0.14	$0.17	**$0.30**
Total Consumption (kWh) for Climate Management	11,616	35,668	**47,284**
Total Consumption kWh/ft^2	1.2	3.6	**4.7**
Total Consumption kWh/(ft^2-100 degree days)	0.85	2.6	**3.5**

Table 33: Total Energy Costs and Consumption for Climate Management for Site D During the Mixed Season.

APPENDIX E: SITE E – DESCRIPTION, DATA AND RESULTS

E.1 DESCRIPTION OF SITE E

Site E is located in New York. It is located in two high-rise buildings and takes up several floors in each building, but both buildings also house spaces that serve other functions, such as offices and meeting spaces. Originally constructed in 1995 – 1996, the buildings were gutted and their interiors reconstructed in 1998-2000 to make them appropriate for tight control of the indoor conditions. The climate-managed areas under consideration in this study comprise a library, an archive, an art gallery, and a conservation laboratory – each of which, excepting the laboratory, is located on multiple floors. The total floor area for the climate managed spaces is approximately 46,700 ft^2. The building envelope is comprised of an exterior skin of brick masonry; the interior walls are plasterboard with foil backing to act as a vapor barrier, and insulation. Site E is in an urban setting, it faces the street to the south and has adjacent buildings to the east and west. Other tall buildings also are to the north of the site. Site E is open to the public all year long. The hours of operation are 9:30 AM – 5:00 PM on Monday – Thursday, 9:00 AM – 3:00 on Friday, and 11:00 AM – 5:00 PM on Sunday.

E.2 SITE E – CLIMATE MANAGEMENT SYSTEM

Site E attempts to maintain a constant indoor environment of 69°F ±2°F and 47% RH ±5% RH. Due to the size of the climate managed spaces and the fact that the spaces are located in two separate buildings, Site E's climate management system is complicated. The system uses pre-heat, cooling (which also provides dehumidification), re-heat, and humidification to manage the indoor conditions. Seven air handlers are used to condition the air and deliver it to the indoor spaces of the buildings. All components of the climate management system operate year-round.

The majority of cooling is provided by a chilled water system that uses two gas-fired absorption chillers to create the chilled water, and two cooling towers to receive the rejected heat from the chilled water. Absorption chillers are complicated pieces of equipment, but they basically derive the energy for cooling from combustion, rather than from electricity. The chilled water is pumped into air handlers, which use the chilled water to cool and dehumidify the supply air. Most of the air handlers also have pre-heat and re-heat capability, giving the site tighter control over the temperature and relative humidity of the supply air. One air handler is not fed by the chilled water system. Instead, a direct expansion air-conditioner provides cooling for that air handler.

Humidification is provided both by atomizing humidifiers and by gas-fired steam humidifiers. For all but one on the air handlers, the humidifiers are located in between the pre-heat coil and the cooling coil. One air handler has the humidifier placed after the cooling coil. Two of the site’s air handlers use the gas-fired steam humidifiers to add moisture to the supply air, the others use the atomizing humidifiers.

Heating is provided by a hot water system that uses a gas-fired boiler. The hot water system also feeds the air handlers. After the supply air has been cooled and dehumidified, the hot water system re-heats the air to achieve the proper supply air temperature and relative humidity. For some locations in the site, the hot water system feeds fan coil units or baseboard heating instead of the air handler. One air handler uses electric heating strips, not hot water, to re-heat the supply air.

Because Site E is a modern structure that recently was retrofitted specifically to function as a museum, library, and archival storage space, it falls into ASHRAE's building class V, for which they recommend ducted heat, cooling, reheat, and humidification. ASHRAE's recommended level of control for this type of building in New York's climate is A, indicating an indoor temperature setpoint of 59 - 77°F and tolerance of ±4°F, and an indoor relative humidity of 50% RH ±5% RH are reasonable (see Tables 2 and 3).

E.3 SITE E – PROVIDED DATA

Monitoring data for Site E was provided for the period of January 2005 – December 2005. However, the entire month of February is missing, as well as several days scattered throughout the year. The temperature and relative humidity were measured using a hand held analog device in fourteen locations throughout the two buildings. The temperature and relative humidity were recorded only once per day. While a more consistent record of the temperature and relative humidity recorded once per hour would provide a better understanding of the indoor climate of the site, the provided data are all that were available and will have to suffice.

Site E provided electricity bills and natural gas bills for the period of this study. Luckily, the site's Facilities Engineer already had separated the energy costs and consumption of the climate management system, thus no assumptions will need to be made in determining the cost and consumption of the system, making the data very reliable. Only the energy costs and consumption for the climate management system were provided, the overall costs and consumption for the entire site were not provided.

E.4 SITE E – DIVISION OF SEASONS

By analyzing the engineering climate data[206] for the period of the monitoring data, the heating season lasted from January – May 2005, and from October – December 2005. The cooling season lasted from June – August 2006. Due to the number of both heating and cooling degree days that occurred during September 2005, this month is classified as the mixed season. The engineering climate data is presented in Table 34 and Figure 61.

New York Heating and Cooling Degree Days

Month - Year	Heating DD	Cooling DD
JAN 2005	1225	0
FEB 2005	970	0
MAR 2005	976	0
APR 2005	447	0
MAY 2005	320	3
JUN 2005	4	196
JUL 2005	1	290
AUG 2005	3	315
SEP 2005	34	136
OCT 2005	338	4
NOV 2005	587	0
DEC 2005	1079	0

Table 34: Engineering Climate Data for Site E (source: National Climatic Data Center).

---

[206] Engineering climate data was downloaded from the National Climatic Data Center website: http://www.ncdc.noaa.gov/oa/mpp/freedata.html.

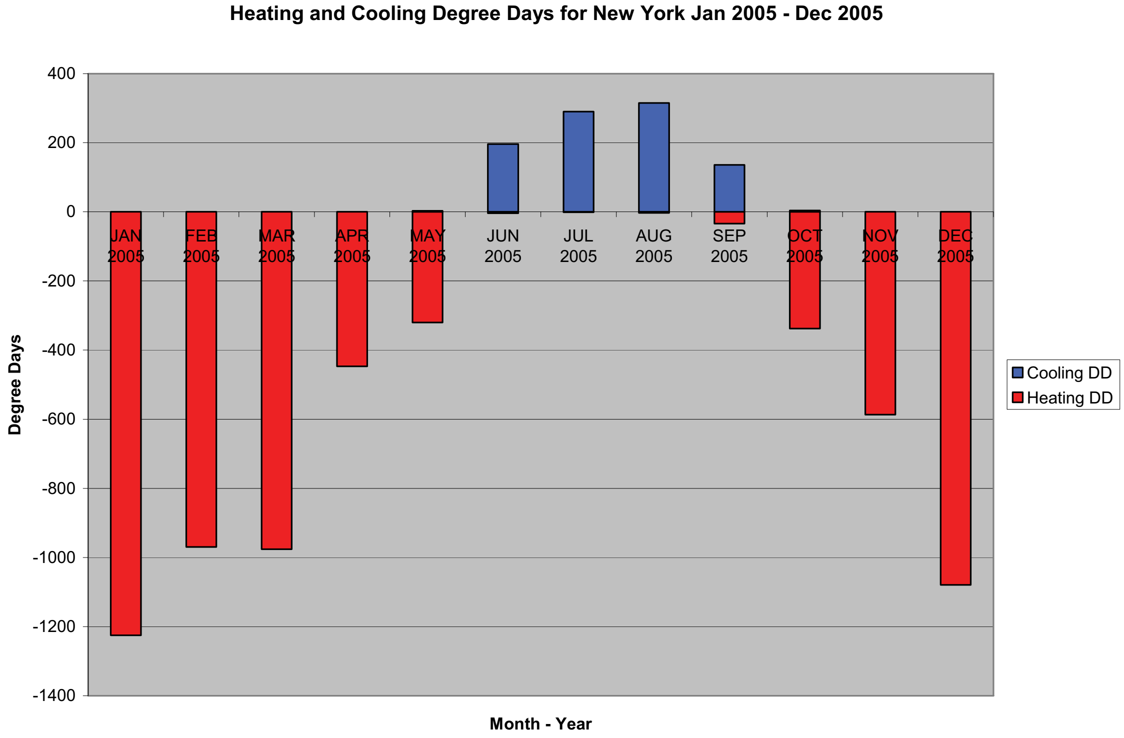


Figure 61: Graph of Heating and Cooling Degree Days for Site E.

E.5 SITE E – RESULTS FOR THE HEATING SEASON

E.5.1 Indoor Environment During the Heating Season

The heating season for Site D lasted from January – May 2005, and from October – December 2005. During this period there was a total of 5942 heating degree days.

The average indoor temperature recorded in Site E's monitored spaces during the heating season was 70ºF. The standard deviation of the entire temperature record during the heating season was 2º, indicating that the variance of the indoor temperature during the heating season was ±4ºF.

The average indoor relative humidity recorded in all of Site E's monitored spaces during the heating season was 47% RH. The standard deviation of the entire relative humidity record was 3% RH, indicating that the variance of the indoor relative humidity during the heating season was ±6% RH.

Overall, during the heating season, Site E was able to maintain an indoor climate of 70°F ±4°F and 47% RH ±6% RH.

E.5.2 Energy Costs and Consumption During the Heating Season

The heating season for Site E lasted from January – May 2005, and from October – December 2005. See Table 35 for a presentation of the electricity bill data for the heating season. During the heating season, Site E spent a total of $273,150.37 on electricity and consumed a total of 1,594,200 kWh of electrical energy to operate the climate management system. Dividing these numbers by the total floor area of the site (46,700 ft^2) shows that Site E spent $5.85/ft^2 for electricity and consumed 34.1 kWh/ft^2 of electrical energy for climate management during the heating season.

Electricity Bill Data For Site E During the Heating Season

Bill Month	Total Charges	Charges for Climate Management	Total Energy Use (kWh)	Energy Use for Climate Management (kWh)
JAN 2005	*	$30,190.04	*	203,880
FEB 2005	*	$29,754.75	*	212,220
MAR 2005	*	$25,969.60	*	191,640
APR 2005	*	$30,225.08	*	198,360
MAY 2005	*	$34,192.38	*	208,860
OCT 2005	*	$36,118.18	*	169,020
NOV 2005	*	$50,553.89	*	222,660
DEC 2005	*	$36,146.45	*	187,560
Total		**$273,150.37**		**1,594,200**

*The total electricity cost and consumption for Site E were not provided.

Table 35: Electricity Bill Data For Site E During the Heating Season.

There was a total of 5942 heating degree days for Site E during the heating season. Dividing the cost and consumption of electricity per square foot by the total number of heating degree days divided by 100 yields that Site E spent \$0.098/(ft^2-100 degree days) on electricity for climate management during the heating season, and consumed 0.57 kWh/(ft^2-100 degree days) of electrical energy.

The natural gas bill data for Site E during the heating season is presented in Table 36. The natural gas consumption was given in therms. For ease of comparison to Site C, which also uses natural gas, the consumption was converted from therms to ccf using the conversion factor 1 therm = 1.031 ccf. During the heating season, Site E spent a total of \$95,458.45 for natural gas to operate the climate management system, and consumed 76,914 ccf of gas. Dividing these values by the total floor area of the site indicates that Site E spent \$2.04/ft^2 for gas and consumed 1.65 ccf/ft^2 of gas to operate the climate management system during the heating season. Further dividing these values by the total number of heating degree days divided by 100 shows that Site E spent \$0.034/(ft^2-100 degree days) for gas and to operate the climate management system during the heating season, and consumed 0.028 ccf/(ft^2-100 degree days) of natural gas.

The natural gas consumption (converted from therms to ccf) was converted to kWh using the conversion factor of 1 ccf = 30.097 kWh. This conversion gives a total energy consumption of 2,314,871 kWh of energy in the form of gas for climate management during the heating season. When divided by the floor area of the site, Site E consumed 49.6 kWh/ft^2 of energy in the form of gas for climate management. Dividing this value by the total number of heating degree days divided by 100 yields that Site E consumed 0.83 kWh/(ft^2-100 degree days) in the form of gas for climate management during the heating season.

Natural Gas Bill Data for Site E During the Heating Season

Bill Month	Total Charges	Charges for Climate Management	Total Consumption (therms)	Consumption for Climate Management (therms)	Consumption for Climate Management (ccf)	Consumption for Climate Management (kWh)
JAN 2005	*	$15,997.02	*	9861	9565	287,863
FEB 2005	*	$13,160.08	*	10,575	10,257	308,706
MAR 2005	*	$12,155.09	*	10,790	10,466	314,982
APR 2005	*	$9,837.09	*	8960	8691	261,561
MAY 2005	*	$12,381.46	*	11,018	10,687	321,638
OCT 2005	*	$7,983.99	*	8525	8269	248,862
NOV 2005	*	$11,939.64	*	10,092	9789	294,606
DEC 2005	*	$12,004.08	*	9477	9192	276,653
Total		**$95,458.45**		**79,298**	**76,914**	**2,314,871**

Table 36: Natural Gas Bill Data for Site E During the Heating Season.

.

When the costs and consumption of both electricity and natural gas are combined, Site E spent a total of $368,608.82 for climate management during the heating season, and consumed a total of 3,909,071 kWh of energy. Dividing these values by the total floor area of the site indicates that Site E spent a total of $7.89/ft^2 for climate management during the heating season, and consumed a total of 83.7 kWh/ft^2 of energy. Further dividing by the total number of degree days divided by 100 yields that Site E spent a total of $0.13/(ft^2-100 degree days) and consumed a total of 1.4 kWh/(ft^2-100 degree days) of energy to operate the climate management system during the heating season (see Table 37).

Total Energy Costs and Consumption for Climate Management for Site E During the Heating Season

	Electricity	Natural Gas	Electricity + Natural Gas
Total Cost for Climate Management	$273,150.37	$95,458.45	**$368,608.82**
Total Cost/ft^2	$5.85	$2.04	**$7.89**
Total Cost/(ft^2-100 degree days)	$0.098	$0.034	**$0.13**
Total Consumption (kWh) for Climate Management	1,594,200	2,314,871	**3,909,071**
Total Consumption kWh/ft^2	34.1	49.6	**83.7**
Total Consumption kWh/(ft^2-100 degree days)	0.57	0.83	**1.4**

Table 37: Total Energy Costs and Consumption for Climate Management for Site E During the Heating Season.

E.6 SITE E – RESULTS FOR THE COOLING SEASON

E.6.1 Indoor Environment During the Cooling Season

The cooling season for Site E lasted from June – August 2005. During this period there were 801 cooling degree days.

The average indoor temperature recorded in all of Site E's monitored spaces during the cooling season was 72ºF. The standard deviation of the entire temperature record was 2ºF, indicating that the variance of the indoor temperature during the cooling season was ±4ºF

The average indoor relative humidity recorded in all of Site E's monitored spaces during the cooling season was 47% RH. The standard deviation of the entire relative humidity record was 3% RH, indicating that the variance of the indoor relative humidity during the cooling season was ±6% RH.

Overall, during the cooling season, Site E was able to maintain an indoor climate of 72°F ±4°F and 47% RH ±6% RH.

E.6.2 Energy Costs and Consumption During the Cooling Season

The cooling season for Site E lasted from June – August 2005. See Table 38 for a presentation of the electricity bill data for the cooling season. During the heating season, Site E spent a total of $107,403.94 for electricity and consumed a total of 611,760 kWh of electrical energy to operate the climate management system. Dividing these values by the total floor area of the building yields that Site E spent $\$2.30/ft^2$ for electricity for climate management during the heating season, and consumed 13.1 kWh/ft^2 of electrical energy.

Electricity Bill Data For Site E During the Cooling Season

Bill Month	Total Charges	Charges for Climate Management	Total Energy Use (kWh)	Energy Use for Climate Management (kWh)
JUN 2005	*	$36,606.15	*	214,500
JUL 2005	*	$37,061.17	*	203,400
AUG 2005	*	$33,736.62	*	193,860
Total		**$107,403.94**		**611,760**

*The total electricity cost and consumption for Site E were not provided.

Table 38: Electricity Bill Data For Site E During the Cooling Season.

There was a total of 801 cooling degree days during the cooling season for Site E. Dividing the electricity cost and consumption per square foot by the total number of cooling degree days divided by 100 reveals that Site E spent $\$0.29/(ft^2\text{-}100$ degree days) for electricity and consumed 1.7 $kWh/(ft^2\text{-}100$ degree days) of electrical energy for climate management during the cooling season.

The natural gas bill data for Site E during the heating season is presented in Table 39. Again, the natural gas consumption for Site E during the cooling season was converted to ccf using the conversion factor 1 therm = 1.031 ccf. During the cooling season, Site E spent a total of $37,468.20 for natural gas to operate the climate management system, and consumed a total of 35,071 ccf of gas for climate management. Dividing these values by the total floor area indicates that Site E spent \$0.80/ft^2 for gas for climate management during the cooling season, and consumed 0.75 ccf/ft^2 of gas. Dividing further by the total number of cooling degree days divided by 100 yields that Site E spent \$0.29/(ft^2-100 degree days) for natural gas and consumed 0.094 ccf/(ft^2-100 degree days) of gas for climate management during the cooling season.

Natural Gas Bill Data for Site E During the Cooling Season

Bill Month	Total Charges	Charges for Climate Management	Total Consumption (therms)	Consumption for Climate Management (therms)	Consumption for Climate Management (ccf)	Consumption for Climate Management (kWh)
JUN 2005	*	$12,181.93	*	11,329	10,988	330,717
JUL 2005	*	$12,495.04	*	12,300	11,930	359,062
AUG 2005	*	$12,791.23	*	12,529	12,152	365,747
Total		**$37,468.20**		**36,158**	**35,071**	**1,055,526**

*The total natural gas cost and consumption for Site E were not provided.

Table 39: Natural Gas Bill Data for Site E During the Cooling Season.

The natural gas consumption (converted from therms to ccf) was converted to kWh using the conversion factor of 1 ccf = 30.097 kWh. This conversion gives a total energy consumption of 1,055,526 kWh in the form of natural gas for climate management during the cooling season. Dividing this value by the total floor area yields that Site E consumed 22.6 kWh/ft^2 in gas, and dividing by the number of cooling degree days divided by 100 yields a consumption of 0.94 kWh/(ft^2-100 degree days) in gas for climate management during the cooling season.

When the costs and consumption of electricity and natural gas are combined, Site E spent a total of $144,872.14 for climate management during the cooling season, and consumed a total of 1,667,286 kWh of energy. Dividing these numbers by the total floor area of the site indicates that Site E spent a total of $3.10/ft^2 for climate management during the cooling season, and consumed 35.7 kWh/ft^2 of energy. Further dividing these values by the total number of cooling degree days divided by 100 shows that Site E spent a total of $0.39/(ft^2-100 degree days) for climate management during the cooling season, and consumed a total of 4.5 kWh/(ft^2-100 degree days) of energy (see Table 40).

Total Energy Costs and Consumption for Climate Management for Site E During the Cooling Season

	Electricity	**Natural Gas**	**Electricity + Natural Gas**
Total Cost for Climate Management	$107,403.94	$37,468.20	**$144,872.14**
Total Cost/ft^2	$2.30	$0.80	**$3.10**
Total Cost/(ft^2-100 degree days)	$0.29	$0.10	**$0.39**
Total Consumption (kWh) for Climate Management	611,760	1,055,526	**1,667,286**
Total Consumption kWh/ft^2	13.1	22.6	**35.7**
Total Consumption kWh/(ft^2-100 degree days)	1.6	2.8	**4.5**

Table 40: Total Energy Costs and Consumption for Climate Management for Site E During the Cooling Season.

E.7 SITE E – RESULTS FOR THE MIXED SEASON

E.7.1 Indoor Environment During the Mixed Season

The month of September 2005 is considered the mixed season, because of the number of both cooling and heating degree days that occurred during this month. There were a total of 34 heating degree days and 136 cooling degree days during this period.

The average indoor temperature recorded in all of Site E's monitored spaces during the mixed season was 71ºF. The standard deviation for the entire temperature record during the mixed season was 1ºF, indicating that the variance of the indoor temperature during the mixed season was ±2ºF.

The average indoor relative humidity recorded in all of Site E's monitored spaces during the mixed season was 49% RH. The standard deviation for the entire relative humidity record during the mixed season was 3% RH, indicating that the variance of the indoor relative humidity during the mixed season was ±6% RH.

Overall, during the mixed season, Site E was able to maintain an indoor climate of 71°F ±2°F and 49% RH ±6% RH.

E.7.2 Energy Costs and Consumption During the Cooling Season

The mixed season for Site E was September 2005. See Table 41 for a presentation of the electricity bill data for the mixed season. During the mixed season, Site E spent a total of $38,936.00 for electricity and consumed a total of 202,920 kWh of electrical energy for climate management. Dividing these values by the total floor area of the site indicates that Site E spent $0.83/ft^2 for electricity to operate the climate management system during the mixed season, and consumed 4.3 kWh/ft^2 of electrical energy.

Electricity Bill Data For Site E During the Mixed Season

Bill Month	Total Charges	Charges for Climate Management	Total Energy Use (kWh)	Energy Use for Climate Management (kWh)
SEP 2005	*	$38,936.00	*	202,920
Total		**$38,936.00**		**202,920**

*The total electricity cost and consumption for Site E were not provided.

Table 41: Electricity Bill Data For Site E During the Mixed Season.

There were totals of 34 heating degree days and 136 cooling degree days for Site E during the mixed season, making 170 total degree days. Dividing the electrical energy cost and consumption by the total number of degree days divided by 100 indicates that Site E spent \$0.49/(ft^2-100 degree days) for climate management during the mixed season, and consumed 2.7 kWh/(ft^2-100 degree days) of electrical energy.

The natural gas bill data for Site E during the heating season is presented in Table 42. Again, the natural gas consumption for Site E during the cooling season was converted to ccf using the conversion factor 1 therm = 1.031 ccf. During the mixed season, Site E spent a total of \$9743.29 for natural gas for climate management during the mixed season, and consumed a total of 9273 ccf of gas. Dividing these values by the total floor area of the site shows that Site E spent \$0.21/ft^2 for natural gas for climate management during the mixed season, and consumed 0.20 ccf/ft^2 of gas. Further dividing these values by the total number of degree days divided by 100 yields that Site E spent

$0.12/(ft^2-100 degree days) for gas and consumed 0.12 ccf/(ft^2-100 degree days) of gas for climate management during the mixed season.

Natural Gas Bill Data for Site E During the Cooling Season

Bill Month	Total Charges	Charges for Climate Management	Total Consumption (therms)	Consumption for Climate Management (therms)	Consumption for Climate Management (ccf)	Consumption for Climate Management (kWh)
SEP 2005	*	$9,743.29	*	9560	9,273	279,076
Total		**$9,743.29**		**9560**	**9,273**	**279,076**

*The total natural gas cost and consumption for Site E were not provided.

Table 42: Natural Gas Bill Data for Site E During the Cooling Season.

The natural gas consumption (converted from therms to ccf) was converted to kWh using the conversion factor of 1 ccf = 30.097 kWh. This conversion gives a total energy consumption of 279,076 kWh in the form of gas during the mixed season for climate management. Dividing this number by the floor area indicates that Site E consumed 6.0 kWh/ft^2 in the form of gas during the mixed season for climate management. Dividing further by the total number of degree days divided by 100 yields that Site E consumed 3.5 kWh/(ft^2-100 degree days) in the form of gas for climate management during the mixed season.

When the costs and consumption of electricity and natural gas are combined, Site E spent a total of $48,679.29 for climate management during the mixed season, and consumed a total of 481,996 kWh of energy. Dividing these values by the total floor area of the site shows that Site E spent a total of $1.04/ft^2 for climate management during the mixed season, and consumed a total of 10.3 kWh/ft^2 of energy. Further dividing by the total number of degree days divided by 100 shows that Site E spent a total of $0.61/(ft^2-

100 degree days) and consumed a total of 6.1 kWh/(ft^2-100 degree days) for climate management during the mixed season (see Table 43).

Total Energy Costs and Consumption for Climate Management for Site E During the Mixed Season

	Electricity	**Natural Gas**	**Electricity + Natural Gas**
Total Cost for Climate Management	$38,936.00	$9,743.29	**$48,679.29**
Total Cost/ft^2	$0.83	$0.21	**$1.04**
Total Cost/(ft^2-100 degree days)	$0.49	$0.12	**$0.61**
Total Consumption (kWh) for Climate Management	202,920	279,076	**481,996**
Total Consumption kWh/ft^2	4.3	6.0	**10.3**
Total Consumption kWh/(ft^2-100 degree days)	2.6	3.5	**6.1**

Table 43: Total Energy Costs and Consumption for Climate Management for Site E During the Mixed Season.

INDEX